Separation of bricks and mortar using pressure waves

PhD thesis

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Abstract

This thesis describes a series of investigations performed to determine the possibility of separating bricks and mortar using pressure waves.

A study of the current brick recycling practised within the UK was performed. This study identifies a need for improved brick reclamation processes.

Initial investigations were performed using one-sixth scale couplets. The one-sixth scale bricks and mortar could be separated by placing them in an ultrasound bath. Further investigations were performed to determine the vibrations that would be necessary to recreate the separation of one-sixth scale couplet using an ultrasound bath at full scale. Based on these investigations, a prototype designed to separate full scale couplets was constructed. A series of specimens were tested in the prototype and the vibrations passing through the specimens were recorded. These results showed that the prototype was able to achieve vibrations at the intended frequency and amplitude within the specimens. However, no separation occurred and therefore it was concluded that this process was not appropriate for brick reclamation of full scale bricks in this manner.

An investigation of the bond strength developed between the bricks and mortar of one-sixth scale and full scale couplets was performed. It was found that the full scale specimens developed a bond strength greater than that developed in the one-sixth scale specimens.

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1. Introduction

1.1. The Use of Masonry

Man has used masonry for many centuries. It was among the first construction techniques used to build structures to protect man and his possessions. Over time, man's creativeness has allowed improvements to be made on this basic process, for example the shaping of rocks into square blocks, the use of clays and sand as primitive mortar, the use of geometry such as the arches to give additional strength. More recent years have seen the development of mass-produced bricks, and the introduction of reinforced brickwork and modern mortars. This permits a modern masonry structure to be engineered to achieve the properties required for a specific project. Today man has the ability to build an almost limitless range of structures using bricks and cement.

Perhaps the main reason for the use of masonry construction throughout history, and today, is its flexibility, which allows the standard masonry construction methods to be adapted to the particular requirements of each individual construction project. This flexibility makes masonry construction a method that is suitable for many different applications, and man has certainly taken advantage of this. Of all the construction techniques used down the ages, there are more masonry structures that remain intact today; this provides us with an insight into the robustness of masonry construction built by previous generations.

It is possible to build a masonry structure without any mortar, and rely on the self-weight and the shape of the blocks to keep the structure stable. This kind of construction is used to construct the traditional dry stone walls that are still used today in the Yorkshire Dales. They are made using naturally occurring stones that are carefully laid so that they interlock and the integrity of the wall is maintained. The walls are only used to define the extents of individual fields and do not have any additional load to support, so they do not need mortar to provide extra strength and stability. However, as there is no mortar to hold all the stone components together, the walls are easily damaged and require regular maintenance to keep them in good condition. A superb example of mortar-free masonry construction is the Pont Du Gard, a Roman aqueduct built under the orders of Marcus Agrippa when he was the governor of Gaul in the years 19 and 20 BC[1]. Although the Romans did later use an early type of cement, this aqueduct is 275 m long and rises 49 m above the River Gardon in Southern France and was built without cement. Instead, the structure gains its stability from the inherent strength of the arches, as each block is held in place by the weight of the blocks next to it. The individual blocks that make up the aqueduct weigh as much as six tonnes each. It is a tribute to the engineering abilities of the Roman builders that they could build such a structure and that the aqueduct remains today in its original form.

Masonry construction has not been considered to be the standard method for some engineering construction projects for a long time. The completion in 1779 of the bridge at Ironbridge meant that many engineers began to build iron bridges instead. In turn, this construction method was superseded by several new technologies, and bridges today are most commonly made from reinforced concrete and steel. The only reasons to construct a masonry arch bridge today would be historical or aesthetic, as a reinforced concrete bridge could be built at a lesser cost and in a quicker time. Concrete and steel are also the basis for the modern multi-storey office blocks and apartment complexes that are often built in town centres to maximise the floor space that can be created on a small "footprint". There are significant advantages to this method. The main advantage is the speed with which the project can be completed. The building is based on large components that can be prefabricated and only assembled onsite, reducing the time taken for the erection of the building. These prefabricated members can be made while the site is prepared, which saves a large amount of time. It is possible to build a structure in this manner that retains the appearance of a traditional masonry by cladding it with pre-stressed masonry panels. This means that for some building projects the use of masonry in the traditional manner is no longer a viable construction method. However, there is still a large amount of masonry construction work being performed today. Importantly, masonry remains the usual method for the construction of standard housing units and other small buildings, so masonry construction remains a significant construction process within the UK. In addition, existing masonry structures require maintenance work in order to keep them in a satisfactory condition. This includes obligation from legislation "to ensure that any changes or additions do not adversely affect the essential character of the building or its setting" [2] Hence it can be a legal requirement for repairs to be performed using traditional masonry techniques. There will thus be a considerable amount of construction and maintenance work to be performed with masonry and it should not be considered obsolete or unworthy of development for many years to come.

1.2. Background for the investigation

Population expansion and increasing affluence in developing nations and "societal changes" in developed countries are causing a need for the provision of an increasing number of dwellings. In the UK, centuries of building mean that the availability of "Green Field Sites" is becoming increasingly limited. In order to protect the remaining countryside, many UK urban areas are surrounded by "Green Belts" to prevent urbanisation migrating into the undeveloped area around them, and in undeveloped areas it is becoming difficult to get planning permission for Green Sites. This leads to the need to concentrate on building on previously developed, or "Brown Field", sites. Of course, the first requirement of constructing "new build" on any Brown Field site is the complete removal of any previously existing structures. Buildings have a design life of at least 50 years, and the large capital cost mean that demolishing a relatively new building is not financially acceptable. However there are many buildings in the UK which were built 100, 200 or even 300 years ago that are becoming "worn out" and difficult to keep in a sound structural state. The majority of old buildings are not "flexible" enough to be adapted for modern uses. These structures are mostly built using traditional brickwork and hence the structures most "suitable" and available for demolition in the next 100 years will mostly be brickwork structures.

This leads to the problem of removing these existing structures efficiently, safely and without damage to any reusable materials. Currently, the common practice for the removal of old masonry structures involves using heavy machinery to knock down the structures and break them up into small pieces. Whilst many of the materials that are present in old building have potential recycling value, once the structure is knocked down in this manner these materials are damaged and mixed together. The difficulties of selecting and separating the recyclable materials from the general debris that remains after a building is levelled make any attempt at recycling much more difficult and reduces the economic viability of the process. Instead, any hazardous material will be removed for safe disposal and the remaining material will be transported to a landfill disposal site and dumped. This process is far from ideal, because of the negative environmental effects of landfill, and because the materials that are being dumped often have high potential to be re-used. Ideally, it should be possible to perform a careful demolition of an old building (known as a de-construction) so that all the parts of the building that have the potential to be recycled can be removed undamaged for reuse and recycling.

Currently, only a very small percentage of demolitions includes any attempt at significant recycling. If a structure contains materials that can be easily removed, which are of high market value, they may be removed prior to demolition. For example, old roof tiles with a distinctive aged appearance just need to be removed from the roof before demolition and can then be sold to customers who are specifically looking for old roof tiles in order to construct new buildings with an old character. In the UK many people are attracted to the idea of owning an "old" house, which means that such houses command a high price. However, old houses do not come with the modern facilities that the people looking to buy houses want as well. Newly built houses that can be made to look "old" by using reclaimed materials can provide both the "old" appearance and the modern facilities, which increases their market value. This means that recycled materials that can be re-used in a new build to give the new structure a characteristically old appearance are also of high enough value to potentially make recycling them worthwhile. The properties of bricks make them well suited to recycling as they are very durable, not easily damaged, and can remain in storage without any special conditions for a long time without suffering any degradation. However, bricks from demolished structures are much harder to recycle because after demolition they are still held together in the mortar in large fragments of brickwork. In order for them to be reclaimed, it is necessary to develop a process to separate these fragments of masonry into the original brick and mortar components. Currently the author knows of no such technology that can achieve this aim, other than manual chiselling. Therefore the principal idea behind this project is to examine the way in which the methods available for the recycling of the bricks within brickwork buildings could be improved. Currently, the recycling of bricks is very limited, but the author believes that with the right technology brick recycling could become commonplace and give huge economical and environmental benefits.

1.3. Objectives and scope of investigation

The objective of the investigation is to develop new techniques that will make brick recycling a more attractive process to those carrying out the demolition of brickwork structures. The main obstacle to such recycling is the process of separating the bricks and the mortar so that the bricks can be re-used. In addition, it is necessary to achieve this at a cost that is competitive with that of dumping the masonry rubble and manufacturing new bricks. If this could be achieved, then marketing the proposal to large demolition companies would be plausible, and if the methods were widely adopted, the environmental and economic benefits could be of significance. Hence the scope of this project is the investigation of any existing processes and the evaluation of any new techniques to that might be able to achieve mortar separation.

Ideally, the separation process should work on most of the different types of bricks and mortar. However, the most important conditions to consider initially are those that are most commonly present at demolition sites today. Hence the investigation should begin by considering the separation of bricks and mortar from the old buildings that are most often demolished. This means giving prime consideration to masonry consisting of handmade bricks and lime mortars. If the separation process developed is only successful on certain types of bricks or mortar, that in itself may still be worthwhile, with further necessary development depending on the occurrence of those conditions in structures that are demolished. For the technology to be attractive to industry it will need to be able to deal not just with purpose made masonry units but also with chunks of masonry in odd shapes that would result from a demolition. It would also need to be capable of separating a large number of bricks in a reasonable amount of time if it is to be suitable for industry. However, in the initial stages of the investigation any process that can separate bricks and mortar is of interest, and worthy of further development.

1.4. Layout of the thesis

This thesis is divided into nine chapters.

Chapter 1 details the background for the study and outlines the objectives and scope of the research.

Chapter 2 is a review of literature, which is sub-divided into three sections. The first section presents a brief history of the use of brickwork. The second section considers the properties of the different types of brickwork construction. This section has two additional subsections that consider the variations in bricks and mortar, the two main components of brickwork.

Chapter 3 presents the theory upon which the study was based. The first two sections detail the process that occur when the bonds that hold brickwork together are formed and how they can be broken. The remaining sections of Chapter 3 provide theory and information on the processes occurring within an ultrasound bath.

Chapter 4 presents two investigations that were performed to provide information on the response of bricks and brickwork when they are subjected to vibrations. The first section details test that were designed to investigate the ability of the waves produced within an ultrasound bath to separate one-sixth scale couplets. The second investigation was performed using full scale bricks. Impact tests were performed on individual full scale bricks to allow speed at which waves travelled through the bricks and the natural frequency of the bricks to be determined.

Chapter 5 outlines the process that was followed to produce a prototype designed to produce the range of frequencies that the experiments performed in Chapter 4 had indicated would give the best potential for separating full scale brickwork. It also details the principal considerations during the construction process and the health and safety issues involved during operation of the prototype.

Chapter 6 details the experiments that were performed with the prototype. The prototype was used to determine the vibrations caused within a full scale couplet when it was subjected to waves with different frequencies. This allowed the frequencies that produced the greatest vibrations within the specimens to be determined. These frequencies occurred within the range that was determined to be the most effective during Chapter 4. However, no signs of separation were observed during the testing and it was conclude that the prototype was not able to separate full scale couplets.

Chapter 7 details the bond wrench testing program that was performed on both full scale and one-sixth scale couplets to identify the differences between the power required to separate the couplets at different scales.

Chapter 8 is a discussion of the work that was performed and Chapter 9 presents the conclusions of the research, and details the potential for further research to be performed in the same area.

2. Review of Literature

2.1. History of brickwork

It is commonly believed that prefabricated clay units were first used in hot countries, when mud and clay were allowed to dry in the sun until they became hard so they could be used as building materials. According to Pliny[3], the first "bricks" and tiles were baked in Cyprus by Cinyra, son of Agrippa, although he fails to specify a date for this event. In his historical notes on the contents of theLangley Museum in London, Dobson[4] records a 230 × 190 mm tile from Greece which he claims must date from 1800 BC or before, and that they "are probably the oldest baked clay roof tiles that have been identified anywhere in the world". Examples of Greek buildings made using brick and tile can be found throughout much of southern Italy and Sicily, such as the temples at Paestum, near Naples. Here there is also a tomb, the Hypogean Scaellum, which is tiled with 20 large clay tiles. In "*Roman brick and tile*" Broadribb[5] claims that these tiles are the oldest tiles that remain in situ in the world.and indicates that by the 6th Century BC the use of tiles and bricks had been adopted by Roman engineers, who built buildings with brick walls and tiled roofs extensively through out the Empire. He identifies different types of tiles and five types of brick that were commonly used by the Romans. In addition, Broadribb[5] provides details and drawings of how each type of brick was used, and gives locations of structures that can still be found today in the areas that formed part of the Roman Empire. For example, the brick type first discussed is Bessalis, square bricks that were usually used to build *pilae* (columns or piers) such as those that would support the suspended floor above the hypocaust. The name "Bessalis" comes from the Roman word Bes, which means "two thirds of a unit". There are 12 Roman inches (*unicae*) in a Roman foot (*pes*), and the Bessalis were 8 Roman inches, or two thirds of a foot square. A Roman foot is 11.64 English inches, so it was not very different from the English foot. There is a considerable variation in the sizes of the Bessalis that have been found. The biggest was found in London, and measured 235mm whereas Bessalis measuring 170mm have also been found. The other brick types used by the Romans also varied in size. The typical sizes of the different bricks and Tiles used in Roman construction can be found below in Figure 2-1.

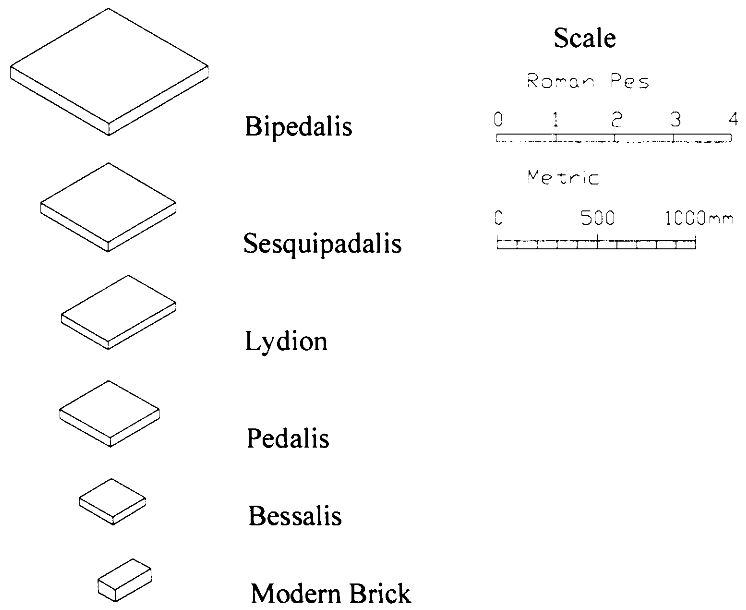


Figure 2-1. Scaled isometric drawings of the bricks types in Roman Buildings (from Broadribb [5])

It is difficult to be precise about the methods the Romans used for making bricks because over time the methods they used would have been modified and improved. It is known that they made their bricks from soils dug from shallow pits in the earth or riverbanks and they fired them in basic kilns. The Roman conquest of Britain that began in AD 43 brought with it the first bricks to be used in the UK.

When the Roman occupation of Britain ended in AD 412, the British people looted bricks from the Roman buildings and used them in their own constructions, although there is no proof that they made their own bricks at that time. Roman engineering and construction skills were far more advanced than the countries they occupied, but as the Roman empire collapsed it was rare for the liberated people to take advantage of the new technologies that the Romans had introduced. Instead they tended to return to the traditional technologies and ways of life that they had been following prior to the Roman invasion. However, it is known that bricks began to be imported into Britain from Flanders and Holland, and sometime during the 13th Century it is believed that bricks were once more manufactured in the UK. At this time some improvements had been made on the process used to manufacture bricks. The bricks were made in wooden moulds, but there was no defined size for a brick, and so brick manufacturers were free to make them at a size of their choosing. The bricks were still fired in a kiln similar to the kilns that had been used by the Romans, although coal was now available. However, coal was a new product and was expensive, so the fuel used would still usually be wood, charcoal or turf. The bricks that could be made in early kilns would vary in quality, as there was no way to regulate the firing process. Instead, the bricks were placed in the kiln, which was then lit and the bricks were fired until the fuel was all spent. There would be a large variation in the firing of each brick in the kiln depending on its position in the kiln. Bricks in the centre of the kiln would often be over-fired, causing them to become cracked and brittle. Bricks at the edges of the kiln would be under-fired, and fail to achieve their maximum potential strength. These problems would cause some of the bricks to develop unacceptable flaws, and some would be thrown away. There was a large variation in the bricks produced within the UK, as their properties were influenced by the use of different practices. The brick makers would use the clays that were available locally, and this would affect the colour and material properties of the bricks produced.

A variety of different moulding techniques and firing processes were also used. However, although the use of bricks in the UK increased, it was not until 1571 that the first laws to control the quality bricks were passed. These laws determined that bricks should all be the same size, and defined the size of a brick to be 229 × 115 × 51mm. Since this first law, there has always been a size specified in the UK for the prefabricated brickwork unit called a brick. A major improvement was made to the brick manufacturing process in the 17th century when the horse-powered pug mill was introduced. Before this technology the raw components of the bricks had to be mixed by hand, which was time consuming and caused problems in the brick if the mixture was not mixed to a sufficiently homogeneous material. However, the use of a horse-powered pug mill reduced the preparation time and ensured that the raw materials were properly mixed into an even workable mass before being moulded. The decreed size of bricks was changed in 1725 and again in 1776, when they were required to be 215 × 102.5 × 65mm. In 1784 a brick tax was introduced, but the numbers of bricks being produced still continued to rise. As the price of coal began to fall in the 18th Century it became commonly used in the brick firing kilns and the greater temperatures that could be achieved by the coal fired kilns allowed stronger bricks to be produced. At the beginning of the 19th Century the first machines to make bricks were developed to cope with the high demand. These machines were used to shape the raw material into the brick shape. Several different methods were developed; including various pressing and wire cut processes. The mechanisation of the processes used in the manufacturing of bricks allowed bricks to be produced to a constant specification. As technology advanced, machines performed more and more of the brick manufacturing process, and today very few bricks are not entirely machine made.

2.2. Properties of brickwork

The commonly accepted definition of a brickwork structure is one that is made using construction methods which utilise prefabricated brickwork units. The units can be laid in various ways and are usually joined together in a matrix of mortar. There is a huge number of brickwork buildings made using a range of different construction techniques standing in the world today. Brickwork construction is very flexible, and can be tailored to fit most design briefs using a variety of different materials and techniques which have been developed over many years.

The positioning of the brickwork units during construction influences the characteristics of a brickwork structure. Brickwork units are usually laid in a set pattern or "bond" throughout the structure. The bonds that are most frequently used in brickwork within the UK are shown in Figure 2-2.

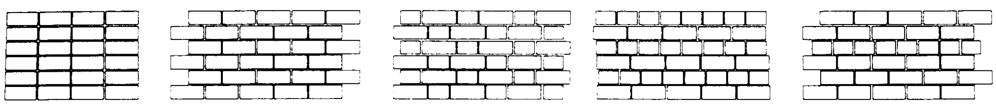


Figure 2-2. Bonds commonly used for brickwork according to BS 5390:1976 [6].

The bond can be used to change the appearance of brickwork, and different bonds can be used in adjacent areas to improve the appearance of the structure. More importantly, the bond can influence the failure mechanism of the brickwork. When brickwork begins to fail visible cracks are typically formed running through the mortar around the bricks. Most bond patterns ensure that the joints between the bricks in adjoining courses are not aligned, as this would create a line of weakness within the brickwork.

The process by which the mortar hardens and bonds with the brickwork units is termed curing. There are a large number of factors that influence the strength that is gained by the mortar during curing. The environmental conditions in which the curing process takes place affect the strength that the brickwork actually develops. Different mortars require different conditions in order to achieve their maximum strength. A typical modern mortar will cure most effectively in a moist environment, as this ensures that there is sufficient water within the bricks to maintain the chemical process that occurs within the cement as it hardens (see Section 3.1). The pressure with which the wet mortar is pressed against the brickwork units during curing is known as the "confining pressure". The magnitude of the confining pressure is largely dictated by the brickwork and any other dead loads above, so it is usually dictated by the height of brickwork that is laid.

All developed countries publish standards giving details of how brickwork should designed and constructed. The flexibility[i] of brickwork makes it a construction method suitable for a wide range projects, but it also leads to variations in different brickwork structures that make it difficult to develop a standard to govern brickwork constructions. Until the 1950's calculations concerning load-bearing brickwork were solely based on approximate empirical formulae and hence walls were built with conservative thickness. Further work has allowed modern standards to prescribe much more accurately, although the variations in the properties of brickwork structures limit the total reliance on direct calculations, and so the design codes still contain formulae derived from experiments performed on brickwork elements.

The variations in brickwork structures occur because of the properties of bricks[ii] and mortar, as outlined in the two previous sections above, and also because of the composite nature of brickwork structures. The different ways in which the two components can be used together make brickwork more complicated than a homogeneous material such as steel. So, for example, a simple calculation to quantify the failure load of a simple solid square steel column would need to consider the cross sectional properties of the column, the strength of the steel being used and the degree of fixity at the ends of the column. The equivalent calculation for a brickwork pillar would be much more complicated, and, according to Hendry[7] would be related to the square root of the nominal brick crushing strength and the third or fourth root of the

[i] The adaptability of brickwork, allowing it to be suitable for a wide scope of applications
[ii] Or other prefabricated masonry unit

mortar cube strength. In fact, if a simple brickwork couplet is placed in compression and the load is increased, the resulting failure is not caused by compression, but instead by tension. The geometric properties of the mortar and the "bricks" influence the strength of the whole brickwork unit. The ratio between brick depth and mortar thickness has a significant effect on the strength of a brickwork column.

2.3. Properties of bricks

The current standard size for bricks in the UK is 215 × 102.5 × 65mm, and only prefabricated brickwork units which adhere to this size may be called bricks. Figure 2-3 shows the dimensions of a brick and gives the names of the three faces.

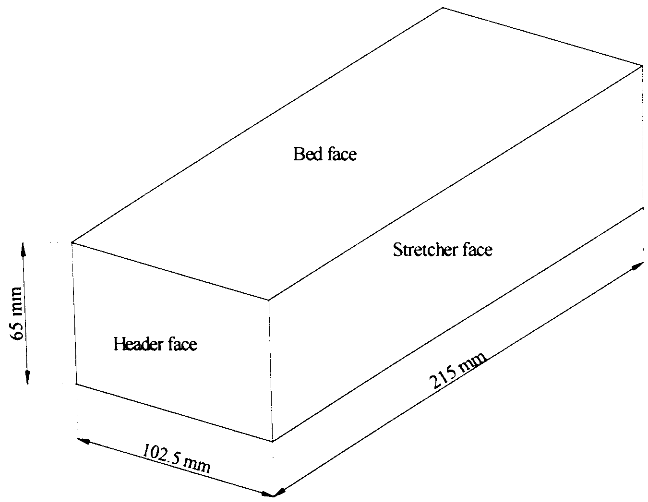


Figure 2-3. The dimensions and names for the faces of a brick

There is a second defined unit, the block, which is any squared unit with a size greater than 337.5 × 225 × 112.5mm. Although there is a specified size for both bricks and blocks, they can be made from a wide range of different materials using a variety of manufacturing processes. There is a wide range of bricks available, and they can be classified by considering a number of different properties, as shown in

Figure 2-4. Many bricks are constructed with voids, as shown in Figure 2-5. The presence of voids within a brick can give a number of advantages. Voids through the middle of the brick improve the distribution of heat throughout the brick during the firing process. This helps to ensure that each brick is fired evenly, even when a large number of bricks are fired in a large kiln together. When a structure is built from brick with perforations or frogs, mortar will enter the voids. This improves the connections between the bricks, and hence the load capacity of the structure. The presence of a void reduces the quantity of raw materials required, thus reducing the economic and environmental cost of the brick. It also reduces the weight of the brick, making them easier to manipulate and reducing the cost of transportation.

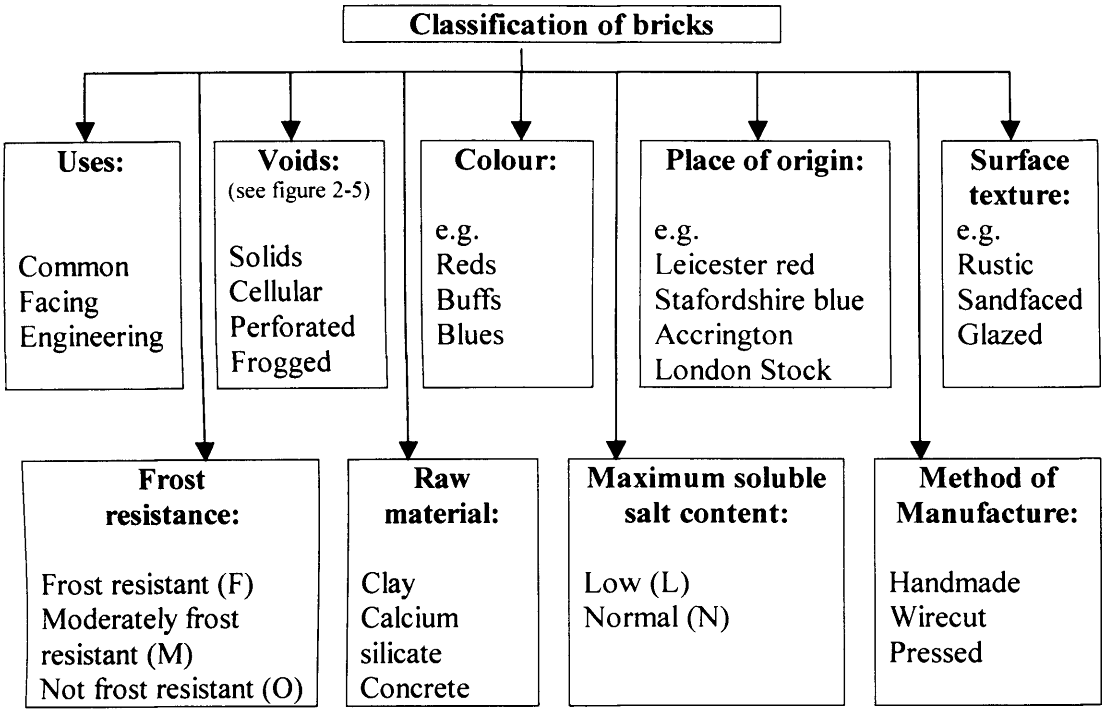


Figure 2-4. The classification of bricks (taken from Boon Seng [8])

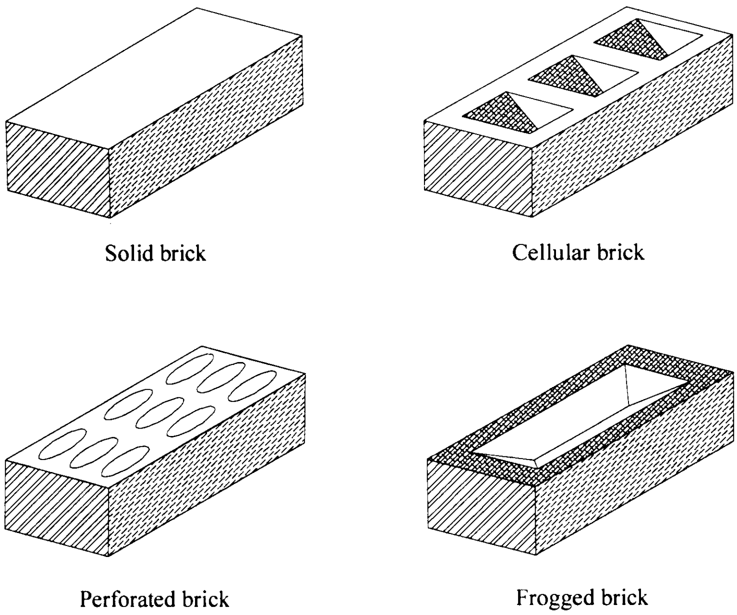


Figure 2-5. Common void types found in bricks

It is material properties of the brick that are likely to be of most interest to an engineer, as they will largely determine its structural capability. A brick can be manufactured to meet a specification desired by the designer by manipulating the materials and manufacturing processes used to produce the brick. Some material properties that a designer may specify are listed below.

- Compressive strength

The first property usually considered when designing a structure using bricks is the compressive strength of the brick. This will usually be the most influential property of the brick on the strength of the brickwork. The manufacturer would always be expected to provide a minimum compressive strength for the bricks they supply, and a designer could use this figure if it were necessary to perform any calculations on the structure.

- Absorption

All bricks contain pores, and during the firing process all the moisture is removed from the brick, leaving these voids full of air. However, when the bricks are removed from the kiln the pores will begin to absorb moisture from the atmosphere again. If a brick is placed in an environment where the moisture content in the surroundings is greater than the water content within the pores in the brick, the brick will absorb moisture until an equilibrium is achieved. The absorption properties of a brick concern the rate at which moisture is absorbed and the quantity of water that can be absorbed into the pores.

- Frost resistance

Bricks that are saturated are vulnerable to frost attack if the temperature falls low enough. As the water within the brick turns into ice and expands, it can cause the brick to crack. A regular freezing/thawing cycle will be most damaging, and can lead to complete disintegration of the brick. Frost damage is not usually a problem for general brickwork in the UK as the rainfall does not saturate the bricks and the temperature does not regularly fall below zero.

- Thermal movement

The amount of expansion/contraction of a brick due to any increase/decrease in the temperature of the environment is only a concern if the expansion joints provided are not adequate, or the bricks are going to be subjected to large temperature changes, or if there is a special need to limit any expansion. This is not an issue for brickwork constructed using lime mortar, as lime mortar is flexible enough to allow for any thermal expansion that occurs.

- Moisture movement

The expansion/contraction of the brick due to an increase/decrease in the humidity of the environment needs to be considered if there is a special need to limit expansion, or if the brick is likely to be subjected to significant changes in moisture levels.

- Fire resistance

This is the ability of the brick to resist the effects of fire allowing the structure to resist collapse in the event of a fire. All fired bricks have a good level of fire resistance compared to other construction materials because of the temperature they endure during the firing process, but some bricks are made from special materials so that they can withstand particularly high temperatures.

- Soluble Salts

Sulphate attack

Salts within the brick can cause complications if certain conditions are present within the structure. If the brick remains persistently saturated sulphates from the brick can be absorbed into the water, which can then react with the tri-calcium aluminate in Portland Cement of the mortar as the water passes the joint. This will cause damage and weakening of the mortar, and can significantly reduce the strength of the mortar. This effect can be reduced or prevented by minimising the quantity of the offending salts within the brick.

Efflorescence

When water evaporates from a surface it will leave behind a crust of any soluble salts it contained. When this process occurs with soluble salts from the interior of the brick being deposited on the surface of the brick, it is called efflorescence. This often occurs on brickwork as a new building dries for the first time after construction, and a white deposit develops on the surface of the bricks. The colour of the efflorescence will depend on the salts, but it is usually white and some salts may cause some damage to the brick.

- Acoustic properties

For some specialist buildings it may be necessary to consider the acoustic characteristics of the bricks in order to achieve the desired acoustics within the building.

There are different kinds of brick available, but clay fired bricks are the standard for brickwork construction within the UK, and are the only type of brick used in the testing performed for this study. The UK standard regulating the quality and use of clay-fired brick is BS EN 771-1 2003 [9], and this divides clay bricks into three classes. Common bricks are used for general building purposes, such as standard housing units, where there are no particular special requirements. Facing bricks are available in a variety of colours and textures and can be used to give a desired appearance in order to increase the visual appeal of the structure. Engineering Bricks have increased strength and density, with defined absorption and strength parameters, so that they can be used for high loads or in difficult or harsh conditions e.g. below the damp proof course.

Clay bricks are usually graded with regard to their frost resistance and their soluble salt content. There are three frost resistance categories, although only two types are commonly used within the UK. Those with little or no frost resistance are given a frost rating of O, and are only used for interior walls. The next category is M, which signifies medium frost resistance. In the UK, the generally mild weather conditions mean that these bricks can usually be used for exterior walls without any problems. The bricks with the best frost resistance are given a frost resistance classification of F, and can be used where the potential for frost damage is high. In the UK it would only be necessary to use these bricks if they were likely to be continuously saturated. In countries where the temperature often fluctuates around zero degrees it would be necessary to use frost resistance category F bricks for all exterior brickwork. Additionally, clay bricks are also graded with regard to their soluble salt content. Any brick without controlled levels of soluble salts is categorised as S 0, but bricks that meet defined limits for soluble salt content can be categorised as S 1 or S2, shown in Table 2-1.

Category	Sodium and Potassium	Magnesium
S 0	No requirement	No requirement
S 1	0.17 %	0.08 %
S 2	0.06 %	0.03%

Table 2-1. Permissible active soluble salts content categories (from BS EN 771-1:2003 [10])

After clay bricks, the next most commonly used type of brick are calcium silicate bricks. Calcium silicate bricks are used much less often than clay bricks throughout the UK, but in some other countries they are the most commonly used brick. Despite their lack of popularity within the UK, the British Standard BS EN 771-2:2003 [10] covers Calcium Silicate bricks so they are an alternative choice for brickwork constructions within the UK.

In addition to clay bricks and calcium silicate bricks modern buildings also frequently use lightweight blocks. The usual way of making make a lightweight block is to manufacture the block in a way that ensures there is a large amount of air voids into the block. The low density of the blocks means that they can be larger than normal bricks with out becoming too heavy for one man to lift comfortably. There is a variety of concrete blocks available, which are all designed to give properties favourable to brickwork construction. They have good insulation value and the greater size of the blocks means that fewer blocks need to be laid to make a structure, reducing the construction time. However, the air voids make such blocks more porous than standard bricks, and it is generally accepted that a brickwork construction made from blocks is not very aesthetically pleasing. After the second world war in the 1940s it became the standard practise to build the walls of standard buildings with two layers, concrete thermal blocks on the inside, and bricks on the outside. The inclusion of a cavity between the two skins of a wall provides additional insulation and permits sufficient airflow to enable any moisture that penetrates the wall to evaporate. Using a combination of blocks on the inside with a brick exterior allows the aesthetic benefits of bricks and the practical benefits of block to be exploited within a single structure.

Brickwork construction also includes the use of any other pre-manufactured brickwork units as well as the use of fired bricks. The term pre-manufactured does not just include materials that are initially soft and hence have to be fired; natural materials that are already hard when they are extracted are also included. Some materials can simply be extracted in a form that is already suitable for use in brickwork construction. The material most commonly used in this way in the UK is stone, which is regulated by BS EN 771-6 :2001[11]. Some types of stone are more suited for use in brickwork construction than others, depending on the properties of that type of stone. Although most stones have a more than adequate compressive strength, many types of stone are porous and would allow the ingress of water. In addition, some types of stone are so hard that they are difficult to quarry and hence they are not a practical alternative to fired bricks. However, in areas where there was an abundant local supply of stone that was well suited for building, the majority of the old buildings may be made from stone. In some stone buildings all the stones were cut and shaped to a standard size, but often stones structures are constructed with stones of varying sizes, which were carefully placed in the wall so that they fitted together neatly. Stone structures were more commonly built in the UK before mass produced cheaper bricks became available. Today it is rare for new constructions to be built from natural stone and it would only occur if there were overriding aesthetic or planning reasons making the use of other materials inappropriate.

2.4. Properties of mortars

The majority of brickwork constructions use some form of mortar to hold the bricks in position. Mortar is a mixture typically consisting of cement and sand and lime mixed together with water. Additional ingredients, such as air entraining agents, retardants, pigments and plasticisers are also frequently added to modern cements. Placing mortar in between the prefabricated brickwork units fills any voids that exist and compensates for any size irregularities. The correct use of mortar allows the construction of a level uniform structure that provides a good level of protection from the elements, even if irregular bricks are used.

Mortar is found in two different forms. Traditional lime mortar was used in brickwork construction for many centuries. Around 1900, the first Portland Cement was invented, and Portland Cements are used in most brickwork structures today. Traditional lime mortars gain only a small amount of strength compared to that of Portland Cement mortar. They also retain a good deal of flexibility and porosity even a long time after the lime has been applied. These three characteristics are advantageous to old buildings, as they allow some movement to occur in the structure without cracking occurring. Hence the structural members of the building have some freedom to move slightly without causing structural failure.

The properties of the different ingredients all affect the characteristics of the mortar, and hence it is possible to design a mortar to meet the requirements for a particular construction project. This means that a designer can determine the characteristics of the mortar needed for a project, and a suitable mix can be produced to meet the specification. Some of the properties that a designer might consider specifying are listed below.

- Compressive strength
- Workability
- Frost resistance
- Resistance to chemical attacks
- Retention of water
- Appearance

The most important ingredient of mortar is the cement and ordinary Portland cement is usually used, although specialist cements, such as those that gain strength rapidly or can resist sulphate attack, are also available. The compressive strength of mortar is most closely related to the water/cement ratio. The effect of the water cement ratio on the crushing strength of a cube is shown in Figure 2-6.

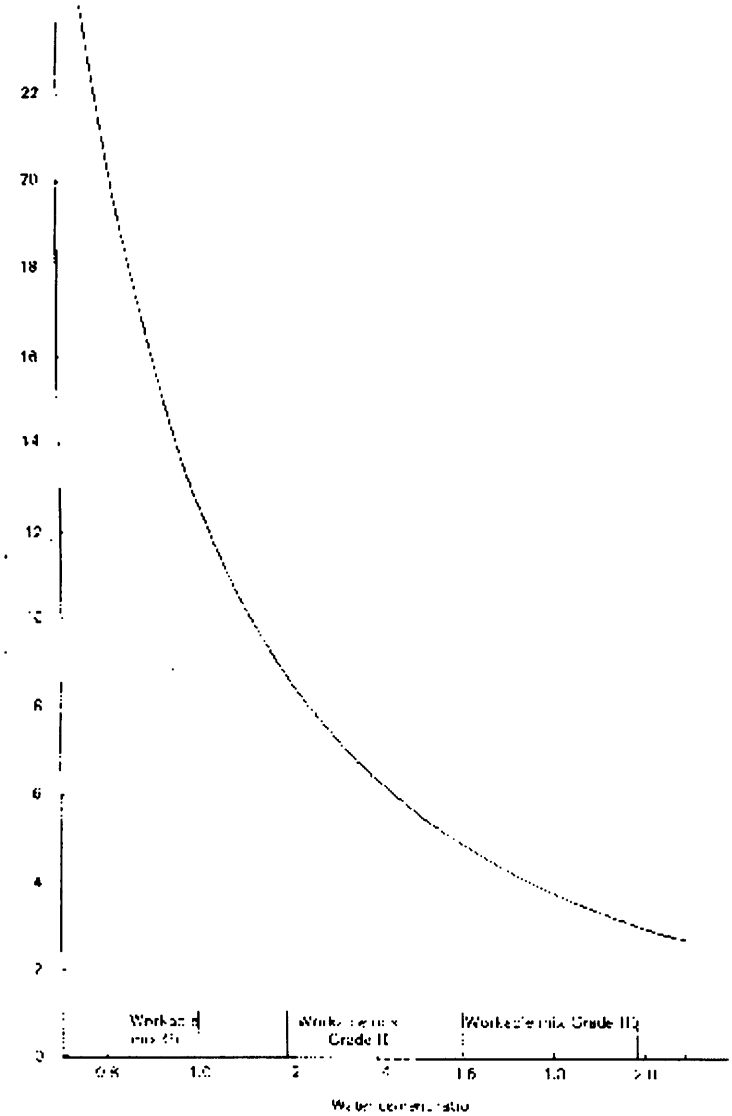


Figure 2-6. Effect of water cement ratio on the compressive strength of mortar of grades I, II and III, taken from Hendry [7]

The amount of water added to the cement determines the workability of the mortar. Mortar needs to be viscous enough to allow it to be worked onto the bricks, and to allow the bricks to bed down into the mortar. However, if too much water is added, the strength of the mortar will suffer, and the time the brickwork takes to set fully will increase.

The proportions of the different components that make up the mortar also influence the properties it will develop. If an exact mix is required, a designer may specify the ratio proportions of the materials that are to be used. However, it is more likely that the designer will instead specify a standard mix that is commonly used. The British Standard that was used during this project was BS 4551 [12], although this has since been partially replaced by BS EN 998-2:2003 [13]. However, both these standards provide the same information and instructions for mixing the five grades of mortar. The mix proportions used in the mortars specified by the standard are shown in Table 2-2.

Grade	Lime mortar				Non-lime mortar	
	Cement	Lime	Sand	Water (ml)	Cement	Sand
1	22.9	1.5	75.6	175	22.8	77.2
2	17.0	3.1	79.9		20.5	79.2
3	13.6	5.1	81.3	196	14.0	86.0
4	9.0	6.4	84.6		10.5	89.5
5	7.1	8.0	84.9	213	9.8	90.2

Table 2-2. Mortar mixes specified in BS 4551 [12], all proportions are detailed by mass percentage.

Following the process described in the BS 4551 means that the properties of the mortar will meet the values detailed in the standard. Therefore, by instructing the builder to use one of the mixes specified in Table 2-2 above, a designer can ensure that the mortar will meet the properties that he has used when performing the design calculations. In addition, some manufacturers also supply information with their materials that details the properties that will be developed when certain other mix proportions are used.

Different types of sand also influence the qualities of the mortar. The sand should not have too many impurities as these may react with the cement and prevent the full strength of the mortar from being developed. Use of a fine sand makes the mortar more workable, but reduces the compressive strength of the mortar. The sand should meet the particle grading defined in BS 1199 and1200:1976[14] and shown in Figure 2-7 below.

BS sieve	Percentage by mass passing BS sieves	
	Type S	Type G
mm		
6.30	100	100
5.00	98 - 100	98 - 100
2.36	90 - 100	90 - 100
1.18	70 - 100	70 - 100
μm		
600	40 - 100	40 - 100
300	5 - 70	20 - 90
150	0 - 15	0 - 25
75	0 - 5[a]	0 - 8[b]

[a] 0 – 10 % for crushed stone sands
[b] 0 – 12 % for crushed stone sands

Figure 2-7. The grading details for sands defined in BS 1199 and1200:1976

Lime can also be added to mortar in order to increase the workability. It also affects the water retentivity and how the mortar bonds to the brick. There are two types of lime that can be added to mortar, hydraulic lime and non-hydraulic lime.

Additional ingredients can be added to mortar to increase its workability, reduce susceptibility to frost or change the colour of the mortar.

2.5. Brickwork Recycling

In recent times it has been acknowledged that the habits of the expanding global population is placing increasingly unsustainable demands on the finite natural resources of the Earth. One of the main ways of extending the use of the Earth's resources is recycling. Recycling is usually used as a general term for re-using an item in a productive manner and not disposing of it as waste material. Hence re-using bricks in their original form and re-using crushed bricks as a fill material are both considered recycling. The term reclamation is used more specifically to mean the re-use of materials in their original form; hence this precludes bricks that are crushed before they are re-used.

Currently work is underway to ensure that future constructions can be deconstructed in a way that allows as much of the materials as possible to be recycled when the building is no longer wanted. However, this work will not yield any benefits until the buildings constructed using these methods are ready for demolition. There will be a large number of bricks that will be available for recycling in the intervening period. Hence, it is perhaps more important that attention is drawn to the buildings that are being demolished today. These buildings were built before the importance of recycling was recognised, so how they could be carefully dismantled was not considered in their design. Recycling materials from these buildings is not straight forward, and it generally involves more consideration to recycle the materials than to dispose of them as waste. This means that often no attempt is made to recycle any materials during demolition; and hence the quantity of bricks recycled within the UK today is very small. The bricks that are discarded are not only a large resource that is not exploited, but they also increase the quantity of waste that is produced, adding to the economic and financial costs of disposing them acceptably.

2.5.1. Existing brick recycling

It is difficult to achieve a reliable estimate of the amount of construction waste and the amount of recycling that currently takes place in the UK. It is necessary to recognise that the estimates given later are based on limited data, and further work would be needed to establish reliable figures. In 1991 Arup[15] estimated that some 70 million tonnes of demolition rubble and construction waste were generated annually. The study concluded that 44 million tonnes (or 63% amount of the total amount) was recycled in some form or other. However, these figures were based on all demolition rubble and construction waste, and no figures were given for individual materials such as bricks.

More recently, the BigREc[16] survey was performed in 1998. This data is now more than five years old, but there are no current plans to update or repeat the survey because of a lack of funds. The survey was conducted on behalf of Salvo and the UK government Department of the Environment, Transport and the Regions. It was based upon information gathered from questionnaires sent to relevant companies in the UK. The report suggests a figure of 100 million tonnes for the total amount of construction waste generated (this figure was estimated in a previous study performed by Arup) and estimated that 8.1 million tonnes of construction waste is reclaimed or recycled per year. These figures indicated that no attempt was being made to recycle more than 90% of the construction waste generated in the UK.

It is likely that since the BigREc report the amount of bricks that are recycled today has increased, but there is no recent data to support this. The bulk of the BigREc report consists of paragraphs giving details for each type of material. The section on bricks states that each year some 2500 million bricks are available for recycling as the structures they were part of are demolished. It states that between 600 and 1,200 million bricks are crushed and re-used as a fill and approximately 140 million bricks are reclaimed and sold at brickyards. However, independent approaches via the Brick Development Association have indicated that they believe the figure of 140 million overestimates the amount of bricks that are reclaimed. The BigREc report estimates that there are some 2,500 companies recycling and reclaiming building materials and architectural antiques within the UK and that these companies had a combined turnover of around £1 billion in 1998. Based on these figures, in the region of half the bricks available for recycling are discarded as waste.

The BigREc [16] report goes into further detail and considers how the bricks are re-used when they have been reclaimed. The majority of recycled bricks pass through small wholesale yards and are sold in small numbers (typically less than six thousand bricks) to private customers and the small scale construction industry. It reports that these brick wholesale companies typically have a stock in their yards of around some 29,000 handmade, 21,000 wire cut and 9,000 machine-made pressed bricks. Most of the materials reclaimed travel only short distances (usually within 50 miles) to local recycling yards and are ultimately resold to private customers. The survey reports that the quality of reclaimed bricks tends to be poor, and found that only three quarters of the bricks sold had one clean end and one clean face, and only five percent had any frost resistance guarantee.

The BigREc [16] report highlights the two different ways in which bricks can be recycled. These two methods and the end products produced are very different, and it is necessary to understand how both of these methods are applied within the UK. The most common way in which bricks are recycled is by crushing them and using the resultant material as a hardcore fill. A large amount of energy is needed in order to crush bricks, which means that heavy machinery is required. There is a range of crushing machinery available that is designed to crush materials such as brickwork, concrete and stone. These machines are expensive and require a lot of room to operate, so they are only appropriate at sites where there is a large amount of the appropriate material available for crushing. The crushing process is simple, and any brickwork chunks can be fed through the crusher without the need to separate the mortar and bricks. After crushing, the material will be uniformly graded and much easier to transport than demolition rubble. Hardcore is not a valuable material, and the cost of running a crushing machine is considerable. However, if there is a large amount of brickwork rubble to be removed, the substantial cost of transporting it to a landfill site and tipping can be avoided.

There are several web-based systems that provide information on reclamation and salvage companies within the UK. The Salvo Website[17] provides information on architectural or garden antiques and reclaimed building materials. The website has recently been updated, and now includes a database of dealers and restorers which includes many companies that reclaim bricks, postings for demolition jobs and theft alerts. In addition, the site also includes a materials exchange scheme, which allows users to advertise reclaimed materials they have available for sale, or to put in a request for a particular item that they would like to acquire. There are entries for companies looking to buy and sell a variety of reclaimed bricks in this way on the website.

Recently a new web-based system to locate appropriate recycling companies has been launched. The Smartwaste Website[18], was launched to "help the Construction Industry to identify cost savings, improve resource use, improve productivity" and offers four tools to "help your company apply the concept of sustainable waste management". One of the tools available on the website is BREMAP[19], a system which allows the user to locate recycling and waste management services in a county or within certain distances from any given postcode. Figure 2-8 below shows a map taken from the BREMAP, showing the location of recycling activities near Aylesbury, including Site 77, a typical example of the brickyards that sell reclaimed bricks.

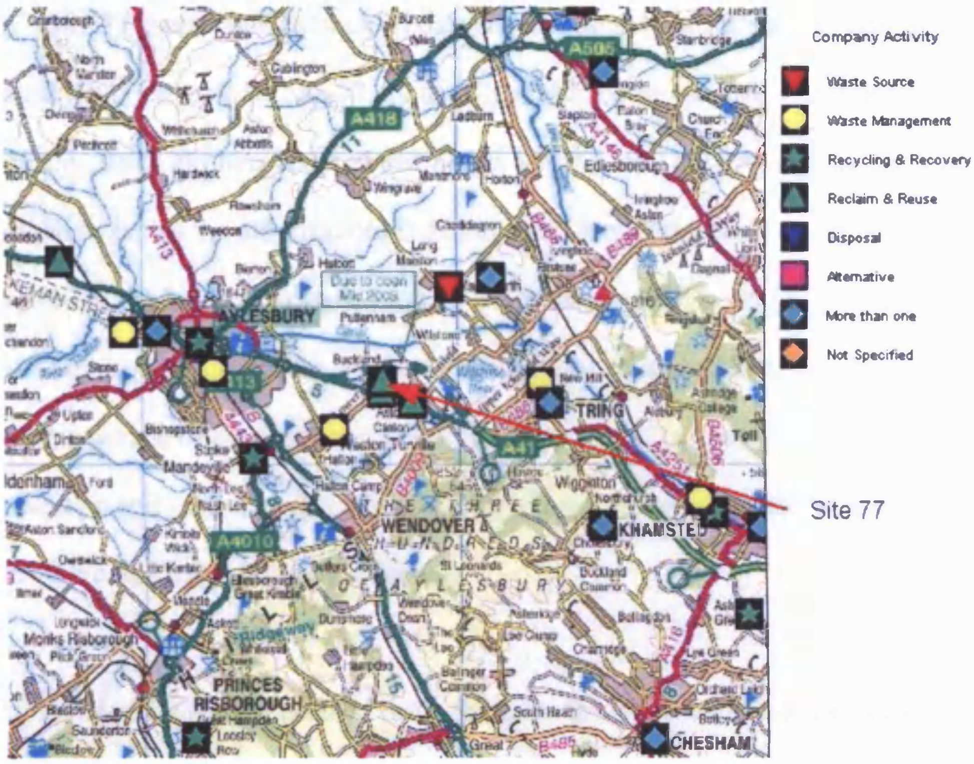


Figure 2-8. BREMAP, showing the location of Site 77
(reproduced with permission from the BRE)

Site 77 is situated on just over one acre of hard standing (of which 840 square metres is under cover) on a small industrial park that is shared with several other small companies near Aylesbury. There are three main types of brick available at Site 77, handmade, wire cut and multis, and each have a distinctive appearance. Details on the bricks that were available when the author visited the site are detailed below, although it must be stressed that the bricks available at Site 77 change depending on the demolition work that is being performed in the area. In addition, Site 77 also sells other reclaimed materials, such as timber, slates, tiles, door and window fittings and architectural antiques.

Site 77 is essentially a brick wholesaler and carries out little demolition work; instead the bricks sold by Site 77 are usually reclaimed by another demolition company. Brick cleaning is not performed at Site 77; they are prepared at the demolition site as the old structure is demolished. Any damaged bricks and mortar removed as the bricks are cleaned can be left at the demolition site. This reduces the cost of transportation and the need to dispose of the mortar. When demolition work begins, a sample of the reclaimed bricks is sent to Site 77 in order for the product to be checked and valued, and if a priced is agreed the reclaimed bricks are delivered to Site 77 where they are displayed for sale.

When a building is deemed ready for demolition, a brick wholesaler such as Site 77 would attempt to predict the worth of the materials that could be reclaimed and sold on. Items of value that can be reclaimed are known as "credits" and a contractor will be willing to carry out the demolition for a low price if the value of the credits in the building is high. Indeed, some buildings may have such a high credit value that contractors will pay for the right to carry out the demolition because the money generated by the reclaimed materials will cover the cost incurred in the demolition process and leave a profit. However, only items that can be easily reclaimed as the building is demolished have any value. If the masonry in the building was constructed using a modern hard cement, it is currently very difficult to remove the mortar from the bricks without causing damage. A demolition contractor will therefore only consider the value of the bricks in a building if it was built using a soft lime mortar, which can be easily removed now because it is old and weak. With experience, it is possible for the contractor to form an opinion on the strength of the mortar by performing a simple penetration test with a sharp instrument. If the mortar is weak enough, it is preferable for the building to be demolished by hand a brick at a time, so each brick can be individually cleaned and placed on a pallet as it is removed. If the mortar is too strong to allow the individual bricks to be removed by hand, the walls can be pushed over with machinery, and the force of the fall will loosen bond between the bricks, allowing them to be picked up and cleaned by hand. This method will cause damage to some of the bricks, and may render some unsuitable for reclamation, so this method is only used when absolutely necessary. The mortar is subsequently removed from the bricks by hand using a small light hand axe (see Figure 2-9) and an experienced person can clean some 1000 bricks in a day.

Figure 2-9. Typical hand-axe used to clean lime mortar from bricks

The most valuable items in a building are usually the bricks, but roofing tiles and timber are also frequently reclaimed. Many people believe that a wall of modern bricks looks too featureless, whereas a wall constructed with old bricks will have more character. In conservation areas the use of reclaimed bricks may be stipulated to ensure that the new building fits in with the appearance of the surroundings. In addition, if it is necessary to perform repairs or extensions to existing structures, reclaimed bricks can be used to ensure the appearance of the new brickwork matches the existing structure. This can enable new work to be completed without spoiling the aesthetics of the structure.

The most expensive bricks available at Site 77 were the oldest bricks that were made by hand. For example, there was a large number of handmade bricks called soft reds on sale at a price of £0.80 per brick,[iii] although they can command prices up to as much as £1 per brick at other yards. The soft reds were handmade by skilled craftsmen, and the soft red bricks at Site 77 have retained a shape that would allow them to be used for building work. However, there were some soft reds at Site 77 that have chipped corners and roughly shaped edges as it can be seen in Figure 2-10. These defects are likely to have been caused by the reclamation process and during transportation to the brickyard rather that during the initial manufacturing process.

[iii] Prices provided by staff at Site 77 and relate to the time of the visit in 2001.

Figure 2-10. Close-up of soft red bricks

As with all the other bricks, the units still have some mortar remaining on the surfaces of the bricks, but the author was assured that the bricklayer can simply place the new mortar over the remaining old intact mortar when the bricks are reused.

The second most expensive type of bricks on sale at Site 77 were known as "multis", because of their multicoloured appearance. These bricks were commonly made by unskilled craftsmen, who took little care in the construction process. There were often lumps of foreign material in the bricks, because a common method of reducing cost at that time when the bricks were made was to crush old bricks and mix them in with the new bricks before firing. As a result, all the multis on sale at Site 77 were very poorly shaped, with rough edges and missing corners. The poor shape and irregularities in the brick surfaces mean that it would be difficult to use them in building work. However, a skilled bricklayer could use most of the bricks by patching the holes in the bricks with mortar and laying the bricks so that the damaged areas would not affect the appearance of the structure. Despite this, the author suggests that some of the multi bricks that were on sale at Site 77 would not be suitable for the construction of anything more than a simple structure which requires little strength or precision, such as a garden wall.

The cheapest bricks available were wire cut bricks. These were not as old as the more expensive bricks, but they appeared to be better quality than the multi bricks, and similar to the soft reds in terms of the shape they have retained. They were similar in colour and appearance to modern bricks, whereas the hand-made soft reds have a noticeably different colour and texture. Like the multi bricks, some of the wire cut bricks also contain foreign materials as shown in Figure 2-11.

Figure 2-11.Wire cut brick containing foreign material

Whilst the shape of both the soft red and wire cut bricks would not prevent them from being used as if they were new bricks, the strength properties of the recycled bricks is variable. No quality control regarding the strength of the bricks is usually perform at the recycling yard; the principle applied is that if the bricks were part of an original structure that remained stable for 100 plus years, they should be strong enough to be used today. This principle does not always guarantee success, especially if the bricks are not used in the same manner as they were originally used, or have been damaged during the reclamation process. When buildings are demolished, the bricks are not graded in any way, so some of the bricks that were part of internal walls in the original structure may be recycled and used externally. Operators at Site 77 ask what the intended use of the bricks will be, and try to avoid selling bricks that are inappropriate to the customer. In addition, experienced bricklayers will select the bricks that are judged to be most suitable for exterior use from those suitable only for internal use. If this selection is not made correctly and bricks that were used internally are used externally in new build, the bricks would be subjected to a much greater attack from frost and other weathering processes than they were prior to being recycled. The author suggests that it is not always reasonable to assume that a structure built from recycled bricks will be structurally sound simply by assuming the recycled bricks would have the same specifications as modern bricks.

It is possible to increase the strength of reclaimed bricks to match the properties of new bricks produced today. Previous work at Cardiff University [20] was performed to determine if the strength of a brick could be improved by re-firing them. The investigation was performed using Laybrook Red Multi-stock Pavers, but the same process would give an increase in strength for any clay bricks, including reclaimed bricks. Seven bricks from a batch delivered to the university for research purposes in 1997 were used, each of which was cut down to produce a number of specimens one-sixth the size of a normal brick. The specimens were examined with a electron scanning microscope and a chemical analysis was performed on four specimens taken from each full sized brick. This provided information on the initial properties of the brick, which could be used as a benchmark to determine any effects of re-firing. The elements found in the bricks (in order with the greatest first) were Aluminium, Silica, Iron, Potassium, and titanium. This order was correct for each of the samples bar one, in which the iron content was greater than any other element. It is hypothesised that this anomaly occurred because that sample was obtained from very close to the surface of the original brick, where there is more iron to give the brick the red colour.

An investigation into the possibility of improving the strength of bricks by re-firing to a greater temperature, or by soaking the bricks in a solution and then re-firing was detailed. One-sixth-scale bricks taken from the same full-scale brick were re-fired to temperatures of 1000, 1100 and 1200^{0}C, and an electron scanning microscope was used to examine the surfaces of the bricks. The surfaces of the bricks were compared with the benchmark one-sixth-scale bricks, which were not re-fired. At 1000 °C and 1100 °C, fewer voids were present in the surface of the brick, and those that remained were smaller than the voids in the benchmark bricks. At 1100 °C glassy smooth areas that had developed during the re-firing process were also identified. The surface of the bricks re-fired to 1200 °C is very different in appearance to the other surfaces, and it is suggested that the bricks had begun to melt. A series of one-sixth-scale bricks were then soaked in a chemical solution for 2 hours before being re-fired. The solutions used were magnesium sulphate, calcium sulphate and sodium chloride. When these bricks were compared with the benchmark under the microscope, it was found that the bricks had an increased magnesium or calcium content depending upon the additive that had been used.

The report contains the results of mechanical tests completed to determine if the additive and/or re-firing process improved the structural properties of the bricks. The tests on re-fired bricks showed that the specimens re-fired at temperatures of 1000°C and 1100°C had gained in strength. The test on bricks soaked in additives and then re-fired at 1000°C showed an increase in strength of the brick for all the additives used, although this could simply be due to the re-firing process. However, since some additives gave greater strength increase than others, it was concluded that some additives must give an increase in compressive strength. However, the environmental and economic cost of the re-firing process will reduce the savings that can be made by reclaiming the bricks. The author of this thesis estimates that re-firing bricks in this manner takes over 40% of the energy required to manufacture new bricks (see energy calculations in Appendix E). Therefore it will be preferable to reclaim bricks that can be re-used without being re-fired.

2.5.2. Re-use of mortar

In order to recycle brickwork as efficiently as possible, it is necessary to consider not only the bricks that are recovered, but also the mortar. It is important to acknowledge the potential for the recovered mortar, instead of thinking of it as a by-product of the brick reclamation process.

There is little potential for the re-use of traditional lime mortar. The properties of the traditional lime mortar within old buildings vary a great deal. There was no defined standard for the production of the traditional lime mortar, giving a large variation in the proportions and quality of the materials used. There is also a large variation in the "hardness" of the lime mortar found in old buildings. The texture of the mortar can be crumbly on the exposed faces and soft and flexible within. The variation in the properties of the traditional lime mortar found in old buildings would make it difficult to develop a process to allow traditional lime mortar to be re-used. In addition, the quantity of brickwork made with traditional lime mortar is small compared to brickwork made with modern cements and as very little new build is constructed with traditional lime mortar. Hence there is very little demand for the reclamation of lime mortar from masonry.

However, there is considerable need for reclamation of brickwork made with modern cements, and mortar based on a Portland cement is better suited to recycling. After the bricks and mortar have been separated, the recovered mortar will largely consist of small pieces of mortar. It may also include some irregularly shaped chunks of mortar, depending on the method of separation used. The mortar could simply be used as a fill material in this form. However, with some processing the value of the recycled mortar could be increased. In order to prepare the mortar for recycling, it is likely that the first step would require the chunks of mortar to be crushed, reducing the mortar to a constant consistency. After this process is performed the material produced would be the same regardless of the separation process employed. Hence recovered mortar from many different sources could be mixed, and processed together before reuse.

The crushed mortar recovered from recycled brickwork consists of the materials that were mixed to make the mortar, so the ingredients present in the greatest quantities are sand and modern cement. Perhaps the first application that should be considered for the processed mortar is as a replacement for sand in new mortar of concrete. It should be possible to replace a large proportion of the sand within a mortar or concrete with the recycled mortar without any degradation in performance. In fact, the strength of the mortar or concrete made with recycled mortar may even be improved. When cement hardens, there are always some particles that do not fully hydrate. Un-reacted particles within the recycled mortar would be likely to increase the rate of curing and improve the strength of the bonds formed between the sand particles. The economic value of recycled mortar that was appropriate for re-use in this manner would be greater than the value of a fill material in the current market.

However, the reduction in the quantity of sand required for concrete and mortar production would achieve environmental savings, because the quantity of sand requiring extraction from the earth would be reduced.

However, work would be required to study the effects that the additives present within recycled mortar may have on the new concrete and mortar. For example, the workability of new concrete or mortar could potentially be affected if it was made with a recycled mortar that contained impurities.

2.6. Potential for increased brickwork recycling

Since people first became aware of the potential problems that were being created by the rapid use of non-renewable resources, there has been increasing recognition of the need to promote and practise recycling. Today, most governments throughout the world are adopting policies aimed at maximising recycling within their country. Despite this, the majority of waste materials requiring disposal today are deposited at landfill sites. The landfill process involves placing waste materials in large holes in the ground until the capacity of the site is reached and soil is placed over the top of the waste material. In its guide "Managing and minimising construction waste[21]" the Institution of Civil Engineers acknowledge that the construction industry is responsible for producing around half of the waste that is disposed of in landfill sites.

The problems with landfill are numerous and wide-ranging and the cost of landfill is increasing due to current sites becoming full and higher standards of management are required when the site is opened and greater pollution control now exists when the site is eventually closed are now required[22]. In 1990 the UK government published a white paper entitled "This common inheritance"[23] and began its attempts to encourage sustainable development. In 1994 "Sustainable development – the UK strategy[24]" was published, which included the waste management hierarchy reproduced in Table 3-1 below.

Most favourable	1 Reduction	By using technology which requires less material in products and produces less waste in manufacture, and by producing longer lasting products with lower pollution potential.
	2 Reuse	For example: returnable bottles and reusable transport packaging
	3 Recovery	Finding beneficial uses for waste including: Materials recycling to produce a useful product Composting – creating products such as soil conditioners and growing media for plants Energy recovery – producing energy by burning waste or by using landfill gas
Least favourable	4 Disposal	By incineration or landfill without energy recovery

Table 3.1 - The waste management hierarchy [24]

The reclamation and re-use of bricks falls into the second category of Table 3.1, crushing and recycling bricks is in the third, and disposing of bricks in landfill site is the fourth and the least desirable option. Therefore the re-use of bricks in their original form is the most favourable option for bricks that can be recovered from an existing building when it is demolished. Crushing bricks for re-use as a hardcore fill is still preferable to dumping them in landfill, which should be avoided if at all possible.

In 1996 the UK government published a National Waste Strategy "Making waste work"[25] which set out the series of targets below.

- To stabilise house waste productions levels at 1995 levels
- To reduce the proportion of controlled waste going to landfill to 69% by the year 2005
- To recover 40% of municipal waste by the year 2005
- The provision of close to home recycling facilities for 80% of the households by the year 2000
- For 40% of domestic properties with a garden to carry out composting by the year 2000

The government has remained committed to increasing taxation on landfill[26] to encourage alternative methods of waste disposal. In addition to increasing taxes on the disposal of old bricks, there will also be rises in the taxes levied on the extraction processes involved in the production of new bricks. The main constituents of new bricks are clay and shale. Extracting such raw materials from the earth lead to a negative environmental impact. The increased production cost to "offset" the extraction tax is passed on to the cost of newly manufactured bricks, which would give reclaimed bricks a greater saving potential.

Brick reclamation is currently only practised at small yards and the majority of bricks used in construction in the UK are new bricks manufactured by the larger companies. However, with the future rises in land fill and extraction tax charges intended by the government, recycling will offer a way for brick manufactures to save an increasing amount of money in the future.

There are important savings to be made by practising all forms of recycling, but additional advantages apply if the bricks are reclaimed. Reclamation is usually preferable to recycling, because there is less energy expenditure involved in changing the materials into their new form and the end product is usually more valuable. A large amount of energy is required in the process used to manufacture new bricks, and so there is a large potential saving if reclaimed bricks were used instead. Re-using bricks in a crushed form does not make this saving, and therefore is less efficient (hence the potential economic and environmental saving is less). Despite this, crushing bricks is far more common in the UK than any other recycling process at this time.

In order to use bricks for reclamation, it is necessary for the items to be in a suitable condition for them to meet a standard fit for re-use. The durability of bricks means that they will remain in a suitable condition for reclamation for a long period of time even if they are stored outside. However, additional care must be taken during the demolition process to ensure that the bricks are not damaged. This involves performing a careful demolition of the old structure without the excess use of heavy plant, which increases the time it takes for the demolition to be completed. In addition, it is necessary to remove most of the old mortar from the brick so that the faces are clean enough to allow the bricks to be re-laid successfully. There are problems with the current methods used in small brickyards, which are detailed above in Section 2.5.1. Unless the mortar is weak and soft it is too difficult to remove it from the bricks using a hand axe. The harder the mortar, the longer it takes to clean each brick, and more mortar will remain on the bricks, making them less suitable for reuse. Cleaning bricks in this way is labour intensive and the labourers need experience[iv] in order to clean the brick well enough to make them suitable for reuse. In addition, any new construction that is planned for the site after the demolition of the existing structure can not begin until all the bricks have been removed and cleaned. This is a big disadvantage as there are often tight deadlines set for the completion of new buildings that do not allow the necessary time to clean and reclaim the bricks from the old structure. These limitations mean that this kind of recycling process can only be used when demolishing an old building on a site that is not needed for immediate redevelopment, and only then when the bricks that can be reclaimed are worth enough money to cover the cost of the skilled labour required to recover them. However, the reclamation methods used in the UK, at brickyards such as Site 77, are very simple. With the application of modern technology it may be possible to develop a new process that does not suffer from these problems.

The UK construction industry could make a significantly large reduction in the amount of the bricks that are currently placed in landfill sites by reclaiming more for re-use, using methods such as those used by Klang et al [27]. This would have a significant effect on the total amount of waste placed in landfill site in the UK. Furthermore, the author believes that if further development was performed to improve the current methods of brick recycling the financial savings would make it economically worthwhile for companies to make the investment needed to adopt recycling technology. However, it is likely that it would be difficult to persuade

[iv] Typically an hour of training and a day of supervision

companies to invest in recycling technology without seeing a demonstration of the processes working successfully on a large scale and proof of the resulting financial savings. It is the development of the new technology and persuading a company to give it an effective trial that will be the most difficult stages to achieve.

2.6.1. *Possibilities for new brick recycling technology*

The author believes that many industries, including the brick industry, could be improved by adopting recycling processes. The prime difficulty to overcome is persuading the relevant industries and individuals to adopt any new recycling technologies and carry them out effectively. Companies usually require proof that there are savings to be made by adopting the technology before they will consider making the necessary investments. It is difficult to develop successful recycling techniques without financial investment and it is usually very difficult to obtain funding for projects to develop recycling techniques. This has meant a worrying lack of research into recycling techniques for demolition material and construction waste.

Klang et al [27]performed a case study considering the environmental, economic and social aspects of recycling and re-using steel, bricks and porcelain sanitary ware. An "electronically-powered hydraulic machine with steel edges" manufactured by KomServ was used to reclaim the bricks. Two people were needed to operate the machine, and two other people brought the bricks to the machine and stacked the cleaned bricks onto pallets. The emissions required to generate the electricity to power the machine were compared with the emission generated during the creation of new bricks. In this way it was found that the environmental impact of reclaiming the brick was only a small fraction of the potential impact of primary production. During the study the reclaimed bricks were re-used on site, and no transport was necessary.

However, using data from a previous study by Klang et al. it was calculated that it would be possible to transport the bricks a distance of 15000 – 20000 km before the CO_2 emissions would become similar to those produced during the manufacture of new bricks. Additional calculations performed in Appendix E based on information provided by Klang show that reclaiming bricks using this process used less than one percent of the energy required to manufacture new bricks. This clearly shows that environmental savings could be made re-using bricks using this method.

A workforce of four was needed to operate the brick cleaning machine, which therefore incurred a high wage bill. The labour costs accounted for 99% of the cost of the reclaimed bricks [27], although it should be noted that a team of five people were used and the labourers were paid at a rate for skilled workers. Despite this, the case study reported that "brick cleaning would still be economically sustainable" even if the labourers were paid at a rate on a par with regular construction workers. However, the majority of the workers who operated the machine rated "one or more phases of the brick cleaning procedure as unsatisfactory or highly unsatisfactory". The main reason cited for this was the weight of the bricks, as much as 5kg, which were moved by hand. The project managers introduced measures to minimise the manual handling and lifting of bricks, but the report does not give an indication of the success of these measures. It was also noted that brick recycling using this kind of process takes time, and that therefore "the mere fact that a recycling or re-use activity is economically viable is therefore not enough to ensure that it is carried out." This present author believes that this case study is a good example of the environmental and economic savings that can be made.

There are several processes that could form the basis for a machine to reclaim bricks from brickwork. Mortar can be cleaned from bricks by simply placing them in a container and then covering it with a 10 – 25% Hydrochloric Acid solution. However, there are a number of issues that lead the author to believe a process based on immersing the brickwork in acid would not provide a practical method of brick recycling. In order to separate and clean full-scale bricks in quantities large enough to enable a significant environmental saving to be made a large volume of acid would be required. The acid could be re-used a number of times, but over time it would become less effective, and require replacing. Hence a there would be a regular need for large quantities of acid. Furthermore, the "used" acid would need to be disposed of in an environmentally sensitive manner. In addition, the production of acids requires energy, and generates by-products that cause damage to the environment. The environmental savings by reducing the amount of bricks requiring landfill would have to be considered against these adverse environmental effects. Acid is expensive, making it very difficult to recycle brick economically. In addition, the steps necessary to meet the health and safety requirements for such a procedure would be considerable.

A variety of mechanical cutting and abrasion processes present possibilities. The main difficulty with this approach is to design a machine able to identify the position of the joint between the bricks and the mortar and manipulate the specimen to enable the separation to be made in the correct place. However, it could be possible to develop a method of separating brick and mortar using less obvious methods.

During previous work at Cardiff University, it had been observed that couplets made from one-sixth scale bricks placed in an ultrasound bath often broke into the two bricks and a separate piece of mortar.[28 29] This process seemed promising, as the couplets were cleaned in less than three minutes and the surfaces of the bricks were left undamaged and the clean mortar and suitable for reuse. It was therefore decided to perform an investigation of this process in order to determine the reasons behind the separation, and determine if it would be possible to use the same process on full-scale bricks.

In contrast to the extensive information available concerning the construction of brickwork structures, there is very little information available on how to dispose of brickwork structures efficiently. There have been four previous small studies into the possibilities for further brick recycling at Cardiff University.

Boon Seng [8] (1998) considered the possible demand for any recycling technology that could be developed. The main content of the MSc thesis considers current recycling processes and products. The report differentiates between the non-homogeneous mixture produced by rapid low technology processes (i.e. a typical demolition with heavy machinery such as a wrecking ball, bulldozers etc.), and the sorted piles of homogeneous materials that can be achieved with careful selective demolition. The economic performances of these methods are considered. The report explains that of the two methods, a selective demolition is more expensive than a rapid demolition but has the advantage that it renders materials that require less processing before they are in a state that is suitable for recycling. However, it fails to identify which is the most economical overall method. The report then considers the processes that occur at the recycling plant and the different machines that can be used. The report identifies two main products that can be produced from recycled bricks. It states that bricks can be cleaned and used in their whole original form, but this requires the bricks to be in good condition after demolition; the report briefly considers the possible uses for of crushed bricks.

A feasibility study for recycling brickwork conducted by Boon Seng[8] covers two areas, the availability of structures that require demolition, and the market for recycled brick products. The report attempts to predict the amount of brickwork from housing that will be suitable for demolition "from 1997 onwards" by assuming that houses become unfit for occupancy once they were 50 years old. The paper considers data concerning the numbers and ages of houses to calculate how many houses will be likely to be demolished. By estimating the average number of bricks in a typical house, the paper also determines the total number of bricks likely to be available for recycling in 1997 to be 150 billion.

The author of this thesis believes that assuming a house will typically be demolished 50 years after construction is difficult to accept, as many houses remain serviceable for more than twice this length of time. Therefore the author of this thesis suggests that the figure of 150 billion is likely to overestimate the number of bricks available for recycling in 1997, and the calculation would be more accurate if a 100-year life was assumed for houses. However it is acknowledged that assumptions do need to be made when there is insufficient data to make a more accurate prediction and the figure determined in the report is clearly intended only to be a rough estimate. Boon-Seng decides that this approximation provides sufficient evidence to conclude that enough bricks will be available for demolition to make developing brick recycling technology a worthwhile goal, and the author of the current thesis concurs with this conclusion.

The report considers the market for recycled brick products and concludes that if the quality of the recycled product is similar to original products there will be a market for recycled brick if they are competitively priced. The report highlights areas that influence the cost of producing recycled bricks and identifies that the economical viability of brick recycling will be dependant on the speed and efficiency of recycling, and government policy.

In conclusion, the report claims that brick recycling is a viable concept that is environmentally sound, with a large supply of bricks for recycling which can be used instead of original bricks. However, the report identifies that with funding for recycling technology being difficult to achieve, a lack of standards and specifications for recycled products, low landfill taxes and unlimited, untaxed extraction of raw materials being possible it will be difficult to maintain a profitable and stable market for recycled bricks.

3. Theory

3.1. Chemical processes that occur during curing

The mortar found in structures today can be categorised into two distinct types. Modern mortar made with a Portland Cement hardens because of the chemical reactions that take place. The key chemical ingredients contained within a Portland Cement are lime, silica, alumina and iron oxide. These components are combined and fired within a kiln, following the process summarised in Figure 3-1.

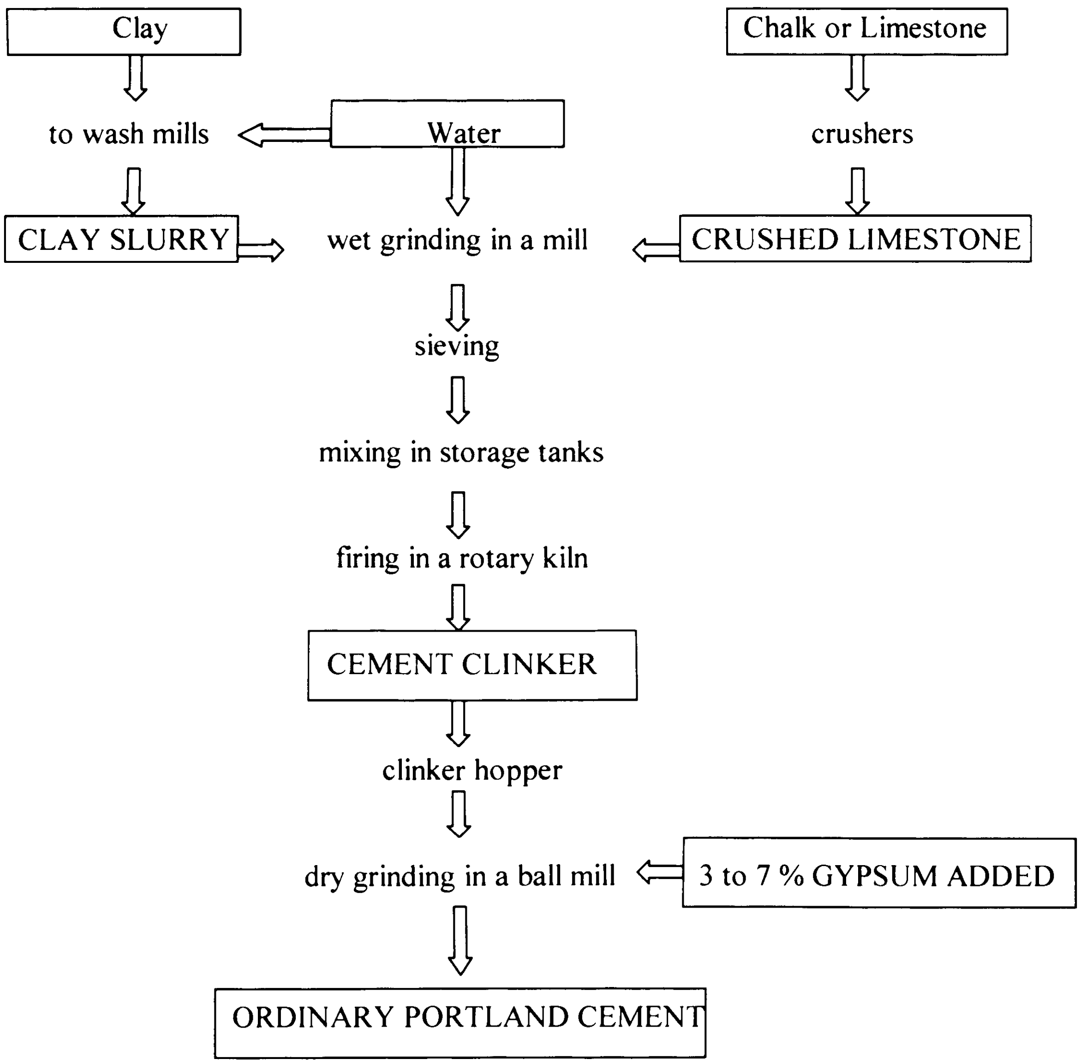


Figure 3-1. The key stages in the production of Portland Cement

During the firing process the ingredients react to form a number of new substances. When this mixture is taken from the kiln and allowed to cool it becomes stable, save for any un-reacted lime. The chemical composition and method of evaluation of a typical Portland Cement is shown in Figure 3-2.

substance	percent
Ignition loss	2.0
Insoluble residue	0.5
SiO_2	20.0
Al_2O_3	6.0
Fe_2O_3	3.0
CaO	63.0
MgO	1.5
SO_3	2.0
K_2O	1.0
Na_2O	
Balance	1.0
Total	100

Figure 3-2. Chemical composition of a typical Portland Cement (taken from Czernin[30])

Most of the elements present within cement are combined with oxygen, and hence the process that occur are usually considered to occur between their oxides [31]. When water is added to the cement a water-cement paste is formed and a series of chemical reactions are triggered within the paste. The full extent of these chemical reactions is too complex to be fully explained in this thesis, but the key processes that cause the gain in strength can be identified. The names and chemical compositions of the key components involved in the hardening process of Portland Cement are shown in Table 3-1.

Name of compound	Oxide composition
Tricalcium silicate (C_3S)	$3CaO . SiO_2$
Dicalcium silicate (C_2S)	$2CaO . SiO_2$
Tricalcium aluminate (C_3A)	$3CaO . AlO_2$
Tetracalcium aluminoferrite (C_4AF)	$4CaO . AlO_2 . FeO_3$

Table 3-1. The Main components of Portland Cement (taken from Neville[32])

When the cement is mixed with the water, the tri-calcium silicate breaks down and hydrated calcium silicate and calcium hydroxide are formed. The oxides within the cement paste are then hydrated as they react with the water. These reactions are highly complex and are considered to be outside the scope of this thesis. Indeed, it is recognised that "there are still uncertainties with regard to this scheme of the reactions".[31] It has been shown that the oxides within the cement paste hydrate at different rates, which are initially proportional to the rates with which they hydrate when in pure form, as shown in Figure 3-3.

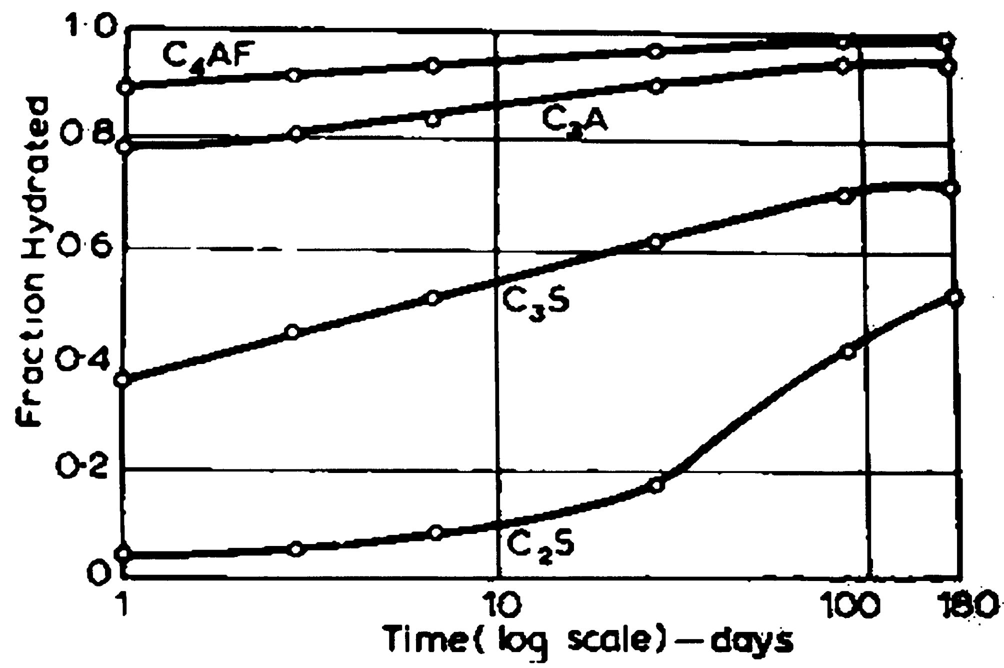


Figure 3-3 - Rate of hydration of the oxides present within cement (taken from Neville [32])

The rate at which the cement paste hardens depends on a number of factors, including many variables that are difficult to control. This makes the rate at which cement develops strength difficult to predict. However, manipulating the ratios of the oxides present within the cement can influence the hardening process. This allows the properties of cements to be determined by specifying the mix proportions for the substances within the cement.

A traditional lime mortar hardens as it reacts with water within the environment. Lime mortar is applied to the bricks as a "putty", and hardens slowly over time. There are two different types of lime, which are known as non-hydraulic lime and hydraulic lime. Non-hydraulic lime initially relies on the reduction of moisture within the mortar, which typically occurs through water loss to the environment or to the bricks as evaporation occurs. This enables slow carbonation to occur, and the mortar hardens further. Hydraulic mortar does not need to "dry" before hardening can occur, as it sets by chemical reaction with water, enabling it to harden in wet conditions.

Traditional lime mortar hardens very slowly and may only do so on the surface. This is especially true of mortar that is not exposed to the air, as this inhibits the hardening process. Even mortar in very old structures that is fully cured remains far weaker and more flexible than modern mortar. In addition, traditional lime mortar remains highly porous even when fully hardened. These three properties are often beneficial to old structures. The flexibility of the mortar provides considerable freedom for movement to occur without any structural deficiencies occurring. Lime mortar is sufficiently porous that it enables a structure to "breathe", letting water evaporate out and providing ventilation to the structure. This was a considerable advantage in the days before cavity walls and modern heating.

3.2. Failure of brickwork

Work has been performed to establish the factors that determine the strength of brickwork for many years.[33] [34] [35] The majority of this work has considered brickwork in the state that it is mostly frequently used, and has therefore usually investigated the failure of columns loaded in axial compression. A typical failure of a brickwork column tested in this manner is shown in Figure 3-4. In this figure four vertical cracks parallel to the axis of loading can clearly be identified. The brickwork on the left of the column has split away from the rest of the column by the largest crack.

Figure 3-4 – Failure of a brick column

It is difficult to predict the strength of brickwork because of its compound nature. The load that will result in the failure of a brickwork structure is generally much smaller than the nominal compressive strength of the bricks, but greater than the cube crushing strength of the mortar. Hendry [7] surmises that a brickwork column load tested under an axial load will fail by "the development of tension cracks parallel to the axis of loading". This failure mechanism can be seen in Figure 3-4. A representation of this failure mechanism for a brickwork couplet is shown in Figure 3-5.

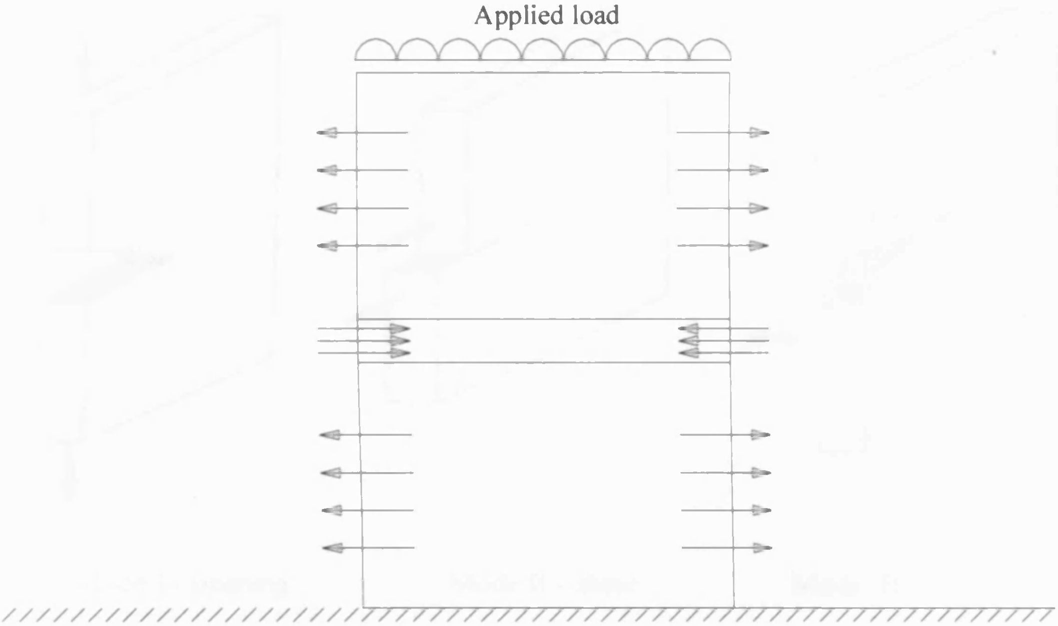
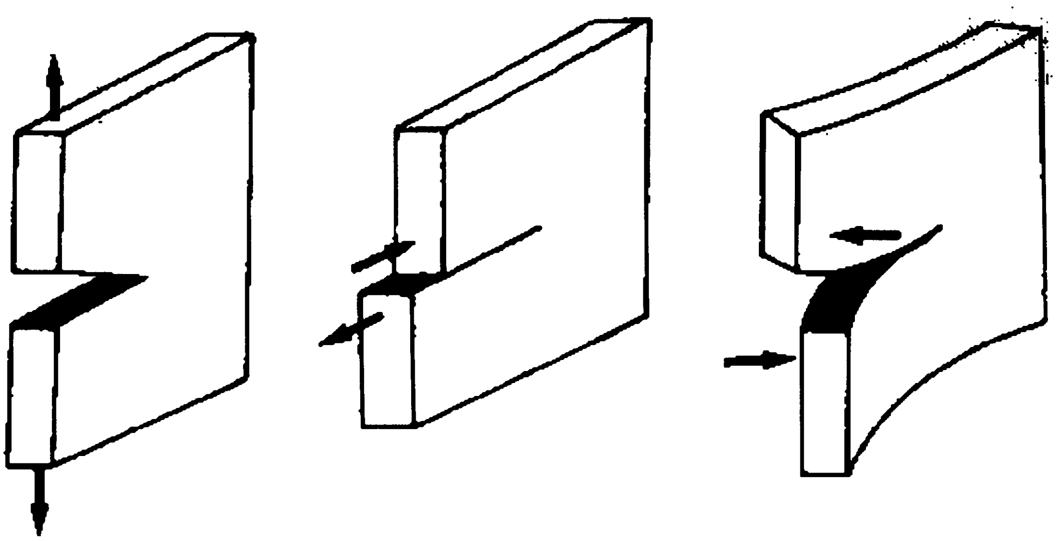


Figure 3-5 - The stresses developed in a couplet subjected to an axial load.

The nature of this failure mechanism shows that cracking is a key part of the failure of brickwork. Therefore it is necessary to consider the process that causes cracks to develop within a material. There has been a significant amount of work performed on the role of cracking in the failure of structures. Irwin observed that there are three fracture modes that can cause cracking to occur, as shown in Figure 3-6.



Mode I - opening Mode II - shear Mode III - tearing

Figure 3-6. The three modes of fracture
(taken from Broek [36])

All materials contain inherent flaws within them, including small cracks. In addition, cracks can be induced within a material during loading.

In Smith[37] elasticity theory is used to determine the stress at the edge of an elliptical opening subjected to remote stress σ as shown in Figure 3-7. For such a situation the stress σ_y can be evaluated using the following equation:

$$\sigma_y = \sigma\left(1 + 2\sqrt{\frac{a}{R}}\right) \qquad (1)$$

where σ_y is the stress at the edge of the opening

σ is the plane stress

a is the half length of the opening

R is the radius of the curvature at the edge of the ellipse

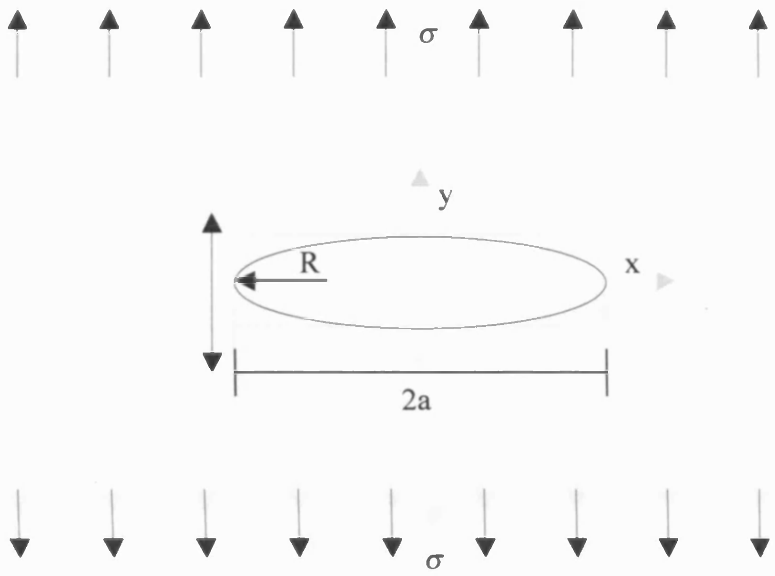


Figure 3-7. Elliptical crack in a tensile field
(taken from Owens and Fawkes [38])

The ratio of $\frac{\sigma_y}{\sigma}$ is know as the stress concentration factor. It can be shown that for a circular opening where R is equal to a the stress concentration factor will have a value of 3.[37] However, circular cracks are not usually found in material. Instead a crack begins as a hairline crack with a negligible width. If Equation (1) is applied to a hairline crack, the radius of curvature at the end of the crack becomes very small. As R tends to zero, the stress concentration and hence σ_y tends to infinity. However, in practise σ_y can not exceed the material yield stress, and consequently a plastic zone develops at the tip of the crack, as shown in Figure 3-8.

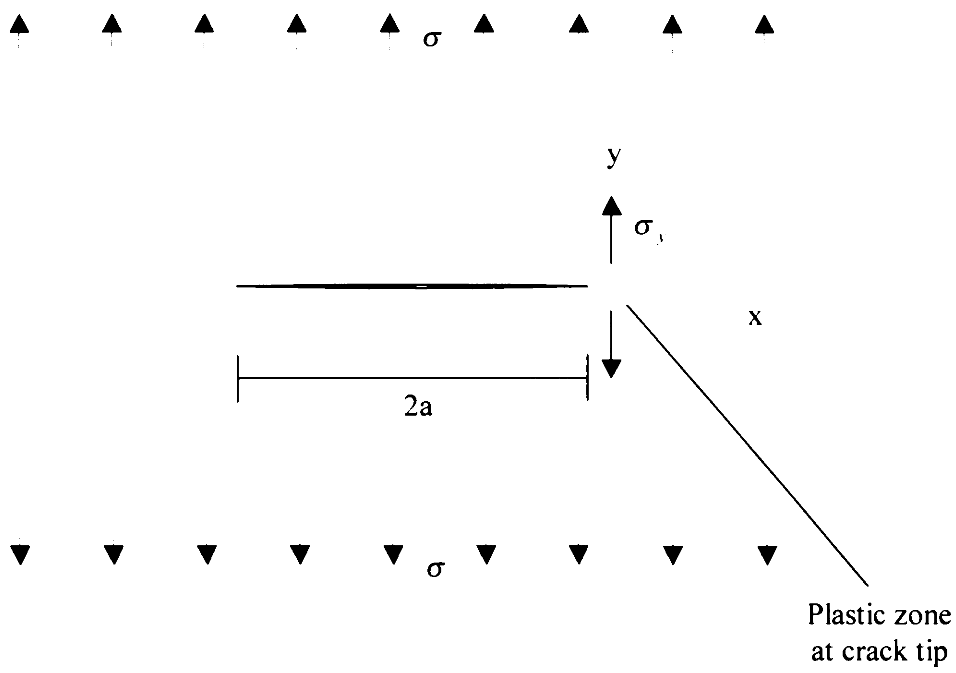


Figure 3-8. Hairline crack in a tensile field

The stress developed at the tip of a hairline fracture can be evaluated using the following equation taken from Smith [37]:

$$\sigma_y = \frac{K_I}{\sqrt{2 \pi x}} \qquad (2)$$

where σ_y is the stress at the edge of the opening

K_I is the stress intensity factor

x is the horizontal distance from the edge of the crack

For a hairline crack such as that shown in Figure 3-8 above, the stress intensity factor K_I takes the following form:

$$K_I = \lim_{x \to 0} \sigma_y \sqrt{2 \pi x} \qquad (3)$$

The simplest form of the stress intensity factor is for a hairline crack that is not influenced by any boundaries. This stress intensity factor for this situation is know as K_0 and can be evaluated as shown:

$$K_0 = \sigma \sqrt{\pi \, a} \tag{4}$$

Stress intensity factors for cracks in more complicated geometrical configurations can be considered with the addition of a factor Q to allow for the proximity of boundaries as shown below:

$$K_1 = Q \, K_0 \tag{5}$$

$$K_1 = Q\sigma \sqrt{\pi \, a} \tag{6}$$

Therefore the stress developed at the tip of a hairline fracture σ_y subjected to a remote plane stress σ can be evaluated thus:

$$\sigma_y = \frac{Q \, \sigma \sqrt{\pi \, a}}{\sqrt{2 \, \pi \, x}} \tag{7}$$

Further work was performed to by Griffith[39], who determined the following equations to evaluate the strain energy released by the propagation of a crack U and the energy required to create the crack surface W:

$$U = \frac{\sigma^2 \pi\ a^2 t}{2E} \tag{8}$$

where	U	is the strain energy released by the propagation of a crack
	t	is the thickness of the crack
	E	is the Young's modulus of the material

$$W = 2a\ t\ \gamma \tag{9}$$

where	W	is the energy required to create the crack surface
	γ	is the surface energy density

Griffith proposed that a crack under a constant remote stress σ would develop when the rate of energy release due to the extension of the crack was equal to or greater than the energy associated with the crack surfaces created. This is expressed mathematically thus:

$$\frac{\partial U}{\partial a} = \frac{\partial W}{\partial a} \tag{10}$$

The expressions in Equations (8) and (9) can be substituted into Equation (10) and rearranged to give the magnitude of the remote plane stress required to achieve crack development:

$$\sigma_C = \sqrt{\frac{2E\ \gamma}{\pi\ a}} \tag{11}$$

where σ_C is the remote plane stress required to achieve crack development

Substituting $K_I = K_{IC}$ from equation (6) gives the stress intensity factor for unstable crack growth as shown below:

$$K_{IC} = \sqrt{2E\gamma} = \left(Q\sigma\sqrt{\pi a}\right)_C \qquad (12)$$

where K_{IC} is the critical stress intensity factor or fracture toughness of the material

The fracture toughness property has units of $N/mm^{3/2}$ and can be used to determine the critical plane remote stress that will cause a crack to develop.

The cracking process within brickwork specimens is difficult to quantify because of the compound nature of the material. Although work has been performed in this area, "fracture mechanics methods to deal with crack growth in composites are practically non-existent".[36] Further extensions which give an allowance for limited plastic deformation have been suggested[40 41], but these are too complex and are therefore not considered as part of this thesis.

The requirement for cracking to occur can be related to both stress and energy. In fact a crack may be caused either by a direct stress, or with cyclic loading over a period of time, which is limited by an energy requirement. A failure that occurs because of a gradual degradation of material strength under either constant amplitude (static) or variable amplitude (cyclic) loading is know as fatigue. Fatigue is usually associated with cyclic loading, where a material subjected to a number of cycles, n. Static fatigue only affects certain materials under specific conditions, and is not considered as part of this thesis. Under cyclic loading fatigue occurs because the repeated plastic straining induced at the crack tip, allows the crack to develop at a stress less than the stress that would be required under constant stress. This reduction can be evaluated by considering the induced stress intensity factor range ΔK, which can be evaluated using Equation (12) as shown:

$$\Delta K = Q\ \Delta\sigma\sqrt{\pi\ a} \qquad (13)$$

Experimental work[42] has provided sufficient understanding of the fatigue phenomenon to allow the effects of fatigue to be expressed graphically, as shown in Figure 3-9.

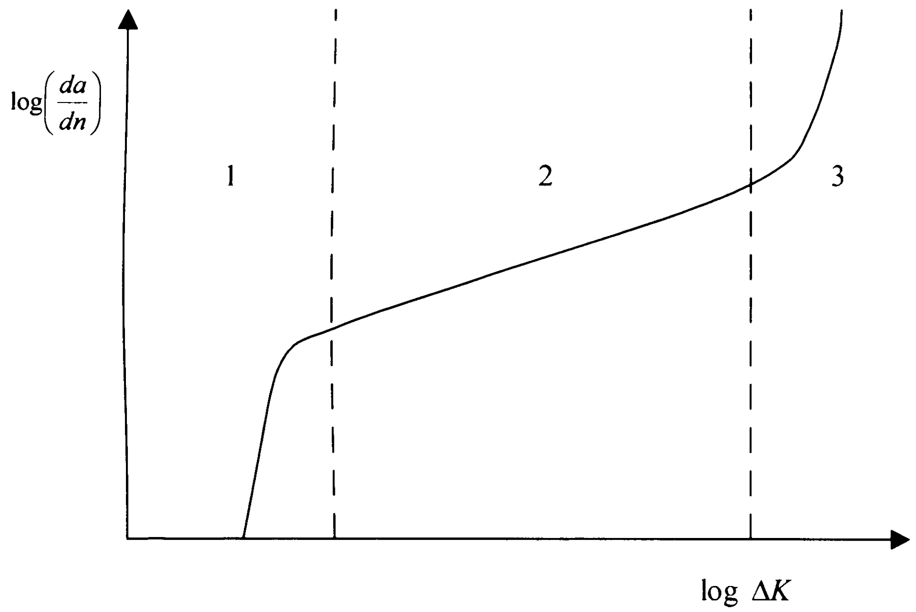


Figure 3-9. Crack growth rate with number of cycles $\log\left(\frac{da}{dn}\right)$ against ΔK

The graph shown in Figure 3-9 above is split into three regions corresponding to the different processes that occur within the region surrounding the crack tip.

Region 1 represents crack initiation, where the pre-existing micro-cracks present in the material extend and join together to form cracks up to 0.1mm long. Region 3 represents unstable crack growth which will allow the crack to develop until failure occurs. Region 2 represents stable crack growth and it can be seen in Figure 3-9 above that within this region the log-log plot is approximately linear, and hence this relationship is represented by the following expression:

$$\log\left(\frac{da}{dn}\right) = m \ \log(\Delta K) + \log(C) \tag{14}$$

where $\left(\frac{da}{dn}\right)$ Is the crack growth rate with number of cycles n

C is a material property

m is a property of the material

This expression can be rearranged as shown below:

$$\frac{da}{dn} = C(\Delta K)^m \tag{15}$$

Equation (15) shown above is known as the Paris equation [43]. This equation can be used to determine the relationship between the number of cycles and the increase in the length of the crack. Substituting Equation (13), separating the variables and assuming Q to be a constant gives the following equation:

$$\int_0^N dn = N = \frac{1}{C\left(Q\Delta\sigma\sqrt{\pi}\right)^m}\int_{a_1}^{a_F}\frac{da}{a^{\frac{m}{2}}} = \frac{1}{C\left(Q\Delta\sigma\sqrt{\pi}\right)^m}\left(\frac{a_1^{1-\frac{m}{2}} - a_F^{1-\frac{m}{2}}}{\frac{m}{2}-1}\right) \tag{16}$$

where a_1 is the initial crack length

a_F is the final crack length

Taking logs gives:

$$\log N = \log\left\{\frac{1}{C\left(Q\sqrt{\pi}\right)^m}\left(\frac{a_1^{1-\frac{m}{2}} - a_F^{1-\frac{m}{2}}}{\frac{m}{2}-1}\right)\right\} - m\log\Delta\sigma \tag{17}$$

Assuming the term in brackets is a constant determined by the properties of the material and structural detail Equation (17) can be simplified to give:

$$\log N = \log A - m \log \Delta\sigma \quad (18)$$

This equation can be used as a basis to define the fatigue strength curve for a material. However, in order to do this it would be necessary to determine the constants C and m experimentally. Therefore fatigue strength curves are usually constructed from experimental data after exhaustive testing of specimens known as structural details (i.e. welded joints). The fatigue life of a structure under loading at known frequency and intensity can be predicted by relating it to an appropriate structural detail. For example, BS EN 1993-1-9 Eurocode 3: Design of steel structures[44] gives fatigue strength curves for a range of structural details from detail category 36 to detail category 160. The detail category corresponds with the stress that would produce a fatigue failure in $2x10^6$ loading cycles. The form taken by the fatigue strength curves used in BS EN 1993-1-9 is shown in Figure 3-10. The curves show the constant amplitude fatigue limit $\Delta\sigma_D$ and the cut-off limit $\Delta\sigma_L$, which are the minimum stresses required for fatigue to occur, under constant amplitude and varying amplitude respectively. The fatigue strength curves in BS EN 1993-1-9 can be used to determine the number of load cycles that a material can sustain before structural failure occurs due to the development of a crack of critical length.

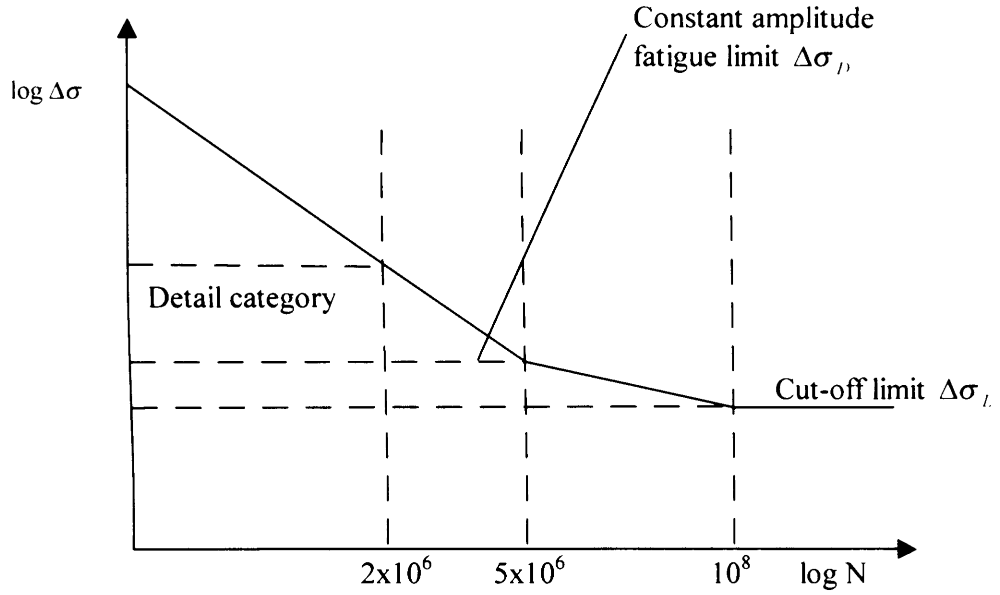


Figure 3-10. Form taken by the fatigue strength curves used in BS EN 1993-1-9 [44]

Work is being performed[45] to investigate how fatigue cause failure of brickwork. However, at this time the British Standards do not provide any fatigue strength curves for brickwork.

3.3. Generation of ultrasonic vibrations

The U 400 ultrasound bath used for the initial testing is actually designed to clean dirt from small items such as jewellery and glass instruments. Like most commercial ultrasound baths available, it has additional features including a timer and a heater. However, at its most basic level an ultrasound bath consists simply of a water [v] container and a transducer, which generates the ultrasonic vibrations in the water.

Vibrations with frequencies that are too high to be audible to humans are considered ultrasonic. There is some variation, as some people can detect higher frequencies than others, but the threshold is usually quoted at 20kHz[46 47 48]. The vibrations within an ultrasound bath are generated by ultrasonic transducers. There are several different types of transducer available, but the ones in the U 400 bath are crystal transducers, which are the most commonly used transducers for small ultrasound applications. Crystal transducers consist of a crystal made up of charged ions between two plates. The simplest crystal transducers use a crystal with only two types of atom present. An ultrasonic transducer can be fabricated from a range crystals, and each crystal will produce vibrations at a specific frequency. A crystal transducer made up of Silicon and Oxygen atoms is shown in Figure 3-11 below.

[v] Many different liquids can be used to transmit the vibrations generated by the transducer, but for simplicity it is assumed that water will be used.

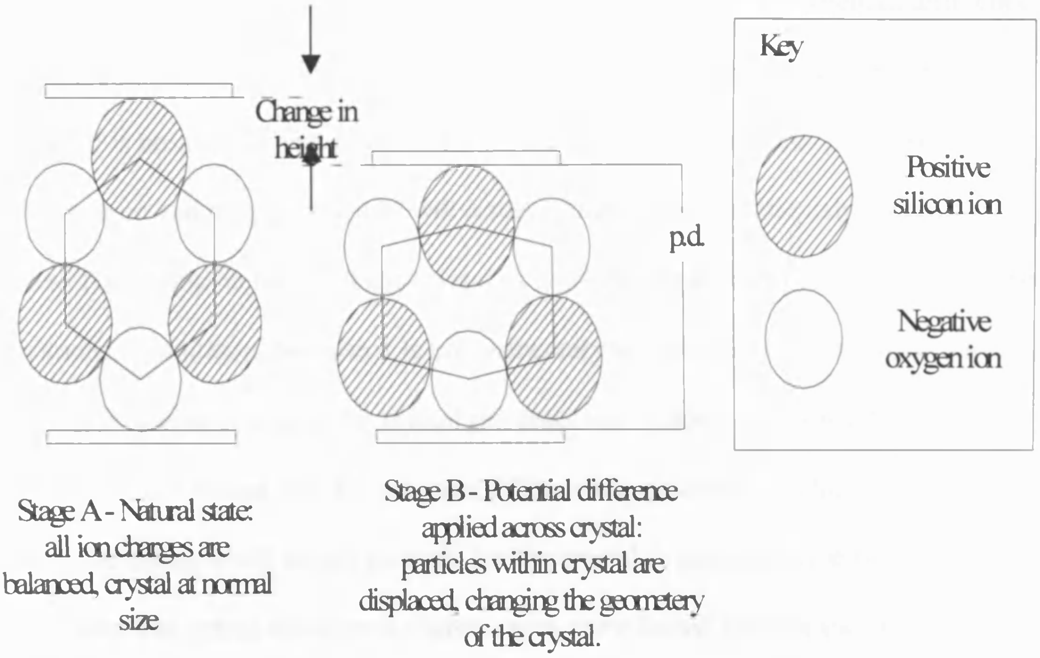


Figure 3-11. Diagram of crystal contracting from Blitz [48]

When no charge acts on the crystal (shown in Stage A of Figure 3-11) the ions move to positions that cause the charges on the ions to balance out, allowing the crystal to adopt a state of stability. When a potential difference is applied across the plates on either side of the crystal (shown in Stage B of Figure 3-11 above) the ions are attracted to the plates with a charge opposite to their own. The positively charged Silicon ions move towards the negatively charged cathode and the negatively charged oxygen ions move towards the positively charged anode. The ions move until the charges on the ions and the plates are balanced, allowing the crystal to become stable, and the ions settle into their new positions. The movement of the ions required to balance out the charges causes a change in the shape of the crystal, which becomes shorter and wider. If the potential difference across the plates is removed, the charges in the crystal become unbalanced while the ions are still in the positions they adopted when they were attracted to the plates. The ions thus move to balance the charges, and the crystal shape reverts back to the natural state it had before the potential difference was applied. So, by applying a small charge across the plates on either side of a crystal, it is possible to change the shape of the crystal. Applying the potential difference on and off continuously will result in the crystal continuously switching states. The change in height of the crystal as it adopts the different states produces the vibrations. In addition, because it is only necessary for several ions to move to allow the crystal to change shape, the crystal can react very quickly to balance the potential difference. This means that if a potential difference is oscillated at a high frequency across the plates it will be still possible for the crystal to respond at the same frequency. The actual situation is slightly more complicated because the crystal has its own natural frequencies and will not function in the same way for all frequencies of the applied potential difference. However, there are a number of different crystals that respond to a potential difference in this manner, and hence it is possible to select a particular crystal that will vibrate well at the frequency desired for a particular application. This is why ultrasound baths are designed to operate only at a specific fixed frequency.

3.4. The movement of vibrations within an ultrasound bath

When an ultrasound bath is operated the vibrations are transmitted through the water as shown in Figure 3-12.

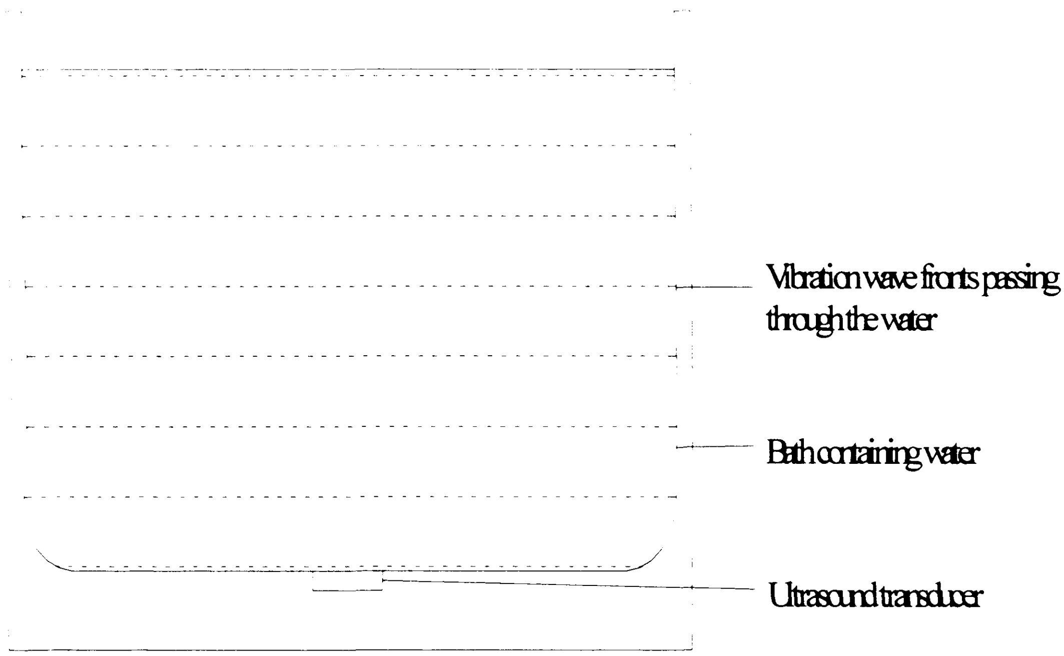


Figure 3-12. The key features of an ultrasound bath

However, this is a greatly simplified and idealised explanation of how an ultrasound bath works. There are many more complications that need to be understood before the processes that occur in the U400 bath can be followed sufficiently.

Crystal transducers, such as those used in the U400, are point sources for vibration, since the vibrations are emitted from a single crystal. This means that instead of the straight wave fronts as shown in Figure 3-12, the wave fronts produced in the water will be emitted radially from the point source in a hemispherical shape. It is impossible to cause anything much larger than a single crystal to vibrate fast enough to create frequencies in the ultrasound range. However, a new method of producing ultrasonic vibrations using a matrix of point transducers that produce synchronised vibrations has recently been developed. If a large number of point sources are placed in a matrix with only small gaps between them it is possible to produce a near flat wave front over the area covered by the matrix of transducers. However, this method is expensive and only worthwhile when it is necessary to generate uniform ultrasonic vibrations over a large area. Instead, the U400 bath has two point transducers that are housed in the base of the bath. It is possible to evaluate the vibrations occurring around a point source within a rectangular bath using advanced mathematics. These theoretical results have since been shown to be accurate by experimental work[49]

However, it is more difficult to evaluate the vibrations produced when two or more sources act within the same bath. The U 400 ultrasound bath has two transducers, enabling the bath to provide twice as much energy to the water in the bath. This also produces vibrations that are distributed more evenly through the water. Ultrasound vibrations can also be reflected, depending on the materials they encounter. Some portion of the energy in the wave will be reflected off the new medium instead of continuing on through it. The sides of an ultrasound bath are made usually from a material that reflects as many of the vibrations as possible, as this will maximise the energy in the bath and increase its effectiveness. However, it is difficult to quantify the portion of the vibrations that are reflected, and this makes modelling the vibrations occurring in the ultrasound bath difficult. Figure 3-13 below shows how the wave fronts produced from two point source transducers in an ultrasound bath such as the U400 will create interference and be reflected off the sides of the bath.

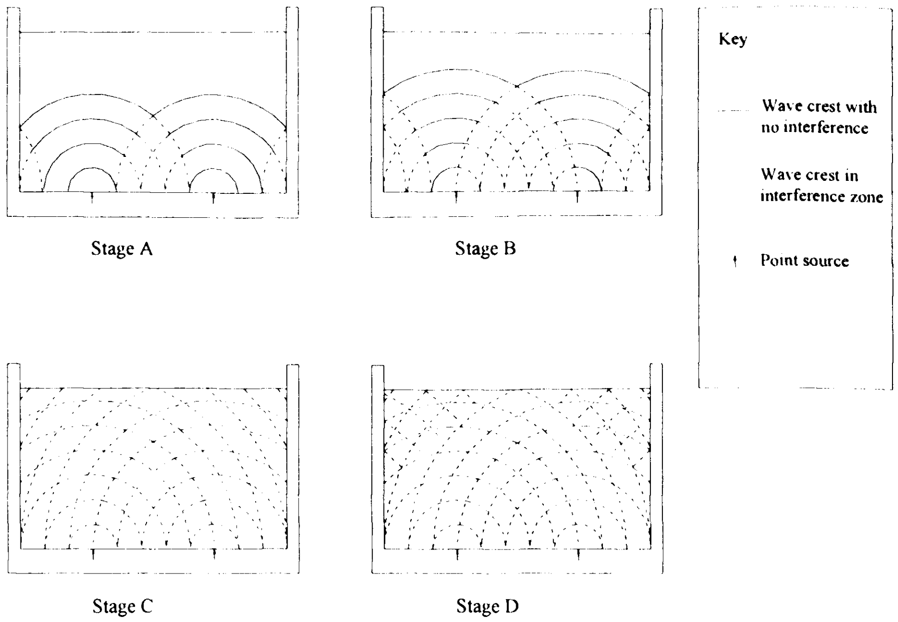


Figure 3-13. Vibration wave fronts in an ultrasound bath with two transducers

In Figure 3-13, Stage A shows the first four wave fronts produced when the bath is operated, and the zone of interference that is produced between the transducers where the two sets of wave fronts meet. Stage B shows that as the bath continues to operate and additional wave fronts are produced, the zone of interference is extended. By Stage C, the vibrations generated by both the transducers have travelled throughout the bath, and the vibrations produced at any point in the bath are the result of a combination of the vibrations from both transducers. Stage D shows the wave fronts that have been reflected off the sides of the bath. For simplicity, only the reflections from the transducer on the left have been shown. There would also be some reflection off the surface of the water, although this would not result in waves like those produced when the waves are reflected off the sides of the bath. It is also necessary to note that the diagram above is two dimensional, whereas any attempt to model the vibrations produced in an ultrasound bath in a realistic manner would need to be three dimensional.

If the vibrations produced in the U400 bath were as simple as those shown in Figure 3-13 above, it might be possible to produce a model of the vibrations that are produced in the bricks and mortar when a couplet is placed in the bath. A model that accounts for the complications discussed above (the interference from the two transducers, the reflection off the sides of the bath and the reflection and interference effect within the couplet) would also perhaps be possible, although it would certainly be a major modelling exercise. However, in addition to these complications, there are further small effects that would need to be included in a realistic model. The vibrations from the transducer at the base of the bath are transmitted by conduction up the sides of the ultrasound bath, causing increased vibration of the water near the sides of the bath. Any objects placed in the bath are shaken about by the vibrations and moved around on the floor of the bath, so the orientation and position of the couplets are constantly changing. This means that a detailed model is an unachievable goal, and small scale experimental testing will be the only source of information available before a full-scale prototype is designed and built.

3.5. Cavitation

In addition to the actions of the vibrations themselves, there is another process that occurs within an ultrasound bath, which could be involved with the separation of the one-sixth scale couplets. When the ultrasound bath is operating, the high frequency waves passing through the water can cause a process known as cavitation. Cavitation occurs when the passage of the waves cause the water to be subjected to a pressure amplitude greater than the cohesive strength of the water. As the waves pass through a fluid, it causes the fluid to be subjected to alternating high and low pressures. During the low pressure (rarefaction) phase the water molecules are subjected to tensile stress and the space between the molecules increases. During the high pressure (compression) phase the water molecules are subjected to a compression and the spaces between the molecules are reduced. If the pressure amplitude produced by the passage of the waves is sufficiently high then a void can be formed in the water as the molecules are pulled apart during the low pressure phase. The size of the void increases until it becomes unstable and an implosion occurs. The void is re-filled as the surrounding water re-occupies the space that had been taken by the void. The pressure amplitude required to achieve separation depends on the properties of the fluid and the present impurities within the fluid. The pressure at which the tensile force of a fluid (with no impurities present) is exceeded is knows as the rupture pressure. In addition, the magnitude of the rupture pressure depends on the forces between the molecules of the fluid and therefore depends on the atomic structure of the fluid. Any impurities present in the fluid will disrupt this structure and create weaknesses, therefore reducing the pressure amplitude at which cavitation will occur. The Rayleigh-Plesset Equation (shown in Equation 19) can be used to determine the maximum size that be achieved by a void within a fluid before it implodes. The maximum size that is achieved by the voids is important because it determines the energy that is released when the bubble collapses.

$$\frac{p'_b - p'_\infty}{\rho'} = \frac{3}{2}\left(\frac{dR'}{dt'}\right)^2 + R'\frac{d^2R'}{dt'^2} \qquad (19)$$

where
R' is the radius of the bubble
$\frac{dR'}{dt'^2}$ is the velocity of the bubble
$\frac{d^2R'}{dt'^2}$ is the acceleration of the bubble
ρ' is the density of the fluid medium
t' is the time
P'_∞ is the pressure at infinity

A large amount of work based on the Rayleigh-Plesset Equation has been performed[50 51], but the "general motion of an oscillating bubble" is still not fully understood. Therefore the exact processes that occur during void collapse are considered to be outside the scope of this thesis. The work performed includes the use of high speed photography, which has shown that "micro-jets" and "a flash of light" can be produced as a void collapses [51 52 53]. These phenomena occur because as the void collapses the surrounding fluids moves at a very high speed as it re-fills the void. It has been shown that the void collapse associated with cavitation releases a large amount of energy. Hence the effects of cavitation can cause significant damage. A piece of aluminum foil can be used to confirm that cavitation is occurring. Under the action of cavitation a piece of aluminium foil will visibly erode away. However, cavitation can affect items that are far more substantial than aluminium foil. Indeed, the action of cavitation was discovered because of the damage it was causing to ship propellers [54].

However, more recently useful applications for cavitation have been developed. For example, a large amount of work has been performed on a range of sonochemical processes [55 56]. However, the most commonplace use of cavitation is to clean dirt from metallic objects by placing them in an ultrasound bath. A simple representation of how cavitation removes dirt from the surface of an object is shown in Figure 3-14.

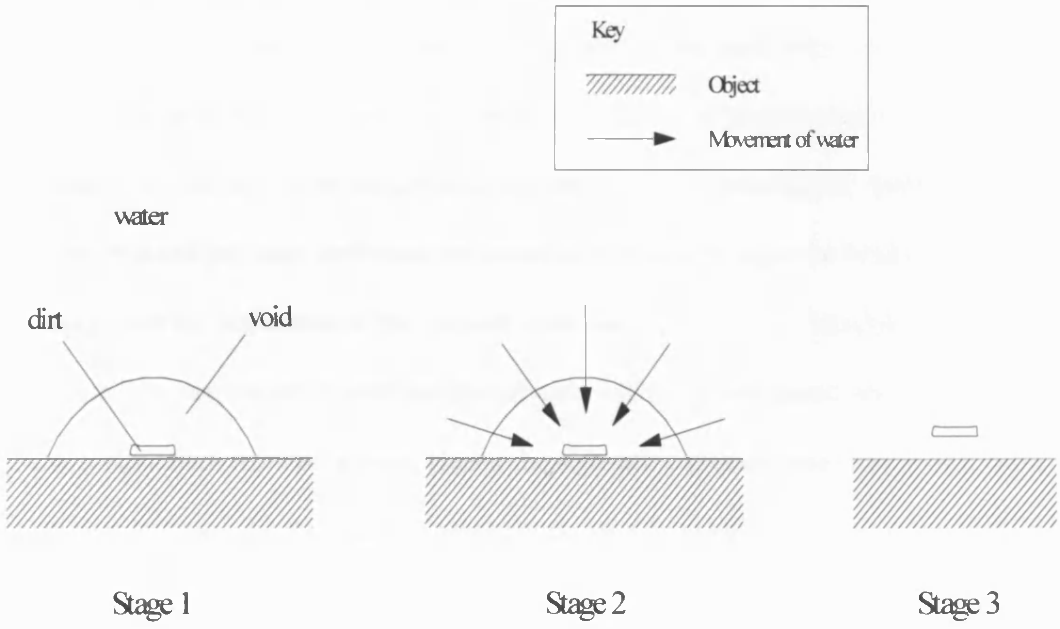


Figure 3-14. The separation of dirt from the surface of an object in an ultrasound bath due to cavitation (Stage 1) and implosion (Stage 2).

In Stage 1, the process of cavitation causes the formation of a void on the surface of the object around the dirt by the action of cavitation. In Stage 2, water floods in at very high speed to fill the void. The third stages shows that as the void is closed the force of the water filling the void acts upon the face of the object and the dirt, breaking the adhesion between them.

If the process of cavitation can erode solid metal, then it is clearly possible that the process of cavitation could provide the energy necessary to break the bond between the mortar and the bricks. Throughout the bricks and the mortar, there are series of pores and air voids, and when the couplets are soaked in water prior to testing, the majority of these holes (especially near the surface) become full of water. At the interface between the bricks and the mortar, there would be a larger amount of air voids, and if they were saturated with water, some of these may be large enough to allow cavitation to occur along the joint between the brick and the mortar. This would weaken the bond between the bricks and the mortar, in the same way that dirt can be cleaned from jewellery. However, in order for cavitation to be part of the separation process, it would need to be occurring along the interfaces between the bricks and the mortar. It is unlikely that cavitation can occur in this area because the bricks were not saturated during fabrication of the couplets (see Section 4.2.1.1). Therefore the interface between the bricks and the mortar joint will not be saturated, and this will prevent cavitation from occurring. Hence the separation process observed in one-sixth scale couplets must be the result of other processes occurring within the ultrasound bath.

3.6. Vibrations passing though specimens in a bath

The vibrations pass through the water and through any objects present in the water, causing them to vibrate. Provided the vibrations imparted into the water have sufficient energy, the objects within the bath will also be excited to vibrate at the same frequency as the transducers. In addition, the objects may also vibrate at their own natural frequencies, using energy from the transducer. All objects have a number of significant natural frequencies, which are determined by their shape and bulk modulus.[57, 58, 59] If the applied vibrations have a frequency that is close to the natural frequency of the specimen then resonance will occur. This will allow the amplitude of the vibrations caused within the specimen by the waves to be significantly increased.

If the natural frequency of the specimen is lower than the frequency of the applied vibrations then the specimen will not be able to vibrate significantly. However, if the natural frequency of the specimen is higher than the frequency of the applied vibrations then it still may vibrate significantly. This occurs when the frequency of the waves is greater than the natural frequency of the brick by a factor that is a whole number. For example if the frequency of the incident waves is three times greater than the natural frequency of the specimen, every third wave will coincide with the natural frequency of the specimen. The size of the third mode vibration will be much smaller than the fundamental mode. However, it will still produce some increase in the magnitude of the vibrations within the specimen, by the same process as when the frequency of the waves was the same as the natural frequency of the specimen, as described above.

The principal material property influencing the natural frequency of a material is the bulk modulus, which can be calculated as shown in Equation (20).

$$\text{Bulk modulus} = \frac{E}{3(1-2\upsilon)} \tag{20}$$

where E is the Young's modulus

υ is the Poisson's ratio

If an object is subject to a vibration at or near its own natural frequency it will vibrate readily. In addition, an object can be caused to vibrate at a frequency that is not close to its own natural frequency. This is known as forced vibration. The amplitude of the vibrations within a material will be greater if the applied vibration is close to the natural frequency of the object. Under forced vibration, the dynamic amplitude is related to the static amplitude $U_{dynamic} = D\ U_{static}$. The ratio between amplitudes of dynamic and static vibration can be determined thus:

$$D = \left\{(1-\Omega^2)^2 + (2\ \xi\ \Omega)^2\right\}^{-2} \tag{21}$$

where D is the amplitude ratio for static and dynamic vibration

Ω is the frequency ratio = $\dfrac{\text{excitation frequency}}{\text{natural frequency}}$

ξ is the damping ratio = $\dfrac{\text{actual damping}}{\text{critical damping}}$

For low levels of damping, as $\Omega \to 0$ causing D to become large, the vibrations that correspond to the natural mode of the specimen will become dominant.

When a couplet is placed within the ultrasound bath, the bricks and the mortar will attempt to vibrate at their own natural frequencies. The natural frequencies of the bricks and the mortar will be different because of they have different material properties. Hence, both the bricks and mortar are vibrating at the frequency of the transducers and also, to a certain extent, at their own natural frequencies, which are different. This means that at the interface between the brick and the mortar, stresses and strains are going to be caused as the brick and the mortar try to vibrate at different frequencies. This could lead to the separation of the couplets. However, this is a very simplified version of what is actually happening in the ultrasound bath. The transducers are point sources, so they produce hemi-spherical vibration wave fronts, which are then reflected within the ultrasound bath, so that the bath is filled with waves travelling in many different directions. Advanced mathematical techniques [60 61] are now available to determine the positions of wave fronts as vibrations pass through various media. However, even these methods would be unable to allow for the random movement of a couplet as it moves on the bottom of an ultrasound bath. and in addition these techniques are considered to be outside the scope of this thesis. Therefore a simplified representation of the passage of the waves within the bath will be presented in this thesis as shown in Stage D of Figure 3-13. Although the direct wave from the transducer will be the strongest, the reflected waves make it difficult to determine exactly what is happening within the ultrasound bath, and would make any attempt to model the procedure extremely difficult, and at best, approximate.

As well as reflecting off the sides of the bath as discussed in Section 3.4, the vibrations can also be reflected as they pass through the different parts of the couplet. As the waves pass through different materials some portion of the wave will reflect back off the face of the new material and the rest will continue onwards through the next material as shown in Figure 3-15.

In Stage A of Figure 3-15 three wave fronts can be seen approaching the brick. Each wave front has been numbered, and the arrows next to the numbers indicate the direction in which the fronts are travelling. Stage B shows the same situation after three further cycles have occurred. Some of the energy contained in the first three waves reflected backwards when the wave fronts reached the brick and rest of the waves continued on through the brick. The reflected portion of the waves are labelled 1b, 2b and 3b, and the adjacent arrows show that the waves are travelling away from the brick. Interference will occur between these and the subsequent waves that have not been reflected. This will cause the maximum amplitude of the waves to be increased when the crests of the two waves are superimposed. However, this occurs in the water outside the couplet, and therefore it will not affect the potential for achieving separation.

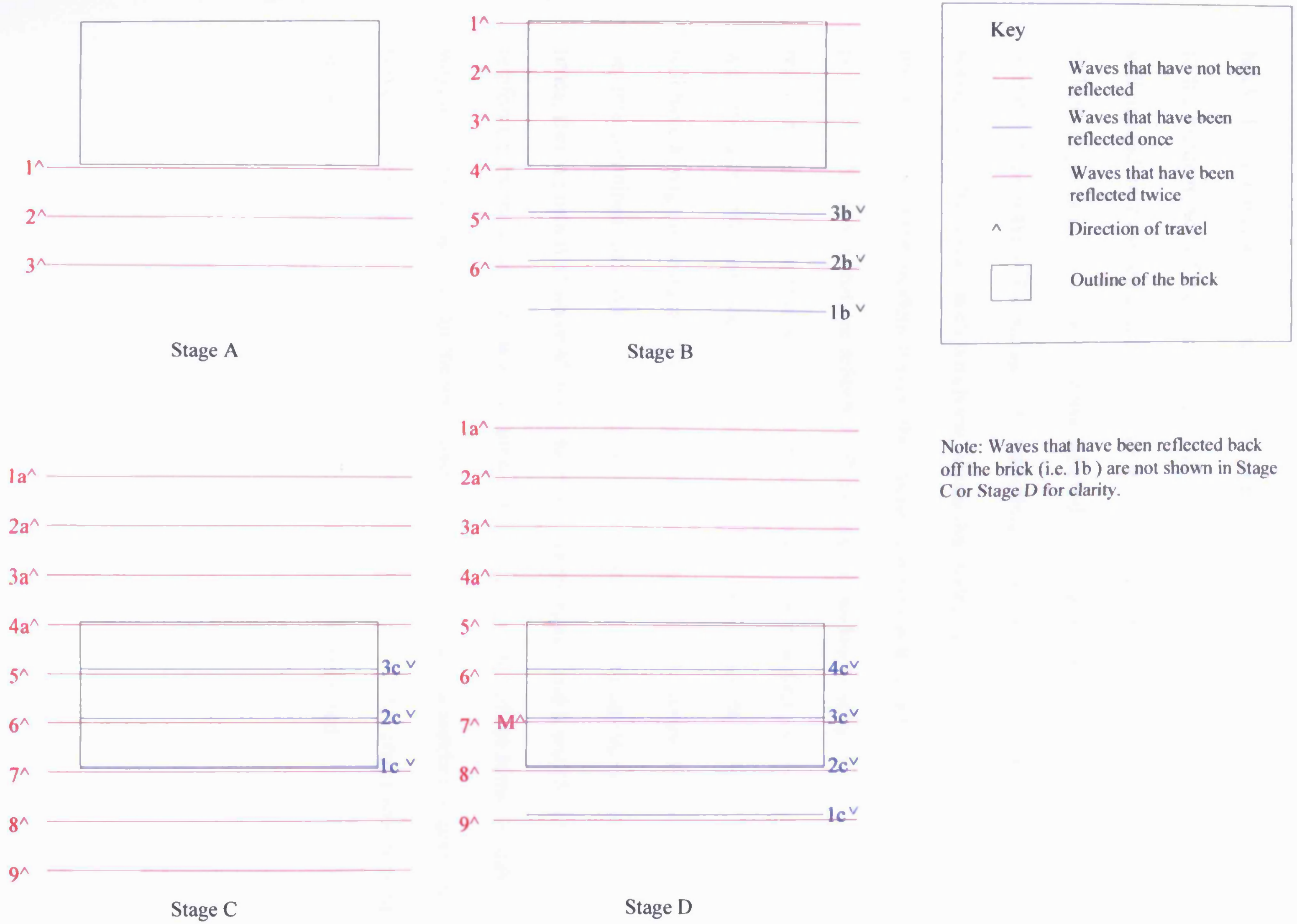


Figure 3-15. Waves reflecting and returning to the incident surface of a brick in an ultrasound bath

Stage C shows that the waves are partially internally reflected as they reach the far side of the brick, causing some energy from the wave to be reflected back within the brick. The wave labelled 1c has reflected off the far face of the brick and had returned to the incident face of the brick. The time taken for the wave to "reflect and return" will depend on its speed and the distance it travels through the bricks. If this wave is reflected again (as shown be the wave labelled M in stage D Figure 3-15) then a portion of the wave will once again be travelling in the same direction as the incident waves. If the frequency with which the waves that reflect and return coincides with the frequency of the incident waves, then incident waves will be reinforced by the portion of the waves that are reflected off the internal surfaces of the brick. This will result in a single wave that is a combination of wave 7 and portion of wave 1c that was internally reflected twice. This wave, labelled as M in Stage D of Figure 3-15, will have a magnitude equal to the sum of the amplitudes of the waves before they became combined. In addition, if some portion of the first wave can be reflected four times, then a portion of wave M will reflect and return again, and it will then be reinforced by the fourteenth wave to arrive at the incident face of the brick. In this way, a wave passing through the specimen can be reinforced by a number of previous waves, increasing the amplitude of the wave. The magnitude of this effect will depend on the quantity of the previous waves that can be internally reflected.

3.7. Influence of waves

Consider a bar subjected to an axial tension, as shown in Figure 3-16.

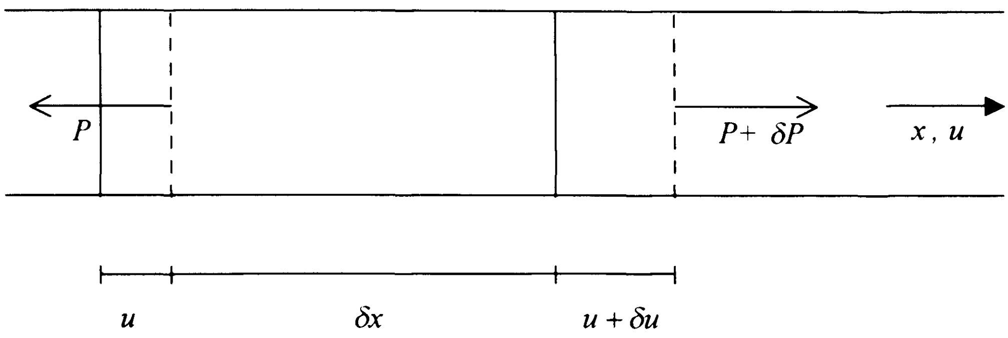


Figure 3-16. A bar subjected to an axial load

Considering only the forces and displacements occurring in a single dimension, the out of balance axial force δP is equal to the mass times acceleration of the element of length δx. This can be expressed mathematically by the expression shown below:

$$\delta P = \rho A \delta x \frac{\partial^2 u}{\partial t^2} \quad \rightarrow \quad \frac{\partial P}{\partial x} = \rho A \frac{\partial^2 u}{\partial t^2} \tag{22}$$

where
- $u\,(x,t)$ is the displacement in the x direction
- $P\,(x,t)$ is the axial force applied
- A is the cross sectional area of the bar
- ρ is the density of the material
- E is the Young's modulus of the material
- t is time

The standard equations for strain, stress and force used in the theory of elasticity are shown below:

$$\text{Strain}\,\varepsilon = \frac{\partial u}{\partial x} \tag{23}$$

$$\text{Stress}\,\sigma = E\varepsilon = E\frac{\partial u}{\partial x} \tag{24}$$

$$\text{Force}\,P = \sigma A = EA\frac{\partial u}{\partial x} \tag{25}$$

The expressions in Equations (22) to (25) can be combined in order to determine the governing differential equation shown below:

$$\frac{E}{\rho}\frac{\partial^2 u}{\partial x^2} = \frac{\partial^2 u}{\partial t^2} \qquad (26)$$

There are two possible solutions to the governing differential equation, as shown below:

$$u = F(z) = F(x \pm ct) \qquad (27)$$

where $z = x \pm ct$
c is the velocity of the travelling wave

$$u = F(x)G(t) \qquad (28)$$

Equation (27) is the transient solution representing elastic waves travelling along the length of the bar.

This solution can be substituted back into the governing equation (26) to give:

$$\frac{E}{\rho}\frac{\partial^2 u}{\partial z^2} = \frac{E}{\rho}\frac{\partial^2 u}{\partial x^2} = \frac{\partial^2 u}{\partial t^2} = c^2\frac{\partial^2 u}{\partial z^2} \qquad (29)$$

Hence from Equation (29):

$$c^2 = \frac{E}{\rho} \qquad (30)$$

The second solution of the governing equation shown in Equation (28) represents a steady state vibration of the bar. The steady state vibration solution can be substituted back into the differential equation, along with equation (30), to give:

$$\frac{c^2}{F}\frac{d^2 F}{dx^2} = \frac{1}{G}\frac{d^2 G}{dt^2} = -\omega^2 \qquad (31)$$

In order for Equation (31) to equate ω^2 must be a constant. Hence Equation (31) can be rearranged to give:

$$\frac{d^2G}{dt^2} + \omega^2 G = 0 \qquad (32)$$

Assuming a solution for Equation (32) of the form:

$$G = B\, e^{\alpha t} \qquad (33)$$

and substituting Equation (33) back into Equation (32) gives:

$$Be^{\alpha t}\left(\alpha^2 + \omega^2\right) = 0 \qquad (34)$$

which implies that:

$$\alpha = \pm i\omega \qquad (35)$$

The general solution of Equation (32) is therefore:

$$G = B_1 \sin \omega\, t + B_2 \cos \omega\, t \qquad (36)$$

Assuming that at time $t = 0$ then $G = u = 0$ gives $B_2 = 0$. Hence:

$$G = B_1 \sin \omega\, t \qquad (37)$$

Also, from Equation (31):

$$\frac{d^2F}{dx^2} + \frac{\omega^2}{c^2} F = 0 \qquad (38)$$

The general solution of Equation (38) is:

$$F = D_1 \sin \frac{\omega}{c} x + D_2 \cos \frac{\omega}{c} x \qquad (39)$$

Now consider a bar of length $2L$ as shown in Figure 3-17.

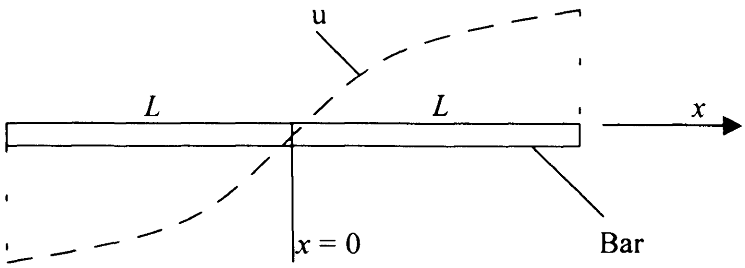


Figure 3-17. Steady state vibration of a bar of length $2L$.

Assuming that at $x = 0$, $u = F = 0$ gives $D_2 = 0$. If it is assumed also that axial straining does not occur at $x = \pm L$, $\frac{du}{dx} = \frac{dF}{dx} = 0$ and hence:

$$\frac{dF}{dx} = D_1 \frac{\omega}{c} \cos\frac{\omega L}{c} = 0 \qquad (40)$$

From Equation (40) either $D_1 = 0$ or $\omega \frac{L}{c} = \frac{\pi}{2} + n\pi$. Ignoring the trivial solution $D_1 = 0$ and hence:

$$F = D_1 \sin\frac{\omega}{c} x \qquad (41)$$

where $\omega = \frac{\pi}{2}\frac{c}{L} = \sqrt{\frac{\pi^2}{4L^2}\frac{E}{\rho}}$

The particular solution of the governing differential equation represented by Equation (28) is therefore:

$$u = B \sin\frac{\omega}{c} x \;\; \sin \omega\, t \qquad (42)$$

where ω is the circular frequency of vibration (as defined in Equation (41) in radians per second.

The amplitude of the stresses and strains produced during the steady state vibration can now be determined. From Figure 3-17 it can be seen that the maximum stress occurs when x = 0. The stress can be determined by differentiating Equation 42 and substituting into Equation 24 as shown below:

$$\sigma = E\frac{\partial u}{\partial x} = E\ B\ \frac{\omega}{c}\cos\frac{\omega}{c}x\ \sin\omega\ t \qquad (43)$$

In addition, Equation (43) can be differentiated twice with respect to t to give the acceleration:

$$\frac{d^2u}{dt^2} = -B\ \omega^2 \sin\frac{\omega}{c}x\ \sin\omega\ t \qquad (44)$$

The maximum acceleration a_m occurs when $\sin\omega\ t = 1$. and $\sin\omega\frac{L}{c} = \sin\frac{\pi}{2} = 1$.

The maximum acceleration a_m can therefore be determined as:

$$a_m = B\omega^2 \qquad (45)$$

$$B = \frac{a_m}{\omega^2} \qquad (46)$$

Hence from Equation (43) the maximum stress σ_m at $x = o$ is given by:

$$\sigma_m = \frac{Ea_m}{\omega\ c} = a_m\rho\frac{2L}{\pi} \qquad (47)$$

3.8. Effectiveness of ultrasonic vibrations

The effectiveness of a process induced by ultrasonic waves is not always directly linked to the power of the waves. T.J. Mason[62] uses the production of Iodine from aqueous KI to illustrate this concept. An aqueous KI solution is subjected to ultrasonic waves and Iodine is produced. Figure 3-18 shows the Iodine yield against the power of the ultrasonic vibrations.

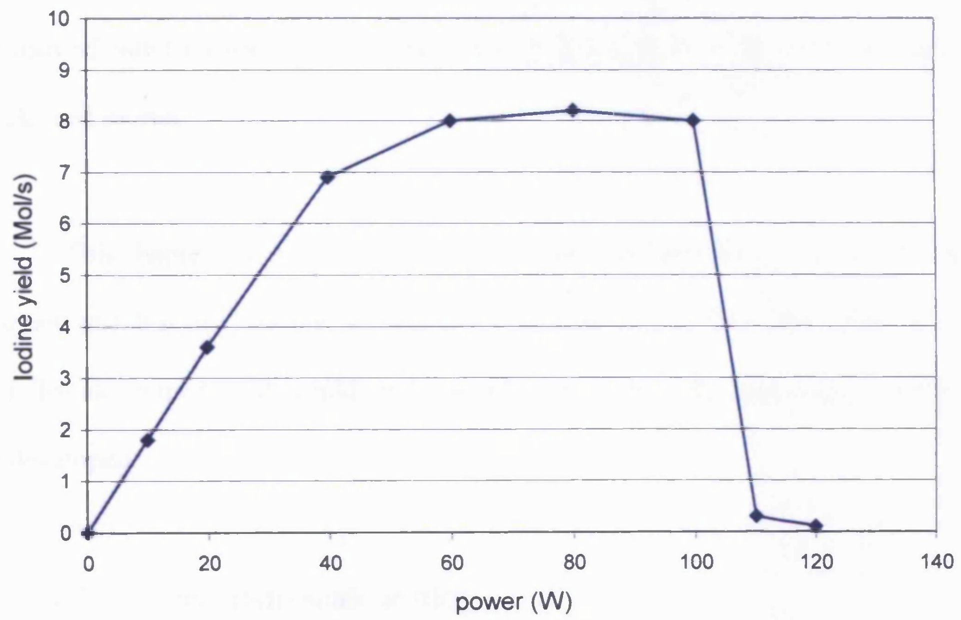


Figure 3-18. The effect of ultrasonic power on Iodine yield in the sonochemical oxidation of IK to iodine in aqueous solution. (from Mason [62])

Figure 3-18 shows that whilst the Iodine yield become greater as the power of the ultrasonic vibrations is increased, a plateau is reached, and subsequently the yield decreases rapidly. This kind of reduction in the effectiveness of a process when the power is increased is known as the "decoupling effect". Mason [62] also indicates that "for any sonochemical process, there will be an optimum power for maximum effect".

4. Initial Studies

4.1. Aim

During previous work [28, 29] it had been noted that one-sixth scale mortar brick couplets could be separated by placing them in an ultrasound bath. However, no detailed studies had been performed and so the immersion time taken for this to occur, and the precise factors affecting the length of time, were unknown. It was therefore decided to perform further work using one-sixth scale bricks to investigate the ability of the ultrasound bath to separate the couplets and allow the recovery of the constituent bricks and mortar.

This chapter also details investigations that were performed with bricks and couplets at full scale. The aim of these investigations was to determine the properties of full-scale couplets that would enable a full-scale brickwork separation prototype to be developed.

4.2. One-sixth scale testing

In order to test the ability of ultrasound to separate mortar from the surface of a brick it was decided to build a series of one-sixth scale couplets and place them within the ultrasound bath. If this was found to be effective it would also be necessary to establish how the process worked, and evaluate the possibility of adapting the same method so that it could be used to reclaim full-scale brickwork.

The ultrasound bath used was an Ultrawave U400, a standard ultrasound bath designed for cleaning jewellery and laboratory equipment. A photograph of the U400 ultrasound bath is shown in Figure 4-1 and the specifications of the bath are given in Table 4-1.

Figure 4-1. The ultrasound bath

Manufacturer	Ultrawave
Model number	U 400
Frequency	30 000 Hz
Internal dimensions	240 x 138 x 140 mm
Capacity	2.75 litres

Table 4-1. Specification of the Ultrawave U 400 ultrasound bath

The main ultrasound bath unit has a switch to turn on the Sonics and a timer so that the bath can be left to clean an object for up to 15 minutes. The bath also has a heater and a thermostat enabling the water in the bath to be heated to a specific temperature. Heating the water makes it easier to clean fat and dirt off some objects. In addition, the ultrasound waves themselves can cause an increase in the temperature of the water within the ultrasound bath. Additional work performed at Cardiff University by Gnanadoss[28] determined that the temperature of the water in the bath would rise by several degrees if the bath operated for fifteen minutes. This work also showed that the time taken to separate couplets in an ultrasound bath was reduced if the temperature of the water was increased. However, the water temperature was not regulated during the initial study performed for this thesis. The bath has a metal lid, but this was not used as it prevented the couplets from being observed while they were in the ultrasound bath. Consideration was given to using a clear Perspex lid during the initial studies performed as part of this thesis. This would refocus energy that would otherwise escape from the top of the bath and reduce heat loss from the bath if it was operating above room temperature. However, when the ultrasound bath was running the Perspex lid was found to vibrate and this made visual identification of the events in the bath difficult, so it was decided to use the ultrasound bath without a lid. There is also a metal basket, into which the objects to be cleaned were placed. The basket could then be lowered into the ultrasound bath so that the objects will be held just above the base of the ultrasound bath.

It was necessary to use scaled bricks because the ultrasound bath was too small to allow full-scale bricks to be used. During some initial trials of the test, it was noticed that a couplet in the ultrasound bath first split down one side of the bed joint to give a clean brick and a brick with the mortar remaining on its surface. If these pieces were left in the bath, the block of mortar would eventually fall off the remaining brick completely, leaving two clean bricks and a single block of mortar. The separation between the first brick to fall off and the mortar was termed "stage 1 separation". The separation between the mortar block and the remaining brick was termed "stage 2 separation". When couplets were tested in the ultrasound bath the time taken for both stages of separation to occur were recorded. In addition, small mortar cubes were made from the mortar used to make the couplets and retained so that strength tests could be carried out to evaluate the crushing strength of the mortar. This would enable an allowance to be made so that specimens fabricated with different batches of mortar could be compared by relating the compressive strength of the mortar.

4.2.1. Effect of mortar strength and joint thickness

For the first experiment, couplets were made with different types of mortar and with a different thickness of mortar joint. The use of couplets allows the ultrasound process to be tested with a number of different types of specimens, to determine how these factors would affect the ability of the ultrasound bath to remove the mortar from the bricks.

4.2.1.1. Test Procedure

The one-sixth scale bricks used to make the couplets were fabricated using a scaled down wire cutting process. This process has produced one-sixth scale bricks that are as good a match for wire-cut full-scale bricks as possible. They have dimensions of 36 x 18 x 11 mm, and have the same shape as a typical wire-cut brick. Close up photographs of some of the one-sixth scale bricks can be seen in Figure 4-2.

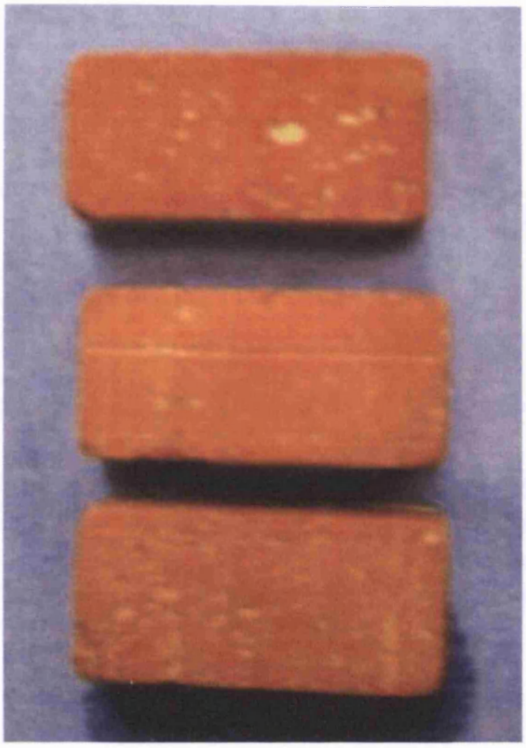


Figure 4-2. One-sixth scale wire-cut bricks

In order to maintain the ratio between the mortar joint depth and the size of the brick it was necessary to build couplets with thin joints. The standard Ordinary Portland Cement and Hydrated Lime components (to BS 12:1991 [63] and BS 890 [64] respectively) specified for mortar in BS 4551 [12] consist of fine aggregates. Hence these ingredients could be used without a risk of abnormal behaviour because of the reduced scale of the bricks. However, the particles within standard building sand were considered to be too large for use in mortar used to make one-sixth scale couplets. Previous work[65, 66, 67] with one-sixth scale bricks at Cardiff University had used a Chelford 95 sand. This sand is comprised of particles approximately one-sixth the size of the particles in normal building sand, as shown by the grading curves in Figure 4-3 below.

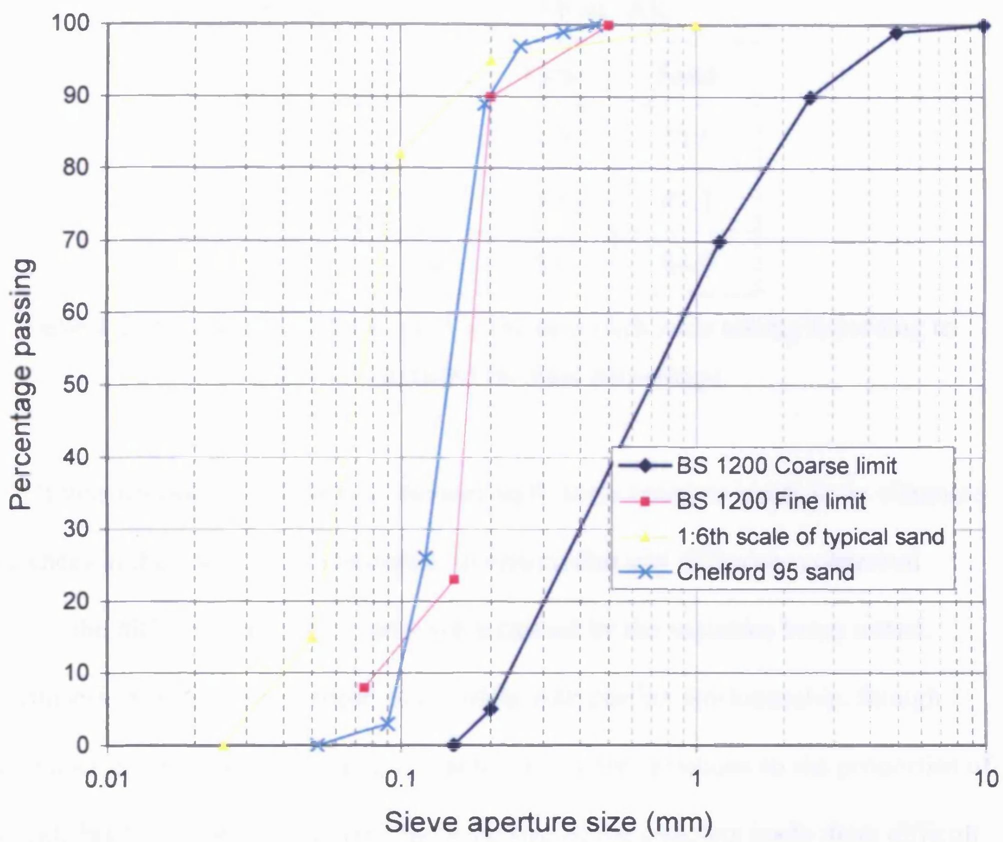


Figure 4-3 Grading curves for mortar sand (taken from Baralos [66])

In addition, this previous work also shows that one-sixth scale couplets made with this mortar should fail at the same stress as their equivalent full-scale bricks. Therefore, it was decided to continue using these constituents to make the mortar for all the one-sixth scale couplets. The constituents used were Ordinary Portland cement [vi], Hydrated Lime [vii] and Chelford 95 sand [viii]. Couplets for the test were made using grades 1, 3 and 5 mortar, as detailed shown in Table 4-2.

[vi] Ordinary Portland cement in accordance with BS EN 197-1, supplied by Blue Circle Cements
[vii] Hydrated lime in accordance with BS 890, supplied by Blue Circle Cements
[viii] HST 95 Dried silica sand, supplied by Hepworth Minerals and chemicals

GRADE	LIME MORTAR		
	Cement	Lime	Sand
1	22.9	1.5	75.6
3	13.6	5.1	81.3
5	7.1	8.0	84.9

Table 4-2. Mortar proportions used in the one-sixth scale testing according to BS 4551, detailed by mass percentage

It was necessary to construct the one-sixth scale couplets carefully to eliminate differences in the level of workmanship, to ensure that any differences observed between the different types of couplet were caused by the variables being tested. Nonetheless, it is difficult to produce couplets with perfect workmanship, though small imperfections would not tend to cause significant variations to the properties of full-scale brick couplets. However, the small size of the couplets made them difficult to handle during fabrication and any small defects within the couplets would therefore have proportionally greater bearing on the results recorded. A wall-making jig as shown in Figure 4-4 was used to ensure that the couplets were built as precisely and consistently as possible.

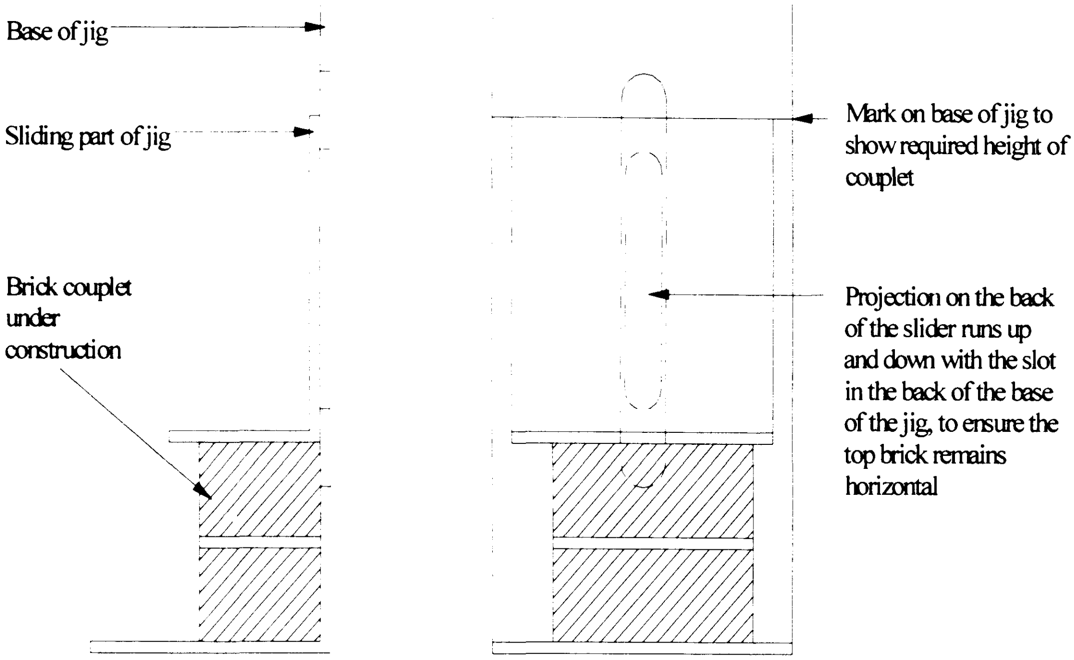


Figure 4-4. Jig used to construct one-sixth scale couplets

Prior to the construction of a couplet, the bricks were soaked in water for a period of two hours. This was not sufficient time for the bricks to become saturated, but would ensure that the bricks absorbed enough water to allow the mortar to set fully during curing. Two of the bricks were then placed in the jig under the sliding part of the jig and a datum line was drawn above the sliding part of the jig. Hence when the top of the sliding part of the jig is level with this zero line, there is no gap between the two bricks below. If a couplet with a 2mm thick joint was required, a new line was drawn two mm above the datum line, and hence when the top of the sliding part of the jig was in line with this new line the joint in the couplet below would have the desired thickness. To construct a couplet, the mortar for the joint was placed upon the bed face of the bottom brick using a small artist pallet knife. This brick was placed upon the jig with the mortar facing upwards and the other brick was then placed on top of the mortar. The sliding part of the jig is then placed on top of the upper brick so that its projection fits into the slot of the base of the jig. The sliding part of the jig was then knocked downwards with a series of gentle taps, until the top of the sliding jig was level with the 2mm line, indicating that the desired joint thickness had been achieved. During this time the bricks are held against the base of the jig, which ensures that the bricks remain level and parallel. A pallet knife was then used to cleaned away any excess mortar from joint face, leaving a smooth joint profile. The completed couplet could then be carefully removed from the jig. Couplets with mortar joints that were of 2, 5 and 10mm thick were made for testing in the ultrasound bath.

The couplets were cured for a standard period of 28 days prior to being tested. The small scale bricks did not absorb much water, and there was a concern that the strength developed by the mortar could be inhibited by a lack of moisture. The couplets were therefore cured under a plastic sheet to limit the evaporation of the water from the couplets during the curing process. No compressive load was applied to the couplets during curing, so the confining pressure applied was determined by the weight of the top brick. Hence the load applied to the mortar joint was proportional to the vertical dimension of the top brick. This would allow couplets fabricated from bricks at different scales to be used, whilst keeping the confining pressure proportional to the scale of the bricks used.

The mortar cubes were made using a 25mm mould; after the mortar cubes had been formed, they were cured under the same conditions as the couplets.

Three specimens were used to test each set of variables, making a total of 27 couplets and 9 mortar cubes. Table 4-3 below shows the different mortar grades and thickness of mortar joints of the specimens that were tested.

	Mortar Grade		
Mortar joint thickness (mm)	1	3	5
2	3	3	3
5	3	3	3
10	3	3	3
Mortar cubes	3	3	3

Table 4-3. Number of mortar cubes and couplets constructed

The ultrasound bath was used in accordance with the user's guide. The ultrasound bath was filled to the recommended level (40mm below the top of the bath) and a detergent [ix] was added. The detergent is added to dissolve any fat deposits, which would occur for many of the items that the bath is designed to clean. As there would not be any fats on the couplets it seemed probable that the detergent was not needed and would not have any effect. The presence of detergent would change the properties of the fluid and thus change its susceptibility to cavitation (see Equation (19), the Rayleigh-Plesset Equation in Section 3.5) However, the manufacturer would not recommend the use of a detergent that would significantly impede cavitation. It was therefore decided that detergent was unlikely to impede separation and hence detergent was added as instructed. The ultrasound bath was then turned on and allowed to operate for a period of 20minutes to allow degassing of the water to occur.

[ix] Neutracon

As degassing was performed in accordance with the manufacture's guidelines it was assumed that following degassing process there was no dissolved gas remaining in the water. Degassing is performed because any dissolved air remaining in the water absorbs some of the movement produced in the water by the passage of ultrasonic waves. This reduces the chances of a void forming, inhibiting the process of cavitation. Initially, the water in the bath will contain some dissolved air, but when the bath operates for the first time the dissolved air forms air bubbles, which float to the surface, thus removing the air from the water. If degassing is not performed prior to use, the operation of the bath will be impeded until degassing has occurred. When complete degassing had been achieved the ultrasound bath was ready for use, and it was turned off.

Prior to testing, the couplets were soaked in water overnight so that they would be saturated during testing, ensuring that there were as few air pockets within the brick as possible. Any that remained could impede the ultrasound waves and the process of cavitation within the specimens. The couplets were tested in the ultrasound bath one at a time by placing each individual couplet in the wire basket and then within the ultrasound bath. Although there was no reason to argue that the orientation of the couplets would affect the separation process, for consistency, the couplets were all placed in the centre of the bath with their greatest dimension parallel to the longest side of the ultrasound bath. The ultrasound bath was turned on, and the couplets were observed closely so that the time taken for both stages of separation to occur could be noted using a stopwatch. Just before the bricks separated, it was possible to see a crack developing and then the two parts of the couplet would fall apart releasing air bubbles. It was thus not difficult to determine exactly when separation occurred. The same process was also observed when the mortar separated from the second brick, and so the stage 2 separation time could be recorded in the same way. The two bricks and the piece of mortar from the couplet were retained for photographing and further examination.

4.2.1.2. Results and discussion

The results from the initial testing are detailed in Table 4-4. The raw data for each specimen can be found in Appendix A 1.1 and A 1.2.

	Mortar joint thickness (mm)	Average ultimate compressive strength at 28 days (N/mm^2)	Stage 1 separation time (seconds)	Stage 2 separation time (seconds)
Mortar grade 1	2	12.5	30.3	79.0
	5		24.3	43.0
	10		66.0	88.0
Mortar grade 3	2	6.3	26.7	256.3
	5		45.0	174.0
	10		41.3	323.7
Mortar grade 5	2	1.5	23.3	48.7
	5		15.7	88.3
	10		23.0	107.0

Table 4-4. Average separation times for one-sixth scale brickwork couplets

The results in Table 4-4 above show that there is a clear difference between the ultimate compressive strength developed by the three different grades of mortar. All the couplets were separated and cleaned by the ultrasound bath in less than two and a half minutes, which was an indication that the process had good potential and was worth further development. The data in Table 4-4 is shown in graphical form in Figure 4-5 to allow any patterns in the results of the initial testing to be identified.

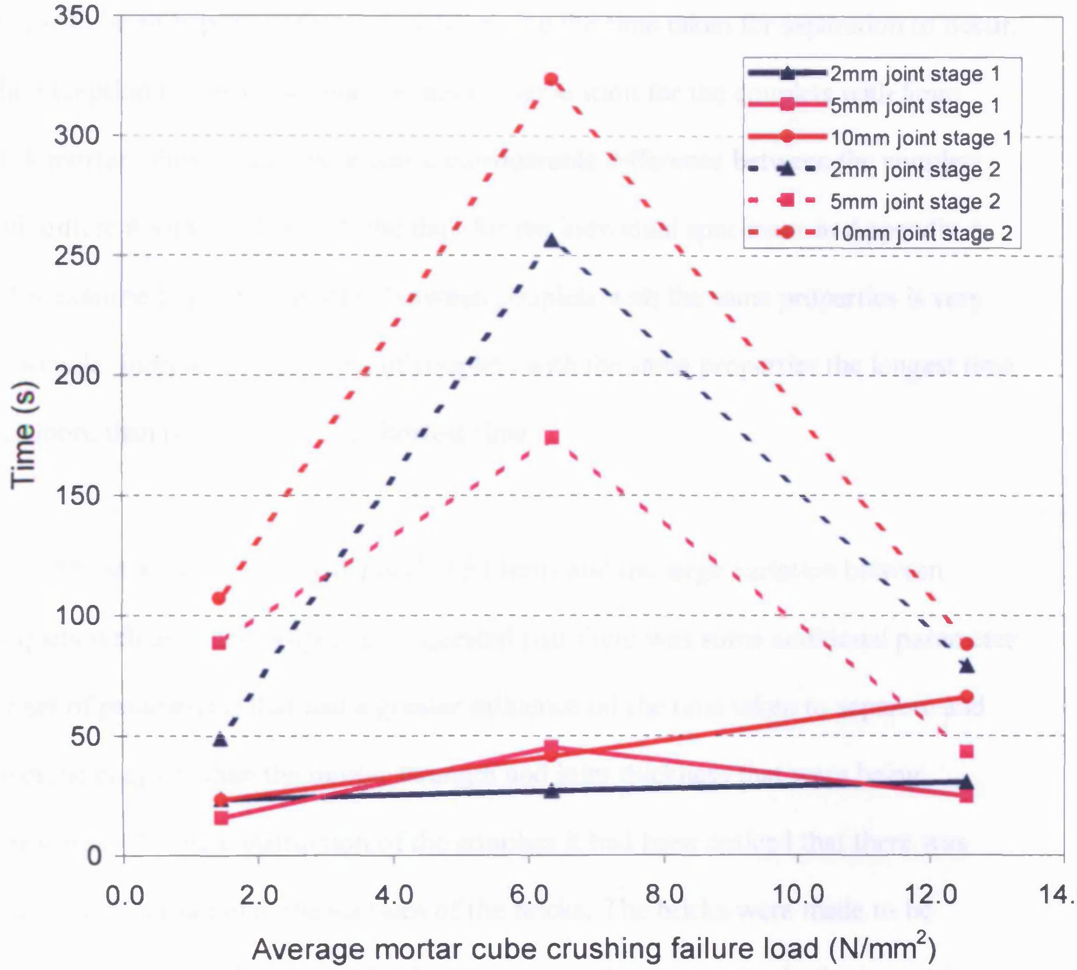


Figure 4-5. Graph to show the mortar strength against the separation times for one-sixth scale brickwork couplets

It is difficult to identify any overall trends from the graph shown in Figure 4-5. However, the time taken for stage 1 separation is proportional to the mortar strength and stage 2 separation takes longer for couplets made with mortar with a cube strength of 6 N/mm^2. It would be logical to assume that the mortar strength would be proportional in some way to the time required for the two stages of separation to occur. However, most often the couplets made with Grade 3 mortar took longer to separate and clean than those with the stronger Grade 1 mortar. There was not much difference between the couplets made with different mortar thickness, so that does not appear to be an important factor in determining the time taken for separation to occur. The exception to this is the time for stage 2 separation for the couplets with 5mm thick mortar joints, where there was a considerable difference between the couplets with different joint thickness. If the data for the individual specimens in Appendix A 1.2 is examined, a large variation between couplets with the same properties is very noticeable. Indeed, for most sets of couplets with the same properties the longest time was more than twice that of the shortest time.

The lack of any clearly explicable patterns and the large variation between couplets with the same properties suggested that there was some additional parameter (or set of parameters) that had a greater influence on the time taken to separate and clean the couplets than the mortar strength and joint thickness that were being considered. During construction of the couplets it had been noticed that there was considerable variation in the surfaces of the bricks. The bricks were made to be identical to a full-scale wire cut brick, and were made using a standard wire cutting process. The wire cutting process typically leaves small indentations and small grooves on the surfaces of the bricks. They are too small to significantly influence the properties of full-scale bricks, but the same grooves on the one-sixth scale bricks were relatively large compared to the surface area of the bricks. Some of the one-sixth scale bricks had one or two grooves down their faces, as shown in Figure 4-6, while others had none.

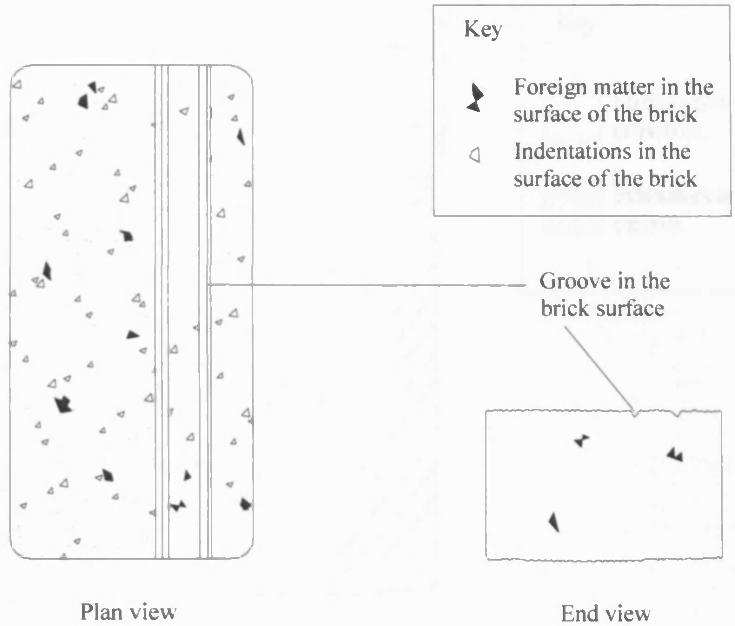


Figure 4-6. A one-sixth scale brick with rough surfaces

It seemed possible that these variations in surface quality could affect the strength of the bond formed between the mortar and the surface of the brick. In addition it was noticed that some of the pieces of mortar that had been separated from the one-sixth scale bricks had a small, raised "lip" around their edges, as shown in Figure 4-7 below.

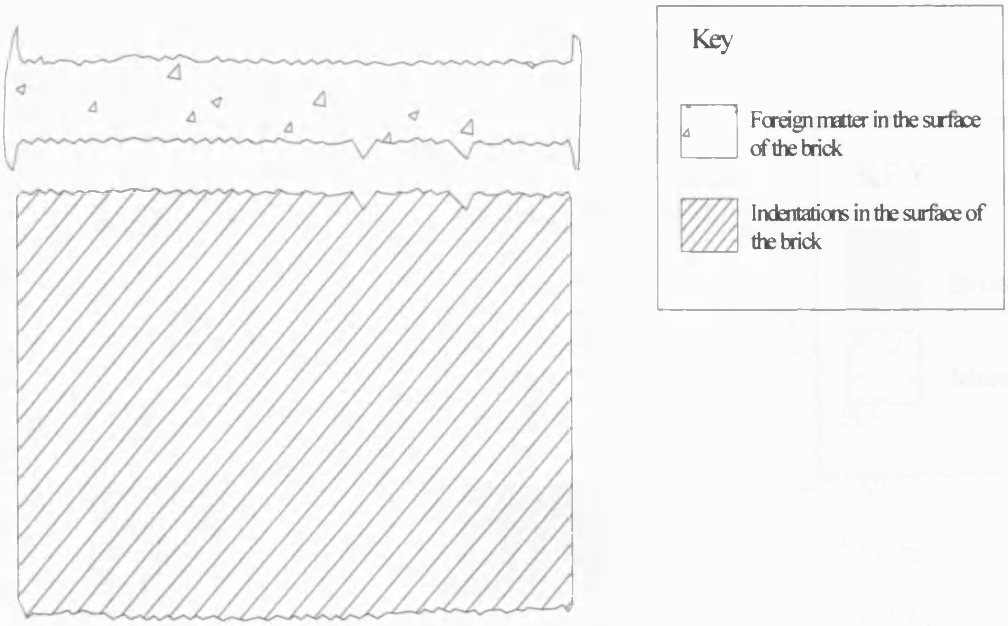


Figure 4-7. A separated mortar joint with raised lips around its edges

These "lips" were not formed when the couplets were made, but must have developed as the mortar was squeezed out from between the bricks by the weight of the top brick whilst the mortar was still flexible just after they were made. Figure 4-8 below shows a typical joint and one with a "lip" similar to those found on some of the scaled brick specimens.

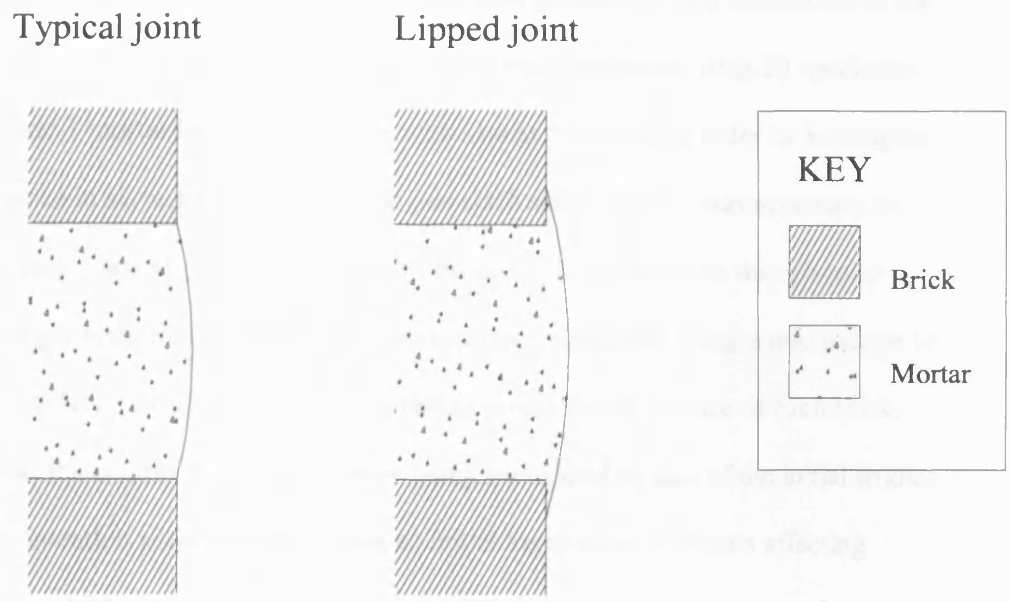


Figure 4-8. A typical mortar joint and one with a "lip"

The results indicated that couplets that had mortar joints with lipped edges take longer to separate and clean in an ultrasound bath. The "lip" not only brings an additional area of mortar into contact with the brick, but if a lip is formed around each edge of the brick then it could mechanically grip the couplet together even after the adhesive bond between the mortar and the bricks has been broken.

4.2.2. *Effect of brick surface roughness and mortar joint edges*

It was deemed necessary to perform some further experiments to try and quantify the importance of the surface quality of the bricks and the shape of the mortar edge.

4.2.2.1. Test procedure

A new set of couplets were made following the same method outlined in Section 4.2.1.1, but all of them were made with a 2mm joint thickness and the curing time was reduced to 7 days. The results could be compared to the previous results, using the different strengths developed by the mortar cubes to allow for any differences in the properties of the mortars used. The experiment was conducted using 20 specimens with Grade 1 mortar and 20 specimens with Grade 5 mortar. In order to investigate the variance in surface properties of the one sixth scale bricks it was necessary to classify each brick as either "rough" and "smooth". Consideration was given to developing a system for quantifying overall surface roughness using a microscope to rate the surface quality at a series of sampling points on the surface of each brick. However, the current experiments were being performed as part of the initial studies with the intention simply being to gain an initial impression of factors affecting separation. As it was only necessary to classify the bricks into two groups it was decided that a visual qualitative assessment using a hand-held magnification lens would be appropriate. The beds of the bricks were visually examined to have their surfaces classified as "rough" or "smooth". Half of these specimens were made from "rough" bricks and half were made from smooth bricks. The surfaces on each brick was not necessarily the same on opposite sides, so it was ensured that the rough surfaces were against the mortar joint.

It was more difficult to ensure that half of the couplets had lipped mortar edges and the other half did not. When the first set of couplets had been made, the lips were not made intentionally but had instead formed before the mortar had set. However, it was necessary to develop a method of producing couplets with a clear difference in the quality of the edges of the mortar. In order to try and prevent lips from forming on the couplets that were required to have normal mortar joints, a cloth was used to wipe the joint to ensure that all excess mortar was removed. A small amount of excess mortar was left on the couplets that were intended to have lipped mortar edges, and this was then smoothed over the surface of the brick. A cloth was then used to remove most of the excess mortar, leaving a small amount to form the lip. The process used to make couplets in this manner is shown in Figure 4-9 below.

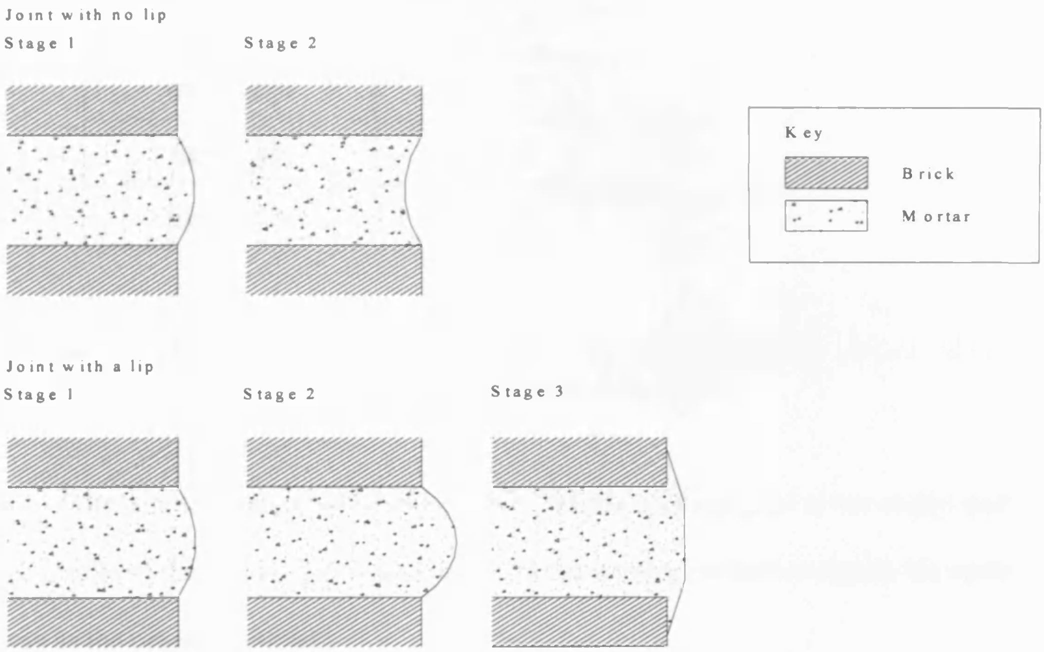


Figure 4-9. Stages used to make couplets with the different types of joint characteristics

When the couplets had cured they were closely examined prior to testing. None of the couplets that had been built to have no lip had developed one. The deliberate lips were not identical to those that had developed on the first set of couplets, but the area covered by the two types of lip was similar. There was thus a clear difference between the couplets with lips and those without.

Table 4-5 below shows the couplets that were made to determine the influence of the surface roughness of the bricks and the profile of the mortar joint.

Joint type / brick type	Mortar grade	
	1	5
no lip/smooth	5	5
no lip/rough	5	5
lip/smooth	5	5
lip/rough	5	5
Mortar cubes	3	3

Table 4-5. The number of specimens made to investigate the effect of brick surface roughness and mortar joint edges

The couplets made to investigate the influence of the surface of the bricks and the profile of the mortar joints were tested in the ultrasound bath in exactly the same way as the original couplets.

4.2.2.2. Results and discussion

The average results from the initial testing are given in Table 4-6 and Table 4-7 below. The raw results with the data for each specimen can be found in Appendix A 1.3 and A 1.4.

Mortar grade	Average ultimate compressive strength at 7 days (N/mm^2)
1	10.7
5	1.0

Table 4-6. Average ultimate compressive strength for the mortar grades used for the additional initial testing

Joint type / brick type	Grade 1 mortar		Grade 5 mortar	
	Stage 1 separation time (seconds)	Stage 2 separation time (seconds)	Stage 1 separation time (seconds)	Stage 2 separation time (seconds)
no lip/smooth	35	149	12	25
no lip/rough	74 (1)	168 (3)	22	32
lip/smooth	520 (2)	No separation	43	137
lip/rough	635 (4)	No separation	118	383

(The figures in brackets indicate the number of specimens that did not separate)

Table 4-7. Average separation times for one-sixth scale couplets with different joint and brick types.

The ultrasound bath was not designed for long periods of use. During previous work at Cardiff University with the same ultrasound bath [29] a loss of performance was recorded. This was attributed to the ultrasound bath being used for "very long periods of time". In order to avoid a recurrence of this problem the maximum time that a specimen was tested in the ultrasound bath was nine hundred seconds. In addition, after each specimen was tested, the ultrasound bath was not operated for a minimum of fifteen minutes. New specimens could then be tested again after fifteen minutes. However, in order for any separation process to be economically viable it would need to be able to achieve separation in a less than fifteen minutes. Hence it was decided that a testing period of fifteen minutes would be appropriate. Seven of the forty couplets did not separate or clean, and a further five were separated but did not clean within the fifteen minute time limit imposed.

As expected, the mortar cube testing results show that there is a clear difference between the mortar grades used. The mortar strengths for this test are slightly weaker than the mortars used in the previous experiment in Section 4.2.1 (see Appendix A). This is because of the reduced curing time that was used for this experiment.

Before the results from the first experiment (to examine the influence of the mortar grade and the thickness of the mortar joint) and the second experiment (to examine the influence of the surface of the bricks and the profile of the mortar joint) can be compared, it is necessary to determine a reference point between the two sets of results.

Most of the couplets from the first experiment were made from bricks with smooth surfaces and had smooth joint profiles without lips. This means that the couplets with the 2mm thick joints from the first experiment should be similar to the couplets in the second experiment made with the same mortar grade and from smooth bricks with joints that do not have a lipped profile. The couplets from the first experiment should take slightly longer to separate and clean because they were cured for longer, and the greater mortar strength should make them more difficult to separate and clean. In addition, the average separation times for the couplets from the first experiment should be slightly longer, given that some of the couplets would have developed lipped joints or been made using bricks with rough surfaces. Furthermore, they should not be as difficult to clean as the couplets made for the second experiment, when especially rough bricks were selected or the joint profile was deliberately made into a lip. Hence it would be expected that the separation times for the couplets with 2mm thick mortar joints from the first experiment (with both types of mortar) should be greater than the times for the "no lip/smooth" couplets, but less than the times for the lip/smooth couplets and the no lip/rough couplets.

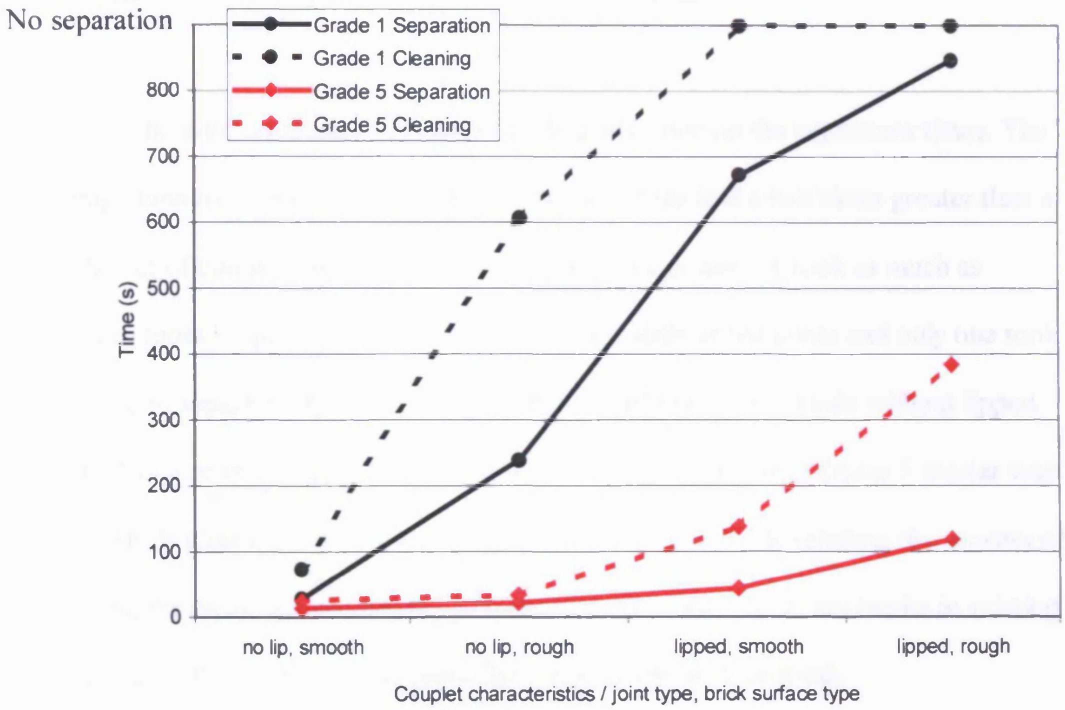
In order to identify the extent to which this occurs Table 4-8 was constructed.

Mortar Grade	Couplet type	Average stage 1 separation time (seconds)	Average stage 2 separation time (seconds)
5	No lip/smooth - experiment 2	12	25
	2mm joint - experiment 1	23	49
	no lip/rough - experiment 2	22	32
	Lip/smooth - experiment 2	43	137
1	No lip/smooth - experiment 2	27	71
	2mm joint - experiment 1	30	79
	no lip/rough - experiment 2	74 (1)	No separation
	Lip/smooth - experiment 2	520 (2)	168 (3)

(The figures in brackets in Table 4-8 indicate the number of specimens that did not separate during the fifteen minute testing period)

Table 4-8. Average separation times for similar couplets from the first and second experiments.

The figures in Table 4-8 above show that the separation times for the different specimens follow the expected pattern for the couplets made with both grades of mortar. This is re-assuring because it indicates that the results from different experiments can be coordinated with each other using a benchmark specimen. It also means that the change in mortar strength caused by the different curing times is not a critical factor on the separation times when compared to the influence of factors such as the joint profile and the surface properties of the bricks. This is unsurprising, as the change in strength due to the different curing time is small (less than 2.5 N/mm^2). Indeed, it is not much greater than the variation in the different mortar cubes made from the same batch of mortar (which is up to 1.25 N/mm^2). Figure 4-10 shows the data in Table 4-8 in graphical form.



Note that an arbitrary figure of 900 seconds was given to the specimens that did not separate/clean to calculate the average values shown on this graph

Figure 4-10. Graph to show the influence of the joint type and brick surface on separation times

Figure 4-10 does show a clear pattern which suggests that it was variations in joint profile and brick surface smoothness that were confusing the data from the first experiment that investigated the influence of the mortar strength and the thickness of the mortar joint.

Figure 4-10 shows that the mortar strength is an important factor in determining the amount of time taken to clean and separate the test specimens because all of the couplets made with Grade 5 mortar were cleaned in the ultrasound bath, but more than half of those made with Grade 1 mortar were not. The difference between the mortar grades is much more significant when the brick surface and the joint profile make the specimens more difficult to clean.

The joint profile also has an important influence on the separation times. The average time for a couplet with a lip was at least three and a half times greater than a similar set of couplets made without a lip, but in some cases it took as much as nineteen times longer. Forty couplets were made with lipped joints and only one took less time to separate than any of the similar couplets that were made without lipped joints. None of the ten couplets with a lipped profile made using Grade 5 mortar was successfully cleaned. However, this is not a reason to cease developing the process of adapting the technique for use in the brick recycling industry, as the bricks in existing structures will not have lipped joints that were deliberately formed.

The effect of the bricks surfaces does not seem to be as important as the joint profile or the strength of the mortar. The couplets made from bricks with rough surfaces that cleaned and separated in the shortest times separated in less time than the similar couplets made with smooth bricks. However, there is still a clear difference in the separation times for the two surfaces.

The failure of some of the couplets to separate in fifteen minutes is a potential problem even though this only occurs when a strong mortar is used in conjunction with rough bricks and/or mortar joints with a lipped profile. Running a machine which can clean full-scale bricks in this manner will be expensive, and will only be economically feasible if the bricks are cleaned in a short amount of time. The technology would only be worth developing for use in industry if the majority of bricks could be cleaned in a short period of time. This means that even if these specimens were found to clean after a much longer period of time in the ultrasound bath, it would not greatly improve the prospect of the process being suitable for commercial development. It is clear from Figure 4-10 that the effect of having a combination of a lipped joint, bricks with rough surfaces and mortar with increased strength can be much greater than the sum of each parameter alone.

It is unsurprising that a couplet with a lipped joint profile is more difficult to clean. The additional mortar in contact with the side of the brick increases the contact area between the mortar and the brick, but more importantly it also causes the mortar to be in contact with up to five sides of the brick. This means that the brick can only be separated by moving in one direction, as shown in Figure 4-11 below.

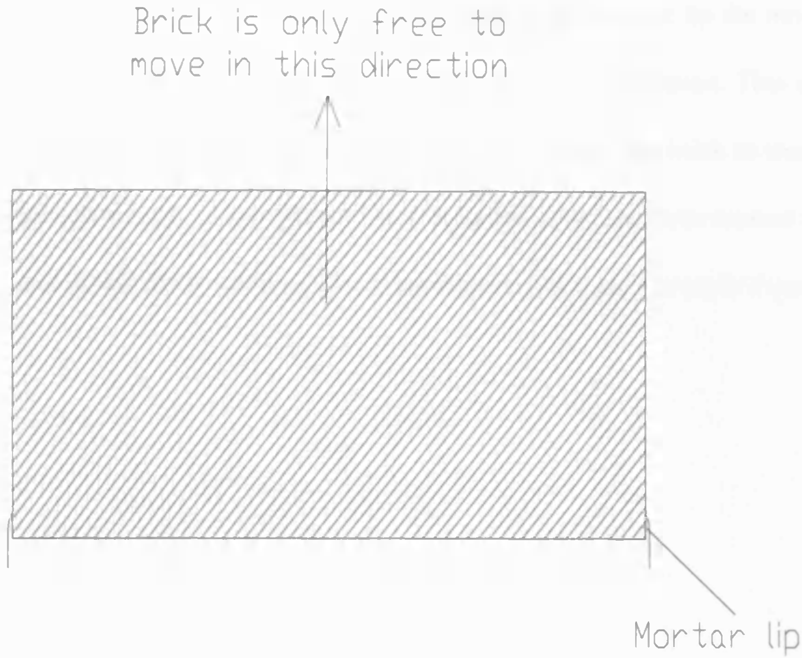


Figure 4-11. Bricks with mortar lips on each side can only move in one direction

Even if the brick has perfectly smooth surfaces and the bond between the brick and the mortar is broken in the ultrasound bath, the brick could remain held between the lips of mortar. However, the largest lips that were noted were only 2mm thick. When these lips are subjected to the vibrations and cavitation in the ultrasound bath it is unlikely that they will remain intact. However, while the lips around the edges of the joint maintain their structural integrity they will prevent separation from occurring.

However, the bricks do not have smooth surfaces and tend to have imperfect profiles near the edges of the brick. When the tension bond between the brick and the mortar has been broken, the brick will still be held in place by the friction or shear between the brick and the adjacent lips of the mortar, on four sides of the brick. In addition, if the edge of the brick flares outward, or if there are ridges, cracks or other imperfections in the side of the brick that is covered by the mortar lip the mortar will be able to "trap" the brick, preventing it from moving in any direction. This situation, where any mortar "latches" must be broken in order to allow the brick to move is called a "mechanical lock". Examples of how a lipped joint can form around the side of a brick causing the development of a "mechanical lock" are shown in Figure 4-12.

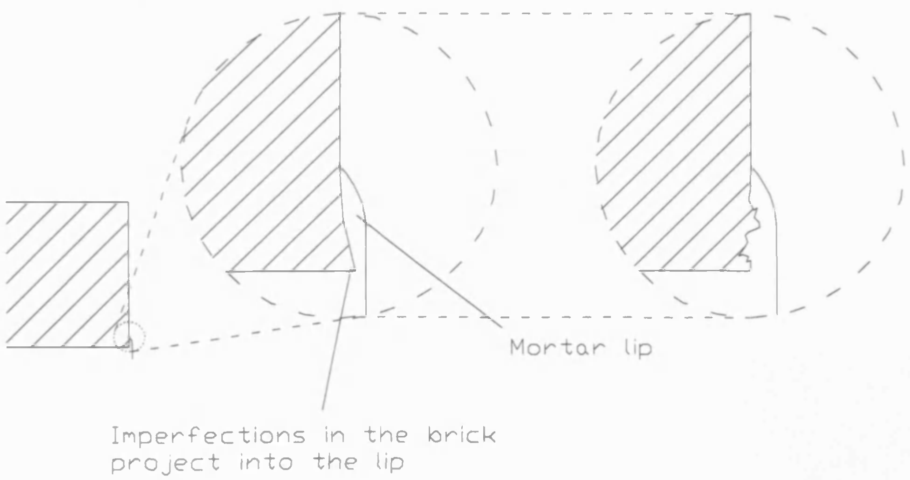


Figure 4-12. "Mechanical locks" formed by a lipped mortar joint bonding onto the sides of the brick

It was more difficult to fully understand why the surface roughness of the bricks made it more difficult to separate and clean the couplets.

When the couplets made with Grade 5 mortar that were separated and cleaned in the ultrasound bath during the second experiment were examined, it was observed that some of the bricks had mortar remaining on the surfaces that had been adjacent to the mortar joint. It became apparent that the smooth bricks had no mortar remaining on their surfaces, but most of the indentations in the surface of the rough bricks were filled with mortar. Figure 4-13 shows a diagram of some of the brick surfaces that were separated from the mortar joints in the ultrasound bath. The smooth brick on the left has allowed the mortar to be cleanly detached from the brick, whereas the rough brick on the right has retained some of the mortar.

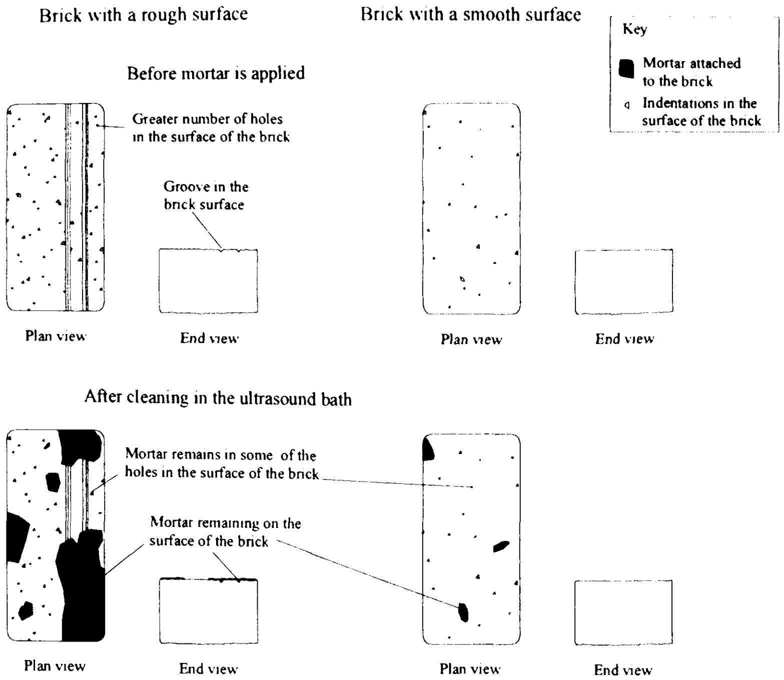


Figure 4-13. The different amounts of mortar that remained attached to bricks with smooth and rough surfaces.

The couplets made with Grade 1 mortar that had been separated in the ultrasound bath were also examined to see if mortar retention also occurred for the couplets made with stronger mortar. Once again the smooth bricks did not have mortar remaining on the surface of the bricks, whereas most of the indentations in bricks with rough surfaces that had been separated contained mortar held in the imperfections in the surface of the bricks. One of the couplets that had been made using Grade 1 mortar, and had not separated or cleaned in the ultrasound bath, was forcibly broken apart by hand to allow the surface of the bricks to be examined. Once again, most of the imperfections on the surface of both the bricks were filled with mortar. If the piece of mortar that had formed the couplet joint, and the brick face that had been against it were placed side by side, it was possible to match the profiles of the two surfaces as complementary. This indicates that when the couplet was made, the mortar had eased into the indentations in the surface of the brick, and when the brick and the mortar were separated the projection had come out of the imperfection in the brick and remained part of the main piece of mortar. Additionally, mortar that had remained in the indentations in the brick could sometimes be matched to the places where they had previously been attached to the piece of mortar.

These observations indicated that all of the imperfections in the surfaces of the bricks were filled with mortar when the couplets were formed. However, when the couplets were separated sometimes the mortar remained in the surface of the brick and sometimes it came away from the brick and remained as a projection on the main piece of mortar. One of the bricks was placed in acid to remove all mortar from the surface of the brick. After the mortar was removed, the imperfections in the surface of the brick that were filled with mortar could be examined and compared with the holes in the surface of the same brick that had not retained mortar after being placed in the ultrasound bath. There was no difference in size between the imperfections that had retained the mortar and those that had not, both large and small imperfections could retain mortar. However, examining some of the largest imperfections under magnification revealed that the imperfections that retained mortar were those where there was a small hole in the surface of the brick and a larger void inside the brick. An imperfection of this kind would lead to a hole in the surface of the brick with a "neck" as shown in Figure 4-14.

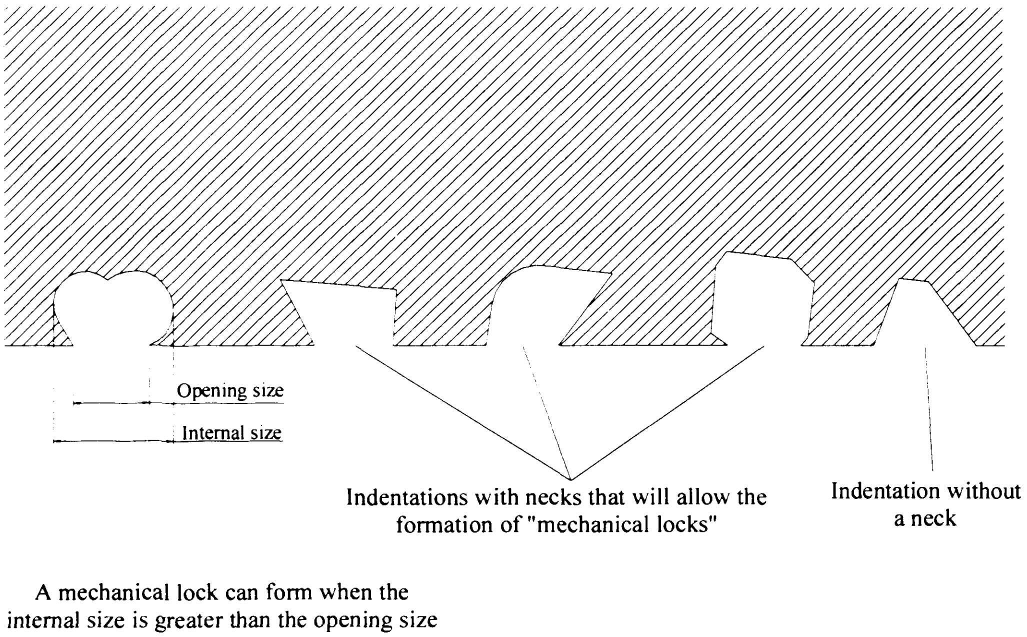


Figure 4-14. Indentations in the surface of a brick

When an imperfection in the surface of a brick with a "neck" is filled with mortar, a "mechanical lock" may form, which will hold the brick and the mortar together. This "mechanical lock" can only be broken by separating the mortar inside the brick from the main mortar joint, or by breaking up the mortar inside the brick into pieces that are small enough to pass through the "neck" of the imperfection. The ultrasound bath transmits vibrations through materials, and can potentially separate materials if they are caused to vibrate at different speeds. However, one of the main reasons why ultrasound is so useful is because it does not damage even fragile items made from a single material. This means that the projection of mortar in an imperfection in a brick forming a "mechanical lock" should not be broken, and hence cannot be withdrawn through the neck of the imperfection. This means that any "mechanical lock" will prevent the separation of the brick and the mortar unless the mortar is so weak that the vibrations generated by the ultrasound bath are sufficient to break through the mortar in the "neck" of the imperfection. If a couplet is made using a Grade 1 mortar it will not be possible to separate the projection of mortar embedded in the surface of the brick away from the main piece of mortar in an ultrasound bath, and hence the mortar will remain attached to the surface of the brick. However, the vibrations generated in an ultrasound bath are likely break a mechanical lock in a couplet made with a weak Grade 5 mortar.

Couplets made from rough bricks with a lipped joint profile can be much more difficult to separate and clean in the ultrasound bath. It has been shown that this is because these characteristics increase the chances of "mechanical locks" forming between the bricks and the mortar. These "mechanical locks" can be broken if the movement between the brick and the mortar is sufficient to break through the mortar holding the lock in place, but this can only occur when the couplets are made with a weak mortar.

4.2.2.3. The influence of mechanical locks

Mechanical locks can make a couplet more difficult to clean and even prevent separation from occurring at all. However, full-scale bricks and mortar recovered from demolition sites are unlikely to have the characteristics needed for mechanical locks to form. The lipped mortar joints were formed because of the difficulties involved with making couplets from small bricks and are not usually found in full-scale brickwork. Indeed, the old brickwork structures that are most frequently available for demolition have been subjected to years of weathering, and there is often scouring on the exposed surface of the mortar joint. This would make the brickwork easier to clean using a process based on the experiments performed with the ultrasound bath. However, some full-scale bricks would have surface properties that would allow mechanical locks to develop. In order for brick recycling technology based on this process to be both economically and financially successful it would be necessary to develop the technology to a level where an acceptably large percentage of bricks could be separated.

4.2.3. Section conclusions

During the initial investigation (described in Section 4.2.1 above) thirty-seven one-sixth scale couplets made with a variety of joint thickness and from mortar of three different strengths were tested. In three minutes or less Stage 1 separation had occurred for all of the specimens and 77% also achieved Stage 2 separation. After nine minutes in the ultrasound bath both stages of separation had been achieved by all the couplets. This success indicates that the process has good potential for being developed into a system for separating full scale bricks so that they can be recycled.

However, the anticipated relationships between the mortar joint properties were not clearly reflected in the results, and further experiments were performed to identify any additional important properties, which could prevent some specimens from separating. It was found that mechanical locks could form between the bricks and the mortar if the bricks had indentations on their surfaces or the joint profile extended around the edge of the brick. The couplets fabricated using Grade 1 mortar and bricks with rough surfaces that developed a lipped mortar joint did not separate, despite being left in the ultrasound bath for fifteen minutes. However, all of the couplets made for the same investigation without lipped joints from bricks chosen to have smooth surfaces were cleaned in less than three minutes. This indicates that provided a mechanical lock is not developed between the bricks and the mortar, there is high probability that it will be possible to separate and clean even a couplet made using strong mortar in a short amount of time in an ultrasound bath.

The energy requirement to separate a single one-sixth scale couplet is calculated to be 33 kJ (see Appendix E). This figure is calculated by considering the power supplied to the ultrasound bath, and hence it includes the energy that is "lost" and not delivered to the specimen i.e. energy lost heating the water in the ultrasound bath. However, as it is impossible to prevent some portion of the energy to the ultrasound bath being lost in this manner the author believes that it is correct to consider it to be part of the energy required to separate couplets using this method.

4.3. Investigations with full-scale bricks and couplets

It was decided that the important properties would be the natural frequencies of the bricks and couplets and the way in which vibrations are transferred through them. As well as performing tests on full-scale couplets, it was decided that conducting tests on separate mortar cubes and bricks would also be worthwhile. In addition, tests were also undertaken on full scale bricks in an ultrasound bath.

It was important to perform the tests on couplets made from appropriate bricks so that the results would be comparable with the brickwork that is available for recycling. This means that the bricks selected should be similar to the bricks that are often found in the old structures that are being demolished. However, the bricks in such buildings vary greatly. In addition, most of the bricks in old structures have been subjected to a great deal of weathering, resulting in the edges and corners of the bricks becoming worn. The easiest way to ensure a good match would be to use reclaimed bricks, but it was thought that this would lead to an unacceptable variation in the quality of the specimens. Instead it was decided that it would be preferable to try and find modern bricks with similar properties. Most modern bricks are made to precise specifications with sharp edges and corners that are very different to reclaimed bricks. In addition, many modern bricks have hollows and cut-outs to reduce the quantities of raw materials required and to aid the firing process. This would therefore alter their response to vibrations and make them unsuitable for the proposed testing. However, some brick manufacturers sell bricks that are specifically designed to look like "old" bricks. These bricks are shaped less precisely and are often "tumbled" to remove the sharp edges from the bricks. Although these processes are performed to change the cosmetic appearance of the bricks, it would also alter their "bonding" properties, making them closer to those of a reclaimed brick. However, this kind of brick also tends to have large frogs or patterns on some of the faces. A number of samples of different types of bricks were ordered so that they could be closely examined. The bricks that had frogs or hollows were rejected but the majority of the remaining bricks were of the right size and shape. From this selection, the Birtley Olde English bricks[x] had surface properties that were the best match for old bricks. Unfortunately, one of the bed surfaces of these bricks had a pattern impressed on the surface. However, as long as the couplets were made with the smooth face against the mortar the patterned surface would not have any effect on the results, and so it was decided to use these bricks for the testing. It was preferable to order all the bricks required in one go, so that the bricks supplied would be from the same batch, giving the maximum possible

[x] Birtley Olde English bricks supplied by Ibstock Brick Ltd.

consistency. A significant number of bricks were therefore ordered to allow all the initial testing to be completed with bricks in reserve to allow specimens to be made for any further experimental work.

The mortar cubes were made from medium strength Grade 3 mortar. The Grade 3 mortar is stronger than the mortar typically found in the old structures that are most frequently demolished, and cubes made from Grade 5 mortar would be of a more appropriate strength. However, not all demolition work is carried out on old structures and the strength of mortar from old structures would vary considerably. For example, the mortar in internal walls would be protected from the effects of weathering, and there would be less deterioration in the strength of the mortar.

4.3.1. Impact testing

The natural frequency of a specimen can be determined by subjecting it to an impact (providing it with energy) and recording the ensuing vibrations.

4.3.1.1. Test procedure

The impact testing method was used to determine the natural frequencies of a single brick, a mortar cube and a full-scale couplet. Prior to testing, two accelerometers were attached to each specimen to measure the frequency of the vibrations.

There is a wide range of accelerometers available and, in order to select the accelerometer most suited to the application, several were tested. The different types of accelerometer were designed to be attached to the specimens in different ways. In order to test the accelerometers so that one suitable for recording the natural frequencies of the test specimens could be selected, they would all need to be attached to the specimens. It was important to attach the accelerometers onto the specimens correctly to ensure that the readings recorded were of the vibration within the specimen itself. If the accelerometer was loose within the fixing, it could vibrate independently of the brick. Some of the accelerometers had a screw thread on the end, so it was necessary to find a suitable method of embedding a corresponding nut into the surface of the specimens. Several methods were tried, but the most effective method involved drilling a small hole into the surface of a brick and then sealing the nut into the hole with epoxy resin. An accelerometer could then be screwed easily into the nut, ensuring that it was held tightly in place. Figure 4-15 shows how the accelerometers with screw threads were attached.

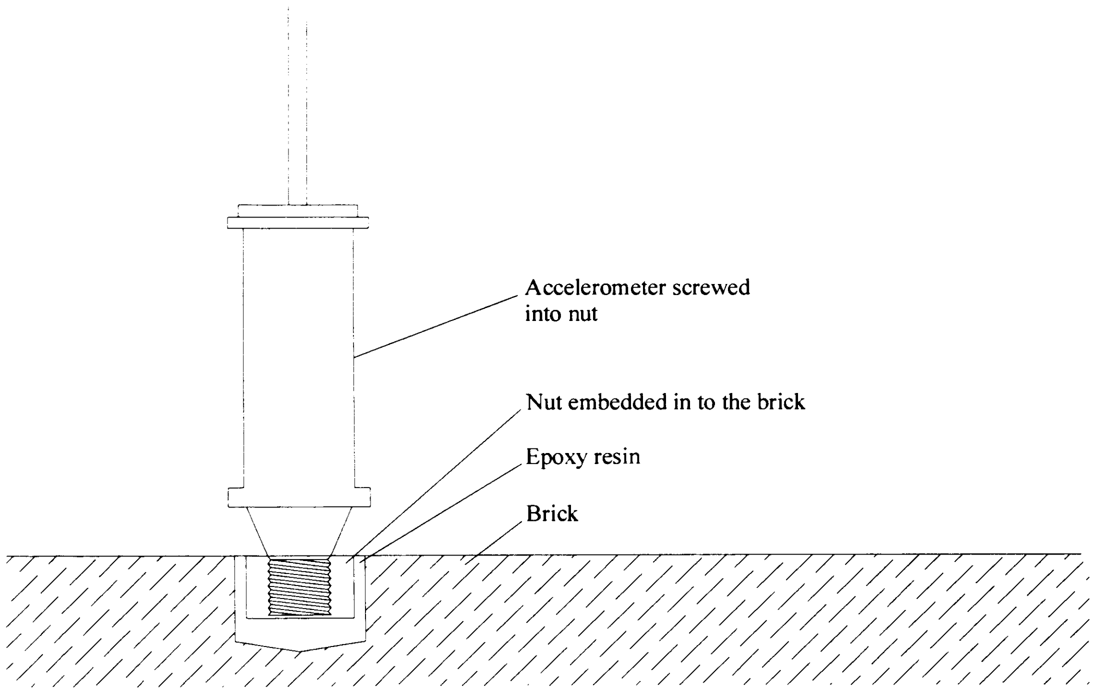


Figure 4-15. An accelerometer with a screw thread attached to the surface of a specimen

The other accelerometers just had two holes in them, to allow bolts to pass through to hold the accelerometer in place, making them more difficult to attach to the surface of a brick. The easiest way would be to pass bolts through the holes in the accelerometers and screw them into nuts embedded in the surface of the brick. However, if too many holes were drilled into the surface of the brick it would start to change the properties of the brick. It would be preferable to attach both types of accelerometers to the bricks using a method that requires only one hole to be made in the brick. Several small plates with a screw thread identical to the ones on the other accelerometers were made to allow the second type of accelerometers to be screwed into the same nuts that were used to hold the first type of accelerometer, as shown in Figure 4-16 below.

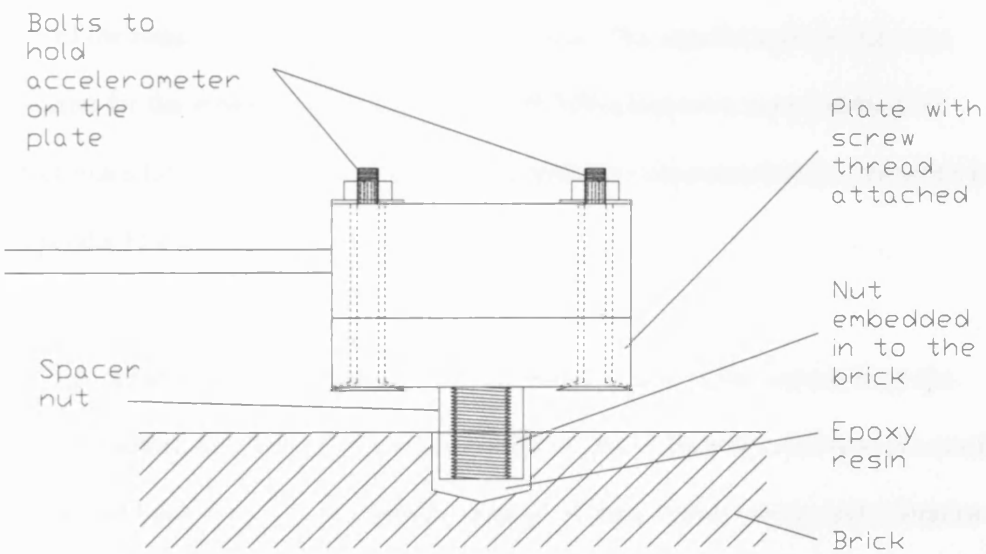


Figure 4-16. An accelerometer without a screw thread attached to the specimen using a plate.

When these methods of attaching an accelerometer to a brick were tested, it was found that the vibrations in the brick could be clearly detected by the accelerometers. The holes in the brick would change the vibration characteristics of the bricks a little, but because they were small and did not penetrate more than 5mm, any effects should be minimal. In addition, the aim of the experiments was only to provide an approximation of the natural frequency of the specimens and the variations between the different bricks was considerable. The specimens were therefore prepared for testing by embedding three nuts into each specimen, one on each type of face.

In order to select the most appropriate accelerometer, several were tested. Accelerometers can be damaged if they are subjected to frequencies above their design range, so initially a high frequency accelerometer was used. If the vibrations were too low to be recorded by that accelerometer, a new accelerometer with a lower frequency range was tried until an accelerometer was found that was capable of detecting the vibrations in the specimens. When the approximate frequency of the vibrations was known, it was possible to select an accelerometer sensitive enough to record the required data with sufficient accuracy. The accelerometers that were selected for the impact testing had a range of 500 g and were supplied by RDP Electronics Ltd. The full specification as supplied by the manufacturer are given in Appendix H 1.3.

A suitable data processing unit was needed to record the signals from the accelerometers. In order to record data with sufficient accuracy, the data processing unit would have to record a sufficient number of data points during each vibration cycle. The most appropriate unit available was a Kontron Signal Memory Recorder (SMR), which was capable of taking readings at 500 nanosecond intervals, permitting it to accurately record data at frequencies of up to 2000 kHz. The ultrasound bath operates at 30 kHz, so the Kontron SMR would be able to record data at a sufficiently frequent intervals. In addition, at the start of the data collection, the Kontron SMR presents the operator with a selection of appropriate sampling size, thus ensuring that the Nyquist criterion [68] is satisfied. Once the data had been recorded onto the Kontron SMR, it was possible to display the data on screen so that it could be ensured that the data had been recorded correctly. The Kontron SMR also has several basis manipulation features, which includes a tool to calculate the frequency of the vibrations recorded. This allows the frequencies of the vibrations to be calculated as soon as each test was performed, so it can be ensured that the test yields consistent sensible results. In addition, the Kontron SMR was capable of recording the signal from up to eight separate accelerometers at once, so it was possible to record all the data from any testing that needed to be performed on the one unit. The data recorded on the Kontron SMR could be imported into a spreadsheet package, where the data could be analysed and manipulated.

In order to allow the brick to vibrate at its natural frequency (or frequencies) it is necessary to provide energy and allow the brick to vibrate free from any restrictions. This can be achieved by suspending the brick on the end of a piece of string and hitting it with a hammer. A bolt was screwed into one of the spare nuts placed in the brick to hold the accelerometers, and the string was tied onto the bolt. Figure 4-17 below shows a brick specimen that has been prepared and suspended on a sting ready for testing.

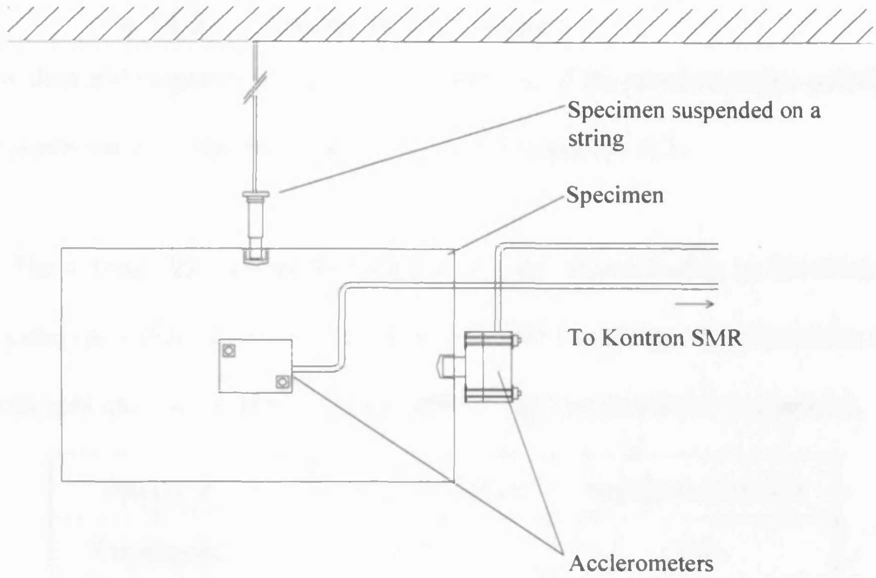


Figure 4-17. A specimen ready for impact testing

In order to try to ensure that all the impacts were as similar as possible the hammer was always held in the same way and swung onto the appropriate surface of the brick in the same manner. It was not possible to drop the hammer a set distance onto the brick, ensuring that the impact speed remain constant, because not all the impacts were made on the top surface of the specimen, and the hammer had to be moved away from the specimen as soon as the impact had been made to prevent it from dampening the vibrations or causing further impacts. However, each specimen was subjected to a sufficient number of impacts to ensure that the recorded vibrations for each specimen were consistent and not dependant on the manner in which they were hit.

4.3.1.2. Results and discussion

The raw data and diagrams to show the positioning of the accelerometers and the impact points for each specimen can be found in Appendix A.2.

The average frequencies recorded during the impact testing on the brick and mortar cube specimens are shown in Table 4-9. The frequencies for the mortar cube have been split into two categories representing the two dominant frequencies.

Specimen	Average frequency	Standard deviation
Single brick	3000	280
Half scale brick	4160	263
Half brick	4160	41
Mortar cube	1710	16
	1340	9

Table 4-9. The average frequencies determined by impact testing

The results for the full-scale couplet are summarised in Table 4-10 below.

Impact on top brick				
	Accelerometer on bottom brick			
position of impact	Impact site 1	Impact site 2	Impact site 3	
average frequency	1380	1440	2430	
standard deviation	90	66	602	
	Accelerometer on top brick			
position of impact	Impact site 1	Impact site 2	Impact site 3	Impact site 4
average frequency	1410	1420	3090	1850
standard deviation	36	5.	590	570
Impact on bottom brick				
	Accelerometer on bottom brick			
position of impact	Impact site 1	Impact site 2	Impact site 3	
average frequency	3190	4130	3610	
standard deviation	893	540	179	
	Accelerometer on top brick			
position of impact	Impact site 1	Impact site 2	Impact site 3	Impact site 4
average frequency	2420	3730	3360	3640
standard deviation	1000	352	292	1130

Table 4-10. Summary of the frequencies recorded during impact testing with a full scale couplet

When the brick specimens were tested, the waveform of the vibrations recorded remained similar for all the different types of brick. Figures 4-18 and Figure 4-19 show examples of the waveform taken by the vibrations travelling through full scale and half scale brick specimens.

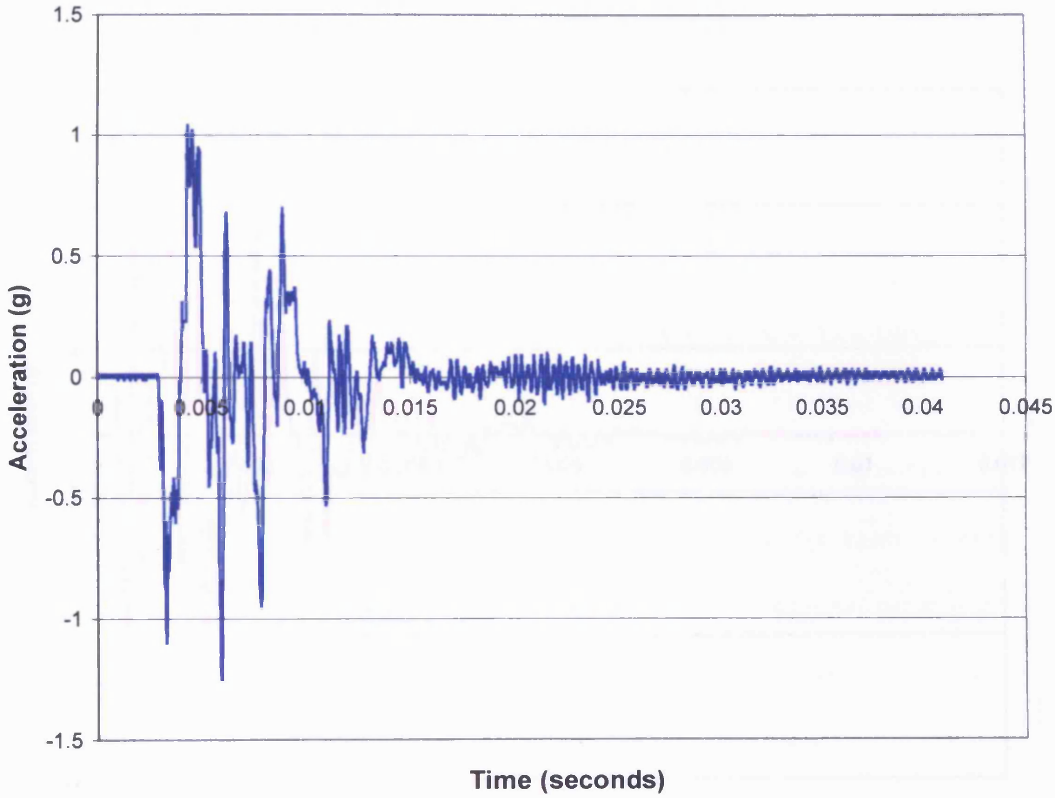


Figure 4-18. The vibrations recorded within a full scale brick.

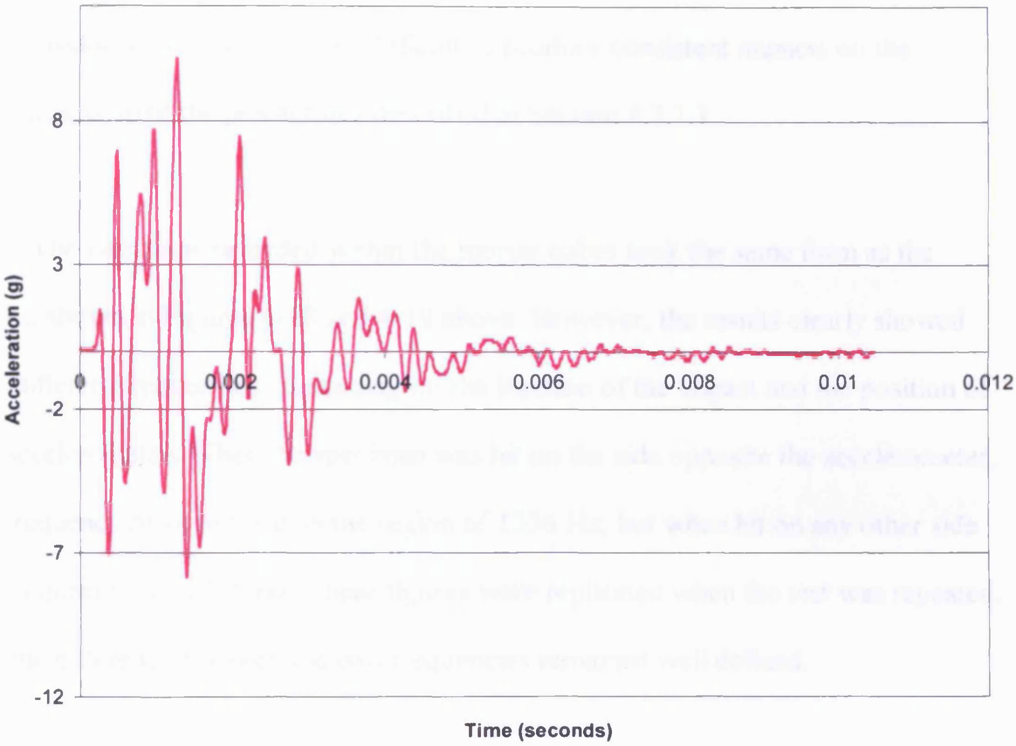


Figure 4-19. The vibrations recorded within a one-sixth scale brick.

While the impact is occurring (from 0 to 0.004 seconds) the characteristics of the manner in which the impact was made have the most influence on the vibrations within the brick. When the impact event has finished and the hammer has been withdrawn from the surface of the brick, the vibrations at the natural frequency can be seen. Hence it is preferable to determine the natural frequency by examining the accelerations recorded in the later stage of the trace, from 0.004 seconds onwards.

A single frequency was detected for each specimen, even when the impact was made on different faces of the specimen and the accelerometer placed at different points. This shows that brick specimens have a single dominant fundamental natural frequency. There was some variation in the frequencies recorded when the brick specimens were tested, which is reflected in the high value of the standard deviations shown in Table 4-9. This variation is largely the result of experimental error, which was introduced because it is very difficult to produce consistent impacts on the specimen, despite the precautions described in Section 4.3.1.1.

The vibrations recorded within the mortar cubes took the same form as the bricks, shown in Figures 4-18 and 4-19 above. However, the results clearly showed two different frequencies, depending on the location of the impact and the position of the accelerometer. When the specimen was hit on the side opposite the accelerometer, the frequency recorded was in the region of 1336 Hz, but when hit on any other side the frequency was 1715 Hz. These figures were replicated when the test was repeated, and the difference between the two frequencies remained well defined.

It was important to understand why the vibrations recorded in the bricks and mortar cubes during the impact testing were different. The most influential factor that determines the magnitude of the natural frequency of any material is the bulk modulus. The bulk modulus of a medium determines the speed at which waves, including vibrations, are transmitted through the medium.

However, differences in the bulk modulus do not explain why the mortar cubes displayed two natural frequencies and the brick specimens only one. The shape of the specimen also changes the value of the natural frequency, but certain shapes can also cause the specimen to have more than one dominant natural frequency. Hence two dominant frequencies were recorded when the mortar cubes were tested, but the shape of the brick specimens caused dominant vibrations at a single frequency.

The response of the couplet was more complicated than that of the other specimens. Figure 4-20 below shows the vibrations recorded in both the bricks during the impact test.

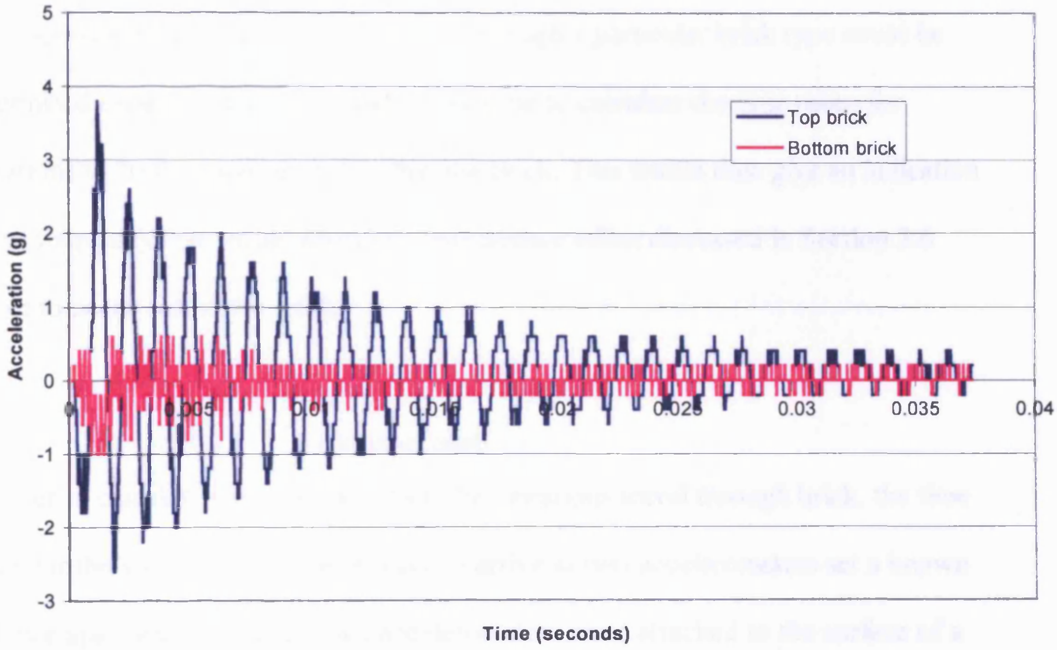


Figure 4-20. Vibrations recorded within the couplet during an impact event on the top brick

There were at least two different natural frequencies that resulted from the impact. During the impact testing it has been shown that several different modes of vibration occur within a couplet after an impact has occurred. The entire couplet can vibrates as one unit whilst both of the bricks and the mortar joint can vibrate individually at the same time. Given this complication, the data recorded when the impact test was performed on the couplets was not sufficient to allow the response of all the components of the couplet to be determined. However, the natural frequencies of a couplet, and the separate components present in a couplet, were found to occur between 1.4 kHz and 4.2 kHz. This means that a full-scale couplet would be expected to give a response with an increased amplitude to one or more frequencies within this range. Hence any process designed to separate and clean full-scale couplets needs to be capable of generating this range of frequencies.

4.3.2. Interference effect frequency calculation

If the speed at which the vibrations travel through a particular brick type could be determined experimentally, it would be possible to calculate the time taken for vibrations to "reflect and return" within the brick. This would then give an indication of the frequency that would allow the interference effect discussed in Section 3.6 above to occur within the brick.

4.3.2.1. Test procedure

In order to calculate the speed at which the vibrations travel through brick, the time taken for the vibrations from an impact to arrive at two accelerometers set a known distance apart was recorded. Two accelerometers were attached to the surface of a brick using the method described in Section 4.3.1.1 above. An impact was then made at one end of the brick using a rubber mallet, dropped from a constant height to ensure that each impact remained as constant as possible. The time for the first vibrations to be detected by both of the accelerometers was recorded. Figure 4-21 below shows the bricks with the accelerometers attached ready for testing.

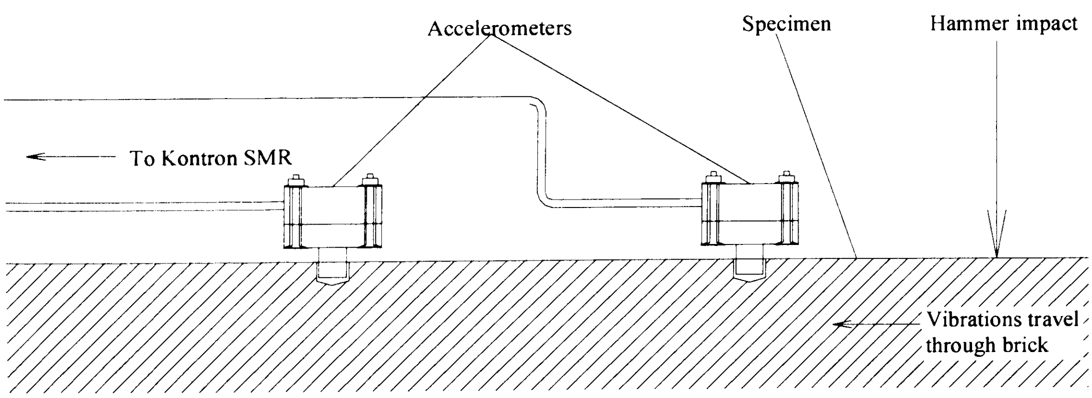


Figure 4-21. The specimen ready for testing to calculate the speed of the vibrations within the brick

4.3.2.2. Results and discussion

The results recorded during the testing to calculate the speed of the vibrations within the brick are shown in Table 4-11 below.

Impact number	Time taken (ms)	Distance travelled (mm)	Speed (m/s)
1	0.08	176	2200
2	0.07	176	2510
3	0.08	176	2200
4	0.07	176	2510
5	0.06	176	2930
6	0.07	176	2510

Average speed = 2500 (m/s)

Table 4-11. The speed at which vibrations travelled through the brick

The small differences in the experimental data caused a significant difference to the calculated wave speed. However, it would still be possible to use the average speed to give an approximate indication of the frequency at which the interference effect would be expected to occur.

The speeds determined in Table 4-12 were used to estimate the frequencies at which the interference effect would be expected to occur for both full-scale and one-sixth scale bricks. The bricks have three dimensions of different sizes, and hence three different frequencies were calculated for each brick size, as shown in Table 4-12 below. The frequencies are calculated using each speed recorded can be found in Appendix A.4.

Speed used	Interference effect frequency for a full scale brick (kHz)			Interference effect frequency for a one-sixth scale brick (kHz)		
	length	width	height	length	width	height
maximum	7	14	23	42	86	135
minimum	5	11	17	32	65	102
average	6	12	20	36	73	115

Table 4-12. The frequencies at which the interference effect would be expected to occur

The variation in the speeds used to calculate the frequencies suggests a wide range of frequencies. However, Table 4-12 shows that the frequency that would allow the interference effect to occur along the length of a one-sixth scale brick would be between 20 and 40 kHz.

4.3.3. Testing of large scale items in an ultrasound bath

The U400 bath was too small to allow full-scale bricks to be placed inside it so it was necessary to determine if the separation previously achieved could be replicated in a different ultrasound bath. This would demonstrate that the success of the processes was not caused by the specific characteristics of the U 400 ultrasound bath. The second ultrasound bath that was used to collect experimental data was a model 55300 manufactured by Ultrasonics Power Corp (U.P.C. bath). The specifications of the U.P.C. bath can be found in Table 4-13 below and a picture of the bath is shown in Figure 4-22 below.

Manufacturer	Ultrasonic Power Corp.
Model number	BT60H-55300
Frequency	40 000 Hz
Internal dimensions	280 x 280 x 350 mm
Water depth	250 mm
Capacity	22.7 litres

Table 4-13. Specification of the U.P.C. bath

Figure 4-22. The U.P.C. ultrasound bath

In addition, the U.P.C. bath was large enough to accommodate several full-scale bricks. Hence a full scale couplet could be placed into the ultrasound bath to see if the separation previously achieved could be replicated at full scale. In addition, instrumentation can be attached to a full scale bricks. This would allow the vibrations within the larger specimens to be recorded whilst they were in the bath.

4.3.3.1. Test procedure

As with the U 400 ultrasound bath, the manufacturer's instructions were followed when using the U.P.C. bath. The instructions for the U.P.C. bath outlined the same procedures and issues as those for the U400 bath, which have previously been outlined in Section 4.2.

Five one-sixth scale couplets were made for testing in the U.P.C. bath. They were fabricated to the same specifications as the couplets with 5mm joints made from Grade 3 mortar described above in Section 4.2.1.1.

Five full scale couplets were fabricated from the Birtley Olde English bricks for testing in the U.P.C. bath. They were fabricated following the methods described in 4.3.1. A builder's trowel was used to apply the mortar instead of a pallet knife, and a ruler was used to measure the mortar joint.

In order to allow a comparison to be made between the couplets at full scale and one-sixth scale it would be preferable to use the same sand for the mortar in both sets of couplets. However, it was decided that it was preferable to make the full scale couplets a good match for the brickwork that is typically available for demolition. The mortar joints were made to a thickness of 10mm, which is a typical thickness for standard brickwork. The Lime and Cement ingredients used previously at one-sixth scale were standard ingredients for use with standard full scale brickwork construction. Therefore there were no issues with using these same ingredients for the full scale couplets. However, the fine sand used for the mortar in the one-sixth scale couplets would not be found in full scale brickwork. Therefore a typical building sand that was compliant with the limits specified in BS 1200[69] was used. All the couplets were made with the weak Grade 5 mortar, to maximise the likelihood of achieving separation.

In order to record the vibrations within the bricks when they were placed in the ultrasound bath it was necessary to find accelerometers that would be able to operate underwater. The accelerometers that were used for the impact testing would be suitable for recording the frequencies of around 40 kHz expected in the ultrasound bath. The accelerometers, which were not designed to work underwater, were therefore sealed so they functioned correctly in an ultrasound bath.

An accelerometer was attached to each specimen to be tested using the same technique described above in Section 4.3.2.1. The specimens were then placed into the ultrasound bath, which was operated for a short time, sufficient for the vibrations travelling through the specimen to be recorded.

The U.P.C. bath has two dials to adjust the modulating frequency and the power level of the vibrations. These settings were varied to identify any effect on the vibrations travelling through the specimens.

4.3.3.2. Results

When one-sixth scale couplets were placed in the U.P.C. bath it was found that separation occurred in the same manner that had previously been observed in the U400 ultrasound bath. The time taken for both stages separation to occur are shown in Table 4-14 below.

Couplet	Stage 1 separation time (seconds)	Stage 2 separation time (seconds)
1	46	145
2	58	212
3	28	129
4	26	248
5	39	187
average	39	184

Table 4-14. Separation times of one-sixth scale couplets in the U.P.C. bath

Each of the five full-scale couplets were tested in the U.P.C. bath for thirty minutes. This was performed in two fifteen-minute sessions, and the ultrasound bath was switch off for a "cooling down period" of fifteen minutes in between to ensure overheating could not occur. One of the specimens was tested for a further sixty minutes, with four equally spaced fifteen-minute cooling down periods. None of the couplets were separated or cleaned whilst they were in the ultrasound bath, and when they were removed and examined there was no apparent change to their appearance.

The frequencies of the vibrations recorded in the different specimens are shown in Table 4-15 below. The raw results, along with the data for the different settings used on the ultrasound bath, can be found in Appendix A5.

Specimen	Average frequency (kHz)
Single brick	38.6
Half brick	39.4
Couplet	38.9

Table 4-15. The frequencies recorded travelling through specimens placed in the U.P.C. bath

It is clear that the frequency of the dominant vibrations within the specimens in the ultrasound bath is the operating frequency of the ultrasound bath. An example of the form taken by the vibrations is shown in Figure 4-23. In addition, the data shown in Table 4-16 was determined during testing. There was very little variation in the form taken by the recorded accelerations. It was found that changing the modulation frequency and the power level settings on the ultrasound bath did not change significantly the vibrations recorded within the bath.

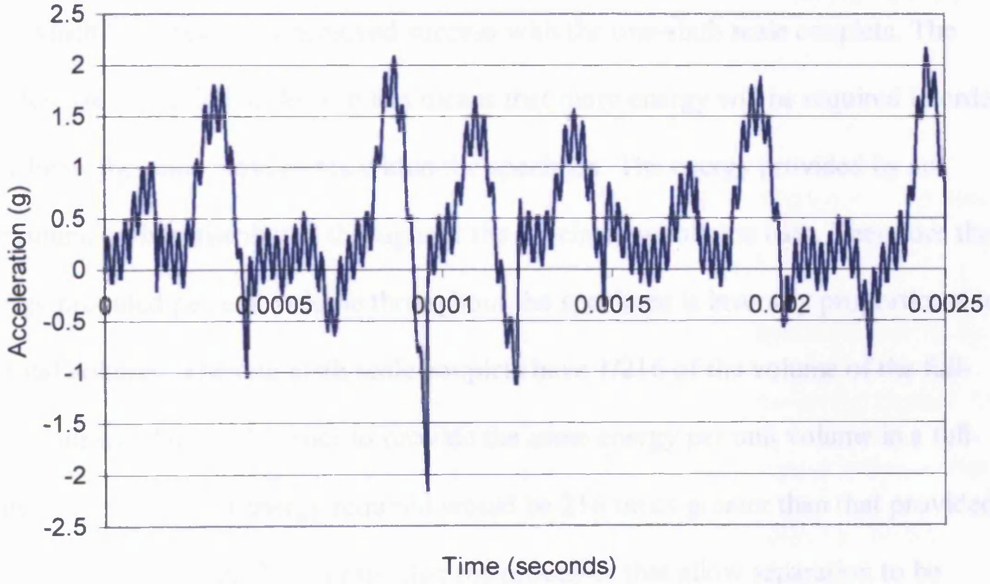


Figure 4-23. Vibrations recorded within the U.P.C. ultrasound bath

Properties determined experimentally			
Frequency	f	=	38941 Hz
Maximum acceleration	a_{max}	=	2.2 g
		=	21.2 m/s^2

Table 4-16. Maximum acceleration, amplitude and velocity experience by a full scale brick in the U.P.C. ultrasound bath.

4.3.3.3. Analysis of results

The five one-sixth scale bricks tested by the author separated and cleaned in a similar time to those which were tested in the U 400 ultrasound bath. The two ultrasound baths that successfully separated and cleaned a series of one-sixth scale couplets had operating frequencies of 30 and 40 kHz. The fact that couplets of the same size could be separated and cleaned by such different frequencies shows that a range of frequencies can achieve success, which suggests that there is no precise frequency that is required for the process to work.

The full-scale couplets did not separate when they were placed in the U.P.C. bath which had previously achieved success with the one-sixth scale couplets. The greater size of the full-scale couplets means that more energy will be required in order to achieve the same movements within the specimen. The energy provided by an ultrasound bath is distributed throughout the specimen within the bath. Therefore the energy provided per unit volume throughout the specimen is inversely proportional to its total volume. The one-sixth scale couplets have 1/216 of the volume of the full-scale couplets. Hence, in order to provide the same energy per unit volume in a full-scale couplet the total energy required would be 216 times greater than that provided by the ultrasound bath. This means that the processes that allow separation to be achieved could be occurring within the full-scale specimen without success, because the power transmitted through the brick does not produce the movements required to break the bond between the mortar and the brick. The amount of energy transmitted can be improved by increasing the amplitude of the ultrasonic vibrations, but the amplitude of the vibrations in an ultrasound bath is limited by the deflections that can be achieved within a transducer.

However, if the frequency required to permit separation to occur is related to the dimensions of the specimen, then it will not be possible to clean full-scale couplets in the ultrasound bath because a significantly different frequency is required.

The results recorded by the accelerometers shown above in Table 4-16 verified that the specimens in the ultrasound bath vibrated at the frequency of the vibrations generated by the ultrasound bath. None of the specimens produced measurable vibrations at any other frequencies. Changing the modulating frequency and the power level of the vibrations did not produce any changes to the frequency or the amplitude of the vibrations recorded travelling through the specimens. This leads to the need to have a bath that can be operated at a range of frequencies.

This chapter has given details on a number of experiments that were performed to allow the frequency required to separate full scale couplets to be estimated. However, the correct frequency can also be estimated using the theoretical methods outlined in Section 3.7. The calculations based on Equation (41) assuming typical material properties are performed in Appendix F, and these calculations indicate that the natural frequency for a brick couplet is approximately 5800 cycles per second.

4.4. Chapter conclusion

The frequencies of the two ultrasound baths which were used to separate and clean one-sixth scale bricks fall within the range of frequencies that the experimental data shown in Table 4-12 predicted would cause the "interference effect" to occur down the length of one-sixth scale bricks. This suggests that the frequencies indicated in the same table to cause the same effect within the length of full-scale bricks are correct. However, it should be remembered that the frequencies predicted in Table 4-12 are based on experimental data that was very variable. It is considered acceptable to use this information to achieve an indication of the range where the optimum frequency would be likely to occur, but it should not be used to indicate the precise optimum frequency.

The U.P.C. bath was used to separate and clean one-sixth scale couplets, but the same procedure was not successful when it was attempted with full-scale couplets.

The results from the experiments performed and analysed in this chapter have indicated the frequencies that would be most likely to allow successful separation of full-scale couplets to be achieved. The results are summarised in Table 4-17 below.

Principle	Data source	Frequency suggested for separation of full-scale couplets (kHz)
natural frequency	Impact testing	3, 1.8, 3.5
interference effect	Speed of vibrations in brick	5.0 to 7.0
scale directly proportional to frequency	one-sixth scale couplets in ultrasound bath	5.0
natural frequency	theoretical result Section 3.7	5.8

Table 4-17. Frequencies that are likely to cause separation to occur in full-scale couplets

Any attempt to build a prototype machine to separate and clean full-scale bricks and mortar would have the best chance of success if it was capable of achieving the frequencies suggested in Table 4-17.

5. Design and construction of the prototype

5.1. Introduction

The success of the separation process on the one-sixth scale bricks in the small ultrasound bath was a good indication that it would be worthwhile developing the technique at full scale. After observing the one-sixth scale couplets in the ultrasound bath, several hypothesises were formulated to try and explain why the mortar is cleaned from the bricks in the ultrasound bath. However, the one-sixth scale bricks were too small to allow instrumentation to be attached so it was impossible to collect much data to test the validity of these theories. It therefore remains unclear whether it is the vibrations themselves, the interference effect, the effects of cavitation or a combination of the above that causes separation to occur at this scale.

If a full-scale couplet made from bricks and mortar with similar properties as the one-sixth scale bricks could be placed in the ultrasound bath it would experience the same vibrations and the effects of cavitation would occur in the same way as the one-sixth scale couplets. However, in order to achieve the interference effect, a different frequency range would be needed. The waves would travel at the same speed within the brick but the distance travelled by the waves that "reflect and return" would be six times further, so it would take six times as long for them to arrive back at the face through which they initially entered the brick. Hence, to achieve the interference effect with full-scale couplets the frequency required would be 5kHz, i.e. one-sixth of the frequency that causes the interference effect for the one-sixth scale bricks.

However, cavitation within water[xi] only occurs at frequencies greater than 20kHz.[70] Therefore, it would not be possible to provide vibrations that would coincide with the natural frequency of the full-scale bricks and achieve cavitation at the same time, and if both processes are required for separation to occur, it would not be possible to achieve success with the prototype.

5.2. Design aim

The primary design aim of the Full Scale Prototype was to achieve the conditions that would allow full-scale couplets to be separated by the same process, or processes, that separated one-sixth scale couplets in the ultrasound bath. However, the ultrasound baths used can only operate at specific frequencies. As the separation processes was successful, the frequencies must have been of the right magnitude. However, it is unlikely that either bath was operating at the optimum frequency that would deliver the most efficient separation. If the prototype was designed in such a way that the operating frequency could be adjusted, it would eventually be possible to set the optimum frequency for separating full scale brick couplets.

The one-sixth scale bricks used in the ultrasound test were specifically made to be as similar as possible to full-scale wire cut bricks, so the shape and material properties should not be significantly different. However, the effect of the scale factor could not be ignored. It seemed likely that in order to achieve the same effects with full-scale bricks it would be necessary to change the frequency.

[xi] cavitation has been achieved at frequencies as low as 8 kHz under certain conditions i.e. using viscous fluids. However, as water was the only fluid used in the experimental work performed for this thesis, the generally accepted threshold of 20 kHz will be assumed.

The investigations performed in Chapter 4 indicated that the range of frequencies that were most likely to allow separation of full scale couplet to occur was from 2 to 7 kHz, and so the prototype should be designed to cover as much of this range as possible.

5.3. Key components

It was decided to use an existing commercially obtained actuator as it would be impractical to design and manufacture an actuator capable of achieving the necessary frequencies in-house. A Derritron VP30 vibration testing unit, usually used for vibration testing of manufactured components was obtained. A VP30 actuator combined with a TW 1500 amplifier is capable of providing a frequency of up to 6 000 Hz. In addition, it is able to achieve the full range of frequencies from 0 to the maximum frequency. A system based on this actuator would thus be able to achieve the frequencies most likely to provide the results sought. The VP30 actuator is capable of achieving a maximum amplitude of 17mm at low frequencies. However, because the actuator can only achieve an acceleration of approximately 100g, the amplitude it can sustain decreases as the frequency is increased. Figure 5-1 shows the performance curve provided by the manufacturer of the VP 30 actuator when used with a TW 1500 amplifier. The performance curve indicates the maximum acceleration that can be achieved when specimens of different weight are vibrated by the actuator.

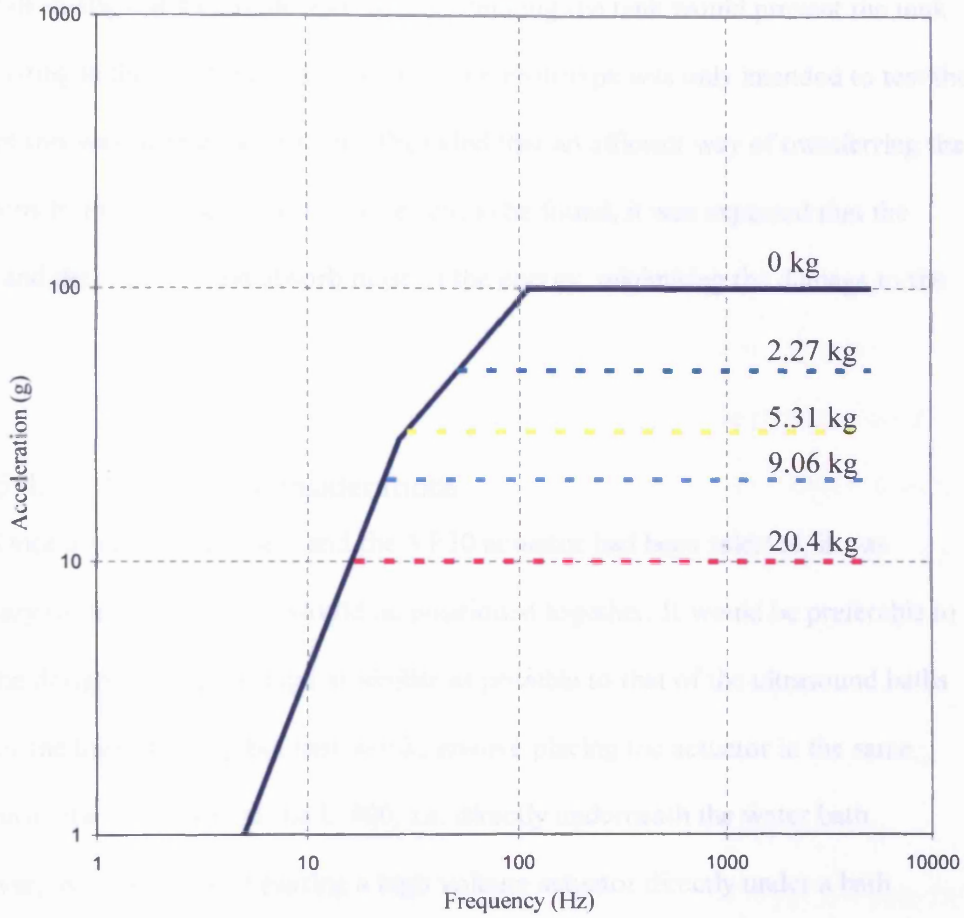


Figure 5-1. The power curve for the actuator provided by the manufacturer.

The VP30 actuator also had several safety features that would ensure that it was not damaged by vibrations beyond its capacity.

The other principal part of the Full-Scale Prototype was the water bath containing the bricks to be cleaned and a fluid to transmit the vibrations. This bath would need to have sufficient size and strength to hold a reasonable number of full-scale bricks and enough water to cover over them. It must also be able to withstand the vibrations caused by the actuator. The simplest construction method for such a bath would be to weld sheets of steel together, but this could lead to problems with the welds failing due to fatigue and rusting. Painting the tank would prevent the tank from rusting in the short term, and because the prototype was only intended to test the concept this was deemed acceptable. Provided that an efficient way of transferring the vibrations from the actuator to the water could be found, it was expected that the bricks and the water would absorb most of the energy, minimising the damage to the bath.

5.4. Structural considerations

Once a welded steel bath and the VP30 actuator had been selected, it was necessary to decide how they would be positioned together. It would be preferable to keep the design of the prototype as similar as possible to that of the ultrasound baths used for the initial testing, but that would involve placing the actuator in the same position as the transducer in the U 400, i.e. directly underneath the water bath. However, the safety risk of putting a high voltage actuator directly under a bath containing a volume of water was deemed prohibitive. It is possible to achieve the arrangement by placing the actuator above the tank, and building the prototype "upside down". However, a large framework would be required to position the 291 kg actuator above the tank. In addition, if the actuator itself was vibrating relative to the ground it would be able to provide less energy to transmit into the water. If the actuator was mounted above the tank it would be difficult to ensure that the actuator was held with sufficient rigidity to keep it still when it was operating at high frequencies. It is simpler to position the actuator on one side of the tank, and it was decided that this would not prevent the prototype from producing the same effects as those seen in the ultrasound bath, especially as the specimens themselves could also be placed in the tank so that they were orientated relative to the actuators in the same way as the one-sixth scale couplets in the ultrasound bath.

With the actuator running at up to 6 kHz, it was necessary to consider how the actuator would be held in position without it causing damage to the surrounding environment. It was intended that the vibrator and the bath should remain fixed, with the only moving parts being the plate and the connections between the actuator and the plate. The floor in the laboratory where the prototype was to be operated has a thick concrete floor, specifically so that large powerful equipment such as the actuator could be bolted down. However, concerns were expressed about the potential for the vibrations from the actuator affecting other experimental work in the vicinity and damaging the floor. In order to isolate the vibrations as much as possible, it was decided to place the actuator and the bath on a large steel channel so that the whole system would be self straining. If necessary the channel could be mounted on vibration dampers in order to limit the vibrations transmitted to the floor. Building the unit on a base in this manner would also allow the prototype to be moved with greater ease once construction was completed.

5.5. Transmitting the vibrations to the water

It was necessary to identify an efficient and reliable way of transmitting the vibrations from the actuator to the water, in order to maximise the energy applied to the separation process. The best way to achieve this would be to have a stiff plate in direct contact with the water. Thought was given to the idea of vibrating one side of the bath itself, by attaching the actuator directly onto the bath, like the transducer in the U 400 ultrasound bath. Although that would have been simple and economic, it was the method most likely to cause damage to the welds. Consideration was given to having an L-shaped arm on the end of the actuator, so that the arm could pass over the sides of the tank and down into the water. However, there was concern that such an arm could not be made stiff and yet light enough, causing it to deform and absorb the vibrations itself instead of transferring the power into the water. In addition, all the weight on the end of the actuator would decrease its performance. This led to the conclusion that the optimal way to attach a plate to the actuator would be with an arm that was as short and stiff as possible.

The best way to meet these criteria was to cut a hole in to one of the panels in the bath, and place a plate into the space, and connect the plate to the actuator with a short straight stocky connector. This would make it difficult to ensure that the bath remained water tight, but would provide the most effective way of transferring the vibrations to the water. It was thought that it would be possible to seal the gap between the plate and the bath and prevent water from leaking out even when the prototype was operating. However, this would take careful construction, because at low frequencies it would need the flexibility to allow the shaker to move up to 20mm, and at high frequencies it must be able to flex at up to 6 kHz without cracking or suffer brittle fracture due to fatigue. In addition, the actuator would be situated directly behind the plate, and so it was absolutely necessary to ensure water from the bath could never come into contact with the electronics in the actuator. As an added precaution, it was decided to construct a partition in between the plate and the actuator so that in the event of a complete failure of the seal, the bath water could not run or splash directly onto the actuator. After considering the different types of seal available, it was decided the best solution would be a rubber membrane, which could be fixed on to the plate and the bath with steel rings bolted in place through the membrane. The gap between the edge of the plate and the bath was designed so that there was a sufficient length of rubber membrane in between to allow it to achieve the maximum lateral movement required by the plate. The rubber chosen was 5mm thick, which was considered to be strong enough to hold the water in place, but yet thin enough to prevent the membrane from limiting the movement of the plate.

The movements provided by the actuator would be impeded not only by the weight of the arm and the plate itself, but also by the pressure exerted on the plate by the body of water in the tank. In order to achieve consistently uniform vibrations and provide maximum power in the water, the plate would need to be as large as possible. There would, therefore, be considerable force acting upon it from the adjacent water. The force resulting from the pressure of the water was calculated (see Appendix G.1) to be in the region of 1 kN. The performance curve supplied by the manufacturer (shown in Figure 5-1 above) indicates that a load of 20.4kg would reduce the actuators maximum acceleration by a factor of ten to 10g. The load from the water would be approximately five times greater than this, and hence a load of this magnitude would reduce the maximum acceleration that the actuator would be able to achieve considerably further, say to 2g. It was decided that the water pressure would limit the movement of the plate, reducing the amplitude of the vibrations that could be produced to an unacceptable level. In addition, the actuator was not designed to operate against the large forces, and it has an electronic switch that prevents the actuator from operating if it is overloaded.

It was therefore necessary to provide a system to counterbalance the water pressure, so that when the prototype was not operating the plate would be in a state of equilibrium. It was decided that the way to achieve this would be to include a spring system to provide a force on the opposite side of the plate to the water. The springs would induce damping in the vibrations of the plate, but as the amplitude of the vibrations would be less than 1mm at the expected operating frequencies, the effect of the damping would be minimal. In order to support the springs, a frame was constructed between the plate and the actuator. The space needed to allow the springs to fit between the actuator and the plate prevented the actuator from being directly mounted onto the plate, and so a short extension was required to connect the two together. A number of springs were needed to ensure the stability of the plate, but they could not be placed in the central region of the plate because the actuator had to be connected to the centre of the plate. It was decided that four springs should be mounted between the frame and the plate, two above the centre of the plate and two below. However, because of the water pressure gradient, in order to balance the water pressure, the bottom pair of springs would need to exert a greater force than the top pair of springs. The most effective method of adjusting the force exerted by a spring is to change the working length of the spring. Hence it was decided to mount the spring onto the frame in such a way that would allow the length of the spring to be individually adjusted. The adjustment mechanism used to hold the springs in place between the frame and the plate is shown in Figure 5-2 below.

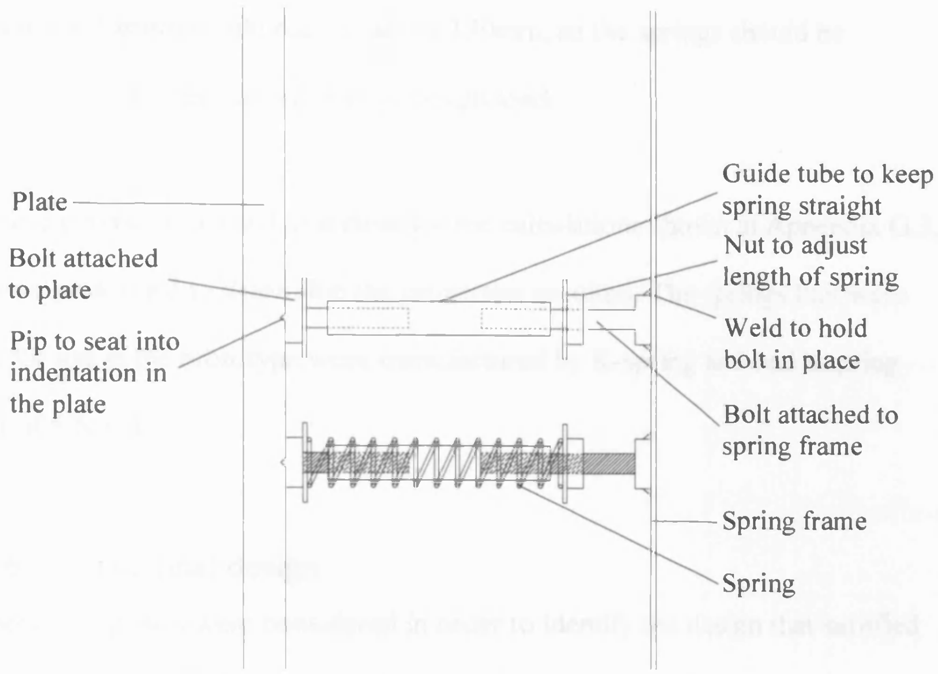


Figure 5-2. The mechanism to allow the length of the springs to be adjusted.

Note: The spring and bolt thread are omitted from the top mechanism for clarity

By attaching the springs in this manner, the forces acting on the plate can be brought into a state of equilibrium by independently adjusting the compression in the four springs.

It was desirable to keep the springs as short as possible in order to minimise the length of the extension. However, in order to provide the force required to balance out the water pressure, shorter springs would require a greater spring stiffness constant. Increasing the stiffness of the springs would increase the dampening that the springs would cause on the movement of the plate. In order to ensure that the vibrations could be transmitted efficiently to the plate it was decided to limit the length of the extension to 250 mm. Therefore the springs, the spring adjustment mechanism and the spring frame would all need to take up less than 250 mm in length. The frame and the adjustment mechanism would require about 130mm, so the springs should be designed to be no longer than 120mm at design load.

These criteria were used as a basis for the calculations shown in Appendix G.3, which were performed to determine the properties required. The springs that were selected for use in the prototype were manufactured by K-spring and had a spring constant of 5 N/mm.

5.6. The final design

A number of proposals were considered in order to identify the design that satisfied all the design criteria most effectively. Figure 5-3 below shows the design that was finally selected for construction. The drawings in Figure 5-3 have been simplified to highlight the main features of the design. Appendix B.2 contains the full working drawings that were used during the construction of the prototype, annotated drawings to indicate the key components and features of the prototype and photographs of the completed prototype.

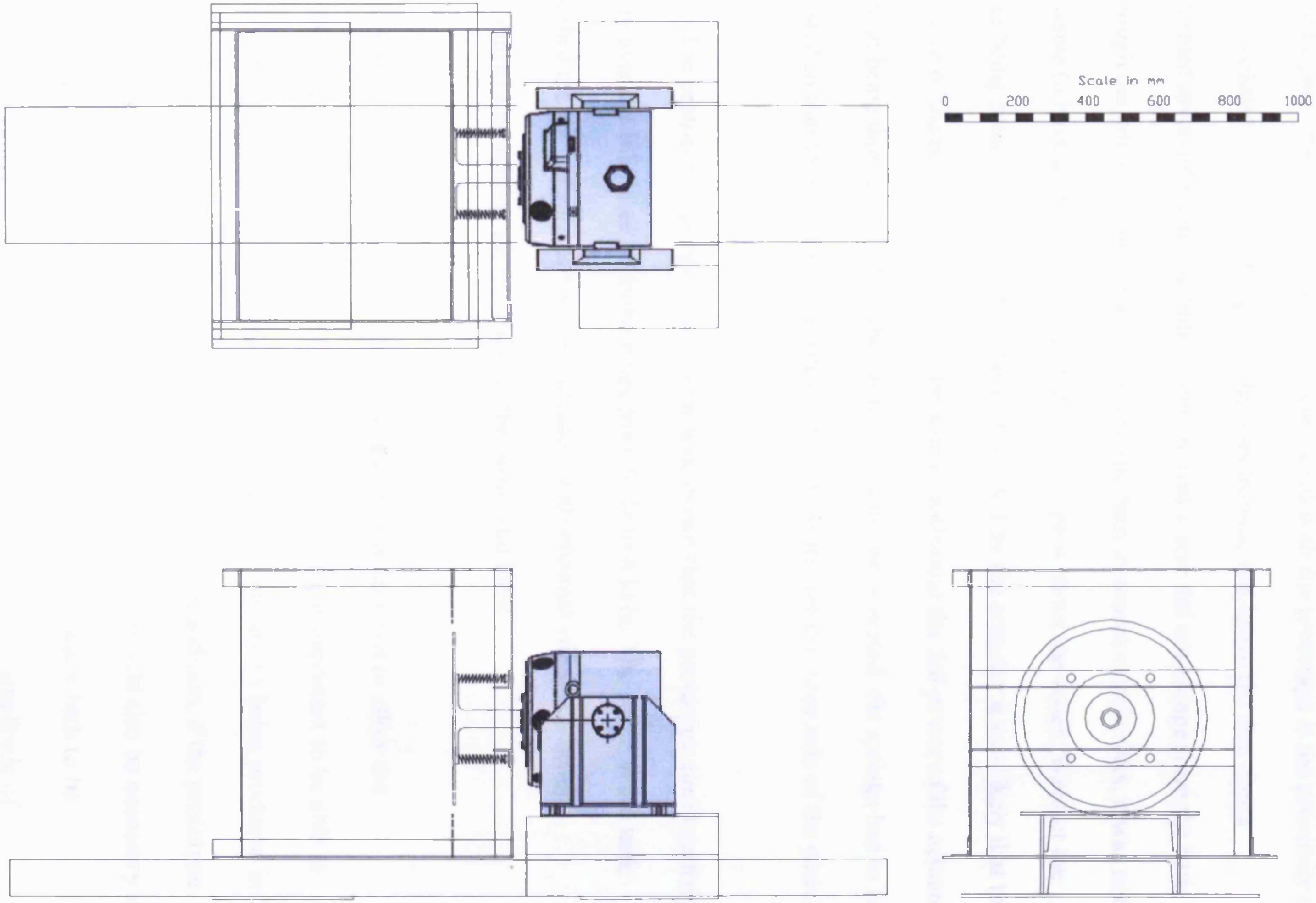


Figure 5-3. Simplified working drawing of the Prototype

5.7. Testing the prototype prior to use

After the prototype had been completed, it was necessary to test the unit to ensure that it was capable of withstanding the energy provided by the actuator before any tests could be performed. The greatest risk associated with the prototype is the proximity of a large volume of water and high voltage electronics, and hence the first check performed involved filling the tank to ensure that water did not escape from the bath. Although the introduction of the water into the bath increases certain risks, it was not advisable to have a "dry run" and test the prototype without the water. Without the water being present to absorb the energy provided by the actuator it was likely that the structure of the prototype would not be able to withstand the full power of the actuator without being damaged. Before the prototype could be operated, the springs had to be adjusted so that they balanced the pressure of the water on the other side of the plate.

The prototype was operated and it was shown that the prototype could perform safely over the full range of frequencies from 5 Hz to 6 kHz. The water in the tank absorbed the energy supplied by the actuator, with minimal vibrations being transmitted throughout the structure of the prototype itself.

Before testing could begin, instrumentation was required to allow the performance of the prototype to be monitored. It was most important to be able to monitor the performance of the plate, to check that the vibrations being produced in the tank were calibrated with those set on the amplifier. In addition, if the prototype were to be used effectively to try and achieve separation, it would also be necessary to record data to allow the process occurring in the prototype water bath to be determined. Comparing these sets of data would then allow the amplitude of vibrations generated in the bricks at different frequencies to be evaluated, enabling the frequencies that were most effective at producing vibrations in the specimens to be identified. An RDP 500g accelerometer was mounted on to the metal plate using the same process used to hold the same kind of accelerometers onto the brick specimens in the impact testing, as detailed in Section 4.3.1.1. A threaded hole was made into the back of the plate allowing it to be bolted in to place on the actuator plate. The prototype was then operated at a series of frequencies and the data recorded on the Kontron SMR. It was shown that the plate was reliably achieving the frequency set on the amplifier. However, it was decided that the accelerometer should remain on the plate and be used to record the operating frequency when the prototype was used because at high frequencies it was difficult to set the controls on the amplifier to a specific frequency with any precision. It was also necessary to maintain visual contact with the specimens to observe any separation as it occurred. The top of the tank was thus left uncovered to allow a clear view of the specimens in the tank from above.

5.8. Health and safety issues

There were several health and safety issues that required consideration before the prototype could be used to perform experiments. The high voltage actuator was a clear electrical hazard, especially as it was operating in close proximity to a large volume of water. However, this issue had been addressed during the design of the prototype (see Section 5.8), and therefore no special requirements were needed. However, there was a potential problem with the noise made by the plate. The plate is designed to produce vibrations in the water, but consequently it also causes vibrations in the air, producing noise. At low frequencies the vibration of the plate produced a humming noise, which whilst undesirable, did not present any health and safety issues. Personnel in the immediate vicinity of the prototype were therefore required to use ear defenders when it was operating. However, as the frequency was increased the noise increased in pitch and volume. As the frequency exceeded 2 kHz it became clear that it was going to be necessary to take precautions against noise. A noise survey was therefore performed with the prototype operating at its full range of frequencies. It was found that whilst the prototype was operating at frequencies less than 3.5kHz the use of ear defenders compliant with BS 6344[71] would be sufficient to provide suitable protection. However, when the prototype was operated at a series of frequencies between 3.5 kHz and 6 kHz the noise levels recorded exceeded 100 decibels. This level of noise meant that the use of ear defenders alone was not sufficient protection against the noise and additional measures were required. During the noise survey the noise levels were also recorded in the rooms adjacent to the prototype. It was found that the noise levels in the adjacent rooms were low enough for ear defenders to provide sufficient protection when the prototype was operated at the high frequencies. It was decided that personnel should not be present in the room containing the prototype when it was operating at frequencies above 3.5kHz. Signs were displayed on the doors to the prototype room to provide information on the nature of the risk posed by the operation of the prototype. When running the prototype at frequencies above 3.5 kHz the operator was required to ensure that no people were in the room before starting the prototype. The operator then left the room containing the prototype and locked the doors to prevent unauthorised access. In this way the operator was only subjected to the nose at a high level for a period of several seconds, and other personnel were unable to be subject to levels of noise that could cause a health and safety issue. The operator could observe the prototype through a window during operation, and was therefore able to ensure it was operating correctly during the test.

6. Separating specimens in the prototype

The prototype had been constructed and had undergone preliminary tests that showed that it was working correctly. The prototype was then used to try and replicate the separation achieved in the ultrasound bath at full scale.

6.1. Testing procedure

There were a number of variables influencing the performance of the prototype, and it was decided to initially use the settings that were likely to give the prototype the greatest chance of achieving separation. The prototype was big enough to hold a number of bricks, so potentially a number of couplets or a stack of bricks could be cleaned together. However, additional brickwork in the bath would cause the energy to be shared between the different specimens. A single couplet was thus tested on its own, which would allow the maximum amount of energy to be delivered to this specimen. The specimen was placed in the prototype so that the orientation of the mortar joint and the source of the vibrations was the same as when the one-sixth scale couplets were tested in the U400 bath. The plate was on the side of the tank, and so the couplets had to be placed with the bed face of one of the bricks on the floor of the tank.

The lowest part of the plate was 140mm above the floor of the tank. This might prevent the lower brick from receiving the maximum amount of energy from the plate. It was decided to suspend the specimen on a piece of string so that it could be level with the centre of the plate. This would also prevent the movements generated within the couplets from being impeded by the floor of the bath. When the one-sixth scale couplets were cleaned in the tank they were placed on the bottom of the bath, directly above the transducers. The full-scale specimen was suspended close to the vibrating plate, leaving sufficient gap to ensure that the plate did not touch the specimen when it was operating at large amplitudes. Although several frequencies at which separation was most likely to occur had been identified during Chapter 4 it was decided to run the prototype at a range of frequencies so that the vibrations in the specimen could be recorded. It was decided to begin testing at a low frequency, and gradually increase it until the limits of the actuator were reached. In order to provide the maximum amount of energy to the specimen, it was necessary to use the maximum possible amplitude. The maximum acceleration that the actuator could sustain was limited, hence it was expected that as the frequency was increased the maximum possible amplitude would decrease correspondingly. This meant that in order to provide maximum energy to the specimen, the amplitude would need to be adjusted as the prototype was set to a new frequency. The amplifier was fitted with a safety cut-off if the current drawn became too high. The current and voltage being drawn by the actuator were shown on dials on the amplifier powering the prototype. The instructions for the actuator provided information on how the maximum permissible current at which the actuator could safely operate can be determined. Therefore, in order to ensure that the actuator was providing the maximum energy to the specimen, the frequency required was set on the amplifier and then the amplitude was increased until the current being drawn by the actuator was at the maximum value. This ensured that the maximum amount of energy was provided by the prototype throughout the entire possible frequency range. In order to record the response of the specimens to different frequencies, it was decided to perform a "frequency sweep" i.e. running the prototype for just long enough to record the data from the accelerometers at range of different frequencies.

6.2. Data sampling procedure

The accelerometer that was attached to the prototype when it was tested prior to use (see Section 5.7) was used to record the vibrations transmitted to the specimens within the bath. It was decided to record five sets of data at each frequency, to ensure that the performance of the prototype was stable and that the frequency set on the amplifier was being maintained. In order to produce a clear record of the movements occurring, it was necessary to record the acceleration at least ten times during every cycle. Therefore, as the operating frequency of the prototype was increased, the sampling rate had to be adjusted accordingly. When the prototype was operating, the Kontron SMR was triggered by the operator and it recorded the data from the accelerometers. The quantity of data to be recorded could be set on the SMR by determining the number of bytes to be recorded. The same number of bytes was recorded for each data set, although because the sampling rate was adjusted, the time during which the data was taken became less as the frequency was increased. This meant that the number of cycles recorded for each set of data remained fairly constant. Although it was only necessary to record ten cycles, more was often recorded. The entire range of data was then used to construct a graph, allowing the operator to ensure that the form of the data remained the same throughout the entire set of data. Once this had been established, ten cycles were selected to represent the performance of the prototype at that frequency.

6.3. Separating full-scale couplets

The most important specimen to test in the prototype was a full-scale couplet with properties which reflect the brickwork available for recycling. If the prototype could separate and clean these couplets, it would be a good indication that it would be capable of separation the bricks and mortar from reclaimed brickwork. The full-scale couplets were fabricated to the same specifications with the same materials and curing process as the full scale couplets that were tested in the ultrasound bath. The construction process and the justification for selecting these methods are detailed in Section 4.2.1.1.

6.3.1. Results

The frequency sweep was started at 7 Hz, and was then increased gradually. The data recorded by the accelerometer attached to the plate showed that the prototype was working successfully, and the vibrations were at the amplitude and frequency that the prototype had been designed to produce. Furthermore, the accelerometers attached to the specimen showed that vibrations were travelling through the specimen. The actuator was capable of running at frequencies up to 6 kHz, but when the prototype was operating at just over 4 kHz, it was noticed that the maximum acceleration recorded by the accelerometer on the plate was 210g. This was more than double the 100g, which was the maximum acceleration that the actuator was designed to sustain. This indicates that the spring system must be balancing out the water pressure as intended; allowing the actuator to operated with minimal resistance.

The frequency was set on the amplifier using an analogue dial, and hence it was not possible to set a frequency on the amplifier with perfect precision. However, the true frequency was recorded by the accelerometer on the plate, as shown in Table 6-1 below.

Intended frequency (Hz)	Frequency of the plate (Hz)
7	6.91
10	10.2
50	53.0
100	106
150	152
350	355
700	713
1000	1010
1250	1260
1500	1480
1750	1750
4000	4180

Table 6-1. The frequencies at which data was recorded during the first frequency sweep

6.3.2. Analysis of results

When the data recorded by the Kontron SMR was examined, it was found that the accelerations achieved by the plate had increased as the frequency sweep progressed, as shown in Figure 6-1 below.

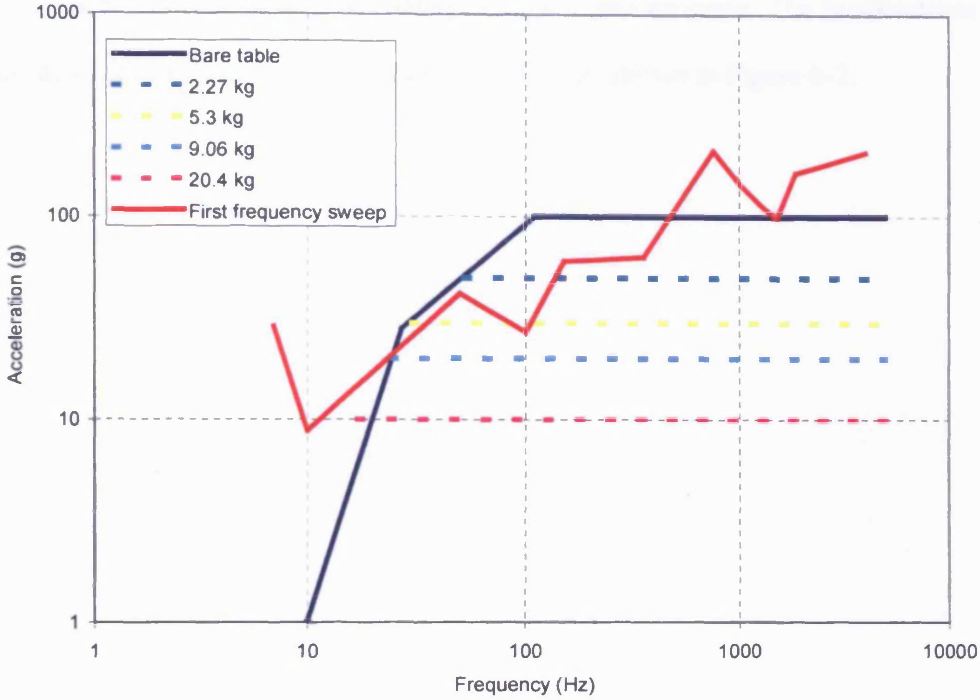


Figure 6-1. The accelerations recorded by the accelerometer on the plate during the first frequency sweep

As the frequency was increased, the acceleration achieved by the actuator became larger. However, this increase did not occur smoothly as there were local fluctuations. There are three main features that occur before the frequency reached 4 kHz. The acceleration achieved is less than expected at 100 Hz, and the acceleration reaches a peak at 700 Hz. These variations are a result of the dynamic characteristics of the prototype. Each of the individual components within the prototype have their own natural frequencies, and some of the components may significantly influence the performance of the prototype as a whole. For example, if the springs have a natural frequency at 500 Hz, the movement will suffer less dampening, enabling the prototype to reach greater amplitudes at this frequency.

The dynamic characteristics of the prototype also affect the movement of the plate. The traces recorded do not always follow a smooth curve. The accelerations recorded with the prototype operating at 1 kHz are shown in Figure 6-2.

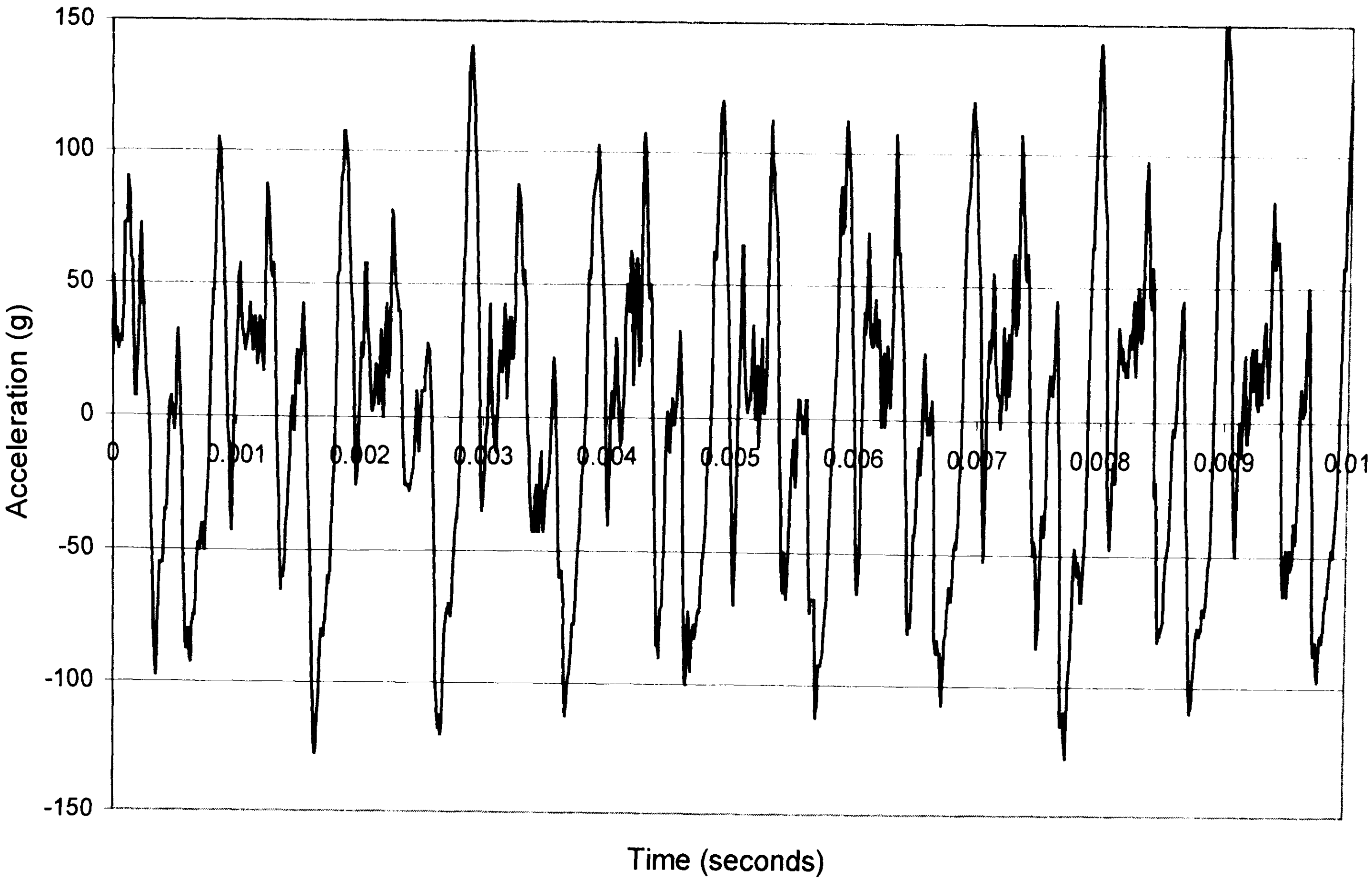


Figure 6-2. The accelerations of the plate recorded at 1 kHz.

The trace shown above in Figure 6-2 does not come to a single peak, but instead fluctuates. In some cases the acceleration even becomes negative during the positive phase of the cycle . This prevents the maximum acceleration from being achieved. The only way to avoid this problem would be to ensure that all of the components within the prototype do not have natural frequencies within the operational range of the prototype.

The data supplied by the manufacturer indicates that the unloaded actuator should achieve a maximum acceleration of 100g at a frequency just greater than 100 Hz. The actuator should then be able to sustain this acceleration as the frequency is increased to the maximum of about 6 kHz. If the actuator is loaded, the maximum acceleration will be reached at a lower frequency, but it will be less than 100g. The accelerations recorded during the first frequency sweep did not match the manufacturer's values, which are based on the actuator loaded with a mass, although the documentation supplied is not comprehensive. The actuator used to power the prototype is attached to a mass that is dampened by the springs and the pressure of the water in the tank. This discrepancy is, therefore, perhaps not so surprising.

When data recorded by the accelerometers attached to the specimen was examined, it showed that the waveform of the vibrations within the couplet had remained the same at all the frequencies. Figure 6-3 shows an example of the waveform taken by the data recorded for all of the frequencies during the first frequency sweep.

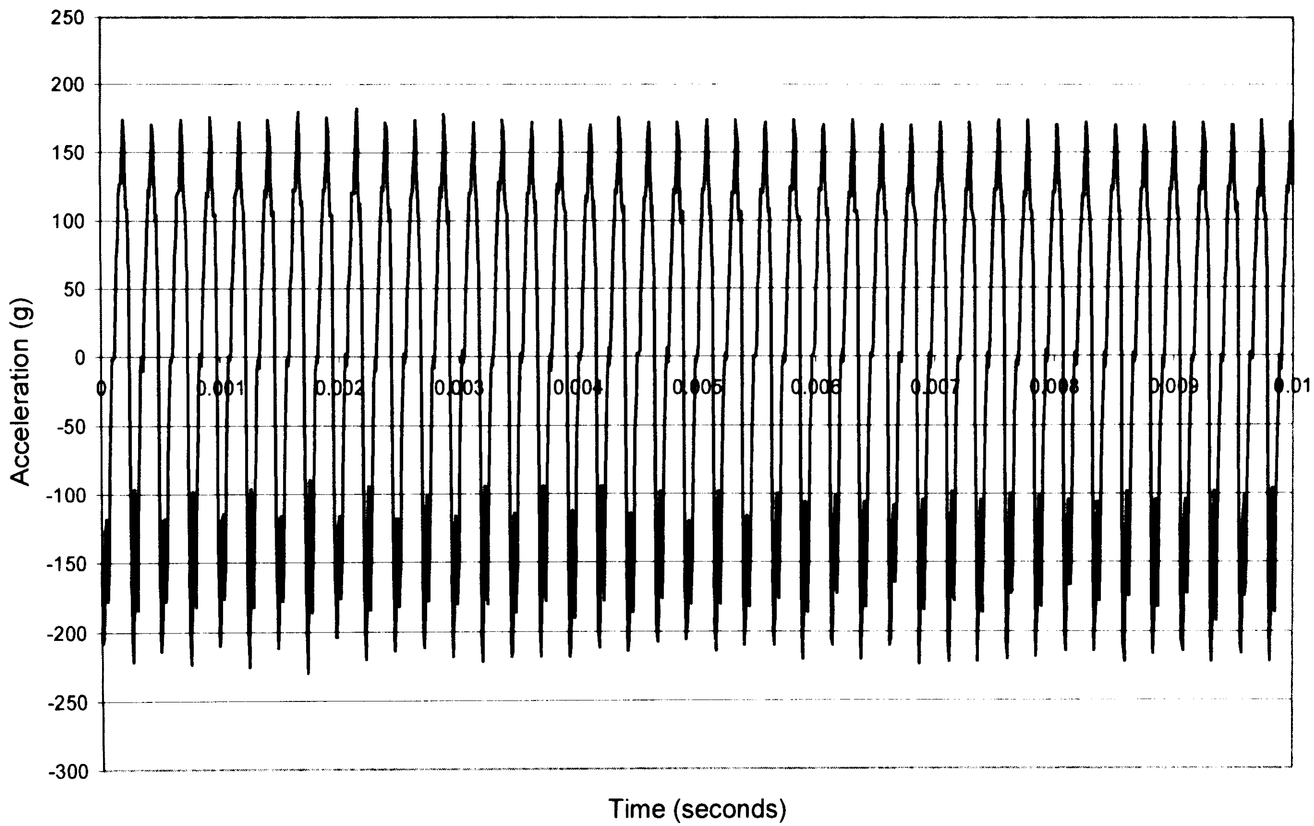


Figure 6-3. The accelerations recorded by the accelerometer attached to the specimen with the prototype operating at 4180 Hz, during the first frequency sweep.

In addition to showing the waveform of the vibrations recorded in the specimen at all the frequencies, the data shown in Figure 6-3 shows that the vibrations with a frequency slightly in excess of 4 kHz had been produce in the specimen. This frequency is in the middle of the range of frequencies that were expected to allow separation to occur. After the frequency sweep had been completed, the specimen was carefully examined and no sign that separation had begun to occur were found.

6.3.3. Additional results

In order to ensure that the prototype was capable of reliable performance, it was decided to perform a second frequency sweep. During the first frequency sweep the prototype had only be operated for long enough for the required data to be recorded. However, it was decided to run the prototype for a period of fifteen minutes at each frequency during the second frequency sweep. This should give ample time for separation to occur if the prototype were capable of replicating the result produced when the one-sixth scale couplets were tested in the ultrasound bath. The amplifier was switched off for a period of fifteen minutes in between each operation of the prototype to minimise the risk of failure due to overheating.

In addition, it was decided to fit accelerometers to the couplets to record the vibrations produced in the brick by the prototype. The accelerometers used to record the vibrations of the full-scale specimens in the U.P.C. bath were well suited to being used on the specimens in that were placed in the prototype. The frequencies and amplitudes expected in the prototype were within their design range. Furthermore, they were known to work underwater and when subjected to ultrasound vibrations. The intended frequencies and the actual frequencies achieved during the second frequency sweep are shown in Table 6-2 below.

Frequency set on amplifier (Hz)	Frequency of the plate (Hz)
7	6.97
10	10.3
50	55.6
100	109
150	137
350	390
700	725
1000	1140
2000	2041
3000	3050
3100	3145
3500	3550
4000	4031
5000	5030
5500	5560
6000	5950

Table 6-2. The frequencies recorded during the second frequency sweep

However, the specimen remained in one piece, and no signs of separation were seen during the second frequency sweep. As no sign of separation was seen, and since the data recorded showed that the prototype was working as anticipated at the frequencies that had been tried, it was decided to continue to increase the frequency despite the possibility of damage to the actuator through excessive accelerations. The second frequency sweep was therefore extended, and the frequency was increased to 6 kHz.

The prototype worked as usual, and the frequency was increased to 6000Hz, and it appeared that fears that increasing the frequency further would raise the accelerations generated in the actuator to levels that would cause damage were unfounded. This was explained when the accelerations recorded by the accelerometer attached to the plate were examined. Once the frequency was increased past 4 kHz the acceleration that could be sustained by the plate decreased rapidly. This does not result from the effects of the natural frequencies of the prototype components, but occurs because the actuator is beginning to exceed its working range, and is not capable of the accelerations required to sustain the amplitude at these frequencies.

6.3.4. Further Analysis of Results

Figure 6-4 shows the accelerations recorded during both frequency sweeps.

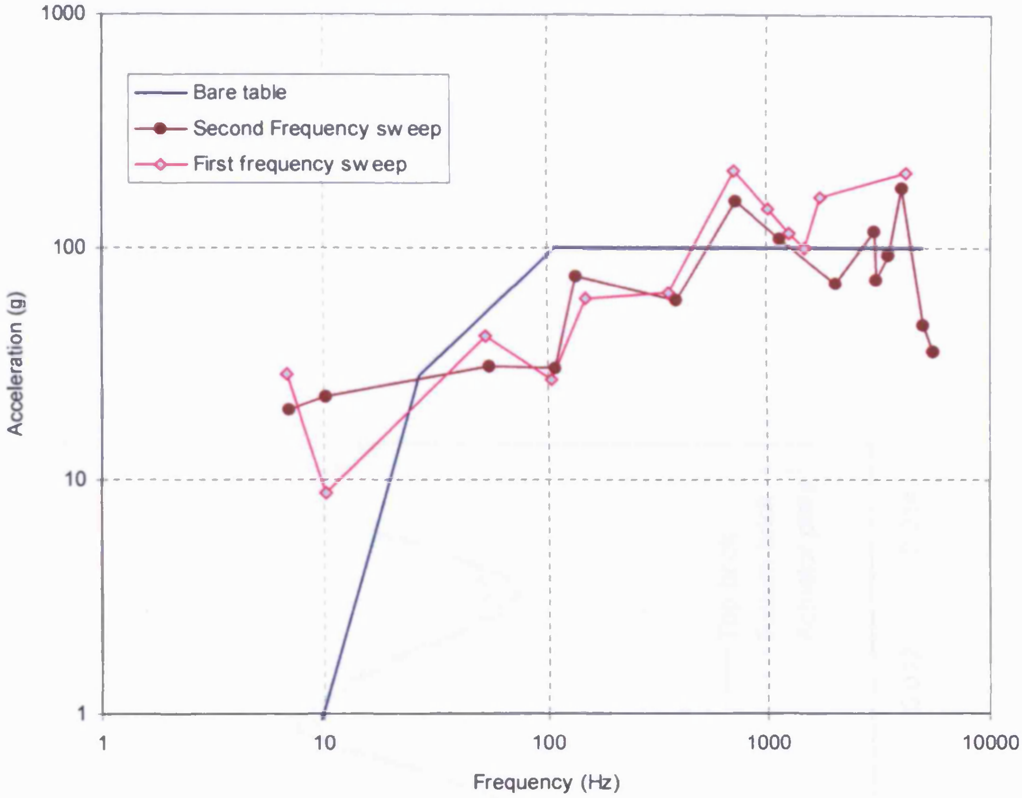


Figure 6-4. Accelerations recorded by the accelerometer on the plate during the two frequency sweeps

Figure 6-4 shows that the accelerations recorded during the two frequency sweeps match up closely, confirming that the values recorded represent the true maximum acceleration that can be sustained by the prototype. This confirms that the local variations in the accelerations are not caused by any errors introduced by the operator or the instrumentation, but rather by the response of the prototype to the frequency at which the actuator is operated.

At frequencies below 3 kHz the accelerations within the couplet followed that of the plate, as shown in Figure 6-5.

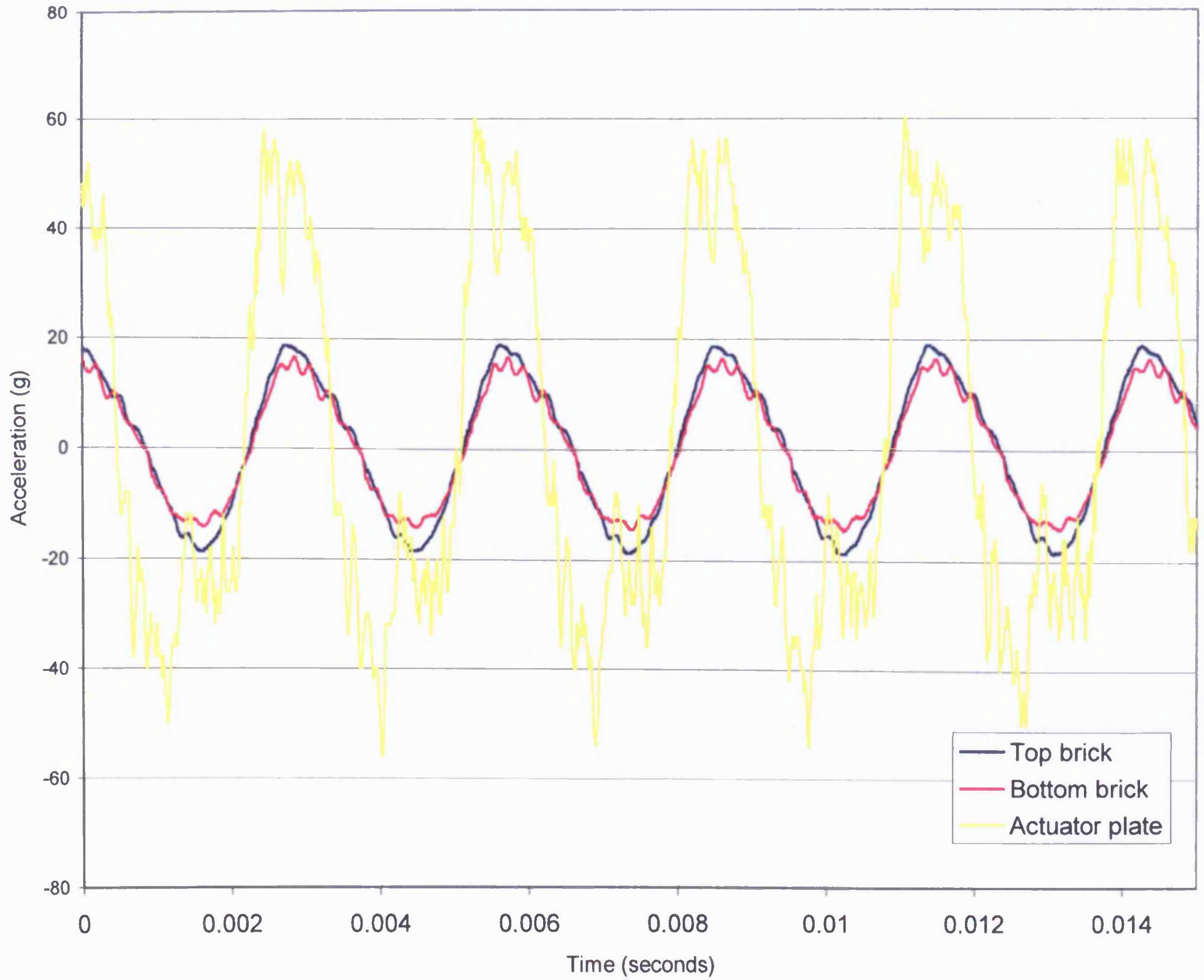


Figure 6-5. The accelerations recorded with the prototype operating at 350 Hz

The traces shown in Figure 6-5 recorded by the accelerometers attached to the couplet at 350Hz above follow a fairly smooth sine wave. They match each other very closely and are in-phase with the movement of the actuator plate. However, at some frequencies the waveform recorded was not a smooth sine curve, as shown in Figure 6-6.

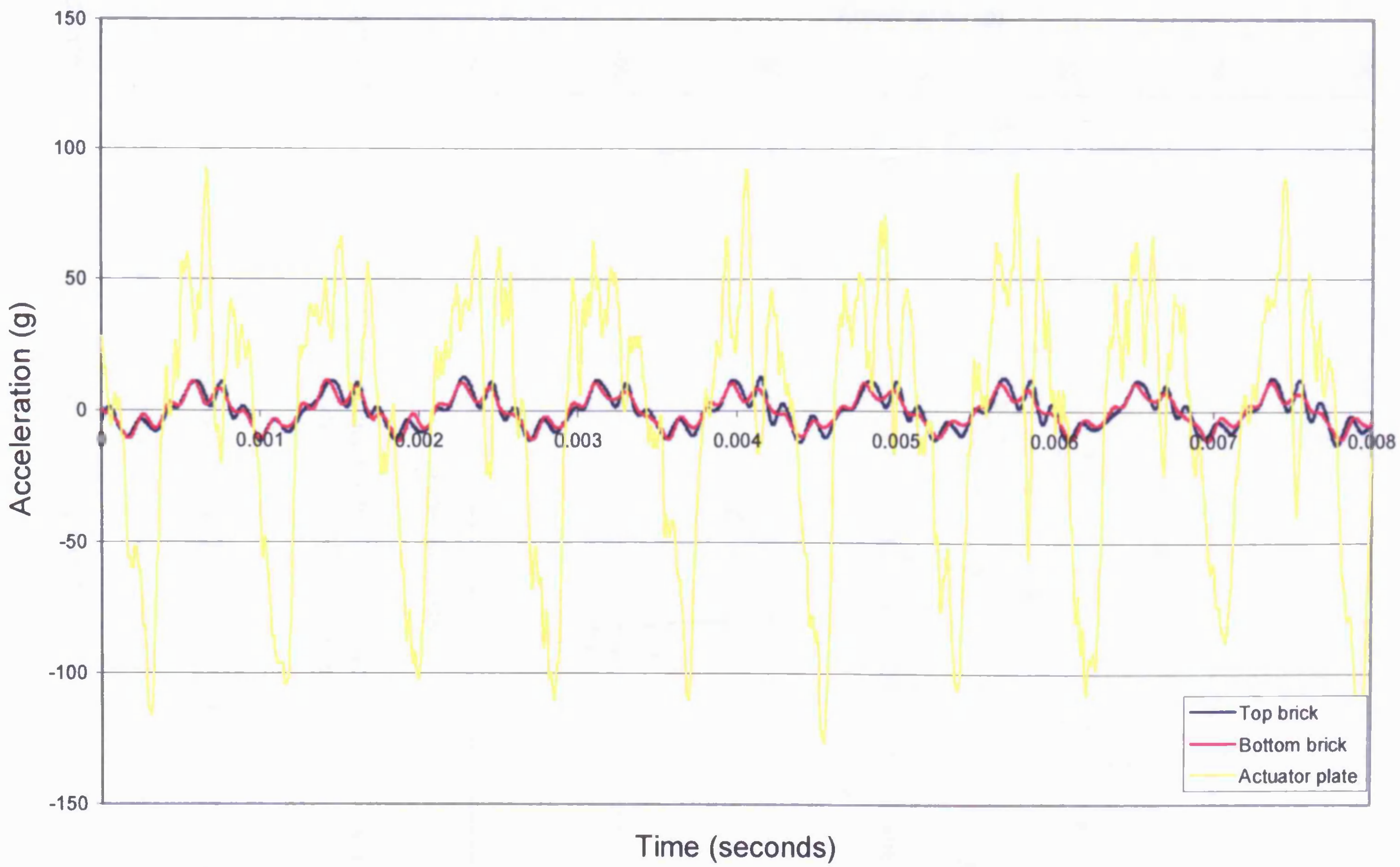


Figure 6-6. The accelerations recorded with the prototype operating at 1 kHz

In Figure 6-6 the trace for the acceleration of the actuator plate does not follow a smooth curve and the peaks are distorted. The same effect was noticed in the data recorded from the first sweep. The graphs recorded at approximately 1 kHz during the two frequency sweeps can be seen together in Figure 6-7.

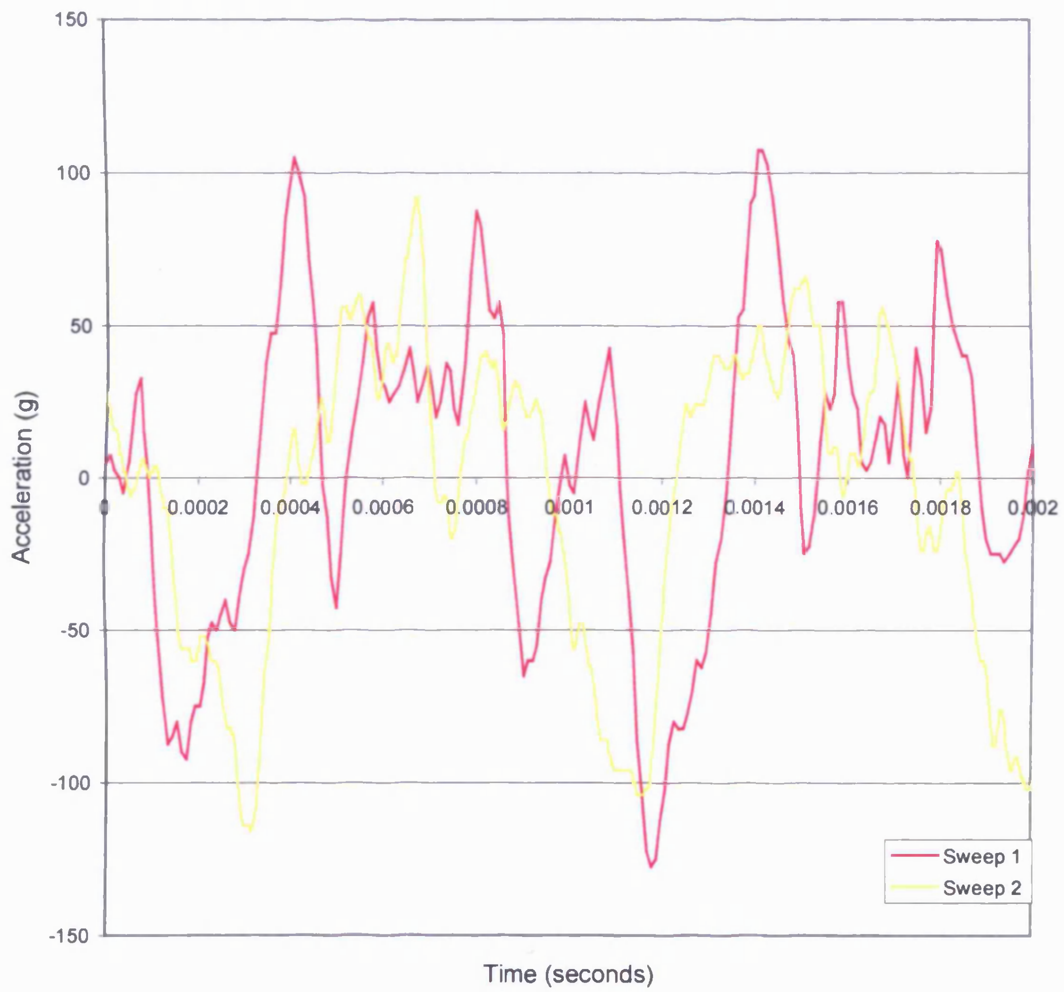


Figure 6-7. Comparison of the acceleration of the actuator plate at 1 kHz during the first and second frequency sweeps.

The similarity between the waveforms in Figure 6-7 demonstrates that the movement of the actuator plate remained constant when the sweep was repeated and indicates that the performance of the prototype can be replicated.

During the first part of the frequency sweep, when the prototype was operated at frequencies less than 5 kHz, the vibrations within the two bricks were in-phase, as those shown in Figures 6-5 and 6-6. However, at higher frequencies the accelerations recorded within the two bricks are no longer the same. Figure 6-8 shows the acceleration recorded within the specimen when the prototype was operating at 5 kHz.

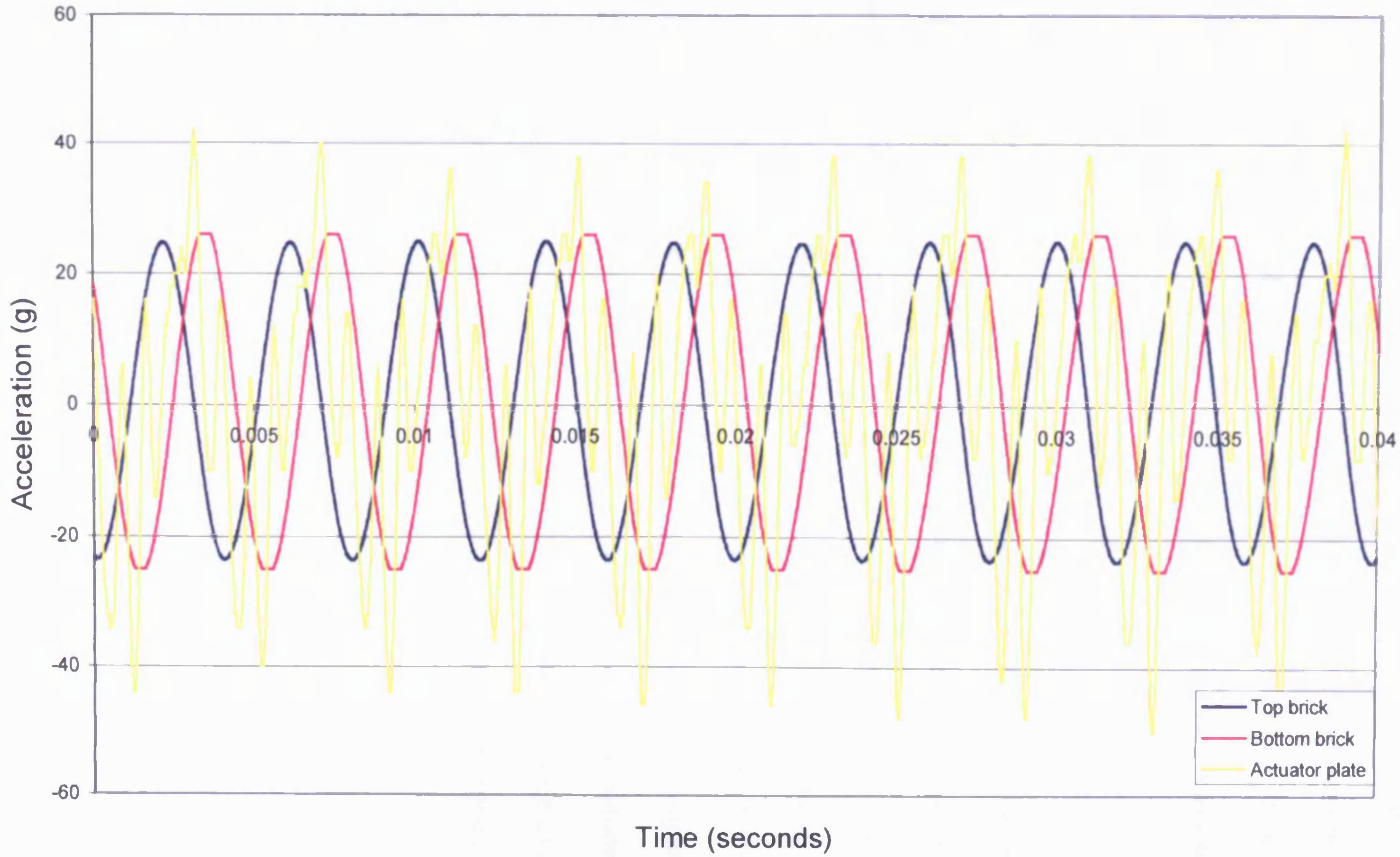


Figure 6-8. Vibrations recorded with the actuator operating at 5 kHz.

When the prototype was operated at a frequency of 5 kHz as shown in Figure 6-8, the vibrations produced within the two bricks were clearly no longer in phase. This would therefore place an increasing amount of stress along the interface between the bricks and the mortar. As the movement of the two bricks becomes increasingly different, a greater stress will be caused at the interface. This increases the likelihood of the interface to fail and for separation of the two bricks to be achieved.

Furthermore, when the frequency was increased to 5.5 kHz, the response of the couplets changed again. When the prototype was operating at frequencies less than 5 kHz, the accelerations recorded were in phase. However, at 5.5 kHz, a different mode of vibration was triggered within the specimen, which caused the three components (the two bricks and the mortar joint) to vibrate independently. Figure 6-9 shows that at 5.5 kHz the vibrations of the two accelerometers attached to the couplets were 180 degrees out of phase. The different vibration mode and constant amplitude steady state vibration shown in Figure 6-9 show that a natural vibration mode of the specimen has become dominant (see Section 3.6). This indicates that the couplet has a natural frequency in the region of 5.5 kHz.

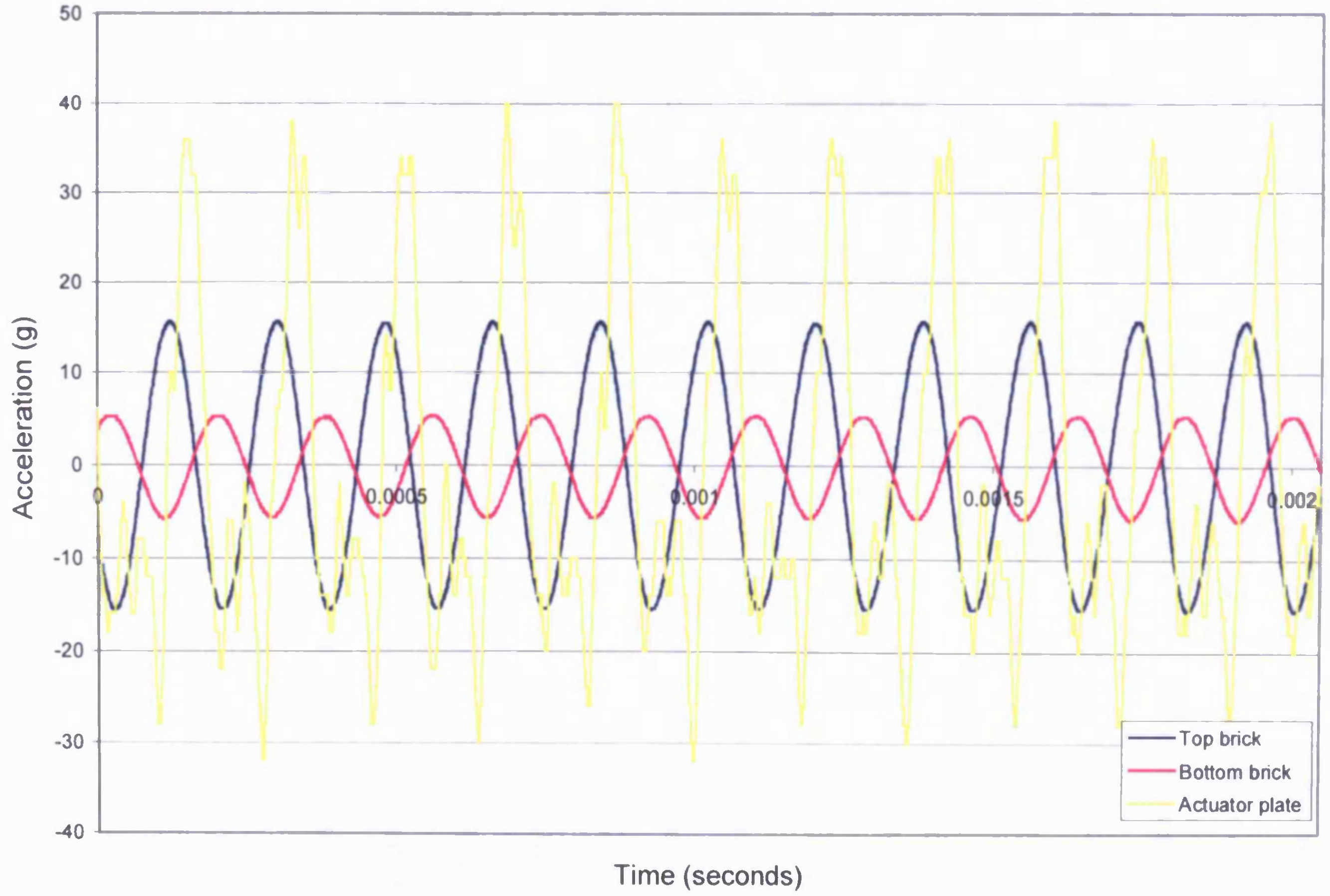


Figure 6-9. The accelerations recorded with the prototype operating at 5500 Hz

When the vibrations within the two bricks are opposing as shown in Figure 6-9 the bricks are moving away from each other or moving together. This means that the joints between the brick and the mortar must be subjected to a stress cycle. In order for the couplet to remain intact, the bond between the bricks and the mortar must withstand the entire force generated by the vibrations. This is a process that could not fail to achieve separation if the energy of the vibrations within the couplet were sufficient to break the interface bond. However, as the couplet remained intact when these traces were recorded, the only conclusion is that the bond between the bricks and the mortar was able to resist the stresses placed upon it.

It was possible that it is this mode of vibration that was occurring when the one-sixth scale couplets were placed in the ultrasound bath, and that it is this mode of vibration that causes separation to occur. If this hypothesis is correct, then achieving this mode of vibration within the full-scale couplet using the prototype should result in separation occurring, but this did not happen. However, the data in Tables 6-2 and 6-3 show that the accelerations achieved by the prototype rapidly decrease after a frequency of 4 kHz. With the prototype operating at 5 kHz, the acceleration of the plate is less than one fifth of the acceleration at 4 kHz. This means that even if the required mode of vibration was occurring at 5.5 kHz, the lack of energy supplied to the couplet could prevent separation from occurring.

The maximum accelerations and amplitudes recorded by the accelerometers attached to the plate and the specimen at each frequency during the second frequency sweep are shown in Table 6-3.

Frequency (Hz)	Maximum acceleration recorded (m/s^2)		
	Plate	Top brick	Bottom brick
6.97	196	7.85	7.85
10.3	226	32.4	28.4
55.6	304	79.5	75.5
109	294	150	152
138	736	78.5	76.5
390	579	186	154
725	1540	106	150
1140	1070	125	112
2041	687	98.1	71.6
3050	1160	82.4	135
3145	706	56.9	218
3550	903	98.1	141
4031	1780	80.4	224
5030	452	238	250
5560	353	153	54.9

Table 6-3.The maximum accelerations, amplitudes recorded during the second frequency sweep.

The figures in Table 6-3 show that as the frequency was increased, the general trend was for the amplitude of the vibrations to decrease. This was expected to occur because as the frequency is increased, the amplitude that the actuator is capable of sustaining is reduced.

This reduction is also shown in the amplitude of the vibrations recorded by the accelerometers attached to the specimen. Once again, this is unsurprising since it is the movement of the plate that causes the vibrations to pass through the specimen. However, whilst this general trend holds true, it is also clear that there were local variations at several frequencies. In order to allow these features to be detected, the data shown above in Table 6-3 was plotted on a series of graphs. The graph in Figure 6-10 shows the amplitudes and accelerations recorded during the second frequency sweep by the accelerometers attached to the couplet.

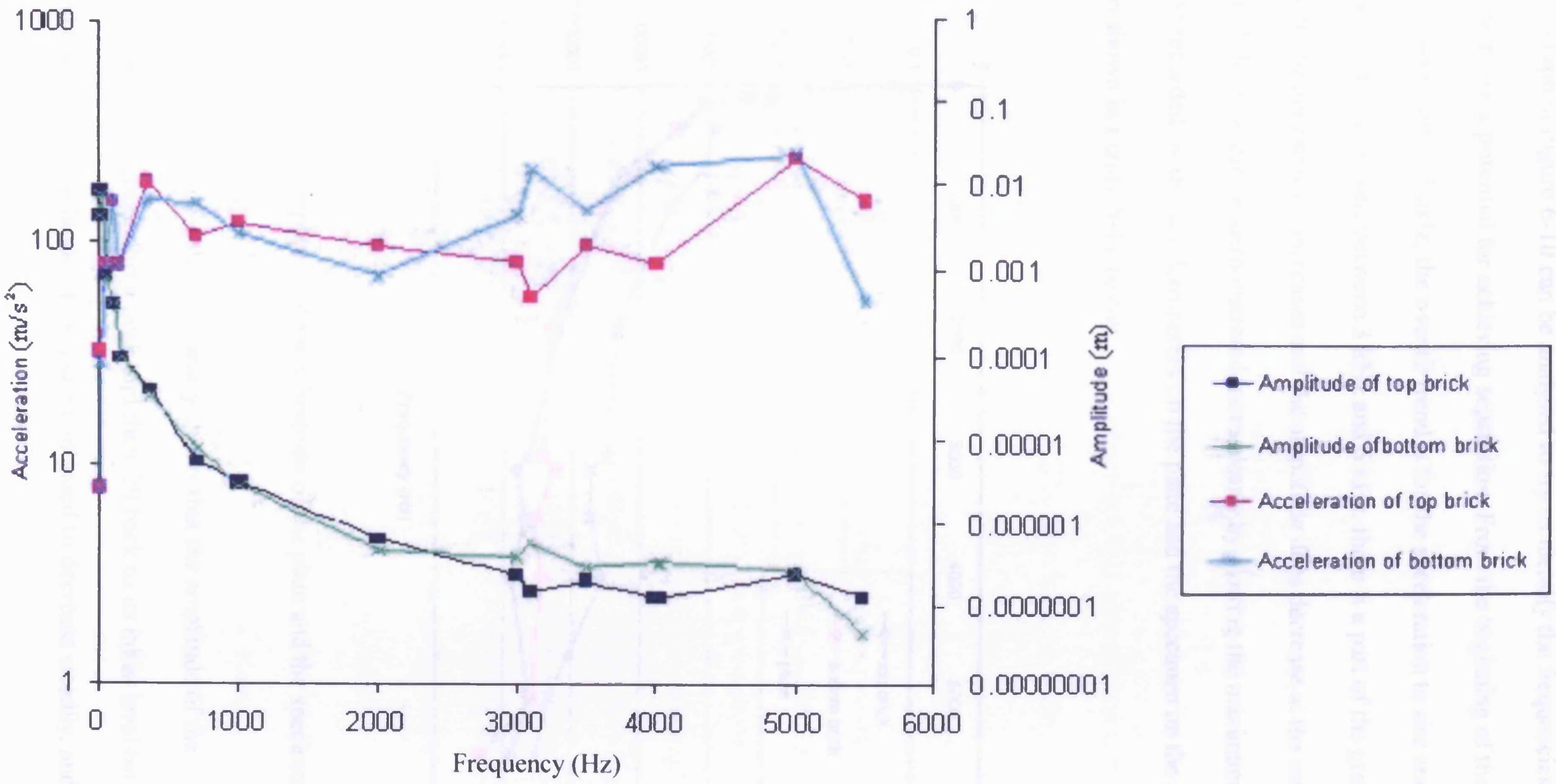


Figure 6-10. The displacements and accelerations recorded in the specimen during the second frequency sweep.

The graph in Figure 6-10 can be analysed to try to identify the frequencies that present the highest potential for achieving separation. From the beginning of the frequency sweep up to 3 kHz, the overall trend is for the acceleration to rise and the amplitude to fall. However, between 3 kHz and 6 kHz, there is a part of the graph where both the acceleration increases and the amplitude does decrease at the same rate. This difference can be demonstrated more clearly by plotting the maximum amplitude recorded by the accelerometers on the plate and the specimen on the same graph, as shown in Figure 6-11 below.

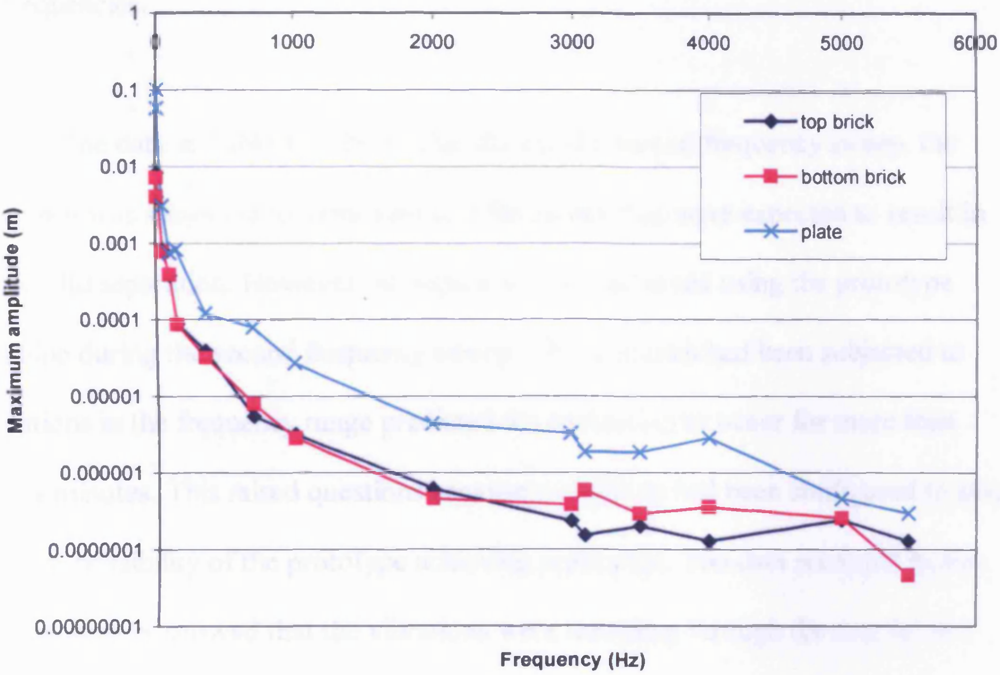


Figure 6-11. The amplitude of the vibrations of the plate and the specimen

The graph in Figure 6-11 above clearly shows that the amplitude of the vibration in the brick increased to a peak and then fell back to its initial level between 3 kHz and 6 kHz. The amplitude of the plate continued to decrease steadily, and hence could not be responsible for the increased vibrations recorded in the bricks. The increase in the amplitude of the vibrations within the couplet must therefore occur because the response of the couplet is different. The calculations and experiments performed in Chapter 4 attempted to predict the frequencies at which the interference effect would occur. These frequencies coincide with the range of frequencies at which the graph shows an increase in the acceleration achieved within the specimens, which will increase the likelihood of separation being achieved. This suggests that the predictions made during the initial studies were correct. It is reasonable to assume that if the prototype is able to achieve separation it will be most effective within this range of frequencies.

The data in Table 6-3 shows that during the second frequency sweep, the specimen was subjected to vibrations of a frequency that were expected to result in successful separation. However, no separation was achieved using the prototype machine during the second frequency sweep. The specimen had been subjected to vibrations in the frequency range predicted for separation to occur for more than ninety minutes. This raised questions because everything had been configured to give the best possibility of the prototype achieving separation. The data recorded by the accelerometers showed that the vibrations were travelling through the couplet in a manner that would be expected to cause separation to occur. Furthermore, the prototype had been operated at the maximum possible frequency and amplitude, so there was no possible increase in the power transmitted to the specimen.

6.3.5. Evaluating the stress produced within couplets in the prototype

An evaluation of the stress produced within the couplet can be performed using Equation (47).

$$\sigma_m = a_m \rho \frac{2L}{\pi}$$

where
- σ_m is the maximum stress
- a_m is the maximum acceleration
- ρ is the density of the couplet
- L is the length of the couplet

From Figure 6-9 it can be seen that the maximum acceleration achieved within the couplet with the bath operating at 5.5 kHz was 15g.

Therefore $a_m = 15 \times 9.81 = 147$ m/s^2

Assume length (with allowance for less stiff mortar)	$L = 0.085$	m
Assume typical value for density of brick	$\rho_b = 1850$	kg/m^3

Therefore the maximum stress σ_m produced within the specimens with the prototype can be determined as:

$$\sigma_m = 147 \times 1850 \frac{2 \times 0.085}{\pi}$$
$$= 14731 \quad \text{N/m}^2$$
$$= 0.015 \quad \text{N/mm}^2$$

This method could be used to provide a comparison between the maximum stresses produced in the one-sixth scale specimens that were separated in the ultrasound bath and the full scale couplets in the prototype. However, it is not possible to attach instrumentation to the one-sixth scale specimens, and hence the maximum amplitude of the stress within the one-sixth scale couplets can not be determined.

6.4. Separating one-sixth scale couplets in the prototype

Six couplets were made for testing in the prototype, allowing two specimens to be tested at three different frequency settings. The couplets tested in the prototype were made to the same specification outlined in Section 4.2.1.1 with joints 5mm thick made from Grade 3 mortar. The specimens were placed on a metal platform in front of the actuator plate at the same position as the full scale couplets, described in Section 6.1. Six one-sixth scale couplets were tested in the prototype. Six specimens were tested in total, two at 50, 350 and 3000 Hz.

6.4.1. Results

The prototype was able to achieve Stage 1 and 2 separation of the one-sixth scale specimens at all the frequencies that were tested. The ripples on the surface of the water made it difficult to see the specimens clearly and because the specimens were small it was not possible to easily determine the time at which separation occurred. However, the prototype was only operated for a period of two minutes and this was sufficient time for each of the couplets to be separated.

6.4.2. Analysis of results

The prototype had successfully separated all of the specimens, proving that it was possible to achieve separation using the prototype. The one-sixth scale couplets had now been separated at frequencies of 50 Hz, 350 Hz, 3kHz, 30 kHz and 40 kHz. This shows that it is not necessary to use ultrasonic vibrations to achieve separation of one-sixth scale couplets. In addition, the large variation of these frequencies seems to disagree with the hypothesis that couplets can only be separated and cleaned by vibrations within a range of frequencies which is determined by the dimensions of the specimen. Instead, the belief that there is a range of frequencies that will give separation is maintained and enhanced. The one-sixth scale couplets could have been separated at frequencies outside this range because the energy supplied was so great that it was not necessary to use the vibrations with the optimal frequency.

6.5. Separating modified couplets

There were several small changes that could be made to the way in which the prototype was used. For example, the positioning and orientation of the specimen, the fluid present with in the bath, and the temperature of the fluid within the bath could all be changed. However, there was no reason to believe that changing these variables would improve the ability of the prototype to cause separation, as the methods most appropriate for achieving separation had been used during the first frequency sweeps. Instead it was decided to try and achieve separation by using a specimen that would be less difficult to clean. Achieving separation of a specimen that was designed to be easier to clean than the sort of bricks available for recycling would not demonstrate that the process had benefits suited to being develop for industry. However, a positive result would demonstrate that the prototype could potentially separate and clean full-scale couplets, making further work to improve the prototype worthwhile.

6.6.Method

A series of new specimens were constructed in such a way that they would be easier to separate. Firstly, a couplet was made using a Grade 5 mortar, so that the bond strength between the bricks and the mortar was reduced. The couplet was made to the same specifications as the couplets that had previously been tested in the prototype. In order to ensure that the mortar could not form a lip around the edges of the bricks, the joint was recessed by 10mm. In addition, it was decided make a couplet with Grade 5 mortar, but with a reduced area of contact between the mortar and the bricks. In order to achieve this, a foam template was used. The foam was 20mm thick, and it was cut down so that it just covered the bed face of the bricks. Two holes were cut out of the centre of the foam, giving the foam template the dimensions shown in Figure 6-12 below.

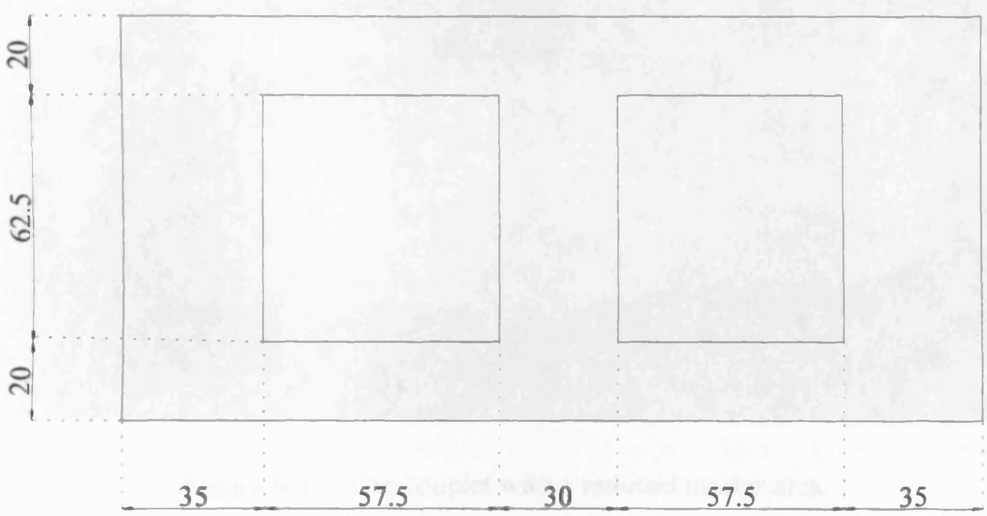


Figure 6-12. The foam template used to make the couplet with a reduced mortar area.

The template was placed on top of a brick and fixed in place with tape. The holes in the template were filled with mortar until level with the top of the foam. A second brick was placed on top of the foam, which compressed under the weight of the top brick, ensuring that the mortar in the holes was in contact with both bricks. The couplet was then cured in the same manner as the other specimens tested in the prototype. After curing, the foam was cut away, leaving a couplet with approximately half the contact area between each brick and the mortar. The resulting specimen is shown in Figure 6-13 below.

Figure 6-13. The couplet with a reduced mortar area

This couplet would be much less difficult to separate in the prototype. The reduced contact area means that a smaller force would be able to break the bond between the bricks and the mortar. In addition, the mortar joint is less stiff, permitting greater vibrations to occur within the two bricks that form the couplet. Finally, there is no possibility that the mortar can form lips around the edges of the bricks, as it is only in contact with the central area of the bed face of the bricks.

The two specimens were then tested in the prototype at the full range of frequencies that were achieved during the frequency sweeps. As before, the specimens were tested individually, and each frequency was sustained for a period of fifteen minutes.

6.6.1. Results

During testing, neither of the modified couplet specimens separated. When they were removed from the tank and examined, they appeared to be unchanged. No signs that separation had begun to take place could be found.

6.6.2. Analysis of results

The modified couplets were designed to reduce the difficulty of achieving the separation of a full-scale mortar joint. However, after more than three hours in the prototype, no signs of separation occurring could be found. During the time in the prototype, the modified couplets had been subjected to the range of frequencies that should give the best chance of achieving separation. The failure to separate such a specimen despite a more efficient use of the prototype means that there were few options other than to accept that it was not going to be possible to separate and clean full-scale couplets using the present prototype.

6.7. Chapter Conclusion

The prototype was operated with full scale couplets in the tank to see if separation could be achieved. The vibrations passing through the specimen showed that the prototype was producing vibrations throughout the intended range of frequencies within the specimens.

At low frequencies the vibrations within the two bricks were synchronised, but when the frequency exceeded 3 kHz a difference developed. As the frequency was increased further the difference became more noticeable, until at 5.5 kHz the vibratory movement of the two bricks were completely out of phase. This would cause the maximum possible amount of stress to be placed on the interface between the bricks and the couplet, giving the best chance of separation occurring. These frequencies matched the frequencies shown in Table 4-12, determined by the tests detailed in Chapter 4, to indicate the frequencies that would give the best chance of achieving separation at full scale.

However, no signs of separation occurring were detected during the testing process or when the specimens were examined after the tests.

One-sixth scale couplets were successfully separated within the prototype when it was operating at frequencies of 50, 350 and 3000 Hz.

Two couplets were made in such a way that they would be particularly easy to separate and clean in the prototype. A comprehensive attempt was made to separate and clean these specimens using the full range of frequencies that could be achieved within the prototype. These couplets remained intact, which indicated that the performance of the prototype needed significant amount of improvement before it could have any success at full scale.

7. Bond wrench testing

7.1. Introduction

The prototype produced vibrations with the intended frequency and amplitudes, but it failed to separate or clean full-scale couplets. In order to determine the factors that prevented separation from occurring it was decided to perform a bond wrench test on a series of full-scale and one-sixth scale bricks to allow the bond strength of the joints to be evaluated.

7.2. Method

The majority of the specimens were fabricated to the same specifications used for specimens made for previous tests in Chapter 4. All of the specimens were tested at twenty-eight day mortar strength. The specimens described as "full-size couplet" were made with the joint thickness shown in Table 7-1. The specimens described as "full-scale couplet reduced to 1/6th scale after curing" were fabricated and cured to the same specifications as the standard full size couplets. However, these couplets were cut down to one-sixth scale size prior to testing. This was achieved by slicing through the couplet in two directions and then making additional cuts to trim the remaining specimen to the correct size. This process was performed as carefully as possible to minimise the stress placed on the mortar joint. However, it was impossible to ensure that this process did not weaken the mortar joint. Indeed, as many of the specimens were cut, the joint between the mortar and the brick was broken and the specimen had to be discarded. It should therefore be noted that the bond strength of the cut specimens that were tested could have been weakened during the cutting process. However, these specimens would provide the possibility of detecting any variation in the bond strength at different areas of the brick/mortar interface, for example, reduced bond strength near the edges of the couplet.

The specimens described as "full-size couplet, top brick cut to give 1/6th scale load" was altered so that the confining pressure on the mortar joint would be the same as that imposed by a one-sixth scale couplet. This was achieved but cutting away the top five-sixths of the top brick prior to the fabrication of the couplet.

The "standard one-sixth scale couplet" was fabricated to the specification given in Section 4.2.1.1. The pre-loaded one-sixth scale couplet was also fabricated in this manner, but five one-sixth scale bricks were placed on top of the couplets during curing. The height of these bricks is the same as the height of the full-scale bricks used to make the full-scale couplets. The curing load stress on the pre-loaded one-sixth specimens would be the same as the load on the standard full-scale couplets. Table 7-1 shows the specimens that were subjected to a bond wrench test.

Couplet description	Ref no.	Number of specimens	Mortar joint thickness (mm)
full size couplet	A	5	15
standard full size couplet	B	5	12
full size couplet	C	5	8
full size couplet	D	5	4
full size couplet	E	5	2
full size couplet, top brick cut to give 1/6th scale load	F	5	12
full scale couplet reduced to 1/6th scale after curing	G	3	12
standard1/6th scale couplet	H	5	2
pre-loaded 1/6th scale couplet	I	4	2

Table 7-1. The test specimens made for the bond wrench test

The mortar thickness used for the standard full-scale couplets was 12mm, six times greater than the mortar joint thickness of the one-sixth scale couplets. Hence the dimensions of the standard one-sixth scale couplets are an exact reproduction of the dimensions of the standard full-scale couplets at one-sixth scale.

The bond wrench test was performed following the procedure outlined in *Technical recommendations for the testing and use of construction materials* [72]. This document provides a full description of how the test should be performed, and the calculations required to determine the bond strength. The test involves clamping the top and bottom brick of a couplet or stack of bricks into a frame, and allowing a force to be applied until the joint between the bricks is broken. Several methods for loading the specimen during test outlined in the standard, but the method selected involved loading the end of the jig clamped onto the top brick with a loading test unit. Figure 7-1 below shows how the test is performed using this procedure.

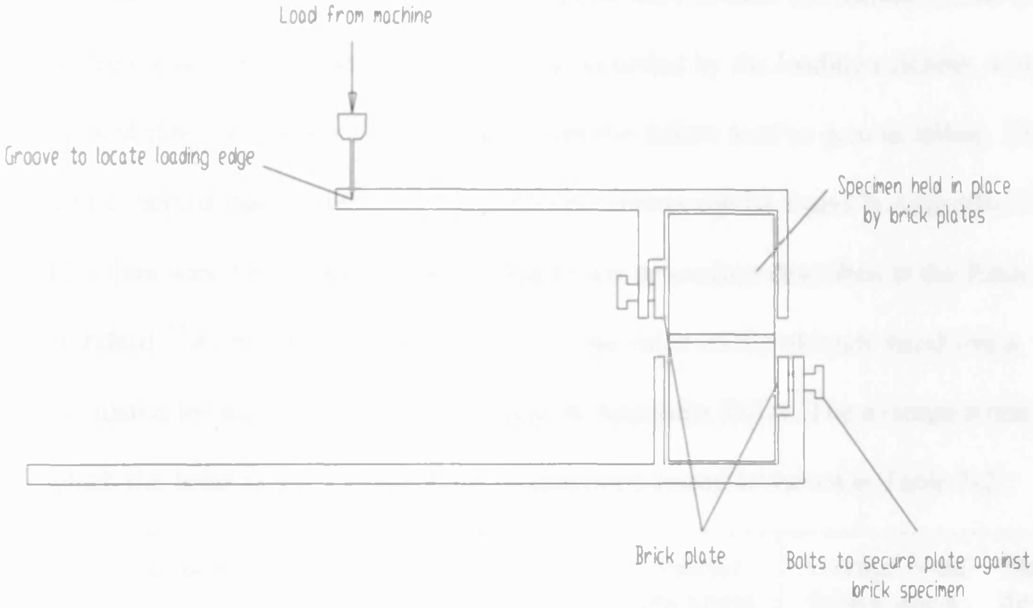


Figure 7-1. The testing system for performing the bond wrench test using a loading machine.

The bond wrench test had previously been performed on one-sixth scale brick couplets at Cardiff University and the jig required was therefore already available. However, the same test had not been performed before on full-scale brick couplets, and so it was necessary to design and build an equivalent jig.

Full drawings and photographs of the equipment used for the bond wrench test can be found in Appendix D.2. Photographs of the test being performed can be found in Appendix D.3.

7.3. Results

A visual inspection of the couplets was performed during the bond wrench testing to determine the failure method that occurred. No cracks were observed as the specimens were loaded, and all the specimens were seen to fail suddenly. The sudden failure method was confirmed by the data recorded by the loading machine, which showed that the applied load changed from the failure load to zero at failure. The raw data collected during the bond wrench experiments can be found in Appendix D.2. This data was then processed according to the procedure described in the Rilem Standard [72] as shown in Appendix D.1.3. The value of the ultimate bond stress calculated for each couplet can be found in Appendix D.1.4. The average stress at which the bond failed for each type of specimen tested is shown in Table 7-2.

Couplet description	Ref no.	Mortar thickness	Average bond failure stress	Standard deviation
		(mm)	(N/mm^2)	(N/mm^2)
standard full size couplet	A	15	0.208	0.030
standard full size couplet	B	12	0.183	0.036
standard full size couplet	C	8	0.159	0.025
standard full size couplet	D	4	0.166	0.034
standard full size couplet	E	2	0.140	0.031
full size couplet, top brick cut to give 1/6th scale load	F	12	0.147	0.051
full scale couplet reduced to 1/6th scale after curing	G	12	0.931	0.514
1/6th scale couplet	H	2	0.044	0.008
pre-loaded 1/6th scale couplet	I	2	0.063	0.035

Table 7-2. The average failure stress for each type of specimen

7.4. Analysis of results

The results in Table 7-2 can be used to determine the effect of the mortar thickness, the contact area between the mortar and the bricks and the load on the mortar joint during curing.

There are two pairs of specimen sets that can be compared to quantify the effect of the load during curing. Firstly, the standard full-scale couplets can be compared to the full-scale couplets with the top brick cut down to give a 1/6th scale load. Secondly the standard one-sixth scale couplets can be compared with the one-sixth scale couplets that were pre-loaded with five one-sixth scale bricks. The difference in the load during curing is the only factor that could cause a difference in the bond strength between these types of specimens. Hence the effect of the pre-load can be identified by plotting the results recorded for these specimens on the same axis, as shown in Figure 7-2 below.

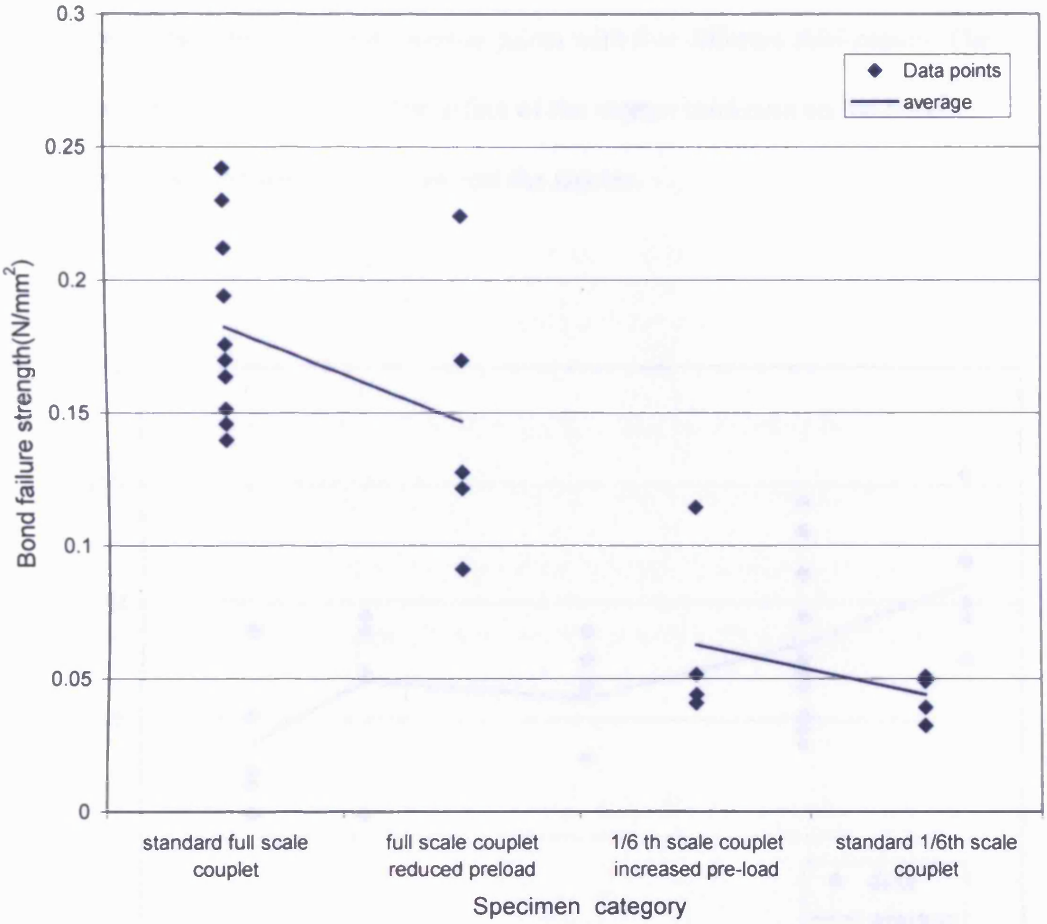


Figure 7-2. The effect of the pre-load on the bond strength developed

The lines on the graph in Figure 7-2 above show the effect of changing the pre-load stress by a factor of six for both full-scale (shown on the left) and one-sixth scale couplets. it can be seen in Figure 7-2 that a couplet cured with an additional pre-load will develop an increased bond strength. Reducing the pre-load stress on the joint in a full-scale couplet caused a 20% reduction in the average ultimate bond strength. Increasing the pre-load stress on the joint in a one-sixth scale couplet caused a 30% increase in the average ultimate bond strength.

The standard full-size couplets made for the bond wrench testing program are identical, but they were made with mortar joints with five different thicknesses. The graph shown in Figure 7-3 shows the effect of the mortar thickness on the bond strength developed between the bricks and the mortar.

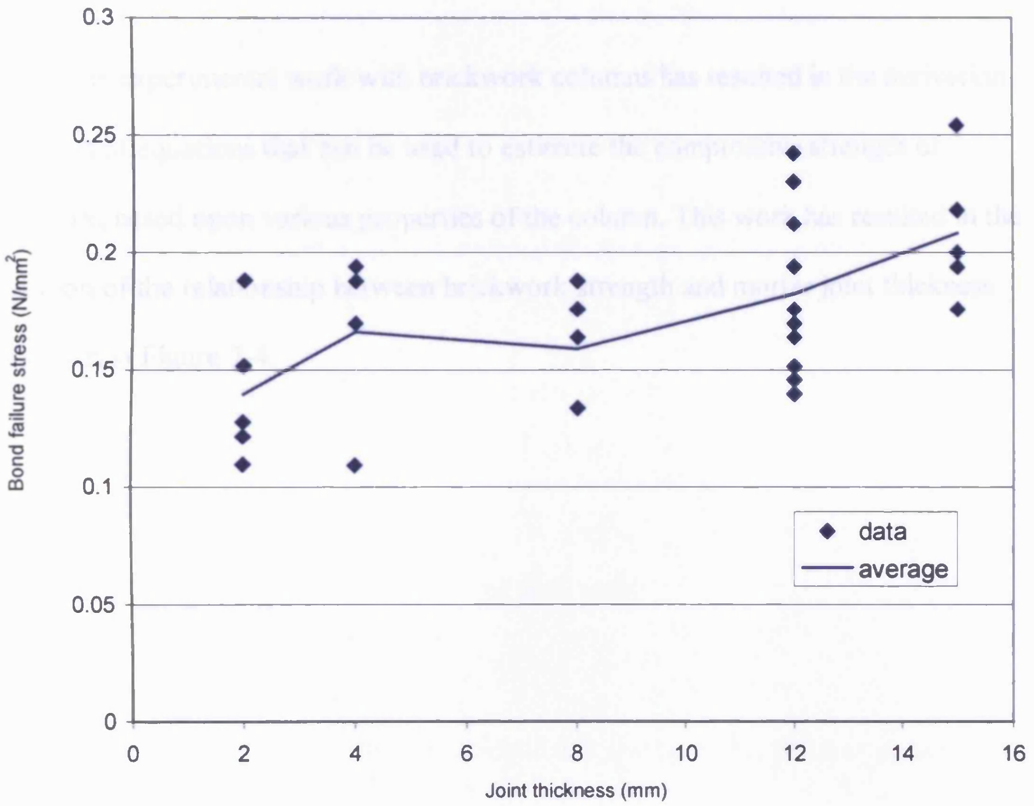


Figure 7-3. The effect of joint thickness on the bond strength developed

From the graph in Figure 7-3 above it can be seen that the overall trend is for the average bond strength to increase as the mortar joints become thicker. Previously little work has been performed on the tensile strength of brickwork. Brickwork structures are usually required to carry compressive loading and the tensile strength of typical brickwork is "relatively small and variable and consequently codes of practice discourage reliance on this property"[73]. Instead, the majority of the work performed to determine the strength of brickwork has considered brickwork columns. There is not necessarily a relationship between the tensile and compressive strength of brickwork. However, it has been shown that a brickwork couplet subjected to an axial compression will fail in tension (see Figure 3-6) and the bond strength will influence the compressive strength of brickwork that fails in this way.

The experimental work with brickwork columns has resulted in the derivation of a series of equations that can be used to estimate the compressive strength of brickwork, based upon various properties of the column. This work has resulted in the derivation of the relationship between brickwork strength and mortar joint thickness and shown in Figure 7-4.

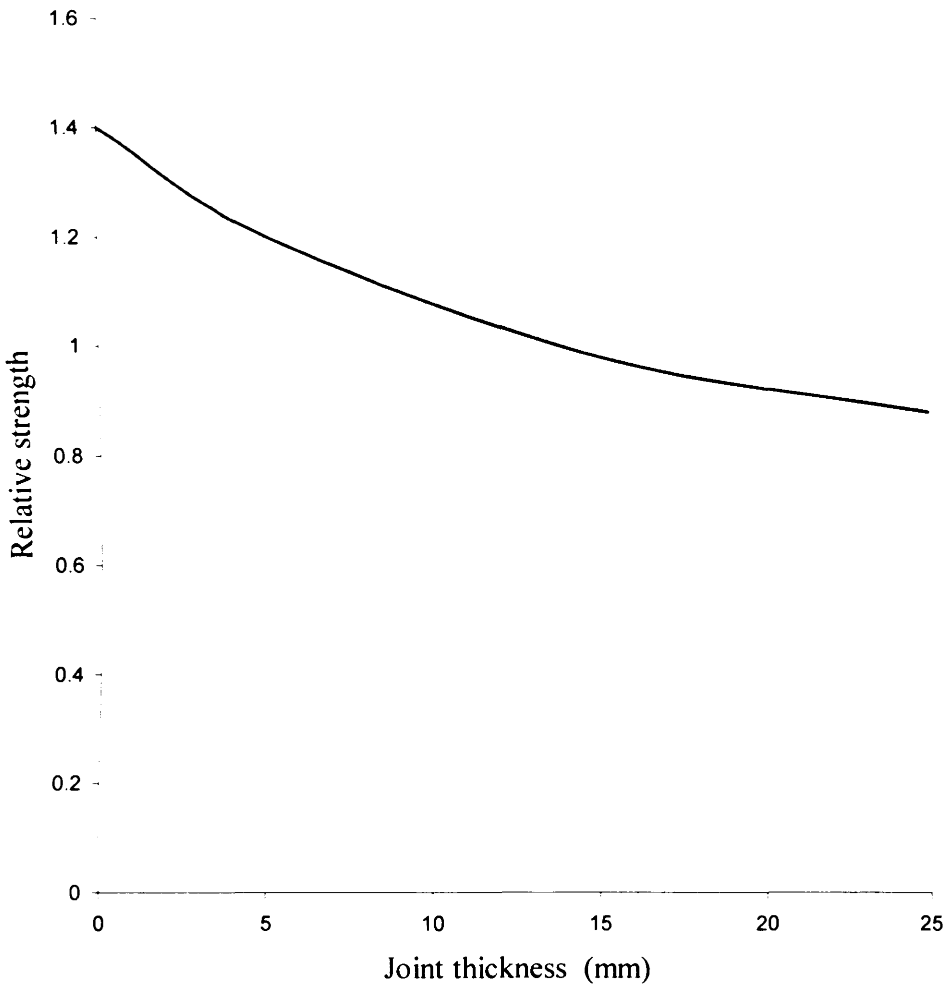


Figure 7-4. The relationship between strength and mortar joint thickness (taken from Hendry [73])

The experimental data recorded during the bond wrench testing performed for this thesis has shown that reducing the thickness of the mortar joint will reduce the tensile strength of the bond between the brick and the mortar. However, the graph shown in Figure 7-4 shows that reducing the thickness of the mortar joint will increase the overall strength of the brickwork. Hence any small increase in bond strength caused by increasing the thickness of the mortar joint would not be seen. It should be noted that graph in Figure 7-4 was derived for bricks and mortar in compression, failing by the mechanisms shown in Figure 3-6. However, during a bond wrench test there is no such failure mechanism and the couplet fails in tension. This means that the thickness of the mortar joint does not affect the magnitude of the stress placed upon the bond, allowing the increase in bond strength caused by increasing the joint thickness to be detected.

The full-scale couplets made with a mortar joint 2mm thick, and the pre-loaded one-sixth scale couplets, have the same pre-load and mortar joint thickness. Therefore the only difference between the specimens is the type of brick, allowing these specimens can be compared to quantify the effect of the brick type. This involves comparing a one-sixth scale couplet with a full-scale couplet, and so the contact area between the bricks and the mortar is different. However, the bond strength calculation allows for the size of the contact area, and so the results can still be compared. Figure 7-5 shows the results recorded for the specimens that allow the influence of the brick type to be identified.

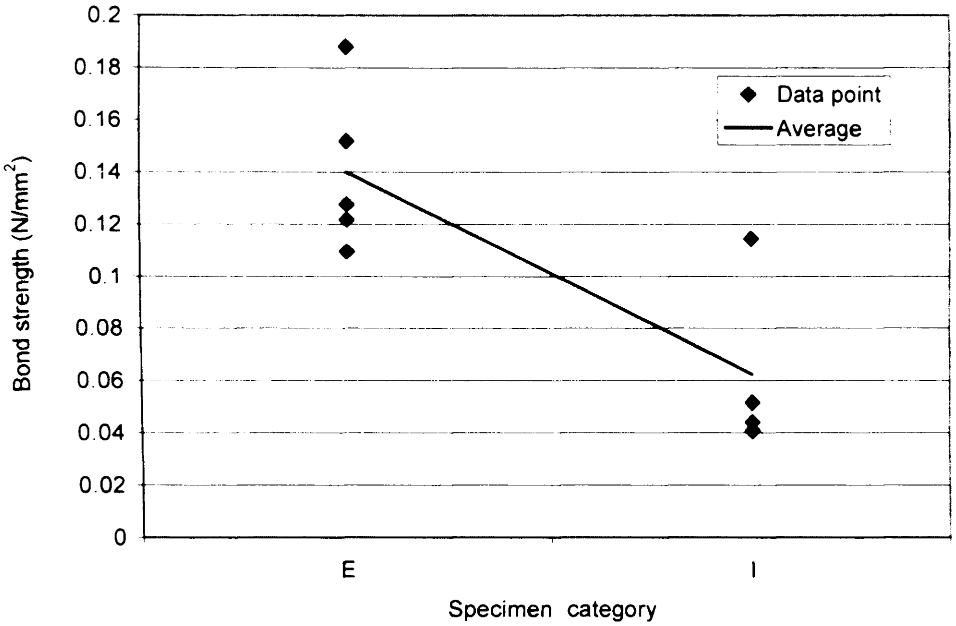


Figure 7-5. The effect of the brick type on the bond strength developed

The line on the graph in Figure 7-5 above shows the effect of the brick type on the average bond strength. It shows that couplets fabricated from full-scale bricks develop a higher bond strength than those fabricated from one-sixth scale bricks. However, the brick type changes the bricks surface and the surface area of the brick. The experiments performed cannot identify which (or both) of these factors is responsible for change in the bond strength developed.

When specimens with different pre-loads, mortar joint thicknesses and brick types were considered, the average failure stress for each type of specimen showed a clear overall trend. However, there was a large variation between the specimens made to the same specification. This makes it difficult to prove that the trend is caused by the effects of changing the joint thickness, contact area and pre-load. This problem could be overcome by increasing the number of each type of specimen.

The standard deviation shown in Table 7-2 above has a similar value for the majority of the types of specimen that were tested. However, the full scale couplets that were cut down to one-sixth scale size after curing had occurred have a standard deviation ten times greater than any of the other types of specimens. The reason for this becomes clear if the bond failure strength for each of the specimens tested is plotted on a graph, as shown in Figure 7-6 below.

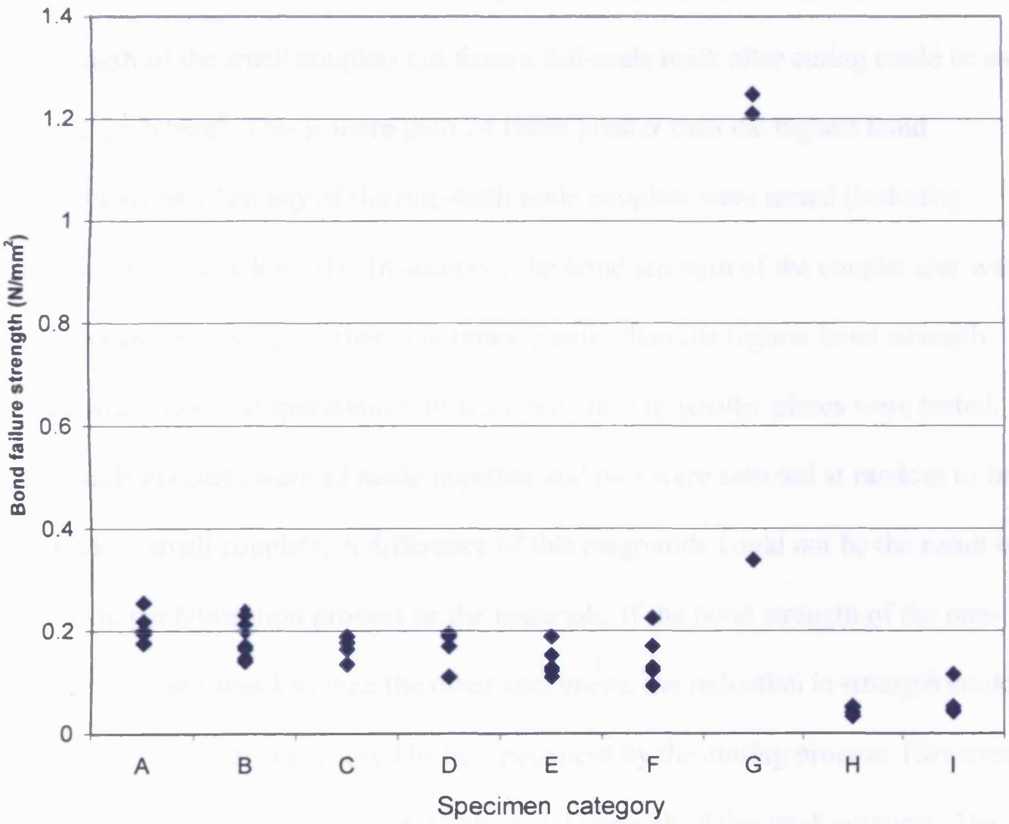


Figure 7-6. The variation in the bond strength for each type of specimen

The specimens made by cutting a full-scale couplet into one-sixth scale specimens have a bond strength greater than any of the other specimens. Only three of these specimens were made as several broke during the cutting process. One of the specimens failed at a stress only slightly higher than the stress that caused the full-scale couplets with thick mortar joints to fail. However, the other two specimens achieved a bond wrench stress more than four and a half times greater than the highest failure strength in any other type of specimen. A difference in the bond strength of this magnitude is difficult to explain given that all the specimens failed in the same manner (a sudden opening[xii] failure). Before they were cut down to one-sixth scale size the couplets used to produce the specimen G couplets were identical to the couplets made with a 100mm thick mortar joint. However, the results show that the bond strength of the small couplets cut from a full-scale brick after curing could be as much as 1.25 N/mm^2. This is more than 24 times greater than the highest bond strength recorded when any of the one-sixth scale couplets were tested (including those cured with a pre-loaded). In addition, the bond strength of the couplet that was cut into pieces was also more than five times greater than the highest bond strength recorded when identical specimens that were not cut into smaller pieces were tested. The full-scale couplets were all made together and two were selected at random to be cut down into small couplets. A difference of this magnitude could not be the result of variations in the fabrication process or the materials. If the bond strength of the one-sixth scale couplets was less than the other specimens, the reduction in strength could be explained by the damage caused to the specimens by the cutting process. However, this process could not possibly improve the bond strength of the small couplets. The calculations performed to determine the failure stress that causes a brick/mortar joint to separate when subjected to pressure waves (in the ultrasound bath or the prototype) assumes that the stress caused by the vibrations is constant throughout the contact area between the brick and the mortar. However, this need not necessarily be correct.

[xii] The opening mode of fracture is shown in Figure 3-8

The experiments performed in Chapter 4 showed that the surface of the brick influence the bond strength that can be developed between the bricks and the mortar. There will always be some variation in the surface quality of any brick. In addition, the mortar at the edges of the bricks is less restrained and able to move under the weight of the top brick. As the mortar bulges out from between the bricks it can lose contact with brick faces. Even if the mortar remains in contact with the brick the pressure between the mortar and the brick will be reduced. This will impair the bond strength around the edge of the mortar joint. Hence there will always be some variation in the bond strength across the face of an interface between the brick and the mortar the same couplet. The small couplets that remained intact during the cutting process would be those with the greatest bond strengths, and hence the calculated bond strength would be closer to the maximum than the average. However, the bond strength within a single couplet would need to vary a considerable amount to cause the difference in the bond strengths of the small couplets cut from the full scale couplets shown in Figure 7-6.

7.5. Conclusion

The principal reason for performing the bond wrench test was to determine if the failure of the prototype to separate full-scale bricks could be explained by a difference in bond strength developed in the two specimens. The bond wrench test found the following differences in the bond strength of the specimens.

- Full-scale couplets develop a bond strength approximately four and a half times stronger than that of couplets made from one-sixth scale bricks

- The bond strength of a couplet was found to increase with the thickness of the mortar joints.
- The highest bond strength recorded for a one-sixth scale size specimen cut out of a full-scale couplet after curing was 24 times greater than the highest bond strength recorded when any of the one-sixth scale couplets were tested

It is difficult to determine if these variations in bond strength could prevent the separation process from being replicated in the prototype. However, this hypothesis could be tested by fabricating one-sixth scale couplets that have the same bond strength as the full-scale couplets and attempting to separate them in the ultrasound bath.

8. Discussion

An investigation has been performed in the current work to provide information on the current levels of recycling within the UK construction industry. It was found that the majority of the waste produced is disposed of at landfill sites without any attempt being made to process any of the materials for recycling. This augments the pollution of the earth and increases the rate at which finite resources are consumed. The author believes that the current levels of recycling fall short of what could reasonably be expected. This problem cannot be addressed effectively unless new more effective recycling techniques for construction materials are developed. However, the review of literature on brick recycling performed as part of this study highlighted the lack of work that has been performed in this area.

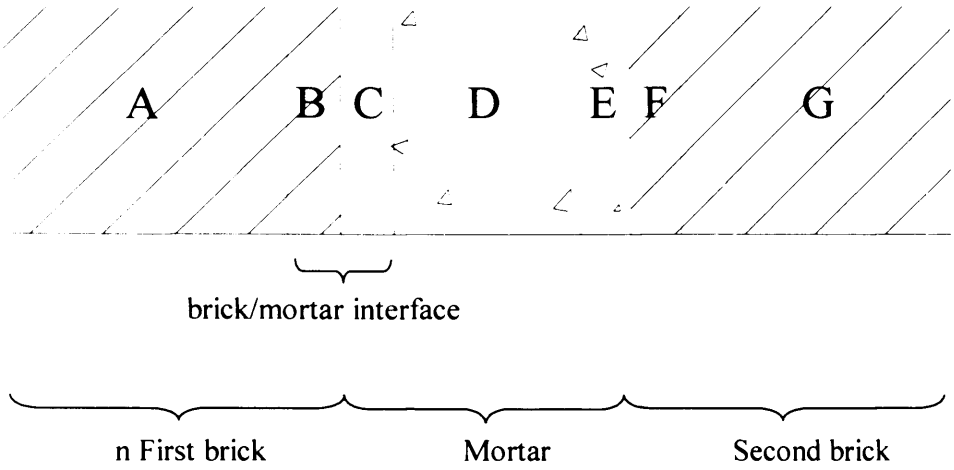
A search was made to identify any processes that could be used as a basis for the development of a new brick recycling technique. It was found that an ultrasound bath could be used to separate couplets fabricated from one-sixth scale bricks. The mortar was removed from the surfaces of the bricks, which would allow the recovered bricks to be reused without any further cleaning. The processes that occur within an ultrasound bath that could allow this separation process to be achieved were identified.

A series of investigations were performed with full size brick specimens to determine if the success achieved with the one-sixth scale specimens in the ultrasound baths could be replicated at this scale. It was proposed that this should be possible if a machine to provide vibrations with the correct amplitude and frequency could be provided.

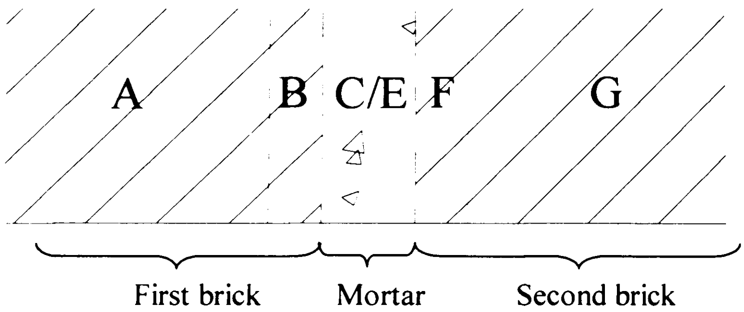
A prototype to reproduce the vibrations within the ultrasound bath at a greater scale to allow full scale bricks to be reclaimed was designed and constructed. The instrumentation attached to the specimens within the prototype showed that the prototype was causing vibrations with the desired frequency and amplitude to pass through the specimens. It was determined that the prototype was able to produce a stress of up to 0.015 N/mm^2 within the couplets.

A bond wrench test was performed to determine that strengths of the bond developed between the bricks and the mortar in one-sixth scale and full scale couplets. The results showed that the bond strength developed between the bricks and mortar of a one-sixth scale couplets was typically 4.5 times less than that developed in full scale couplets. The size of this difference was unexpected. The one-sixth scale bricks were constructed in such a way that they should be a good match for the full scale bricks. In addition, the same grade of mortar had been used, and although different sand had been used it was not expected to produce much change in the bond strength of the couplets. It was therefore suspected that there was an additional factor that was reducing the strength of the bond developed between the bricks and the mortar in the one-sixth scale couplets.

Two hypotheses are put forward to explain these results. Firstly, despite curing the couplets under a plastic sheet to retain moisture, it is possible that a lack of moisture inhibited the development of the mortar strength. This is not usually a concern when fabricating full scale couplets, because the bricks absorb water, which can than be sucked into the mortar as the hardening process occurs. However, the one-sixth scale bricks do not absorb as much water, reducing the quantity of water available. Secondly, the thin mortar joint between the one-sixth scale bricks may have been too shallow to allow the interface between the bricks and mortar to form. The interface between a brick and the adjacent mortar usually consists of separate zones, as shown in Stage I of Figure 8-1. Zone D is important because this is the area of mortar that is unaffected by the surface of the bricks. In this area, the mortar particles can interact and harden together to allow the full strength of the mortar to be achieved. However, if the couplets are fabricated with a mortar joint that is only two millimetres thick, there will not be space for the formation of these zones. The depth of the brick/mortar interface is determined by the properties of the mortar and surface qualities of the brick. Hence it will not change because the total thickness of the mortar joint has been reduced. Therefore, if the thickness of the mortar joint is very small, there will not be space for the formation of a Zone D. Instead, the entire area of mortar between the bricks becomes a single zone, where the mortar is influenced by the surface characteristics of the bricks, as shown in Stage II of Figure 8-1. Therefore the formation and hardening of the cement paste is restricted by the surface qualities of the bricks, which prevents the mortar from achieving its full strength.



Stage I – Standard mortar joint thickness



Stage II – Thin mortar joint thickness

Zone A	The part of the first brick that has not been penetrated by any mortar
Zone B	The face of the brick where mortar has penetrated and filled the voids and pores of the brick.
Zone C	The mortar directly adjacent to the face of the first brick, where the structure of the mortar is disrupted by the variations in the surface of the brick
Zone D	The area of mortar that is unaffected by the brick and can form full strength
Zone E	The mortar directly adjacent to the face of the first brick, where the structure of the mortar is disrupted by the variations in the surface of the brick
Zone F	The face of the brick where mortar has penetrated and filled the voids and pores of the brick
Zone E	The part of the second brick that has not been penetrated by any mortar

Figure 8-1. The zones formed at the interface between a brick and a mortar joint

However, the full scale couplets fabricated with a mortar joint 2mm thick (the same thickness as the one-sixth scale couplets) achieved a similar bond strength to the full scale couplets with a mortar joint 10mm thick. Therefore it is hypothesised that it is a combination of the lack of water and the thin mortar joints that causes the reduction in the bond strength developed.

The experimental work performed for this thesis did not produce data that allowed the hypothesis put forward to explain the differences in bond strength to be tested. However, experimental work could be performed to test the validity of the hypothesis. For example, the bond wrench test could be repeated with specimens that were kept in an environment with sufficiently high moisture content to ensure that the strength developed by the mortar was not inhibited by a lack of moisture. If the bond strengths determined in this new experimental work replicated the bonds strengths recorded in this thesis it would establish that the difference in bond strength was caused by additional factors that were not identified in this thesis. However, in order to fully verify the effects of the zones shown in Figure 8-1 it would be necessary to quantify the moisture levels and the rates of hydration of the cement at a series of points within each zone. This data would be difficult to achieve, especially for the smaller couplets, where the mortar joint is only 2mm thick. A series of samples would need to be taken from a couplet to allow the moisture content and rate at which the cement is developing strength to be determined. The author of this thesis believes that this could only be achieved by complex chemical analysis at a molecular level. The moisture content testing would be able to determine the presence of any zones within the brick mortar interface. The hypothesis suggested above would be validated if the chemical analysis showed that the development of mortar strength was inhibited in the zones where there was a lack of moisture.

The natural frequency of a full scale couplet was estimated to be 5779 cycles per second (see Appendix F) using the theory presented in Section 3.7. This corresponds with the results in Figure 6-9 that show that the full scale couplets vibrate in a different mode when the excitation frequency is in the region of 5.5 kHz. Together these results lead to the conclusion that the couplet had a natural frequency in the region of 5.5 kHz, and that the theory presented provides reasonable quantitative results that are in agreement with the results determined experimentally.

Under constant amplitude steady state vibrations (shown in Figure 6-9) the input energy is equal to the energy dissipated by damping, making it difficult to evaluate the energy supplied to the specimen. Therefore it was necessary to use the instrumentation attached to the specimens to determine the stress produced within the specimens to allow the results from the testing with the prototype to be compared with other experimental work quantitatively.

In order to explain why the full scale couplets did not separate in the prototype the stress developed in the specimens can be compared with the results from the bond wrench test. From the results of the bond wrench testing (see Table 7-2 and Figure 7-6) it can be seen that the stress required to separate a full scale couplet is approximately 0.2 N/mm^2. However, a stronger bond is formed at the centre of a couplet, and the stress required to separate the interface at the centre of the couplet is approximately 1.2 N/mm^2. The maximum stress induced within the couplets in the prototype was calculated to be 0.015 N/mm^2. The stress produced in a specimen in the prototype is therefore less than 10% of the bond strength developed at the edge of a couplet, and only about 1% of the bond strength that can be developed within the centre of the couplet. It is likely that the stresses produced in the specimens were below the threshold stress $\Delta\sigma_L$ (see Figure 3-10) required for fatigue to occur. This means that the brick/mortar interface will not be separated by fatigue regardless of the number of load cycles applied.

The bond wrench testing showed that the one-sixth scale couplets failed at a stress of approximately 0.04 N/mm^2. The stress within the one-sixth scale couplets could not be determined as they were too small for the necessary instrumentation to be attached. The full scale and one-sixth scale have similar material properties and hence the same wave would be expected to produce similar stresses within both types of couplet. Assuming that the same stresses were developed within both the full scale and one-sixth scale couplets, the one-sixth scale couplet would have been subjected to cyclic loading with a maximum stress equal to approximately 40% of the bond strength developed at the edge of a one-sixth scale couplet. This stress is likely to be well above the threshold stress $\Delta\sigma_L$ and hence the one-sixth scale couplets fail by fatigue in the prototype. This explains why the one-sixth scale couplets separated in the U.P.C. ultrasound bath and the prototype, but the full scale couplets remained intact.

If the prototype had achieved separation of the full scale couplets it would have been necessary to extend the testing program to consider couplets fabricated with different types of bricks and mortars. There is a large number of variables that could be investigated, such as the effect of frogs and voids, the effect of mortar thickness, and the ability of the prototype to separate several couplet or a chunk of brickwork at once etc. In addition, further work would be needed to investigate any improvements that could be made to the prototype to make it more efficient. This would allow the full potential of the prototype to be realised. However, since it has been determined that the prototype is unable to separate full scale bricks, these further investigations were not performed.

9. Conclusions

When the state of the current brick recycling industry in the UK was investigated, it was found that less than ten percent of bricks that were suitable for re-use were being reclaimed. The figures available indicated that in excess of one thousand million bricks were being disposed of at landfills annually. The literature review showed that little technical work was being performed in this area and highlighted the need for new brick reclamation technology to be developed.

It had previously been discovered that a standard commercial ultrasound bath could be used to separate and clean one-sixth scale brickwork couplets. Calculations were performed which indicated that the optimum frequency for separating full scale couplets would be between 3 and 5 kHz. A prototype designed to separate full scale bricks and mortar was constructed and operated successfully. However, no signs of separation occurring were observed when the prototype was used to try and separate full scale couplets.

There were several factors that could be preventing the prototype from separating full scale bricks. The results of a bond wrench test showed that the joints in the one-sixth scale couplets were weaker than the bond strength found between the bricks and mortar in full scale couplets. The stresses that were expected to achieve separation of full scale couplets were estimated based on the results of the initial studies. Hence it is likely that the stresses required to separate full scale brick couplets were underestimated. The maximum stress produced in the specimens in the prototype was found to be less than 10% of the failure stress calculated from the bond wrench test data. Therefore it is likely that the fatigue limit stress was not achieved, preventing the full scale specimens from failing due to fatigue, regardless of the number of load cycles applied.

The failure of the prototype to separate even couplets with a reduced mortar area means that it is very unlikely that any other machine designed on a similar concept would be successful. Therefore it must be concluded that additional systems designed along the same principals would also prove to be unsuccessful. Hence it was decided not to continue with further development of the technology.

The author remains confident of the potential economic and environmental benefits that could be achieved by implementing a successful brick recycling technology into the UK construction industry.

9.1. The potential for further work

The one-sixth scale couplets were too small to allow the movements that allowed them to be separated to be determined. Smaller instrumentation could be attached to one-sixth scale specimens to allow data to be recorded during separation. Alternatively, experiments could be performed with half-scale couplets, which are large enough to allow the instrumentation used for the current work to be attached to them. New data from this further work would provide further information on the processes that cause the separation of one-sixth scale couplets to be achieved within an ultrasound bath. This information would aid the design of any further attempts to build machinery to separate full scale couplets.

Further work could be performed to investigate the out of phase vibration that was recorded in the full scale couplets when the prototype was operating at frequencies of 5 kHz and above. This mode of vibration is important because it represents the best chances of achieving separation. The transition between the two modes of vibration could be investigated to determine if the change occurs at a specific frequency or over a range of frequencies.

The bond wrench test could be performed on additional specimens to identify the factors that prevent full scale couplets from separating in the prototype with greater precision. It may be possible to fit a bond wrench test specimen with instrumentation to record the stresses occurring at sampling points along the joint interface. This would enable the exact failure mode that occurs when the bond breaks to be determined. In addition, this would allow the variation in the bond strength throughout the contact area between the brick and the mortar joint to be quantified.

The bond wrench test showed that the bond strength developed between the bricks and the mortar of the one-sixth scale couplets was typically 4.5 times weaker than that of the full scale couplets. Two factors that may account for this have been suggested in the discussion of this thesis, and experimental work could be performed to validate these hypotheses.

The experiments performed as part of this project have shown that the prototype is unable to achieve effective separation of full scale brick couplets. However, it may be possible to perform improvements or modifications to allow some success to be achieved. An investigation into properties such as the type of fluid within the bath could identify conditions that will increase the chances of achieving success. The process achieved within the prototype could be combined with additional process or processes to allow separation of full scale brick couplets to be achieved. For example the specimen could be subjected to fluctuations in temperature during the separation process. The prototype could also be used for other similar applications. For example, the prototype may be suitable for reclaiming smooth materials that are joined together with mortar, such as tiles.

The prototype developed as part of this study was unable to separate full scale brick couplets. Hence this study has not produced any developments that can be used to improve the current recycling practises. However, there are many more processes that could be developed into new brick recycling technologies. The author believes that further research into these areas should be performed.

References

1 Durham County Council Information Service [web page]
http://www.balvac.co.uk/experience/projects/causey_arch.html
accessed on (30.09.2003)

2 UK Government Environmental and Heritage Service [web page]
http://www.ehsni.gov.uk/built/legeslation/lerislation.shtml.
accessed on (31.03.2005)

3 PLINY
Cited by
BRODRIBB, G. (1987). *Roman brick and tile.* Alan Sutton. Gloucester.

4 DOBSON, C.G. (1960) *Some historical notes on the Langley museum of ancient, curios or otherwise interesting roofing materials and on the development of the pitched roof from early times.* Langley. London.

5 BRODRIBB, G. (1987). *Roman brick and tile.* Alan Sutton. Gloucester.

6 BS 5390:1976. Code of practise for stone masonry.

7 HENDRY, A.W, SINHA, B.P. and DAVIES, S.R. (1987). *Loadbearing brickwork design.* Second edition. John Wiley & Sons.

8 N.G. BOON SENG. (1998). *Recycling of brickwork.* M.Sc. Thesis. University of Wales, Cardiff.

9 BS EN 771-1:2003. Specification for masonry units - Part 1: Clay masonry units

10 BS EN 771-2:2003. Specification for masonry units - Part 2: Calcium silicate masonry units

11 BS EN 771-6 :2001. Specification for masonry units. Natural stone masonry units.

12 BS 4551- 2 :1998 Methods of testing mortars, screeds and plasters. Physical testing.

13 BS EN 998-2:2003. Specification for mortar for masonry. Mortar masonry.

14 BS 1199 and1200:1976, Specifications for Building sands from natural sources

15 ARUP. (1991).
Cited by
Managing demolition and construction wastes
London, HMSO, 1994

16 BigREc [web page]
http://old.salvoweb.com/articles/bigrec.html
accessed on 17.02.04

17 Salvo Website [web page]
http://www.salvo.co.UK/
accessed on 17.02.04

18 Smartwaste Website [web page]
http://www.smartwaste.co.UK/
accessed on 17.02.04

19 BREMAP [web page]
http://www.bremap.co.UK/bremap/search.jsp
accessed on 24.02.04

20 OKLETEY AKORNOR. (2000). *An investigation of the material properties of recycled bricks*. M. Sc thesis. University of Wales, Cardiff

21 FERGUSON, J., KERMODE, N., NASH, C.L. SKETCH, W.A.J. and HUXFORD, R.P. (1995). *Managing and minimising construction waste – a practical guide* Institution of Civil Engineers, Thomas Telford, London

22 Council directive 1999/31/EC of 26 April 1999 on the landfill of waste (1999). *Official journal of the European Communities*
[accessed via the EU website]
http://europa.eu.int/eurlex/pri/en/oj/dat/1999/l_182/l_18219990716en00010019.pdf
accessed on 17.02.04

23 THE DEPARTMENT OF THE ENVIRONMENT (1992) *This common inheritance*. HMSO, London

24 THE DEPARTMENT OF THE ENVIRONMENT. (1994). *Sustainable development: the UK strategy*. HMSO, London.

25 THE DEPARTMENT OF THE ENVIRONMENT. (1995). *Making waste work*, HMSO, London.

26 The waste strategy 2000 for England and Wales (Part 1&2), Section 5.97
[accessed via the Defra website]
http://www.defra.gov.UK/environment/waste/strategy/cm4693/12.htm#9
accessed on 17.02.04

27 ANDERS KLANG, PER-ÅKE VIKMAN and HELGE BRATTEBØ. (2002) Sustainable management of demolition waste – an integrated model for the evaluation of environmental, economic and social aspects, *Resources, Conservation and Recycling*, Volume 38, Issue 4, July 2003, Pages 317 –334

28 GNANADOSS, P.C. (2003) *Masonry separation with ultrasound*, M.Sc thesis, University of Wales, Cardiff

29 STRAVORAVDIS SPYRIDON. (2002). Masonry separation with ultrasound, M.Sc thesis, University of Wales, Cardiff

30 CZERNIN, W. *Cement chemistry and physics for civil engineers.*(1980) Georg Godwin Ltd. London.

31 LEA, F.M. *The chemistry of cement and concrete.* (1970) Third edition. Edward Arnold Ltd.

31 NEVILLE, A.M. *Properties of Concrete* (1981) Third Edition. Pitman Publishing Limited, London.

33 LENCZNER, D. *Elements of load bearing brickwork.* (1972). Pergamon, Oxford

34 HILSDORF, H.K. (1969). An investigation into the failure mechanics of brick masonry loaded in axial compression. *Designing engineering and constructing with masonry products,* ed. F.B. JOHNSON. Gulf, Houston, Texas. 34-41

35 FRANCIS, A.J, HORMAN, C.B. and JEREMS, L.E. (1972). The effect of joint thickness and other factors on the compressive strength of brickwork. *Proceedings of the second international brick masonry conference* Stoke On Trent

36 BROEK, D. (1989). *The practical use of fracture mechanics.* Kluwer academic publishers, London.

37 SMITH, R.N.L. (1991). Basic fracture mechanics. Butterworth-Heineman Ltd.

38 OWENS, D.R.J. and FAWKES A.J. (1983). *Engineering fracture mechanics.* Pineridge press ltd, Swansea.

39 GRIFFITH, A. A. (1924). *Proceedings of the 1st International congress for applied mechanics.* Delft. 55

40 OROWAN, E. (1955). Energy criteria of fracture *Weld Journal. Res. Supplemental.* **20**.

41 IRWIN, G.R. (1957). Analysis of stresses and strains near the end of a crack transversing a plate. *Trans. A.S.M.E. Journal of applied mechanics.*

42 CHALANT, G. and RÉMY, L. (1982).*Plastic strain distribution at the tip of a fatigue crack. application to fatigue crack closure in the threshold regime.* Engineering Fracture Mechanics Volume 16, Issue 5, 707-720

43 CORTIE, M. B. and GARRETT, G. G. (1988). *On the correlation between the C and m in the paris equation for fatigue crack propagation* Engineering Fracture Mechanics Volume 30, Issue 1, 49-58

44 BS EN 1993-1-9:2005. Eurocode 3: Design of steel structures Part 1-9: Fatigue

45 ROBERTS, T.M. HUGHES, T.G. DANDAMUDI, V.R. and BELL B. (2005). *Quasi-static and high cycle fatigue strength of brick masonry* Construction and Building Materials xxx (2005) xxx–xxx

46 CRAWFORD, A.E. (1955). *Ultrasonic Engineering: with specific reference to high power applications.* Butterworths scientific. London.

47 CRACKNELL, A.P. (1980). *Ultrasonics.* Wykeham Publications ltd. London

48 BLITZ, J. (1967). *Fundamentals of Ultrasonics.* Butterworths & Co Ltd. London

49 MORI, E. and ITOH, K. (1973). Measurements and applications of normal modes of vibration in a rectangular bath. *Ultrasonics International conference proceedings.* Imperial College, London. Pages 20 to 23.

50 KLASEBOER, E and CHEONG KHOO, B. (2005). *A modified Rayleigh–Plesset model for a non-spherically symmetric oscillating bubble with applications to boundary integral methods.* Engineering Analysis with Boundary Elements. xxx1-13

51 LAUTERBORN, W. and OHL, C.-D. (1997). *Cavitation bubble dynamics.* Ultrasonics Sonochemistry 4 65-75

52 LIANG, Z. ZHOU, G. LIN, S. ZHANG, Y. and YANG, H. (2005) *Study of low-frequency ultrasonic cavitation fields based on spectral analysis techniques.* Ultrasonics xxx (2005) xxx

53 LAUTERBORN, W. and OHL C.D. (1998). *The peculiar dynamics of cavitation bubbles.* Appl. Sci. Res. 58 63–76.

54 Cited by
MORSE, P.M. (1984). Vibration and sound. 2nd Ed. McGraw-Hill. New York.

55 RIERA, E. GALLEGO-JUÁREZ, J.A. AND MASON T.J. (2006). *Airborne ultrasound for the precipitation of smokes and powders and the destruction of foams.* Ultrasonics Sonochemistry. Volume 13, Issue 2, Pages 107-116

56 GEDANKEN, A. (2004). *Using sonochemistry for the fabrication of nanomaterials.* Ultrasonics Sonochemistry, Volume 11, Issue 2, 47-55.

57 FAHY, F. (1985). *Sound and structural vibration.* Academic. London.

58 GRAFF, K.F. (1975). *Wave motion in elastic solids.* Clarendon Press. Oxford.

59 KELLY, S.G. (1993). *Fundamentals of mechanical vibrations.* McGraw-Hill. New York.

60 KAGAWA, Y. TSUCHIYA, T. FUJII, B. and FUJIOKA, K. (1998) D*iscrete huygens' model approach to sound wave propagation.* Journal of Sound and Vibration 218(3) 419-444

61 CYWIAK, M. SERVIN, M. and SANTOYO, F. (2001). *Wave-front propagation by Gaussian superposition method.* Optics Communications 195 351-359

62 MASON, T.J. (2000) Large scale sonochemical processing: aspiration and actuality. *Ultrasonics Sonochemistry.* 145-149

63 BS 12:1991. Specification for ordinary and rapid hardening Portland Cement

64 BS 890:1995. Specification for building limes

65 TAUNTON, P. (1997). *Centrifuge modelling of soil/masonry structure interaction.* PhD Thesis, University of Wales, Cardiff.

66 BARALOS, P. (2002) *The small-scale modelling of repair techniques for masonry arch bridges using a geotechnical centrifuge.* PhD Thesis, University of Wales, Cardiff.

67 BURROUGHS, P. (2002). *A study of parameters that influence the strength of masonry arch bridges using a geotecnical centrifuge.* PhD Thesis, University of Wales, Cardiff.

68 NYQUIST, H. (1932) Bell System Tech J 11 p126.

69 BS 1199 and 1200:1976, Specifications for Building sands from natural sources

70 J-L. LABORDE, C. BOUYER, J.-P. CALTAGIRONE and A. GERARD, (1998) *Acoustic bubble cavitation at low frequencies,* J. Ultrasonics 36 589-594

71 BS 6344:1:1989 Industrial hearing protectors. Specification for ear muffs

72 INTERNATIONAL UNION OF TESTING AND RESEARCH FOR MATERIALS AND CONSTRUCTION. (1994). LUMB3 Bond strength of masonry using the bond wrench method. *Rilem - Technical recommendations for the testing and use of construction materials.* E and FN Spon. London

73 ARNOLD W HENDRY.(1981). *Structural Brickwork* The Macmillan press ltd. London.

74 BRICK DEVELOPMENT ASSOCIATION. (2004). *Sustainability strategy for the brick industry*
[accessed via BDA website]
http://www.brick.org.uk/private/PDFs/KPI_update.pdf

75 ENVIRONMENTAL PROTECTION AGENCY. (2000). *Carbon Dioxide Emissions from the Generation of Electric Power in the United States,* DEPARTMENT OF ENERGY, Washington D.C.
[accessed via DOE website]
http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2emiss.pdf

Appendix A

A 1 - Experimental data from initial studies

A 1.1 Mortar cube strengths for couplets used in the initial studies

	Ultimate Compressive Strength (N/mm^2)		
Mortar grade	1	3	5
Cube 1	13.25	6.01	1.55
Cube 2	11.99	6.16	1.48
Cube 3	12.39	6.84	1.33

A 1.2 Separation times for couplets used in the initial studies

	Thickness (mm)	Stage 1 separation (seconds)			Stage 2 separation (seconds)		
		couplet 1	couplet 2	couplet 3	couplet 1	couplet 2	couplet 3
Grade 1	2	27	18	46	132	33	72
	5	31	14	28	43	47	39
	10	65	47	86	68	53	143
Grade 3	2	25	23	32	387	42	340
	5	78	18	39	163	236	123
	10	29	46	49	302	128	541
Grade 5	2	25	23	22	50	58	38
	5	8	9	30	90	35	140
	10	19	31	19	50	198	73

A 1.3 Mortar cube strengths for couplets used in the additional initial studies

	Ultimate Compressive Strength (N/mm^2)	
Mortar grade	1	5
Cube 1	10.99	0.94
Cube 2	11.36	1.11
Cube 3	9.81	0.99

A 1.4 Separation times for couplets used in the additional initial studies

	Joint type, brick type	Time for stage 1 separation (seconds)				
		couplet 1	couplet 2	couplet 3	couplet 4	couplet 5
Grade 1	messy, rough	900	900	900	634	900
	messy, smooth	900	360	500	702	900
	clean, rough	900	100	126	56	11
	clean, smooth	43	16	35	22	18
Grade 5	messy, rough	26	29	29	200	306
	messy, smooth	18	60	46	37	53
	clean, rough	13	25	22	21	28
	clean, smooth	20	7	16	11	8
		Time for stage 2 separation (seconds)				
		couplet 1	couplet 2	couplet 3	couplet 4	couplet 5
Grade 1	messy, rough	900	900	900	900	900
	messy, smooth	900	900	900	900	900
	clean, rough	900	900	185	900	150
	clean, smooth	129	54	51	57	66
Grade 5	messy, rough	435	220	175	370	716
	messy, smooth	96	174	148	111	155
	clean, rough	21	48	29	30	34
	clean, smooth	34	21	28	19	22

A 2 - Experimental data from "hammer" vibration testing

A 2.1 Full-scale brick

Impact number	Frequency (Hz)		
	Impact site 1	Impact site 2	Impact site 3
1	2600	3451	3255
2	2813	3142	3260
3	2629	3000	3225
4	3089	3104	3138
5	2512	3014	2702
average	2728.6	3142.2	3116

Natural frequency detected at 2995.6 Hz

Standard deviation 280.82 Hz

A 2.2 Half-scale brick

Impact number	Frequency (Hz)		
	Impact site 1	Impact site 2	Impact site 3
1	4237	4098	4052
2	4098	4068	4477
3	5000	4032	4049
4	4167	4032	4044
5	3968	3985	4062
average	4294	4043	4136.8

Natural frequency detected at 4157.93 Hz

Standard deviation 263.96 Hz

A 2.3 Full-scale brick cut in half through longest axis

Impact number	Frequency (Hz)		
	Impact site 1	Impact site 2	Impact site 3
1	1190	1077	1179
2	1179	1168	1179
3	1116	1130	1172
4	1183	1096	1168
5	1174	1078	1202
average	1168.4	1109.8	1180

Natural frequency detected at 1152.73 Hz

Standard deviation 41.83 Hz

A 2.4 Mortar cube

Accelerometer 1

Impact number	Frequency (Hz)			
	Impact site 1	Impact site 2	Impact site 3	Impact site 4
1	1709	1709	1325	1695
2	1709	1709	1333	1709
3	1724	1709	1333	1709
4	1724	1709	1325	1709
5	1709	1709	1333	1709
average	1715	1709	1330	1707

Accelerometer 2

Impact number	Frequency (Hz)			
	Impact site 1	Impact site 2	Impact site 3	Impact site 4
1	1724	1695	1739	1351
2	1739	1695	1739	1351
3	1724	1681	1754	1333
4	1709	1709	1739	1342
5	1724	1695	1724	1333
average	1724	1695	1739	1342

Average frequency recorded by accelerometer 1 is 1615 Hz

Average frequency recorded by accelerometer 2 is 1625 Hz

First natural frequency detected at 1714.92 Hz

Standard deviation 16.20 Hz

Second natural frequency detected at 1336.07 Hz

Standard deviation 9.49 Hz

A 2.5 Brick and mortar couplet

Impact on top brick

Impact number	Frequency recorded by accelerometer on top brick		
	Impact site 1t	Impact site 2t	Impact site 3t
1	1264	1448	2878
2	1304	1432	3098
3	1448	1544	2119
4	1456	1440	2451
5	1432	1360	1590

Impact on bottom brick

Impact number	Frequency recorded by accelerometer on top brick			
	Impact site 1b	Impact site 2b	Impact site 3b	Impact site 4b
1	1352	1424	4000	2835
2	1408	1416	2661	1586
3	1416	1420	3364	1362
4	1436	1430	2769	1716
5	1444	1426	2631	1753

Impact on top brick

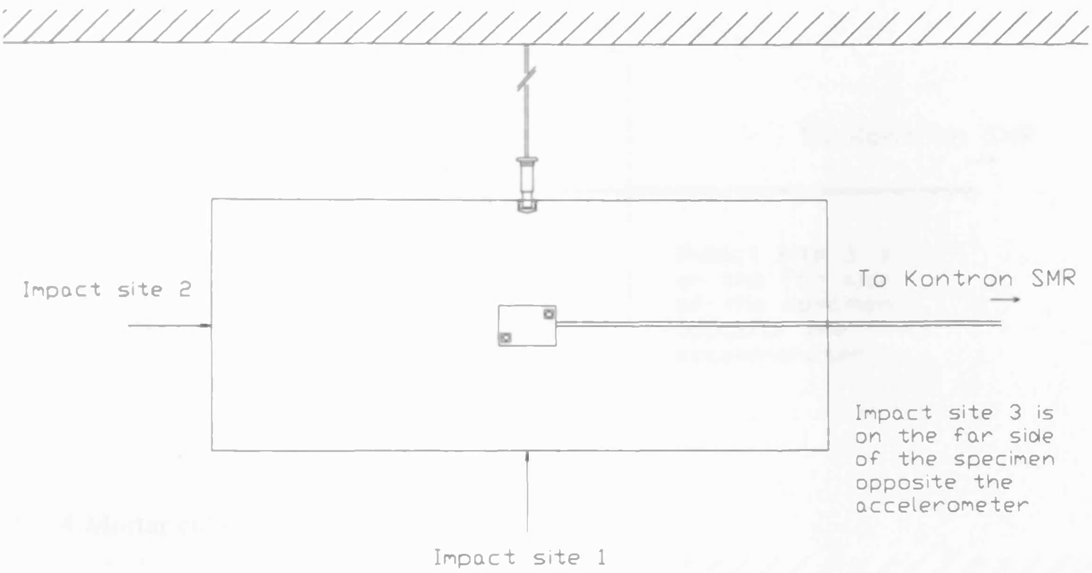
Impact number	Frequency recorded by accelerometer on bottom brick		
	Impact site 1t	Impact site 2t	Impact site 3t
1	2222	4135	3783
2	2315	3360	3814
3	3458	4747	3556
4	4251	4508	3483
5	3726	3905	3416

Impact on bottom brick

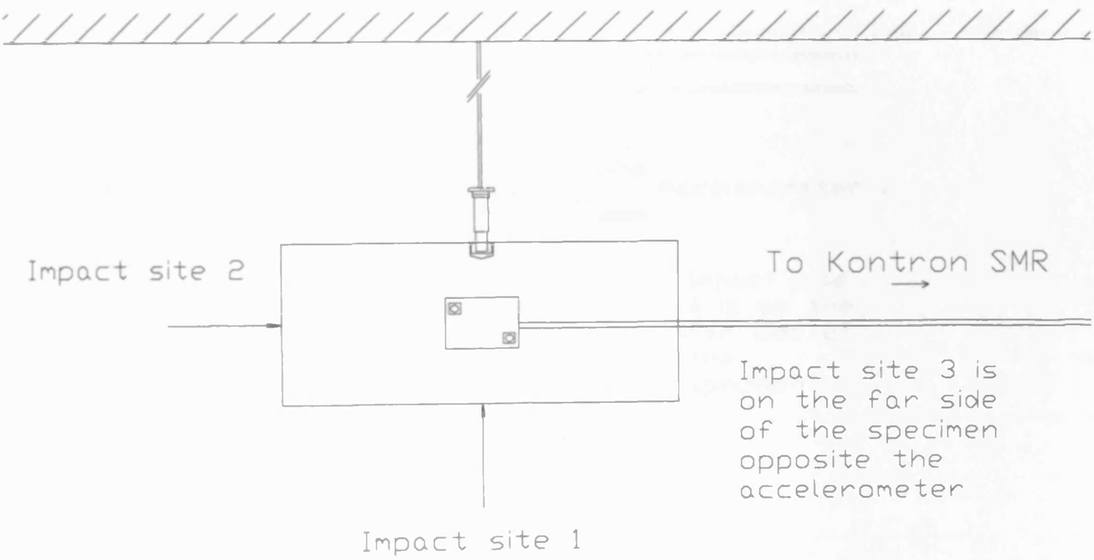
Impact number	Frequency recorded by accelerometer on bottom brick			
	Impact site 1b	Impact site 2b	Impact site 3b	Impact site 4b
1	1426	4008	3611	4618
2	3046	4083	3501	2971
3	2505	3419	3495	2000
4	3711	3857	3309	4033
5	1420	3305	2872	4583

A 3 - Diagrams to show locations of accelerometers and impacts for all specimens

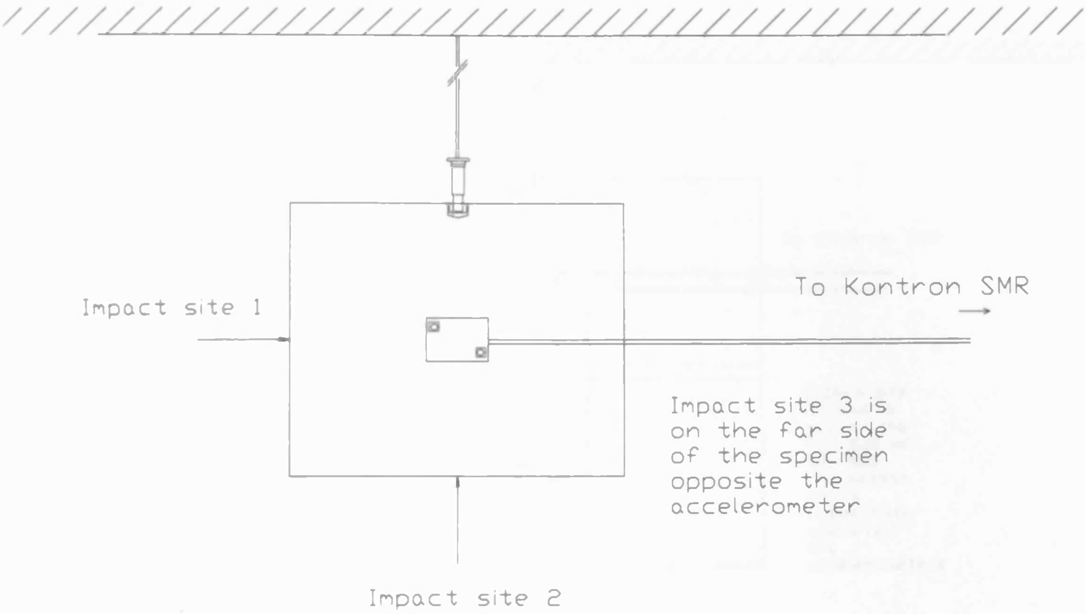
A 3.1 Full-scale brick



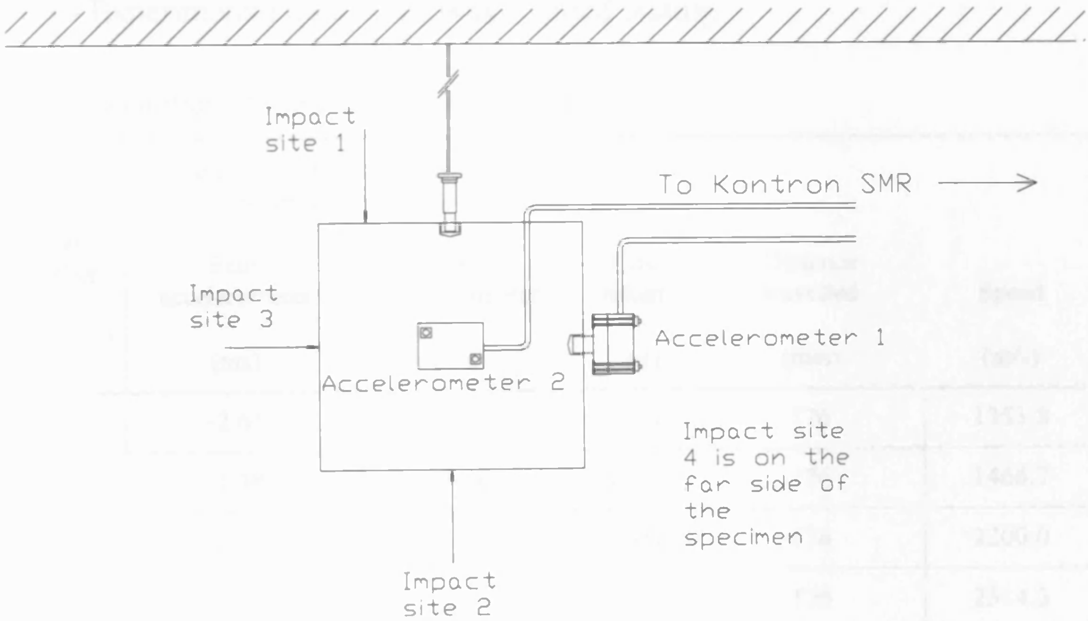
A 3.2 Half-scale brick



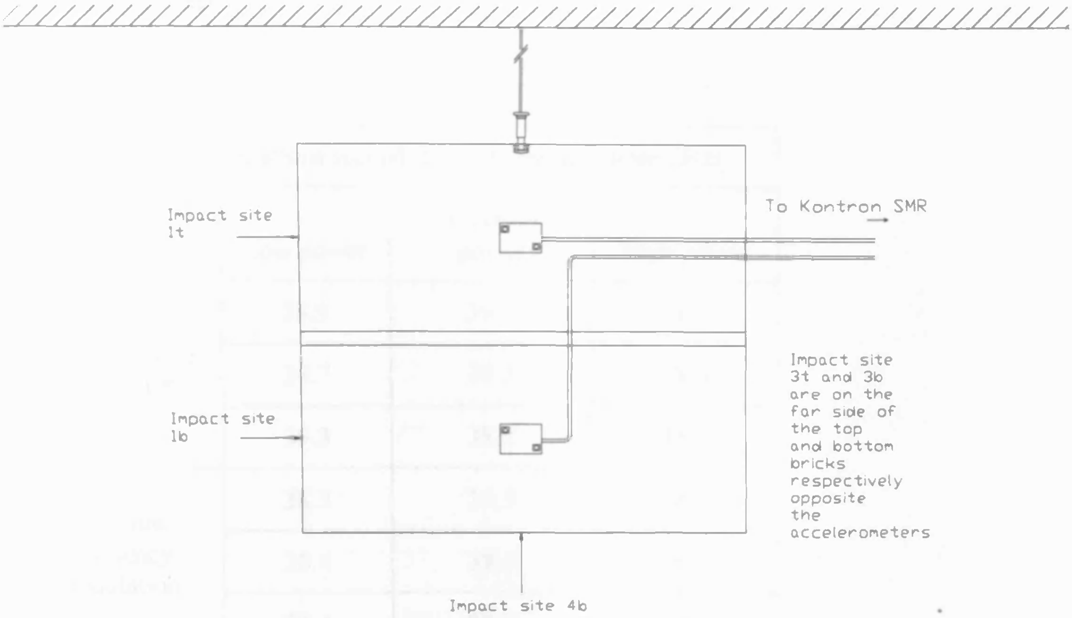
A 3.3 Full-scale brick cut in half through longest axis



A 3.4 Mortar cube



A 3.5 Brick and mortar couplet



A 4 - Experimental data from wave speed testing

A 4.1 Calculation of wave speed with in brick

Impact number	Time to register on accelerometers relative to a datum		Time taken	Distance travelled	Speed
	near accelerometer	far accelerometer			
	(ms)	(ms)	(ms)	(mm)	(m/s)
1	-2.61	-2.48	0.13	176	1353.8
2	-1.38	-1.26	0.12	176	1466.7
3	-1.4	-1.32	0.08	176	2200.0
4	-1.81	-1.74	0.07	176	2514.3
5	-1.48	-1.42	0.06	176	2933.3
6	-1.57	-1.5	0.07	176	2514.3

Average speed = 2164 m/s

A 5 - Experimental data from large scale brick testing in the U.P.C. bath ultrasound bath

A 5.1 Full-scale brick

Frequency of vibrations recorded within the specimen (Hz)			
	Low power	Medium power	High power
Low frequency modulation	38.9	39.3	38.7
	38.7	39.2	38.3
	39.3	38.8	38.7
Medium frequency modulation	38.3	38.5	38.0
	38.4	38.5	38.4
	38.4	38.2	38.1
High frequency modulation	38.7	38.8	38.0
	38.7	38.7	38.0
	39.8	38.7	38.1

A 5.2 Full-scale brick couplet

Frequency of vibrations recorded within the specimen (Hz)			
	Low power	Medium power	High power
Low frequency modulation	39.6	39.1	39.2
	39.9	39.4	39.5
	40.2	39.7	39.3
Medium frequency modulation	38.8	39.2	38.8
	38.9	38.5	39.0
	38.3	39.0	38.4
High frequency modulation	39.0	38.1	37.6
	38.8	38.1	38.6
	39.2	38.0	37.6

A 5.3 Half brick

Frequency of vibrations recorded within the specimen (Hz)			
	Low power	Medium power	High power
Low frequency modulation	39.8	39.6	40.1
	39.8	39.6	39.2
	39.7	39.4	40.2
Medium frequency modulation	39.5	39.5	39.5
	39.5	39.9	39.4
	39.6	39.3	39.5
High frequency modulation	38.5	38.9	39.4
	38.3	39.1	39.0
	38.7	38.8	39.3

A 5.4 Extract from the accelerations recorded by the accelerometer attached to the full scale brick in the U.P.C. ultrasound bath

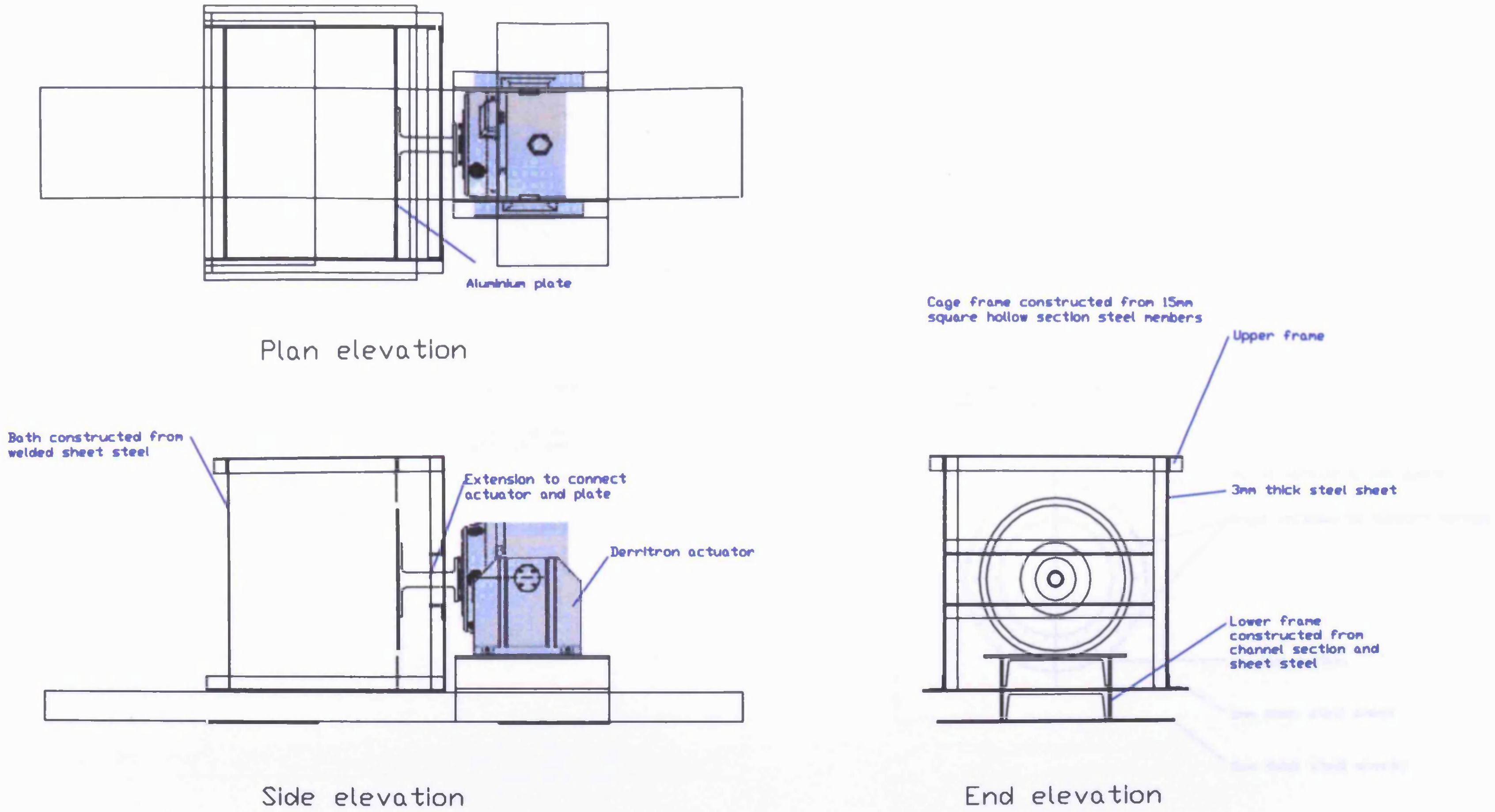
(This data is shown in full in graphical form in Figure 4-23)

	DATASET WWSMRII VERSION 1 SIGNAL IMPORT_DAT DATE 04-25-03 TIME 15:40:29.00 INTERVAL 0.0000008 HORZ_UNITS Sec VERT_UNITS Volts COMMENT Signal generated			
Reading	DATA	milli volts	Time (seconds)	g
1	0.0088	0	0.0000008	0
2	0.0096	0.8	0.0000016	0.04
3	0.0104	1.6	0.0000024	0.08
4	0.0112	2.4	0.0000032	0.12
5	0.012	3.2	0.000004	0.16
6	0.0136	4.8	0.0000048	0.24
7	0.0144	5.6	0.0000056	0.28
8	0.0144	5.6	0.0000064	0.28
9	0.0144	5.6	0.0000072	0.28
10	0.0144	5.6	0.000008	0.28
11	0.0152	6.4	0.0000088	0.32
12	0.0152	6.4	0.0000096	0.32
13	0.0144	5.6	0.0000104	0.28
14	0.0144	5.6	0.0000112	0.28
15	0.0136	4.8	0.000012	0.24
16	0.0128	4	0.0000128	0.2
17	0.0112	2.4	0.0000136	0.12
18	0.0112	2.4	0.0000144	0.12
19	0.0104	1.6	0.0000152	0.08
20	0.0096	0.8	0.000016	0.04
21	0.0088	0	0.0000168	0
22	0.0072	-1.6	0.0000176	-0.08
23	0.0072	-1.6	0.0000184	-0.08
24	0.0072	-1.6	0.0000192	-0.08
25	0.0064	-2.4	0.00002	-0.12
26	0.0072	-1.6	0.0000208	-0.08
27	0.0064	-2.4	0.0000216	-0.12
28	0.0064	-2.4	0.0000224	-0.12
29	0.0064	-2.4	0.0000232	-0.12
30	0.0072	-1.6	0.000024	-0.08
31	0.008	-0.8	0.0000248	-0.04
32	0.0088	0	0.0000256	0
33	0.0096	0.8	0.0000264	0.04
34	0.0104	1.6	0.0000272	0.08
35	0.0112	2.4	0.000028	0.12
36	0.012	3.2	0.0000288	0.16
37	0.0128	4	0.0000296	0.2

Table A 5.4 continued...

38	0.0136	4.8	0.0000304	0.24
39	0.0152	6.4	0.0000312	0.32
40	0.0152	6.4	0.000032	0.32
41	0.0152	6.4	0.0000328	0.32
42	0.016	7.2	0.0000336	0.36
43	0.016	7.2	0.0000344	0.36
44	0.016	7.2	0.0000352	0.36
45	0.0152	6.4	0.000036	0.32
46	0.016	7.2	0.0000368	0.36
47	0.0152	6.4	0.0000376	0.32
48	0.0144	5.6	0.0000384	0.28
49	0.0128	4	0.0000392	0.2
50	0.0128	4	0.00004	0.2
51	0.012	3.2	0.0000408	0.16
52	0.0112	2.4	0.0000416	0.12
53	0.0104	1.6	0.0000424	0.08
54	0.0096	0.8	0.0000432	0.04
55	0.0088	0	0.000044	0
56	0.008	-0.8	0.0000448	-0.04
57	0.0072	-1.6	0.0000456	-0.08
58	0.0072	-1.6	0.0000464	-0.08
59	0.0072	-1.6	0.0000472	-0.08
60	0.0072	-1.6	0.000048	-0.08
61	0.0072	-1.6	0.0000488	-0.08
62	0.008	-0.8	0.0000496	-0.04
63	0.0088	0	0.0000504	0
64	0.0096	0.8	0.0000512	0.04
65	0.0096	0.8	0.000052	0.04
66	0.0112	2.4	0.0000528	0.12
67	0.012	3.2	0.0000536	0.16
68	0.0128	4	0.0000544	0.2
69	0.0136	4.8	0.0000552	0.24
70	0.0144	5.6	0.000056	0.28
71	0.0152	6.4	0.0000568	0.32
72	0.0168	8	0.0000576	0.4
73	0.0168	8	0.0000584	0.4
74	0.0176	8.8	0.0000592	0.44
75	0.0184	9.6	0.00006	0.48
76	0.0176	8.8	0.0000608	0.44
77	0.0184	9.6	0.0000616	0.48
78	0.0184	9.6	0.0000624	0.48
79	0.0184	9.6	0.0000632	0.48
80	0.0168	8	0.000064	0.4
81	0.0168	8	0.0000648	0.4
82	0.016	7.2	0.0000656	0.36
83	0.016	7.2	0.0000664	0.36
84	0.0152	6.4	0.0000672	0.32
85	0.0144	5.6	0.000068	0.28
86	0.0128	4	0.0000688	0.2
87	0.0128	4	0.0000696	0.2
88	0.012	3.2	0.0000704	0.16

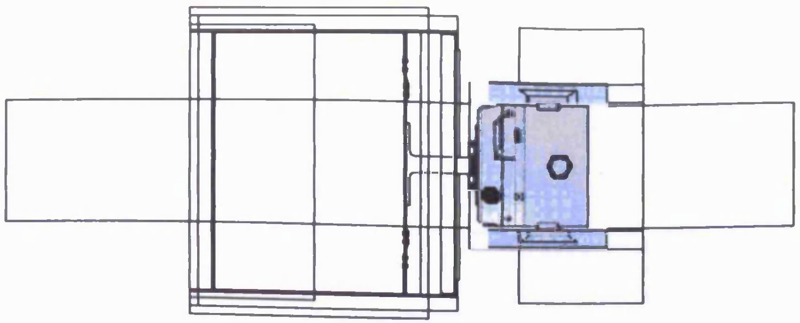
Appendix B - Drawings and photographs of the prototype



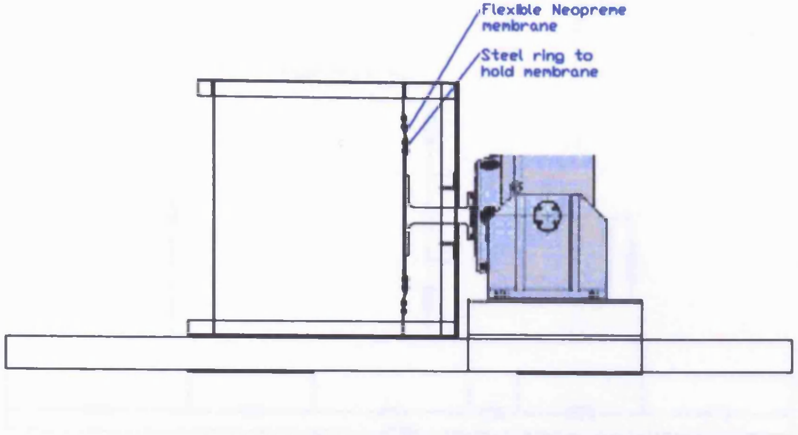
Scale in mm
0 200 400 600 800 1000

B.1.1 Annotated drawing to identify the main components of the prototype.

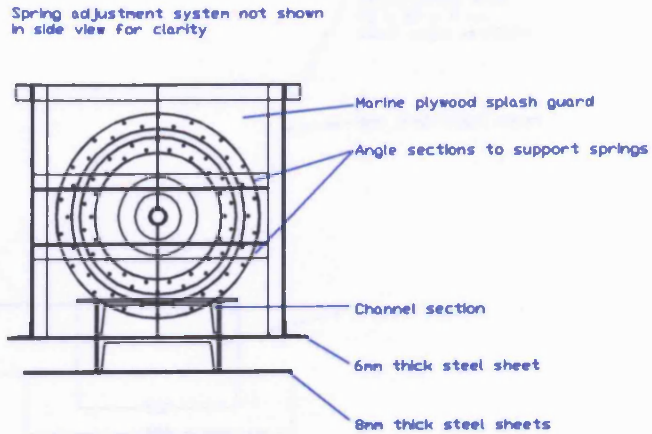
Drawn by:	Richard Gregory	Notes
Drawing number:	Appendix B.1.1	
Date:	September 2002	



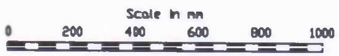
Plan elevation



Side elevation

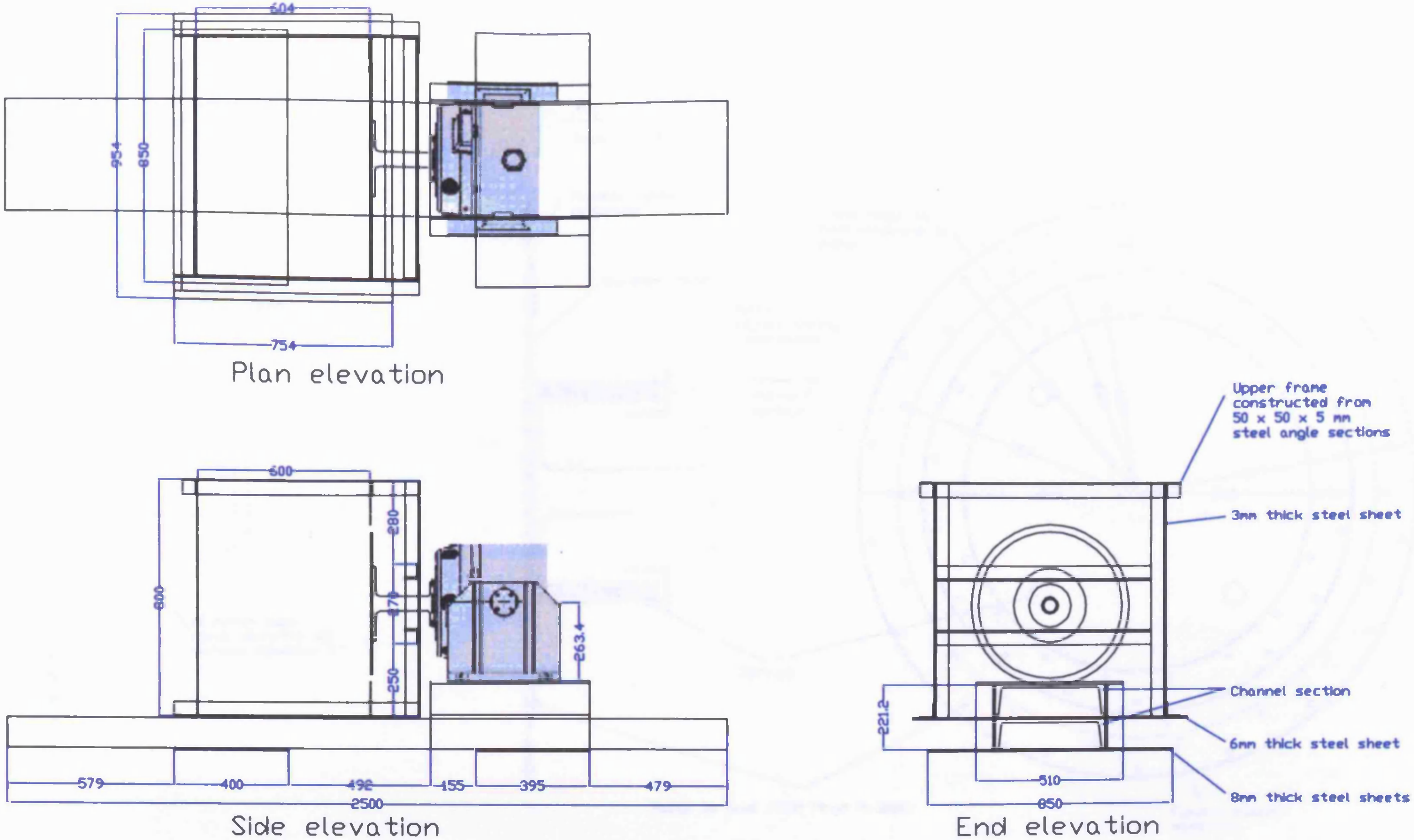


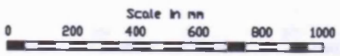
End elevation



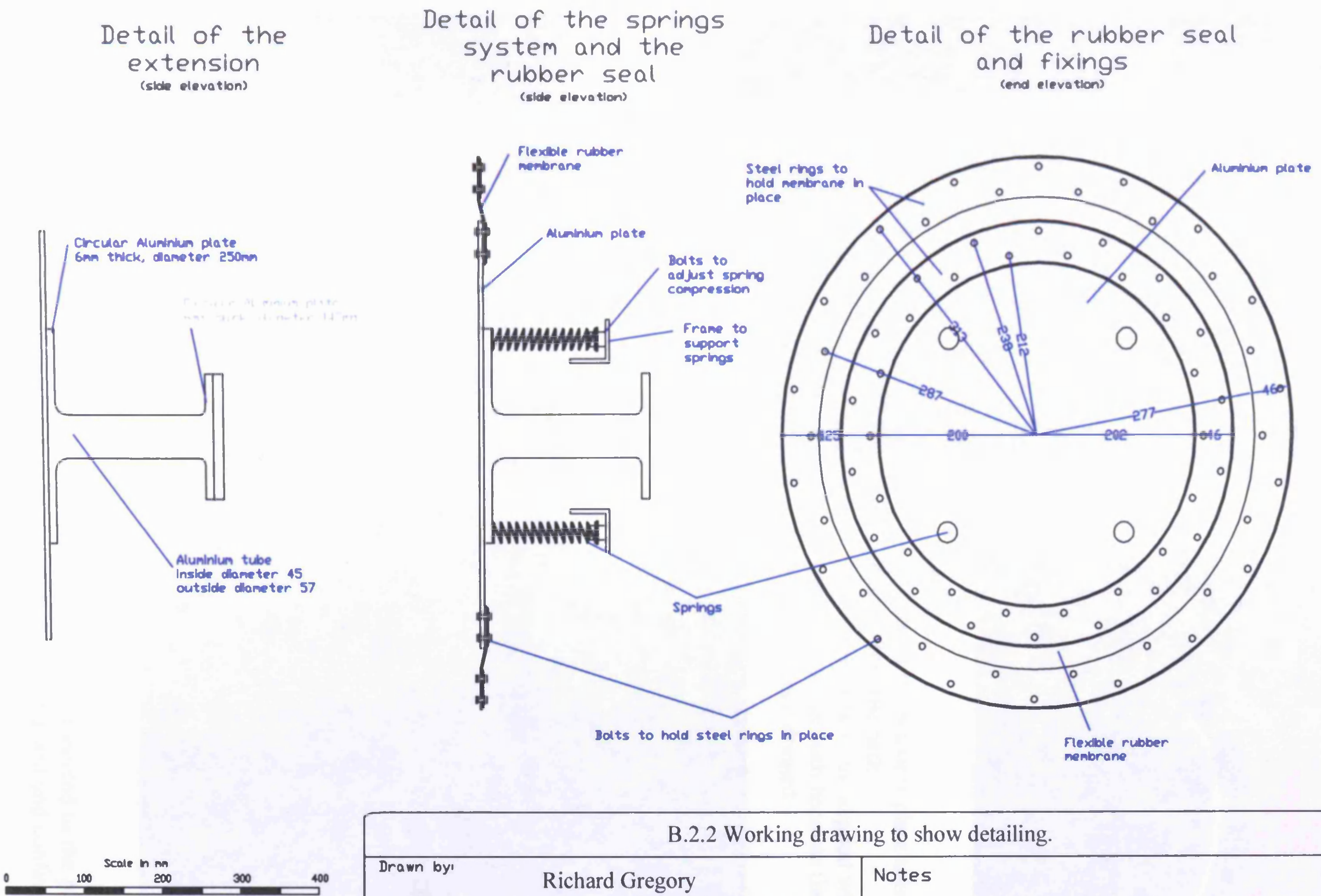
B.1.2 Annotated drawing to identify the individual elements of the prototype.

Drawn by:	Richard Gregory	Notes
Drawing number:	Appendix B.1.2	
Date:	September 2002	



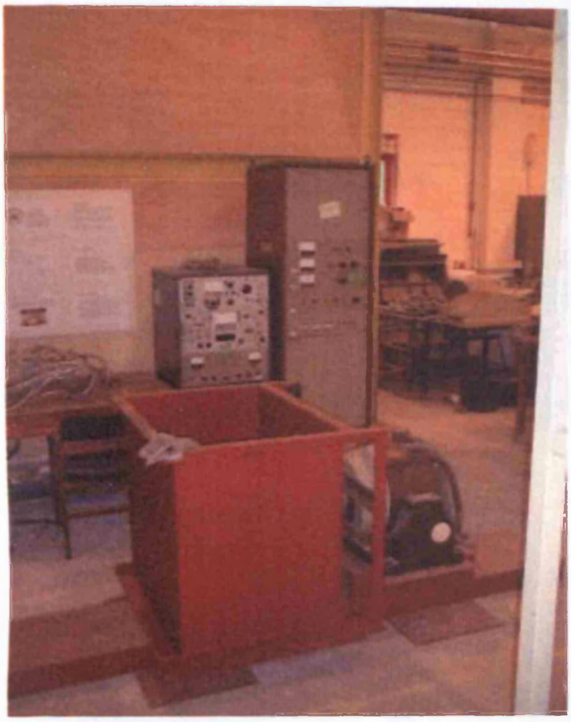


B.2.1 Working drawing to show the main components of the prototype.	
Drawn by: Richard Gregory	Notes
Drawing number: Appendix B.2.1.	
Date: September 2002	



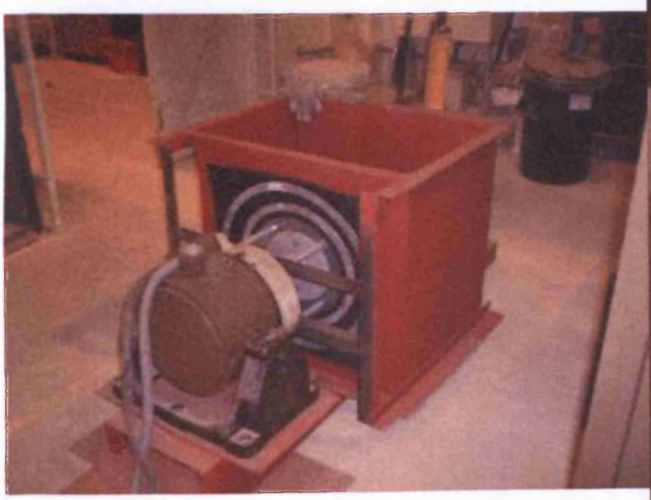
B.2.2 Working drawing to show detailing.	
Drawn by: Richard Gregory	Notes
Drawing number: Appendix B.2.2	
Date: September 2002	

B 3 - Photographs of the prototype

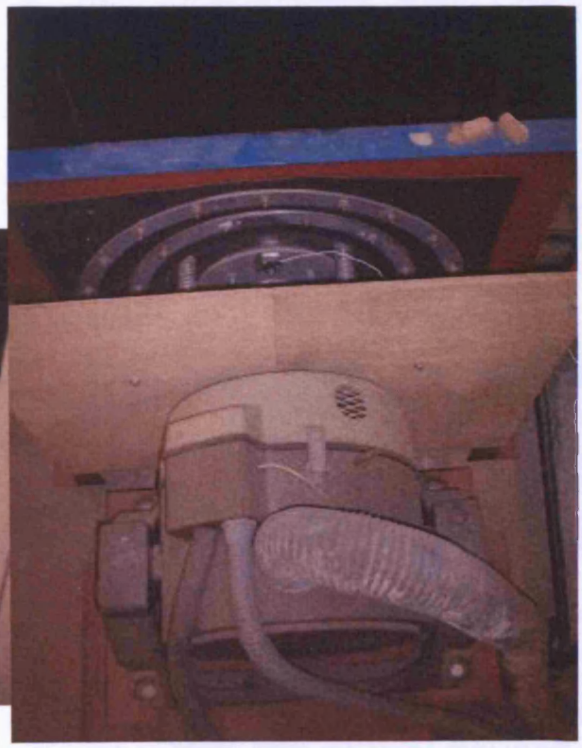


B 3.1
The prototype machine

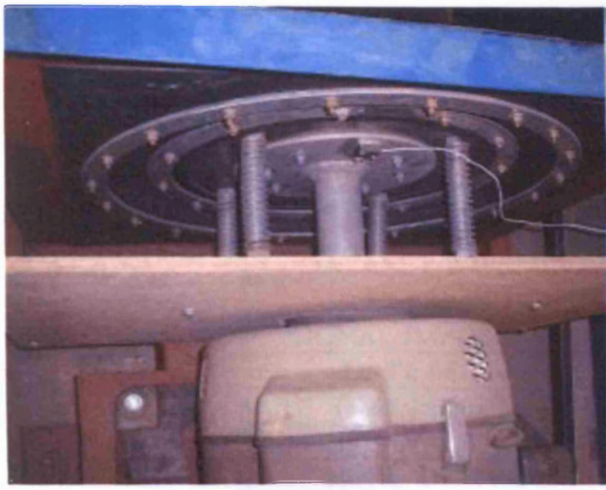
B 3.2
A view of the actuator plate taken from within the bath
Note: The plate is not aligned with the inside of the bath because the water has been drained.

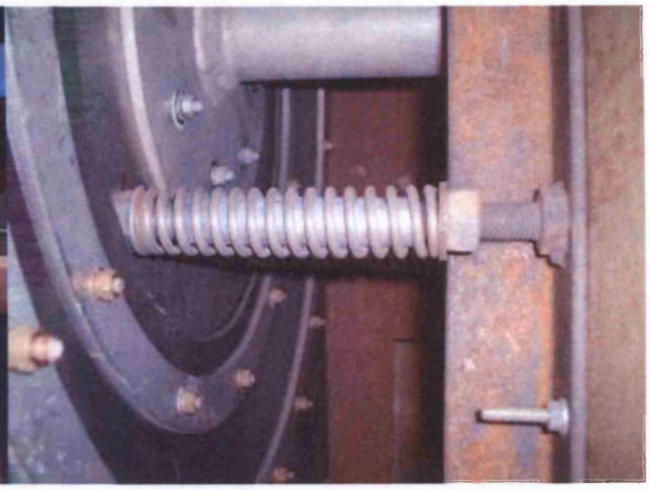


B 3.3
The actuator connected to the bath
Note: The marine plywood splash guard and the cooling pipe have been removed



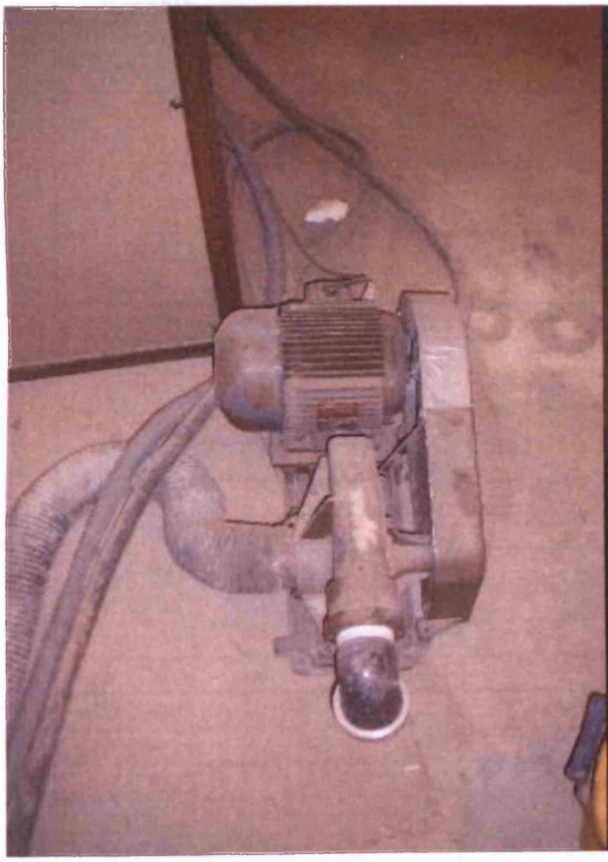
B 3.4
The actuator connected to the plate with the splashguard and cooling duct in position





B 3.5
The extension and the spring system between the actuator and the plate

B 3.6
Close up photograph to show the construction of the spring system



B 3.7

The cooling pump

B 3.8

The control panel on the amplifier

Appendix C

C 1 – Raw data recorded during the first frequency sweep.

C 1.1 Accelerations recorded by the accelerometer on the actuator plate at 713.3Hz. (This data is shown in full in graphical form in C.3.7)

Time (s)	DATASET WWSMRII VERSION 1 SIGNAL IMPORT_DAT DATE 06-23-03 TIME 15:20:27.00 INTERVAL 0.00001 HORZ_UNITS Sec VERT_UNITS Volts	Acceleration (g)
0	-0.59	-147.5
0.00001	-0.69	-172.5
0.00002	-0.77	-192.5
0.00003	-0.79	-197.5
0.00004	-0.74	-185
0.00005	-0.72	-180
0.00006	-0.72	-180
0.00007	-0.69	-172.5
0.00008	-0.6	-150
0.00009	-0.51	-127.5
0.0001	-0.49	-122.5
0.00011	-0.49	-122.5
0.00012	-0.43	-107.5
0.00013	-0.34	-85
0.00014	-0.2	-50
0.00015	-0.07	-17.5
0.00016	0.01	2.5
0.00017	0.04	10
0.00018	0.04	10
0.00019	0.05	12.5
0.0002	0.08	20
0.00021	0.06	15
0.00022	0	0
0.00023	-0.09	-22.5
0.00024	-0.18	-45
0.00025	-0.2	-50
0.00026	-0.18	-45
0.00027	-0.13	-32.5
0.00028	-0.07	-17.5
0.00029	0.01	2.5
0.0003	0.09	22.5
0.00031	0.17	42.5
0.00032	0.22	55

Table C 1.1 continued

Time (s)	Raw data	Acceleration (g)
0.00033	0.25	62.5
0.00034	0.23	57.5
0.00035	0.18	45
0.00036	0.18	45
0.00037	0.19	47.5
0.00038	0.18	45
0.00039	0.14	35
0.0004	0.06	15
0.00041	-0.01	-2.5
0.00042	-0.02	-5
0.00043	0	0
0.00044	0.01	2.5
0.00045	0.04	10
0.00046	0.09	22.5
0.00047	0.17	42.5
0.00048	0.29	72.5
0.00049	0.39	97.5
0.0005	0.45	112.5
0.00051	0.47	117.5
0.00052	0.48	120
0.00053	0.41	102.5
0.00054	0.35	87.5
0.00055	0.33	82.5
0.00056	0.33	82.5
0.00057	0.33	82.5
0.00058	0.33	82.5
0.00059	0.36	90
0.0006	0.41	102.5
0.00061	0.49	122.5
0.00062	0.54	135
0.00063	0.58	145
0.00064	0.7	175
0.00065	0.8	200
0.00066	0.81	202.5
0.00067	0.83	207.5
0.00068	0.88	220
0.00069	0.84	210
0.0007	0.73	182.5
0.00071	0.67	167.5
0.00072	0.65	162.5
0.00073	0.69	172.5
0.00074	0.71	177.5
0.00075	0.65	162.5
0.00076	0.61	152.5
0.00077	0.63	157.5
0.00078	0.61	152.5
0.00079	0.55	137.5

Table C 1.1 continued

Time (s)	Raw data	Acceleration (g)
0.0008	0.5	125
0.00081	0.46	115
0.00082	0.36	90
0.00083	0.29	72.5
0.00084	0.26	65
0.00085	0.22	55
0.00086	0.17	42.5
0.00087	0.16	40
0.00088	0.15	37.5
0.00089	0.11	27.5
0.0009	0.11	27.5
0.00091	0.09	22.5
0.00092	-0.02	-5
0.00093	-0.09	-22.5
0.00094	-0.05	-12.5
0.00095	-0.01	-2.5
0.00096	0	0
0.00097	-0.01	-2.5
0.00098	-0.02	-5
0.00099	-0.03	-7.5
0.001	-0.05	-12.5
0.00101	-0.09	-22.5
0.00102	-0.12	-30
0.00103	-0.14	-35
0.00104	-0.15	-37.5
0.00105	-0.2	-50
0.00106	-0.19	-47.5
0.00107	-0.1	-25
0.00108	-0.07	-17.5
0.00109	-0.15	-37.5
0.0011	-0.17	-42.5
0.00111	-0.19	-47.5
0.00112	-0.19	-47.5
0.00113	-0.14	-35
0.00114	-0.13	-32.5
0.00115	-0.21	-52.5
0.00116	-0.25	-62.5
0.00117	-0.29	-72.5
0.00118	-0.37	-92.5
0.00119	-0.4	-100
0.0012	-0.42	-105
0.00121	-0.5	-125
0.00122	-0.53	-132.5
0.00123	-0.45	-112.5
0.00124	-0.42	-105
0.00125	-0.43	-107.5
0.00126	-0.39	-97.5

C 2 – Raw data recorded during the second frequency sweep.

C 2.1 Extract of the accelerations recorded by the accelerometer on the actuator plate at 713.3Hz.

(This data is shown in full in graphical form in C.4.7)

Time (s)	DATASET WWSMRII VERSION 1 SIGNAL IMPORT_DAT DATE 08-01-03 TIME 11:58:17.00 INTERVAL 0.00001 HORZ_UNITS Sec VERT_UNITS Volts	Acceleration (g)
0	-0.12	-1.2
0.00001	-0.18	-1.8
0.00002	-0.24	-2.4
0.00003	-0.32	-3.2
0.00004	-0.4	-4
0.00005	-0.4	-4
0.00006	-0.34	-3.4
0.00007	-0.32	-3.2
0.00008	-0.3	-3
0.00009	-0.3	-3
0.0001	-0.3	-3
0.00011	-0.34	-3.4
0.00012	-0.38	-3.8
0.00013	-0.42	-4.2
0.00014	-0.46	-4.6
0.00015	-0.48	-4.8
0.00016	-0.5	-5
0.00017	-0.52	-5.2
0.00018	-0.52	-5.2
0.00019	-0.56	-5.6
0.0002	-0.58	-5.8
0.00021	-0.58	-5.8
0.00022	-0.6	-6
0.00023	-0.6	-6
0.00024	-0.6	-6
0.00025	-0.56	-5.6
0.00026	-0.52	-5.2
0.00027	-0.5	-5
0.00028	-0.46	-4.6
0.00029	-0.46	-4.6
0.0003	-0.48	-4.8
0.00031	-0.52	-5.2
0.00032	-0.6	-6
0.00033	-0.7	-7
0.00034	-0.8	-8
0.00035	-0.9	-9
0.00036	-0.98	-9.8

Table C 2.1 continued

Time (s)	Raw data	Acceleration (g)
0.00037	-1.04	-10.4
0.00038	-1.06	-10.6
0.00039	-1.04	-10.4
0.0004	-0.98	-9.8
0.00041	-0.88	-8.8
0.00042	-0.76	-7.6
0.00043	-0.64	-6.4
0.00044	-0.52	-5.2
0.00045	-0.42	-4.2
0.00046	-0.36	-3.6
0.00047	-0.34	-3.4
0.00048	-0.36	-3.6
0.00049	-0.42	-4.2
0.0005	-0.54	-5.4
0.00051	-0.66	-6.6
0.00052	-0.78	-7.8
0.00053	-0.9	-9
0.00054	-0.98	-9.8
0.00055	-1.04	-10.4
0.00056	-1.06	-10.6
0.00057	-1.02	-10.2
0.00058	-0.96	-9.6
0.00059	-0.86	-8.6
0.0006	-0.72	-7.2
0.00061	-0.58	-5.8
0.00062	-0.46	-4.6
0.00063	-0.32	-3.2
0.00064	-0.2	-2
0.00065	-0.1	-1
0.00066	-0.04	-0.4
0.00067	0.04	0.4
0.00068	0.1	1
0.00069	0.16	1.6
0.0007	0.16	1.6
0.00071	0.14	1.4
0.00072	0.1	1
0.00073	0.08	0.8
0.00074	0.04	0.4
0.00075	0.04	0.4
0.00076	0.04	0.4
0.00077	0.04	0.4
0.00078	0.08	0.8
0.00079	0.12	1.2
0.0008	0.16	1.6
0.00081	0.22	2.2
0.00082	0.28	2.8
0.00083	0.38	3.8

Table C 2.1 continued

Time (s)	Raw data	Acceleration (g)
0.00084	0.48	4.8
0.00085	0.54	5.4
0.00086	0.6	6
0.00087	0.66	6.6
0.00088	0.7	7
0.00089	0.7	7
0.0009	0.7	7
0.00091	0.66	6.6
0.00092	0.62	6.2
0.00093	0.58	5.8
0.00094	0.58	5.8
0.00095	0.56	5.6
0.00096	0.58	5.8
0.00097	0.6	6
0.00098	0.64	6.4
0.00099	0.64	6.4
0.001	0.68	6.8
0.00101	0.7	7
0.00102	0.72	7.2
0.00103	0.76	7.6
0.00104	0.82	8.2
0.00105	0.86	8.6
0.00106	0.92	9.2
0.00107	1	10
0.00108	1.02	10.2
0.00109	1.04	10.4
0.0011	1.04	10.4
0.00111	1.02	10.2
0.00112	1.02	10.2
0.00113	1.02	10.2
0.00114	0.98	9.8
0.00115	0.92	9.2
0.00116	0.84	8.4
0.00117	0.72	7.2
0.00118	0.62	6.2
0.00119	0.52	5.2
0.0012	0.42	4.2
0.00121	0.38	3.8
0.00122	0.38	3.8
0.00123	0.44	4.4
0.00124	0.52	5.2
0.00125	0.6	6
0.00126	0.68	6.8
0.00127	0.76	7.6
0.00128	0.8	8
0.00129	0.82	8.2
0.0013	0.82	8.2

C 2.2 Extract of the accelerations recorded by the accelerometer on the top brick at 713.3Hz.
(This data is shown in full in graphical form in C 4.7)

Time (s)	DATASET WWSMRII VERSION 10 SIGNAL IMPORT_DAT DATE 08-01-03 TIME 11:58:17.00 INTERVAL 0.00001 HORZ_UNITS Sec VERT_UNITS Volts	Acceleration (g)
0	-0.04	-0.4
0.00001	-0.08	-0.8
0.00002	-0.06	-0.6
0.00003	-0.04	-0.4
0.00004	0.02	0.2
0.00005	0.08	0.8
0.00006	0.18	1.8
0.00007	0.24	2.4
0.00008	0.3	3
0.00009	0.38	3.8
0.0001	0.38	3.8
0.00011	0.34	3.4
0.00012	0.26	2.6
0.00013	0.14	1.4
0.00014	0.02	0.2
0.00015	-0.1	-1
0.00016	-0.22	-2.2
0.00017	-0.42	-4.2
0.00018	-0.54	-5.4
0.00019	-0.7	-7
0.0002	-0.76	-7.6
0.00021	-0.74	-7.4
0.00022	-0.72	-7.2
0.00023	-0.68	-6.8
0.00024	-0.64	-6.4
0.00025	-0.58	-5.8
0.00026	-0.56	-5.6
0.00027	-0.5	-5
0.00028	-0.5	-5
0.00029	-0.5	-5
0.0003	-0.52	-5.2
0.00031	-0.58	-5.8
0.00032	-0.66	-6.6
0.00033	-0.76	-7.6
0.00034	-0.86	-8.6
0.00035	-0.94	-9.4
0.00036	-1.02	-10.2

Table C 2.2 continued

Time (s)	Raw data	Acceleration (g)
0.00037	-1.06	-10.6
0.00038	-1.04	-10.4
0.00039	-1.04	-10.4
0.0004	-1.02	-10.2
0.00041	-0.98	-9.8
0.00042	-0.94	-9.4
0.00043	-0.9	-9
0.00044	-0.84	-8.4
0.00045	-0.82	-8.2
0.00046	-0.78	-7.8
0.00047	-0.82	-8.2
0.00048	-0.88	-8.8
0.00049	-0.94	-9.4
0.0005	-1.04	-10.4
0.00051	-1.1	-11
0.00052	-1.18	-11.8
0.00053	-1.22	-12.2
0.00054	-1.22	-12.2
0.00055	-1.18	-11.8
0.00056	-1.12	-11.2
0.00057	-1.06	-10.6
0.00058	-0.98	-9.8
0.00059	-0.92	-9.2
0.0006	-0.88	-8.8
0.00061	-0.82	-8.2
0.00062	-0.78	-7.8
0.00063	-0.74	-7.4
0.00064	-0.72	-7.2
0.00065	-0.7	-7
0.00066	-0.66	-6.6
0.00067	-0.64	-6.4
0.00068	-0.58	-5.8
0.00069	-0.56	-5.6
0.0007	-0.52	-5.2
0.00071	-0.5	-5
0.00072	-0.46	-4.6
0.00073	-0.44	-4.4
0.00074	-0.4	-4
0.00075	-0.34	-3.4
0.00076	-0.26	-2.6
0.00077	-0.18	-1.8
0.00078	-0.08	-0.8
0.00079	0.04	0.4
0.0008	0.16	1.6
0.00081	0.24	2.4
0.00082	0.28	2.8
0.00083	0.32	3.2

Table C 2.2 continued

Time (s)	Raw data	Acceleration (g)
0.00084	0.28	2.8
0.00085	0.28	2.8
0.00086	0.28	2.8
0.00087	0.24	2.4
0.00088	0.2	2
0.00089	0.16	1.6
0.0009	0.14	1.4
0.00091	0.14	1.4
0.00092	0.16	1.6
0.00093	0.22	2.2
0.00094	0.32	3.2
0.00095	0.42	4.2
0.00096	0.52	5.2
0.00097	0.62	6.2
0.00098	0.72	7.2
0.00099	0.8	8
0.001	0.86	8.6
0.00101	0.92	9.2
0.00102	0.98	9.8
0.00103	1.02	10.2
0.00104	1.04	10.4
0.00105	1.04	10.4
0.00106	1	10
0.00107	1	10
0.00108	0.96	9.6
0.00109	0.92	9.2
0.0011	0.9	9
0.00111	0.86	8.6
0.00112	0.84	8.4
0.00113	0.84	8.4
0.00114	0.84	8.4
0.00115	0.86	8.6
0.00116	0.9	9
0.00117	0.96	9.6
0.00118	1.04	10.4
0.00119	1.12	11.2
0.0012	1.16	11.6
0.00121	1.2	12
0.00122	1.22	12.2
0.00123	1.22	12.2
0.00124	1.2	12
0.00125	1.16	11.6
0.00126	1.1	11
0.00127	1.06	10.6
0.00128	0.98	9.8
0.00129	0.94	9.4
0.0013	0.86	8.6

C 2.3 Extract of the accelerations recorded by the accelerometers on the bottom brick at 713.3Hz.
(This data is also shown in a graphical form in C 4.7)

Time (s)	DATASET WWSMRII VERSION 12 SIGNAL IMPORT_DAT DATE 08-01-03 TIME 11:58:17.00 INTERVAL 0.00001 HORZ_UNITS Sec VERT_UNITS Volts	Acceleration (g)
0	0.88	88
0.00001	0.84	84
0.00002	0.8	80
0.00003	0.72	72
0.00004	0.6	60
0.00005	0.5	50
0.00006	0.42	42
0.00007	0.3	30
0.00008	0.22	22
0.00009	0.22	22
0.0001	0.24	24
0.00011	0.26	26
0.00012	0.22	22
0.00013	0.18	18
0.00014	0.2	20
0.00015	0.2	20
0.00016	0.2	20
0.00017	0.16	16
0.00018	0.14	14
0.00019	0.12	12
0.0002	0.04	4
0.00021	-0.04	-4
0.00022	-0.1	-10
0.00023	-0.14	-14
0.00024	-0.26	-26
0.00025	-0.38	-38
0.00026	-0.5	-50
0.00027	-0.64	-64
0.00028	-0.72	-72
0.00029	-0.84	-84
0.0003	-0.92	-92
0.00031	-1.02	-102
0.00032	-1.08	-108
0.00033	-1.04	-104
0.00034	-1.02	-102
0.00035	-1.02	-102
0.00036	-1.04	-104

Table C 2.3 continued

Time (s)	Raw data	Acceleration (g)
0.00037	-1.06	-106
0.00038	-1.12	-112
0.00039	-1.16	-116
0.0004	-1.16	-116
0.00041	-1.2	-120
0.00042	-1.24	-124
0.00043	-1.24	-124
0.00044	-1.22	-122
0.00045	-1.18	-118
0.00046	-1.18	-118
0.00047	-1.14	-114
0.00048	-1.1	-110
0.00049	-1.1	-110
0.0005	-1.14	-114
0.00051	-1.14	-114
0.00052	-1.14	-114
0.00053	-1.16	-116
0.00054	-1.16	-116
0.00055	-1.18	-118
0.00056	-1.22	-122
0.00057	-1.24	-124
0.00058	-1.24	-124
0.00059	-1.2	-120
0.0006	-1.22	-122
0.00061	-1.26	-126
0.00062	-1.22	-122
0.00063	-1.1	-110
0.00064	-1.06	-106
0.00065	-1.04	-104
0.00066	-0.94	-94
0.00067	-0.86	-86
0.00068	-0.9	-90
0.00069	-0.96	-96
0.0007	-0.94	-94
0.00071	-0.9	-90
0.00072	-0.96	-96
0.00073	-1.04	-104
0.00074	-1.04	-104
0.00075	-0.96	-96
0.00076	-0.84	-84
0.00077	-0.8	-80
0.00078	-0.72	-72
0.00079	-0.62	-62
0.0008	-0.52	-52
0.00081	-0.4	-40
0.00082	-0.3	-30
0.00083	-0.3	-30

Table C 2.3 continued

Time (s)	Raw data	Acceleration (g)
0.00084	-0.38	-38
0.00085	-0.4	-40
0.00086	-0.38	-38
0.00087	-0.34	-34
0.00088	-0.3	-30
0.00089	-0.26	-26
0.0009	-0.22	-22
0.00091	-0.2	-20
0.00092	-0.08	-8
0.00093	0.04	4
0.00094	0.12	12
0.00095	0.1	10
0.00096	0.14	14
0.00097	0.22	22
0.00098	0.26	26
0.00099	0.2	20
0.001	0.22	22
0.00101	0.28	28
0.00102	0.34	34
0.00103	0.42	42
0.00104	0.52	52
0.00105	0.56	56
0.00106	0.56	56
0.00107	0.58	58
0.00108	0.74	74
0.00109	0.92	92
0.0011	1	100
0.00111	1.06	106
0.00112	1.14	114
0.00113	1.2	120
0.00114	1.32	132
0.00115	1.52	152
0.00116	1.64	164
0.00117	1.64	164
0.00118	1.6	160
0.00119	1.62	162
0.0012	1.62	162
0.00121	1.54	154
0.00122	1.48	148
0.00123	1.52	152
0.00124	1.54	154
0.00125	1.5	150
0.00126	1.46	146
0.00127	1.58	158
0.00128	1.62	162
0.00129	1.48	148
0.0013	1.4	140

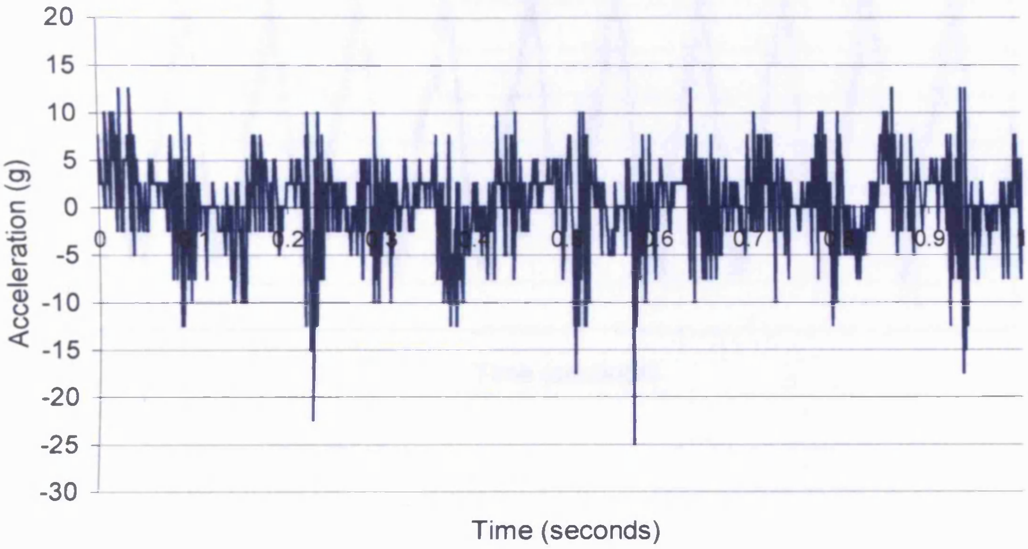
C 2.4 Extract from the accelerations recorded by the accelerometer attached to the full scale brick in the U.P.C. ultrasound bath

	DATASET WWSMRII			
	VERSION 15			
	SIGNAL IMPORT_DAT			
	DATE 08-07-03			
	TIME 12:44:01.00			
	INTERVAL 0.000005			
	HORZ_UNITS Sec			
	VERT_UNITS Volts			
	COMMENT Signal generated by WW SMR II			
	DATA			
Reading		Millivolts	Time (seconds)	g
1	0.64	360	0.000005	16
2	0.64	280	0.00001	16
3	0.56	280	0.000015	14
4	0.56	280	0.00002	14
5	0.56	120	0.000025	14
6	0.4	120	0.00003	10
7	0.4	40	0.000035	10
8	0.32	-40	0.00004	8
9	0.24	-40	0.000045	6
10	0.24	-200	0.00005	6
11	0.08	-200	0.000055	2
12	0.08	-360	0.00006	2
13	-0.08	-360	0.000065	-2
14	-0.08	-520	0.00007	-2
15	-0.24	-520	0.000075	-6
16	-0.24	-600	0.00008	-6
17	-0.32	-680	0.000085	-8
18	-0.4	-760	0.00009	-10
19	-0.48	-840	0.000095	-12
20	-0.56	-840	0.0001	-14
21	-0.56	-920	0.000105	-14
22	-0.64	-1000	0.00011	-16
23	-0.72	-1000	0.000115	-18
24	-0.72	-1080	0.00012	-18
25	-0.8	-1080	0.000125	-20
26	-0.8	-1160	0.00013	-20
27	-0.88	-1240	0.000135	-22
28	-0.96	-1240	0.00014	-24
29	-0.96	-1240	0.000145	-24
30	-0.96	-1320	0.00015	-24
31	-1.04	-1320	0.000155	-26
32	-1.04	-1400	0.00016	-26
33	-1.12	-1400	0.000165	-28
34	-1.12	-1400	0.00017	-28

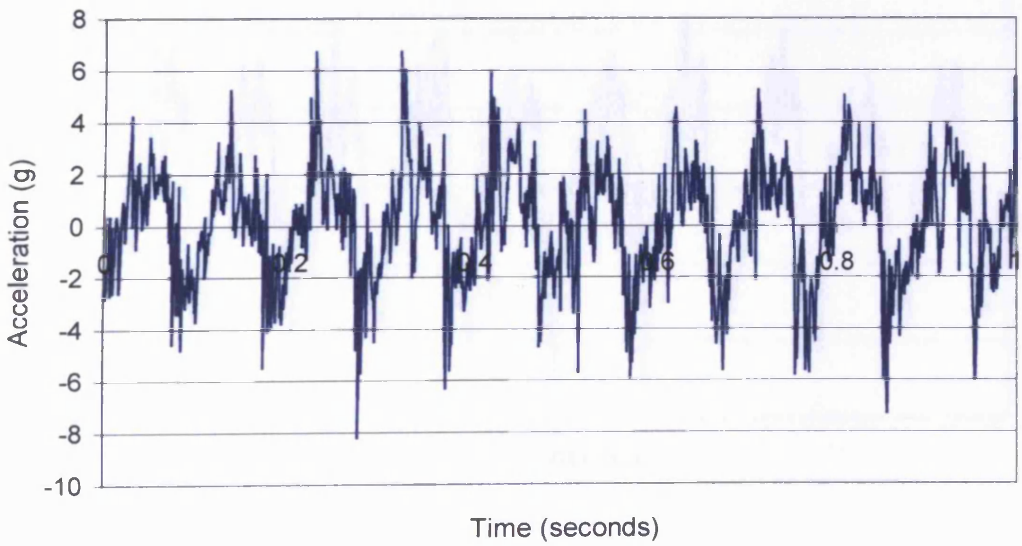
35	-1.12	-1400	0.000175	-28
36	-1.12	-1480	0.00018	-28
37	-1.2	-1480	0.000185	-30
38	-1.2	-1560	0.00019	-30
39	-1.28	-1560	0.000195	-32
40	-1.28	-1560	0.0002	-32
41	-1.28	-1560	0.000205	-32
42	-1.28	-1560	0.00021	-32
43	-1.28	-1560	0.000215	-32
44	-1.28	-1560	0.00022	-32
45	-1.28	-1640	0.000225	-32
46	-1.36	-1640	0.00023	-34
47	-1.36	-1640	0.000235	-34
48	-1.36	-1640	0.00024	-34
49	-1.36	-1640	0.000245	-34
50	-1.36	-1640	0.00025	-34
51	-1.36	-1640	0.000255	-34
52	-1.36	-1640	0.00026	-34
53	-1.36	-1640	0.000265	-34
54	-1.36	-1640	0.00027	-34
55	-1.36	-1640	0.000275	-34
56	-1.36	-1560	0.00028	-34
57	-1.28	-1560	0.000285	-32
58	-1.28	-1560	0.00029	-32
59	-1.28	-1560	0.000295	-32
60	-1.28	-1560	0.0003	-32
61	-1.28	-1560	0.000305	-32
62	-1.28	-1480	0.00031	-32
63	-1.2	-1400	0.000315	-30
64	-1.12	-1400	0.00032	-28
65	-1.12	-1320	0.000325	-28
66	-1.04	-1240	0.00033	-26
67	-0.96	-1240	0.000335	-24
68	-0.96	-1080	0.00034	-24
69	-0.8	-1080	0.000345	-20
70	-0.8	-1000	0.00035	-20
71	-0.72	-920	0.000355	-18
72	-0.64	-920	0.00036	-16
73	-0.64	-760	0.000365	-16
74	-0.48	-760	0.00037	-12
75	-0.48	-600	0.000375	-12
76	-0.32	-600	0.00038	-8
77	-0.32	-600	0.000385	-8
78	-0.32	-440	0.00039	-8
79	-0.16	-440	0.000395	-4
80	-0.16	-360	0.0004	-4
81	-0.08	-280	0.000405	-2
82	0	-280	0.00041	0
83	0	-200	0.000415	0
84	0.08	-120	0.00042	2
85	0.16	-120	0.000425	4

C 3 - The acceleration recorded by the accelerometer on the actuator plate during the first frequency sweep.

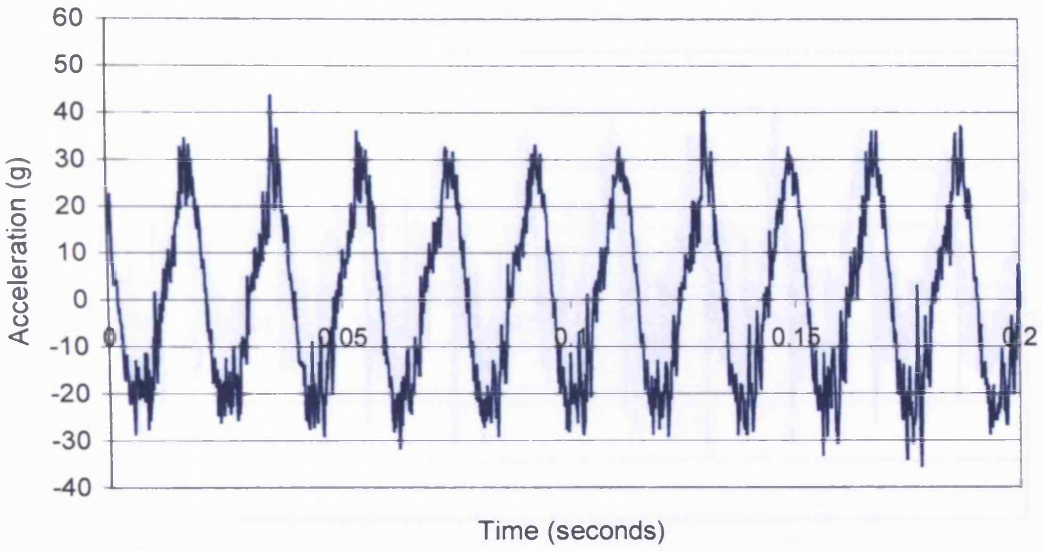
C 3.1 6.9Hz



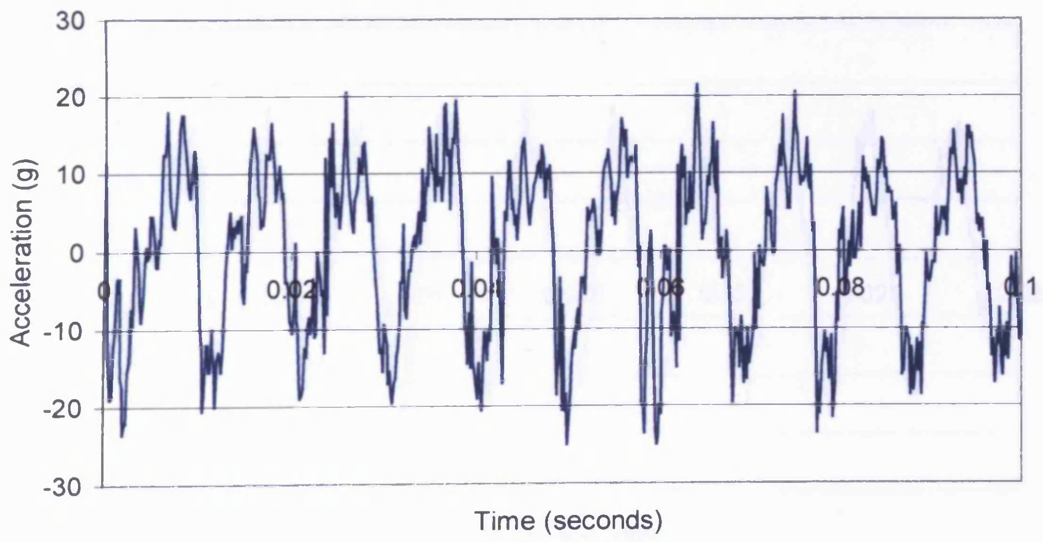
C 3.2 10.2 Hz



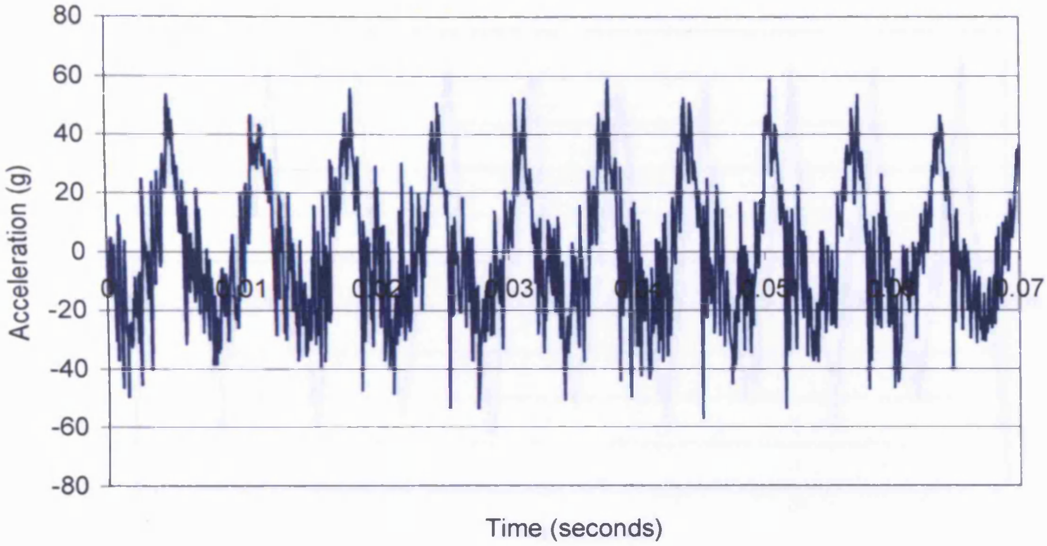
C 3.3 53 Hz



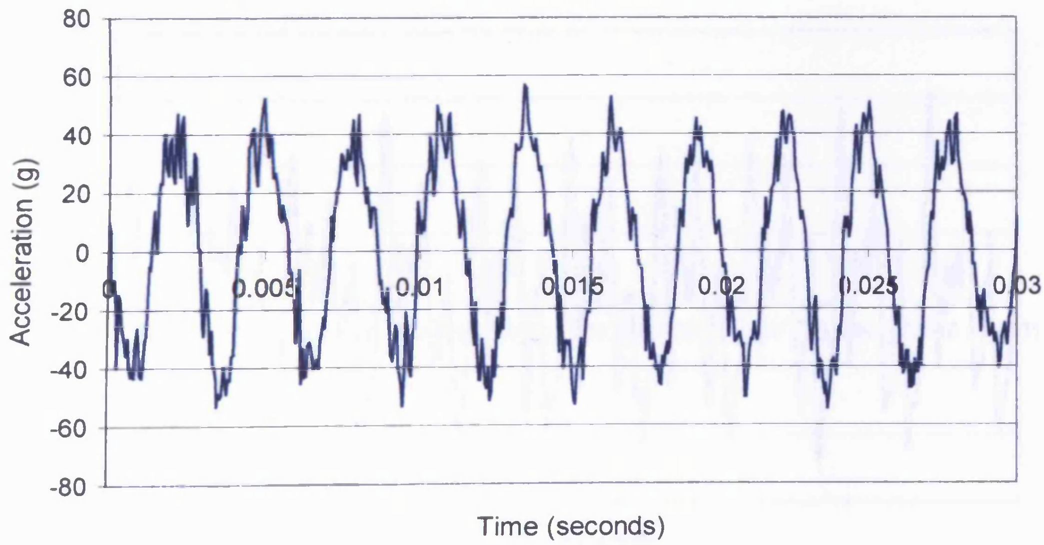
C 3.4 106 Hz



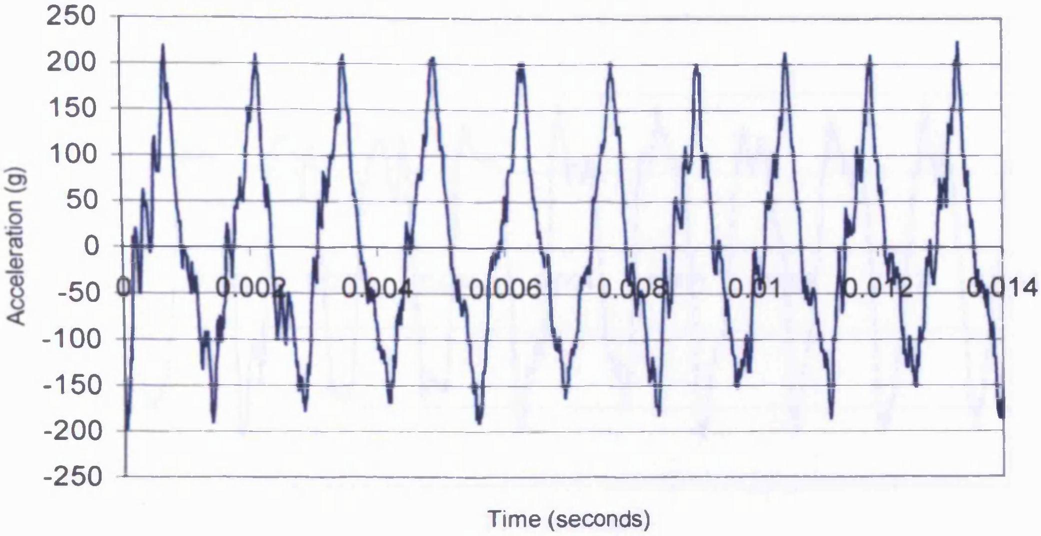
C 3.5 150 Hz



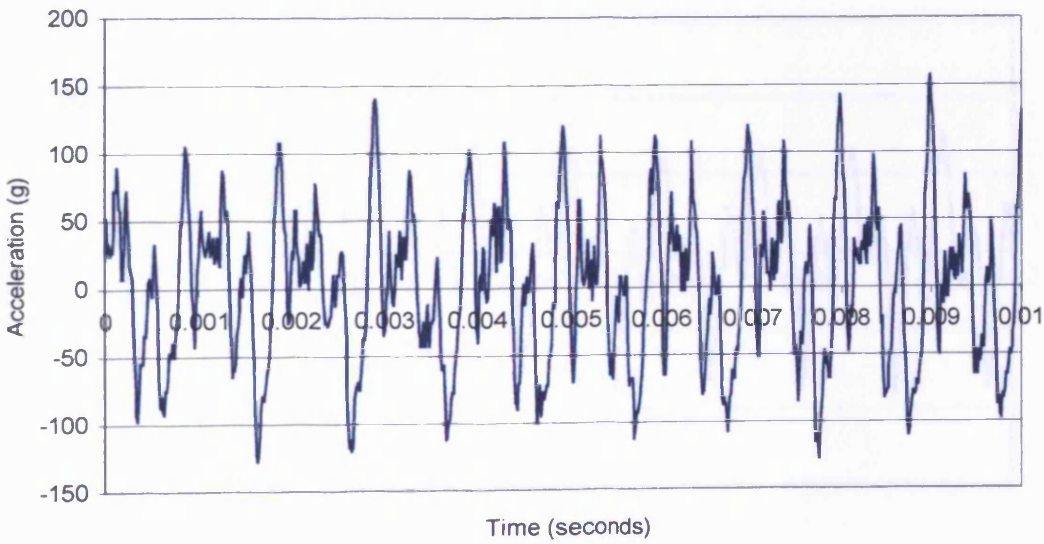
C 3.6 360 Hz



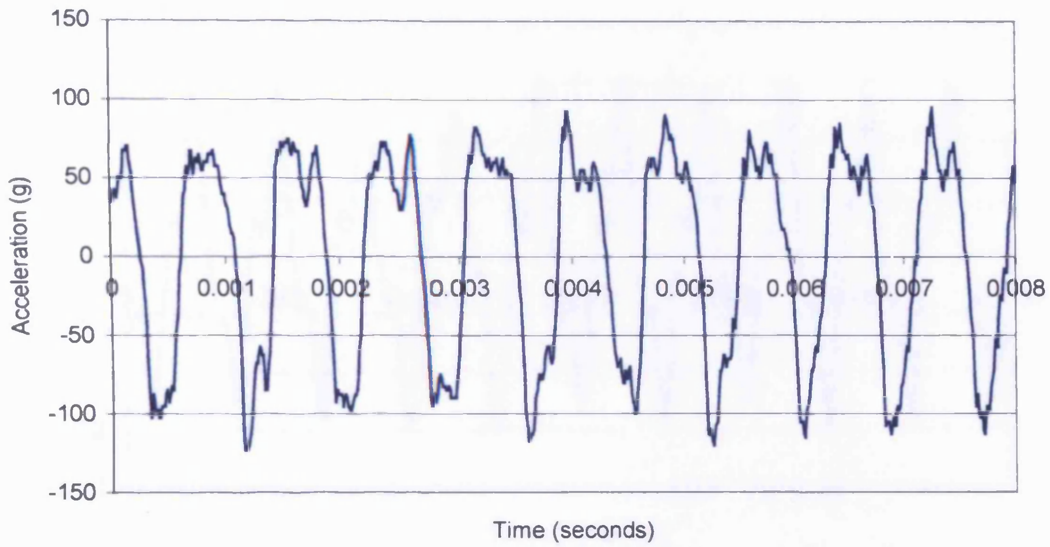
C 3.7 710 Hz



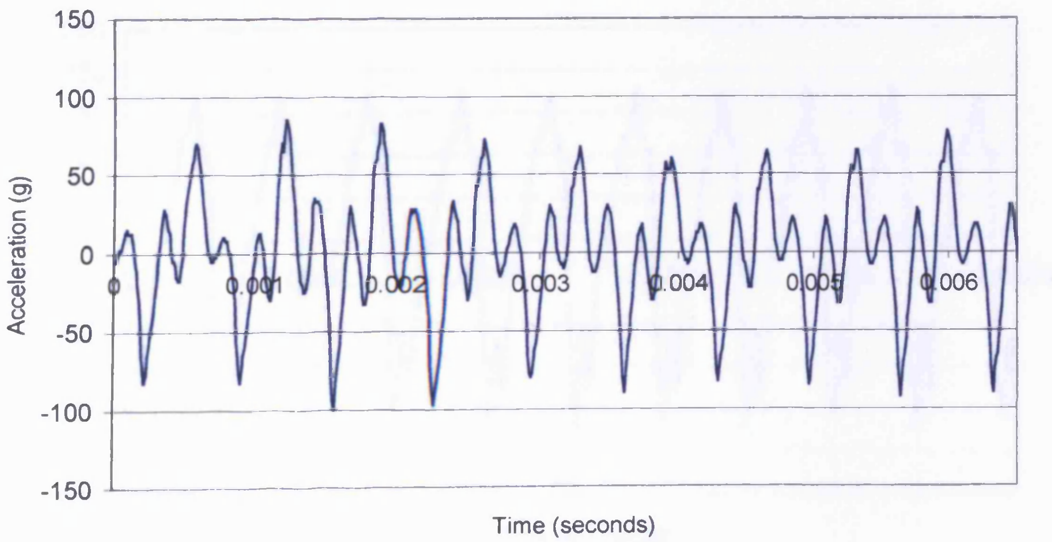
C 3.8. 1010 Hz



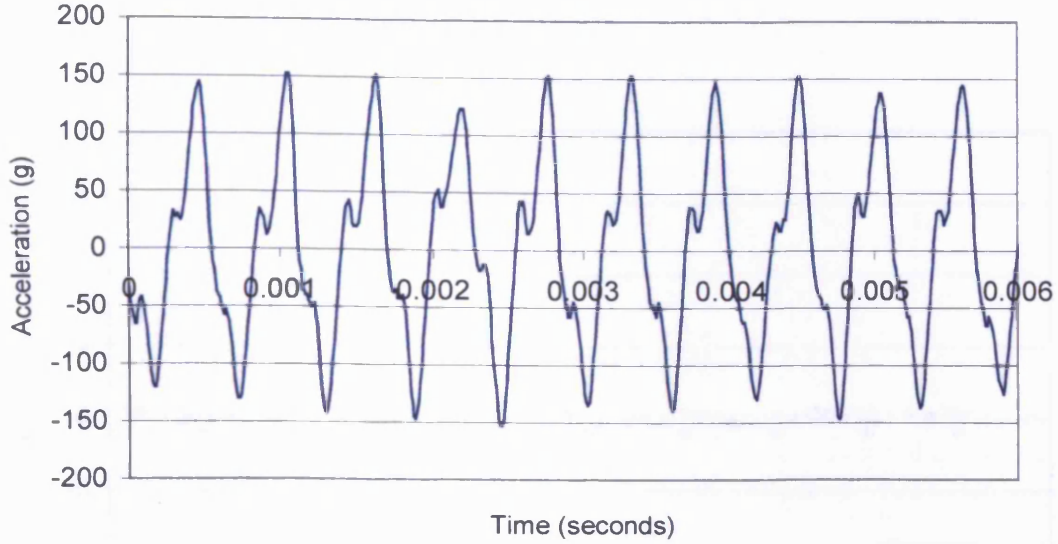
C 3.9 1260 Hz



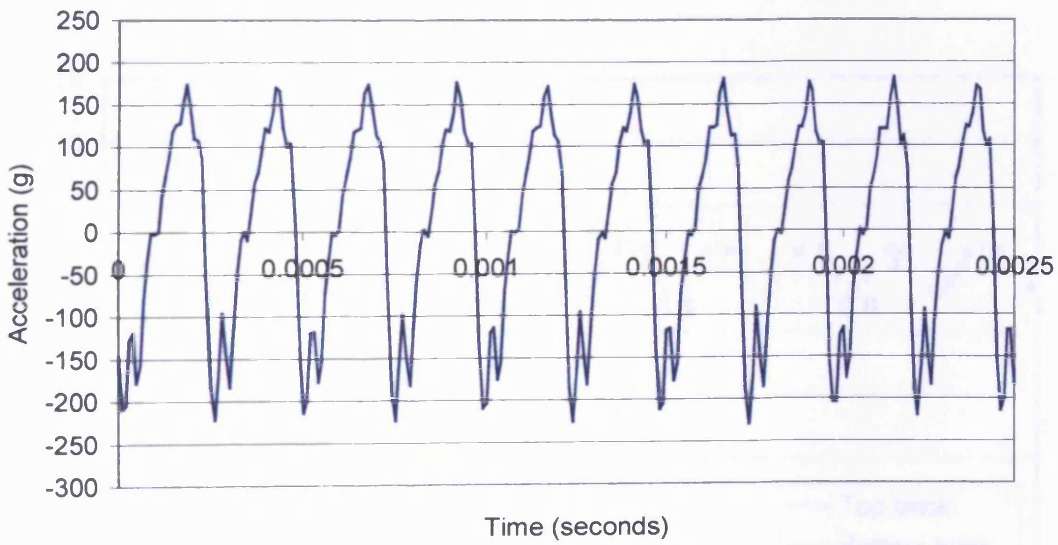
C 3.10 1480 Hz



C 3.11 1750 Hz

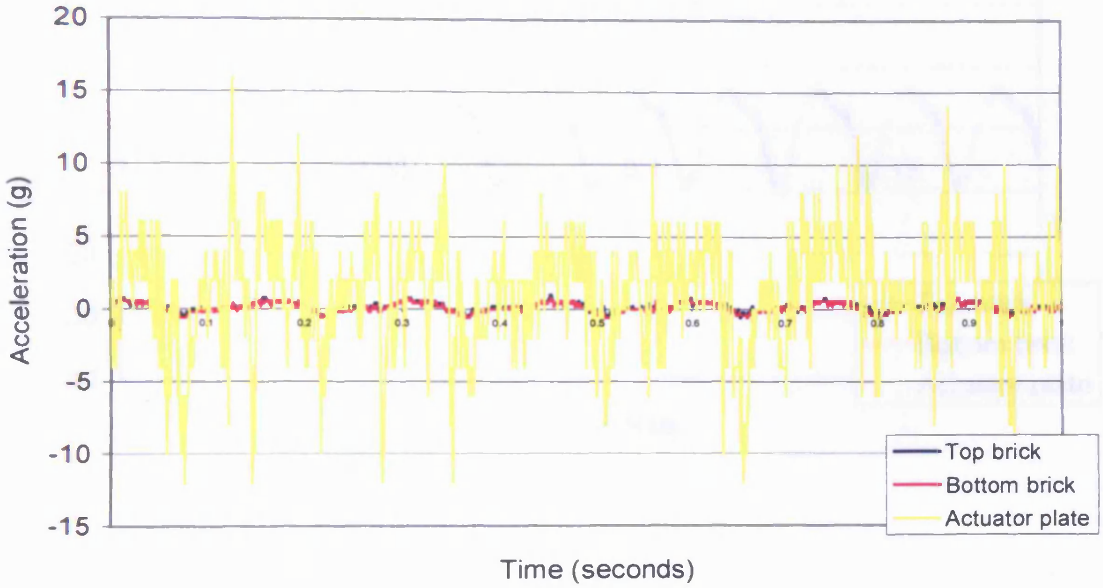


C 3.12 4180 Hz

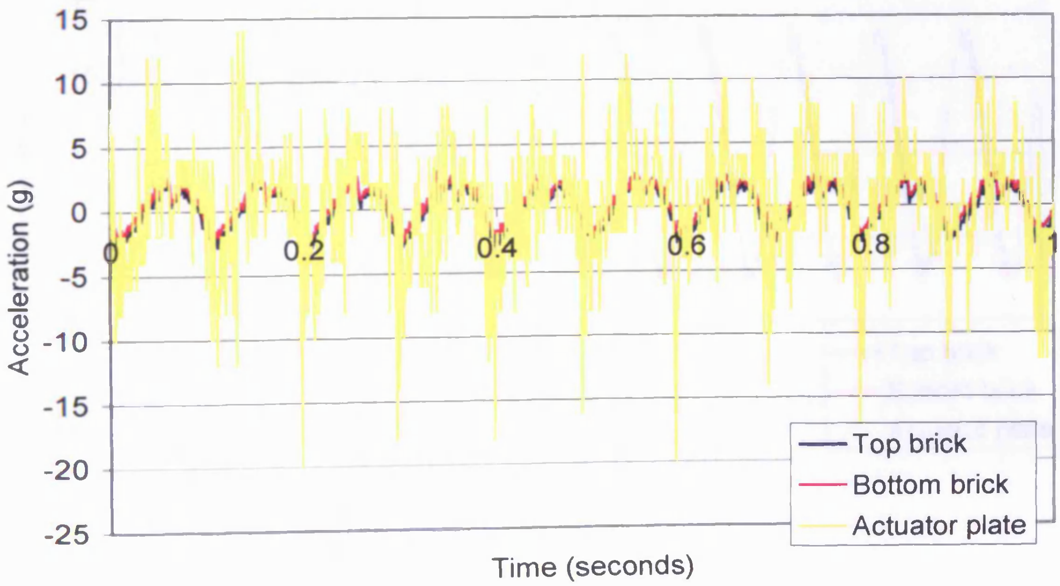


C 4 - The accelerations recorded by the accelerometers on the actuator plate and the top and bottom bricks of the couplet during the second frequency sweep.

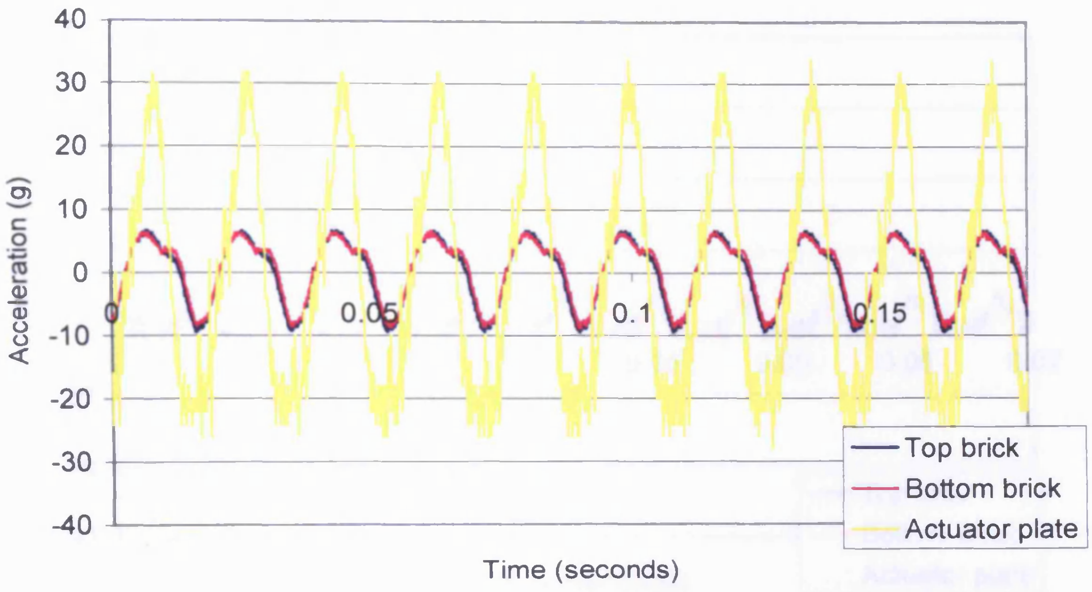
C 4.1 7 Hz



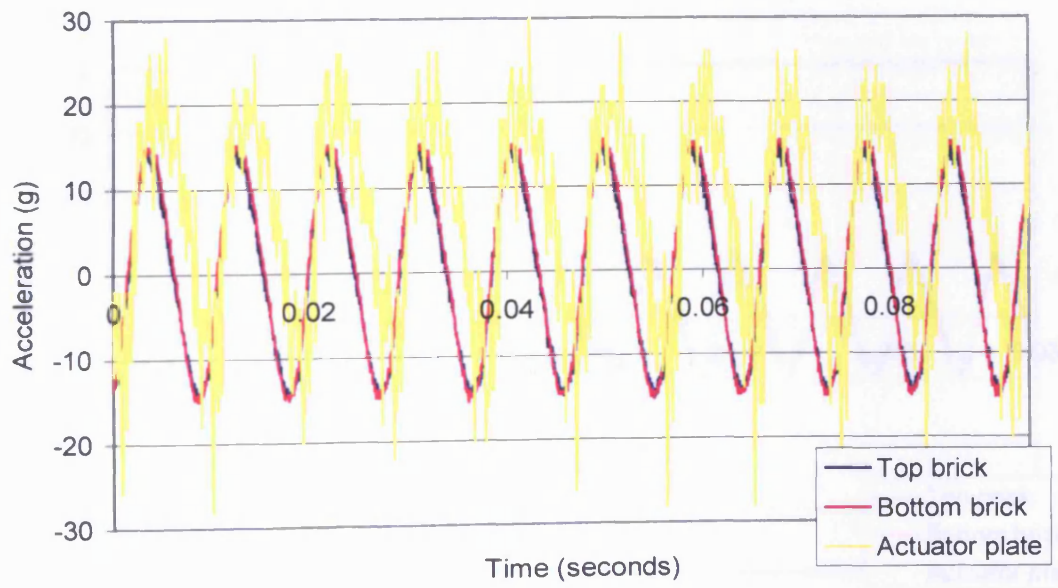
C 4.2 10 Hz



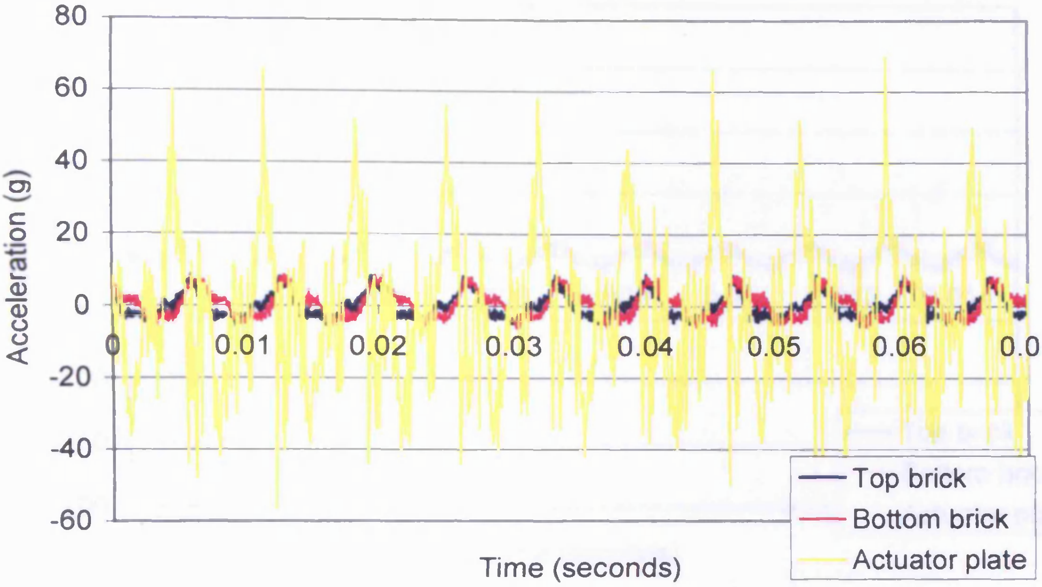
C 4.3 56 Hz



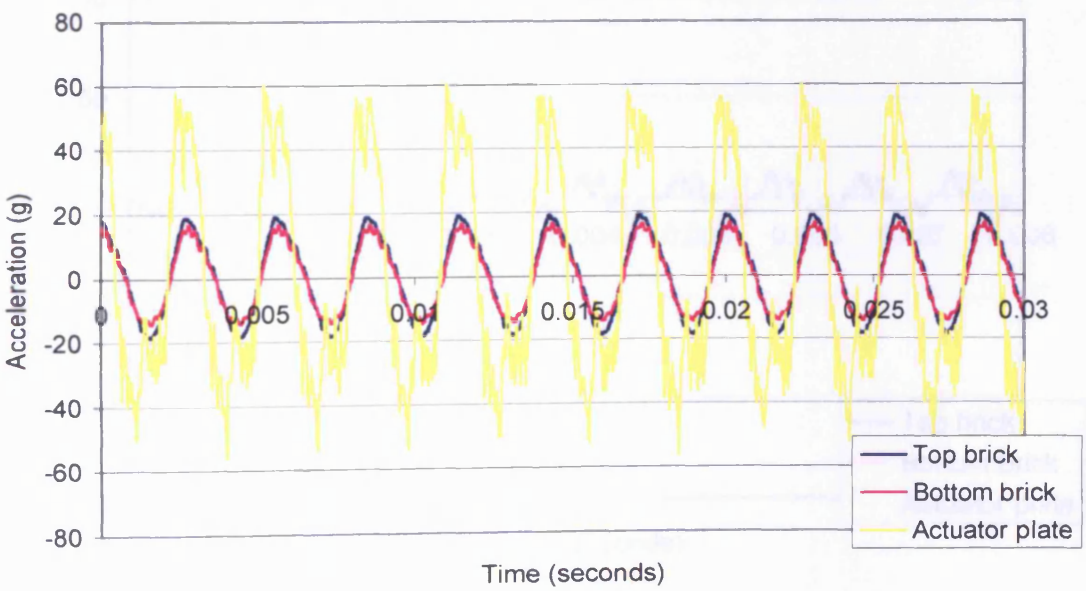
C 4.4 109 Hz



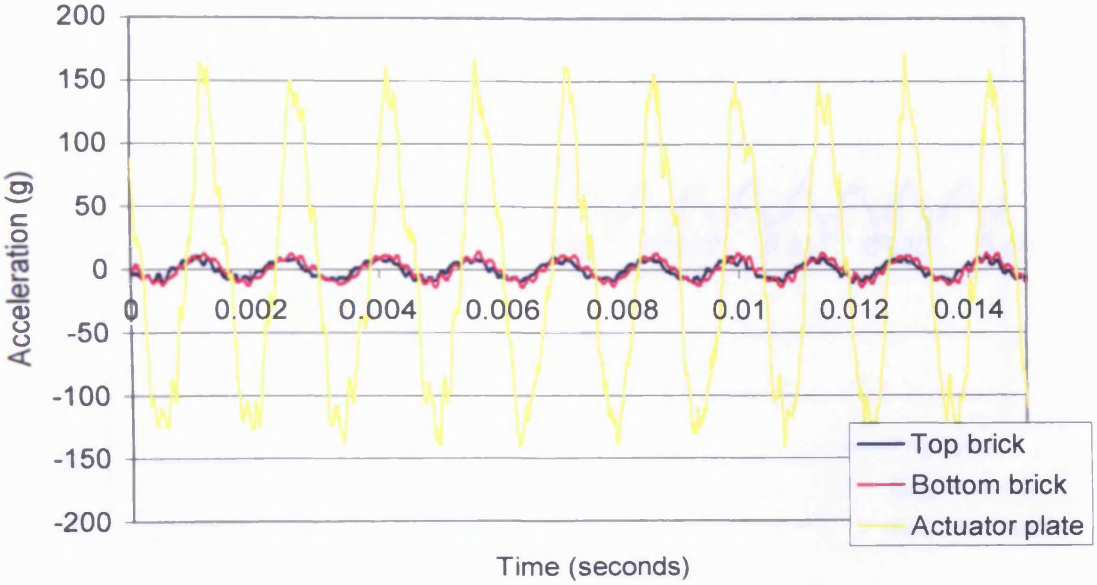
C 4.5 138 Hz



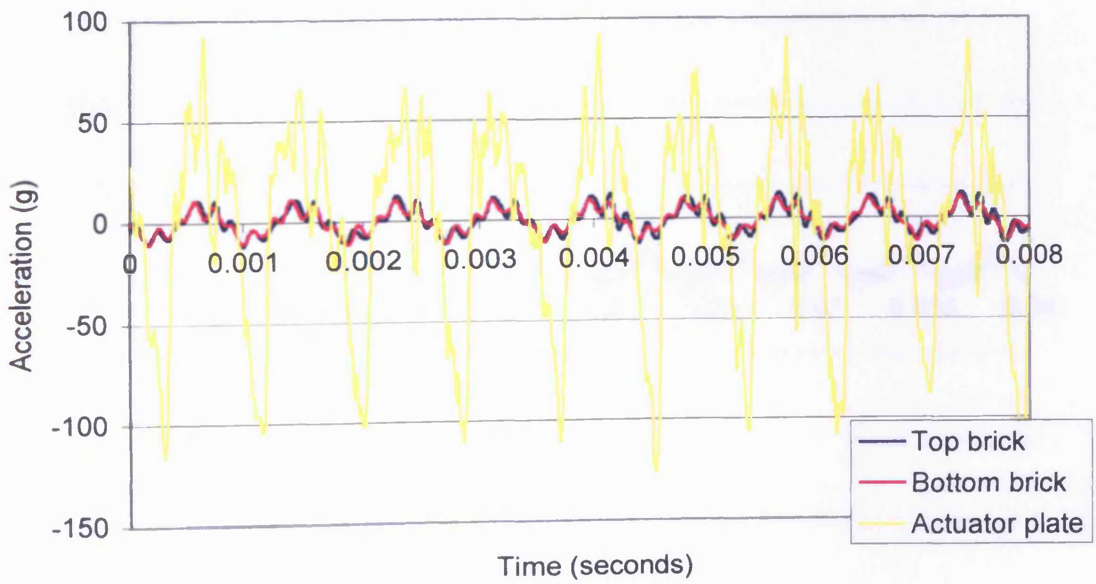
C 4.6 390 Hz



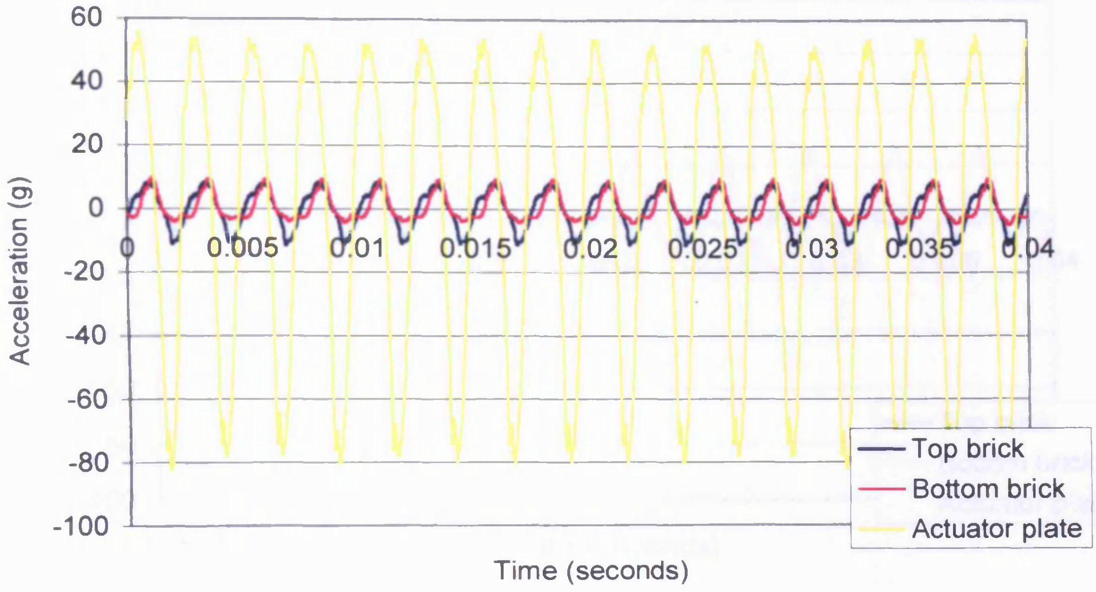
C 4.7 720 Hz



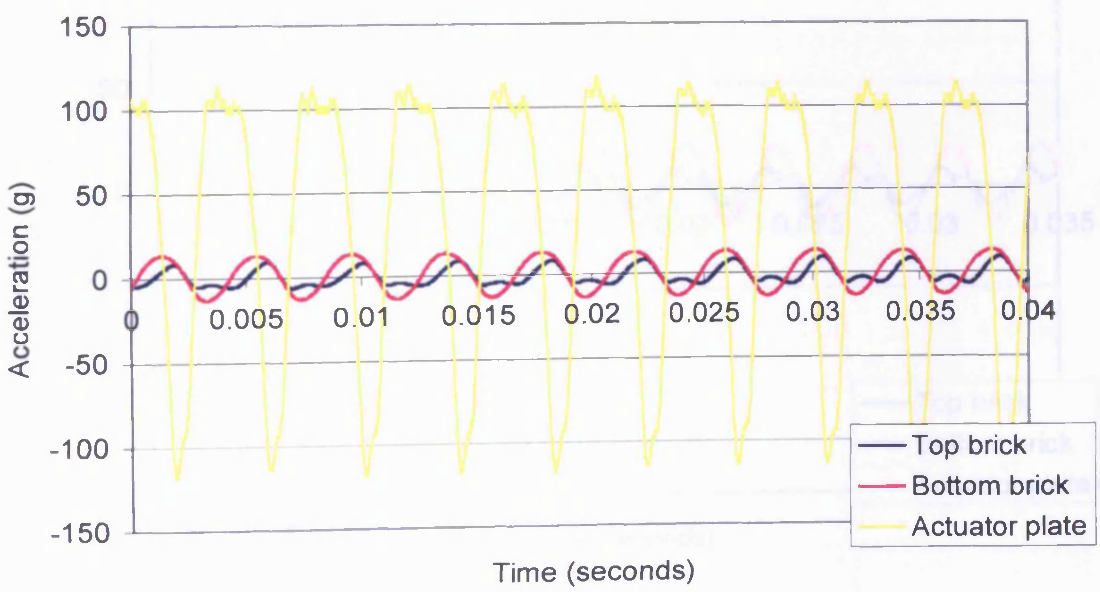
C 4.8 1140 Hz



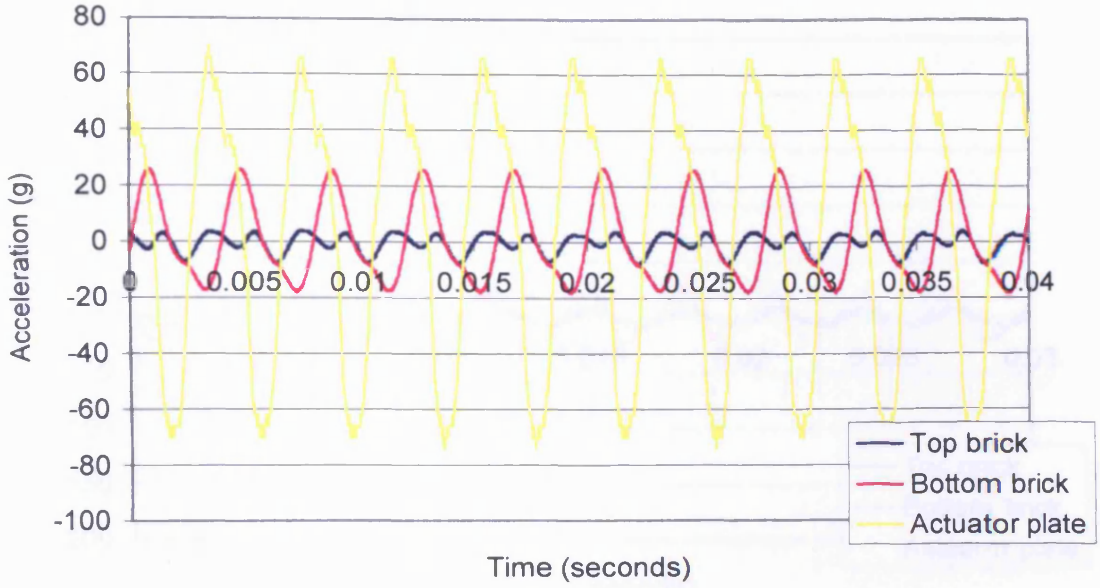
C 4.9 2040 Hz



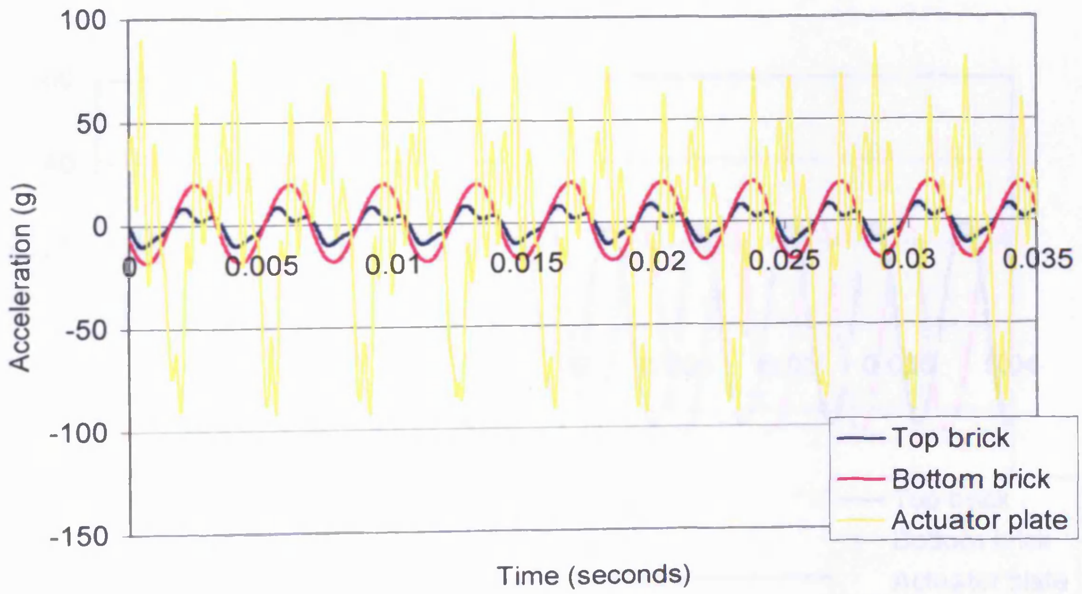
C 4.10 3050 Hz



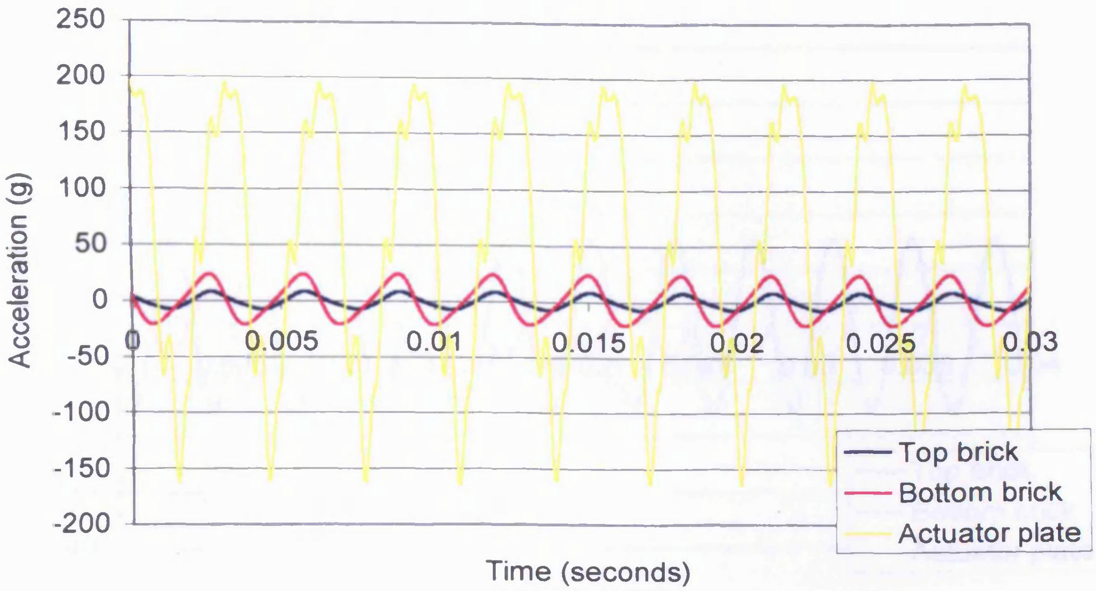
C 4.11 3150 Hz



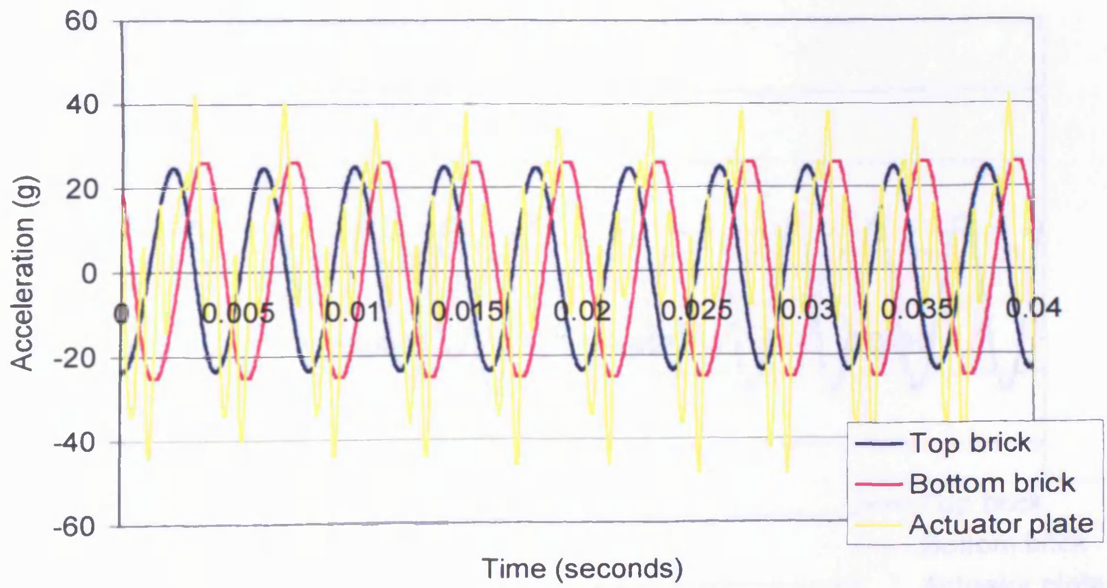
C 4.12 3550 Hz



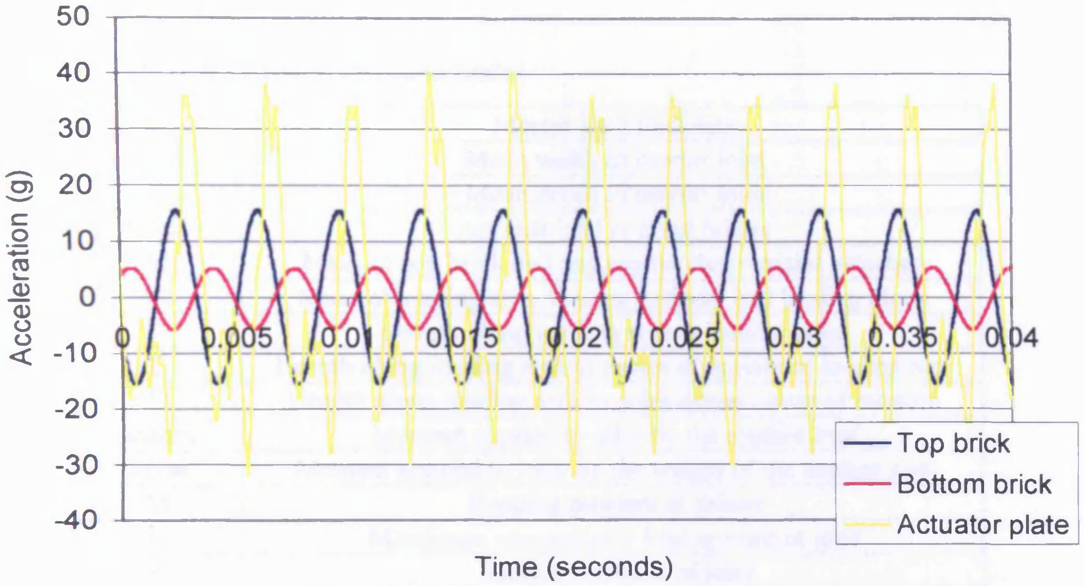
C 4.13 4030 Hz



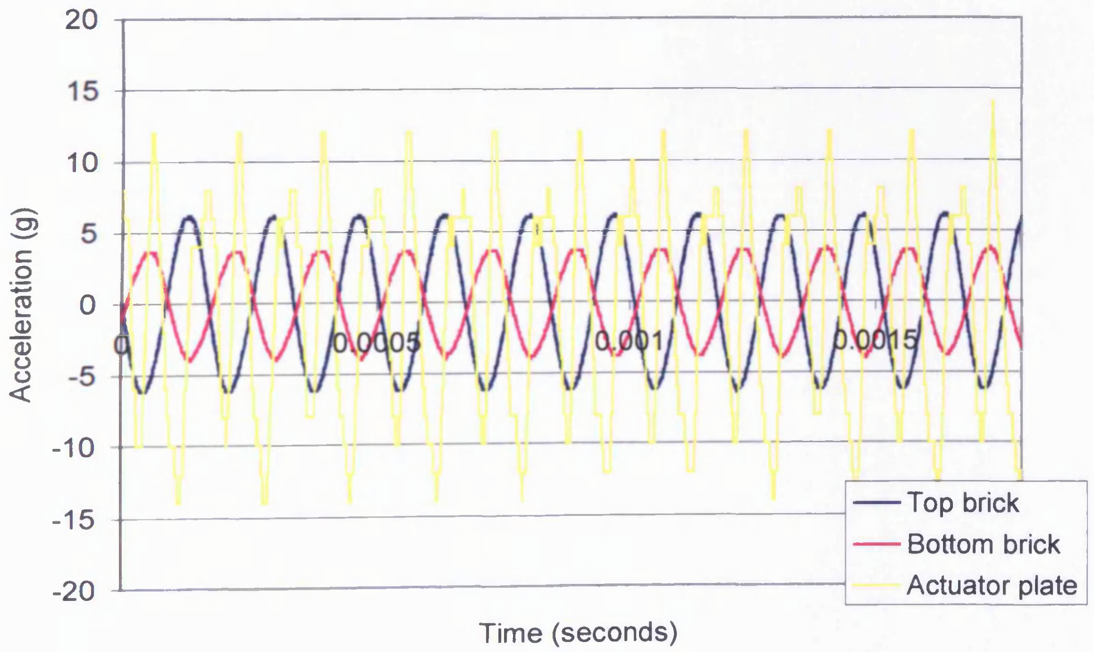
C 4.14 5030 Hz



C 4.15 5560 Hz



C 4.16 5950 Hz



Appendix D

D 1 - Bond wrench test data

D 1.1 Key for bond wrench test data tables

t	Mortar joint thickness
b	Mean width of mortar joint
d	Mean depth of mortar joint
load	Applied load at bond failure
m1	Mass of top brick and any mortar that remains attached
m2	Mass of loading arm, loading cylinder and loading block
l1	Length along loading arm to loading point
l2	Length along loading arm to centre of gravity of loading arm
l3	Length along loading arm to point above centre of rotation
loadm	Moment applied to joint by the applied load
m1m	Moment applied to joint by the weight of the loading arm
M	Bending moment at failure
W	Maximum compressive load applied ot joint
Z	Section modulus of joint
S	Failure stress

D1.2 Raw data

Specimen	t	b	d	load	m1	m2	l1	l2	l3
	mm	mm	mm	N	g	g	mm	mm	mm
A1	15	218	103	400.0	3280.0	19197.0	394	190	144
A2	15	218	103	300.0	3400.0	19197.0	394	190	144
A3	15	218	103	270.0	3070.0	19197.0	394	190	144
A4	15	218	103	310.0	3050.0	19197.0	394	190	144
A5	15	218	103	340.0	3530.0	19197.0	394	190	144
B1	10	218	103	360.0	2999.0	19197.0	394	190	144
B2	10	218	103	260.0	3000.0	19197.0	394	190	144
B3	10	218	103	330.0	2880.0	19197.0	394	190	144
B4	10	218	103	210.0	2800.0	19197.0	394	190	144
B5	10	218	103	220.0	2740.0	19197.0	394	190	144
B6	10	218	103	300.0	2940.0	19197.0	394	190	144
B7	10	218	103	270.0	3130.0	19197.0	394	190	144
B8	10	218	103	250.0	2980.0	19197.0	394	190	144
B9	10	218	103	380.0	3120.0	19197.0	394	190	144
B10	10	218	103	230.0	3580.0	19197.0	394	190	144
C1	8	218	103	250.0	2820.0	19197.0	394	190	144
C2	8	218	103	270.0	2940.0	19197.0	394	190	144
C3	8	218	103	290.0	3250.0	19197.0	394	190	144
C4	8	218	103	200.0	2940.0	19197.0	394	190	144
C5	8	218	103	200.0	2990.0	19197.0	394	190	144
D1	4	218	103	260.0	2920.0	19197.0	394	190	144
D2	4	218	103	160.0	2880.0	19197.0	394	190	144
D3	4	218	103	260.0	3030.0	19197.0	394	190	144
D4	4	218	103	300.0	2820.0	19197.0	394	190	144
D5	4	218	103	290.0	3060.0	19197.0	394	190	144
E1	2	218	103	190.0	2930.0	19197.0	394	190	144
E2	2	218	103	180.0	2780.0	19197.0	394	190	144
E3	2	218	103	230.0	2800.0	19197.0	394	190	144
E4	2	218	103	290.0	2690.0	19197.0	394	190	144
E5	2	218	103	160.0	2770.0	19197.0	394	190	144
F1	10	218	103	260.0	2940.0	19197.0	394	190	144
F2	10	218	103	190.0	2880.0	19197.0	394	190	144
F3	10	218	103	130.0	2980.0	19197.0	394	190	144
F4	10	218	103	180.0	2850.0	19197.0	394	190	144
F5	10	218	103	350.0	2990.0	19197.0	394	190	144
G1	10	218	103	24.8	22.5	13.7	52	26	21
G2	10	218	103	79.5	21.9	13.7	52	26	21
G3	10	218	103	84.8	16.4	13.7	52	26	21
H1	2	37.16	17.54	2.2	15.8	13.66	52	26	21
H2	2	37.99	19.2	3.3	15.1	13.66	52	26	21
H3	2	37.57	18.91	4.1	16.4	13.66	52	26	21
H4	2	37.63	18.54	3.8	15.9	13.66	52	26	21
H5	2	37.87	17.75	3.5	16.1	13.66	52	26	21
I1	2	37.74	18.08	3.8	15.7	13.66	52	26	21
I2	2	38.06	17.98	3	18.3	13.66	52	26	21
I3	2	36.64	18.21	3.2	17.5	13.66	52	26	21
I4	2	36.37	17.76	7.8	15.8	13.66	52	26	21

D1.3 Calculated properties

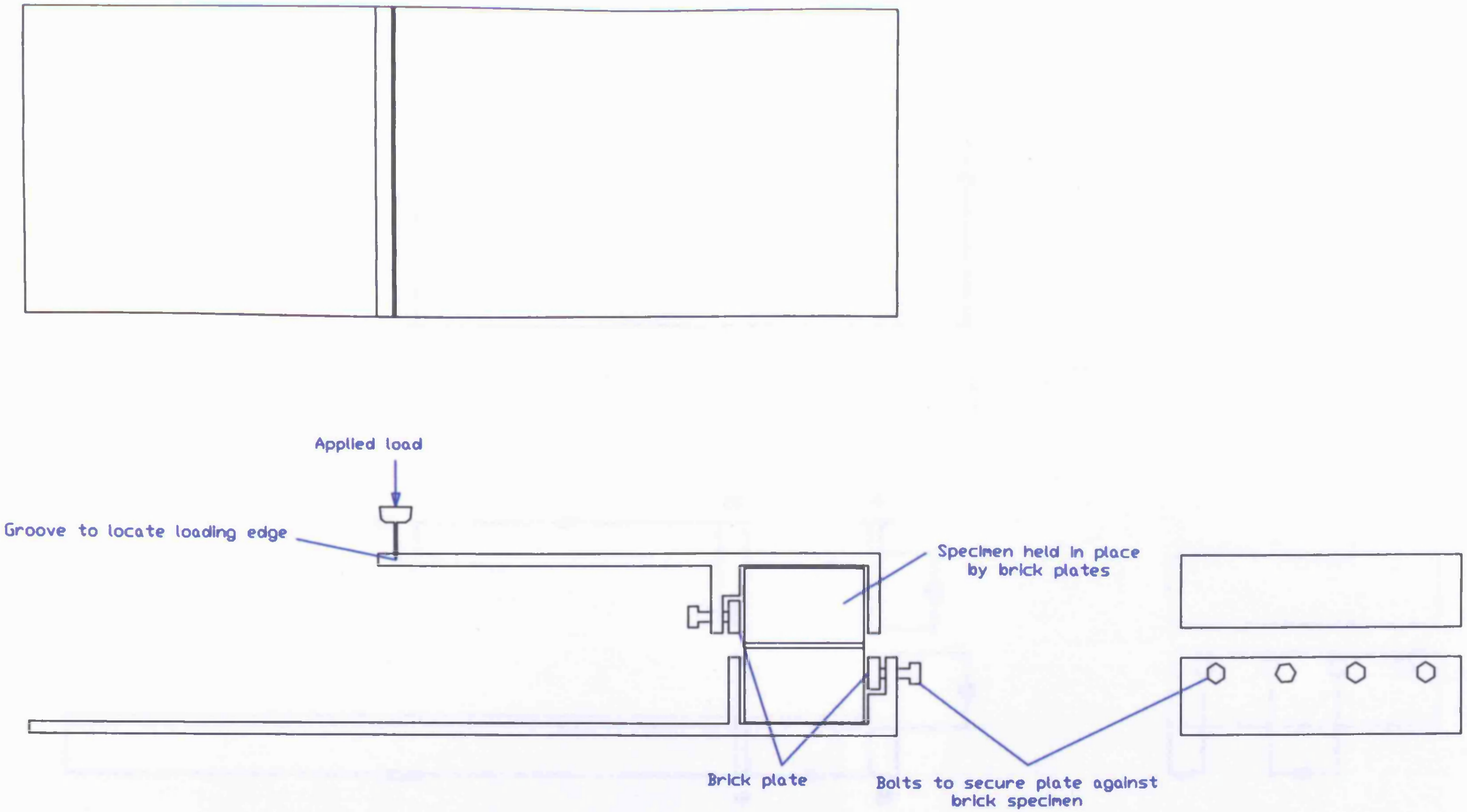
Specimen	w1	w2	loadm	m1m	M	W	Z	S
	N	N	Nmm	Nmm	Nmm	N	mm^3	N/mm^2
A1	188.32	32.18	100000.0	8662.8	108662.8	620.50	385460.3	0.25
A2	188.32	33.35	75000.0	8662.8	83662.8	521.68	385460.3	0.19
A3	188.32	30.12	67500.0	8662.8	76162.8	488.44	385460.3	0.18
A4	188.32	29.92	77500.0	8662.8	86162.8	528.24	385460.3	0.20
A5	188.32	34.63	85000.0	8662.8	93662.8	562.95	385460.3	0.22
B1	188.32	29.42	90000.0	8662.8	98662.8	577.74	385460.3	0.23
B2	188.32	29.43	65000.0	8662.8	73662.8	477.75	385460.3	0.17
B3	188.32	28.25	82500.0	8662.8	91162.8	546.58	385460.3	0.21
B4	188.32	27.47	52500.0	8662.8	61162.8	425.79	385460.3	0.14
B5	188.32	26.88	55000.0	8662.8	63662.8	435.20	385460.3	0.15
B6	188.32	28.84	75000.0	8662.8	83662.8	517.16	385460.3	0.19
B7	188.32	30.71	67500.0	8662.8	76162.8	489.03	385460.3	0.18
B8	188.32	29.23	62500.0	8662.8	71162.8	467.56	385460.3	0.16
B9	188.32	30.61	95000.0	8662.8	103662.8	598.93	385460.3	0.24
B10	188.32	35.12	57500.0	8662.8	66162.8	453.44	385460.3	0.15
C1	188.32	27.66	62500.0	8662.8	71162.8	465.99	385460.3	0.16
C2	188.32	28.84	67500.0	8662.8	76162.8	487.16	385460.3	0.18
C3	188.32	31.88	72500.0	8662.8	81162.8	510.21	385460.3	0.19
C4	188.32	28.84	50000.0	8662.8	58662.8	417.16	385460.3	0.13
C5	188.32	29.33	50000.0	8662.8	58662.8	417.65	385460.3	0.13
D1	188.32	28.65	65000.0	8662.8	73662.8	476.97	385460.3	0.17
D2	188.32	29.72	40000.0	8662.8	48662.8	378.05	385460.3	0.11
D3	188.32	29.72	65000.0	8662.8	73662.8	478.05	385460.3	0.17
D4	188.32	27.66	75000.0	8662.8	83662.8	515.99	385460.3	0.19
D5	188.32	30.02	72500.0	8662.8	81162.8	508.34	385460.3	0.19
E1	188.3	28.7	47500.0	8662.8	56162.8	407.1	385460.3	0.1
E2	188.3	27.3	45000.0	8662.8	53662.8	395.6	385460.3	0.1
E3	188.3	27.5	57500.0	8662.8	66162.8	445.8	385460.3	0.2
E4	188.3	26.4	72500.0	8662.8	81162.8	504.7	385460.3	0.2
E5	188.3	27.2	40000.0	8662.8	48662.8	375.5	385460.3	0.1
F1	188.32	28.84	65000.0	8662.8	73662.8	477.16	385460.3	0.17
F2	188.32	28.25	47500.0	8662.8	56162.8	406.58	385460.3	0.13
F3	188.32	29.23	32500.0	8662.8	41162.8	347.56	385460.3	0.09
F4	188.32	27.96	45000.0	8662.8	53662.8	396.28	385460.3	0.12
F5	188.32	29.33	87500.0	8662.8	96162.8	567.65	385460.3	0.22
G1	0.13	0.22	767.6	0.7	768.2	25.11	2043.7	0.34
G2	0.13	0.22	2463.0	0.7	2463.6	79.80	1791.5	1.25
G3	0.13	0.16	2628.4	0.7	2629.1	85.08	1957.1	1.21
H1	0.134005	0.154998	68.2	0.670023	68.87002	2.489003	1905.389	0.032326
H2	0.134005	0.148131	102.3	0.670023	102.97	3.582136	2334.106	0.039204
H3	0.134005	0.160884	127.1	0.670023	127.77	4.394889	2239.097	0.050877
H4	0.134005	0.155979	117.8	0.670023	118.47	4.089984	2155.77	0.049092
H5	0.134005	0.157941	108.5	0.670023	109.17	3.791946	1988.569	0.049258
I1	0.134005	0.154017	117.8	0.670023	118.47	4.088022	2056.115	0.051627
I2	0.134005	0.179523	93	0.670023	93.67002	3.313528	2050.675	0.040836
I3	0.134005	0.171675	99.2	0.670023	99.87002	3.50568	2024.996	0.044064
I4	0.134005	0.154998	241.8	0.670023	242.47	8.089003	1911.956	0.114295

D.1.4 The bond strength calculated for each specimen

Specimen	Failure stress N/mm^2
A1	0.25427
A2	0.193813
A3	0.175836
A4	0.200007
A5	0.217918
B1	0.230231
B2	0.169827
B3	0.212162
B4	0.139712
B5	0.145779
B6	0.194014
B7	0.17581
B8	0.163795
B9	0.242259
B10	0.151452

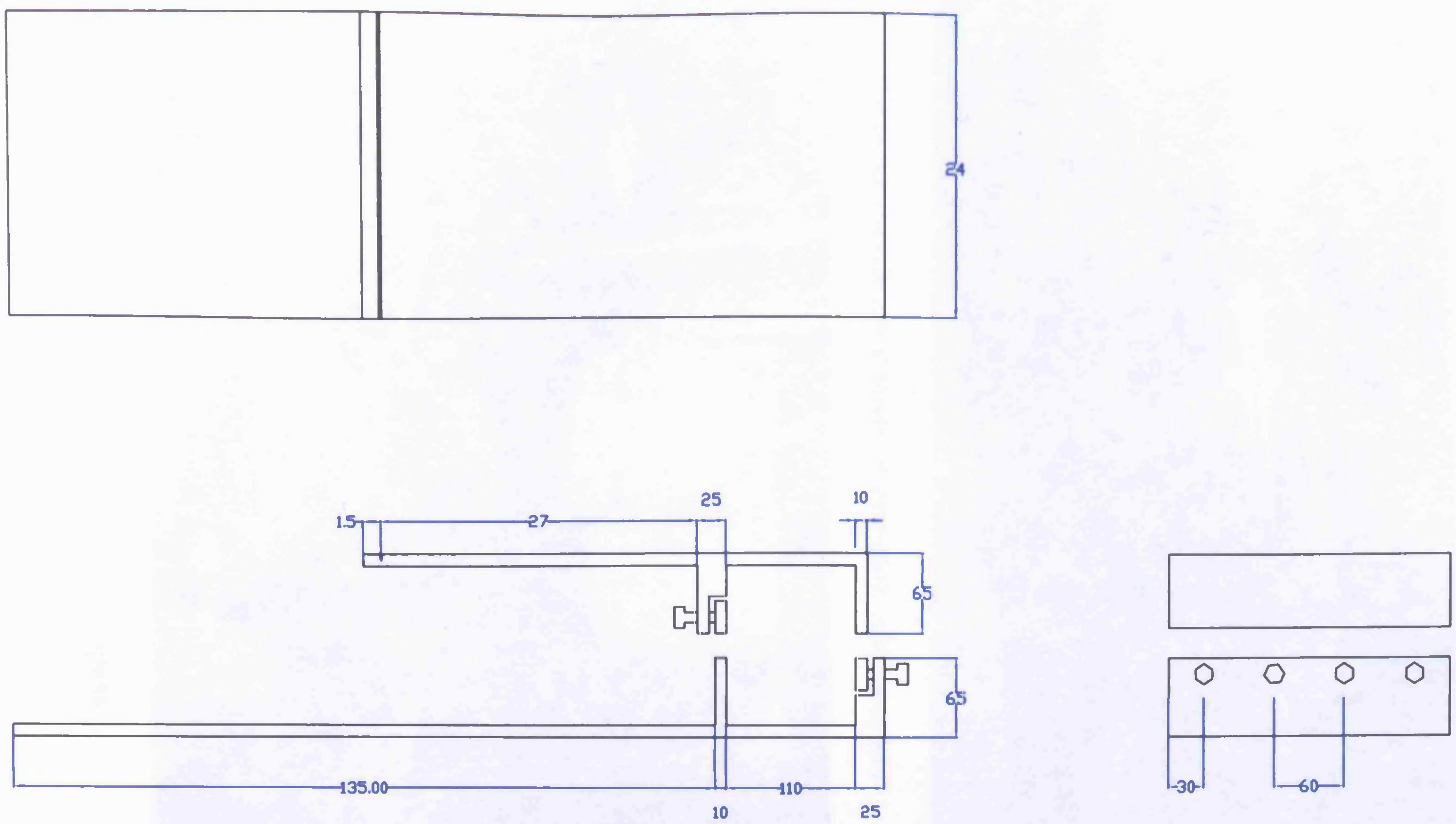
Specimen	Failure stress N/mm^2
C1	0.163865
C2	0.175893
C3	0.187839
C4	0.13361
C5	0.133589
D1	0.169862
D2	0.10941
D3	0.169813
D4	0.194067
D5	0.187922
E1	0.127574
E2	0.1216
E3	0.151793
E4	0.188083
E5	0.109523

Specimen	Failure stress N/mm^2
F1	0.169853
F2	0.127596
F3	0.09131
F4	0.121569
F5	0.224195
G1	0.338189
G2	1.246958
G3	1.209312
H1	0.032326
H2	0.039204
H3	0.050877
H4	0.049092
H5	0.049258
I1	0.051627
I2	0.040836
I3	0.044064
I4	0.114295



Drawing to show the main features of the full scale bond wrench testing jig

Drawn by:	Richard Gregory	Notes
Drawing number:	Appendix D.2.1	
Date:	September 2003	

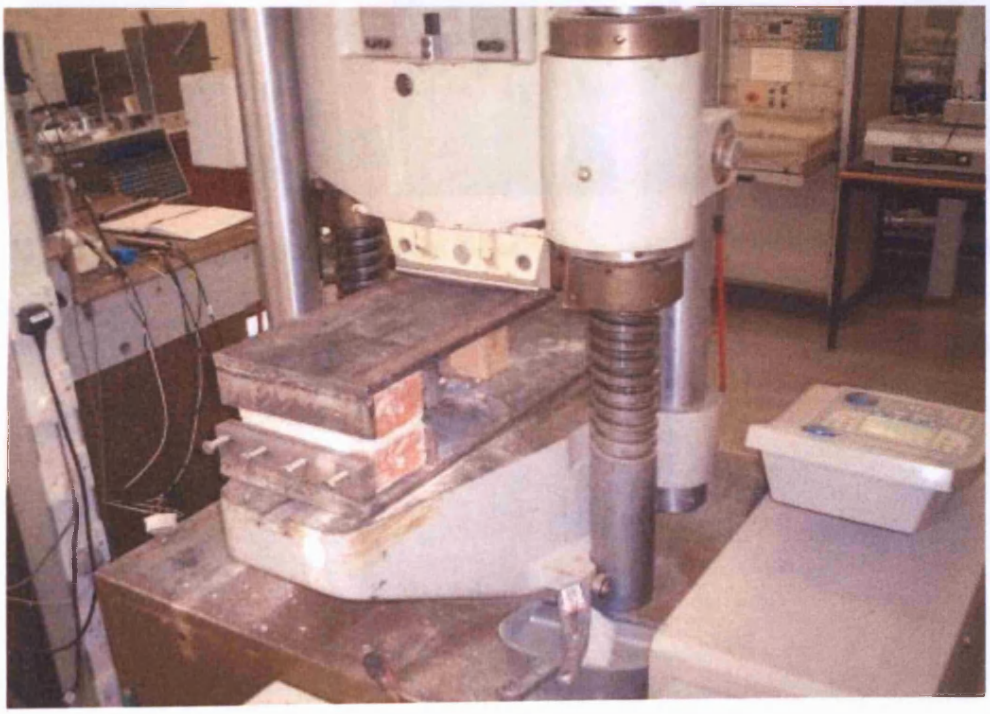


Working drawing of the full scale bond wrench testing jig

Drawn by: Richard Gregory	Notes
Drawing number: Appendix D.2.2	
Date: September 2003	

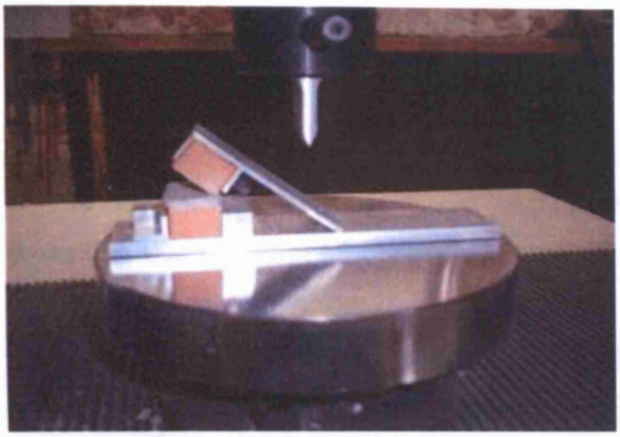
D 3 - Photographs of the equipment used for the bond wrench tests

D 3.1. The bond wrench test system for one-sixth scale couplets



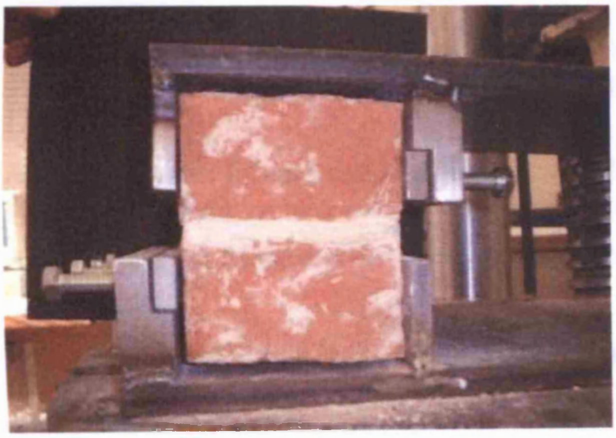
D 3.2. The bond wrench test system for full-scale couplets

D 4 - Photographs of the bond wrench test being performed



D 4.3 The one-sixth scale bond wrench test after failure has occurred

D 4.4 The mechanism for loading the full scale bond wrench testing jig.



D 4.5 The system used to hold the full-scale couplet

D 4.6. The full-scale bond wrench test after failure has occurred

Appendix E - Energy requirements

E 1 - Manufacture of new bricks

Energy used during primary manufacture of bricks

= 924 kW h per tonne[74]

Assuming that the mass of a brick is 2.5 kg

Energy required = 2.3 kW h per brick

= 8280 kJ / brick

E 2 - Re-firing reclaimed bricks

(as performed by Boon Seng see page 2-34)

A Carbolite GPC 12/200 laboratory furnace has internal dimensions of 400 x 500 x 900mm and has a power rating of 24kW, enabling it to be heated to a temperature of 1200°C.

Assume that this furnace can accommodate 60 bricks, allowing for space between the bricks to allow air circulation and the required shelving.

Assume that the furnace takes ninety minutes to reach 1200 °C.

Therefore energy requirement to re-fire 60 bricks at 1200°C for 1 hour

= 24 x 2.5

= 60 kW h

Energy required = 1.0 kW h per brick

= 3600 kJ per brick

E 3 - Mechanical removal of mortar

(as performed by Klang et al. see page 2-42)

Energy required to reclaim 42 bricks = 0.84 MJ [27]

= 840 kJ

Energy required = 20 kJ per brick

E 4 - Separation of one-sixth scale bricks in the U400 ultrasound bath

The U400 ultrasound bath with a power rating of 250W achieved stage 2 separation of one-sixth scale bricks in an average time of 134 seconds (times taken from Table 4-4)

Therefore energy requirement = 0.25 kW x 0.037 hours

= 0.00925 kW h

= 33 kJ per brick

E 5 - Carbon di-oxide emissions

Average emission of carbon di-oxide per kW h of electricity generated = 1.341 lbs[75]

which is equivalent to 0.61 kg of CO_2 per kW h

E 6 - Energy comparison

Process	Energy requirement	CO_2 emissions
	(kJ / brick)	(kg / brick)
Manufacture of new bricks	8280	1.4
Re-firing reclaimed bricks	3600	0.61
Mechanical removal of mortar	20	0.0034
Separation of one-sixth scale bricks in the U400 ultrasound bath	33	0.0056

Appendix F - Theoretical calculation of Natural frequencies

F1 - Natural frequency of a brick couplet

Given that the frequency of a vibration is given by $f = \frac{\omega}{2\pi}$

The natural frequency of a couplet can be determined from Equation (41)

$$\omega = \sqrt{\frac{\pi^2}{4L^2}\frac{E}{\rho}}$$

where
- ω Is the circular frequency of vibration
- L is the length of the couplet
- E is the Young's modulus of the couplet
- ρ is the density of the couplet

Assume typical value for Young's modulus	$E = 1\times10^{10}$	N/mm^2
Assume length (with allowance for less stiff mortar)	$L = 0.085$	m
Assume typical value for density of brick	$\rho_b = 1850$	kg/m^3

Allowance for three dimensional effects by increasing the density by

$$\rho = \rho_b \times (1+2\nu)$$

Assume typical value for Poisson's ratio $\nu = 0.2$

Therefore ρ $= 1850\times(1+2\times0.2)$
$= 2590$

Therefore ω $= \sqrt{\frac{\pi^2}{4L^2}\frac{E}{\rho}}$

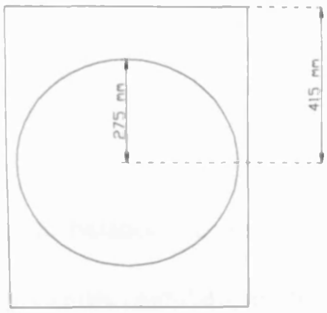
$$= \sqrt{\frac{\pi^2}{4\times0.085^2}\frac{10^{10}}{2593}}$$

$= 36312$ rad/s

Therefore the natural frequency of a couplet $F = \frac{36312}{2\pi} = 5779$ cycles per second

Appendix G - Design calculations

G 1 - Load on plate from water pressure



pressure on plate = depth of water x density of water x gravitational constant
= h . ρ .g

by symmetry, average pressure on plate is at h = 0.415 m

∴ average pressure on plate with full tank = 0.415 m x 1000 kg/m^3 x 9.81 N/kg
= 4071.15 N/m^2

area of plate and membrane = πr^2
= π (550 m /2)^2
= 0.2376 m^2

∴ total force on plate = 4071.15 N/m^2 x 0.2376 m^2

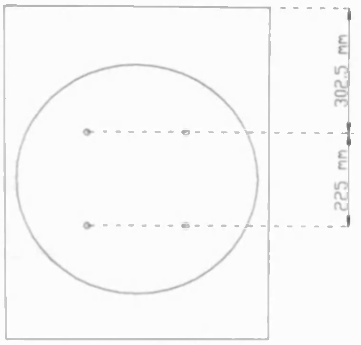
total force on plate when tank is full = 967.24 N

which is equivalent to a weight = 98.6 kg

Hence

Equivalent mass on actuator = 98.6 kg

G 2 - Load on Springs



springs to balance the pressure from the water behind the plate

from previous calculations, force of water = 967.24 N

design for

2 springs at a depth of 302.5 mm from the top of the tank
2 springs at a depth of 527.5 mm from the top of the tank

let a be the force on the top springs
let b be the force on the bottom springs

in order to balance the water pressure $2\,(a + b) = 967.24$ N

$\therefore\ a + b = 483.62$ N .... **Equation A 1**

force $\propto$ water pressure $\propto$ depth

$\therefore$ force on springs $\propto$ depth
$\therefore\ a / b = 302.5 / 527.5$
or $a = (302.5 / 527.5)\,.\,b$

$\equiv a = 0.5735\,b$ .... **Equation A 2**

substituting Equation A 2 into Equation A 1 gives

$0.5735\,b + b = 483.62$ N
$\therefore\ 1.5735\,b = 483.62$ N

$\therefore\ b = 307.36$ N .... **Equation A 3**

substituting Equation A 3 back into Equation A 1 gives

$a + 307.36$ N $= 483.62$ N

∴ a = 176.26 N

hence

design load on upper springs = 176.26 N
design load on lower springs = 307.36 N

allow a factor of safety of 1.2

upper springs to withstand force = 1.2 . 176.26 N
= 211.51 N

lower springs to withstand force = 1.2 . 307.36 N
= 368.83 N

hence

upper springs need to withstand compression of 211.51 N
lower springs need to withstand compression of 368.83 N

G 3 - Spring properties

Maximum design load to be taken by spring	= maximum load with safety factor on bottom spring = 368.83 N
Minimum design load to be taken by spring	= design load on top spring = 176.36 N
∴ spring has to cover range of force	= 368.83 N - 176.36 N = 192.47 N

∴ spring must have stiffness to allow a difference of 192.47 N to be achieved

Maximum length available to allow spring to fit	= 120 mm
Assume solid length of spring	= 80 mm
∴ maximum change in length of spring	= 120 mm - 80 mm = 40 mm
spring constant (stiffness)	= force (N) / change in length (m)
∴ minimum spring constant	= 192.47 / 40 mm = 4.812 N/mm

Try springs with spring constant value of 5 N/mm

To give design load of top spring, spring must be compressed	= 176.36 N / 5 N/mm = 35.27 mm

∴ if top spring is at maximum allowable length for design load:

maximum unloaded length of spring	= 120 mm + 35.27 mm = 155.27 mm

Try springs with an unloaded length of 150mm

top springs to provide load	= 176.36 N
∴ design length of top springs	= 150 mm – 176.36 N / 5 N/mm
design length of bottom springs	**= 114.728 mm**
bottom springs to provide load	= 368.83 N
∴ design length of bottom springs	= 150 mm – 368.83 N / 5 N/mm
design length of bottom springs	**= 76.234 mm**

minimum design length minus half the maximum amplitude must be greater than the solid length, or springs will become full compressed and limit movement of the plate.

Maximum amplitude of actuator = 17 mm

∴ solid length of spring must be less than = 76.234 mm − 17 mm /2
= 67.734 mm

maximum solid length allowable = 67 mm

Appendix H - Details of components used

H 1 – Accelerometers

H 1.1 Kulite 2500g accelerometer

Kulite 2500 g accelerometer	
model number	GS-500-2500G
serial number	4056-2-16
range	±2500 g
sensitivity	0.027 mV/g
excitation	10 VDC

Provided by

Kulite Semiconductor Products, INC.
One Willow Tree Road
Leonia
N.J. 07605

H 1.2 RDP 500g accelerometers

RDP 500 g accelerometer	
model number	060-f482-08
serial number	877053
range	±500 g
sensitivity	0.108 mV/g
excitation	5 VDC

RDP 500 g accelerometer	
model number	060-f482-08
serial number	877054
range	±500 g
sensitivity	0.089 mV/g
excitation	5 VDC

Provided by

RDP Electronics Ltd.
Grove Street, Heath Town, Wolverhampton
WV10 0PY

H 1.3 RDP 50g accelerometers

RDP 50 g accelerometer	
model number	060-f482-05
serial number	852065
range	±50 g
sensitivity	0.811 mV/g
excitation	5 VDC

RDP 50 g accelerometer	
model number	060-f482-05
serial number	852066
range	±50 g
sensitivity	0.890 mV/g
excitation	5 VDC

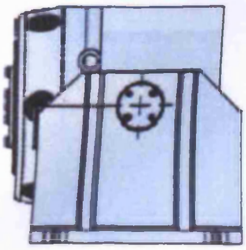
Provided by

RDP Electronics Ltd.
Grove Street, Heath Town, Wolverhampton
WV10 0PY

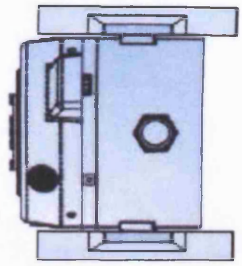
H 2 - Derritron VP50 vibrator and 1500 W.T. Amplifier

Rated output force	
Sine force	500 lbf pk (2224 N)
Random force	300 lbf rms (1338 N)
Shock force	1000 lbdf pk, 11 msec pulse
Displacement	0.7" pk-pk (17.8mm), continuous, 0.75" pk-pk (19mm), between stops
Velocity	60 inches (1.52m/s) p/sec pk
Acceleration	100 g pk, bare table 200 g pk, shock pulse, bare table
Frequency Range	DC- 4 kHz, bare table
Physical characteristics	
Moving element weight	5.5 (2.5 Kg) pounds
Fundamental resonance	3800-3900 Hz
Rated armature current	80 A rms, max
Specimen mounting	9 internally threaded, replaceable stainless steel inserts (1/4-20 or M6) 4 ea on a 5.0" & 2.5" bolt circle and one on center
Armature guidance and suspension system	Six LINK-ARM flexures incorporating twelve "metallastic" bushings for lateral and rotational restraint
Axial suspension stiffness	450 lb/in,(8.5 Kgf /mm) nominal
Stray Magnetic Field	<10 gauss @ 4" above table, stray field adjustable
Shaker weight	390 lbs (234 kg) Shaker only 780 lbs (355 kg) w/ Low Frequency Isolation Base 535 lbs (243 kg)w/Solid Mount Base
Shaker cooling	Air cooled by suction type remote centrifugal blower w/ 10 ft hose
Heat dissipation	10000 BTU/hr @ 300 CFM max.
Environmental conditions	
Ambient temperature	40° f to 100° F @ 85% RH max.
Force derating	Reduce 1% per 4° F

The actuator is represented in the following manner in the prototype working drawings



Side Elevation



Plan Elevation

Provided by

Derritron Vibration Products
12383 Doherty Street Riverside,
CA 92503

H 3 - Springs

Spring properties	
unloaded length	150 mm
spring constant	5 N/mm
wire diameter	4 mm
outer diameter	30 mm
inner diameter	22 mm
maximum compression	425 N
solid length	65 mm
winding	right handed
special conditions	withstand high frequency cyclic loading
ends	closed and ground

Design properties		
Property	Top Springs	Bottom springs
design load	176.26 N	307.36 N
design length	164.75 mm	138.53 mm

Provided by

Flexo springs
Hill Street
Kingswood
Bristol
BS15 4HB
www.flexosprings.com