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2015 J. Phys.: Conf. Ser. 628 012105

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Accurate Damage Location in Complex Composite Structures and Industrial Environments using Acoustic Emission

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Abstract. The ability to accurately locate damage in any given structure is a highly desirable attribute for an effective structural health monitoring system and could help to reduce operating costs and improve safety. This becomes a far greater challenge in complex geometries and materials, such as modern composite airframes. The poor translation of promising laboratory based SHM demonstrators to industrial environments forms a barrier to commercial up take of technology. The acoustic emission (AE) technique is a passive NDT method that detects elastic stress waves released by the growth of damage. It offers very sensitive damage detection, using a sparse array of sensors to detect and globally locate damage within a structure. However its application to complex structures commonly yields poor accuracy due to anisotropic wave propagation and the interruption of wave propagation by structural features such as holes and thickness changes. This work adopts an empirical mapping technique for AE location, known as Delta T Mapping, which uses experimental training data to account for such structural complexities. The technique is applied to a complex geometry composite aerospace structure undergoing certification testing. The component consists of a carbon fibre composite tube with varying wall thickness and multiple holes, that was loaded under bending. The damage location was validated using X-ray CT scanning and the Delta T Mapping technique was shown to improve location accuracy when compared with commercial algorithms. The onset and progression of damage were monitored throughout the test and used to inform future design iterations.

1. Introduction

The use of damage detection tools to monitor the health of engineering structures throughout their service lives has the potential to facilitate significant cost saving by reducing maintenance and down time, whilst improving safety. For example commercial passenger aircraft spend on average 6.6 days per year undergoing inspection. A key requirement of such a structural health monitoring (SHM) system is the ability to accurately determine the position of any damage occurring within a structure. This becomes a very difficult challenge in complex materials and geometries, such as those found in modern composite aerospace structures. It is this poor translation from promising laboratory based

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SHM demonstrators to industrial environments that forms the greatest barrier to commercial up take of technology.

The acoustic emission (AE) technique is a passive damage detection technique with a number of advantages that make it well suited to the in service monitoring required for SHM. The technique uses piezoelectric transducers to detect elastic stress waves (similar to ultrasound waves) that are released by the growth of damage itself and no external excitation is required. As such a damage mechanism must be active in order for it to be detected using AE, i.e. when a structure is under load, or in service. This means that minimum detectable defect size is very small, because a defect need only be active/growing in order for it to be detected. The most powerful attribute of the AE technique is the ability to globally locate damage within a structure using a sparse array of sensors [1]. However, as with all other damage detection approaches the accuracy of AE location calculation is seen to reduce in complex materials and structures. The observed errors results from the assumptions in current commercial algorithms that AE waves travel at a single and constant velocity in all directions and that their path from release at a damage site to detection at a transducer is direct and uninterrupted. Neither of these assumptions are true in complex geometry composite structures where anisotropic wave speed are observed and holes, thickness changes and curvatures can interrupt the propagation path [2].

A variety of approaches have been investigated to account for the anisotropic propagation behaviour experienced in composite materials. Some improvements have been demonstrated through the assumption of an elliptical wave front [3] and commercial software packages now allow the specification of an elliptical velocity profile. However, the velocity profiles in composite materials can often be more complex than this. Beamforming techniques have been used with localised arrays to determine the direction of an arriving wave [4, 5] and Aljets *et al* used the temporal separation of different wave propagation modes to determine the distance, as well as the direction, from the array [5]. Ciampa and Meo [6] used a triangular array of three closely spaced sensor pairs (six sensors in total), allowing the source position to be described by six non-linear equations. Solving the equations with an iterative Newton method provides a source position without the need for prior knowledge of the wave velocity behaviour in the material. However, processing times are high, at around 2 seconds per event, and sensor numbers required are double for similar coverage. Despite very promising results all of the above techniques are flawed by their inability account for geometric complexities that invariably exist in an industrial environment.

An alternative approach to achieving accurate AE source location in complex geometries is that of mapping. The concept of mapping requires that a relationship is formed between known physical positions of AE sources upon a structure and the resulting wave arrival times (and therefore the difference in arrival times between sensor pairs Δt s) at an array of transducers from signals originating at these positions. Such a methodology has the potential to facilitate accurate source location in highly complex materials and structures, accounting for variations in wave speed, changes in thickness, holes, etc. Scholey *et al* [7] approached the mapping concept by analytically determining the expected arrival times (and therefore Δt s) for an anisotropic composite panel from an array of points, or source positions. They describe the best-matched point search method which compares measured Δt s with the analytically determined map to identify the array point at which the difference is minimised and hence give the location. The accuracy is affected by the resolution of the mapping array, so small spacings of 1-2mm are used, and it is also important that accurate wave velocities are known for a given material. The approach is also not well suited to dealing with complex geometries, in which the calculation of arrival times becomes far more problematic. A more robust approach, known as Delta T Mapping, was proposed by Baxter *et al* [8] for location in complex geometries. used artificial AE sources to determine Δt s from known grid positions and therefore generate a map of Δt s to aid source location in complex metallic structures. For Delta T Mapping H-N sources [9, 10], generated at known positions, are used to generate contour maps of constant Δt for each sensor pair, linearly interpolating between training points improves the mapping resolution. Mapped contours corresponding to measured Δt s from real AE test data can then be selected for each sensor pair and overlaid to find a crossing point and hence a prediction of source location. Hensman *et al* [11]

followed a similar methodology, but represented the relationship between the Δt s and the spatial grid using Gaussian processes. Both mapping approaches were shown to improve source location in metallic structures with complex geometries and inherently compensate for variations in wave speed and any obstructions in the wave propagation path. The Delta T Mapping approach has also been demonstrated to improve location accuracy in complex geometry composite structures; detecting and locating fatigue damage [12].

In this work the authors demonstrate the use of the Delta T Mapping technique on a complex geometry composite aerospace component undergoing validation testing in an industrial environment. The tubular component is manufactured from carbon fibre composite with varying wall thicknesses and multiple holes or cut outs. The tube was loaded under bending and the location of damage was validated using X-ray CT scanning. The Delta T Mapping technique was shown to improve location accuracy when compared with commercial algorithms. The onset and progression of damage were monitored throughout the test and used to inform future design and manufacturing iterations.

2. Delta T Mapping Location

The following section details the Delta T Mapping procedure. Firstly the mechanism for wave arrival time determination is discussed, then the methodologies for map training and location calculation are described.

2.1. Arrival time determination

Traditionally the detection of arriving AE waves relies on a user defined threshold level, the crossing of which indicates the signal arrival. It is common that some signal is present prior to the first threshold crossing and the effects of attenuation can mean different phases of the wave trigger its arrival. All of which can lead to additional errors in a calculated location. In this work we adopt an Akaike Information Criterion (AIC) based method to determine wave arrival times. The approach aims to identify the first wave motion by identifying a change in entropy between the uncorrelated noise prior to signal onset and the highly correlated signal after signal arrival. It involves the minimisation of equation (1) for a time series x . The minimum of the AIC function corresponds to the signal onset time, as can be seen in Figure 1 and has been demonstrated to be a very accurate and reliable measure of AE signal arrival time for location calculation [11, 13, 14].

$$AIC(t) = t \log_{10}(\text{var}(x[1; t])) + (T - t - 1) \log_{10}(\text{var}(x[t; T])) \quad (1)$$

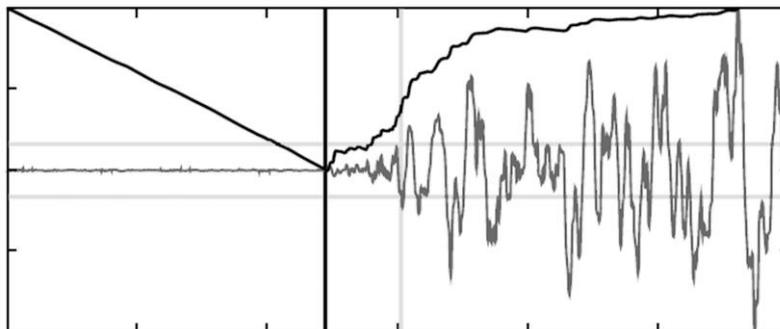


Figure 1. Arrival time estimation using AIC based approach. The vertical grey line indicates the threshold based arrival time. The black trend is the AIC function and the vertical black line indicates the estimated arrival time at its minimum.

2.2. Delta T Mapping Methodology

The Delta T Mapping procedure is described in detail by Baxter *et al* [8] and consists of 5 main steps which are outlined in brief below:

Determine area of interest - Delta-T source location can provide complete coverage of a part or structure, or it can be employed as a tool to improve source location around specific areas of expected fracture, which could potentially be identified via finite element modelling.

Construct a Map System - A grid is placed over the area of interest within which AE events will be located. It should be noted that sources are located with reference to the grid and not the sensors and it is not required that sensors be placed within the grid.

Obtain time of arrival data from an artificial source – An artificial source (nominally a H-N source [9, 10]) is generated at the nodes of the grid to provide AE data for each sensor. An average result of several sources is used for each node. Missing data points can be interpolated from surrounding nodes.

Calculate Delta T map – Each artificial source results in a difference in arrival time or Delta T for each sensor pair (an array of four sensors has six sensor pairs). The average Delta T at each node is stored in a map for each sensor pair. The resulting maps can be visualised as contours of constant Delta T.

Locating real AE data – The Delta T values from a real AE event are calculated for each sensor pair. A line of constant Delta T equivalent to that of the real AE event can then be identified on the map of each sensor pair. By overlaying the resulting contours, a convergence point can be found that indicates the source location. As with time of arrival, a minimum of three sensors is required to provide a point location and more sensors will improve the location. In theory all the lines should intersect at one location, however in practice this is not the case. Thus in order to estimate a location all convergence points are calculated and a cluster analysis provides the most likely location.

3. Test setup and configuration

The component under test takes the form of a composite tube, with dimensions in the order of 550mm in circumference and 600mm in length, shown in Figure 2. The complexity of the structure is increased by a number of holes and inserts seen as well as a significant increase in thickness under central mounting bracket. The tube was restrained at its centre using the mounting bracket observed in Figure 2 and loaded in bending. The mounting orientation and loading direction are shown schematically in Figure 3. The tube was subjected to five quasi-static loading cycles and was unloading between each cycle. The applied loads represented 11%, 48%, 58%, 77% and 100% of the final load achieved. The final failure occurred at the bracket attachment point and failure of the tube itself was not achieved.

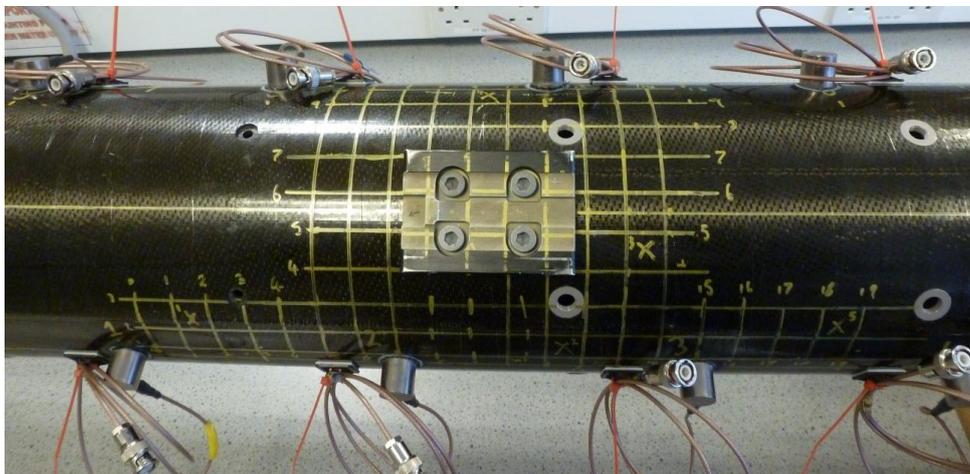


Figure 2. Sensor layout and Delta T Mapping grid on composite component

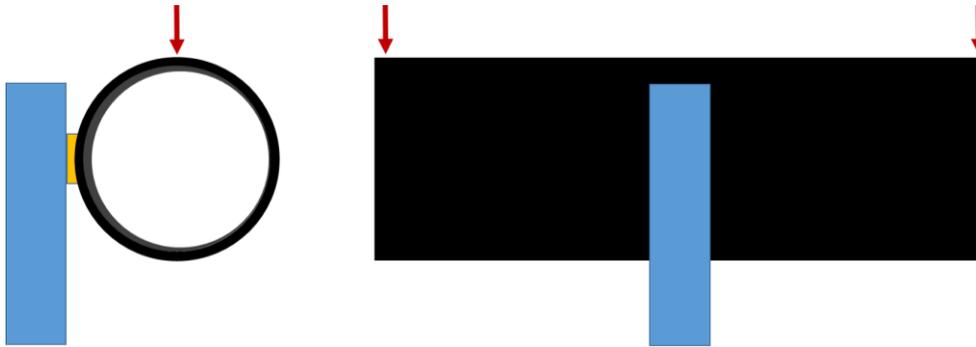


Figure 3. Schematic of composite tube loading arrangement

The tube was instrumented with eight Pancom P15 AE transducers, attached using a cyanoacrylate adhesive that provides an acoustic coupling as well as mechanical attachment. They were arranged in two rows along the length of the tube, as shown in Figure 2, placed 100mm circumferentially either side of the mounting bracket (200mm total separation). The transducer spacing along the rows was 160mm and the two rows were offset by 80mm in the axial direction. A Delta T Mapping training grid was applied to the structure using a 20mm spacing (Figure 2). The grid was an ‘inverted T’ shape spanning up to 380mm in the axial direction and 200mm in the circumferential direction. Five H-N sources were conducted at each available grid point and the resulting signals were recorded for the training of delta t maps. A MISTRAS PCI-2 AE system was used to record all AE data using a threshold level of 45dB. AE waveform data were recorded at 2MHz and used in post processing to correct the signal arrival times based on the AIC function in equation (1). AE monitoring was conducted throughout all five loading and unloading cycles.

4. Results and discussion

Figure 4 presents an image from the X-ray CT inspection undertaken post-test, after completion of all five load cycles. The image shown represents a slice through the thicker reinforced section beneath the central mounting bracket and reveals the cross-section of a delamination crack identified by the red ellipse. A second feature can also be identified in the CT image at the opposite side of the thicker reinforced section. It is not clear from the geometry of this feature whether or not it is a crack, it is noted that the geometry of this feature is different to that of the identified delamination crack. In particular the orientation with which it propagates through the material is different and in previous similar the observed damage in these regions is similar to that of the identified delamination crack. The image in figure 4 represents the final state of the damage following all loading cycles; however, it is cannot be determined from this image at what stage of testing this damage initiated.

During the first loading cycle only six AE events were recorded hence these results are not presented here and instead we first consider the second load cycle. Figures 5 and 6 present the traditional time-of-arrival location results and the Delta T Mapping location results, respectively, for the second loading cycle. The position of the hanger is represented in both figures by a solid rectangle and the position of the hole and insert below the hanger is identified by a solid circle. An area of damage identified by post-test X-ray CT inspection is indicated by a light grey rectangle and represents a large area of delamination. It can be seen in both cases that significant amounts of AE have been detected and located in the locality of this damage. This demonstrates the sensitivity of the AE technique to detect the onset of such damage at an early stage of the test and at a load less than 50% of maximum applied load, which did not induce ultimate failure in the composite structure. The TOA locations are located close to the identified damage region but the majority are located outside of this area. Whereas the Delta T Mapping locations are centred within the damage region; demonstrating the improvement in accuracy achieved. This equates to an improvement in location accuracy over the traditional TOA algorithm of approximately 50mm.

The presented location results suggest that the second feature identified in figure 4 did not develop during the testing undertaken. The origin of this feature is not clear and will be the subject of further investigation. It is possible that it is a manufacturing defect existing prior to testing that did not grow during these tests or that it is damage that occurred during the failure of the mounting bracket (a violent failure that resulted in the decoupling of the transducers).



Figure 4. X-ray CT data from post-test inspection of the tube. The image shows a slice through the reinforced section of the tube below the attachment bracket. The red ellipse identifies the damage corresponding to the highlighted regions in figures 4 and 5.

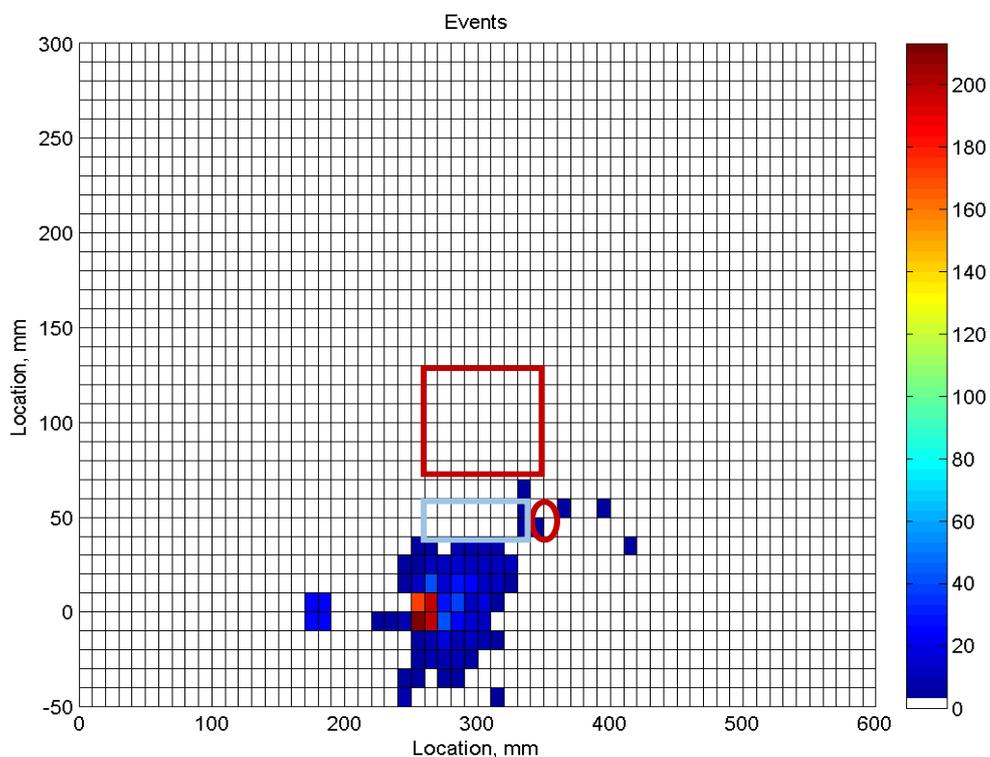


Figure 5. time-of-arrival locations for load cycle 2 – the red rectangle and circle represent the bracket location and the bolt hole seen below it, the light blue rectangle represents the region in which damage was identified by X-ray CT scanning

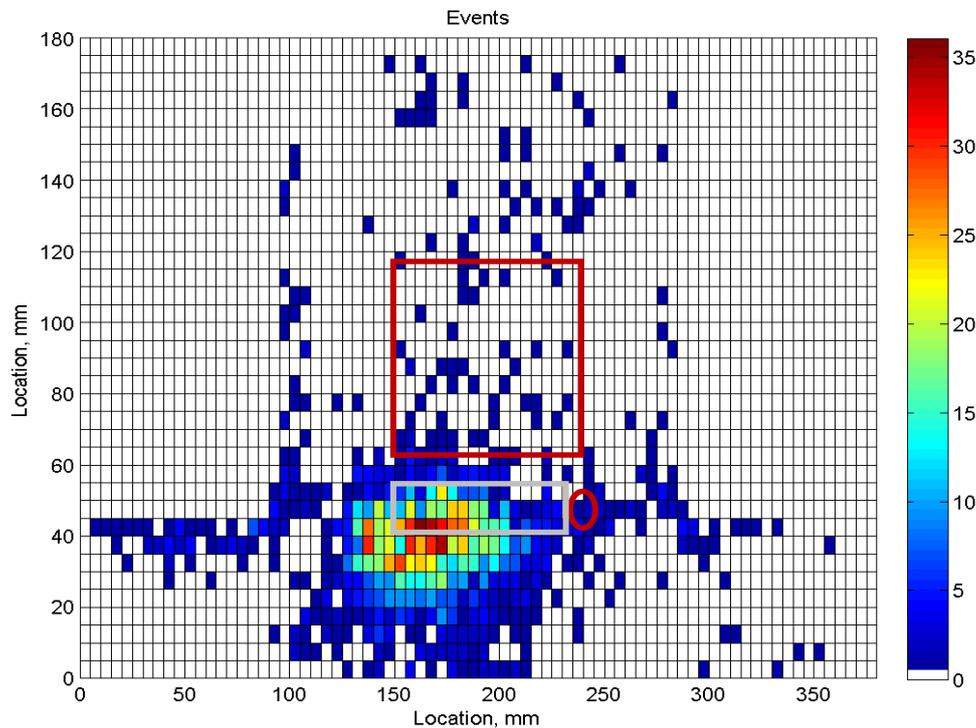


Figure 6. time-of-arrival locations for load cycle 2 – the red rectangle and circle represent the bracket location and the bolt hole seen below it, the grey rectangle represents the region in which damage was identified by X-ray CT scanning

The number of AE events located within the region of the identified damage continued to increase as the remainder of the loading cycles were completed, suggesting that the damage continued to grow throughout the testing. Figure 7 shows a plot of cumulative AE hits located in the region of identified damage versus the applied load for all five cycles (cycle 1 is not visible on this scale). Following the second load cycle the Felicity effect can be observed, whereby significant AE activity begins at a load lower than that of the previously applied maximum. The ratio of the load at which AE activity begins again and that of the previous maximum is known as the Felicity ratio and it can be used to quantify this effect [1]. Composite materials often demonstrate the Felicity effect during repeated loading, even if no significant damage has been induced. As a general rule, if the Felicity ratio is below 0.9 then it can be assumed that damage is present in a structure and the lower the Felicity ratio becomes the confidence that damage is present becomes greater and its expected severity of damage increases. Following the second load cycle Felicity ratios of 0.8, 0.8 and 0.7 were recorded for cycles 3, 4 and 5, respectively. This indicates that damage was induced in this region during the second load cycle and that reducing Felicity ratio indicates that this damage continued to grow with subsequent load applications. It should be noted that this demonstrates a very confident detection of damage using the AE technique and this was achieved at a load far below the maximum applied in a test where catastrophic failure of the composite structure did not occur. This highlights the potential of the AE technique to provide sensitive SHM with the ability to detect and accurately locate damage well before ultimate failure of a structure.

5. Conclusion

It has been demonstrated that the Delta T Mapping algorithm can improve location accuracy in complex structures compared with the traditional TOA algorithm. The ability to detect and accurately locate damage within a complex geometry composite aerospace component was demonstrated and

validated using X-ray CT inspections. The presented results highlight the potential for the AE technique to bridge the gap between laboratory demonstrators and application in challenging industrial environments. This is seen as a key barrier to the uptake of SHM technology and systems by industry and these results show that the AE technique has the capability to achieve this.

The AE analysis undertaken was used to inform component designers of the onset and growth of damage occurring within the component, which occurred far below the ultimate failure load. CT data normally gives a snapshot of the final condition of a component, whereas the AE data informed designers when and where damage occurs during the test and has provided valuable understanding to support future design and manufacture iterations.

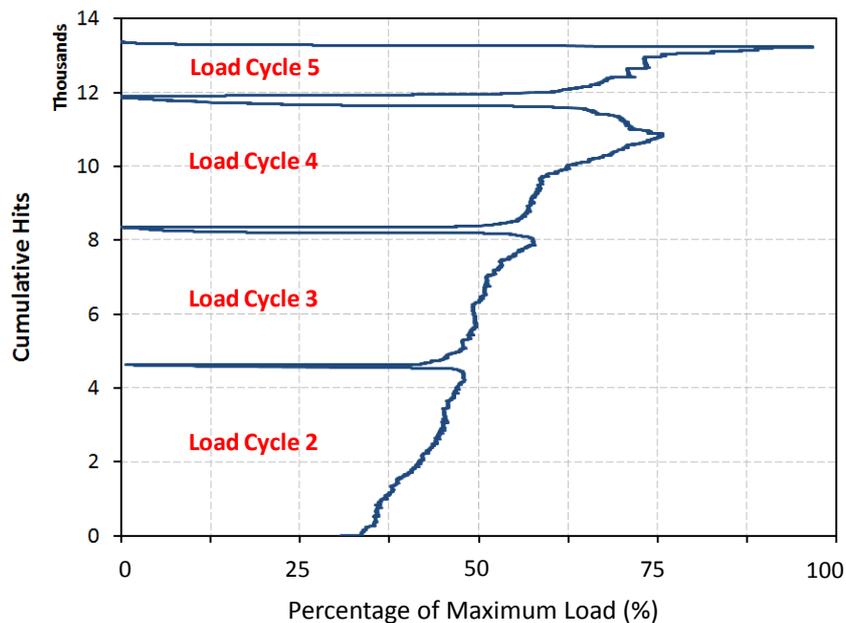


Figure 7. Cumulative AE hits versus applied load for all five load cycles

6. References

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