

Exploring Acoustic Emission for Integrity Assessment of Bolted Anchors used in Rock Climbing and Rope Access

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Abstract

Anchor Bolts are critical safety elements in rock climbing and rope access, where the unexpected failure of a bolt could result in serious injury or death. There is currently no thorough non-destructive method for assessing the integrity of such bolts. It is proposed that the Acoustic Emission (AE) released during tensile loading could be used to characterise the condition of a bolt. To evaluate the efficacy of AE for integrity assessment, two resin and two expansion bolts were installed in C40 concrete. The concrete was then restrained in a load machine with the bolts loaded in tension until failure. The resin bolts achieved a higher maximum load than the expansion bolts, with all bolts exceeding the minimum expected strength of 15 kN. AE activity was observed to increase with applied load for all tests. In the resin bolt tests a marked increase in AE activity occurred shortly before failure. Linear Discriminant Analysis was applied to AE features extracted from the waveforms, which demonstrated that AE hits recorded below 85% of the maximum load can be distinguished from those recorded above this threshold. These results indicate that AE shows promise for the integrity assessment of in-situ bolts.

Keywords: Acoustic Emission, Bolts, Linear Differential Analysis, Integrity Assessment, Rope Access

1. Introduction

Anchor bolts are often installed in concrete and used in rope access work to aid in the vertical access required to inspect large civil infrastructure. They are also common in the recreational sport of rock climbing, where pre-placed bolts in rock are used as a safety measure to catch any falls whilst climbing as shown by Figure 1.

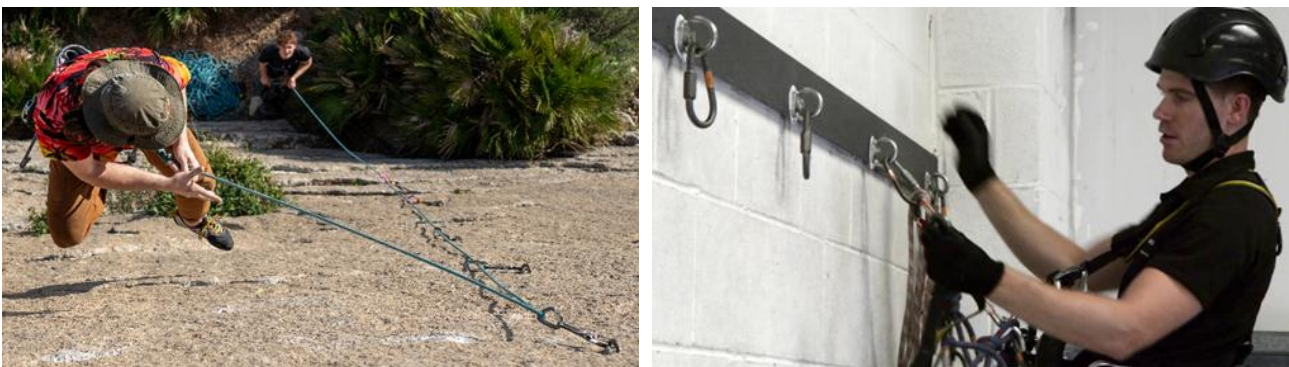


Fig. 1 Left: An example of how bolts are used as a safety measure in Sport Climbing in the event of a fall. Fig 1. Right: A rope access Technician demonstrating how to attach yourself to anchor bolts [1].



Both use cases are examples where the failure of a bolt could result in serious injury. Bolts used in rope access in the UK are subject to both the Working At Height Regulations [2] and British Standard 7883:2019 [3] where the inspection methods and condition requirements are detailed. It is recommended that installed bolts have a minimum static strength of 15 kN. Bolts are required to be tested every 6-12 months, where they are loaded in tension to 6 kN for 15 seconds. The visible areas are also inspected for signs of corrosion or damage, but notably most of the bolt is embedded in the structure and is hidden from view. Currently no Non-Destructive test method exists to thoroughly inspect or characterise the condition of in-situ bolts.

Whilst the same bolts are used in rock climbing, they are not subject to the same regular inspections as in the context of rope access, nor are they required to be installed by qualified professionals. It would be unusual for a bolt installed for the purposes of rock climbing to be tensile tested at any point. Concerns over the integrity of bolts are amplified by the fact that in a fall bolts can be shock loaded with magnitudes as high as 6 kN [4], higher than the static loads expected in rope access.

There are primarily two types of bolts, expansion bolts and resin/glue bolts as shown in Figure 2. Both are installed by first drilling a hole in the material and then brushing out any loose debris. In the case of expansion bolts, they are first hammered in up-to the nut, a separate hanger is then attached, lastly the nut is tightened. Tightening the nut pulls the cone outwards, expanding the collar, and providing outward pressure. The hanger is a separate part which goes between the nut and the materials surface and provides a loop as an attachment point. For resin bolts the hanger is a part of the bolt itself. To install resin bolts the hole is instead filled with two-part structural epoxy, the bolt is then pushed into the hole and the epoxy left to set. The British Mountaineering Council (BMC) has written an installation guide covering both types of bolts in more detail [5].



Fig. 2. The two bolt designs used in this paper. A typical Expansion Bolt with a hanger (left) and Resin/Glue Bolt (right). [6], [7]

The BMC have also carried out limited tensile testing on a variety of bolts installed in Limestone [8], finding that most commercially available bolts can withstand 15 kN when installed correctly, however the Hilti 2000 Anchor Tester used within their study was only capable of producing 20 kN and therefore loads exceeding that were not applied.

A thorough report on bolts has been published by the Union Internationale des Associations d'Alpinisme (UIAA) [9], containing an overview of load requirements and installation instructions. Included is a study of 148 different bolt types, where they were subjected to a quasi-static tensile test until the load reached 25 kN or failed. 21% of the bolts failed before reaching 25 kN. Of the 10 bolts that failed before reaching 15 kN, 50% were due to rock failure, 30% due to rock-bolt bond failure, and 20% due to failure of the bolt itself. It should be noted that the bolts were placed in good quality rock samples for the purposes of testing. It's expected that real in-situ bolts would produce higher failure rates, either due to corrosion, fatigue from use, or inconsistent placement in natural rock. Similarly to the British Standards for rope access and the BMC testing, the inspection method is limited to simple tensile tests and visual inspection. It's possible that submaximal loading as an inspection method could cause damage to the surrounding material, weakening the overall strength of

the bolt. This possibility further highlights the need for a non-destructive method which can ascertain the integrity and determine if significant damage has occurred during loading.

Acoustic Emission (AE) is the term given to describe the release and propagation of elastic waves in a material or structure following damage. These elastic waves can be measured and specific features extracted. AE has been used extensively for damage detection and characterisation in both concrete [10][11] and rock [12]. More relevant is its application to rebar pull out tests [13], where AE was used to monitor the bond integrity between partially embedded steel in concrete. Given AE can be used to identify damage in rock and concrete, and its proven application to rebar pullout, it has potential to be used for integrity assessment of bolts.

The aim of this presented work is to determine if AE activity can be correlated with damage and the eventual failure of bolts in concrete, and to assess if AE features can be used as an indicator of damage progression. If AE activity or features can be linked to damage progression, it would likely be possible to evaluate the integrity of a bolt without loading it to failure. To explore this, bolts were installed in concrete blocks and then tensile tested to failure whilst monitoring for AE.

2. Methodology

The C40 concrete used in this test was mixed in one batch with mix proportions of 1:2.2:3.8:0.46 for cement, fine aggregate, coarse aggregate, and water respectively. The mix had Slump and Vebe values of 25 mm and 16 seconds. Six 100 mm³ cubes and six 300 x 150 mm cylinders were also poured for compressive and indirect tensile testing. Before testing the concrete was allowed to cure for a minimum of 28 days. Using the small cube and cylinder samples the mix was found to have a compressive strength of 43.2 MPa and an indirect tensile strength of 3.46 MPa. The large blocks used for tensile testing had dimensions of 300 x 300 x 200 mm, in order to have a significant amount of material surrounding the bolt to avoid edge effects. The BMC recommend that a bolt be installed a minimum of 150 mm away from any edge or crack [5].

AE data was captured using four MISTRAS WD sensors with a given frequency response of 100 – 900 kHz, connected to a MISTRAS Express 8 system via 28 V 2/4/6 preamplifiers set to 40 dB gain. The system recorded AE waveforms at 10 MSPS, with the threshold set to 47 dB. RS High Temperature Grease was used as a couplant, with the sensors being mounted to the concrete via spring loaded magnetic clamps. These magnetic clamps were attached to the concrete using metal shims, which was glued to the concrete with commercially available hot glue. Each sensor was placed at the centre of the four free faces of the concrete block. This arrangement is shown on the right side of Figure 3. For the AE timing parameters, peak definition time was set to 300 µs, hit definition time was set to 2500 µs, hit lockout time was set to 3000 µs, and a pre-trigger length of 256 samples. The Express 8 system was also used to record load and displacement from the Mayes load machine at one second intervals, and as parametrics for every hit. Sensitivity tests were carried out using pencil-lead-breaks for every sensor placement for every test, if the sensor did not achieve ≥ 97 dB it was re-bonded.

In this test the expansion bolts used were Raumer Hang Fix 10 x 66 mm, and the resin bolts are Raumer Radius P Anchor 10 x 80 mm, both are shown in Figure 2. To install the bolts, a pillar drill was used to drill the holes perpendicular to the top surface at the centre of the face. For the expansion bolts a 10 mm hole was drilled, into which the bolts were hammered in, and then the nut tightened to 30 Nm according to the manufacturer specifications. The resin bolts require a larger diameter hole of 12 mm, this is to accommodate space around the bolt for the epoxy, additionally small recesses are drilled either side of the bolt hole to allow for the bolt to be slightly recessed as is

standard for resin bolts. To install the resin bolts, the hole was cleaned out using a brush and a handheld air pump, ampoules containing the two-part epoxy were then placed into the hole, and then the bolt is hammered into the hole like the expansion bolts. This smashes the ampoule mixing the epoxy and beginning the setting process. Lastly the bolt is rotated and moved in and out to ensure the epoxy is fully mixed, fully coating the bolt, and filling the bolt hole. Lastly the bolt is countersunk using the recesses and any excess epoxy is wiped away. The two-part epoxy used was Petzl Collinox Resin, which was left for a minimum of three days after use to ensure it had fully set. For this testing a Raumer Anellox Sghembo hanger was used to ensure the direction of pull from the load machine was aligned with the bolt itself.



Fig. 3. Photos of the testing setup. An example of resin bolt failure (left), and an image showing the restraining method and sensor mounting method, along with the sling connection between the load machine and bolt.

Once the bolts were installed, tensile testing was carried out. For each test, the block was restrained in the load machine and the bolt connected to the load machine by multiple strands of an 11 mm DMM dyneema sling as seen in Figure 3. This soft linkage was necessary as the geometry of the hanger prevented a hard linkage. The tensile test was load controlled with a loading rate of 10 N/s until bolt failure, in this case failure is defined as complete removal of the bolt from the concrete block. An example of failure for a resin bolt is shown in Figure 3.

After testing the AE and load data were processed using Python, common AE features were extracted from the raw waveforms using the OpenAE's standard feature library [14]. Three filters were then applied to the AE dataset. All hits captured after bolt failure were removed to avoid including hits created by the bolt scraping on the inside of the bolt hole during pull-out. Any hit with a peak amplitude occurring after the midpoint of its waveform was also removed, to avoid analysing AE hits which were triggered early and therefore captured incompletely which would provide erroneous feature calculations. Lastly any hit with a total energy of $< 0.8 \text{ V}^2$ was removed from the dataset, as these hits were never found to be a structured signal, but rather background noise briefly exceeding the 47 dB threshold and triggering the Express 8's acquisition.

Once filtered the features of the AE signals were used to perform Linear Discriminant Analysis (LDA) in an attempt to separate AE signals captured during failure to ones captured before failure. LDA is a dimensional reduction method similar to Principal Component Analysis (PCA), however in contrast to PCA it is a supervised machine learning method based on pre-assigned classes. LDA determines the principal components based on the features which best discriminate between the assigned classes [15]. LDA has previously been used to classify damage in composite specimens based off features extracted from AE waveforms [16].

3. Results & Discussion

Table 1 shows the results of the tensile testing for the four bolts. In all cases the resin bolts outperformed the expansion bolts, achieving higher loads before pull-out. All bolts also exceeded the recommended minimum tensile strength of 15 kN. Resin bolt A performed worse than its counterparts B & C, but obtained a similar number of total hits to Resin bolt B. The failure mode for all expansion bolts was the collar slipping past the cone section, leaving the collar inside the concrete. This could be the cause of the very low number of hits recorded for the expansion bolt tests, as the cone slipping free of the collar would avoid the same scale of material damage as the resin bolts.

Test Name	Max Load (kN)	Total Hits	Hits Post Filtering
Expansion Bolt A	17.47	1164	246
Expansion Bolt B	17.64	1549	510
Resin Bolt A	32.81	7712	2586
Resin Bolt B	49.30	7561	2683

Table 1. Results from the tensile testing of two expansion bolts and two resin bolts, showing the maximum achieved load and the number of recorded hits.

Figure 4 shows the overall AE activity in dBAE plotted for each tensile test, with the displacement over the top for reference. The displacement curve for all tests share a consistent shape, near the beginning of the test a short period of a steep increase, followed by a brief non-linear section, and then a long period of steady increase, finishing with the bolt failing and a sudden sharp increase in displacement. The initial steep section and the elbow that follows are a result of the dyneema sling being pulled into tension.

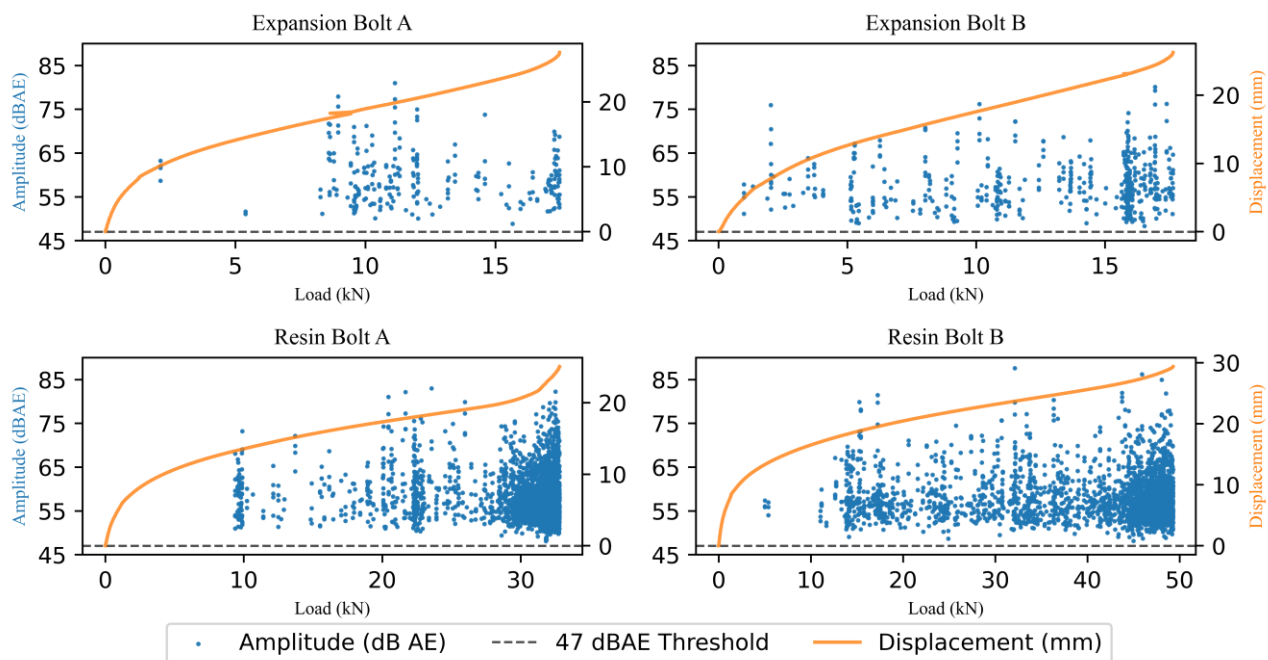


Fig. 4. Plots of AE Hit Amplitude and Displacement against load for each of the four tests.

The AE activity for the tests appears to come in distinct packets during the steady loading period. This is likely small fractures and cracks occurring in the concrete as the force increases, or the expansion bolt slips. For the resin bolts there is lack of AE activity in the early stages of the loading, if damage was occurring during this time, it is expected that AE activity would have been recorded. Meaning that the increase in displacement seen in this period could be explained by the dyneema

sling continuing to stretch more than expected rather than the progression of damage. Lastly the resin bolts show a dramatic increase in AE in the final stages of loading as the bolt begins to fail, this increase in activity shows that there is a correlation between AE and bolt failure.

Figure 5 contains histogram plots representing the results of the Linear Discriminant Analysis (LDA) carried out on each test. For each test, the waveforms were classified into $\leq 85\%$ and $> 85\%$ of the maximum achieved load, LDA was then used to calculate the Principal Component of each dataset based on this classification. Each histogram represents the distribution of Principle Components for each dataset. The resin bolts show a clear separation in Principle Component for early loading (green) vs late loading (red). This means that the AE features of waveforms captured near failure are in general statistically different from those captured early in loading.

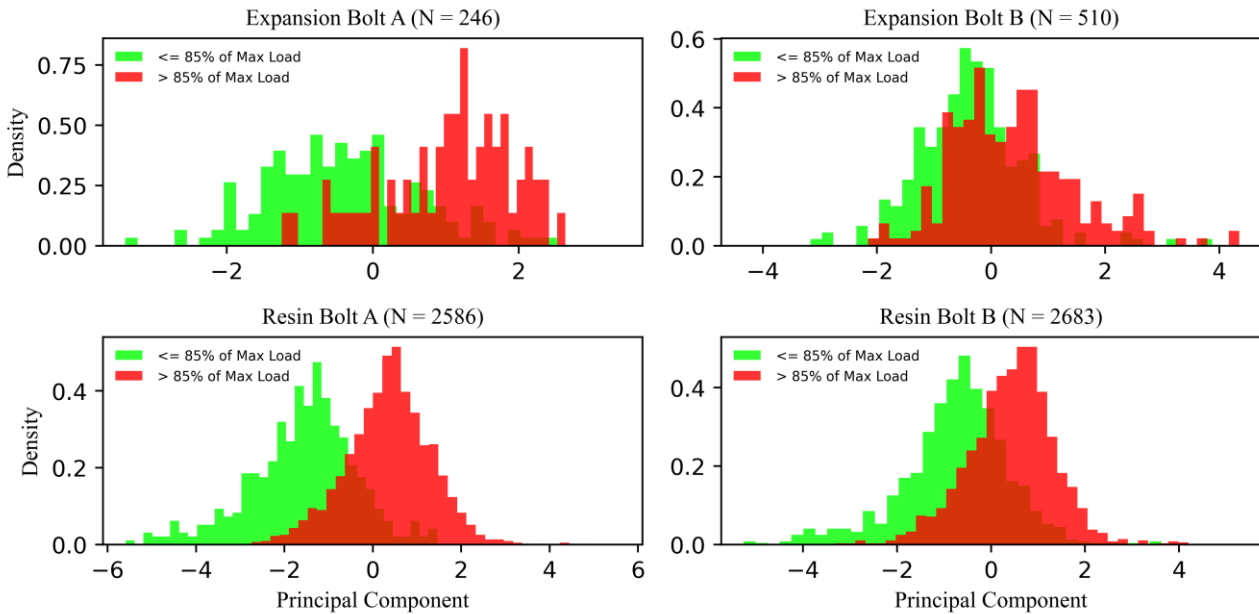


Fig. 5. Histograms representing the distribution of the Principal Component of AE features for each test. With Green being AE captured at $\leq 85\%$ of maximum load, and red captured at $> 85\%$ of maximum load.

Given the AE characteristics change as the damage progresses it could be possible to classify the condition of a bolt and its integrity within the material through AE monitoring during tensile testing. For example, if AE was monitored during a standard 6 kN load for inspection, and the majority of AE waveforms were found to be of the type that usually occur near failure, it would indicate that significant damage has occurred and the integrity of the bolt is compromised.

Such classification work would require a larger more varied dataset. There are many different bolt designs in use, installed in concrete as well as a range of different types of rock, the dataset would also need to include examples of bolts in good and bad condition. Support Vector Machine (SVM) models have been used previously to assess damage in concrete using hit classification [17], and it is believed that an SVM could be trained to predict the integrity of a bolt based off the results of the Linear Discriminant Analysis.

4. Conclusion

In conclusion, four bolts underwent AE monitoring during tensile loading till failure. Common AE features were extracted and analysed. It was found that the rate of AE activity is correlated with proximity to failure, with early loading showing no AE activity in 3 out of 4 cases. This means that common AE metrics such as cumulative energy, counts, or b-value could be used as an indicator of the integrity of a bolt. Linear Discriminant Analysis showed a difference between AE captured at low loads and AE captured at high loads. Whilst not conclusive, this suggests in-situ bolts could be loaded submaximally and the captured AE hits categorized.

Overall, the work showed AE can be used for the monitoring and assessment of bolts under load, and with further testing it could be possible to classify the integrity of a bolt without loading it to failure.

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