

ASSESSING THE STRUCTURAL INTEGRITY OF CRANE BOOMS USING ACOUSTIC EMISSION

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Abstract

Structural failure of crane booms results in either untimely, unplanned, maintenance activities or a threat to Health and Safety requirements. Formerly, a “Proof load test” provided a suitable means of assessment of a structure’s “fitness for purpose.”

LOLER (The Lifting Operations and Lifting Equipment Regulations) (1998) (1) came into force on December 5th 1998. The accompanying Code of Practice states that it is now a matter for the competent person to determine the necessity of a load test. Therefore, whereas it had been previously compulsory to load test most lifting equipment, (2 – 6) this Statutory Instrument revoked all of the compulsion and shifted the onus on to the Duty Holder (owner/operator) to appoint a competent person to determine the applicability and usefulness of any load test.

This paper recounts the efforts of two Duty Holders, specifically, Ministry of Defence (MoD) and bp, to enhance the information generated by the use of acoustic emission in conjunction with the load test.

The paper outlines the complementary approaches undertaken by bp and MoD. With bp a crane boom section was induced with defects and loaded to destruction, with the intention of highlighting and identifying failure sites well in advance of the ultimate failure.

In the case of the MoD, seven Electrical Overhead Travelling (EOT) cranes were tested by the simultaneous measurement of applied load and Acoustic Emission during the commissioning proof test onboard the aircraft carriers HMS ARK ROYAL and HMS INVICIBLE. The results of these tests are presented.

Differing means of evaluating the severity are explored, specifically, the Felicity Ratio, Persistence, the b value and Intensity Analysis. All showed a possible means of trending the defect progression although the most reliable was the Intensity Analysis.

Introduction

The two aircraft carriers HMS ARK ROYAL and HMS INVINCIBLE were recently refitted and part of that work package involved the replacement of electrical overhead travelling cranes. In total, seven of these types of cranes were tested four onboard; ARK ROYAL and three on INVINCIBLE. All were subjected to a post installation commissioning proof load test, a load that surpasses their generally applied or safe working load (SWL), during which the cranes performance was monitored by both AE and traditional deflection tests. The load was fully applied, sustained for five minutes and partially removed and then reapplied to the same value with a view to exploring the Felicity effect.

The results presented from the trials conducted for bp are of a destruction test that was conducted on a single tubular crane boom section that had been removed from service. The section was subjected to induced damage that acted as a stress raiser that propagated under the increasing incremental applied load to a maximum of 10 Te. The nature of the load application was three point bending in order to replicate as closely as possible the service conditions. Post-test, the data was evaluated in order to achieve an evaluation criterion. Four separate methods were examined as a means of ascertaining the defect severity at each load increment.

Literature review

Between 1980 and 1997 greater than half of the North Sea fatal offshore accidents were associated with lifting operations. (7). This figure is not only related to the failure of lifting equipment, but also to unsafe working practises. The “crane accident web site” documents an increasingly worrying trend of crane incidents. The site opened in January 1999 with 110 accidents reported in 1999 of which 51 were fatal, 184 reported accidents in 2000, 74 were fatal, 2001 saw 161 accidents of which 107 accidents were fatal. It is fair to assume that awareness of the web site will increase with respect to time and hence one can anticipate more accidents being reported to the site. It is also fair to assume that not all accidents are reported. (8). An Occupational Health and Safety Administration (OSHA) report cites that there is insufficient data to calculate the actual likelihood of death of the entire worker exposure to lifting operations. However for crane operators alone there is a risk of 1 in 1000 being fatally injured. (9).

In the Navy Crane Centre’s (United States) Fiscal year 01, an audit was conducted of approximately 10% of their crane inventory of 5500 cranes. Approximately a third of these were found to be unsatisfactory. Listings of seventeen separate deficient conditions were compiled which was further disseminated into categories of either mechanical, electrical, structural or administrative. This breaks down into two of the seventeen being administrative nonconformities, four electrical deficiencies, four mechanical and seven structural deficiencies. The most reported non-conformance was a mechanical deficiency, specifically, brakes and clutches being out of adjustment (10). However it is clear that structural integrity of the load bearing elements of cranes contribute a significant threat to health and safety. It is for this reason that a programme of the assessment of crane booms utilising periodic load testing coupled with AE technology was embarked upon. The methodology of periodic testing has already covered in a preceding paper. It utilises a concept known as the Dunegan Corrolary which is the scientific principle that underpins the majority of the existing codes and standards which periodically re-qualify structures (11).

There is limited available information relating to Acoustic Emission inspection of cranes although it is known that the US Navy conducted load testing on crane booms on dockside portal cranes. There additionally exists a strong parallel with the inspection of aerial bucket trucks in that they are both excited by a mechanical load as opposed to hydraulic or a pneumatic stress. In terms of industrial applications there is limited documented work on the assessment of structures excited by a mechanical stress although there has been considerable laboratory work. There has been substantial focus by the AE community on bucket trucks with a resultant standard. (12) Rogers, (13) undertook tests on offshore pedestal cranes although his work examined the slew ring bearing a notoriously difficult component to inspect.

The programme of research reported here aimed to assist the competent person with the provision of information pertaining to the integrity of the item whilst under test. It is felt that if the information that was provided by the load test were enhanced by the simultaneous measurement of Acoustic Emission then it would provide a more reliable empirical means of condition assessment.

In order to ascertain the severity of any indication found during a load test some established methods of evaluation were trialled. The specific methods tried were the Felicity Ratio, Persistence, the β value and intensity analysis. Software was designed to automate these calculations.

Equipment used

A Physical Acoustics 24 Channel DISP system was used with a number of 150 KHz resonant sensors.

Test Set up

For the EOT cranes an arrangement as shown in Figure 1 was used. The boom sections of the cranes were monitored with eight acoustic emission sensors during a static load test. Each boom was treated as a separate linear array for location purposes. The test procedure involved the load being applied up to 6 Tonnes, held for five minutes, removed to 3 Tonnes, reapplied to the maximum and held for a further minute.

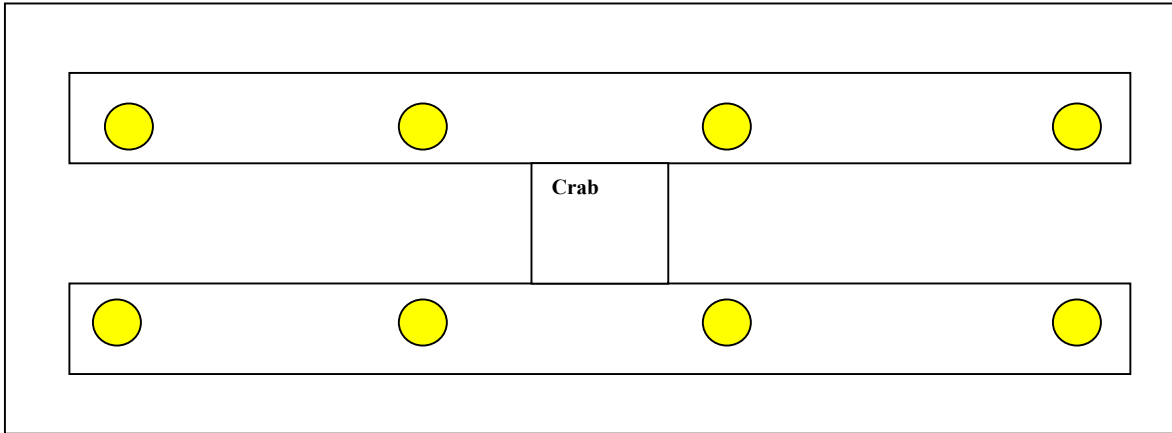


Figure 1: Sensor Set up on EOT cranes

For the destruction test of bp's lattice crane boom section sensors were deployed at the corners and each cord treated as a separate linear arrangement for location purposes. The load was applied in increasing increments of 2.5 Te to a maximum of 10 Te. Fixing the ends of the boom and applying a hydraulic jack to the centre of the section achieved the bending. Notches were induced in the lattice cord connections. The hydraulic pressure in the hydraulic pipe to the jack was measured to give a parametric input into the instrument of the applied load.

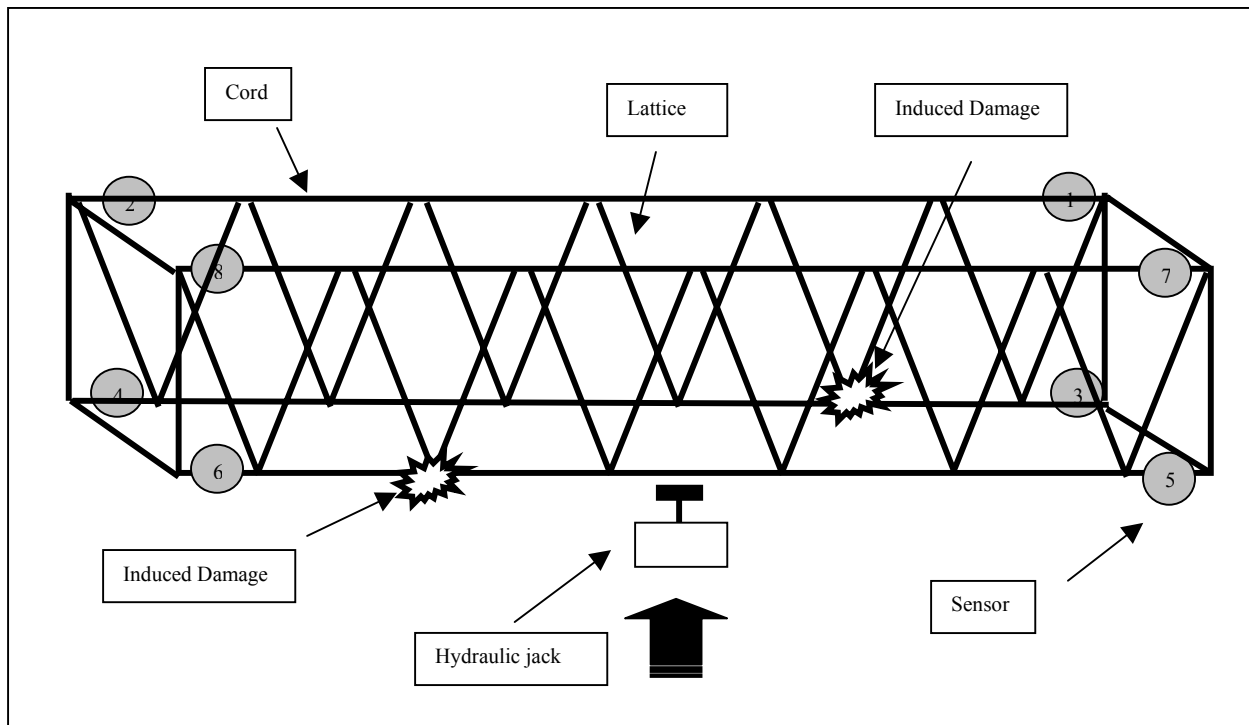


Figure 2: Sensor Set up and bend test arrangement

Results

To provide a general overview a single typical set of the results of the four cranes on HMS ARK ROYAL and three cranes on HMS INVINCIBLE is presented. The destruction test of the lattice crane boom is then presented and the methods of determining a means of severity are examined and evaluated.

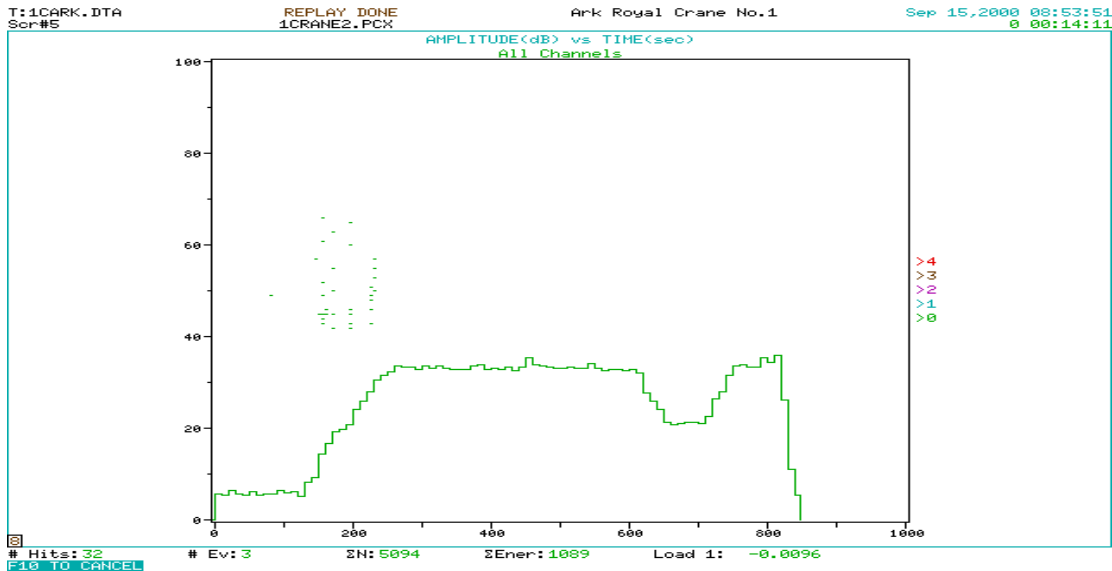


Figure 3: Amplitude and load History for HMS ARK ROYAL Crane No. 1

Figure 3 illustrates a typical result for one of the ship board tests. The solid line is the voltage proportional to the applied load the dots denote the accompanying emission. It is evident that on the initial increasing load there are accompanying emissions although the density and total energy is small. There is no activity on the load hold period nor on the unloading and subsequent reapplication of load. From this, in accordance with the Kaiser effect we can conclude the because there is no activity on the load hold the structure is experiencing no instability at a load greater than the generally applied service load. Further as there is no Felicity effect the structure is “fit for purpose”.

When load testing mechanical handling equipment it is especially important to only partially remove the applied load before the subsequent reapplication. The nature of stresses excited in a pressurised system are generally hydrostatic in nature and act uniformly. However with mechanical load the stresses have a directional component and the likelihood is that if the load was completely removed an identical stress could not be reapplied. This is significant because if the stress is unprecedented it would give rise to a breakdown of the Kaiser effect i.e. a Felicity effect leading to the conclusion of a false indication.

It is unknown whether the booms had undergone a factory acceptance test prior to their installation. This could be one of the reasons that the total energy content for the whole test is so low. Much of the stored energy could have been alleviated by such a test had it been conducted. In all tests it was found that the energy was very low. It is also feasible that due to nature of application of the cranes on a warship the fact that they are designed with very high levels of redundancy the applied static load in these cases could have produced minimal excitation to the structure and hence generated little activity.

The source located events, of which there were few in all cases, generally emanate in the centre of the boom section. This seems sensible in that it is at this point of maximum bending. The two linear arrays for each boom are shown in Figure 4, which is taken from one of the INVINCIBLE crane tests. All deflection measurements yielded no permanent set in the structure.

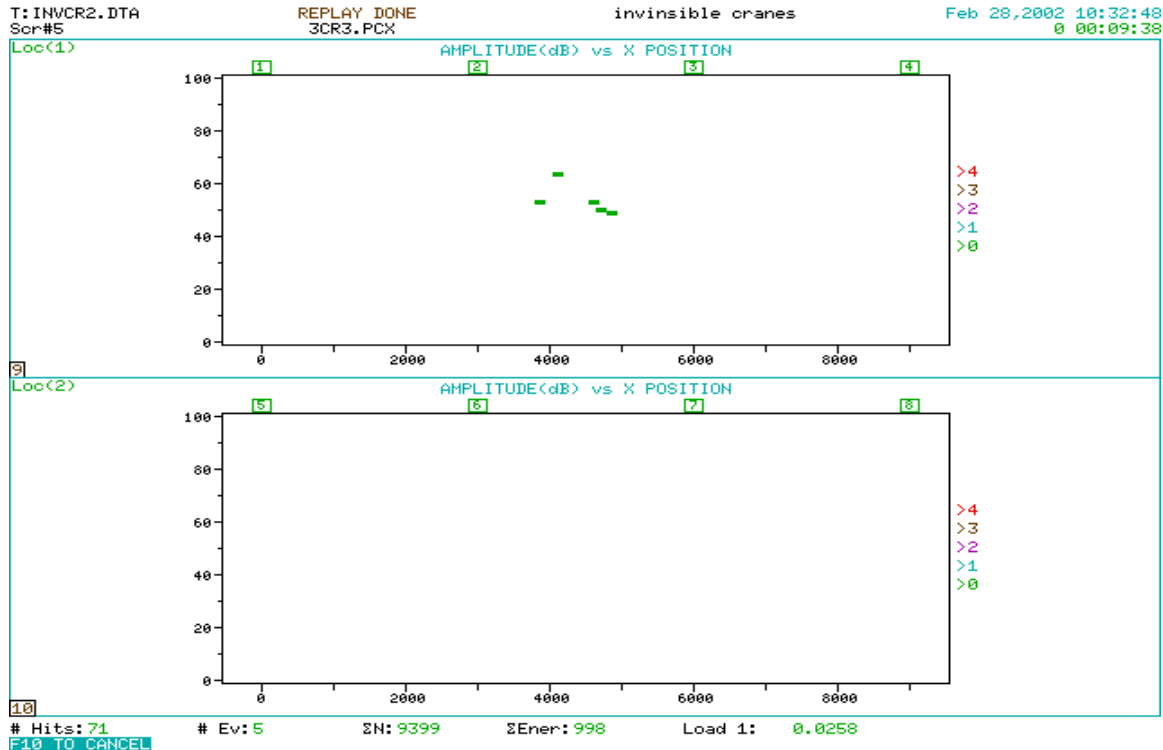


Figure 4: Location of data on HMS INVINCIBLE CRANE No.2

The test conducted for bp is now reported. The incremental load application is shown in Figure 5 in addition to the AE. Even the very first application of load shows a 75 dB hit indicative of a large mechanical source event. With increasing load there is a corresponding increase in activity and amplitude as might be anticipated. Following each load increment the load was slightly reduced and then reapplied to the next maximum level in order to explore the Felicity Ratio. It is interesting to note that on a back to back application of the maximum load of 10 Te the structure continues to sustain the load. In other words this structure never truly fails if failure is defined as an inability to hold the load. One objective of this investigation was to observe the load level at which evidence of the failure site would become apparent and hence illustrate what factors of safety would be inherent within the structure. Some events were source located at the initial load level at the site of failure, but it is important to realise that the structure never failed and therefore the factors of safety are greater than four. Inspection after the destruction test showed one of the lattices being visibly buckled and although there was pronounced activity from another site where the connection had experienced an induced stress raiser there was no evidence of propagation.

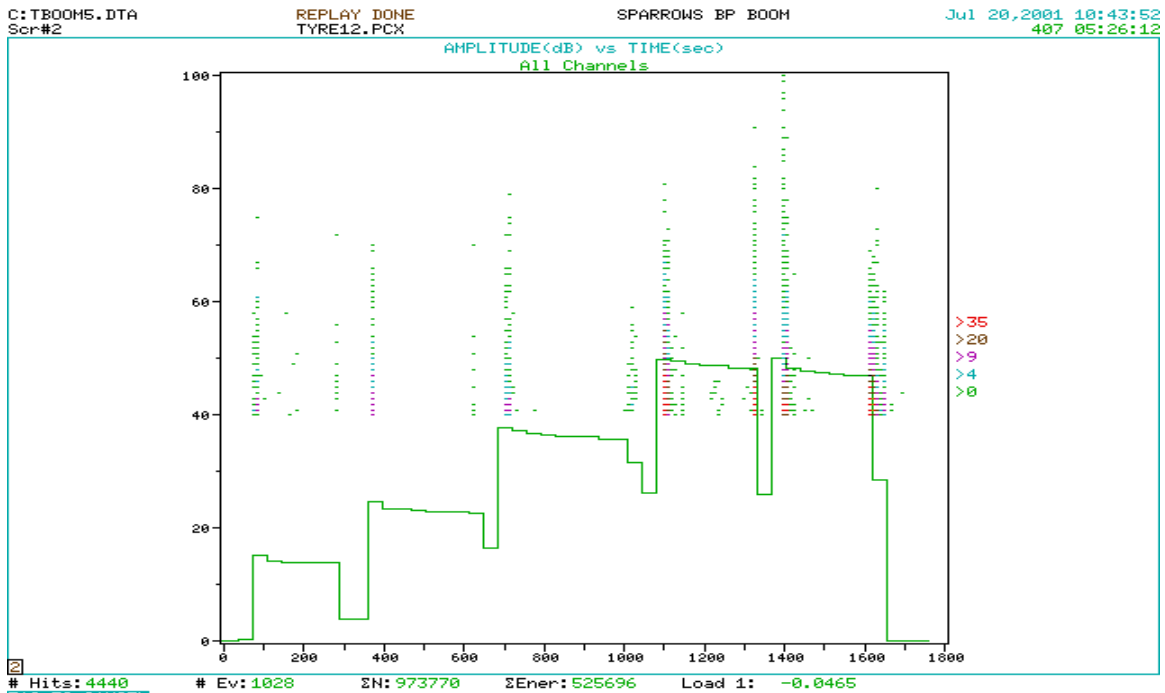


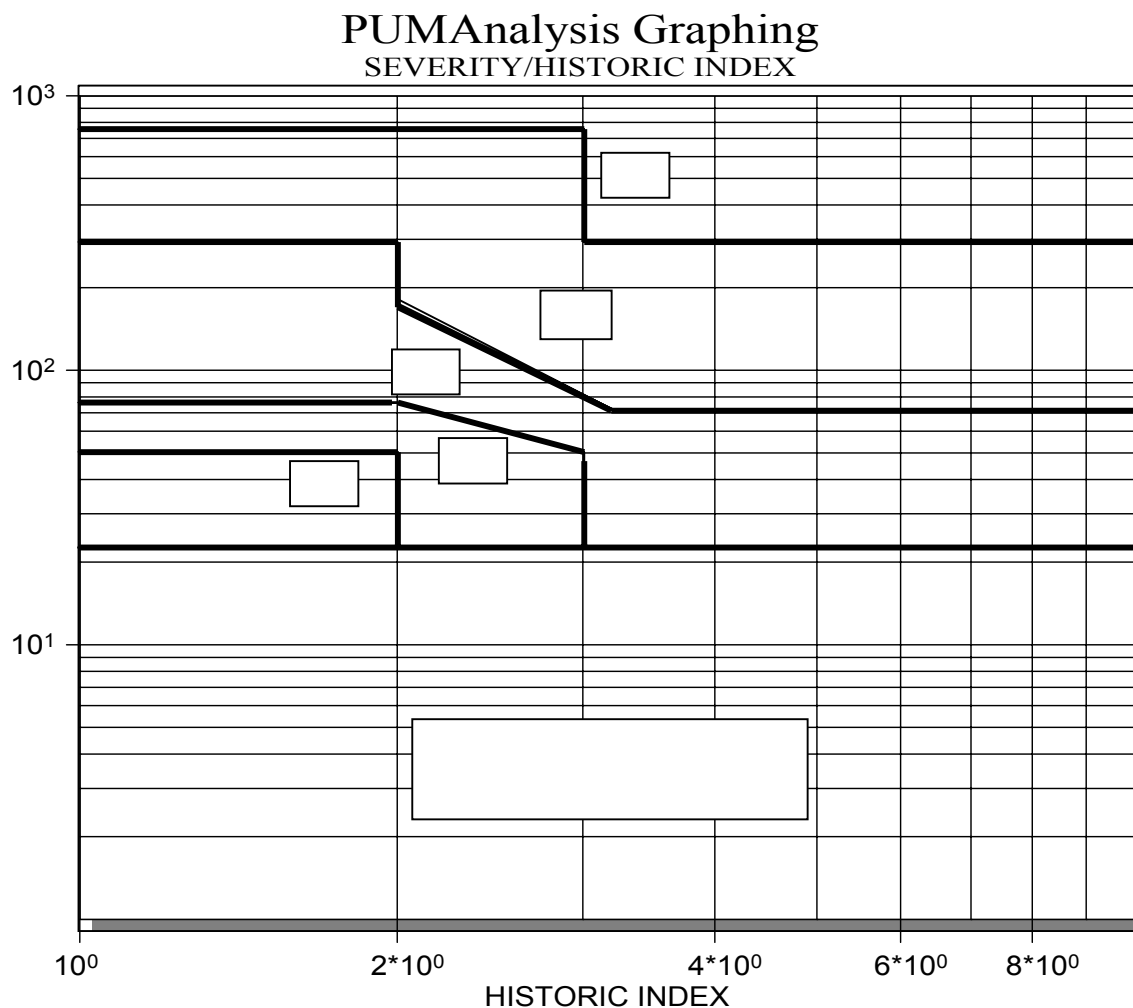
Figure 5: Amplitude and load history on Crane boom section destruction test



Post-test data evaluation strived to achieve the most effective means by which the defect could be graded for its severity. As previously mentioned software was designed to automate the processing. Commencing with the Felicity ratio it was considered that with increasing load the lower the ratio and therefore, the more severe the presence of the defect (14). Secondly, persistence values were examined, persistence is a concept discussed with Adrian Pollack (Head of Training, Physical Acoustics Corporation) and is a measure of how long an item continues to

emit on the load hold (15). If we consider emission analogous to complaining about the ensuing stress then it is believed that the “persistence” of the emission will give information regarding the severity of the distress suffered by the structure. Thirdly, the β Value operates on the premise that with increasing load in the event of a discontinuity there will be increasing Amplitudes of signals. Therefore, on a normalised Log / Log plot of the sum of the signals we can anticipate a change in the gradient with increasing load. Pollack suggests that with increasing load the linear regression should reduce in steepness and approach positivity (16).

Finally, an intensity analysis plot is explored. The means of calculating the analysis plots was discussed by Fowler in the Monpac system (17). Calculations are conducted and a cross plot generated and dependent on where the distribution of hits falls a grade is applied on an A through to E scale, E being the most severe condition. The grading is conducted on a per channel basis. The A through to E scale is shown in Figure 7.



The Software displays the results in a graphical format. By way of example, only those that reached a load level of 7.5 Te have been shown.

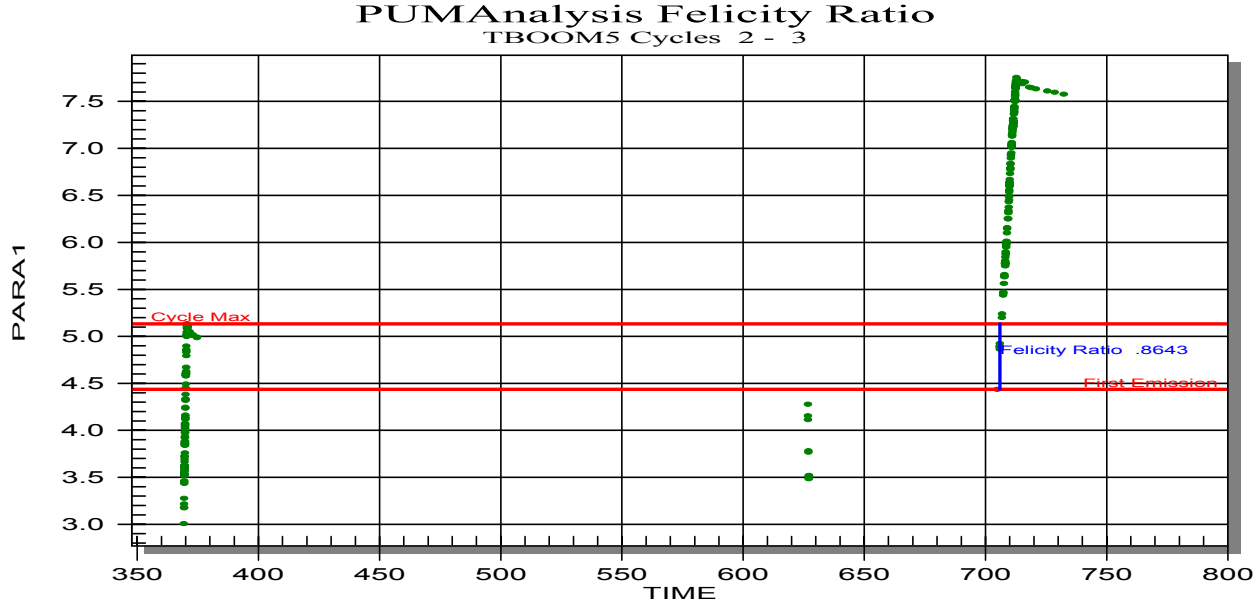


Figure 8: Software computation of Felicity Ratio at 7.5 Te

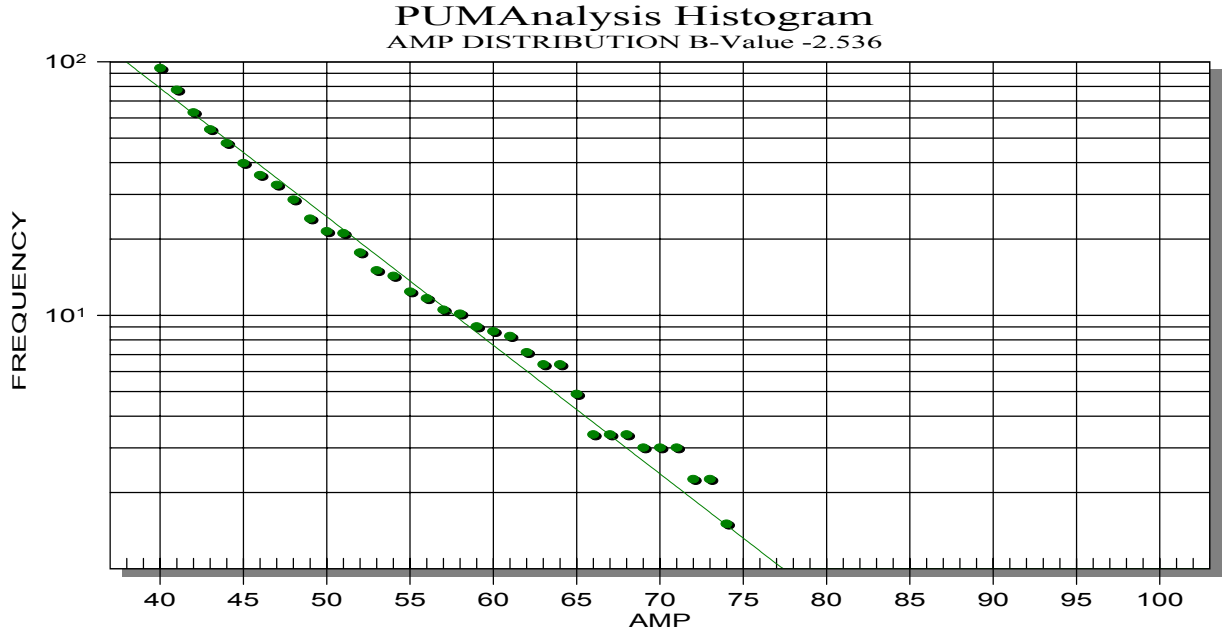


Figure 9: Software computation of B value at 7.5 Te

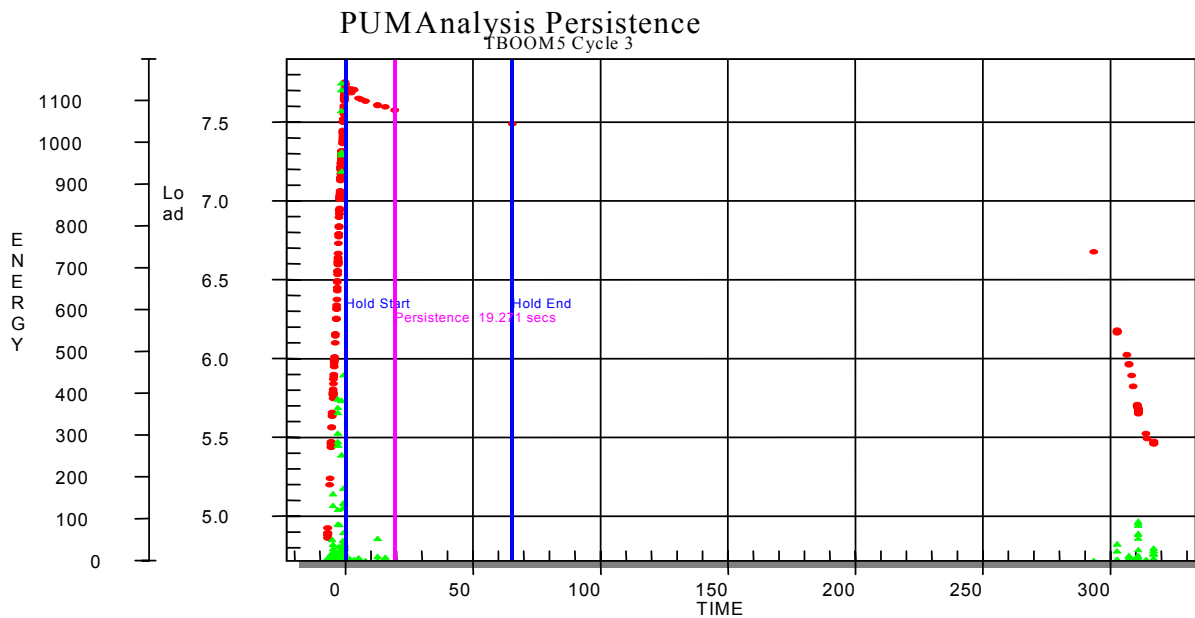


Figure 10: Software computation of Persistence at 7.5 Te

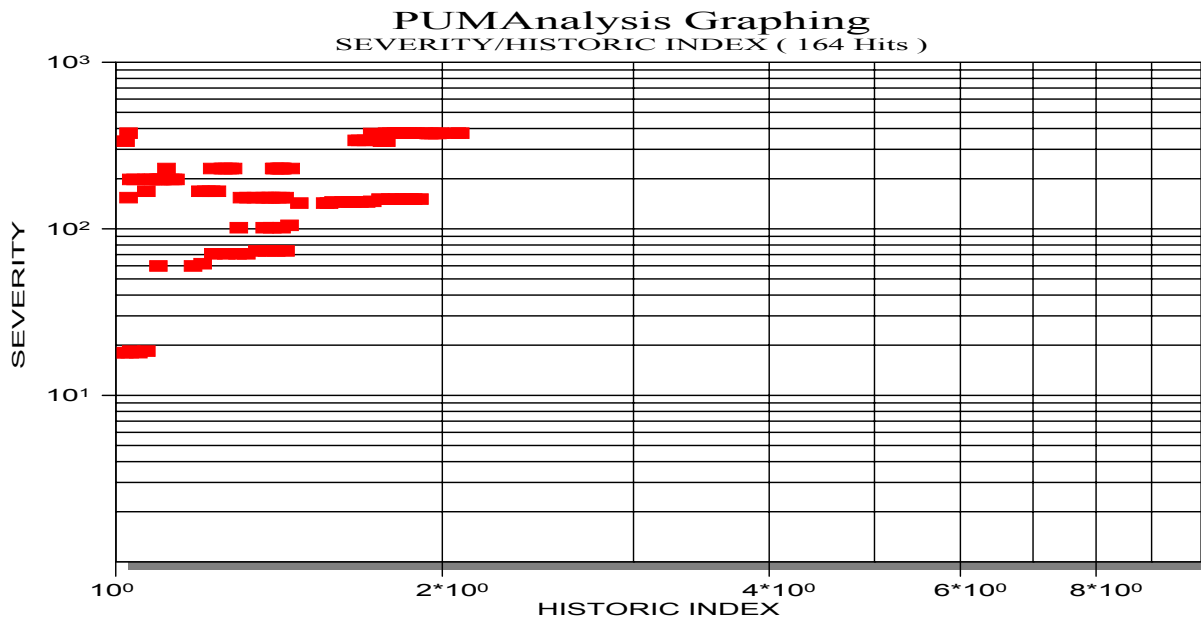


Figure 11: Software computation of Intensity Analysis at 7.5 Te

Table 1 illustrates the effectiveness of each evaluation method as a means of reliably identifying the severity of an inherent defect.

	2.5 Te	5 Te	7.5 Te	10 Te
Felicity Ratio	0.93	0.86	0.97	0.57
Persistence	81.76	4.05	19.27	39.41
β value	-3.13	-2.98	-2.54	-3.43
Intensity Ch. 6	C	C	D	E

Table 1: Outputs of Evaluation Criteria at each stepped Load increment

All evaluation show largely that they could be used as a means of trending or assessing the severity of degradation, but all with the exception of the intensity analysis have an anomaly at one of the load increments. The Felicity Ratio at the 7.5 Te load level shows 0.97 when in theory it should have reduced to at most 0.86. Persistence, again shows a progressive rate of degradation, but for a very long period to reach stabilisation on the initial load application. The β value approaches positivity with increasing severity as anticipated, but at the peak load reduces. Intensity analysis does however show the logical progression and was found to be repeatable on other channels of interest, demonstrating that this would be the most effective means of assessing defect severity.

Conclusion

It has been successfully shown that the conjunction of periodic proof testing and AE will enhance the information gleaned about crane boom integrity than merely load testing alone. This is true of both a qualitative assessment where it is required to merely identify the presence of an integrity threatening flaw, but this work has also illustrated that quantitative assessment of the defect severity is possible. Of the four differing evaluation criteria explored the intensity analysis method performed most effectively, although all methods of evaluation showed largely the progressive nature of the flaw.

Further Work

This paper has shown the proof of concept that Acoustic Emission is applicable to crane booms, but in order to be effective it must address all the structural failure modes that might be experienced in service. For instance, with the EOT crane programme only the stimulus of maximum bending was explored i.e. when the crab was at the midpoint it is necessary to explore the point at which the maximum shear stresses are excited i.e. the point at either extremity of the boom.

Preceding the introduction of LOLER dependent on the item of lifting equipment a prescriptive time was mandatory between period proof load test, typically four annually with offshore pedestal cranes. It would be more appropriate that the frequency of testing was matched to the anticipated lifetime. The frequency of testing might be better suited to a greater concentration and evaluation towards the end of life and less frequent attention whilst the asset was comparatively new. The frequency of testing must also take in account the speed at which the most aggressive failure mode can propagate and result in catastrophic failure.

Work is ongoing on these issues.

Acknowledgements

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