Fracture Mechanics Of Mining Dragline Booms
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ABSTRACT: Mining draglines are large mining machines which have a booms of about 100 m in length. The booms are tubular structures made up of three large chords connected by smaller lacing tubes. There is a regular cracking phenomenon at the welds which means that the cracking must be remotely detected, exactly located and repaired. This paper describes the cracks which grow in the weld joints (called clusters) and the system by which the booms are protected from catastrophic collapse and the maintenance and repair techniques used to keep them in service.

1 INTRODUCTION

The Australian coal mining industry operates a large dragline fleet such as is shown in Figure 1. The draglines generally work 24 hours a day, 364 days a year. The productivity of each dragline is generally estimated to be around $8000/hour and thus the cost of any unscheduled down time is very significant for the operation.

There are two main types of machine designs being used in Australia derived from two separate original equipment manufacturers. This paper concentrates on the Bucyrus Erie (“BE”) design which has a boom made of structural tubular elements. In this design there is a cracking mechanism of the main chords which is common and has the capability of causing major collapse.

Figure 1. The main components of a BE design dragline. The scale is indicated by the vehicles at the bottom of the picture.
1.1 Design

The structural loading on dragline booms is illustrated in Figure 2 and depends mainly on the rated suspended load ("RSL") the machine is working at and the capacity of its hoist and swing motors which create the accelerations. Other factors such as the digging pattern, operator characteristics and electrical motor control systems also influence the loading on booms.

The main structural components such as booms and masts of BE machines are constructed using tubular structural elements with welded connections which are termed clusters. At the clusters the large tubes ("main chords") that form the main structure are welded to the lacings. The main
chords are subjected to predominantly compressive stress cycles while the lacings stabilise the structure against bending and twisting. Lacings can be in compression or tension. A picture of a cluster is shown on Figure 3. This figure also shows some cracking located inside a cluster by removing parts of the lacing tubing.

Typical BE booms (e.g. models 1350 and 1370) have three main chords and are approximately 100m long. The main chords are fabricated by welding together segments of typically 406 mm OD tubes with 12 to 32 mm wall thickness. The lacing members are typically 168 or 207 mm OD and 7 or 8 mm wall. They are welded onto the main chords so that the centre lines of the individual members meet at one point called the cluster node point. Therefore, the lacing members overlap at the cluster as shown in Figure 4(a).

![Figure 4(a) Typical BE cluster](image)

![Figure 4(b) Non-overlapping type of joint](image)

Fatigue design has currently been mainly studied in non-overlapping joints such as shown in Figure 4(b) [Zhao and Packer, 2000, Karamanos et al, 2002]. As will be shown later the highest point stresses and the initiation points of the cracks are often occurring at the intersections of the lacings and thus are not necessarily covered by the work on non-overlapping design.

### 1.2 Prevention of catastrophic failure

Draglines booms have collapsed due to fatigue related component failures. However none of these failures to our knowledge have occurred because of cracking in the main chords. This is because there is a safety system which detects the cracks before they are large enough to cause catastrophic failure.

Fatigue cracks appear in the main chords, mostly underneath the lacing members that have been welded on top of the main chords as shown on Figure 3(b). After initiation the orientation of the growth of the crack after is basically perpendicular to the axis of the main chord. This is because the stress range in the main chord is larger than the other members (see 2.2 below).

The location of the cracking is often embedded underneath the lacing and they are often not detected using visual inspection methods. These cracks are thus not normally detected until they have propagated through the thickness. At this point the detection relies on the fact that main chords are pressurised with air so that through thickness cracks can be detected using loss of air pressure.

The air pressure forms a continuous integrity monitoring system. The air flow is measured continuously and there is an alarm in the operator’s cabin. Once the alarm is showing, the operator requests an inspection and (depending on the air flow rates involved) the operation of the dragline is stopped until the leak can be identified and a repair can be carried out. The cracks are located by a range of methods including noise, detection of pressurisation of the lacing members (using little valves) and ultrasonics.

Urgent repairs are often conducted in poor conditions so the success of hurried and repetitive repairs on clusters is another aspect of interest. The repairs tend to have shorter lives than the original construction. In order to achieve adequate life from the repairs, mines are now replacing long sections of main chords during scheduled outages (as a rule of thumb the clusters are replaced
after about 3-4 main chord crack repairs). The necessity to do this and whether the original design should be altered during these opportunities is thus also a matter of investigation.

Fracture mechanics can play several roles in the failure prevention activity. Some areas of interest are:

- Original manufacturing and repair of clusters: identification of appropriate procedures and inspection to reduce cracking,
- Estimation of growth rates of flaws of different sizes, in particular, time from typical initiation flaw to leak and
- Evaluation of the permitted periods of time for various signals from the air pressure testing system.

2 INVESTIGATION ACTIVITIES

There has been an extensive series of investigations to support studies on the booms.

2.1 Loading on Booms

The loading on dragline booms consists of several components including dead load (i.e. self weight), weight of the bucket acting through the hoist ropes, forces from the suspension ropes, and the inertia forces mainly due to angular accelerations. Some of the main loading components including the angular acceleration are shown in Figure 2. The main components of loading that contribute to fatigue are the forces acting through the hoist ropes and the inertia forces due to accelerations.

A typical loading cycle comprises of: dropping the bucket in the pit; filling the bucket by dragging it towards the machine; lifting the bucket off the ground; swinging the boom while raising the bucket further; decelerating the swing of the boom (an action known as “plugging”); dropping the bucket load; swinging the boom in the reverse direction; and returning the bucket to the pit. One loading cycle generally takes 40-60 sec during normal operations.

2.2 Stress Measurements

MTI has conducted stress measurements on several dragline structures for various modes of operations. Other measurements such as swing and hoist electrical motor outputs, motor references, drag and hoist rope lengths and angular accelerations are also made to determine the position of the bucket, operator response, etc corresponding to the measured stresses. Some of these measurements were obtained from the monitoring system permanently installed in the draglines. We are now able, due to new technology, to monitor the loadings and control the data collection on the drag line remotely by telephone.

Typical stress cycles for the three main chords (the two bottom chords are A and B the top chord is C) and two lacings for a BE 1370 dragline are shown in Figure 5.

The following general features can be identified from the stress measurements:

(a) The largest stress ranges are in the A and B chords. This is the stress range that drives most of the cracking. (See fig 3(b)).

(b) The mean compressive stress in the A and B chords are significant but at some points in the cycle positive stresses can be recorded especially near the bottom of the boom when accelerating during swinging motions.

(c) The stress range in the top chord, C chord, is smaller. There is very little cluster cracking in this chord.

(d) There are both tensile and compressive stresses in the lacings. The diagonal lacings tend to see a higher stress range.
2.3 Stress Analysis

The stress measurements described above can only be made only on a limited number of members and at limited number of locations. Detailed stress analysis is still required. This is broken into two stages:

(a) Large-scale models of the boom, mast and A-frame system with all the external loadings and accelerations are analysed using finite element analysis to determine the stresses and stress ranges for all the members of the structural system. These models can be calibrated using the measured stresses in the chords and lacings.

(b) Detailed models of the clusters of most interest are conducted with 3D solid elements. An example of this is shown in figure 6. The stress range in the highest principal stress area shown is from −290 MPa in the maximum acceleration case to −42 MPa in the self weight case. This gives a stress range of 248 MPa in compression in the longitudinal direction of the main chord.

2.4 Cutting out clusters and residual stress measurements

Several clusters which have been removed from draglines during the course of maintenance have been given to MTI for detailed examination. This has permitted a number of detailed studies of the failures which have never been collected before.

Figure 7 shows a cluster which has had the lacings cut off and had residual stress measurements using the “trepanning” technique carried out. Figure 7 also shows the positions of two repair welds which were found on this cluster. The results of the residual stress measurements are complex with the measured stresses ranging from 220 MPa compressive to 183 MPa tension. Residual stresses are the subject of a separate study which is currently underway.
2.5 Examination of specimens

Figure 8 shows the quality of the repairs and the flaws which were found when the area was sectioned. The original crack which caused repair weld 1 has been lost due to the repairs, but flaws in weld repair weld 1 itself are still present and there are significant flaws present at the interface between repair welds 1 and 2.
Figure 8. (a) is a cross-section through the two repair welds. (b) is a view of the welds from inside the chord before the cross-section was taken indicating the cross-section location.

3 FRACTURE MECHANICS

It is clear from the appearance of the welds shown in Figure 8 and other samples which have been obtained that there are pre-existing flaws in the welded areas of the clusters. Figure 9(a) shows a hypothesised crack in a chord. The analysis tests existing flaws of depth 0.5, 1 and 2 mm with an aspect ratio of 10.

Figure 9(b) shows the stress cycles which have been examined. The cyclic load applied in the chord is taken to be compressive -20 MPa to -150 MPa. To this must be added the residual stress. Using the recommendations of BS7910 [British Standards, 2000], without post weld heat treatment (“PWHT”) the residual stress should be taken to be the yield stress. For a typical low alloy carbon steel tube A 106 Grade B, the yield stress can be taken as 218 MPa. There is assumed to be one cycle every minute, which equates to 525,600 cycles per year assuming 100% time operation. A lower residual stress of 30% yield (65 MPa) was also examined which might correspond to the effects of PWHT.

Crack: 1 mm deep, 10 mm wide

Chord: 19 mm thick

Figure 9(a) Hypothesised crack in a chord.
Table 1 shows the time taken to leak for three different starting sizes. Two growth models have been used, the growth in air relation in BS7910 Table 5 and that in the program NASGRO [2002] for the similar steel A588B. The dry air growth laws are likely to be applicable because of the dry conditions in which these structures generally operate and the internal nature of the cracking.

Table 2 shows the effect of using a different residual stress on the NASGRO analysis. Only NASGRO has a variation in growth rates at this level of residual stress; the BS7910 relations do not give credit for lower residual stress. This is because the value of stress ratio, $R$, is less that 0.5 in both cases.

$$R = \frac{\text{minimum total stresses in cycle}}{\text{maximum total stresses in cycle}} = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \quad (1)$$

<table>
<thead>
<tr>
<th>Starting Flaw Size</th>
<th>Chord Thickness</th>
<th>Fatigue Life (Time to leak)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BS7910</td>
</tr>
<tr>
<td>0.5 x 5 mm</td>
<td>19 mm</td>
<td>10.54 years</td>
</tr>
<tr>
<td>1 x 10 mm</td>
<td>19 mm</td>
<td>1.61 years</td>
</tr>
<tr>
<td>2 x 20 mm</td>
<td>19 mm</td>
<td>0.55 years</td>
</tr>
</tbody>
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Table 1. Fatigue life estimates for different initial flaw sizes with 218 MPa residual stress.

<table>
<thead>
<tr>
<th>Starting Flaw Size</th>
<th>Chord Thickness</th>
<th>Fatigue Life (Time to leak)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>218MPa Residual Stress</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$R=0.34$</td>
</tr>
<tr>
<td>1 x 10 mm</td>
<td>19 mm</td>
<td>1.88 years</td>
</tr>
</tbody>
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Table 2. Effect of reducing residual stress using NASGRO analysis. (BS7910 gives no credit for this reduction of residual stress)

4 DISCUSSION AND CONCLUSIONS

4.1 Discussion

There are still a lot of poorly known features of the fracture mechanics analysis. This situation is typical of large structures containing welds that are difficult to control during manufacture. Nevertheless the analysis has some useful results.

- The initiating flaws sizes are very important. The original manufacture does include features such as unfused lands that may eventually lead to crack growth into the chord. A limit on size can be derived from the analysis to suggest weld quality requirements.
• In the case of repair welds, quite large flaws have been detected and have also been observed to grow due to fatigue. This explains the poor performance of repair welds [Dayawansa, 2004]. Many repairs we have investigated have had multiple failures at the same point as shown in Figure 8. The use of poorly controlled emergency welds is thus shown to be a major issue.

• As can be seen on Figure 6 the variation of stress around the overlapping cluster is very high. The applied stresses are thus not well known since the location of the flaw is not well known. This means there is large variation in flaw tolerance around the cluster. This is an issue that could be considered in cluster design.

• Residual stresses may be a major factor in growth rate. This leads to the need to investigate post weld heat treatment and other ways of reducing residual stress.

4.2 Further work
There is still much to do to clarify the causes of this problem, propose improved operational and maintenance strategies and to improve the design procedures for the booms and tubular structures in general.

Some of the activities in the next period of work include:
(a) Better assessment of residual stresses and the effect of variation of welding procedures.
(b) Improved study of the booms in action and the stresses involved in the boom operation.
(c) Further study of the fracture mechanics of the growth of cracks so that the quality of the welding, manufacturing and non-destructive testing can be better specified.
(d) Improved knowledge of the stresses in tubular structures of this type so that the design of the overlapping clusters and the fatigue design of the welds can be improved.

ACKNOWLEDGEMENTS
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REFERENCES


