Qualification of ultrasonic testing of Cat® ridged dump trucks ball studs from the inferior position of the stud

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Abstract
Background: Ball studs connect the steering linkages in Cat® Ridged Dump Trucks and are a critical component in these trucks. In the event of a cracked ball stud serious accidents can occur as well as very costly losses in service. Manufacturers require that ball studs be tested ultrasonically every 1000 hours of service. Guidelines prescribe that ball studs are tested from the superior position which requires two technicians and 1.5 hours per truck to test including access time to expose the top of ball stud. Some technicians test from the inferior end of the ball stud to reduce time (0.25 hours per truck) required for testing however accuracy of the assessment is questionable. This background has generated two project aims:

1) To determine the sensitivity and specificity of testing ball studs in dump trucks from the inferior versus superior position ultrasonically using usual methods and non-custom/conventional equipment.
2) Should the sensitivity and specificity of testing ball studs from the inferior position using usual methods not meet satisfactory standards, design a method of testing ball studs in dump trucks ultrasonically from the inferior position which meets sensitivity and specificity standards.

Method: A sample of 10 ball studs from Cat® Ridged Dump Trucks were tested ultrasonically inferiorly and superiorly using conventional ultrasonic equipment by two ISO 17025 Ultrasonic Level 2 certified technicians. They were blinded to the condition of ball studs. Inferior and superior testing were done a week apart so technicians could not compare results for each ball stud. The ball studs were then tested using magnetic particle testing to confirm if cracks present or not. As the results indicated unsatisfactory sensitivity and specificity for testing ball studs inferiorly using standard technique, a new procedure using a custom made angled wedge with a 13mm ultrasound probe was developed and tested, with technicians testing the 10 ball studs using this technique and comparing to magnetic particles testing results. Technicians were again blinded to the condition of ball studs.

Results: When testing from the manufacturer recommended superior position versus magnetic particle testing, sensitivity was 100% and specificity 100%. When testing inferiorly with standard probe sensitivity was 40% compared to magnetic particle testing. When testing inferiorly adding a custom made angled wedge with a 13mm probe the sensitivity is 80% and specificity 100%.
Discussion: Testing ball studs superiorly with a standard probe and inferiorly using custom angled wedge with a 13mm probe meet satisfactory sensitivity and specificity standards while testing inferiorly with standard probe does not meet satisfactory sensitivity values. Given that the time taken to test the ball studs in one truck superiorly versus inferiorly is 1.5 hours compared to 0.25 hours, the results for this new technique suggest using a custom angled wedge and 13mm probe is satisfactory and more feasible alternative.

1.0 Introduction

Ball studs connect the steering linkages together in Cat® Ridged Dump Trucks (Figure 1.) and are prone to cracking (Cat 2009). Manufacturing guidelines prescribe regular testing ultrasonically to assess the integrity of ball studs (Cat 2009). There are eight off ball studs per truck (Figure 2) and they come in different sizes depending on the truck size (Cat 2009).

The Cat® dump truck service manuals state that ball studs should be tested ultrasonically every 1000 hours (approximately testing them every 3 months if the trucks work day and night shift) for in-service cracking to prevent loss of steering in the event of one cracking through (Figure 3), (Cat 2006, p.1). Loss of steering is obviously a major safety concern for these giant vehicles (Department of Natural Resources and Mines 2001, Department of Industry and Resources 2004) and (haul) road side repairs are more difficult and labour intensive when compared to planned maintenance performed in the workshop. Government Safety Bulletins have been released in Australia regarding cracking of ball studs and detailing steering failures (Department of Natural Resources and Mines 2001, Department of Industry and Resources 2004).
The Cat® testing procedure specifies removing the grease caps above the ball studs and testing the stud from the “top” (superior position) which is the non-threaded end (Cat 2006 p.6). To test from the superior position a technician is required to remove the grease caps, perform the test and replace the grease caps which on average takes two technicians 0.75-1.5 hours per truck (time specified is the average time taken to test trucks over the last 3 years) (ARI 2015). See Figure 4 to illustrate superior view of ball stud. The testing of the ball studs only takes ~0.25 hours per truck and therefore the majority of the time the truck is out of service is due to obtaining access to the test area.

The threaded end of the ball stud is naturally exposed and therefore does not require any labour or time to gain access to this end. Therefore if testing could be qualified from the inferior end of the stud this would reduce the testing time from ~1.5 man hours (including access time) to ~0.25 man hours.

The challenges are:
- the taper of the stud and attempting to get sound from a smaller diameter to the larger diameter where the studs crack and
- the loss of cross sectional area within the threaded section due to cotter pin holes in this area.

Cubberly and Bakerjihan (1989) explain that a disadvantage of ultrasonic testing is the difficulty testing irregular shapes which is a consistent description of the shape of a ball stud. Figure 5 following shows the area of interest (where the stud typically cracks) from the manufacturer inspection procedure (Cat 2006 p. 6) and the cotter pin locations (Figure 5 and 6).
Asset owners often enquire whether the studs can be tested from the inferior position and report that other companies agree to this method. ARI have numerous cracked reference studs at their workshop which technicians are unable to repeatedly find cracks from the inferior position using standard equipment and currently refuse requests to test from this position. This results in a loss of work with asset owners preferring to reduce costs by having to pay less labour costs for the quicker inferior testing. An example of a statement from another company’s webpage confirms their use of procedures testing from the inferior position – in relation to testing ball studs:

“Asset Management Engineers’ procedure is a non-destructive straight beam examination using high frequency sound energy to conduct the examination and take measurements. A key advantage of the non-destructive UT inspection is that it does not require any fitters to remove covers or bolts.” (Asset Management Engineers 2015)

Therefore the objectives of this project are to:

1) To determine the sensitivity and specificity of testing ball studs in dump trucks from the inferior versus superior position ultrasonically using usual methods and non-custom/conventional equipment.
2) Should the sensitivity and specificity of testing ball studs from the inferior position using usual methods not meet satisfactory standards, design a method of testing ball studs in dump trucks ultrasonically from the inferior position which meets sensitivity and specificity standards.

Within these objectives the term sensitivity refers to the proportion of abnormal samples (cracked studs) identified compared to the true number of abnormal samples (ie. Are all cracked studs correctly identified?) and specificity refers to the proportion of normal samples identified compared with the true number of normal samples (ie. Are all intact studs correctly identified?) (Wei et al 2015).

On a review of the literature, no previous studies have investigated this area of non-destructive testing (NDT). This study will aim to provide new knowledge to the NDT field in regards to testing ball studs and aim to confirm accuracy of current techniques and design new techniques if necessary to ensure time efficient and accurate test methods.
2.0 Experiment 1

Experiment 1 was designed to address the first objective of the study:
To determine the sensitivity and specificity of testing ball studs in dump trucks from the inferior versus superior position ultrasonically using usual methods and non-custom/conventional equipment.

2.1 Methods Experiment 1

2.1.1 Design

A singled blinded randomised sensitivity and specificity study comparing conventional ultrasound techniques testing ball studs for cracks from the superior and inferior position compared to “gold standard” magnetic particle testing.

2.1.2 Equipment

Ball Studs:
ARI have collected numerous studs over the years for training and reference. Not all studs collected are cracked as some have been removed by asset owners for wear during servicing and in some cases studs were not cracked but worn/damaged and when tested ultrasonically in situ were mistakenly called as cracked studs and removed. Ten studs were available for testing, n=10 (Figure 7).

![Figure 7. Ball Studs for Blind Testing](image)

Ultrasonic Set:
The ultrasonic set was required to:
- have A-scan presentation
- have reserve of sensitivity of at least 20 dB at the maximum beam path used
- have a frequency range between 2 MHz to 10 MHz.

Probe:
5MHz 12mm single crystal probe was used.

Coupling Medium:
A satisfactory coupling medium was used to transfer the ultrasound from the probe to the surface of examination object. The coupling medium – polycell solution - had good wetting characteristics at the temperature of test.
Calibration Blocks:
An AS2083 No 1 (IIW V1) block was used for calibration. Blocks were constructed using material with similar nominal acoustic velocity to the material under test.

2.1.3 Procedure

Equipment was calibrated prior to testing being performed. Single blinded randomised ultrasonic testing (Salkind 2010, p.387) of 10 off ball studs (Figure 8) from the superior and inferior position of the stud was performed by two ISO 17025 certified Ultrasonic Testing (UT) Level 2 operators who had extensive experience of testing studs from the top. The studs included in the sample were worn studs that gave indications from wear but were not cracked. Superior and inferior position testing were conducted 1 week apart.

The test procedure used for testing from the superior position was the manufacturer’s procedure (Cat 2006). The same procedure was then slightly modified with an additional 6db for use from the inferior position to compensate for the smaller test surface (diameter) and cotter pins with an increased test sensitivity to attempt to not bias the existing test methodology of testing from the superior position. The use of different frequency probes within the manufacturer’s procedure given range (Cat 2006 p. 5) also did not affect the test results. The use of different size probes was not practicable due to the size of the studs being tested.

The cracking mode is from an in-service fatigue mode (ATTAR 2014) which means the studs crack from the outside surface in making them suitable for magnetic particle testing. The studs were all “gold standard” tested with magnetic particle testing to confirm the presence of cracking (Figure 8) using a surface test method following ultrasonic testing.

**Fig 8. Failed Ball Stud Showing Fatigue Beach Marks (up to ~70% cross sectional area) Before Brittle Fracture**
Magnetic particle testing was chosen as it is a simple but very effective test method that is very sensitive to surface breaking cracking (McKelvey 1980) such as the cracking in the ball studs being examined.

2.2 Results Experiment 1

5 off the 10 studs were confirmed to be cracked using magnetic particle testing. No false positives were detected ultrasonically (100% specificity). Typical cracking evident is shown below in Figure 9.

![Figure 9. Typical Cracked Studs (black circumferential lines are cracking)](image)

Summary of the test results that are shown in Table 1 are detailed below:

- 5 off the 10 studs were cracked (confirmed via magnetic particle testing)
- 2 off the 10 studs that were not cracked were worn/externally damaged
- All 5 cracked studs were detected ultrasonically testing from the superior position of the stud (100% sensitivity)
- Only 2 off the 5 cracked studs were detected ultrasonically from the inferior position of the stud (40% sensitivity)

Therefore there is only a 40% (2 cracks found via the bottom / 5 cracks evident) chance of detecting the cracks with standard (non-custom) test equipment when testing from the inferior end of the stud. Both ultrasonic test methods provided 100% specificity. Both technicians obtained the same results.
### Table 1. Test Results – Whether Cracking Was Present and Found

**Type of Test Vs Test Sample Stud Number**

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7*</th>
<th>8</th>
<th>9^</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic particle testing to confirm whether cracking was evident (gold standard test)</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No (damaged stud)</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No (worn stud)</td>
<td>No</td>
</tr>
<tr>
<td><strong>Top of stud</strong></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Normal probe 12mm Ø / 5MHz</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Reflector evident from damage</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Reflector evident from wear^</td>
<td>No</td>
</tr>
<tr>
<td><strong>Bottom of stud</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Normal probe 12mm Ø / 5MHz</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

*Stud 7 crack was 10mm in length and directly in line with the cotter pin hole and was unable to be detected when tested from the bottom of the stud. This crack could be considered to be minor in length and an acceptable risk when compared to the production loss/expenses of highly time consuming testing from the top of the stud.

^Stud 9 wear reflectors were comparable to cracking reflectors and as a result wear to this level will be identified as cracked studs in the field. Ultrasonic reflectors are unable to differentiate from cracking and wear discontinuities. Note that the level of wear evident required the stud to be replaced to prevent damage to the steering arm from excessive movement.

The **green** highlight indicates cracking found from the bottom with standard equipment.

The **red** highlight indicates cracking not evident testing from the bottom with standard equipment.

### 2.3 Discussion Experiment 1

The results from Experiment 1 indicate that there is a significant reduction from the 100% probability of detection of cracks in balls studs from dump trucks when testing from the superior position of the stud compared with testing from the inferior position using non customised equipment (40% sensitivity). Malhota (2016) reports that sensitivity below 70% or 0.7 is poor and unacceptable.

This initial testing indicates that the testing of ball studs from the inferior position with longitudinal conventional UT is not effective or ethical and supports the second stage of the study to design a more sensitive method for testing ball studs ultrasonically from the inferior position in dump trucks.
3.0 Experiment 2

Experiment 2 was designed to address the second objective of the study.

- Should the sensitivity and specificity of testing ball studs from the inferior position using usual methods not meet satisfactory standards, design a method of testing ball studs in dump trucks ultrasonically from the inferior position which meets sensitivity and specificity standards.

Justification for Experiment 2 is further strengthened by industry complaints regarding some companies testing from the inferior position and questionable accuracy of results. As a result of these complaints and technical discussions with an expert technician with was suggested using longitudinal waves with a small angled wedge. Lhemery et al (2002) reports that the use of angle probes or wedges enables a better detection of flaws in contoured and irregular shapes.

3.1 Methods Experiment 2

3.1.1 Design

A singled blinded randomised sensitivity and specificity study comparing an ultrasound technique testing ball studs for cracks from the inferior position with a custom angled wedge compared to “gold standard” magnetic particle testing. Using Snell’s Law different angled wedges could be made to induce different longitudinal waves within the stud. For example, as per Snell’s law a 5 degree wedge will induce a 11 degree longitudinal wave in the test item, which calculates the angle of refraction into a medium based on the incident angle and velocity of sound waves in the two mediums.

\[
\text{Snell’s Law: } \frac{\sin \alpha}{\sin \beta} = \frac{V_A}{V_B}
\]

Where \( \alpha \) is the wedge angle; \( \beta \) is unknown (angle of sound in the stud); \( V_A \) is 2.68km/s; \( V_B \) is 5.9km/s

3.1.2 Equipment

Equipment is as for 2.1.2 except for differences in probe and addition of custom angle wedge to the probe (see Figure 10).

Figure 10. Custom Angled Wedge (made from a standard order 45 degree wedge)
3.1.3 Procedure

A single blinded randomised ultrasonic testing of 10 off ball studs (Figure 8) from the inferior position of the stud using the custom wedge and 0.5” singe crystal probe was performed by two ISO 17025 certified Ultrasonic Testing (UT) Level 2 operators. The same studs were used as for Experiment 1. Testing occurred 6 weeks after Experiment 1.

The test procedure used for testing from the inferior position was developed by ARI. The results of the ultrasonic testing in Experiment 2 were compared with magnetic particle testing results as for Experiment 1 and sensitivity and specificity were calculated. The significant details of the testing procedure with custom degree wedge are outlined below.

**Method of Examination**
- Manually with direct contact coupling, using the pulse-echo method.
- The stud was tested from the inferior position of the stud.
- Peak memory was used and reset for each stud tested.

![Figure 11. Positioning of probe for ultrasonically testing ball stud inferiorly with custom angle degree wedge](image)
**Interpretation of Signals**

Areas of concern that are susceptible to cracking are highlighted below (Figure 12) in red and indications in these areas were assessed as acceptable or not as per the acceptance criteria detailed within the procedure (Appendix 1).

![Figure 12. Area of ball stud susceptible to cracking highlighted in red](image)

**Acceptance Criteria**

Results were recorded and assessed against the following criterion. Ultrasonic indications greater than 20% full screen height (FSH) when at evaluation sensitivity as detailed in ARI’s test procedure, in the area identified as susceptible to cracking shall be rejected.
3.2 Results

The results in Table 2 on the following page include the magnetic particle testing of the 10 ball studs and the results indicating if cracking was evident using the 0.5” probe with custom angled wedge.

The sensitivity when ultrasonically testing ball studs using a 0.5” probe with custom angled wedge to detect flaws is 80% when compared with magnetic particle testing and specificity 100%.

Table 2 Test Results – Whether Cracking Was Found or Present
Type of Test Vs Test Sample Stud Number

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<th>7*</th>
<th>8</th>
<th>9^</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic particle testing to confirm whether cracking was evident</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Bottom of stud - Custom equipment 13mm Ø</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Reflector evident from wear^</td>
<td>No</td>
</tr>
<tr>
<td>Crack reflector height at evaluation sensitivity % FSH</td>
<td>30%</td>
<td>35%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Shank 40% Groove 35%</td>
<td>Not evident</td>
<td>Shank 25% Groove 10%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Stud 7 crack was 10mm in length and directly in line with the cotter pin hole and was unable to be detected when tested from the bottom of the stud. This crack could be considered to be minor in length and an acceptable risk when compared to the production loss/expenses of highly time consuming testing from the top of the stud.

^Stud 9 wear reflectors were comparable to cracking reflectors and as a result wear to this level will be identified as cracked studs in the field. Ultrasonic reflectors are unable to differentiate from cracking and wear discontinuities.

Note that cracks found from testing from inferior position with standard equipment was half the amount of cracking found with custom made equipment shown in green.
3.3 Discussion Experiment 2

The use of a 0.5” probe with a custom angle wedge meets acceptable standards (Malhotra 2016) for sensitivity when testing ball studs ultrasonically for cracks from the inferior position. A sensitivity of 80% was achieved. Some critics may consider a higher sensitivity level should be required, however it should be noted that the crack in the ball stud in which the inferior wedge approach could not detect the crack is likely to be considered negligible risk.

The development of a proven testing technique from the inferior position of ball studs in dump trucks is beneficial to industry as it can save industry thousands of dollars in both the amount of truck down time and in testing costs. These feasibility issues need to be weighed up in relation to test accuracy to decide on the best approach for each client.

If the suggested solution had not achieved viable results then the use of phased array longitudinal probes that can be electronically steered of up to 5-10 degrees could have been considered as a potential solution. This would not be the preferred option as it would add additional problems such as higher level of training required for the testing operator and higher inspection equipment costs.

4.0 Conclusion

Testing ball studs superiorly with a standard probe and inferiorly using custom angle wedge with a 0.5” probe meet satisfactory sensitivity and specificity standards while testing inferiorly with standard probe does not meet satisfactory sensitivity values. Given that the time taken to test the ball studs in one truck superiorly versus inferiorly is 1.5 hours compared to 0.25 hours, the results for this new technique suggest using a custom wedge and 0.5” probe is satisfactory and more feasible alternative in relation to labour costs and truck down time.

Caution should be taken with results due to small number of ball studs tested (n=10) and further testing would strengthen evidence.

Acknowledgement

The author wishes to acknowledge the contribution of Mr Paul Grosser CEng, ISO9712 Level 3 UT, RT, MT, PT, ET, PAUT, ToFD for the idea of the angled wedge for Experiment 2.
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