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THE ASSET RELIABILITY ISSUE

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

Ball studs connect the steering linkages in Cat® Ridged Dump Trucks and are a critical component in these trucks.

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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 top 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 bottom (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 accuracy of testing ball studs in dump trucks from the bottom versus top position ultrasonically using usual methods and non-custom/ conventional equipment.
2) Should the accuracy of testing ball studs from the bottom position using usual methods not meet satisfactory standards, design a method of testing ball studs in dump trucks ultrasonically from the bottom position which meets accuracy standards.

Method: A sample of 10 ball studs from Cat® Ridged Dump Trucks were tested ultrasonically inferiorly (bottom) and superiorly (top) using conventional ultrasonic equipment by two ISO 17025 Ultrasonic Level 2 certified technicians. They were blinded to the condition of ball studs. Top and bottom 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 are present or not. As the results indicated unsatisfactory accuracy for testing ball studs from the bottom 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 particle testing results. Technicians were again blinded to the condition of ball studs.

Results: When testing from the manufacturer recommended top position versus magnetic particle testing, true positives were 100% and true negatives 100%. When testing from the bottom with a standard probe true positives were 40% when compared to magnetic particle testing, therefore indicating 60% false negatives. When testing from the bottom adding a custom made angled wedge with a 13mm probe the true positive rate was 80% with a 0% false positive rate.

Discussion: Testing ball studs from the top with a standard probe and bottom using custom angled wedge with a 13mm probe meet satisfactory accuracy standards while testing from the bottom with standard probe does not meet satisfactory accuracy values. Given that the time taken to test the ball studs in one truck from the top position versus the bottom position 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 a satisfactory and more feasible alternative.

1. Introduction

Ball studs connect the steering linkages together in Cat® Ridged Dump Trucks (Figure 1.) and are prone to cracking1. Manufacturing guidelines prescribe regular testing ultrasonically to assess the integrity of ball studs1. There are eight off ball studs per truck (Figure 2) and they come in different sizes depending on the truck size[1].

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)[2] Loss of steering is obviously a major safety concern for these giant vehicles[3,4] 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[3,4]

The Cat® testing procedure specifies removing the grease caps above the ball studs and testing the stud from the top position) which is the non-threaded end2. To test from the top 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)[5] See Figure 4 to illustrate top 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 bottom end of the stud this would reduce the testing time from ~1.5 person hours (including access time) to ~0.25 person hours.

Fig. 1: Cat® Ridged Dump Truck

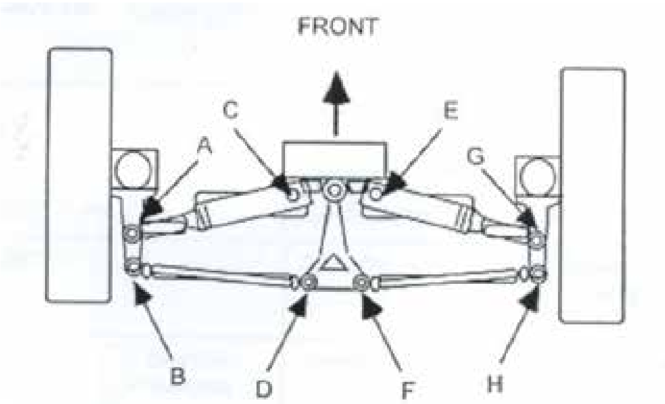


Fig. 2: Cat® Ridged Dump Truck Ball Stud Locations (shown by arrows/ letters)

Fig. 3: Failed Ball Stud

Fig. 4: Access Point to the Top of the Ball Stud (position A & B from Figure 2.)

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)[6] 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

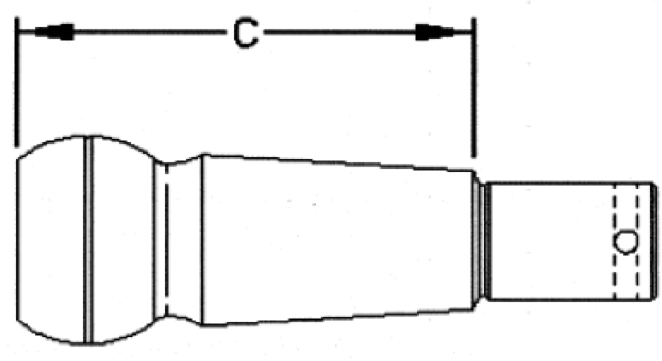


Fig. 5: Area of Interest (Cracking) Shown as "C" as per Manufacturer Inspection Procedure

Fig. 6: Cotter Pin Holes (2 off) on a Cracked Cat 777 Ball Stud.

area of interest (where the stud typically cracks) from the manufacturer inspection procedure[2] and the cotter pin locations (Figure 5 and 6).

Asset owners often enquire whether the studs can be tested from the bottom 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 bottom 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 testing from the bottom. 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."[7]

Therefore the objectives of this project are to:

1) To determine the accuracy of testing ball studs in dump trucks from the bottom versus top position ultrasonically using usual methods and non-custom/

conventional equipment.

2) Should the accuracy of testing ball studs from the bottom position using usual methods not meet satisfactory standards, design a method of testing ball studs in dump trucks ultrasonically from the bottom position which meets accuracy standards.

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. Experiment 1

Experiment 1 was designed to address the first objective of the study:

To determine the accuracy of testing ball studs in dump trucks from the bottom versus top position ultrasonically using usual methods and non-custom/ conventional equipment.

2.1 Methods Experiment 1

2.1.1 Design

A singled blinded randomised study of accuracy, comparing conventional ultrasound techniques testing ball studs for cracks from the top and bottom 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).

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 13mm 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.

Fig. 7: Ball Studs for Blind Testing.

Fig. 8: Failed Ball Stud Showing Fatigue Beach Marks (up to ~70% cross sectional area) Before Brittle Fracture.

2.1.3 Procedure

Equipment was calibrated prior to testing being performed. Single blinded randomised ultrasonic testing[8] of 10 off ball studs (Figure 8) from the top and bottom 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. Top and bottom position testing were conducted 1 week apart.

The test procedure used for testing from the top position was the manufacturer's procedure[2]. The same procedure was then slightly modified with an additional 6db for use from the bottom 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 top position. The use of different frequency probes within the manufacturer's procedure given range2 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[9] 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.

Magnetic particle testing was chosen as it is a simple but very effective test method that is very sensitive to surface breaking cracking[10] such as the cracking in the

Fig. 9: Typical Cracked Studs (black circumferential lines are cracking)

ball studs being examined.

2.2 Results Experiment 1

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

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

- 5 of the 10 studs were cracked (confirmed via magnetic particle testing)
- 2 of the 10 studs that were not cracked were worn/externally damaged
- All 5 cracked studs were detected ultrasonically testing from the top position of the stud (100% true positive rates, 0% false negative rate)
- Only 2 of the 5 cracked studs were detected ultrasonically from the bottom position of the stud (40% percent true positive rate, 60% false negative rate)

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 bottom end of the stud. Neither technique provided any false positives. Both technicians obtained the same results.

Table 1. Test Results – Whether Cracking Was Present and Found

Type of Test Vs Test Sample Stud Number

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

*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 ball studs from dump trucks when testing from the top position of the stud compared with testing from the inferior position using non customised equipment (40% true positive rate,60% false negative rate). Malhorta (2016)[11] reports that sensitivity (equivalent to true positive) below 70% or 0.7 is poor and unacceptable.

This initial testing indicates that the testing of ball studs from the bottom 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 accuracy of testing ball studs from the bottom position using usual methods not meet satisfactory standards, design a method of testing ball studs in dump trucks ultrasonically from the bottom position which meets accuracy standards.

Justification for Experiment 2 is further strengthened by industry complaints regarding some companies testing from the bottom 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)[12] 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 study of accuracy comparing an ultrasound technique testing ball studs for cracks from the bottom 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 an angled degree wedge will induce an angled 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.

Snell's Law: $$\frac{\sin \alpha}{\sin \beta} = \frac{V_A}{V_B}$$

Where α is the wedge angle; β is unknown (angle of sound in the stud);

V_A is 2.68km/s; VB 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).

3.1.3 Procedure

A single blinded randomised ultrasonic testing of 10 off ball studs (Figure 8) from the bottom position of the stud using the custom wedge and 13mm single 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 bottom 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 the true positive and true negative rates 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.

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 below.

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

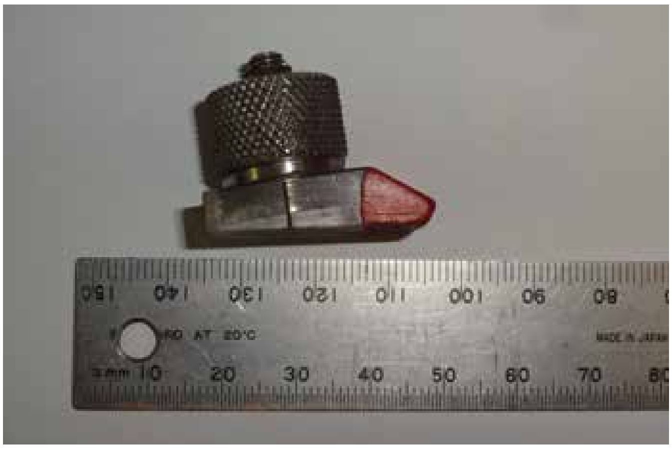


Fig. 10: Custom Angled Wedge.

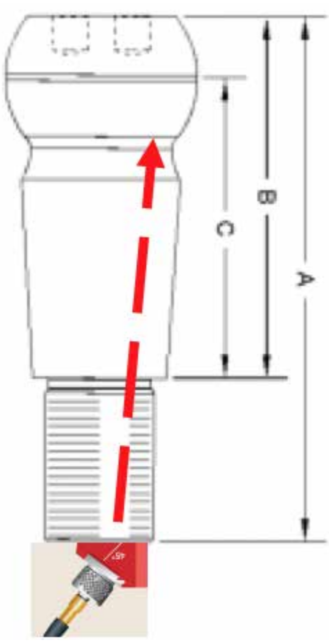
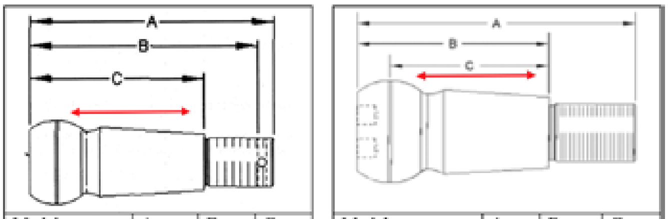


Fig. 11: Positioning of probe for ultrasonically testing ball stud from the bottom with custom angle degree wedge.



Model	A	B	C
768	161	149	112
769, 771	161	149	118
770, 772, 773, 775 B-F, 776, 777	174.8 or 168.15	158 or 155.4	121

Model	A	B	C
784, 785	273	187.8	155.5
789, 793, 797B	295	210.6	178.3
795F AC, 795F, 797B S/N:797B259-UP	341.1	240.3	195.3

Fig. 12: Area of ball stud susceptible to cracking highlighted in red.

13mm probe with custom angled wedge.

The true positive rate when ultrasonically testing ball studs using a 13mm probe with custom angled wedge to detect flaws is 80% when compared with magnetic particle testing and there were 0% false positives.

Table 2 Test Results – Whether Cracking Was Found or Present

Type of Test Vs Test Sample Stud Number

	1	2	3	4	5	6	7*	8	9^	10
Magnetic particle testing to confirm whether cracking was evident	Yes	Yes	No	No (damaged stud)	No	Yes	Yes	Yes	No	No
Bottom of stud - Custom equipment 13mm Ø	Yes	Yes	No	No	No	Yes	Not evident*	Yes	Reflector evident from wear^	No
Crack reflector height at evaluation sensitivity % FSH	30%	35%	N/A	N/A	N/A	Shank 40% Groove 35%	Not evident*	Shank 25% Groove 10%	N/A	N/A

*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 13mm probe with a custom angle wedge meets acceptable standards[11] for sensitivity when testing ball studs ultrasonically for cracks from the inferior position. A true positive rate of 80% was achieved. Some critics may consider a higher accuracy level should be required, however it should be noted that the crack in the ball stud in which the bottom of stud wedge approach could not detect the crack is likely to be considered negligible risk.

The development of a proven testing technique from the bottom 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 from the top with a standard probe and from the bottom using a custom angle wedge with a 13mm probe meet satisfactory accuracy standards while testing from the bottom with standard probe does not meet satisfactory accuracy values. Given that the time taken to test the ball studs in one truck from the top versus the bottom is 1.5 hours compared to 0.25 hours, the results for this new technique suggest using a custom wedge and 13mm probe is satisfactory and a more feasible alternative in relation to labour costs and truck down time.

Organisations should qualify their own angle and procedure to ensure they address the risk with deviating away from OEM methods. Caution should be taken with results due to small number of ball studs tested (n=10) and further testing would strengthen evidence.

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