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EXTENSION OF CONTAINER LIFE THROUGH LOW-COST PROBABILISTIC ASSESSMENT

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ABSTRACT

Three sets of ageing containers, approaching the end of their service life in new fuel transport, were discovered to have worn screw threads in some of the lid attachments. This wear manifested itself as an oversize female screw thread in hexagon nuts welded to the structure.

Following a quarantine period of random sampling and characterisation, the problem was confirmed to be widespread. Options considered to recover the situation included the renewal of all nuts, repair by helical insert, use of over-size fasteners, and use of a backing nut on lengthened fasteners. The practical difficulties of all of these approaches, together with the costs and disruption to the transport programme associated with repair of over 4,000 screw threads, favoured the use of a non-intrusive solution.

A programme was therefore initiated to provide detailed characterisation of samples of worn nut threads by putty replication, with test specimens made up by artificially creating a range of worn threads. By ensuring that the test specimens covered a wide spectrum of thread wear, and by testing these for bolt pull-out under controlled conditions, a probabilistic case was made that the incidence of a container thread failure occurring at a load below the design intent was very small. This design intent load is characterised by failure of the flanges, which occurs before that of the bolted connection, and so the concept of a 'weak link' was generated that sets a minimum value for fastener strength.

As part of the justification, potential causes of the thread damage were investigated. Factors relevant were found to be weld distortion during container manufacture or re-build, and the use of thread-cutting taps to clear deposits during the course of maintenance activities.

The probabilistic approach to justification of these container designs has been reviewed and accepted by the UK Competent Authority, with the award of a Fissile certificate for shipment of each set.

INTRODUCTION

Three sets of containers for transporting new fuel assemblies for PWR reactors had been in service for over three decades, in various guises for differing types of fuel assembly and under various approvals from the UK Competent Authority. Prior to obtaining design re-certification to the 1985 IAEA regulations, one set of containers (Set B) was undergoing ‘Turnaround Maintenance’. This involved full strip, clean, examination and re-assembly, followed by leak-testing and dispatch back to the nuclear facility for subsequent loading with a new fuel assembly.

CONTAINER DESCRIPTION

The outer container design is of a long rectangular-profile box, constructed of low-alloy steels and painted inside and out for corrosion protection. Along the horizontal centre-line is a flanged joint that allows the upper half, and its shock-absorbing features, to be lifted away for access to the inner container that carries the fuel assembly. A part view of the outer container is shown as Figure 1, the inner container omitted for clarity. The lower flange has clearance holes for the bolts and 5/8-11 UNC hexagon full-nuts welded to its lower surface. These nuts are attached by continuous fillet welds along the five accessible edges of the hexagonal nut, and were renewed at major overhaul thirteen years prior to this. Material for the nuts is a carbon steel, and because of the risk of corrosion of these female threads, a legacy instruction for each turnaround maintenance had been to pass a thread-cutting tap several times through each nut to clear out any loose debris or corrosion. Main flange bolting uses carbon steel hex-head bolts, with nickel-plated threads to negate the need for lubrication on assembly.

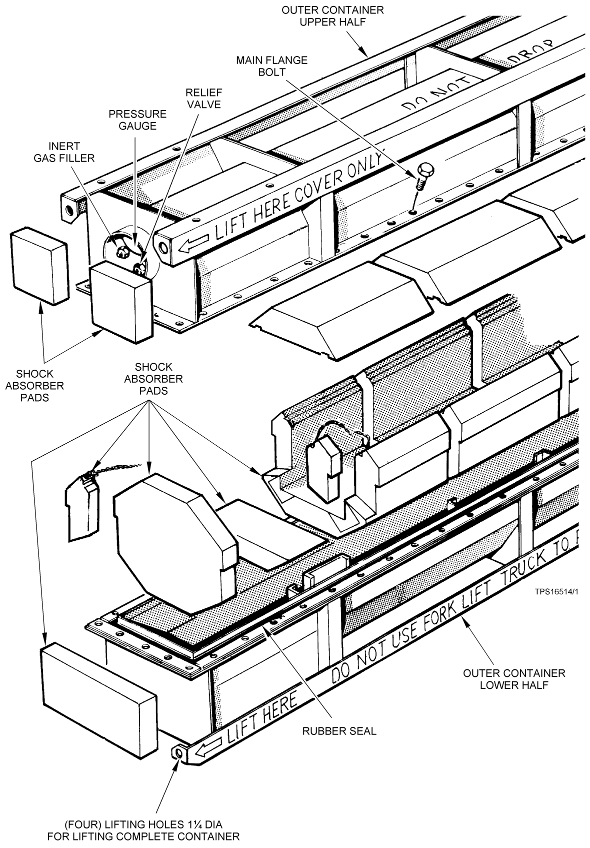

Figure 1 Exploded View of New Fuel Assembly Shipping Package

IDENTIFICATION AND QUANTIFICATION OF THE PROBLEM

The welded flange nuts were required to be “inspected” for damage as part of the schedule, and accordingly a 100% visual inspection of over 1,300 female threads was conducted. However, because of some ambiguity in these legacy maintenance instructions, of having no imposed technique for inspection, a random thread-gauging exercise was also undertaken. The results of this were far-reaching, as a large proportion of the samples allowed the NO-GO gauge to pass. Many of the female threads were evidently oversize.

Following a review of the drawings, in which the threads were specified to British Standard BS1580 to be of “normal fit” Class 2B, a thread gauge for the “free-fit” Class 1B was procured, and the random sampling repeated. The logic behind this approach was that it could be possible to quantify the thread wear to fall within the band bounded by the free-fit class. When the free-fit gauge was applied, a small number were found compliant, but again a large number failed the test.

Of these 1,300-plus locations on Set B containers, a small group of 32 were selected at random for detailed quantification of the wear problem. Although these locations were selected without prior knowledge of their condition in order to maintain an unbiased approach, it was ensured that the batch represented all of the generic locations on the design. This included flange corners, short edges, long edges adjacent to bulkheads, and other positions remote from any local stiffeners. The batch was also taken across a group of eight different containers selected at random, to avoid any bias to the results arising from a container-specific issue, such as material batch, or bias in tolerances at the time of manufacture. These 32 thread positions were replicated with Microset Replication Putty. A typical replica is shown on Figure 2.

Other than for Set B under investigation in maintenance, Sets A & C of similar containers existed to service a new fuel shipment programme. These sets had minor differences relating to inner containers and shock absorber features, but had outer containers of the same design. The service life of these three sets were all similar, and all had been exposed to the same maintenance regime. Accordingly sets A & C were also inspected. Because these sets were stacked for storage, options for access to the flange bolting were more limited. An initial survey established that wear was prevalent, in that many threads failed against the normal fit gauge, but failures against the free-fit gauge were less frequent than for Set B.

Random sampling was again taken for Sets A & C. The same criteria were adopted in selecting positions for replication, and amounted to 29 (Set A) and 30 (Set C) samples from ten different containers. Inspection of the replicas was undertaken with a 3-axis digital viewer with macro lens and camera, and ‘a4i Docu Image’ measurement software, to inspect profiles of the thread flanks, roots and crests, to quantify the major and minor diameters, and record the images with measurements. Again, the orientation of each specimen on the viewer was taken at random, recognizing the possibility of variability occurring around the perimeter of each thread. A typical replica with measurements is shown on Figure 2.

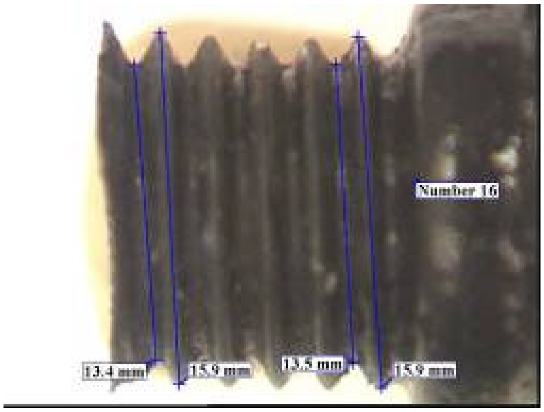

Figure 2 Typical Replica from Worn Flange Thread

OPTIONS FOR RECOVERY

Clearly, a large proportion of the female flange threads were not in accordance with design intent. The implications of this discovery were very significant to the transport certificates, as it was necessary to quarantine all three container sets from further transport duty. In the absence of the planned replacement container design arriving in the required timescales, a solution was necessary to restore these three sets back into transport service.

Brainstorming identified five intrusive repair options, and one potential route for justification of the status quo. These were:

a) Fit longer bolts with back nuts
b) Helical insert (‘Helicoil’) repair
c) Open out holes to accept a larger thread diameter
d) Remove existing damaged ‘captive’ nuts and substitute new ‘loose’ nuts
e) Full repair to meet design intent
f) Justify the failure load of the existing worn assemblies as adequate to satisfy the extant transport safety case.

Across the three sets of containers there were potentially around 4,000 damaged captive nuts, and so any intrusive solution was going to be intensive in labour, cost and time. A delay to the fuel shipment programme would be inevitable, and this was unacceptable to Rolls-Royce’s client. Of the lesser intrusive methods, option a) above was not physically feasible in all fastener positions, and options b) & c) may not have provided adequate nut wall thickness to become a reliable joint, without further justification by testing. The focus was shifted to option f), that is to justify the prevailing situation without repair.

JUSTIFICATION APPROACH

In support of earlier licence applications, testing work had been completed on mock-ups of the container flange, to allow representative behaviour to be modelled in an LS-DYNA analysis. This testing work had determined the failure load of the joint, and equally importantly, the mode of failure. Failure load for each bolted connection had been determined to be 60 kN for quasi-static tests, and 90 kN for a dynamic test. In all cases the joint strained by extreme flange distortion, with ultimate failure by the head of the bolt and its washer pulling through the relatively thin flange. For the static tests, this separation was typically 60 mm at peak load, and for the dynamic test it was 50 mm. As expected, strain-rate effects resulted in higher loads and lower ductility. In all samples tested, the bolts were essentially undamaged, with threads able to be unscrewed by hand. Clearly the limiting factor for the joint was flange strength; in effect the bolts were under-utilised. A “Weak-link” concept of flange failure had thus been demonstrated. Drop testing of container prototypes in the most adverse attitudes had also demonstrated that no joints reached this limiting condition; and although flanges had minor distortions, these were trivial compared with the 60 – 88 mm needed to pull a bolt head clean through the flange.

The current task was to demonstrate that the bolted fasteners, although worn, would still have a margin to failure greater than that of the flanges. To this end, a test programme was initiated that would assess the failure strengths of fasteners in a wide range of thread conditions; from new to severely degraded. This test programme required a reliable quantification method for the nut damage, to enable meaningful results to be produced. Classical methods for assessing shear strength of threads apply interactions of male and female threads at the spread of diameters between external ‘Major’ and internal ‘Minor’. However these methods assume a design 60-degree thread profile, which is absent in these cases. An adapted approach was taken in which each nut putty replica was assessed at the design nominal effective diameter (14.5 mm from BS 1580), to measure the mean shear thickness of the residual female threads. This technique was chosen as being more relevant to strength of the irregular thread forms than measures of major and minor diameter. These measurements are shown on a sample in Figure 3. This shear thickness, developed around the theoretical surface of the effective diameter, over the number of threads engaged (typically six), gave a measure of the female thread shear area. Accordingly, this was an indicator of shear strength, that could be plotted against failure load and assessed for trends.

Assessment of the failure load results against this shear area, together with a quantification of the damage on the containers, would form the basis of the safety case.

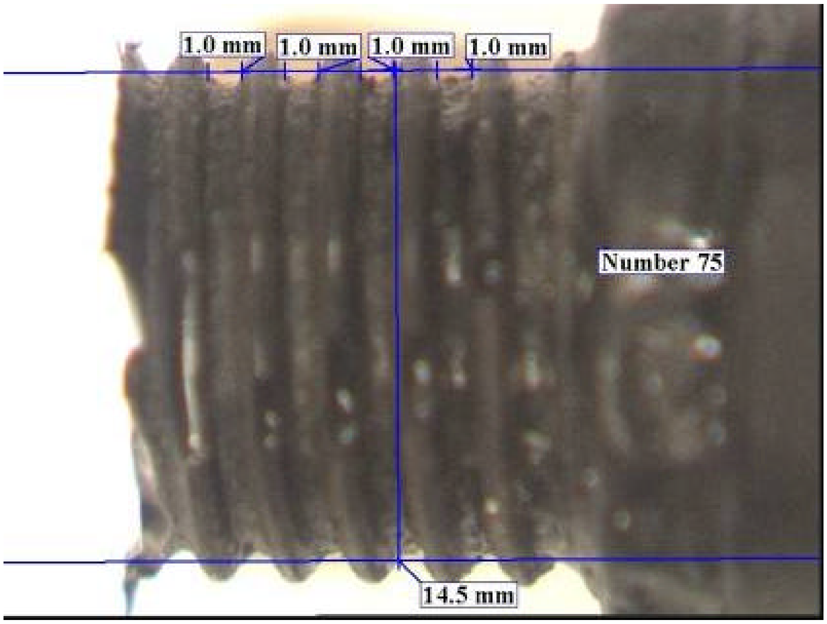

Figure 3 Thread Shear Area Measurement

BASIS OF SAFETY CASE

Wear damage to over 4,000 nuts cannot be readily quantified, and so a statistical approach was taken, based on a sample of approximately 30 positions taken randomly from each of the three container sets. Each set of containers was treated as a separate entity. The criterion adopted was that the container sample data would be shown to comply with a recognised statistical distribution. A 99% confidence level would then be calculated for lower bound shear area across all container nuts; and test nuts, artificially worn to a smaller shear area than this, would be shown to fail at loads much greater than the flange “weak link” load. The size of this margin for test nut failure load was set to be 50% above the flange ”weak link” load. This resulted in a pass criterion of 90 kN under slow (quasi-static) strain rate testing.

As a further demonstration of the absence of “cliff-edge” effects, the exercise was to be repeated with 99.9% confidence values, and the aim was that conclusions would be unaffected.

CREATING TEST SPECIMENS

A quantity of new hexagon nuts to the container specification British Standard BS1768 Grade 3 was procured. This also specified material composition and hardness testing, and three of these nuts were forwarded for tensile testing, for confirming performance. All held the minimum test load of 12.6 ton (125.5 kN) specified by the British Standard. Ultimate failure occurred through bolt tensile failure.

Thirty-eight of these nuts were deliberately abused by running a tap through them a large number of times by hand, to simulate the cumulative effect of many maintenance periods. Replication putties were taken at intervals to monitor the degree of damage, and when the damage was deemed to be comparable with, or worse than, the container replicas, these nuts, with a spectrum of degrees of thread "wear", were forwarded to the test programme. A piece of steel plate with a clearance hole, to represent the container flange, was used in the test machine for giving support to these nuts. Figure 4 and Figure 5 show typical variations in the thread wear created.

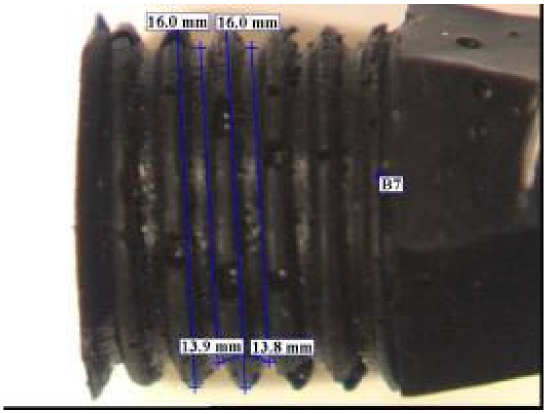

Figure 4 Test Nut Replica with Minor Wear

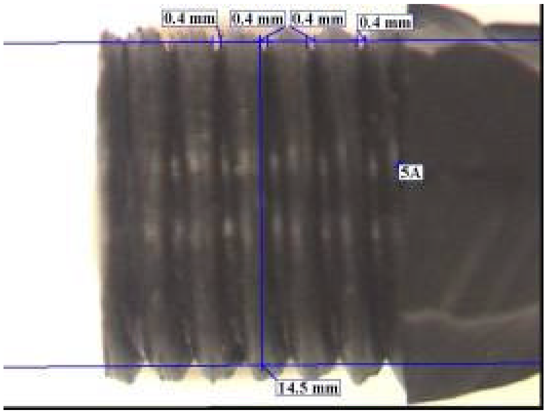

Figure 5 Test Nut Replica with Gross Wear

New bolts to BS1768 Grade T, and also nickel plated, were used in all testing. The use of new was justified on the basis that container bolts were 100% visually inspected at maintenance and any with damaged threads (readily identified by damage to the plating) were renewed. Bolts as supplied were too short to be gripped in the test machine heads, and so were extended by Electron Beam welding a 25 mm diameter rod to their heads. This welding technique was selected to minimize the heat input and potential change to bolt material properties.

Ten of the new nuts, undamaged, were welded to pieces of 5 mm thick plate in a manner representative of the captive nuts on the containers. It was noted that in eight of these welded specimens, a new bolt could not be screwed in by hand, requiring the careful application of a hand tap to open out the threads as necessary. These ten specimens were finally replicated.

TEST RESULTS

The testing of each specimen to failure was conducted on a calibrated Denison tensile testing machine, using slow extension rates. All but six specimens failed by stripping of the worn nut threads. Those that failed by bolt tensile failure were generally those with the least amount of wear. All results are plotted on Figure 6. Included in this summary are the welded nut specimens, whose performance was not distinguishable from the whole population, as indicated by the pink data points on Figure 6.

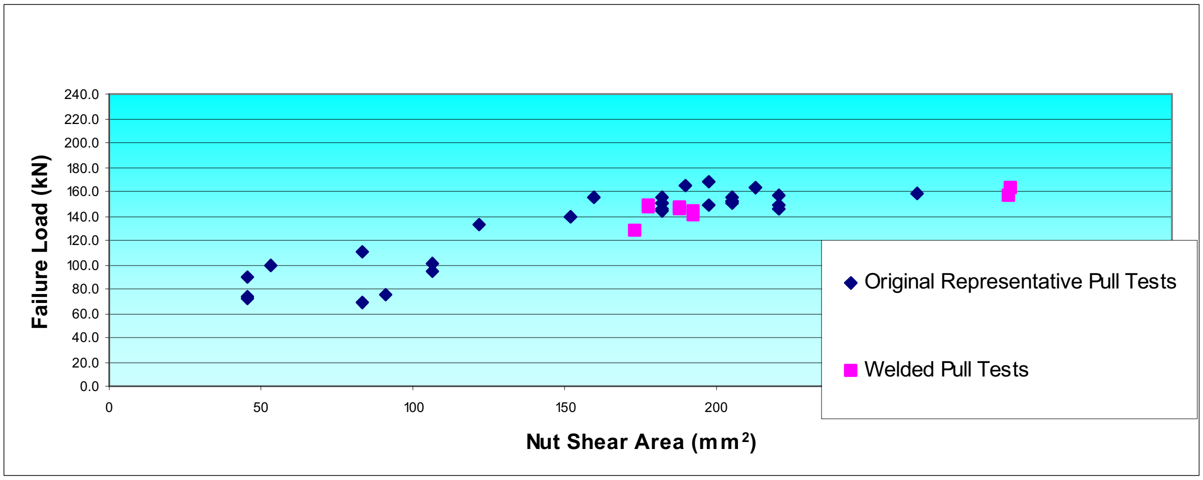

Figure 6 Test Data

STATISTICAL ANALYSIS RESULTS FOR CONTAINER THREADS

Results of the container thread shear areas were analysed, first for statistical 'normality', and then for determining lower bound values to 99% confidence levels. Container Set A was shown to meet the criterion for a normal distribution by analysis of the 30 data points, and the lower bound shear area to 99% confidence level was 199.6 mm^{2,} shown in yellow on Figure 7. The majority of the tested nuts fell below this shear area, and the failure loads in testing were generally above the pass criterion of 90 kN, as shown in Figure 7. The conclusion reached is that Set A is justified. To assess for absence of cliff-edge at 99.9% confidence level, a lower bound shear area of 186.1 mm^2 was calculated. This line, although not plotted on Figure 7, is shown on Figure 9 and clearly does not undermine the conclusion for Set A.

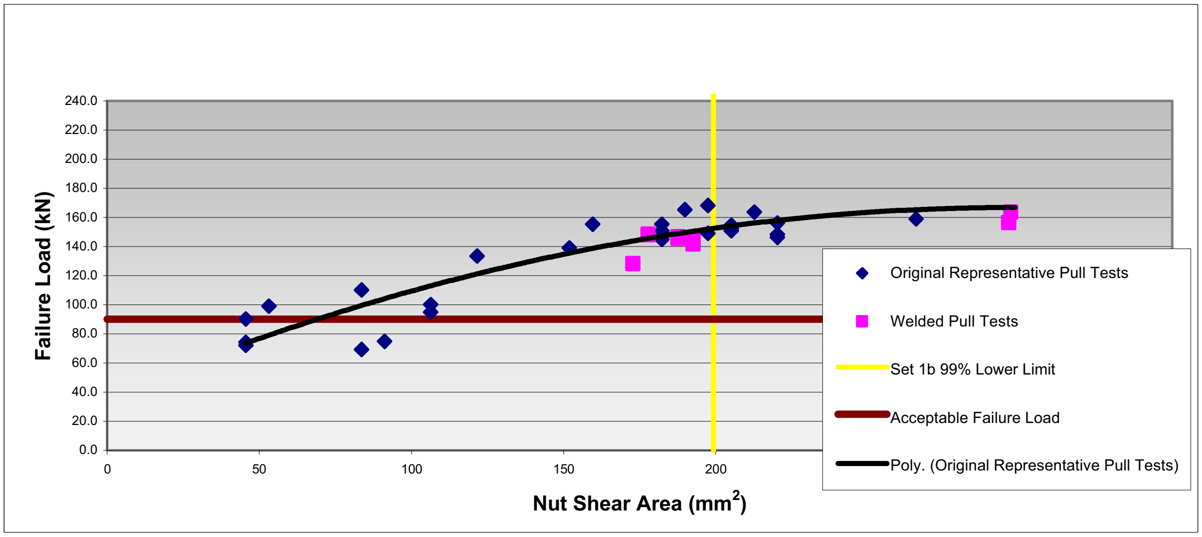

Figure 7 Results for Set A to 99% Confidence Level

Container Sets B and C had significantly skewed result sets, and failed against the Anderson-Darling criterion for 'normality'. However, they were assessed against other types of distribution and found to comply with the criteria for a Weibull distribution. Of these two sets, Set B was the worst in respect of general shear area, and as an example is shown as Figure 8 for the data and the fitness test.

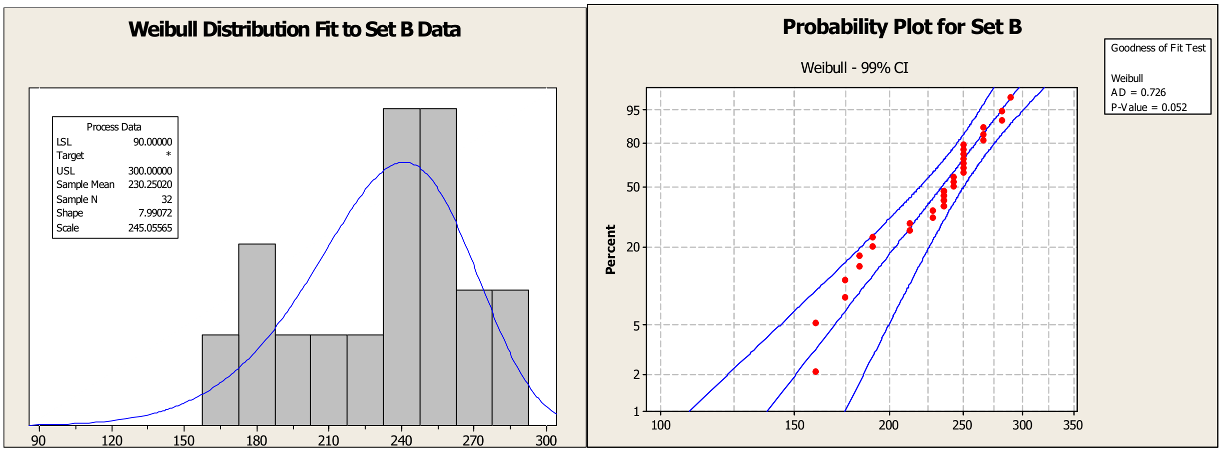

Figure 8 Set B Weibull Distribution and Fitness Test

Due to the pressing need for a justification for Sets B and C, only the second leg of the safety case was adopted, ie the absence of a cliff-edge at a 99.9% confidence level, as this would bound any result for the main approach to 99% confidence level. The lower-bound shear areas to 99.9% confidence level were 96.7 mm^2 for Set B and 146.9 mm^2 for Set C. The results are shown on Figure 9.

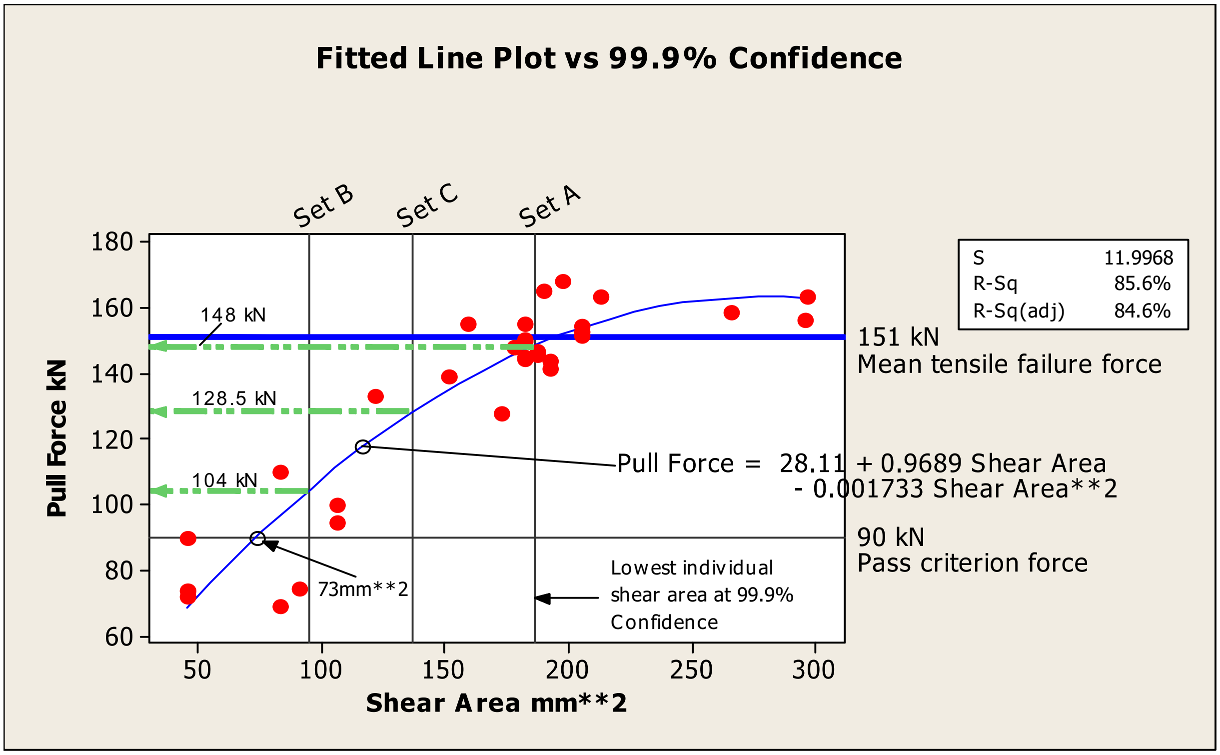

Figure 9 Results to 99.9% Confidence Level

The test data is now separated into two groups, to better represent the mechanistics of failure. Those bolts that failed in tension are represented by the horizontal blue line, set at the mean of the six relevant data points, being 151 kN. This line is horizontal because tensile failure of the bolt is independent of nut shear area. All failures by stripping are represented by the best-fit polynomial line. These test results may be subject to some scatter, mainly caused by uncertainty of shear area resulting from a less than ideal resolution on the camera/software system used for measuring replicas. However, because this study is based on a conservative approach in the use of 99.9% confidence level data from the containers, the nominal test line shown by the blue polynomial in Figure 9 is deemed to be acceptable.

Container Set A is clearly justified on this probabilistic basis. The results for Sets B and C also show that, although the margins are reduced, there remains a significant margin between the worst-case nominal failure load of 104 kN and the pass criterion of 90 kN. All three container sets are justified for continued service, on the basis that integrity of the lid attachment is not undermined.

POTENTIAL ROOT CAUSES

Inspection of the replicas indicated a general loss of material from the thread forms of the nuts, characterised both by receding of the crests, and narrowing of the thread included angle. In addition, the roots were very broad and ill-defined. Artificially worn test nuts, created by consolidated hand-tapping, exhibited very similar characteristics. The adoption of aggressive container maintenance procedures in the use of thread-cutting taps to clean holes, was clearly contributory. A further factor is believed to be weld distortion at build and overhaul maintenance, requiring many holes to be opened up with a tap prior to service.

CONCLUSIONS

Through the application of probabilistic justification techniques, all three container sets have been shown to remain with an unchanged level of safety, despite significant wear on the main flange female threads. This conclusion is reached because

- Under design conditions, the integrity of the fastened connection of the outer container lid to base is not as limiting as the strength of the flanges;
- On a probabilistic basis to a 99.9% confidence level, the worn threads do not degrade the bolted fasteners to a strength lower than the flanges;
- At the confidence levels quoted, a margin remains before the fasteners become the limiting feature;
- In drop testing at the worst attitudes, flange separation loadings did not closely challenge the strength of the flanges, thus showing further margins.

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