VALIDATION OF IMPACT PERFORMANCE FOR THE CROFT SAFKEG® 4087A THROUGH ANALYSES AND TESTING

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ABSTRACT

A large cavity SAFKEG®, Design N° 4087A (Figure 2), has been developed by Croft Associates Ltd. for the shipment of solid radioactive materials. It has been designed to satisfy all safety requirements of a Type B(U) transport package, as specified within the IAEA SSR-6 [1] Transport Regulations.

As part of the package substantiation, in-depth analyses of the impact and thermal performance under Normal & Accident Conditions of Transport (NCT & ACT) were undertaken through physical impact testing and Finite Element Analysis (FEA) methods. These analyses methods were used in conjunction with an impact test program, where the testing strategy was derived utilising a benchmarking / decision matrix approach.

This combination of physical impact testing and FEA was used to validate the impact performance of the package. The testing consisted of a sequence of tests with the package in the centre of gravity over lid edge orientation followed by a sequence of tests in the axis parallel to target orientation. High speed photography and 'FaroArm' metrology measurements were used to analyse impact deformations.

Once benchmarked, the FEA model accurately demonstrated the performance of the package under impact conditions. Furthermore, the benchmarked model was also used to examine package behaviour under conditions not feasible to undertake within the physical testing.

Further analysis was completed to validate the performance of the novel 'weak-link' tie-down system. This analysis was based upon a calculation approach substantiated by a component testing series. This paper presents a summary of the packages regulatory testing and performance validation with an emphasis on modelling, test strategy, analysis, and evaluation.

INTRODUCTION

The 4087A (Figure 1) package has been developed as a new variant in the Croft SAFKEG® range, to meet the client's specification for a large cavity Type B(U) transport package.

The design has been subjected to a series of regulatory impact tests and thermal analyses, as defined within IAEA SSR-6 [1] regulations for both NCT and ACT. The deformation and knock back measurements resulting from these tests subsequently formed the basis of the validation of FEA impact and thermal assessment for the ACT conditions discussed within this report.

The basis of the package design utilises the proven concept of an outer stainless steel welded keg, providing impact and thermal protection under ACT for the inner Containment Vessel (CV). The keg incorporates TISAF (Thermal Insulating Shock Absorbing Foam) which is manufactured by Croft using a proprietary process and formulation. TISAF has been used extensively within Croft Type B packaging designs for over 40 years and has been subject to extensive testing and evaluation, including physical impact and pool fire testing within Type B transport packages. Typically, within Croft SAFKEG® designs, further thermal and impact protection is provided by a cork packing set surrounding the CV.

This form of keg structure and construction has been proven to provide a corrosion resistant, deformable structure with progressive and predictable impact performance.

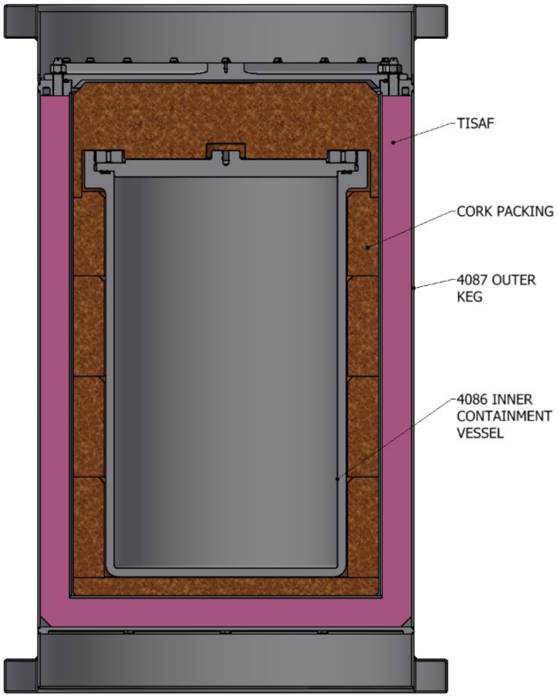


Figure 1. SAFKEG® General Assembly

IMPACT AND THERMAL ANALYSIS OF SAFKEG

SAFKEG® Physical Drop Test Performance

The 4087A SAFKEG® design has successfully completed a cumulative series of NCT and ACT impact tests. The test series strategy was derived utilising a benchmarking / decision matrix approach, using evidence and professional experience from previous drop tests on existing SAFKEG® designs.

Two prototype 4087A's were used, one was orientated in the centre of gravity over lid edge and the other in the horizontal orientation. Extensive metrology points were identified and marked upon each of the keg body, keg rims, lid, lid studs and base to allow measurement of point displacements using a 'FaroArm', which were fed back into the regulatory FEA to accurately model impact damage [2].

SAFKEG® Thermal and Impact FEA Performance

The impact FEA assessment was used throughout the design development at several stages, to assess the impact performance and iterate the design against the prescribed damage criteria. The regulatory impact assessment [3] aligned very closely with the test evidence from the physical impact test program. The physical testing was used to benchmark the FEA model and was then used to perform a series of regulatory impact scenarios, including several beyond design basis impacts to demonstrate the absence of cliff edge effects. During analysis, the largest transient CV lid gap opening of the closure reported in the impact FEA was 0.055 mm. This was seen to be within the working compression range of the containment seal with no residual gap remaining post impact.

The impact analysis additionally assessed several alternative drop test orientations in a sensitivity study. These were certain orientations that would prove difficult to control and complete in physical tests but would provide bounding deformations for the thermal FEA assessments (Figure 2).

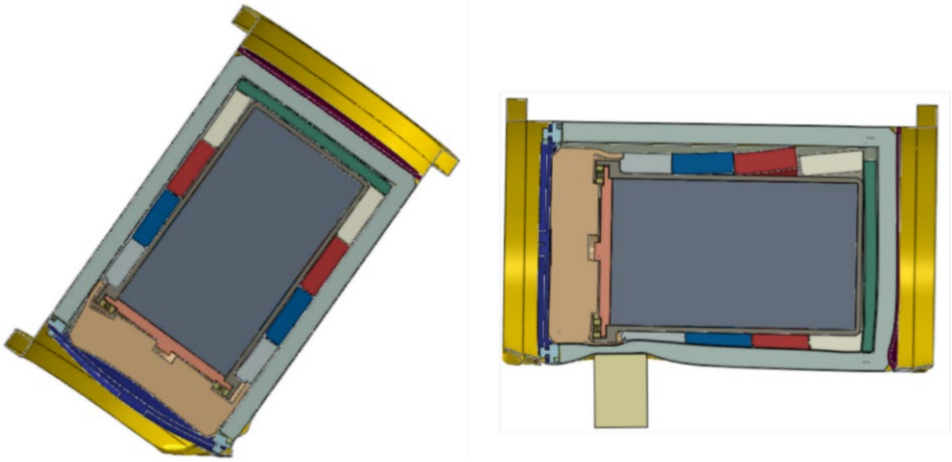


Figure 2. SAFKEG® FEA Impact Analysis (LHS Lid Edge 9m Drop and RHS Punch Test post 9m Side Drop)

A series of NCT and ACT thermal FEA assessments [4] were undertaken in accordance with SSG-26:2018 guidance [5]. The thermal assessments used initially undamaged and then damaged (ACT) models resulting from the physical drop tests with worst case pessimistic assumptions in terms of initial conditions, material properties and applied heat loads. All results were shown to be within the SSR-6 2018 regulation [1] requirements for Type B(U) transport packages, as described within the Design Safety Report.

SAFKEG® FEA Validation

Comparing the deformed benchmark FEA model geometry with photographs of the damaged impact test specimen (Figure 3), shows that the FEA model accurately reflects the nature and distribution of the damage seen in the physical impact tests, as reported in [3].

Figure 3. SAFKEG® FEA Benchmarking

RESTRAINT SYSTEM ANALYSIS

For the package to meet regulatory requirements, it has been designed such that at acceleration loads above NCT, the package will come free from the pallet using ‘weak-link’ method discussed within TCSC 1006 [6] (Figure 4). This ensures that the pallet does not compromise the package integrity, under ACT scenarios.

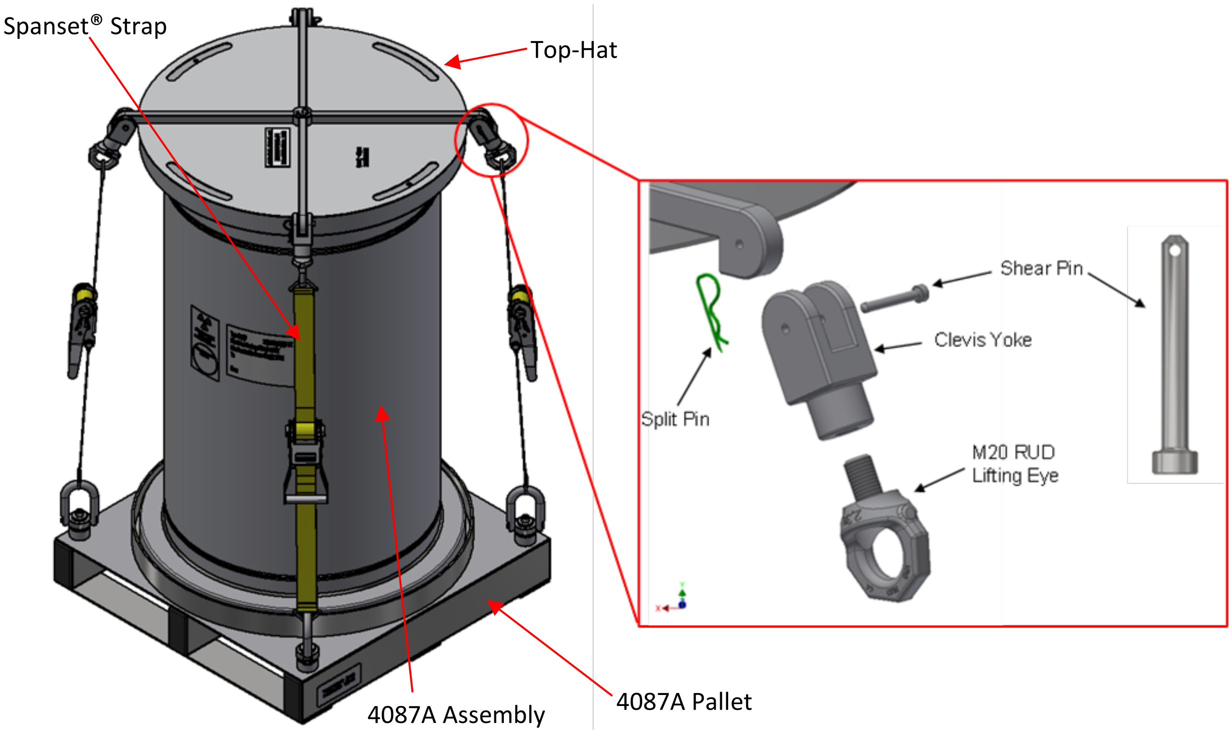


Figure 4. SAFKEG® Restraint System

The design consists of a 7 mm, 8.8 grade carbon steel solid shear pin (acting in double shear) as shown in Figure 4 & Figure 5 which is the ‘weak-link’ feature.

The retention system allows the package to remain situated on the pallet to withstand NCT accelerations. However, between NCT and ACT acceleration loads, the shear pin will fail, and the package and restraint system will be released from the pallet.

The package retention system incorporates a ‘top-hat’, which secures the package down onto the pallet via 4-off Spanset® straps and RUD Swivel Eye Bolts. Connecting the Spanset® strap to the top hat is a clevis yoke, shear pin and an M20 RUD Lifting Eye, see Figure 4.

The calculated NCT acceleration loads acting through the tie-down straps, and therefore the yoke assembly and shear pin (reported in [7]), results in a reserve factor of 2.60 in comparison to shear pin yield point. This ensures that the pin will not fail during NCT accelerations. Clearly, the reserve against ultimate shear strength will be even greater than this shear yield point value.

The failure load of the shear pin can be determined using the ultimate shear strength of the 8.8 grade carbon steel material. This can be equated to the acceleration loads required to break the pin in pure shear as reported in [8].

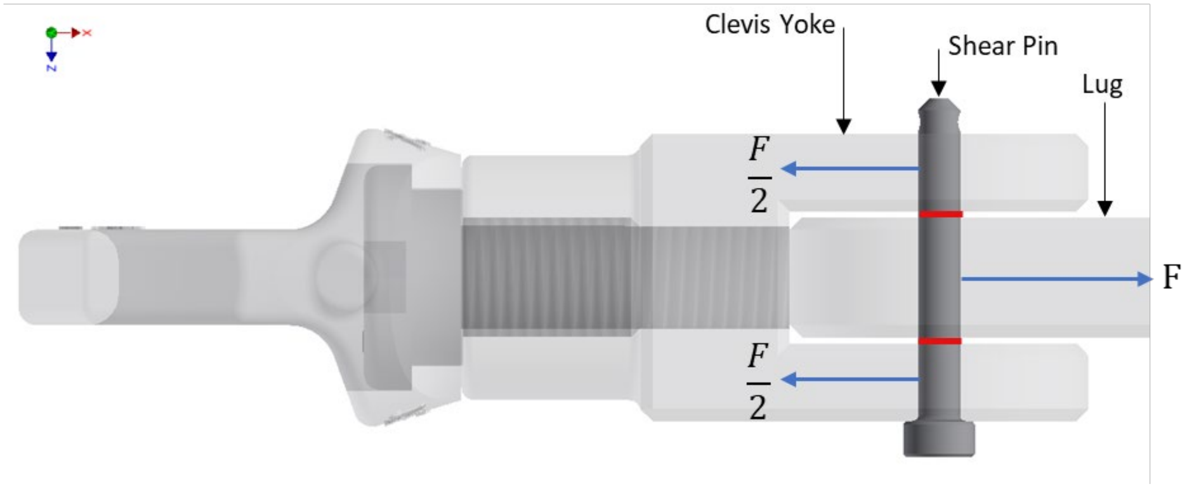


Figure 5. Shear Pin Free Body Diagram

From this, the lug tensile, shear and fatigue stresses for the clevis yoke and top hat were calculated, as reported in [8]. This would ensure that the shear pin at the required acceleration will be the first component to fail in the retention system, as detailed below.

Progressive Failure Modes

It is important to show progressive failure of the shear pin system, from the associated calculations on the tie-down system ([7] and [8]) the following can be confidently stated:

1. At NCT accelerations defined by TCSC 1006 [6], the restraint system has significant margin to yield.
2. As NCT acceleration values are exceeded, the system will fail progressively as follows:
    - The shear pin will fail at circa 5.5g. The straps will be rated to fail at a g value greater than NCT values.
    - The top hat lug is designed such that it would fail in either shear or tension at values above 5.5g.
    - The clevis yoke is demonstrably more resilient than both the shear pin and top hat lug [7].
    - Various RUD components are rated for high loads, and therefore would not fail prior to items stated above.
3. Finally, with respect to fatigue, the margins are high when compared to specified operational cycles, such that fatigue failure is not anticipated. In addition, the shear pin is replaced annually during maintenance which negates this failure mode.

MECHANICAL TESTING OF SHEAR PINS

Element Materials Technology were contracted to perform mechanical load tests on the shear pins with Croft witnessing and following a Croft Associates Procedure [9]. The results provided confidence in the performance of the tie-down system under both loading conditions and substantiated the design calculations and analysis.

METHEDOLOGY

NCT Load Test of Shear Pin

The components were assembled as shown in Figure 5. The NCT loads and predicted failure loads used for testing were taken from the analysis calculations [8]. For NCT testing, the system was placed under a preload of 5,000 N, to replicate the tension within the tie-down straps, the load was then gradually increased up to 16,500 N, reflecting maximum predicted NCT loads (calculated in [7]) and then decreased back to zero. The system was then disassembled and inspected for any deformation through various NDE methods. Following the NCT tests, the same pin was then subject to a destructive test as defined below.

ACT Destructive Load Test of Shear Pin

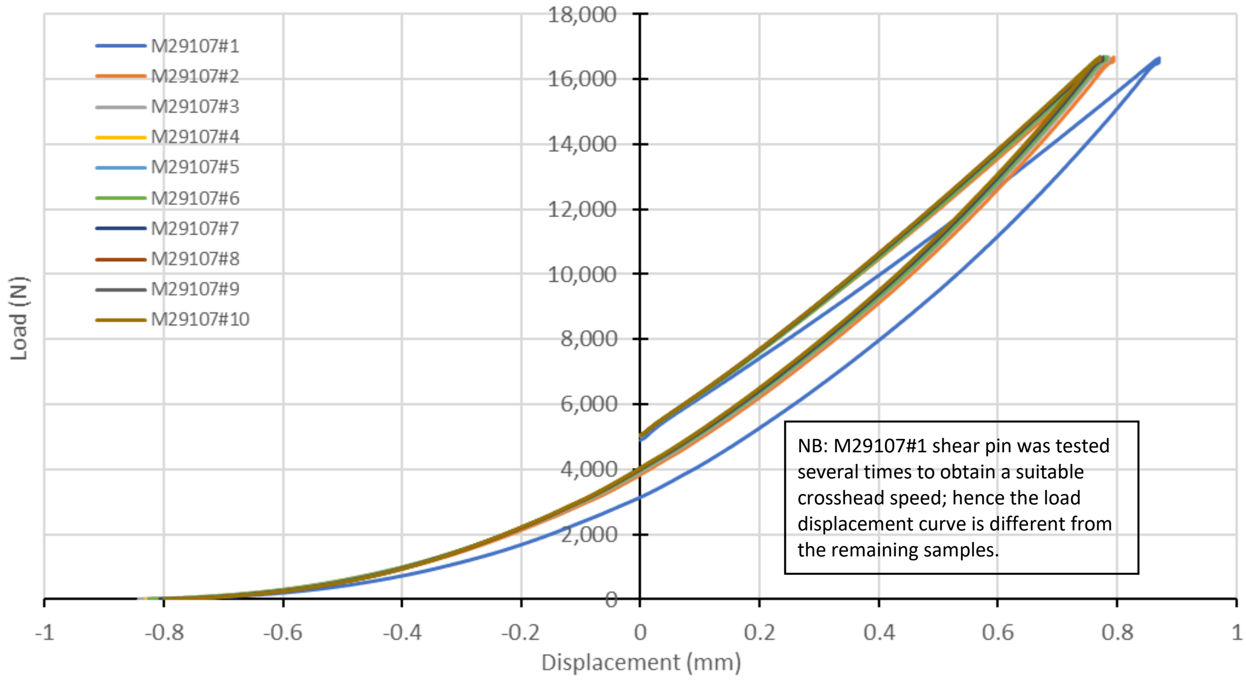
The components were reassembled as shown in Figure 5, reusing the components from the NCT load case. The assembly was placed under a preload of 5 kN, the load was then gradually increased until the shear pin failed. The pin was expected to fail at approximately 48 kN, as per calculation sheet [8]. Following the tests, the failed shear pin was then removed, and the remaining components inspected for deformation and damage.

TEST RESULTS

Documented below are the shear pin results from testing.

NCT Load Cases

The load vs displacement curves for the tested shear pins at NCT loads are presented below in Figure 6.



NB: M29107#1 shear pin was tested several times to obtain a suitable crosshead speed; hence the load displacement curve is different from the remaining samples.

Figure 6. NCT Load Vs Displacement Graph

ACT Load Case

The load Vs displacement curves for the tested shear pins at ACT loads (to failure) are presented below in Figure 7. All shear pins failed into three pieces between 43 kN – 46 kN which is extremely close to the predicted value within the calculations, providing a high level of confidence within the design.

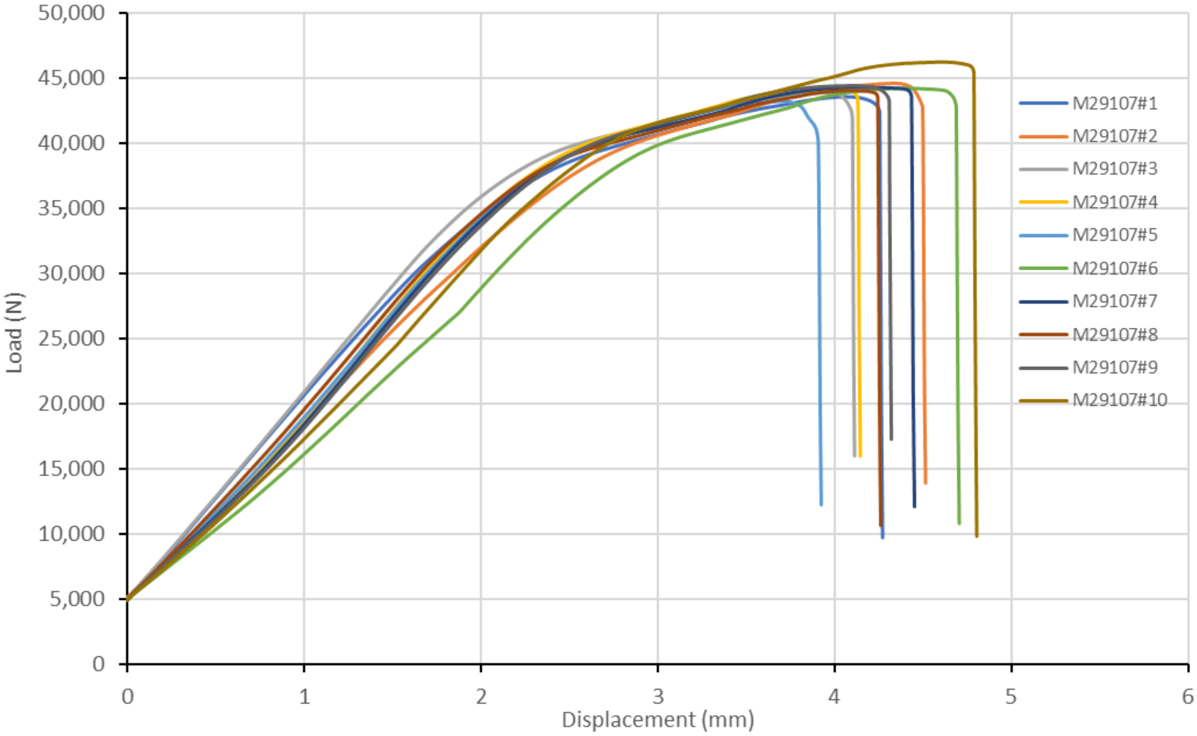


Figure 7. ACT Load Vs Displacement Graph

Observation of the ACT tested pin provides evidence that the pin failed in shear as per design intent, where the central section remained within the lug, and the two remaining sections were situated in their respective sides of the clevis yoke, as per design intent (Figure 8).

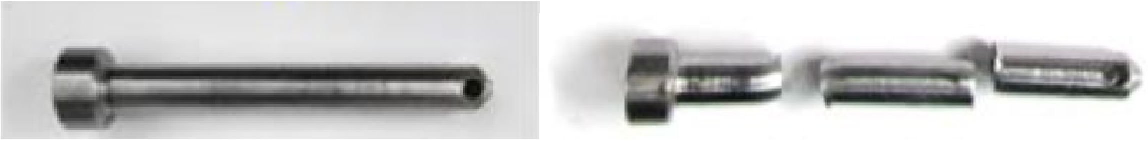


Figure 8. Pre and Post testing of Sample ID M29107#1

Test Result Review

Verification tensile testing of shear pins was performed under NCT (5 kN pre-load + 11.5 kN) and ACT (5 kN pre-load + load until failure) load cases providing evidence that the system is viable and aligned with the original analysis. Visual, dimensional and NDE inspections were carried out before and after the NCT load case and post ACT, the results are summarised below in Table 1.

Table 1. Summary of NCT and ACT Results

Test	Pre NCT Test	Post NCT Test	Post ACT Test
Visual	Some surface scratches and score marks		Failed into three pieces
Dimensional	Negligible changes		N/A
NDE	Free from defects		N/A
Av. Maximum Load (N)	-	16,683	44,277
Av. Maximum Displacement (mm)	-	0.79	4.13
Failure?	-	No	Yes

CONCLUSION

This paper has outlined the processes adopted by Croft Associates when developing a new Type B(U) packaging, in this case utilising an optimised process based upon the existing SAFKEG® range. Focus has been placed on the development and substantiation of the novel shear pin tie-down design and the challenges faced with developing a failure link. Insight has been given into the level of analysis used to provide confidence in the system and verify the containment performance of the package, this includes prototype manufacture, testing and physical trials.

ACKNOWLEDGEMENTS

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