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Bolt Study – Behaviour of Bolts in Drop Accident Scenarios of the Nirex 3m³ Box ILW Package

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1. Background

The mission of Nirex is to provide the UK with safe, environmentally sound and publicly acceptable options for the long-term management of radioactive materials. One of the key tasks is to ensure that waste is packaged by waste producers in a form which is suitable for safe storage, transport, handling and potential disposal.

In pursuit of this key requirement, Nirex has developed specifications to set the standard for the design and performance of waste packages, and has developed standard containers for the packaging of intermediate level (ILW) and some low level waste (LLW) - one of these is the 3m³ Box for immobilised operational and decommissioning ILW. The dimension envelope of this package is 1716 mm x 1716 mm in plan with 430 mm corner radii, 1226 mm tall. The maximum loaded weight is 12 tonnes. A generic design of this container has been developed, which is a welded structure manufactured from austenitic stainless steel (EN 10088-2 steel number 1.4404). The lid is connected to the body by 28 stainless steel bolts [1]. Figure 1 shows a prototype of the box during manufacturing.

One of the key principles in the Nirex specifications for performance under normal and accident conditions is that activity release should be low and predictable. For impact conditions, Nirex has developed performance criteria based on drops onto an unyielding target from three heights that are representative of the waste package life cycle: 0.3 m drop - representative of normal handling conditions; 10 m drop – representative of an impact accident while transported within a transport overpack; and 25 m drop – representative of an impact accident within an emplacement facility. The performance criteria are based on activity release of specific sizes of particulates, but not on extent of deformation, or amount of stress or strain in the package, although these will have an effect on the activity release.

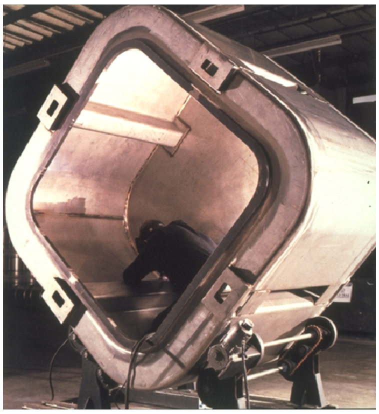

Figure 1: A prototype 3m³ Box during manufacturing

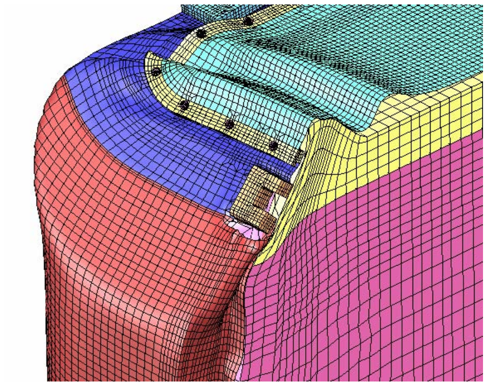

Figure 2: A cross section of the 3m³ Box showing a typical deformation after a 25m drop

In accident events, the design relies on deformation of the package itself to absorb the impact energy. Knockback deformations are most significant in edge and corner drop orientations. The bolted lid-body connection is the weakest link in the package. In the lid edge and lid corner drop orientations, the bolts experience significant stresses and deformations in maintaining the lid-body connection. Good understanding of bolt behaviour, including plastic deformation behaviour until failure, coupled with a robust finite element (FE) model for simulating its behaviour, are the key to developing a robust lid-body connection design utilising the strength and ductility of the bolts to meet the package's performance requirements.

An extensive study [3] was carried out to develop a robust FE model of the bolts. The specific focus of this work was to use improved bolt modelling to optimize the design of the 3m³ Box, although this work could be applied to other bolted containers.

This paper presents a summary of the findings from the study as follows:

1. Development of a FE bolt model for application in a $3m^3$ Box model.
2. Development and execution of a bolt testing programme which included tensile and shear tests on a total of 88 bolts, representing four grades of stainless steel materials, three thread sizes, and two geometries at three strain rates.
3. Benchmarking of the FE bolt model that can be used with confidence in simulating waste package behaviour in drop scenarios.

2. Materials

This work concentrated on the austenitic stainless steel bolt grades A2 and A4 applied in the Nirex standard waste containers, including the $3m^3$ Box, as defined in BS EN ISO 3506-1:1998 [4].

The bolt designation in the above standard consists of two parts: a steel grade which identifies the corrosion resistance and chemical composition of the steel (e.g. A2 and A4 are austenitic steels); and a property class which specifies the minimum mechanical properties (e.g. 50 indicates a minimum tensile strength of 500 N/mm^2).

The chemical composition of the A2 and A4 grades are shown in Table 1.

Table 1: Chemical composition

Grade	Chemical Composition, % (mass/mass) (values are max. unless otherwise stated)								
	C	Si	Mn	P	S	Cr	Mo	Ni	Cu
A2	0.1	1	2	0.05	0.03	15 to 20	-	8 to 19	4
A4	0.08	1	2	0.045	0.03	16 to 18.5	2 to 3	10 to 15	1

The specified mechanical properties are shown in Table 2.

Table 2: Property class

Steel Group	Steel Grade	Property Class	Thread diameter range	Tensile strength (N/mm^2)	Stress at 0.2% permanent strain (N/mm^2)	Elongation after fracture (mm)
Austenitic	A2, A4	50	≤M39	500 min.	210 min.	0.6d min. **(1)**
		70	≤M24	700 min.	450 min.	0.4d min. **(1)**
		80	≤M24	800 min.	600 min.	0.3d min. **(1)**

Note: **(1)** where d is the nominal thread diameter.

3. FE bolt model development

The deformation of the $3m^3$ Box waste package in a 10 m or 25 m drop onto an unyielding target is modelled using the LS-DYNA explicit transient non-linear FE code [2]. In the lid edge and lid corner drop orientations, the bolts experience significant stresses and deformations in maintaining the lid-body connection. Bolt performance at the extremes of the material property capabilities needs to be accurately modelled to give confidence in the analysis of the impact test.

Modelling Options

Four options for modelling bolts were considered, each having a different level of sophistication. They are as follows:

1. Simplified Model - using one-dimensional elements such as springs and spotwelds.

2. Simple Hybrid - solid elements to describe two regions of the bolt – the head/shank and the engaged portion of the shank. These are joined together using a failure interface.

3. Equivalent System Hybrid - this bolt model is similar in form to the simple hybrid described above, except that it makes use of a plastic beam element to represent the failure connection.

4. Explicit Model - this bolt representation describes the bolt entirely with solid elements.

The option chosen was the Explicit Model (to replace the former Simple Hybrid) in which the entire bolt is represented using a continuous mesh of solid elements. This model has the advantage of allowing the bolt to be loaded in any manner and accurately predict the point and mode of failure, but requires more computational effort than the other options. The model is shown in Figure 3. Figure 4 shows the model within the context of a typical lid-body interface of a 3m³ Box FE model.

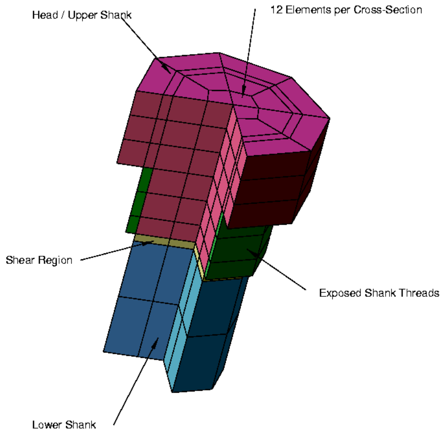

Figure 3: Sectioned view of bolt model

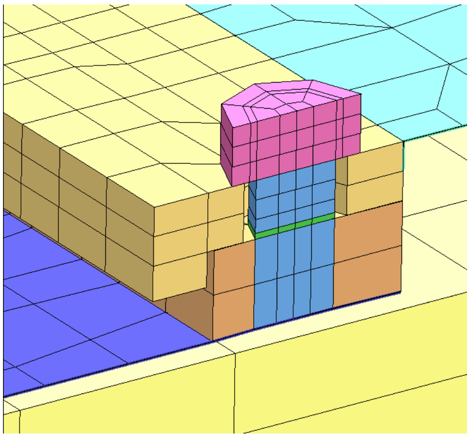

Figure 4: Bolt model in the context of the lid-body interface of a 3m³ Box model

The model required no prior assumption of where or how a bolt would fail. This made the model versatile, in that it was not limited to any particular lid-body design, or any drop scenario and robust as a predictive tool. That is, as different lid-body designs may cause the bolts to be loaded in different ways, and to fail in different ways, it will allow the behaviour to be predicted with confidence.

Description of the model

There were four key regions in the model. They are as follows:

Head/Upper Shank - the bolt head and upper shank were modelled from fully-integrated solid elements which were resistant to zero-energy modes of deformation.

Exposed Shank Threads - exposed threads were not modelled individually. To do so would require an extremely refined model with very small elements. This was not warranted. Instead, they were modelled with a single layer of elements with a crush behaviour equivalent to the threads. They were modelled such that local crushing of the threads - which may happen as the lid is sheared along the body to bear onto the bolt - can be simulated properly. For bolts without exposed threads, this need not be modelled.

Shear Region - this region was an area of mesh refinement which specifically allowed for deformation of the bolt under the loadings that tend toward pure shear. In order to capture the ‘cropping’ action, a single layer of small elements was located between the upper and lower shank. This assumed that this part of the bolt at the interface between the lid and the container experienced the highest shear loads. For different bolting arrangements this shear area could be placed in any location along the bolt shank. If shearing could truly occur anywhere along the length of the bolt then the use of small elements throughout could be adopted. Such a modification would, however, incur a computing cost penalty.

Lower Shank - this part of the bolt model took the same form as the upper shank in terms of material properties and mesh size. The size of the bolt here had the diameter corresponding to the stress area and was fully meshed into the mating container. There was no provision for failure of the threaded region through explicit means, other than bulk failure of the bolt elements themselves. Failure by thread stripping was not accounted for. This was a sufficient assumption as no bolts in waste package drop tests have ever failed by thread stripping.

Material Model

The BS EN ISO 3506-1:1998 [4] tensile stress / strain criteria are based on the original cross-section of the test specimen (termed the engineering stress / strain). For elastic-plastic models in FE analyses, the true stress /

strain (the actual stress / strain in the necked region of the test specimen) is required, which can be derived from the test results.

For dynamic loadings typical of an impact, strain rate effects tend to increase the loading capacity of the material and decrease the elongation. The Cowper-Symonds formula is the standard method in LS-DYNA for taking account of this strain rate effect. It scales yield stress by the factor:

$$1+\left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}}$$

where $\dot{\varepsilon}$ is strain rate and C and P are material factors determined empirically, and off-set the post-0.2% proof stress strain curve in the stress axis by the same amount.

The LS-DYNA material model MAT_PIECEWISE_LINEAR_PLASTICITY model (type 24), which utilises the Cowper-Symonds model, was enhanced in a new material model to include the additional capability to model the effect of strain rate on failure strain. The variation of failure strain with strain rate was defined by a load curve of "strain rate" vs. "factor on failure strain". The defined values of failure strain were then scaled by this factor corresponding to the current strain-rate.

4. Bolt testing

The test programme covered a range of size, material grade, bolt geometry and loading speed relevant to bolts on 3m³ Boxes, detailed below:

- Size: M14, M16 and M18. (The bolt size relates to the nominal diameter of the threaded section. For example, M18 indicates a metric diameter of 18 mm.)
- Materials: A4-50, A4-70, A4-80, A2-70.
- Loading rates: 0.001/s, 0.1/s and 4/s - although the expected strain rate of a lid bolt in a 3m³ Box or a 500 litre Drum is expected to be in the order of 100/s to 1000/s, testing at a maximum strain rate of 4/s is sufficient because (1) the cost and time to test the bolts at these strain rates is prohibitive, and (2) it was deemed sufficient to extrapolate to strain rates beyond 4/s.
- Bolt geometry: fully threaded and plain shank.
- Manufacturer - because BS EN ISO 3506-1:1998 [4] defines only minimum properties and no corresponding maximum properties (e.g. tensile strength > 700MPa), bolts procured from different manufacturers (or one manufacturer at different times), although satisfying the requirements of the standard, may have different compositions and exhibit different properties. To evaluate the possible extent of the difference, bolts from three manufacturers were tested.

Three identical tests were carried out for tests with strain rates of 0.1/s and above. Two identical tests were carried out for tests with strain rates of 0.001/s. This schedule amounts to 88 bolt tests in total.

Typical bolts used in the testing are shown in Figures 5 and 6. Test set-up for the tensile tests and shear tests are illustrated schematically in Figures 7 and 8.

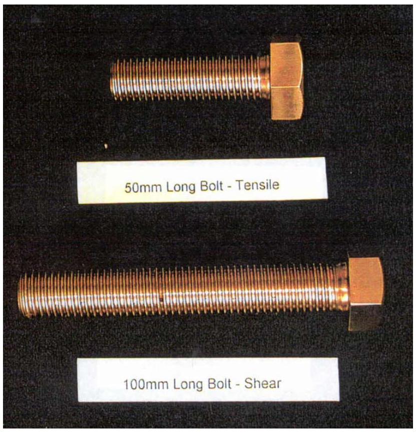

Figure 5: Typical fully threaded bolts for tensile and shear tests

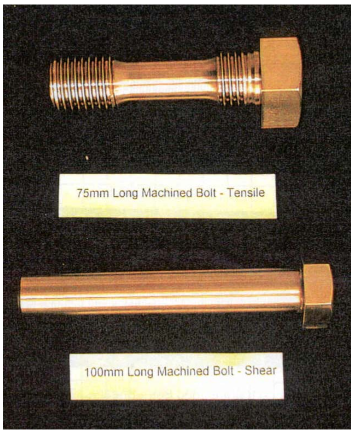

Figure 6: Typical waisted shank bolt for tensile testing and plain bar for shear testing

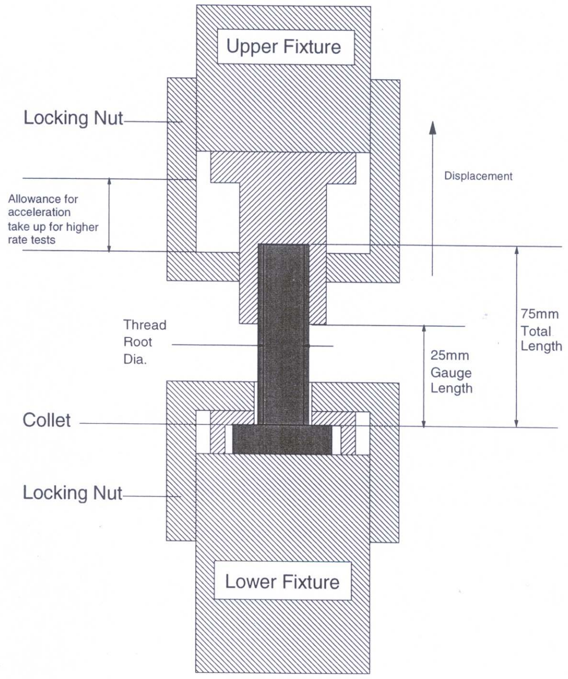

Figure 7: Set-up for the tensile tests

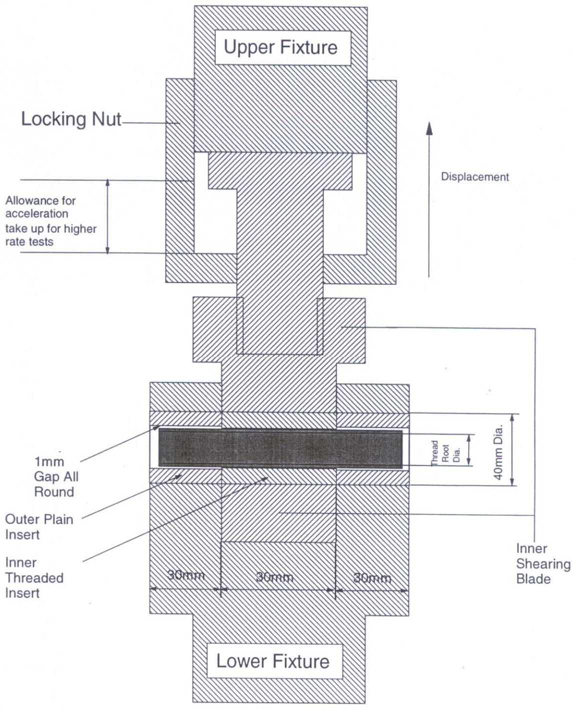

Figure 8: Set-up for the shear tests

Because of the way chemical composition and mechanical properties are specified in BS EN ISO 3506-1:1998 [2], bolts satisfying the standard will always have properties higher than the values stated in the standard. It was not sensible to specify bolts to satisfy the minimum requirements of the standard. In fact, it is extremely difficult to procure bolts which possess minimum properties as stated in the standard or procure a set of property class 50, 70 and 80 bolts with properties following the same ratios as those in the standard – e.g. tensile strength ratios of 8:7:5 following the ratios of minimum tensile strength as specified in the standard, or 0.2% proof stress ratios of 600:450:210, following the ratios of minimum 0.2% proof stress as specified in the standard.

The results indicated the following regarding variation of bolt properties with bolt size, material, strain rate and bolt geometry (see also Table 3):

- Bolt Size: M14, M16 and M18 – little effect on the “yield” stress or the tensile strength.

- Materials: A4-50, A4-70, A4-80, A2-70 – higher ductility with lower strength bolts.
- Loading rates: 0.001/s, 0.1/s and 4/s - there was a clear indication that both “yield” stress and ultimate stress increased with strain rate, while ductility reduced with strain rate.
- Bolt geometry: bolts with a waisted shank exhibited a higher ductility than the threaded bolts.
- Manufacturer - there was a large variation of properties between nominally identical bolts supplied by different manufacturers, and the differences were larger than the differences between the documented properties of the corresponding starting stocks.

Table 3: Test results

Tensile Tests **(1) (2)**		Bolt Size		
		M14	M16	M18
Bolt Material	A4/50	-	0.001/s, 553, 741, 42.3	0.001/s, 560, 766, 35.0
			0.001/s, 487, 732, 22.9 **(3)**	
			0.001/s, 745, 946, 30.0 **(4)**	
			0.1/s, 622, 753, 38.1	
			4/s, 572, 816, 37.2	
			4/s, 574 ,813, 813 **(3)**	
			4/s, 831, 1011, 22.9 **(4)**	
	A4/70	0.001/s, 750, 926, 26.8	0.001/s, 787, 925, 29.6	0.001/s, 681, 872, 29.5
			0.001/s, 849, 1018, 23.3 **(3)**	0.1/s, 765, 895, 27.3
			0.001/s, 690, 896, 30.6 **(4)**	4/s, 826, 963, 26.4
	A4/80	0.001/s, 755, 929, 26.3	-	-
		0.1/s, 859, 963, 21.2		
		4/s, 916, 1036, 20.6		
	A2/70	-	0.001/s, 611, 886, 27.7	-
			0.1/s , 737, 895, 25.9	
			4/s, 742, 964, 25.3	
Shear Tests **(1) (2)**		Bolt Size		
		M14	M16	M18
	A4/50	-	0.001/s, 494, 1033, 42.4	-
			0.1/s, 641, 1011, 40.3	
			4/s, 612, 967, 31.0	
	A4/70	-	-	0.001/s, 646, 1100, 38.1
				0.1/s, 786, 1068, 35.8
				4/s, 838, 1038, 22.6
	A4/80	0.001/s, 852, 1193, 44.3	-	-
	A2/70	-	0.001/s, 745, 1147, 26.9	-
Tensile Tests **(1) (2)**		Shank Size waisted from ∅22mm to ∅16mm		
		∅14	∅16	∅18
Bolt Material	A4/50	-	0.001/s, 440, 636, 71.0	-
			0.1/s, 517, 641, 51.3	
			4/s, 520, 700, 52.5	
Shear Tests **(1) (2)**		Bar Size		
		∅14	∅16	∅18
Bolt Material	A4/50	-	0.001/s, 460, 980, 37.9	-
			0.1/s, 488, 936, 37.5	
			4/s, 553, 952, 24.7	

Note: **(1):** the four items tabulated are: strain rate; engineering 0.2% proof stress and UTS (MPa); elongation to failure (%).

(2): Results shown above for each combination of parameters are averaged values from tests on identical samples.

(3), (4): Manufacturer 1 unless indicated otherwise as (3) for Manufacturer 2, or (4) for Manufacturer 3.

5. Derivation and benchmarking of material properties

A selection of the bolt tests was chosen for calibrating the material input for the bolt model. The tests were chosen such that for each material, a material model, can be obtained, calibrated for both tensile and shear behaviour at the full range of strain rates.

Static stress strain properties were calculated from load-extension data from the quasi-static tensile tests (strain rate of 0.001/s).

Cowper-Symonds constants were derived by "curve fitting" the stress-strain curves from tensile tests across the three strain rates tested.

Failure strains were obtained by benchmarking directly against the tests using a “like-for-like” FE model of the tensile and shear tests. Quasi-static stress properties and Cowper-Symonds parameters as discussed above were used as input. "Static" failure strains were obtained by correlating with the quasi-static tests. Factors on failure strain for higher strain rates were deduced by correlation with results from the tests of the higher strain rates.

The “like-for-like” FE model for the tensile tests is shown in Figure 11. It was based on the new bolt model shown in Figure 9 but extended geometrically either by scaling or replication of elements to the dimensions of the test bolts.

Development of stress and displacement from a typical test, from initial loading to failure, is shown in Figure 11. Necking and subsequent failure of the sample can clearly be seen.

(Note that both the shear region and the elements representing the threads were present in the model, consistent with the model shown in Figure 9. The shear region was modelled with the same properties as the rest of the shank and it was not a “weak plane” in the model. The elements representing the threads did not carry any appreciable loads in the tensile loading scenario.)

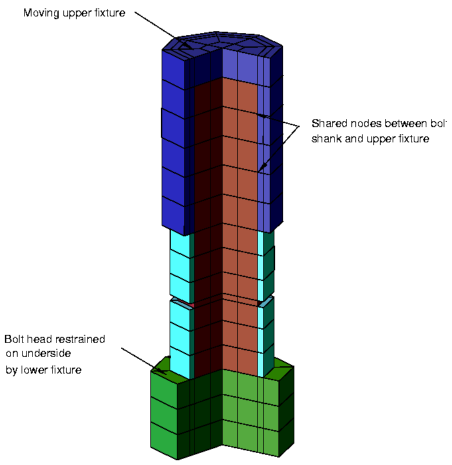

Figure 9: Bolt model for tensile test benchmarking (sectioned view)

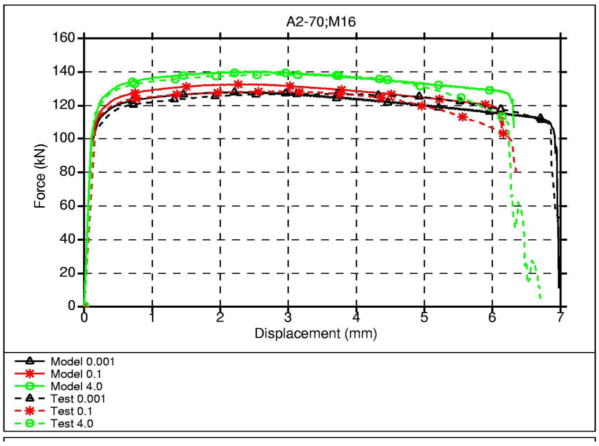

Figure 10: Typical correlation of force-deflection between tensile test and analysis (see Table 3 for the three tests)

A typical comparison of test results and analysis results are shown in Figure 10. There was close correlation between test and analysis.

Similarly, a “like-for-like” FE model of the shear tests were carried out, and typical development of stress and deformation is shown in Figure 12.

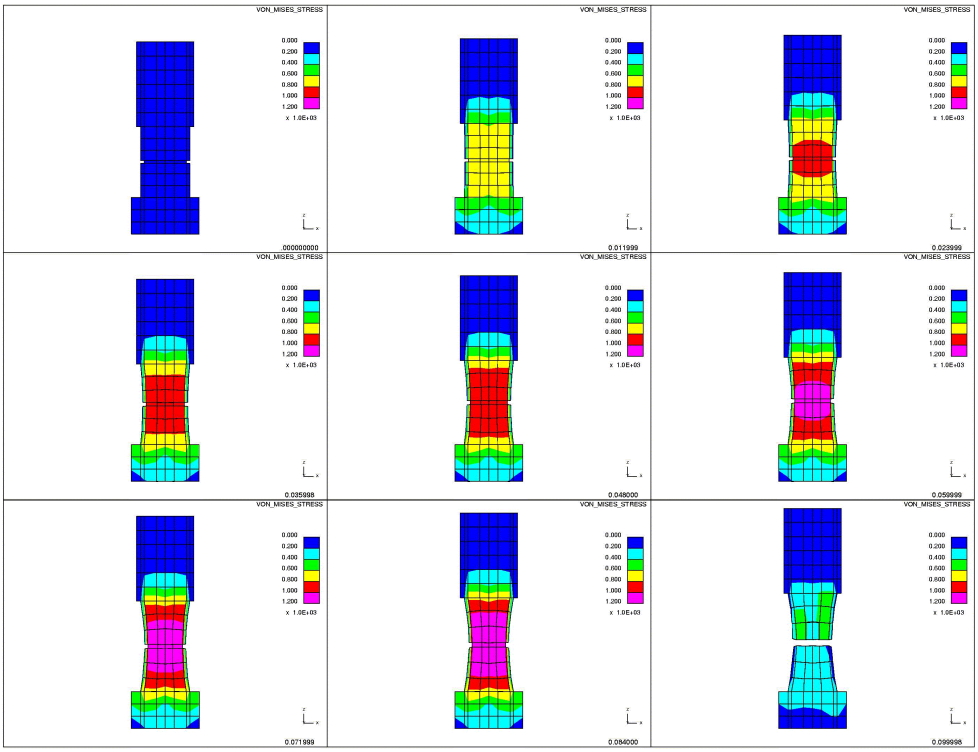

Figure 11: Development of (Von mises) stress and deformation until failure in a tensile test (Units: MPa)

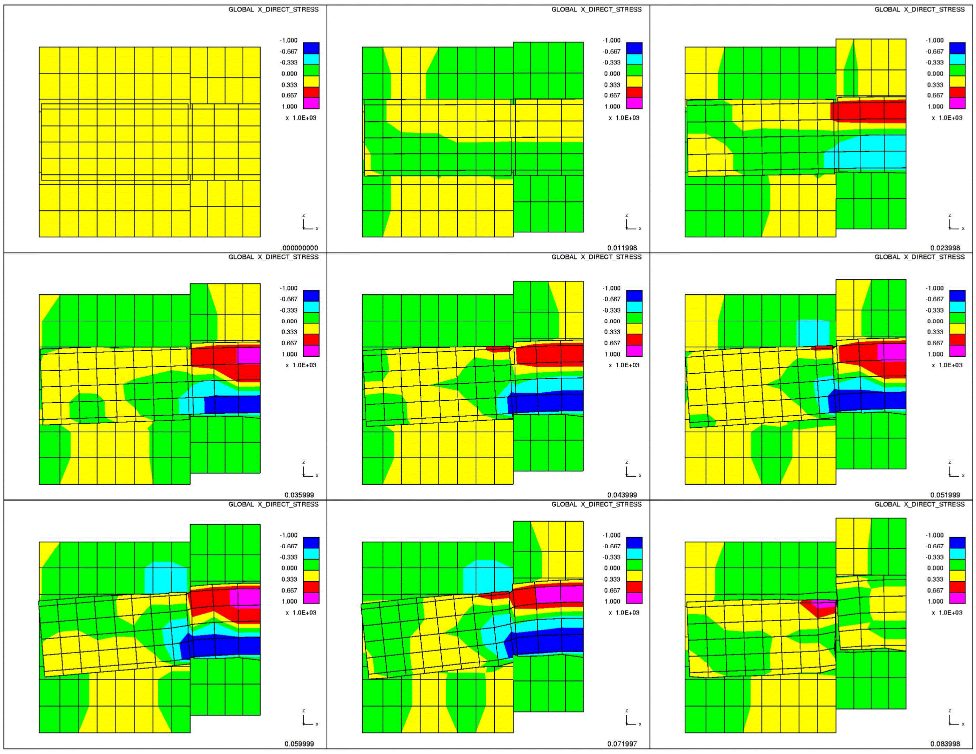

Figure 12: Development of stress (stress in the axial direction of the bolt) and deformation until failure in a shear test (Units: MPa)

To assess the adequacy of the correlations, energy absorbed by the bolt in the test and in the analysis were compared. Comparison for all the tensile test analyses is shown in Table 4. The percentage difference indicates that the correlation is extremely good.

Table 4: Absorbed energy for tensile results

Material And Bolt Size	Strain Rate 0.001/s			Strain Rate 0.1/s			Strain Rate 4.0/s		
	Energy (J)		Diff	Energy (J)		Diff	Energy (J)		Diff
	Test	Analysis		Test	Analysis		Test	Analysis	
A4-50, M16	1088	1084	0%	961	970	+1%	1047	1064	+2%
A4-70, M18	1076	1064	-1%	999	1000	0%	1068	1070	0%
A2-70, M16	841	839	0%	765	777	+2%	836	844	+1%
A4-80, M14	602	599	0%	507	514	+1%	548	552	+1%

The correlation against the shear tests is not as good as for the tensile tests, with analysis conservatively under-predicting the energy absorbed. The most likely causes of difference between test and analysis results were compliance in the test rig and local deformation of the threads.

Table 5: Absorbed energy for shear results

Material And Bolt Size	Strain Rate 0.001/s			Strain Rate 0.1/s			Strain Rate 4.0/s		
	Energy (J)		Diff	Energy (J)		Diff	Energy (J)		Diff
	Test	Analysis		Test	Analysis		Test	Analysis	
A4-50, M16	719	475	-34%	674	423	-37%	536	494	-8%
A4-70, M18	1016	531	-45%	910	548	-40%	577	650	-11%
A2-70, M16	604	443	-27%	-	-	-	-	-	-
A4-80, M14	577	317	-45%	-	-	-	-	-	-

6. Conclusions

An improved bolt model has been developed for use in modelling impact performance of waste packages.

To provide detailed input data for the bolt model, a comprehensive test programme was conducted on full-size bolts to provide tensile and shear properties. Some geometry factors, such as bolt size, have little influence on material behaviour, e.g. UTS, whereas there is an appreciable influence of thread vs. waisted shank e.g. elongation to failure. In general, higher ductility was associated with lower strength bolts. There was a clear indication that both yield stress and ultimate stress increased with strain rate, while ductility reduced with strain rate.

The bolt model was calibrated and benchmarked against the test data by modelling the test specimens in the tensile and shear test rigs.

This robust and versatile bolt model can be used with confidence in demonstrating the performance of the 3m³ Box waste package as well as other bolted waste packages.

7. References

The Nirex reports quoted in this paper can be obtained by accessing the Nirex web site: **www.nirex.co.uk** or e-mailing **info@nirex.co.uk**.

[1] Nirex, Data sheets for standard and non-standard radioactive waste packages, Nirex Report N/012, 2000

[2] Livermore Software Technology Corporation, LS-DYNA Keyword user's manual – Non-linear dynamic analysis of structures, Version 950, May 1999

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[4] BS EN ISO 3506-1:1998, Mechanical properties of corrosion-resistant stainless steel fasteners – Part 1: Bolts, screws and studs