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Evaluation and verification of a structural safety analysis for a type B transport package for a radioactive waste drum

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Abstract

We conducted and verified the structural safety analyses for a type B transport package for a radioactive waste drum. The type B package is used to transport one high-level radioactive waste drum from a waste facility to a temporary site in a nuclear power plant. It is important that the structural integrity of a type B transport package should be maintained under normal transport conditions such as the free drop test, the stacking test and the penetration test, and accident conditions of transport such as the 9 m height free drop test and the puncture test. Based on the ASME Boiler and Pressure Vessel Code, Section III, Division 3 we evaluated the structural safety integrity of the type B package for a radioactive waste drum using finite element analysis. For the stacking test condition the maximum stress is a very low value when compared with the stress limits. The impact of the penetration bar on the overpack does not affect the containment part. For the free drop test condition and the puncture test condition the local stresses appear at the impact part and the containment part connected with the inner structure. The maximum stresses for all of the conditions are lower than the stress limits, so the structural integrity of the type B package for a radioactive waste drum was maintained. Also, the structural safety analyses were verified by using the data acquired from the 9 m drop and the puncture tests of the real model. The analytic accelerations of the 9 m drop test are similar to the test results. For the puncture test condition the analytic result is conservative when compared to the test. The analysis for the structural safety of the type B package reveals conservative results and it is proved that its structural integrity is maintained under normal and accident conditions of transport.

Keywords: Type B transport package; Structural safety analysis; Normal transport conditions; Accident conditions of transport

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1. Introduction

The radioactive waste generated from nuclear power plants has to be transported in accordance with the designated regulations[1-3], which are to protect radiation workers and the public against a potential radiation exposure caused by their transportation. A package to transport radioactive materials should have enough safety to fulfill the regulations and the technical standards in the regulations[1-3]. In accordance with the IAEA safety standard series TS-R-1[1], which is accepted widely by most of its member states, the types of packages are classified as Excepted package, Industrial package type 1, Industrial package type 2, Industrial package type 3, Type A package, Type B(U) package, Type B(M) package and Type C package, which are subject to the activity limits and material restrictions. Among these packages, a type B transport package should contain the above specified activity, which is listed in regulations for radio-nuclides, so its safety should be certified by the authorities.

A type B transport package shall be designed to meet the requirements which include the general requirements for all packagings and packages and the

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requirements for type A packages. It is important to pass the tests for demonstrating its ability to withstand normal and accident conditions of transport. The tests for normal conditions of transport are the water spray test, the free drop test, the stacking test, and the penetration test. The water spray test simulates exposure to rainfall of approximately 5 cm per hour for at least one hour. For the free drop test, a specimen is dropped onto a rigid target to suffer the maximum damage with the specified height related to a package mass as shown in Table 1. Under the stacking test the specimen is subjected to a specified compressive load for a period of 24h. A compressive load for the stacking test is equal to the greater of the equivalent of 5 times the mass of the package and the equivalent of 13 kPa multiplied by the vertically projected area of the package. The penetration test is conducted by dropping a penetration bar onto the center of the weakest part of the specimen. A penetration bar has 3.2 cm in diameter with a hemispherical end and a mass of 6 kg and is made from a rigid material.

For accident conditions of transport, a type B transport package is subjected to the cumulative effects of tests such as the mechanical test, the thermal test and the water immersion test. The mechanical test consists of three different drop tests: the 9 m free drop test, the puncture test and the crush test. For the 9 m free drop, a package must be dropped onto the rigid target to suffer the maximum damage with a 9 m height of the drop. For the puncture test, the specimen is dropped onto the puncture bar rigidly mounted perpendicularly on the rigid target to suffer the maximum damage. The puncture bar is solid mild steel with a circular section of 15 cm in diameter and no less than 20 cm long. The upper end of the puncture bar is flat and horizontal with its edge rounded off to no more than a 6 mm radius. The crush test is done by the drop of a 500 kg mass from 9 m onto the specimen. When the package has a limited mass, overall density and radioactive content, the specimen must be applied to the crush test. For all other packages, the 9 m free drop test is conducted instead of the crush test. If a package were subjected to the tests, it would restrain a sufficient shielding to ensure the specified radiation level and restrict the loss of radioactive contents to a limited value per certain periods of time.

Table 1. Free drop height for testing packages to normal conditions of transport.

Package mass (kg)	Free drop height (m)
package mass < 5,000	1.2
5,000 ≤ package mass < 10,000	0.9
10,000 ≤ package mass < 15,000	0.6
15,000 ≤ package mass	0.3

A type B transport package is being developed to transport a radioactive waste drum from a waste facility to a temporary storage site in a nuclear power plant by Korea Nuclear & Hydro Power co. Ltd.[4] For the type B transport package for a radioactive waste drum, safety tests for the accident conditions of transport were conducted.[5] The 9 m free drop test, the puncture test, the fire test, and the immersion test were conducted in that order. The pressure rise test and a measurement of the shielding material thickness were done before and after the tests. The safety of the type B package for a radioactive waste drum is proved experimentally under accident conditions of transport.

In this paper we analytically evaluated the structural safety of the type B package for a radioactive waste drum under normal and accident conditions of transport. The ASME Boiler and Pressure Vessel Code, Section III, Division 3[6] specifies the evaluation procedures of the containment for the transportation of spent nuclear fuel and high level radioactive waste. Based on the ASME code an analytic structural safety evaluation was conducted for the free drop test, the stacking test, the penetration test, and the puncture test conditions. To verify the analytic structural safety evaluation we compared the analytic accelerations with the results acquired from the 9 m free drop test and the puncture test, which were done by using a real model of the type B package.

2. Type B package for a radioactive waste drum

Fig. 1 shows a schematic diagram of the type B package for a radioactive waste drum used in nuclear power plants. It contains one radioactive waste drum, which is assumed to be 620 mm in diameter, 890 mm in height and weight of 400 kg. The type B package consists of a shielded package and an overpack. The shielded package is made from carbon steel with an 80 mm thickness, which serves a structural part as well as a shielding material. There is a 100 mm clearance between the waste drum and a shielding package, for room to handle the waste drum. An inner supporter is used to maintain the clearance gap and to

Fig. 1. A schematic diagram of the type B package for a radioactive waste drum.

Table 2. Dimensions and weights of the type B package for a radioactive waste drum. The height of a center of gravity was measured from the bottom of overpack from model used in finite element analysis.

Dimension (mm)	A shielding package	Inner dim.	D 820 X H 910
		Outer dim.	D 980 X H 1,070
	overpack	Inner dim.	D 970 X H 1,115
		Outer dim.	D 1,380 X H 1,510
Weight (kg)	A shielding package		2,530
	Overpack		1,274
	Load		400
	Gross weight		4,204
Height of a center of gravity (mm)			749

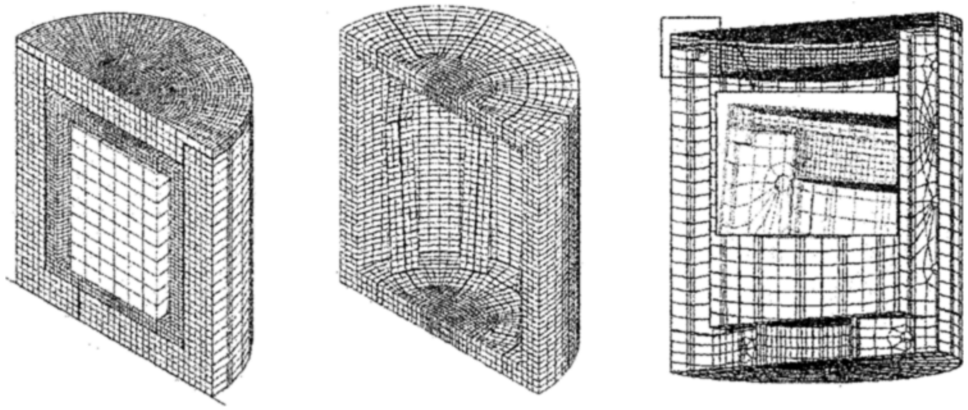
easily handle the waste drum during loading and unloading. The inner and outer diameter and height of the shielding package are 820 X 910 mm and 980 X 1,070 mm, respectively.

The overpack consists of a body and a lid to protect the shielding package from a mechanical impact and a thermal condition. An overpack has a double shell structure made from carbon steel. There are polyurethane foam and a 3M mat between the shells for a thermal isolation and a shock absorbing. Also, a steel structure is used to protect a deformation of the inner shell. The inner and outer diameters of an overpack are 970 mm and 1,380 mm and the inner and outer heights are 910 mm and 1,510 mm, respectively.

Twelve M24 bolts are used to fasten a body and a lid of the shielding package and a body and a lid of the overpack are fastened by using sixteen M12 bolts. Weights of the shielding package and the overpack are 2,530 kg and 1,274 kg, respectively. The load and gross weight of the type B package are 400 kg and 4,204 kg, respectively. Table 2 shows the dimensions and weights of the type B package for a radioactive waste drum. The height of the center of gravity is measured from the bottom of the overpack from the model of the finite element analysis.

3. Finite element analysis

Fig. 2 shows a finite element model for the structural analyses. A half of the model was used due to the symmetry of the geometry and a load condition. The inner supporter of the shielding package and a steel structure and a bushing of the overpack were modeled. The 3M mat was not considered because its



(a) The entire model (b) The shielding package (c) A case of the overpack

Fig. 2. A half symmetric model of the type B package for a radioactive waste drum.

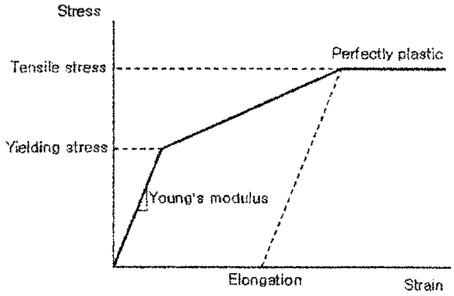


Fig. 3. The stress-strain relationship of carbon steel.

thickness was thin when compared with the thickness of the poly-urethane foam and its mechanical effect was insignificant. Bolting was considered as a tied constraint and relationships between parts were regarded as a frictionless contact constraint. ABAQUS[7] is used as a finite element code for this analysis. The model employed C3D8R (8-node linear brick, reduced integration with an hourglass control). The number of elements and nodes for the type B package were 33,801 and 52,697, respectively.

The shell of the shielding package was made from A-105 carbon steel and other steel parts, such as the bottom and top of the shielding package, were made from A-36 carbon steel. The shell, the bottom and the top part of the shielding package were regarded as an elastic material because these parts were a containment boundary and should be evaluated based on ASME Boiler and Pressure Vessel Code, section III, division 3. Other parts were assumed as an elastic-plastic material. The elastic-plastic stress-strain relationship of carbon steel was assumed as shown Fig. 3. After the yielding stress, carbon steel was deformed as a linear strain hardening until a tensile stress and then perfectly plastic behavior. The plastic strain at a tensile stress was assumed as an elongation value. The Young's modulus, the yield stress and the tensile stress of the carbon steel used the data specified in ASME Boiler and Pressure Vessel Code, section II[8].

The material properties of the polyurethane-foam were determined from a static compression test using a 50 X 50 X 50 mm specimen. The stress-strain relationship of the polyurethane-foam was determined until the plastic strain was 1 by a linear extrapolation. The waste drum includes the drum and the radioactive waste. For the density of the waste drum it was assumed that the weight of the waste drum was 400kg. The material properties of the carbon steel, the polyurethane foam and the waste drums inside are shown in Table 3.

Table 3. Mechanical properties used in the finite element analysis.

Mechanical properties	Carbon steel (A-36)	Carbon steel (A-105)	Waste drum	Poly-urethane foam
Density (ton/m3)	7.89	7.89	1.488	0.205
Elastic modulus (MPa)	202.706	202.706	1,000	0.0928518
Poisson's ratio	0.3	0.3	0.1	0.1
Yield stress (MPa)	248.21	250	-	5.9767
Tensile stress (MPa)	399.9	485	-	69.0122
Elongation (%)	23	30	-	100

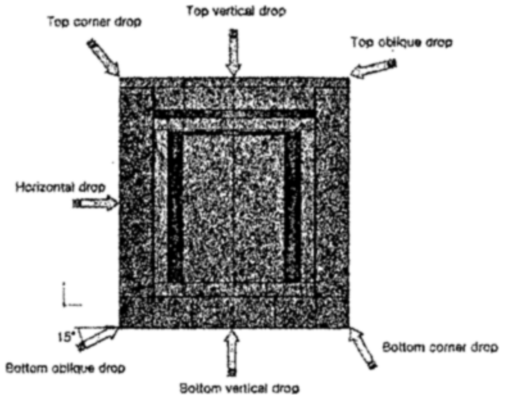


Fig. 4. Directions for the free drop analysis.

Using finite element analysis we simulated the stacking test, the free drop test and the penetration test for normal transport conditions and the 9 m free drop test and the puncture test for accident transport conditions. For the stacking test condition, ABAQUS/ Implicit was used for a static analysis. The dynamic impact analyses for other conditions were conducted with ABAQUS/Explicit. The model was dropped on a rigid plate for the free drop conditions and a puncture bar for the puncture test, and a penetration bar was dropped on the model for the penetration test.

Possible orientations for the free drop conditions are horizontal, top or bottom vertical, top or bottom corner, and top or bottom oblique drop as shown in Fig. 4. A vertical drop means that an axial direction of a package is parallel with a drop direction. For a horizontal drop condition a package impacts the target with the direction that a side of a package is parallel with the rigid target surface. In a corner drop, a corner of a package is impacted with the center of gravity of a package above the point of an impact. A package impacts the target with an oblique angle for an oblique

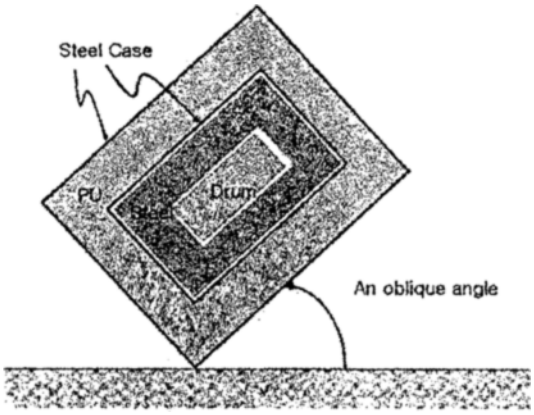


Fig. 5. A simplified model to determine an oblique angle.

drop, so that after a primary impact of one end of a package, the container is set into rotation. This causes a second impact at the other end of the package with an impact velocity possibly much higher than the velocity reached from the free drop.

An oblique angle was determined from analyses of a simplified model as shown in Fig. 5. The inner and outer shell of the overpack, the poly-urethane foam and the shielding package were modeled with a hollowed cylinder. A dynamic impact analysis was conducted for the simplified model with an oblique angle which is from 5° to 70° with 5° intervals. Fig. 6 shows the reaction forces with various oblique angles. Reaction forces for a second impact were smaller than those for a primary impact. For the 15° oblique angle, the maximum reaction force for a second impact was the largest value. It is determined that the inclined angle for the oblique drop is 15°.

For the penetration test we analyzed three conditions. The penetration bar impacted on the top, the bottom and the side of the overpack. For the puncture test, the model was impacted on the puncture bar. The impact positions for the puncture test were the top, the bottom and the side of the package.

The initial velocity of the model just before the impact was used as the initial condition in the simulation to consider the free-drop rigid body. The initial velocity, which was obtained by the height of the drop, and an acceleration of the gravity, 9,806 mm/sec^2, was applied. The model for the free drop and the puncture drop was rotated appropriately for the drop directions.

The stress intensity for the finite element analysis was compared with the stress limits according to ASME Boiler and Pressure Vessel Code, section III, division 3. The stress intensity is defined as twice the maximum shear stress, which is the maximum Tresca stress. The stress limits differ depending on the stress category from which the stress intensity is derived and the conditions of transport. Stress limits for A-36 carbon steel and A-105 carbon steel are shown in Table 4 under normal and accident conditions of transport. For normal conditions of transport 1.0 S_m and 1.5 S_m are used as the stress limits for a general primary membrane stress and a local primary membranes stress, respectively. S_m means a design stress intensity value, which is specified in ASME Boiler

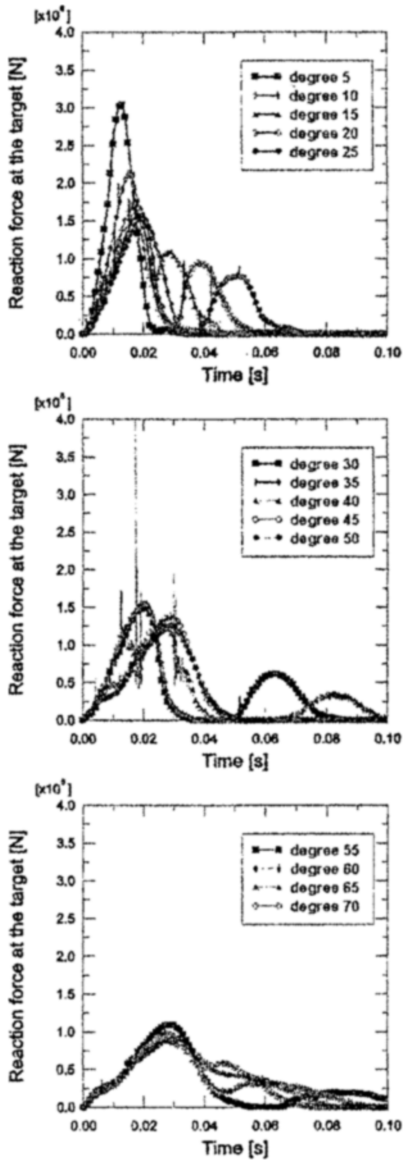


Fig. 6. Reaction forces with an oblique angle for the simplified model.

Table 4. Stress limits for A-36 carbon steel and A-105 carbon steel under normal and accidental conditions of transport based on ASME Boiler and Pressure Vessel Code, Section III, Div. 3. S_m and S_u mean the design stress intensity and the tensile stress, respectively.

Material		A-36 carbon steel	A-105 carbon steel
Normal conditions of transport	1.0 S_m	133.07	155.82
	1.5 S_m	199.60	233.73
Accident conditions of transport	The greater of 2.4 S_m and 0.7 S_u	279.93	337.84
	The greater of 3.6 S_m and 1.0 S_u	399.90	482.63

and Pressure Vessel Code, section II, Part D. A general primary membrane stress means the average primary stress across a solid section at its discontinuities and concentrations are not considered. A Local primary membrane stress is considered at a section which has discontinuities and is determined by averaging the stress across a section. The stress limits under accident conditions of transport are the greater of 2.4 S_m and 0.7 S_u and the greater of 3.6 S_m and 0.7 S_u for a general primary membrane stress and a local primary membranes stress, respectively. S_u means the tensile stress value.

4. Evaluation of the structural safety analysis

4.1 Stacking test condition

For the stacking test condition of the type B package for a radioactive waste drum, the equivalent load of 5 times its mass is about 215.6 kN and the equivalent load of 13 kPa for the vertically projected area is about 19.5 kN. So the model of the shielding package was assumed to be directly subjected to a compressive load, 215.6kN. The load was applied uniformly to the top of the shielding package which rests on a rigid surface. If the load were applied to the top of the overpack, the shielding package would not be affected because there is a clearance between the shielding package and the overpack.

Fig. 7 shows the stress contour for the stacking test condition. The maximum Tresca stress was 2.21 MPa at the center of the surface of the lid, which was the bending stress. 2.21 MPa is very small when compared with the stress limits 233.73 MPa. So the structural integrity of the type B package for a radioactive waste drum was maintained under the stacking test condition.

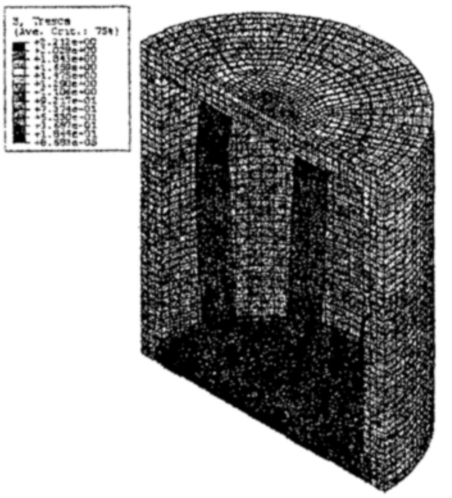


Fig. 7. The Tresca stress contour for the stacking test condition.

4.2 Free drop test condition under normal conditions of transport

The type B package was dropped onto the rigid surface with a 1.2 m height, which is determined from the weight of the package as shown in Table 1. Fig. 8 shows the time history of the Tresca stress curve of the containment boundary with time for a bottom vertical free drop under normal transport conditions. Tresca stress contour is shown at the time when the maximum Tresca stress appears. And the maximum Tresca stress curve is shown at the location when a large local Tresca stress appears. The large local Tresca stress appears at the bottom connected with the inner structure. Other locations show lower Tresca stresses when compared with the local stress. For a bottom vertical drop, the maximum Tresca stress, 280 MPa, appears at an early impact time, and then a stable value is revealed during a rebounding.

For all of the drop directions the local stresses appear at the impact part and the part connected with the inner structure. The maximum Tresca stress at other parts was lower than the stress limits. For most drop directions, the maximum local stresses were larger than the stress limits. We considered the average value of a stress across the thickness of the section to analytically evaluate the structural safety by using ASME Boiler and Pressure Vessel Code, section III, division 3. Table 5 shows the maximum average Tresca stress across the thickness of the section for the 1.2 m free drop analysis. For a top vertical and a top corner drop the maximum stresses mean a local value.

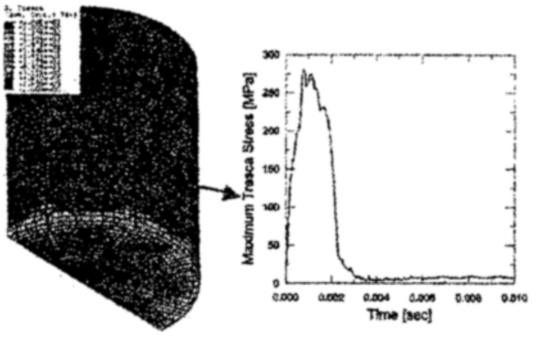


Fig. 8. The Tresca stress contour and the maximum Tresca stress curve of the shielding material with time for the bottom vertical drop under normal transport conditions.

Table 5. The maximum average Tresca stresses across the thickness of the section of the 1.2 m free drop analysis.

Drop direction	Maximum Tresca stress (MPa)	Stress limits (MPa)
Bottom vertical drop	126.4	233.73
Top vertical drop	135.2(local stress)	
Horizontal drop	147.7	
Bottom corner drop	126.4	
Top corner drop	228.9(local stress)	
Bottom oblique drop	113.9	
Top oblique drop	123.2	

The maximum stress was lower than the stress limit for the normal transport conditions.

4.3 Penetration test condition

Under the penetration test conditions a stress and a deformation mainly appear at the impact location. Fig. 9 shows the Tresca stress and the displacement at the impact point for the top penetration test condition. The maximum displacement at the impact point is 2.5 mm, which is smaller than the clearance between the shielding package and the overpack. So, the penetration of a bar does not affect the shielding package.

4.4 9 m free drop test condition

Fig. 10 shows the stress contour of a containment part when the maximum Tresca stress appears for the 9 m bottom oblique free drop analysis. Because the kinetic energy was larger than that under a normal transport condition, the shielding package rotated rapidly and an opposite bottom of the impact side

Fig. 9. The Tresca stress contour and the displacement at the impact point for the penetration test condition.

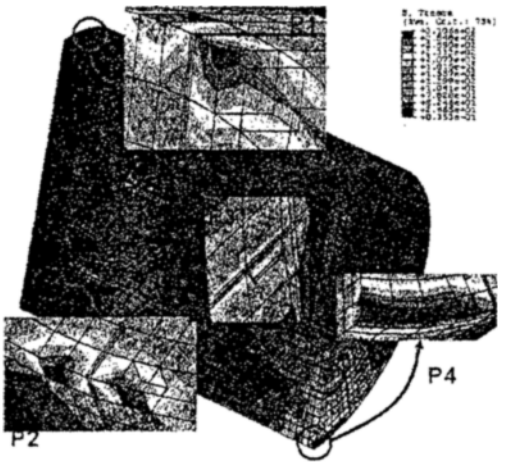


Fig. 10. A stress contour at the time that the maximum Tresca stress appeared for the 9 m bottom oblique free drop analysis.

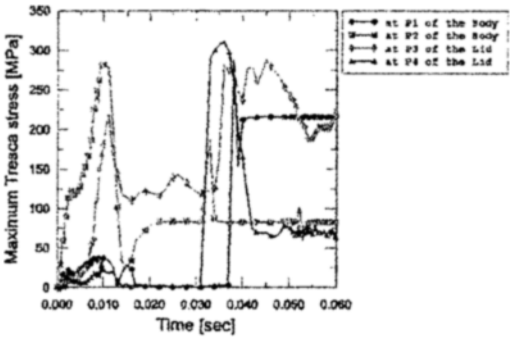


Fig. 11. Tresca stress curves at the point as shown in Fig. 10 for the 9 m bottom oblique free drop analysis.

contacted the inner shell of the overpack so that a local stress appeared at that point. Local stresses were also revealed at impact points of the bottom and the lid, and the lid part connected with an inner structure.

Fig. 11 shows the Tresca stress curves at the points as shown in Fig. 10 for the 9 m bottom oblique free drop analysis. The P2 point, which was an impact point at a body of the shielding package, showed a maximum Tresca stress, 287.5 MPa at 9.8 msec. At the P3 point, which was the lid part connected with an inner structure, a relatively large stress appeared at the first impact time, and a maximum stress of 310.6 MPa was shown at the second impact time. The maximum stresses, 287.5 MPa and 313.8 MPa, occurred at the body and lid of the shielding package during the second impact, respectively. The points at which the maximum Tresca stresses appeared were made from A-105 carbon steel so that the maximum value should be compared with the stress limit of A-105 carbon steel, 337.84 MPa. All of the maximum Tresca stresses are lower than 337.84 MPa so the safety of the type B package for radioactive waste is proved under the 9 m bottom oblique free drop condition.

Table 6 shows the maximum Tresca stresses when compared with the stress limits for various drop directions under the 9 m free drop condition. For all of the drop directions the local stresses are revealed at the impact parts and the parts connected with the inner structure. If the maximum local Tresca stress were lower than the stress limits, a local stress would be considered. If not, the average value of a stress across the thickness would be evaluated. The shell, bottom and lid of the shielding package were made from different materials so the stress limit of each part was different. The maximum Tresca stresses were no larger than the stress limits so the analyses showed the safety of the type B package for a radioactive waste drum for the 9 m free drop test condition.

Table 6. The maximum average Tresca stresses across the thickness of the section of the 9 m free drop analysis.

Drop direction		Maximum Tresca stress (MPa)	Stress limits (MPa)
Bottom vertical drop		284.3(local stress)	337.84
Top vertical drop		196.4(local stress)	337.84
Horizontal drop	Body	145.3	279.9
	Lid	297.8(local stress)	337.84
Bottom corner drop		276 (local stress)	279.9
Top corner drop	Body	152.6	279.9
	Lid	282(v)	337.84
Bottom oblique drop	Body	287.5(local stress)	337.84
	Lid	310(local stress)	337.84
Top oblique drop	Body	213.2	279.9
	Lid	313.5(local stress)	337.84

4.5 Puncture test condition

Fig. 12 shows the stress contour at the time when the maximum Tresca stress appears and stress curves at points where a local stress is shown for the side puncture analysis. Local stresses were revealed at the parts of the body and the lid contacted with the inner structure of the impact side. For the bottom and top puncture, the maximum Tresca stresses appeared at

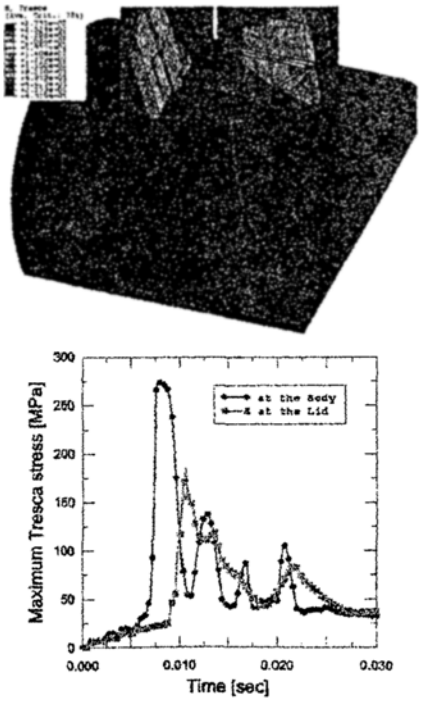
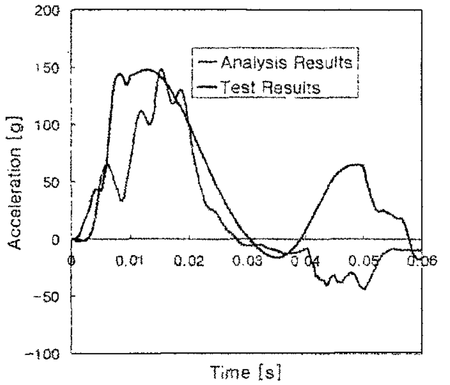
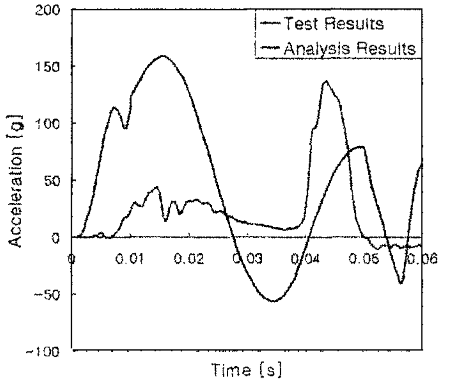


Fig. 12. A stress contour at the time which the maximum Tresca stress appeared and stress curves at point which a local stress was shown for the side puncture analysis.

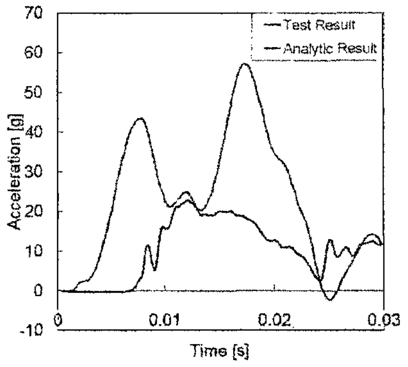


(a) At A1 point

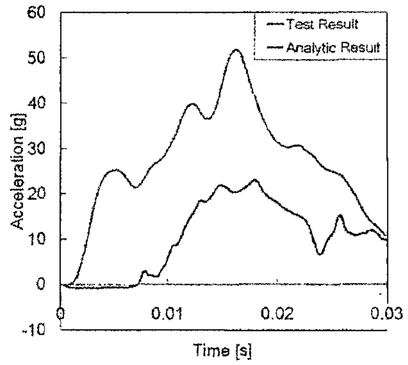


(b) At A2 point

Fig. 13. The comparisons between the test and the analytic accelerations at A1 and A2 for the 9 m bottom oblique free drop condition.



(a) At A3 point



(b) At A4 point

Fig. 14. The comparisons between the test and the analytic accelerations at A3 and A4 for the side puncture test condition.

the center of a bottom and a lid of the shielding package, respectively. The maximum local Tresca stresses were compared with the stress limits as shown in Table 5. The local stress is no larger than the stress limits so that the structural integrity of the type B package for a radioactive waste drum was maintained.

5. Verification of the structural safety analysis

5.1 9 m drop test condition

To verify a structural safety analysis for the free drop test condition, accelerations obtained from the 9 m bottom oblique free drop test[5] were compared with analytic results at the same points. An accelerator was attached in parallel with the drop direction at the lid which was named A1 so the acceleration obtained from the A1 accelerator was considered during the first impact. An accelerator was attached perpendicular to the axial direction of the package at the lid which was designated as A2 so the acceleration acquired from the A2 accelerator was considered during the second impact. Fig. 13 shows a comparison between the test and analytic accelerations at A1 and A2. For the acceleration at the A1 point, the maximum values acquired from the test and analysis are similar during the first impact. During the second impact the maximum acceleration acquired from analysis at the A2 location was larger than the test result. The inclined impact causes the difference between the results from the test and analysis.[9] So the analytic safety evaluation of the 9 m free drop test conditions revealed conservative results for the bottom oblique drop direction. Also, we could conclude that the structural safety of the type B package was maintained under the free drop tests under normal conditions of transport as well as the other drop directions of the 9 m free drop test because the method of the analysis was the same except for a drop direction and an initial velocity.

5.2 Puncture condition

We verified the structural safety analysis of the puncture test condition using a comparison between the accelerations obtained from the test and analysis. Accelerators were attached in parallel with the drop direction at the body and the lid of the shielding package, which were designated as A3 and A4, respectively. Fig. 14 shows the comparisons between the test and analytic accelerations acquired from the A3 and A4 accelerators for the side puncture test condition. For the A3 accelerator the maximum acceleration obtained from analysis was three times that of the test result. For the acceleration from the A4 accelerator the analytic maximum value was two times that of the test value, and these trends were similar. The analysis for the puncture test condition revealed conservative results when compared with the test.

6. Conclusion

Based on the ASME Boiler and Pressure Vessel Code, Section III, Division 3 we evaluated the structural safety integrity of the type B package for a radioactive waste drum by using a finite element analysis. For the stacking test condition, the maximum stress was a very low value when compared with stress limits. The impact of the penetration bar on the overpack did not affect the containment part. For the free drop test conditions and the puncture test condition the local stresses appeared at the impact part and the containment part connected with the inner structure. The maximum stresses for all of the conditions were lower than the stress limits, so it was analytically proven that the structural integrity of the type B package for a radioactive waste drum was maintained. Also, the structural safety analyses were verified by using the data acquired from the 9 m drop and the puncture tests of a real model. The analysis for the structural safety of the type B package for a radioactive waste revealed conservative results when compared with the test. The structural integrity of the type B package is maintained under normal and accident conditions of transport.

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