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Structural Integrity Analysis of MSF Transportable Storage Casks based on Test Results used full-scale and 1/2.5-scale Model

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ABSTRACT

Transportable storage casks for spent fuels are able to be used for transport of spent fuels from nuclear power plants to an interim storage site, and used for storage at the site. Integrities of containment system, shielding system and subcriticality system during transport have to be demonstrated by drop tests and/or numerical simulations in accordance with IAEA transport regulations SSR-6.

Structural integrities of “MSF transportable storage casks fleet” are verified by numerical simulations based on the drop tests with full-scale model and 1/2.5 scale model, and static tests of shock absorbers.

The load-displacement characteristics were obtained by the static element tests of woods. The decelerations and strains at the body and lids were obtained by the drop tests. A numerical simulation tool was developed to evaluate dynamic behavior of the cask body especially behavior at lid parts. The structural integrities of different type casks of MSF-21P and MSF-52B were confirmed with applying the developed simulation tool.

This paper describes outline of MSF cask and structural design of MSF cask validated by test results and the numerical simulation tool.

1. INTRODUCTION

Many spent fuel storage pools in nuclear plant facilities are now reaching their full capacity, and the need for interim storage is growing rapidly in Japan. A dry cask storage system is considered as a realistic and feasible option for the safe management of spent fuels, because it possesses passive safety which does not require electric power for decay heat removal. Especially, a dual-purpose cask, which can store and transport spent fuels before and even after storage without reloading, is robust and safe against accidents in both storage and transport. Therefore, Mitsubishi Heavy Industries, Ltd. (MHI) are working on the development of dry storage facilities with the MSF-type dual purpose cask.

MHI conducted full-scale and 1/2.5 scale drop tests on the MSF-type cask from 2004 to 2005[1] and component tests[2] with the cooperation of BAM (Bundesanstalt für Materialforschung und -prüfung) to demonstrate the containment performance during transport. MHI has analyzed and verified the shock absorber performance and the response of the closure system equipped with metallic O-rings.

Based on these technologies and full-scale drop test results, MHI has developed a high-integrity dual-purpose dry cask, MSF-21P and MSF-52B, the containment integrity of which can be preserved under hypothetical accident drop conditions of transport.

This paper describes outline of the MSF-21P and MSF-52B cask and the containment system verified based on the test results.

2. Features of MSF-21P and MSF-52B cask

(1) Outline of MSF-21P and MSF-52B cask

The MSF-21P and MSF-52B cask has been developed as a high-integrity dual-purpose cask which can accommodate 21 PWR or 52 BWR spent fuel assemblies. Schematic view of the transport configuration of the MSF-21P cask is shown in Figure 1.

Typical specifications of the MSF-21P and MSF-52B cask are shown in Table 1.

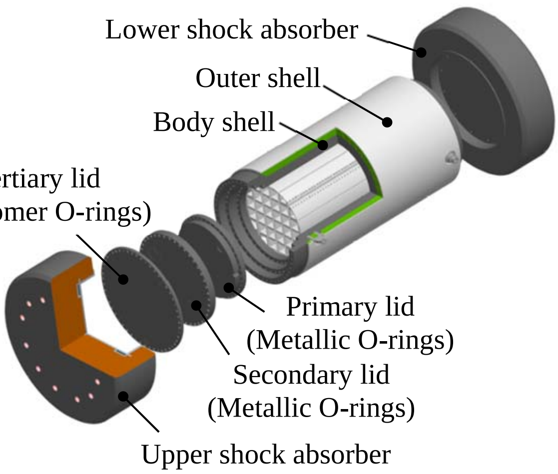


Figure 1 Configurations of MSF-21P

Table 1 Specifications of MSF-21P and MSF-52B cask (design sample).

	Items	Specifications	
		MSF-21P	MSF-52B
Contents	Fuel type	PWR	BWR
	Pay load	21	52
	Burnup (GWd/MTU)	48 (Max.)	50 (Max.)
	U-235 initial enrichment (%)	4.2	3.6
	Cooling period (years)	15	12
Cask	Thermal power (kW)	13.9	13.7
	Dimensions (m)	Φ3.6 x 6.8 (with S/As) Φ2.5 x 5.2 (without S/As)	Φ3.6 x 6.9 (with S/As) Φ2.4 x 5.5 (without S/As)
	Total weight (tons)	131 (with S/As) 117 (without S/As)	135 (with S/As) 116 (without S/As)

(2) Design of closure system

Outline of the MSF-type cask closure system is shown in Figure 2.

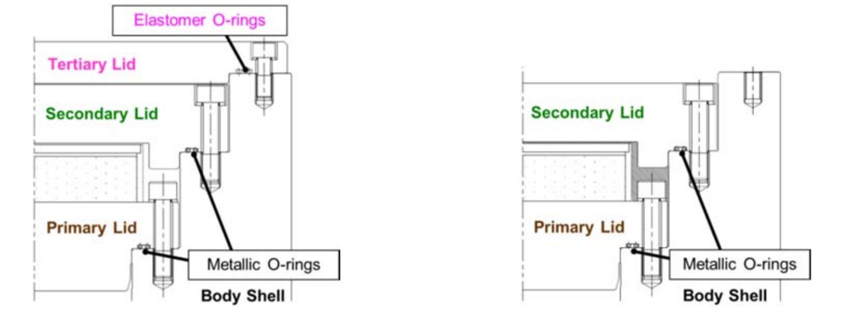
During storage, the primary lid and the secondary lid equipped with metallic O-rings are bolted to the body flange. The sealing performance for long-term services is ensured by metallic O-rings attached to the lids.

During transport, the tertiary lid equipped with elastomer O-rings is bolted to the top of the body flange. The secondary lid and the tertiary lid play the role of a double containment boundary during transport. A pair of wooden shock absorbers covered with stainless steel plates is attached to both ends of the cask. The purpose of shock absorbers is to reduce the impact force on the cask and its contents in the event of an accidental drop.

(3) Development of closure system (See Figure 3)

The closure system of the MSF cask is developed and designed based on full-scale drop test results of the MSF prototype cask.

First of all, Drop tests on full-scale model were conducted to demonstrate the containment and structural integrity of the closure system. Next, a dynamic Finite Element (FE) analysis model for the drop tests was defined and verified based on the drop test results and element test results of shock absorber.



(a) Transport configuration (b) Storage configuration

Figure 2 Closure system of MSF-type cask

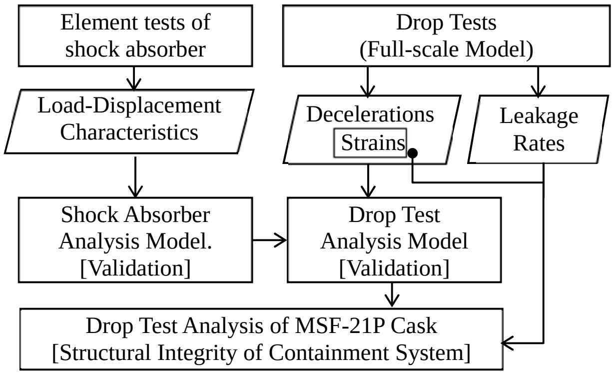
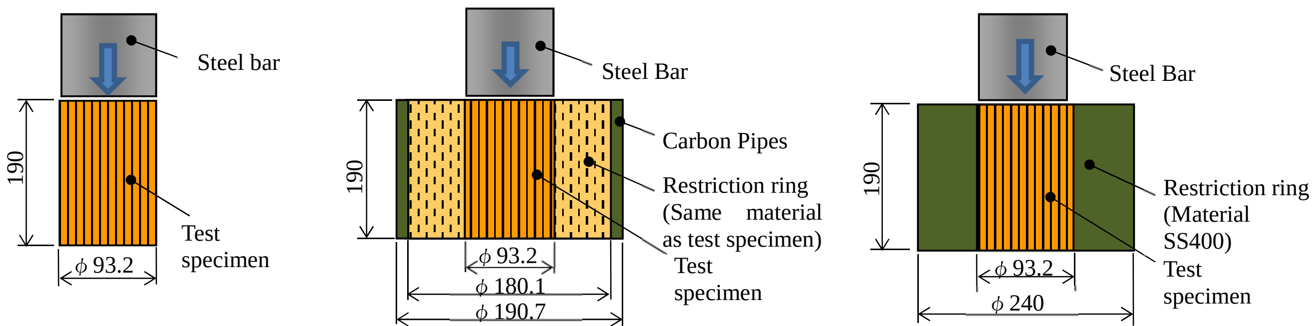


Figure 3 Verification Procedure of Containment System

3. Development of Shock Absorber

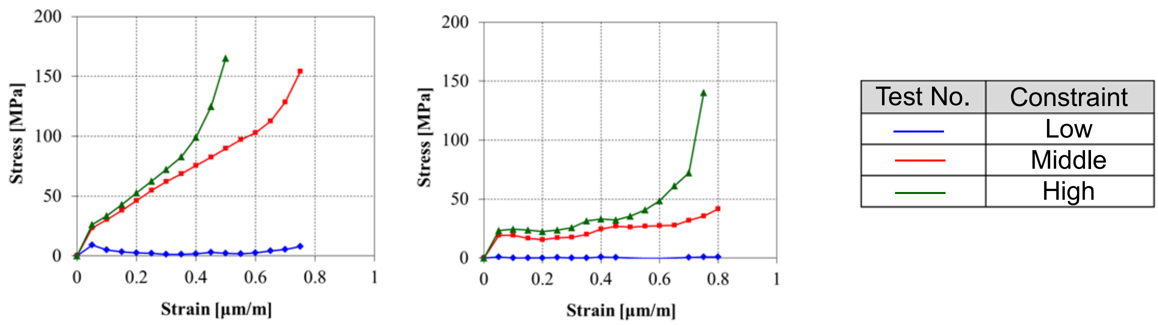
(1) Static compression test on wood elements

The Shock Absorbers are consisted of oak, red cedar and balsa. The outline view of wooden test specimen is shown in Figure 4. A series of static compression test on wood elements was carried out under three kinds of constraint condition and the compression stress-strain characteristic was acquired. The test results are shown in Figure 5. The stress-strain characteristic was influenced by the constraint conditions. Therefore, it is needed to consider and verify the constraint condition of assembled in developing Shock Absorber.



(a) Constraint condition Low (b) Constraint condition Middle (c) Constraint condition High

Figure 4 Wooden test Specimen



(a) Oak (b) Red cedar

Figure 5 Test results of compression test

(2) Component test

The static compression tests were conducted to determine the load-displacement characteristics of the shock absorber and take the effect of constraint condition as a component. A semi-circular type 1/2.5 scale shock absorber model was used for the test [2].

(3) Definition and verification of the component test FE analysis model

Shock absorber component test analyses were performed using LS-DYNA code [3]. The load-displacement characteristics obtained from the analysis results using the characteristics on wood element of middle constraint condition and considered of modulus effect agree well with those of the experimental results is shown in Figure 6. These results indicated that the analysis results using the test results on wood element of middle was higher load than the component test result. The analysis results using the test results on wood element of middle had the potential to underestimate its displacement under absorbing certain of crash energy. Furthermore, that analysis results could not simulate the load transfer to a cask body.

It is thought that the constraint condition of wooden materials at component test is lower than middle constraint at the wooden tests. In the case of MSF-type shock absorber, the load-displacement characteristics at the analysis results that used the stress-strain characteristics considered of modulus effect similar to the component test. In the development of closure system at MSF-type cask, dynamic FE drop test analyses were performed using its stress-strain characteristics.

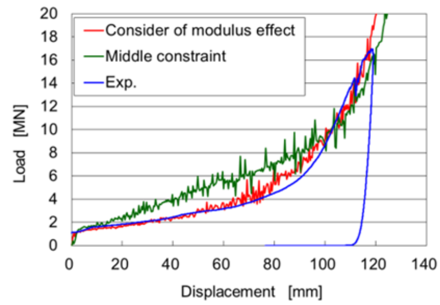


Figure 6 Comparison of load-displacement characteristics

4. Drop Tests

In order to demonstrate the integrity for containment system, drop tests with full-scale and 1/2.5 scale MSF cask model were conducted [1]. It is very difficult and complex to scale down a containment system, especially metallic O-rings, because dimensions and characteristics of metallic O-rings cannot comply with the scaling law. Thus, demonstration for the containment integrity with full-scale model is very important.

(1) Drop Test Models

The weights and dimensions of the drop test models used are shown in Table 2 and Figure 7. These models have double closure lid system with metallic O-rings (there is no tertiary lid.) The test models were manufactured under the supervision of third-party certifiers.

Table 2 Weighs and Dimensions of Drop Test Models

Items	Full-scale Model	1/2.5 Scale Model
Content	BWR(Dummy Fuel)	
Payload	69	
Weight (tons)	113*1) / 127*2)	7.2*1) / 8.0*2)
Dimensions (m)	Φ2.5x5.3 *1) Φ3.1x6.8 *2)	Φ1.0x2.1 *1) Φ1.2x2.7 *2)

(Notes)
*1) Without Shock Absorbers
*2) With Shock Absorbers

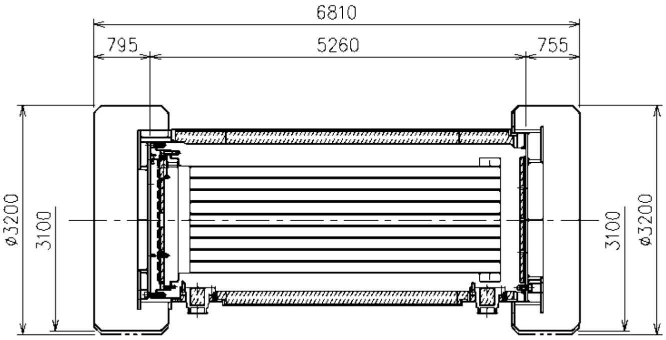


Figure 7. Dimensions of Drop Test Models (Full-Scale Drop Test Model)

(2) Drop Test Results

In order to verify the conformity with the requirements of leak-tightness of the lids, helium leakage tests were performed. Table 3 shows the leakage rates before and after full-scale drop tests. All the leakage rates of secondary lid and primary lid were well below the criteria based on the IAEA regulations [4].

Table 3 Leakage Rates before/after Drop Test with Full-Scale Model [Unit: Pa·m^3/s]

No.	Conditions	Primary Lid		Secondary Lid	
		Before	After	Before	After
1	9.3m Slap down	$< 1\times10^{-11}$	$< 1\times10^{-11}$	7.4×10^{-9}	1.6×10^{-6}
2	9.3m Vertical	1.0×10^{-8}	3.9×10^{-6}	2.0×10^{-11}	1.7×10^{-11}

(a) 9.3m Slap Down (b) 9.3m Vertical Drop

Figure 8 Drop Tests with Full-Scale

5. Drop Test Analysis

In order to verify the drop test analysis model, dynamic FE drop test analyses with full-scale model were performed using LS-DYNA code.

(1) Analysis Model

The drop test analysis model is shown in Figure 9, which includes the body shell with neutron shielding, outer shell, lids, bolts, baskets, and dummy fuel assemblies. The dummy fuel assemblies were modeled as individual 69 rigid bodies. The shock absorbers verified by the component tests have also been modeled and the stress-strain characteristics of wood materials were considered of modulus effect. An elastic-plastic model with actual mechanical properties was used for the analyses. Furthermore, a strain rate dependency of the strength of the wood infills and steel structure was considered in the analysis model.

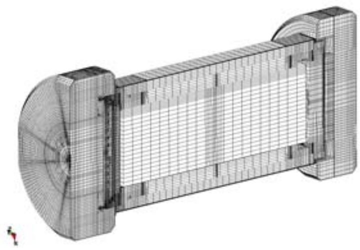


Figure 9 Drop Test Analysis Models (Sectional View)

(2) Verification of Drop Test Analysis Model

The analysis results of the slap down test are shown as an example. Comparisons of the decelerations of the cask body and of the strains near the closure system between the analytical and experimental results are shown in Figure 10 and Figure 11, respectively. These figures show that deceleration time histories and strain time histories of the analytical results using the stress-strain characteristics of wood materials considered of modulus effect agree well with those of the experimental results between the primary impact and the secondary impact.

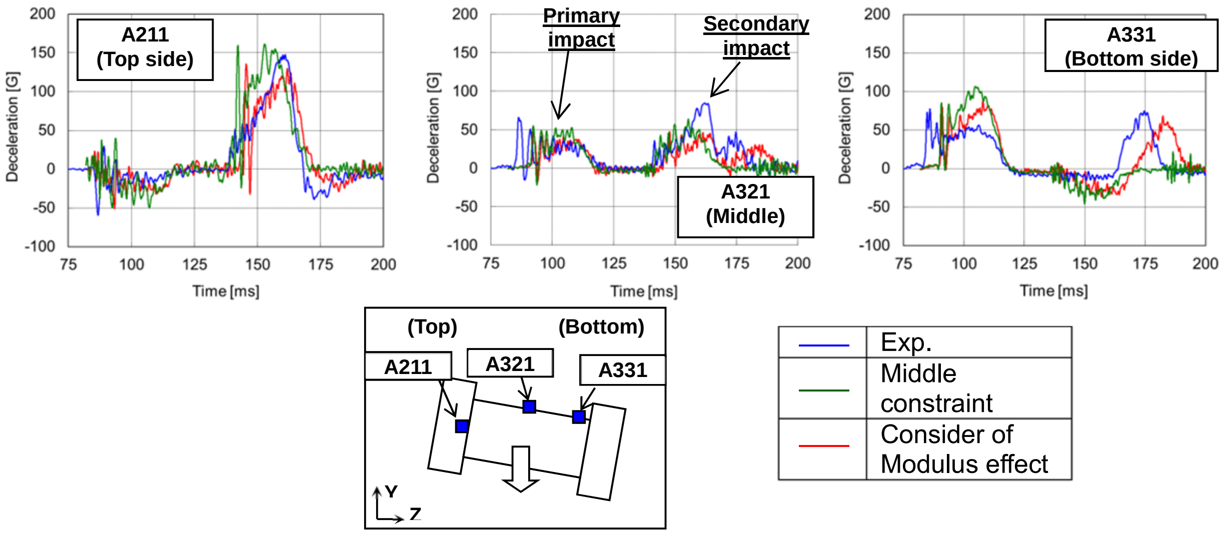


Figure 10 Comparison of decelerations (9.3m Slap down)

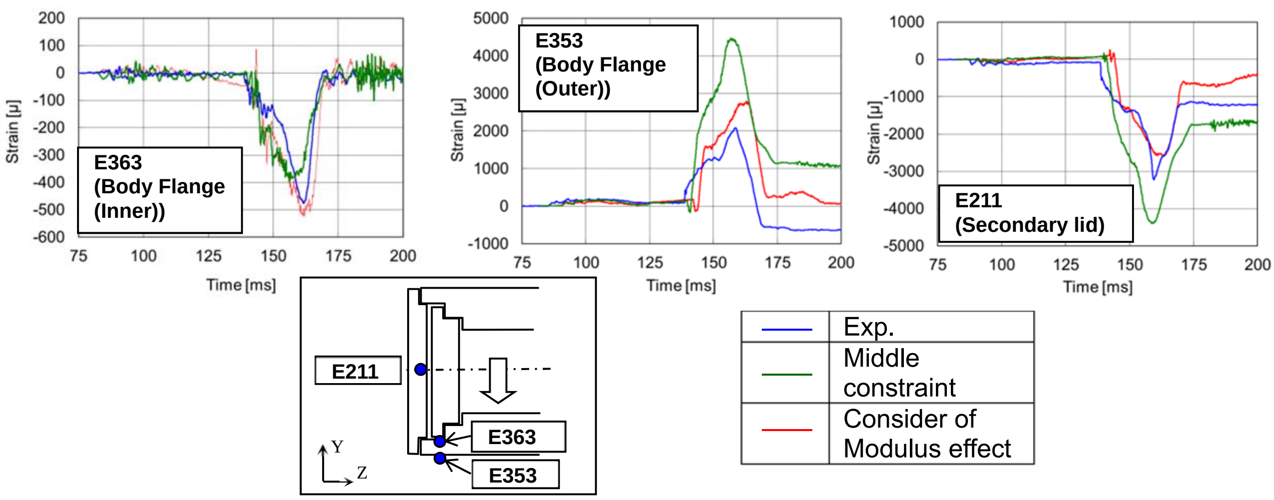


Figure 11 Comparison of Strains (9.3m Slap down)

6. MSF-21P Cask and MSF-52B Cask Containment Integrity Evaluation

(1) MSF-21P cask closure system design

Leakage rates following the 9.3 m/9 m slap down test and the 9.3 m vertical drop test using full-scale model increased by an order of magnitude of two to four compared to those before the tests as shown in Table 3. In consideration of the uncertainty related to the integrity of metallic O-rings after long-term storage, the closure system of the MSF-21P cask should be designed to limit the increase in leakage rate between before and after accident conditions of transport. The closure system is designed on the basis of the full-scale drop test results by comparison of the important parameters such as strains of the body flange and lids. Furthermore, important features of the shock absorbers of the drop test models (i.e.,:arrangement of wood material and inner steel structure) were taken into account in the shock absorber design.

(2) Analysis model

MSF-21P cask analysis model shown in Figure 12 was established on the basis of the verified drop test analysis model as shown in chapter 5. The spent fuel assemblies were modeled individually with actual mechanical properties. Furthermore, delayed internal impact of the content was taken into account. The mechanical properties specified in the material standards were used for the cask. The inclined angle of the slap down was set as 10 degree, which gives the most severe impact force on the closure system than any other angles. The analyses were conducted at the maximum design temperature with the thermal load of 13.9 kW.

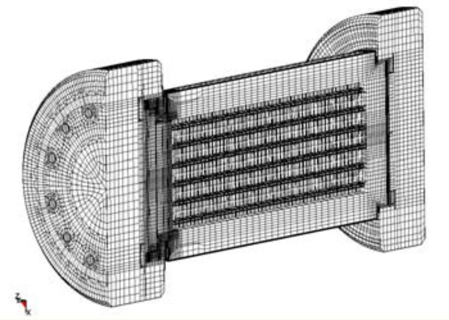


Figure 12 Analysis Model of MSF-21P Cask (Sectional View)

(3) Analysis results

The structural integrity of the closure system of the MSF-21P cask under accident conditions of transport was demonstrated by dynamic FE analyses, which showed that the MSF-21P cask can provide a higher closure system integrity than the full-scale model.

The analysis results of the 9.3m slap down tests, which are considered as severe drop conditions as regards the closure system, are shown below.

Comparison of the important parameters such as strains in the impact area of the body flange and lids between the MSF-21P cask and the full-scale drop test analysis results are shown in Figure 13. These analysis results confirm the structural integrity of the closure system of the MSF-21P cask because the strains are smaller than those applied to the drop test model. It can therefore be considered that the increase in leakage rates is smaller for the MSF-21P cask than for the full scale model. Strains of the secondary lid of the MSF-21P cask are also smaller than those applied to the drop test model although it does not function as the containment boundary under the transport conditions. Furthermore, no plastic strains occurred in the secondary lid and the tertiary lid including the sealing area of the metallic or elastomer O-rings and lid bolts of the MSF-21P cask.

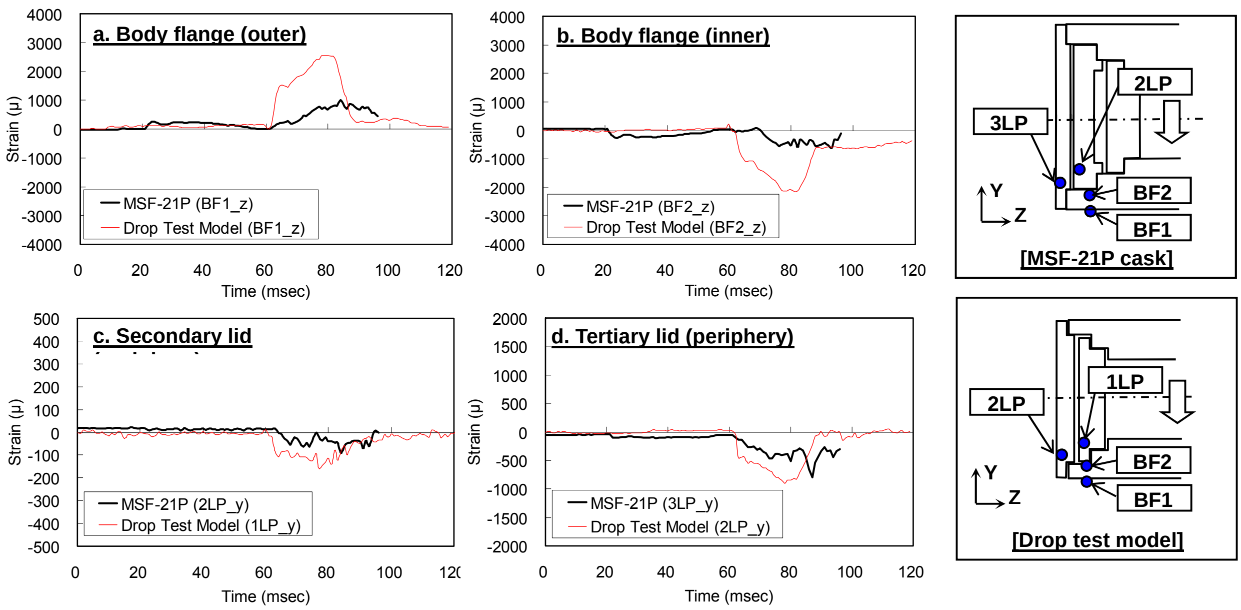


Figure 13. Comparison of strains between MSF-21P cask and full-scale drop test model

7. Conclusions

MHI has developed the high-integrity dual purpose casks, MSF-21P and MSF-52B, for interim storage and transport of spent nuclear fuel. Its containment integrity has been validated by dynamic FE analysis developed on the basis of the drop test and the element test results of shock absorbers, and shows that its closure system has a high robustness even under hypothetical accidental drop conditions of transport.

References

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