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DEVELOPMENT OF FUEL DEBRIS CANISTER

Motoki Nakane[1], Hideaki Uchiyama[2], Toshihiro Matsuoka[3], Tomoya Iwashima[4], Yuichi Matsushita[5], Nodoka Miyamoto[6], Kazuma Hirosaka[7], Noboru Saito[7] and Manabu Ueno[8]

[1] Senior technical staff engineer, IRID/Hitachi-GE Nuclear Energy Ltd., Hitachi-shi, Ibaraki-ken, Japan (motoki.nakane.ze@hitachi.com)
[2] Deputy general manager, International Research Institute for Nuclear Decommissioning (IRID), Minato-ku, Tokyo-to, Japan
[3] Engineering manager, IRID/Mitsubishi Heavy Industries, Ltd., Kobe-shi, Hyogo-ken, Japan
[4] Specialist, IRID/Toshiba Energy Systems & Solutions Corporation, Yokohama-shi, Kanagawa-ken, Japan
[5] Staff engineer, IRID/ Hitachi-GE Nuclear Energy Ltd., Hitachi-shi, Ibaraki-ken, Japan
[6] Planner, IRID/Hitachi-GE Nuclear Energy Ltd., Hitachi-shi, Ibaraki-ken, Japan
[7] Researcher, IRID/Hitachi Ltd., Hitachi-shi, Ibaraki-ken, Japan
[8] Senior engineer, IRID/ Hitachi-GE Nuclear Energy Ltd., Hitachi-shi, Ibaraki-ken, Japan

INTRODUCTION

Development of technologies for safety and rational containing, transportation and storage of the fuel debris are very important for decommissioning of Fukushima Daiichi Nuclear Power Station (FD-NPS). Especially, fuel debris must be treated carefully with consideration of confinement of radio active materials and its sub-criticality because fuel debris includes nuclear fuel materials.

In the process of the Three Mile Island Unit 2 (TMI-2) decommissioning, the system of fuel debris canister (Hereafter called 'canister') was introduced to handle the fuel debris safely. This system successfully satisfied the requirement of containment of radio active materials during decommissioning by applying proven and existing transportation and storage technologies of spent fuel and radioactive waste management technologies to the debris canisters.

International Research Institute for Nuclear Decommissioning (IRID) has been developing a canister dedicated to establish the technology for containing, transportation and storage of the fuel debris which will be retrieved from the FD-NPS. In the development of canister, both lessons learned from TMI-2 and the difference of conditions between TMI-2 and FD-NPS such as reactor type, sea water injection and molten core concrete interaction products are taken into consideration appropriately. One of the important safety assessment of the canister is structural integrity under the postulated severe events because canisters always have to maintain sub-criticality even in the severe situation. Based on the fault analyses, dropped loads are extracted as postulated severe events for the structural integrity of the canister to be used at FD-NPS.

This study discusses the development of the static structural evaluation methodology for canisters under the dropped loads. The validity of developed methods are discussed with drop test results of scale model canister. In addition, this study proposes design methods of impact limiter for the canister based on the dynamic analysis results, and the performance of designed impact limiter and evaluation method using dynamic analysis code are also discussed with results of small scale canister drop tests.

OUTLINE OF FUEL DEBRIS CANISTER

Outline of the canister system is shown in Figure1. A canister is cylindrical shape container made of stainless steel. In this system, retrieved fuel debris will be put into a collection containers called 'Unit can' first, then Unit cans including fuel debris will be installed into the canisters. After that, canisters will be placed into the transportation containers.

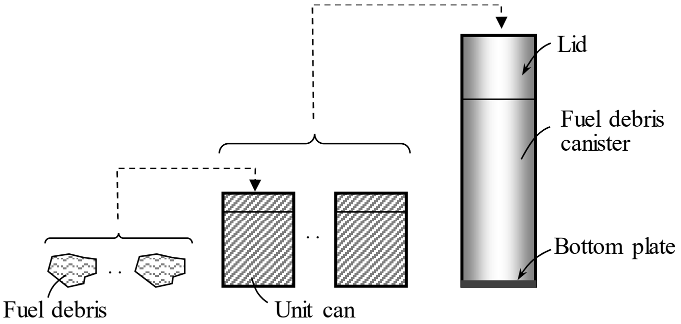


Figure 1 Outline of fuel debris canister system.

STRAIN ENERGY METHODS USING ELASTIC PLASTIC (E-P) STATIC ANALYSIS

In order to simulate the behaviour and to evaluate structural integrity of the canister under the postulated drop loads, this study investigates E-P static analysis technology based on strain energy methods.

In this methods, the canister is simulated by finite element model. The acceleration due to the dropped load is applied to the entire canister model. The dropped load is increased until the strain energy of the canister equals to the drop energy as described following equation.

$$Mgh = E_{\varepsilon}(G) \tag{1}$$

where M is the mass of the canister including Unit can and fuel debris, g is the gravity, h is drop height, G is an impact acceleration and E_{ε} is a strain energy of the canister.

DROP TEST OF SMALL SCALE CANISTER

Drop tests of the canister using 1/3 scale model was conducted to verify strain energy methods using E-P static analysis. Before the test, the drop posture to be applied to the drop test was surveyed and it was concluded that four drop postures are severe to the structural integrity of the canister. Those are vertical drop, center of gravity over (CGO) corner drop, 45 degrees corner drop and horizontal drop. Regarding horizontal drop, one of the dominant collision part is canister lid but detail design of the canister lid is not decided yet. Therefore, horizontal drop was passed on in this study. Also, 45 degrees drop test was conducted only using very limited part of the canister due to the conventional safety issues. Consequently, the results of vertical and CGO corner drop are discussed in this paper.

The outline of vertical drop tests are shown in Figure 2. The test specimen is hung at dead weight frame and test specimen is dropped to the target to simulate canister drop onto the floor. A ballast structure is put into the canister to simulate Unit can including fuel debris. Total mass of test specimen was 32.1 kg. Though the dead weight frame is dropped with test specimen in this test, the dead weight frame is supported by stopper structure of the drop test facility to avoid collision between canister test specimen and dead weight frame. Outline of CGO corner drop test is same as vertical drop test. Although, the material of actual canister is planed to be SUS304L which has high corrosion resistance, SUS304 was adopted to test specimen in this study due to the availability. The material of the target is S45C carbon steel prescribed in JIS (2009). Drop height was set to 9 m according to the expected maximum handling height of the canister. Both vertical and CGO corner drop were executed two times.

DROP TEST RESULTS

Visual inspections were conducted after the drop tests, and it was found that there was no large deformation of the canister and failure of bottom plate was not observed.

The averaged time histories of dropped load for vertical and CGO corner drop are shown in Figure 3. The averaged maximum dropped load for the vertical drop test was 1910 kN and those of CGO corner drop were 1573 kN. These results indicate that vertical drop will give most severe dropped load for the canister.

The maximum axial direction compression strain of the canister body at 5 mm to 50mm from bottom plate for the vertical test were -8500 μ～-4500 μ. At same area, the maximum circumferential direction strain were 2000 μ～9000 μ. These results indicate that vertical dropped load leads axial direction compression and circumferential direction tensile due to the bulge deformation of the canister body.

In terms of CGO corner drop, the maximum axial direction compression stain of the canister body at 5 mm to 50mm from collision point were -29000 μ ～ -20000 μ. At the same area, the maximum circumferential direction strain were 2000 μ～9000 μ. It was shown that the deformations of canister of the CGO corner drop were much larger than that of the vertical drop.

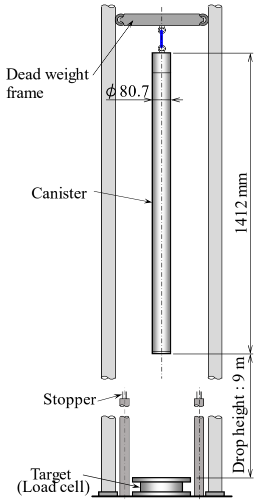


Figure 2 Outline of canister drop test.

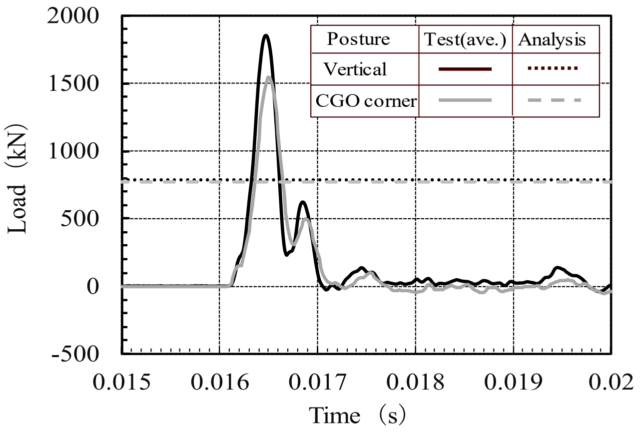
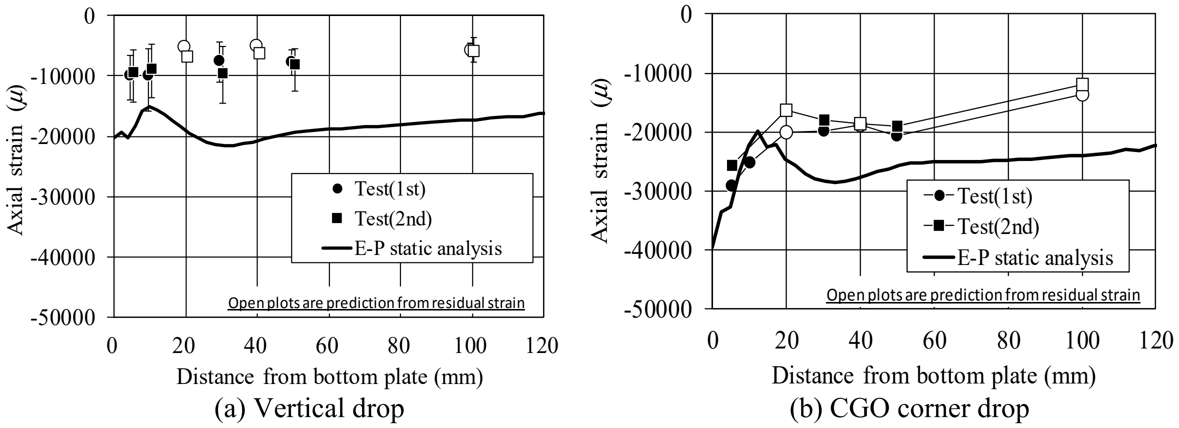


Figure 3 Time history of dropped load



(a) Vertical drop

(b) CGO corner drop

Figure 4 Axial strain of bottom part of canister.

E-P STATIC ANALYSIS

Analysis conditions

E-P static analysis was performed by using finite element (FE) structural analysis code Abaqus® to simulate 1/3 scale model drop test. The numerical analysis model shown in Figure5 is a half model because of symmetricity of the canister test specimen. The target is assumed to be a rigid body in this study in order to evaluate absorbed energy of canister safety side. In this simulation, vertical acceleration is applied to entire FE model and acceleration is increased until absorbed energy of canister equals to drop energy. For the CGO corner drop model, horizontal displacement of top left point of canister and ballast is constrained. The mechanical properties used for analysis is described in Table 1.

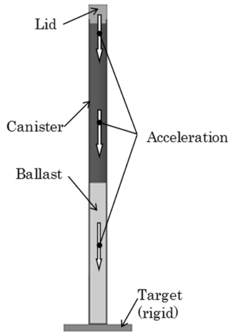


Figure 5 Analysis model.

Table 1 Material properties used for E-P static analysis.

Component	Elastic modulus [MPa]	Poisson's ratio [−]	Plastic strain [-]						
			0	0.003	0.01	0.03	0.1	0.229	0.4
			Stress [MPa]						
Canister	195000	0.3	205	226	263	329	465	−	779
Ballast	201000	0.3	215	−	−	−	−	400	−

Comparison between drop tests and analysis results

The dropped load of tests and E-P static analyses are shown in Figure 3. As mentioned above, the averaged maximum dropped load of vertical and CGO corner drop of tests are 1910 kN and 1573 kN respectively. On the other hand, maximum dropped load of derived from EP static analyses are 786kNand 780kN respectively and those are almost a half of drop tests.

The axial direction compression strains of canister in vertical and CGO corner drops are summarized in Figure 4(a) and Figure 4(b) respectively. These figures express that the profiles of axial strains obtained from static analyses are a little bit larger than measured strains.

The maximum deformation of the canister inner diameter which is important to sub-criticality for vertical drop tests and analyses were 0.62 mm and 0.93 mm respectively, and those of for CGO corner drop were 0.95 mm and 1.53 mm respectively. The deformation derived from analyses is almost twice as large as test results. However, the difference of deformation between tests and analyses is only 0.8 % of the inner diameter and analysis can estimate the deformation of the diameter of the canister precisely. Consequently, from above discussions, it can be concluded that E-P static analysis evaluation methods for canister under the dropped loads can estimate the deformation of the canister in safety side with appropriate margin, and the validity of proposed methods is verified.

The deformation of actual size canister with 10 mm in thickness and ϕ 220 mm in inner diameter was estimated by verified E-P static analysis methods, and it is found that the amount of diameter deformation of the canister is 6 mm for 9 m vertical drop. This value is enough lower than target value of 13mm which is criteria for sub-criticality, and it is confirmed that the canister can maintain sub-criticality under the severe dropped loads.

EXAMINATION OF IMPACT LIMITER

To enhance the safety and to allow design flexibility in the future, the impact limiter which mitigates dropped loads for the canister is investigated. Based on the surveys of existing impact limiter of the canisters used in such as TMI-2 and DOE, the cylindrical shape impact limiter shown in Figure 6 is examined in this study. This type of impact limiters absorbs dropped energy by buckling of the structure and buckling leads very large elastic plastic deformation. In this paper, therefore, the performance of impact limiter is simulated by large deformation dynamic structural analysis code LS-DYNA.

Dimension And Density Of Canister

Parameter study of dimension of the impact limiter was conducted. The dimensions of object canister are set to 2000 mm in length, 900 mm in inner height, 500 mm in thickness of lid, ϕ 220 mm in inner diameter and 10 mm in thickness of body and bottom plate. The examined variable parameters of the impact limiter are thickness of body, both length and diameter of impact limiter and thickness of bottom plate of the canister as described in Figure 7. The material of impact limiter is assumed to be SUS304 in this paper. Also, the density of debris is assumed to be 5310 kg/m^3 which simulates 100% debris storage efficiency. Elastic modulus of debris is assumed to be 21700 MPa and this value is obtained from a concept of effective modulus proposed by Digby et al. (1981) by assuming inside canister is filled with aggregate of sphere debris.

A half model is applied to dynamic analysis because of symmetricity of canister and impact limiter. The initial impact velocity was set to 13.3m/s which simulates 9 m free drop of the canister.

Results Of Parameter Study Analysis And Methodology Of Impact Limiter

After the careful investigation of the results of parameter study analyses, it is found that there are two important criteria for designing the impact limiter. First criteria is that stress of canister body must satisfy allowable limit, and second is that impact limiter must absorb drop energy before impact limiter perfectly crushed or buckled.

The relationships between t_b/t_s and S/S_y obtained from parameter study analyses are summarized in Figure 8. Here, t_b and t_s are thickness of impact limiter and bottom plate of canister respectively, S and S_y are stress intensity (primary membrane stress + bending stress) and design yield stress respectively.

The variety of analysis results can be fallen into a range described following equations.

$$\frac{S}{S_y} = 17.5\left(\frac{t_b}{t_s}\right)^2 + 1.31 \tag{2}$$

$$\frac{S}{S_y} = 17.5\left(\frac{t_b}{t_s}\right)^2 + 0.5 \tag{3}$$

When domestic structural integrity criteria, such as JSME (2007), for components important to sub-criticality of spent fuel interim storage container is adopted to the canister, the canister should be satisfied $P_m + P_b \leqq 1.5S_y$ during drop accident. Here, P_m is the general primary membrane stress and P_b is the primary bending stress. This criteria is also expressed in Figure 8.

Now, the energy absorbed by impact limiter E_b can be written in the form

$$E_b = P_{buc}\delta \tag{4}$$

where P_{buc} is averaged buckling load of impact limiter and δ is crushed height of impact limiter. Here, E_b can be regarded as E_ε in Eq. (1). The averaged buckling load of cylindrical structures proposed by Tanimura (2000) is expressed by next equation.

$$P_{buc} = \frac{\left\{S_y\left(2\pi^3 D t_b^3\right)^{0.5}\right\}}{3^{0.25}} \tag{5}$$

where D is outer diameter of impact limiter. By assuming critical height of impact limiter is proportional to original height of impact limiter L_b, δ at critical height is expressed as

$$\delta = C_1 L_b \tag{6}$$

where C_1 is constant. From Eqs. (4) to (6), if the impact limiter is perfectly crushed, absorbed energy by the impact limiter is written as

$$E_b = P_{buc}\delta = C_1 \frac{\left\{S_y\left(2\pi^3 D t_b^3\right)^{0.5}\right\} L_b}{3^{0.25}} \tag{7}$$

Substituting Eq. (1) into Eq. (8) yields

$$MgH = C_1 \frac{\left\{S_y\left(2\pi^3 D t_b^3\right)^{0.5}\right\} L_b}{3^{0.25}} \tag{8}$$

Finally, following relation is obtained.

$$\frac{L_b}{H} \propto \frac{Mg}{S_y D^{0.5} t_b^{1.5}} \tag{9}$$

The left hand side of Eq. (9), L_b/H, denotes ratio of impact limiter and drop height, and the right hand side of Eq. (9), $Mg/(S_y D^{0.5} t_b^{1.5})$, indicates the parameter related to ratio of weight of impact limiter and averaged buckling load. Hereafter, $Mg/(S_y D^{0.5} t_b^{1.5})$ is called “load ratio parameter”. The relationships between L_b/H and $Mg/(S_y D^{0.5} t_b^{1.5})$ derived from dynamic analysis are shown in Figure 9. In this figure, solid plots indicate that the impact limiter is perfectly crushed before impact limiter absorbs drop energy. On the other hand, open plots in Figure 9 express that drop energies are absorbed by the impact limiter before the impact limiter is perfectly crushed.

The boundary of open and solid plots in Figure 9 can exist between following two lines.

$$\frac{L_b}{H} = 7.36\times10^{-5}\frac{Mg}{S_y D^{0.5} t_b^{1.5}} - 0.01 \tag{10}$$

$$\frac{L_b}{H} = 4.3\times10^{-5}\frac{Mg}{S_y D^{0.5} t_b^{1.5}} + 0.0034 \tag{11}$$

Prototype Design Of Impact Limiter

By using developed relationship shown in Figure 8 and Figure9, a prototype impact limiter for a canister with ϕ 220 mm inner diameter is designed, and the performance of prototype impact limiter is investigated by dynamic analysis code LS-DYNA. The material properties of SUS304 used for analysis is shown in Table 1. Analyses are conducted at ambient temperature and 300℃ which will be maximum design temperature of impact limiter. The deformation of impact limiter after drop is shown in Figure 10. The impact limiter is not crushed perfectly even when at 300℃ which is most soft condition.

The displacement of radial direction of the canister body is described in Figure 11. The maximum displacement of canister body is 0.02mm and this amount is much smaller than displacement limit of 13 mm to ensure sub-criticality of the canister. In addition, it is confirmed that stress of the canister satisfy the limitation mentioned above.

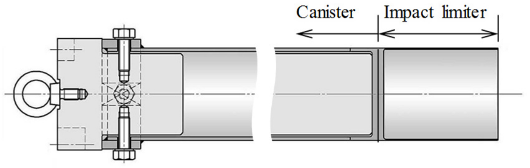


Figure 6 Outline of impact limiter for canister.

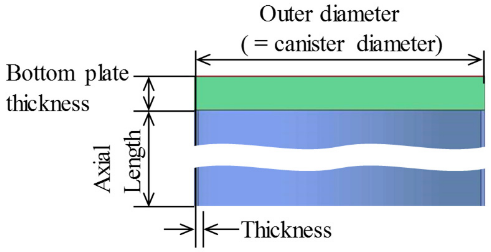


Figure 7 Variable parameters for impact limiter.

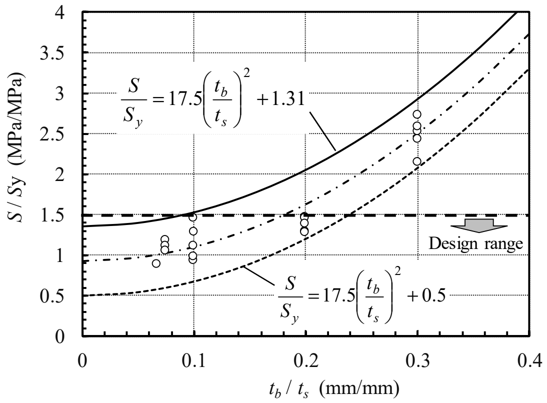


Figure 8 Relationship between S/S_y and t_b/t_s.

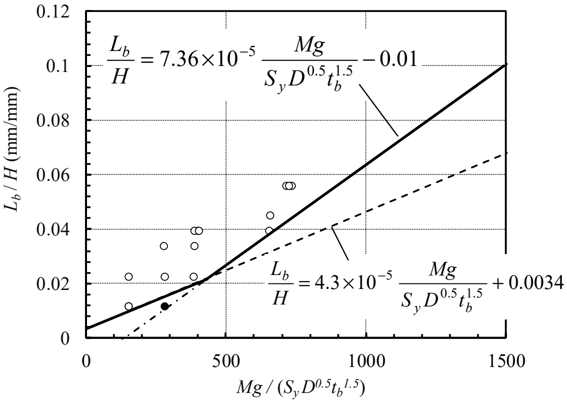


Figure 9 Relationship between L_b/H and load ratio parameter $Mg/(S_yD^{0.5}t_b^{1.5})$.

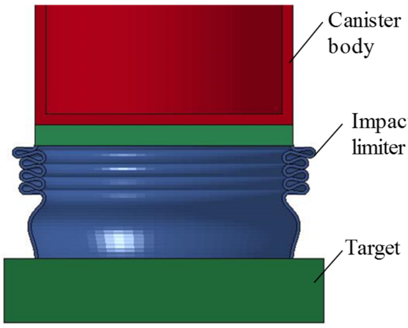


Figure 10 Deformation of impact limiter at 300 ℃ simulated by dynamic analysis.

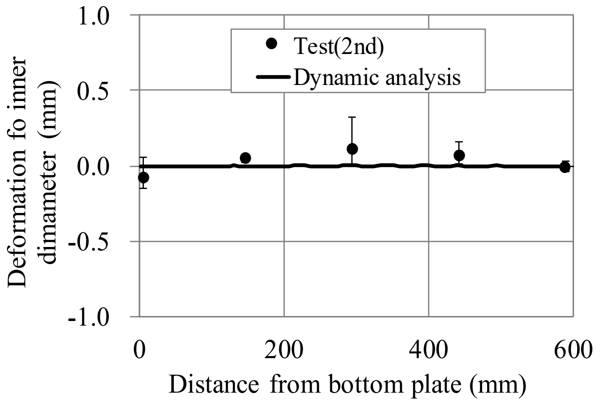


Figure 11 Measured and analysed deformation of inner diameter of canister.

1/3 SCALE MODEL DROP TEST OF CANISTER WITH IMPACT LIMITER

Test Methodology

The 9 m drop tests of 1/3 scale model canister with or without impact limiter were performed to verify the validity of designed prototype impact limiter. The material of the test canister and impact limiter was SUS304. The mass of specimen with and without impact limiter is 21.1 kg and 20.6 kg respectively.

Test Results

The example of appearance of test specimen with impact limiter after 9m drop test is shown in Figure 12. The impact limiter were largely deformed by absorbing drop energy. Time history of dropped loads are shown in Figure 13. The maximum dropped load of the canister without impact limiter is 1693 kN. On the other hand, the maximum dropped load of the canister with impact limiter was74 kN, and it is found that designed prototype impact limiter can mitigate dropped load to 1/23 of the canister without impact limiter.

The measured axial strains of canister body are shown in Figure14. The residual compression strains of canister without impact limiter exceed -3000 μ and these results mean the plastic deformation was introduced to the canister by the drop. In contrast, no residual strain can be seen in measured strain for canister with impact limiter.

From above mentioned results, designed prototype impact limiter is very effective to reduce dropped load for canisters.

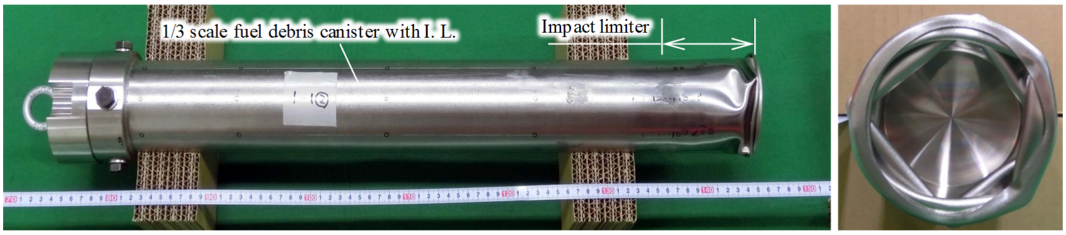


Figure 12 Deformation of impact limiter after 9m drop test.

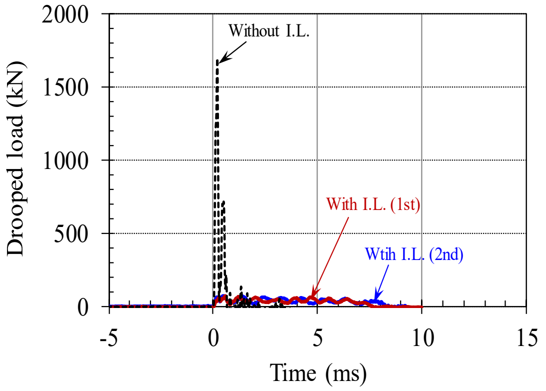


Figure 13 Time history of dropped loads.

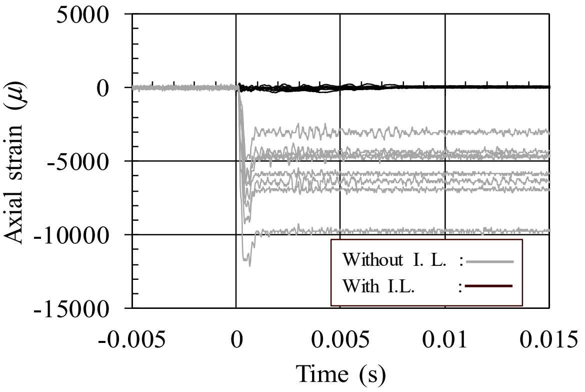
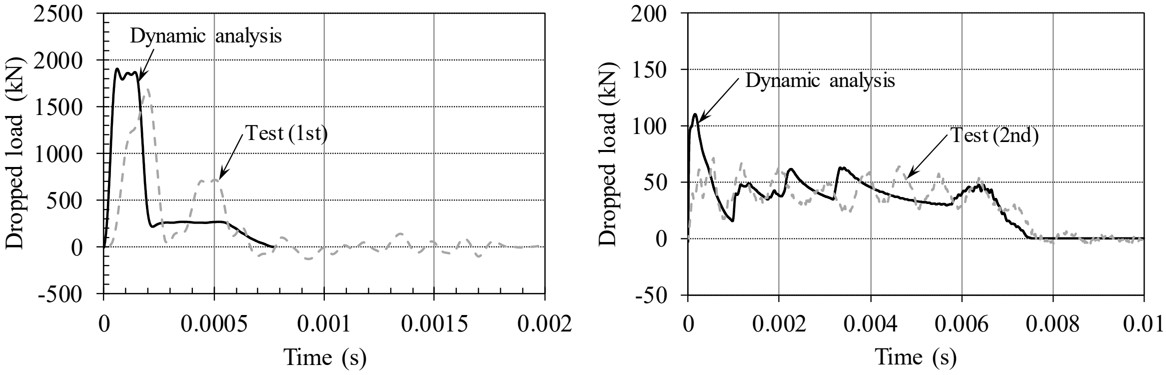


Figure 14 Axial strain of canister during drop test.

Verification Of Evaluation Methodology Using Dynamic Analysis Method

The time histories of measured and analysed dropped loads are compared in Figure 15. Regardless of presence or absence of impact limiter, simulated dropped loads by proposed dynamic analysis method agree well with test results. Measured and analysed time histories of deformation of impact limiter are compared in Figure 15. Deformation of impact limiter in the drop test are derived from analysis of high speed video. Figure 16 indicates that deformation of impact limiter can be predicted by dynamic analysis accurately. Comparison of measured and analysed deformation of inner diameter of canister is shown in Figure 11, and obviously deformation calculated by dynamic analysis almost coincide with test results.

In consequence, the validity of proposed dynamic analysis methods is verified through to the scale model drop tests, and it can be conclude that this methods can evaluate not only performance of impact limiter but also structural integrity for canister.



(a) Without impact limiter (b) With impact limiter

Figure 15 Comparison of measured and analysed dropped loads.

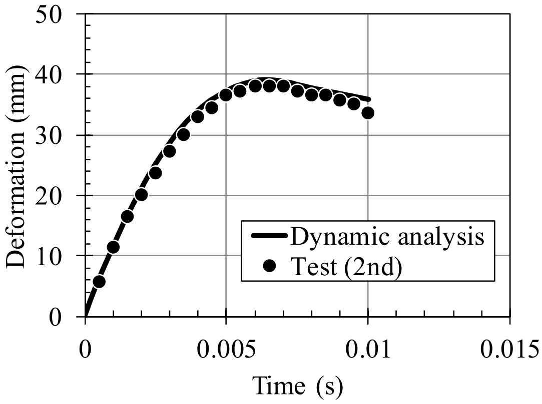


Figure 16 Measured and analysed deformation of impact limiter.

CONCLUSIONS

Elastic plastic static structural evaluation analysis methodology for dropped fuel debris canisters to be used in Fukushima Daiichi power station has been developed. The validity of the method are discussed based on 1/3 scale model drop tests, and it is found that developed method can estimate deformation of the canister safety side with appropriate margin. Also, the impact limiter which mitigates dropped loads of the canister is investigated and the performance of prototype impact limiter is examined with scale model drop tests. It is concluded that the impact limiter is very effective to reduce dropped load of the canister and design method of impact limiter using dynamic analysis code is verified.

ACKNOWLEGEMENT

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