Proceedings of the 19th International Symposium on the
Packing and Transportation of Radioactive Materials
PATRAM 2019
August 4-9, 2019, New Orleans, LA, USA

Tip-over analysis of 14OFA PWR fuel assembly

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ABSTRACT

This objective of this work was to propose a methodology for precise simulation of fuel rod behavior in 14OFA during tip-over impact situation. In order to the satisfy the objective, we tried to analyze tip-over of fuel assembly by comparing cases of spot welding and of line welding at inner connection of mid-spacer grid. The Multi Point Constraints (MPC) method was used to represent spot welding and the simulation results in ABAQUS were evaluated according to MPC options (tie and beam). Compared to the case in which connections are perfectly bonded, in the case in which spot-welding was performed at both ends of the inner connection at the mid-grid spacer, locally large deformation occurs at tip-over impact. It was found that this affected the bowing of the fuel assembly and the maximum load on the fuel rod also decreased. Based on the tip-over analysis results, we analyzed the influence of the interaction between the spacer grid and the cladding tube. The detailed analysis methodology will be used to evaluate the integrity of fuel rods when the spent nuclear fuel will be handled in future.

INTRODUCTION

As the amount of Spent Nuclear Fuel (SNF) in Korea's domestic spent fuel pool increases dramatically, the storage capability of the PWR SNF is expected to reach saturation in 2024 [1]. SNFs in the pool must be transferred to the designated wet or dry spent fuel storage facility. In the issues of the SNF treatment, handling and transport of the SNF have been considered as important factors. The integrity of SNF during dry storage should be assessed. One possible accident during SNF handling is tip-over. Many researchers have studied tip-over impact behavior of dry cask structures with different shapes and types. [2] However, analysis of the fuel assembly has not been performed considering the details of the spacer grid and the fuel rods. Detailed impact analysis considering both the spacer grid and fuel rod is mainly carried out with a part or subunit structure of the spacer grid.[3,4] An analysis method is needed to evaluate the integrity of nuclear fuel rods against tip-over impact of fuel assembly. In this paper, we construct a detailed simulation model to evaluate the tip-over impact of a fuel assembly, which may occur during handling of fuel assembly. The analytical model is based on a fresh 14OFA fuel assembly.

GEOMETRY AND MATERIAL PROPERTIES

Structural shape of 14OFA

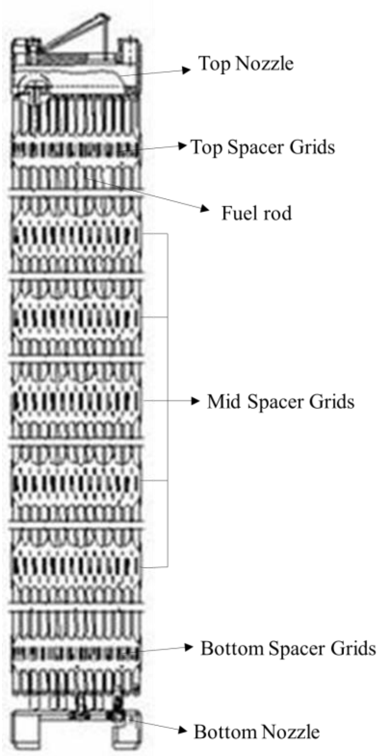


Figure 1. Geometric shape of 14OFA

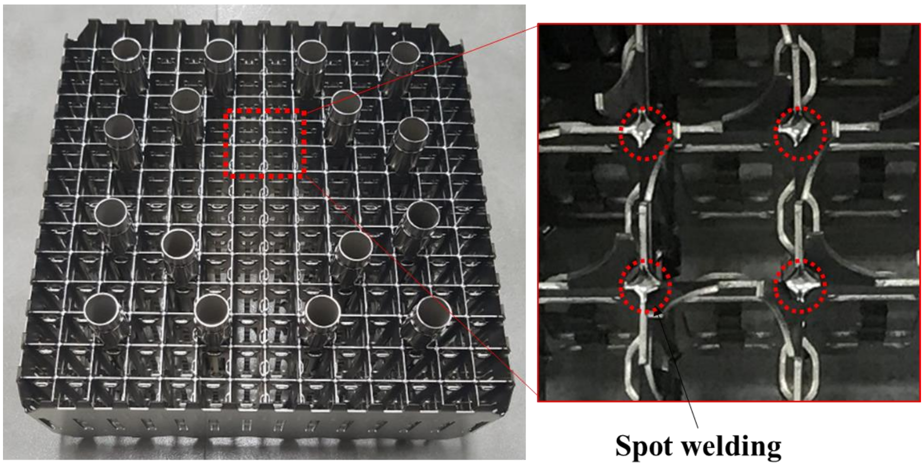


Figure 2. Spot welding of mid spacer grid

As shown in Fig. 1, 14OFA, which is composed of 14 X 14 rods is a Westinghouse type nuclear fuel assembly. The fuel assembly consists of a total of 179 fuel rods, 1 instrumentation tube, 16 guide tubes, top/bottom nozzle parts, top/bottom spacer grids, and 5 mid spacer grids. The actual fuel rods consist of cladding tubes and UO2 pellets. One major source of potential damage to the integrity of the nuclear fuel assembly is cladding deformation due to external impact. To simplify the analysis, the fuel rod was modeled only according to the shape of the cladding tube, with the weight of the cladding added to the weight of the UO2 pellets.

Spacer grids are structural components consisting of interconnected arrays of slotted grid straps; they are welded at inner connections to form an egg-crate structure. In these arrays, intersections of the top and bottom spacer grids are completely welded using the brazing method. In contrast, the mid spacer grid itself is spot welded only at the top of both ends after intersecting the slotted straps, as shown in Fig. 2. The top and bottom spacer grids can be simplified by assuming a perfect combination in modeling. However, for the mid spacer grids, the modeling shape becomes complicated. Therefore, there are some simulation cases in which, for convenience of calculation, the inner connection is completely welded.

Material properties of 14OFA

The top nozzle, bottom nozzle, and guide tubes are defined by the mechanical properties of AISI304 stainless steel. The top and bottom spacer grids are composed of Inconel 718. The remaining cladding tubes and the mid spacer grid are made of Zircaloy-4.

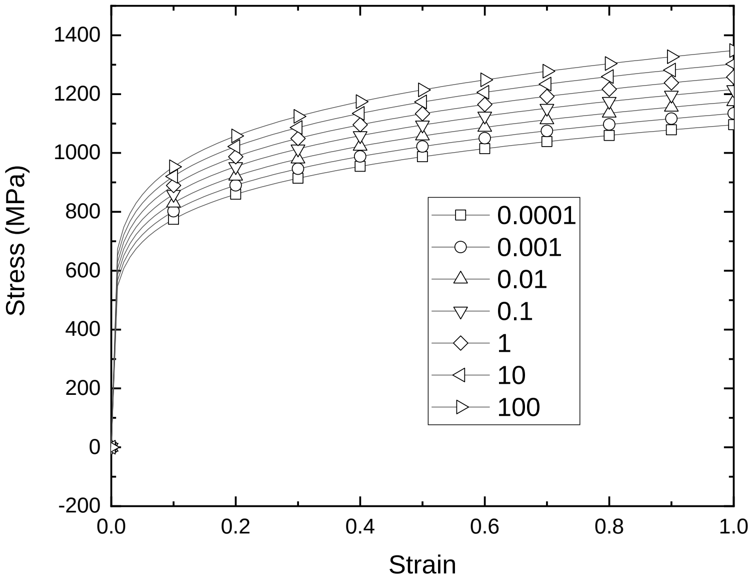


Figure 3. Properties of Zircaloy-4

The properties of zircaloy-4 were determined by the MATPRO data [5], which contain information on irradiated zircaloy material. In this paper, tip-over analysis of 14OFA was carried out at room temperature with fresh materials and without combustion. Figure 3 shows the strain-stress curves of the zircaloy-4 material, determined at room temperature. As the strain rate increases, the stress of the material increases, as with ordinary metal materials.

TIP-OVER COMPUTATIONAL MODEL

Finite element model

The analysis model consisted of 14OFA and ground as a rigid body. Gravity load is applied to the fuel assembly in order to describe the free drop during tip-over motion. Generally, explicit integration is used in tip-over analysis because it is hard to apply implicit integration schemes to the contact-impact problem due to convergence problems. The commercial code

ABAQUS/explicit was used to carry out the impact simulation. Top nozzle and bottom nozzle were designed with 3D solid elements; all other components were designed using 3D shell elements. The total number of modeled elements is 708,805, and the analysis time is analyzed for a total of 1.1 seconds considering the time of complete overturning of the fuel assembly. For the analysis, 32 cpus was analyzed for about 48 hours.

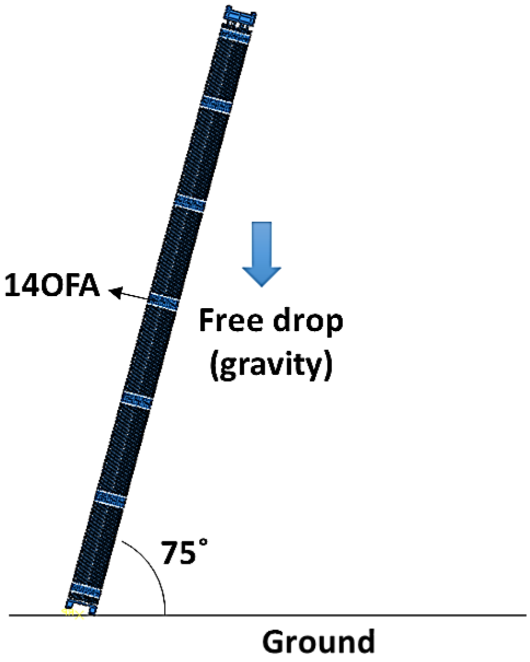


Figure 4. Simulation model and boundary conditions under free drop analysis

Modeling of spot welding in Mid-grid spacer

The Multi-Point Constraints (MPC) method is widely used for spot welding [6]. As shown in Fig. 5, the spot-welded portion at both ends of the interconnection is connected using the MPC method with a certain welding depth.

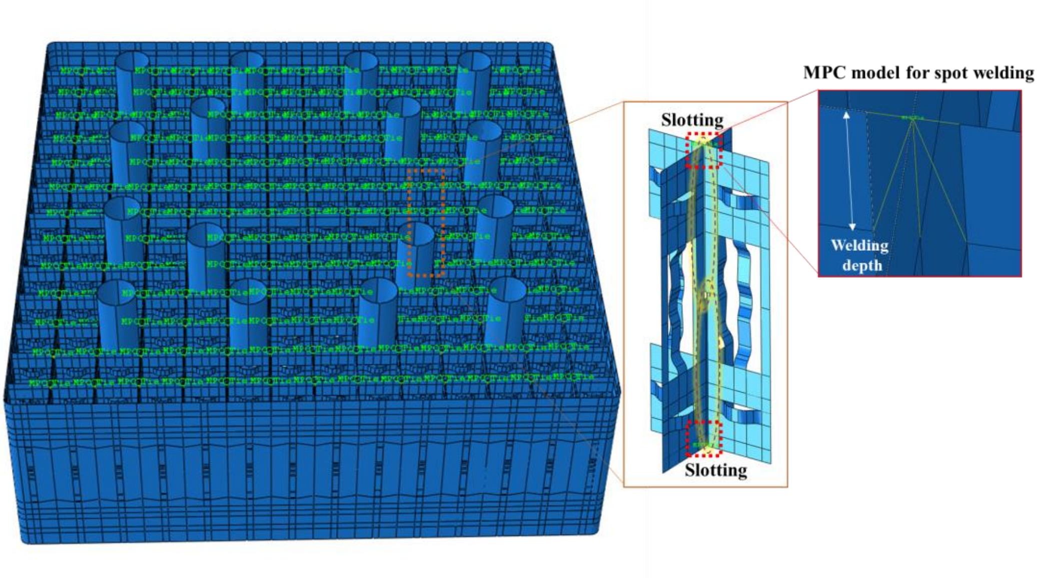
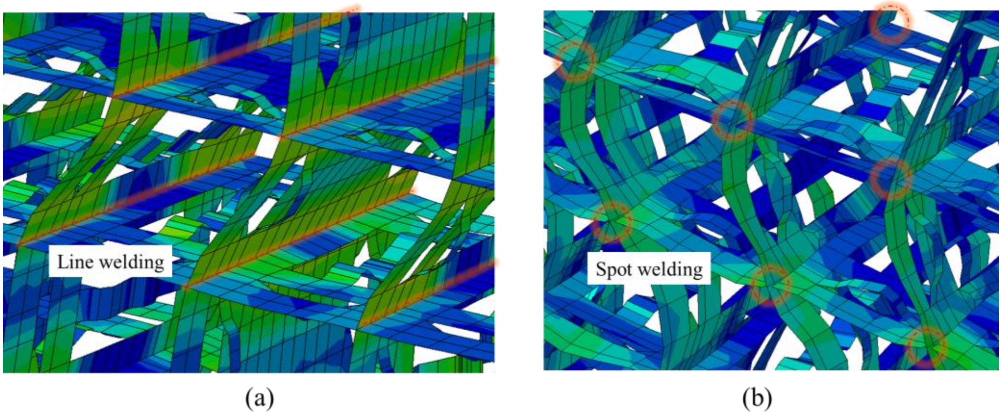


Figure 5. MPC model for spot welding in mid spacer grid

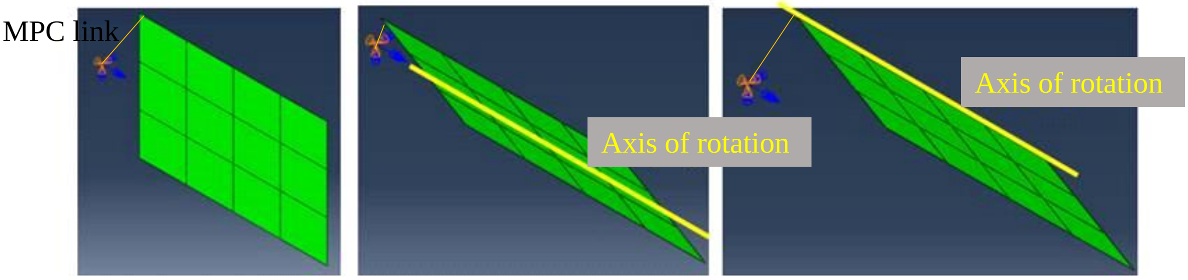
As can be seen in Fig. 6, in the case of spacer grid model with spot welding, since the load cannot be restrained except at both ends, the mid spacer grid is more deformed than the case of spacer grid model with complete bonding at the intersection line. In other words, even in the case of a fully bonded spacer grid, even if the force is less than the external impact, the structure cannot be deformed. [7] It is expected that interpretation of impact analysis assuming perfect bonding will show the results of non-conservative analysis. Therefore, tip-over modeling was carried out considering the spot welds in the mid spacer grid.



(a) (b)

Figure 6. Deformation shapes of mid spacer grid under impact: (a) bonding at intersection line, (b) MPC connection on both ends.

There are various options when applying the MPC model in ABAQUS. Among them, there are the Tie option and the Beam option that can be applied to welded parts. Figure 7 shows different motions in the rotation simulation according to each option. In the case in which the Beam option is used to connect the slave node to the master node, the shell plate rotates around the master node. In the case of the Tie option, the shell rotates around the slave node because the slave node has the same degree of freedom as the master node. [8]



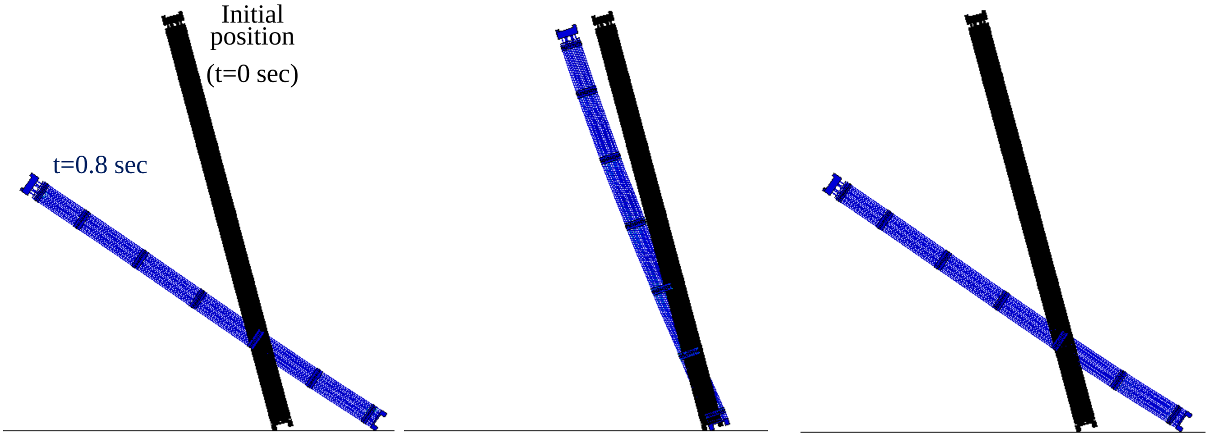
Initial shape

After Rotation
(MPC_Beam)

After Rotation
(MPC_Tie)

Figure 7. Rotational behavior according to MPC options.

Figure 8 shows how behavior in the tip-over analysis varies according to the MPC option. The results of the analysis are for a total of 0.8 seconds with the same model and condition, except for the connection model of the mid spacer grid. It can be seen that the cases of full bonding and the Beam option of MPC show the same behavior, and that when the Tie option of MPC is applied, the amount of rotation is small for the same time period.



(a) (b) (c)

Figure 8. Tip-over motion of 14OFA depending on connection of mid-spacer grid: (a) Bonding, (b) MPC (Tie option), and (c) MPC (Beam option)

In order to analyze these differences, the kinetic energy of the analytical model was examined, as shown in Fig. 9. Generally, in the case of free drop, the kinetic energy should increase to its square. In the MPC, when the Tie option is applied, the kinetic energy increases with time and then decreases. Therefore, the Beam option of MPC should be used to describe the spot weld for tip-over analysis of 14OFA.

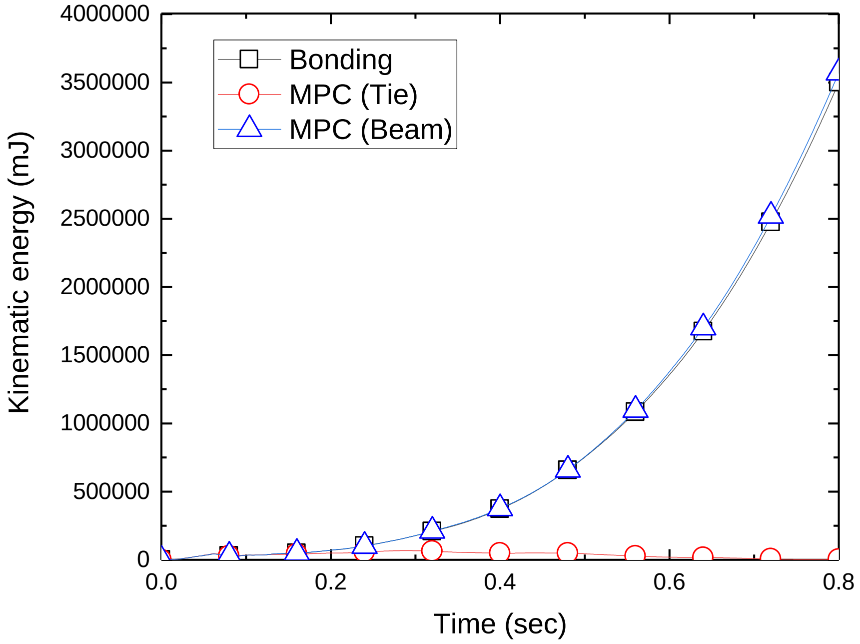


Figure 9. Kinetic energies of 14OFA during free drop

RESULTS AND DISCUSSION

As a result of the analysis of 14OFA, the maximum impact force caused by tip-over impact is shown in Fig. 10. It can be seen that the maximum impact occurs first in the case of spot welding (MPC-Beam option).

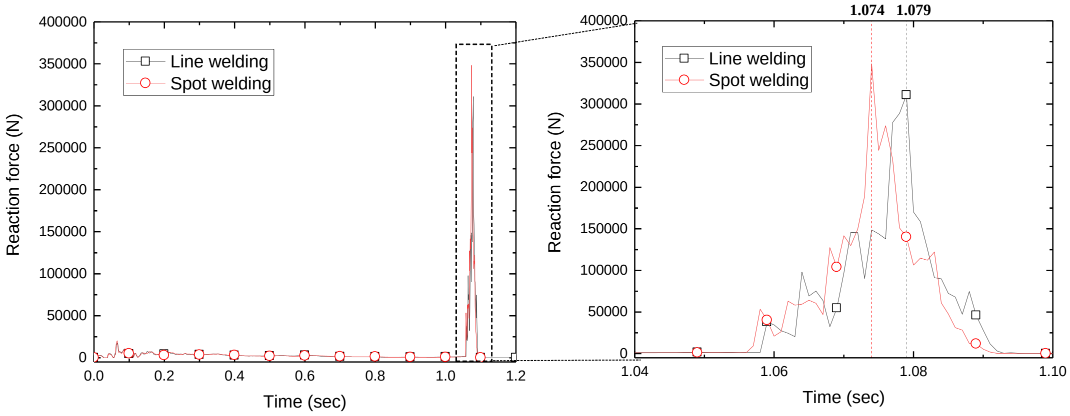
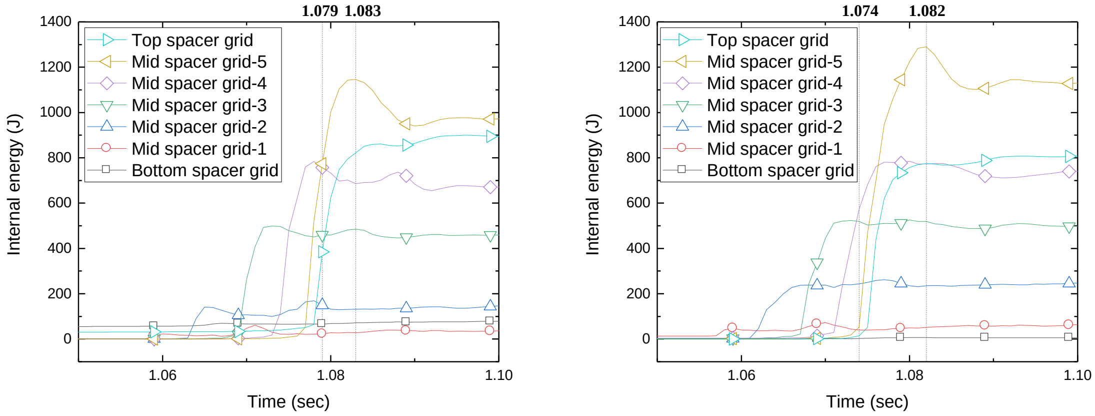


Figure 10. Reaction force against ground during tip-over simulation

The values of internal strain energy of the section where each spacer grid is located are shown in Fig. 11. It can be seen that the internal strain energy is larger in the case of the spot-welded part. It can be seen that the top structure of the mid-spacer grid has the highest strain energy. As the kinetic energy due to rotation and position increases toward the upper part of the fuel assembly, the internal energy received during impact increases. In the case of the top spacer grid, deformation is smaller than that of mid spacer grid-5 because the top spacer grid is completely bonded by brazing. For this reason, the internal strain energy of top spacer grid is smaller than that of mid spacer grid-5.



(a) (b)

Figure 11. Internal energies at spacer grid sections: (a) Line welding and (b) Spot welding (MPC-Beam option)

Figures 12 and 13 show the deformation shape of the fuel assembly and the shape of each spacer grid when the fuel assembly has its maximum reaction force and when mid spacer grid-5 has maximum internal strain energy. In the case of complete bonding, when the maximum reaction force is generated, as shown in Fig. 12, maximum deformation takes place in mid spacer grid-4. This indicates that the point where the fuel assembly first contacts the ground is the fourth spacer grid. After that, the impact force is shown to be transferred to the top of the fuel assembly.

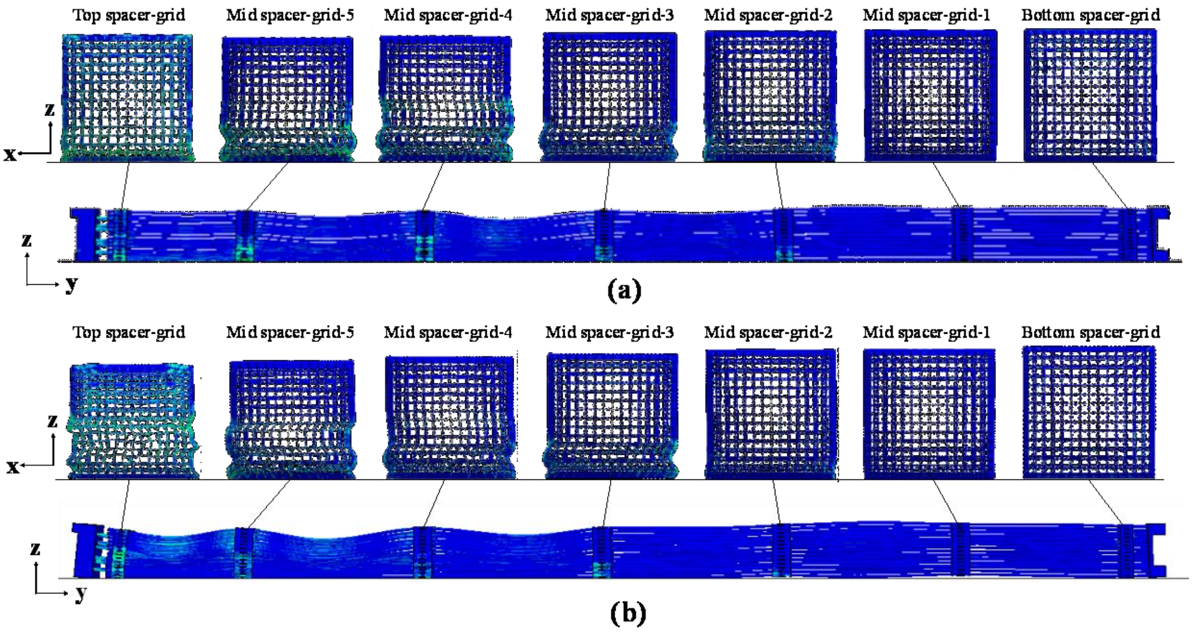


Figure 13. Deformed shapes in cases in which internal connection portions of mid spacer grids are bonded: (a) time=1.079sec (when Max. reaction force occurs) and (b) time=1.083sec (when Max. internal energy of spacer grid sections occurs)

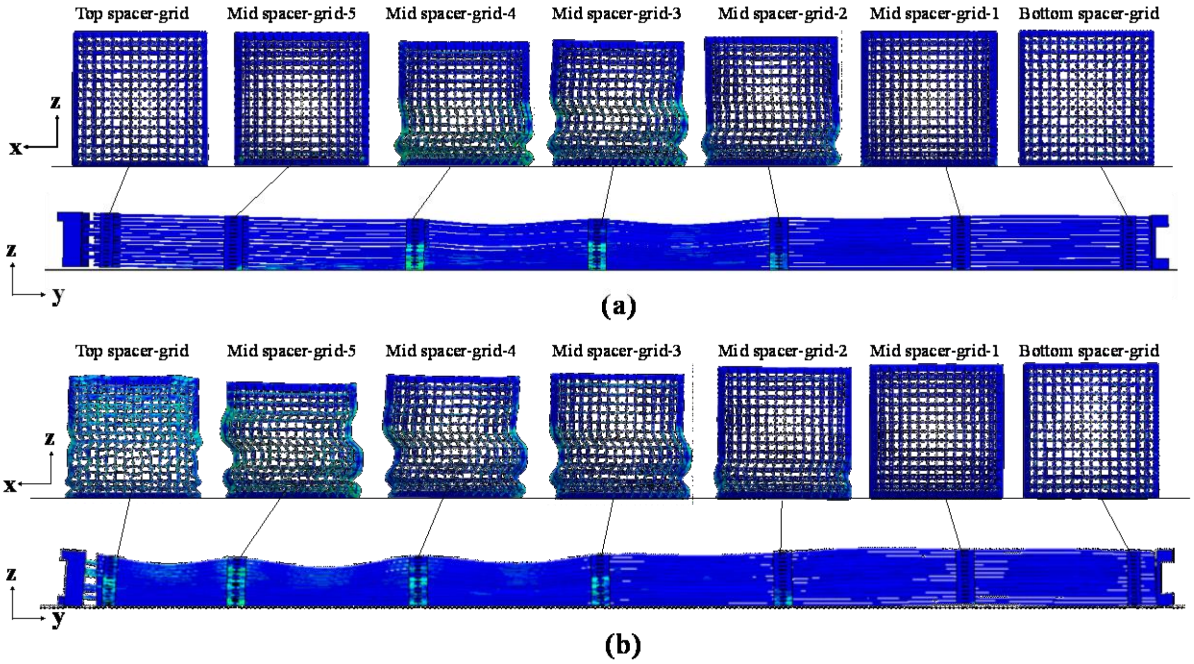


Figure 14. Deformed shapes in cases in which internal connection portion of mid spacer grids are spot-welded (MPC-Beam option): (a) time=1.074sec (when Max. reaction force occurs) and (b) time=1.082sec (when Max. internal energy of spacer grid sections occurs)

In the case of the spacer grid with spot welding, it was confirmed that the maximum reaction force occurred in the region of mid spacer grid-3, this was the primary focus of deformation because the center part of the fuel assembly is slightly bent due to its own weight and its small capacity to support the structure, as compared with the bonding condition of the mid grid spacer. Then, the impact wave progressed to the upper side. For this reason, the time interval between the maximum reaction force and the maximum strain energy becomes longer than that of line welding, as shown in Fig. 11. It can be seen in the tip-over analysis that there is a different impact tendency according to the modeling of the connection part.

Figure 11 shows the maximum contact forces generated between each cladding tube, as well as the spacer grid constructed with spot welding and line welding at the impact analysis model. The maximum value among the loads applied to eacd fuel rod is reduced because the mid spacer grid, which had been spot welded, absorbs the impact energy applied to the fuel rod by a relativelt large deformation.

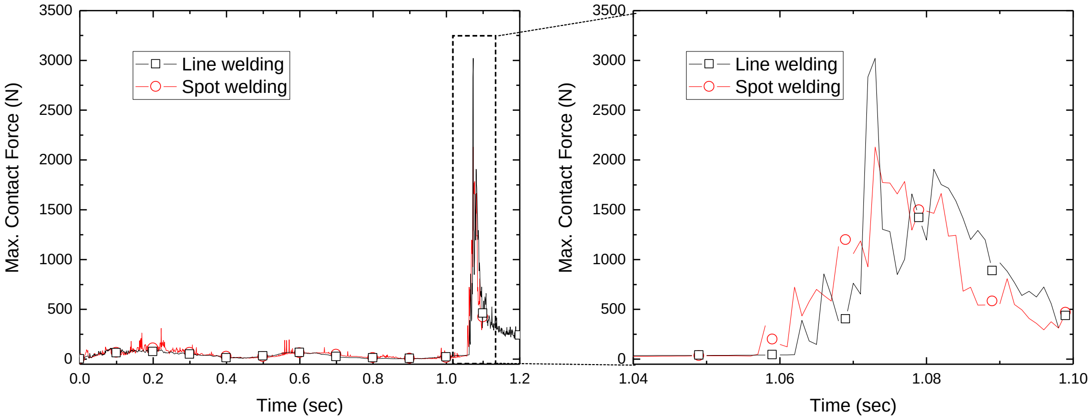


Figure 11. Max. contact force among cladding tubes

CONCLUSIONS

In this paper, we try to construct a detailed simulation model to evaluate the tip-over impact for 14OFA that may occur during handling of the fuel assembly. This paper establishes the effect of spot welding of the mid spacer grid. Results of the analysis of the bonding and actual spot welding at the inner connection of the mid spacer grid are compared. As a result of the analysis, the following conclusions are drawn.

1) A detailed analysis model was constructed to calculate the contact force applied to the cladding tube during tip-over phenomenon, which may occur when handling 14OFA.
2) In order to analyze the actual tip-over behavior, the Beam option of MPC should be applied to spot welds of mid spacer grids.
3) When rotating with free drop, the actual 14OFA with spot welding deflected to the ground first at the central part of the fuel assembly due to bowing of the fuel assembly. Then, the impact is transferred to the upper part of the fuel assembly.

The detailed analysis model will provide meaningful test conditions for a unit spacer-grid impact test, which will be carried out instead of the fuel assembly impact test. To analyze tip-over impact in the future, tip-over analysis of actual spent fuel will be attempted by applying irradiated material properties and deformed shapes that occur due to actual combustion effects. We will evaluate the integrity of the fuel rod by the external impact force during handling of fuel assembly by using the failure criteria according to the burn-up history and try to quantitatively calculate the number of nuclear fuel rods that are destroyed by accidents that occur during handling of fuel assembly. We can use the detailed tip-over impact analysis model as verification data for a simplified analysis model that will be developed in the future to improve calculation capability.

ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 2014171020166A).

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