Preliminary Studies on Vibration Characteristics of Nuclear Power Plant Crashed by Large Civil Aircraft

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SUMMARY:
In 2009, the US Government specified that an obligatory safety evaluation on the aircraft impact shall be carried out for NPP structures to be constructed in the future. The vibrations induced by the external aircraft crash are different from that induced by earthquake event. The external force, representative of the aircraft impact loading, namely impact load-time history is very short time event compared to the earthquake forces. The former is about 0.5 seconds event, while the latter is 20 seconds to 30 seconds event. The frequency contents of the vibration induced by earthquake are mainly 30 Hz below, while the frequency contents of the vibration induced by aircraft crashes are dominant in much higher frequency range. The authors present some vibration characteristics of nuclear power plant crashed by large civil aircraft. Typical nuclear power plant is simplified for the purpose of identifying what factors are resulting in the differences.

Keywords: nuclear power plant, aircraft crash, impact load-time history, impact vibration

1. INTRODUCTION

In this study, nonlinear dynamic analyses on a typical nuclear power plant against large civil aircraft crashes have been performed to figure out the effects of impact vibrations transmitted from the outer reactor containment building to the internal structure. Previous studies show that the main factors affecting the vibration characteristics are such as the surrounding soil stiffness, the foundation geometry and embedment, the mesh sizes and the local nonlinearities, the damping characteristics and also the impact load-time histories. As a preliminary study, numerical analyses with the parameters such as the surrounding soil stuffiness, impact locations and 5% of critical damping ratio have been conducted by using general purpose finite element analysis program. The responses such as the time histories of accelerations and displacements have been computed at the several points and levels on the NPP and the frequency characteristics on these responses have been understood by using the response spectrum.

2. OVERVIEW OF ANALYSIS MODEL

2.1. FE Model of Internal Concrete Structure and Outer Reactor Containment Building

A typical nuclear power plant shown in Fig. 2.1 has been chosen for this study. The interior structure has 4 floors including the base floor above the liner plate on the base slab of reactor containment building. It accommodates the reactor vessel in the central region and other facilities. The first floor (level 3) is supported by wall but the second floor (level 5) and third floor (level 6) are suspended on the thick wall of the shield structure. There are 50mm gap between the internal structure and the reactor containment building. At the third floor the gap is enlarged by 200mm and there void spaces would be filled with non-structural member. The half configuration view of the internal concrete structure is shown in Fig. 2.2.

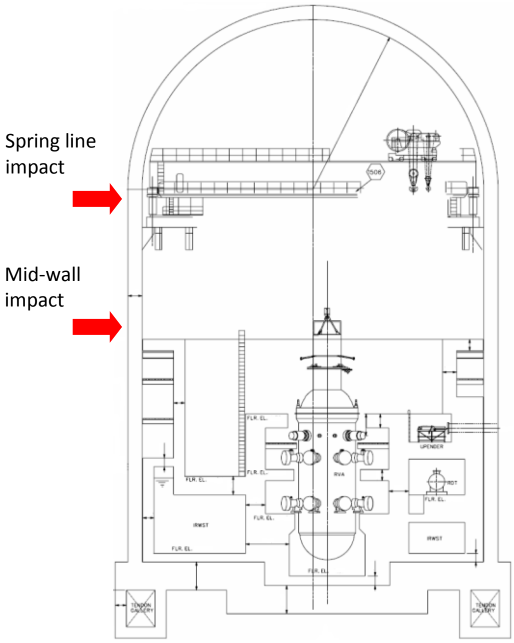


Figure 2.1. Sectional view of reactor containment building

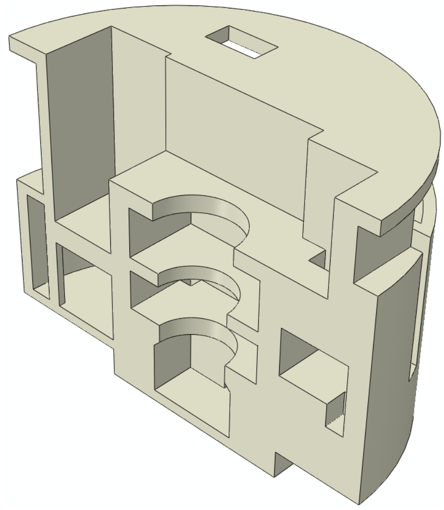


Figure 2.2. Internal concrete structure model

The outer reactor containment building and the internal concrete structure have been modelled as solid elements. The liner plate on the interior of the reactor containment building is modelled as shell elements. The rebar and tendon also have been modelled by using embedded truss elements. Fig. 2.3 shows the finite elements of the reactor containment building, some reinforcement bars on equipment hatch and personnel airlock part, tendons and the internal concrete structures.

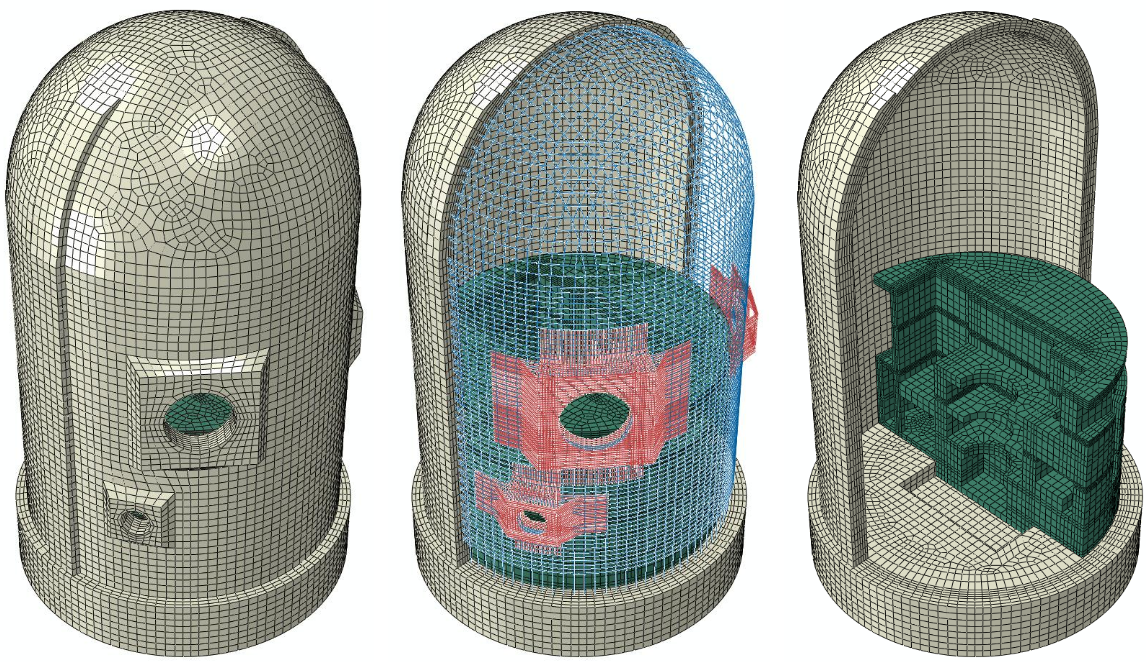


Figure 2.3. Finite element model of internal concrete structure and reactor containment building

2.2. Numerical Analysis Cases

The impact load-time history presented by Takeuchi(2007) is used for this study. The impact area is assumed to be approximately 41.7m^2 and the impact loads are applied to the spring line and the middle wall of the reactor containment building as shown in Fig. 2.1. Table 2.1 summarized the factors used for the numerical analyses. The aircraft impact locations on spring-line and middle wall were selected to evaluate the global behaviours of the outer reactor containment building but also to investigate the potential pounding between outer reactor containment building and internal concrete structure. To evaluate the damping effect, the responses of 5% damping systems have been computed and compared to those of the undamped systems. To investigate the supporting soil condition effects, shear wave velocities of the soil medium are assumed to be 500, 1000, 1500 and 2000m/sec respectively, which the soil spring stiffness are corresponding to 1, 4, 9 and 16 times to that of soil medium with shear wave velocity of 500m/sec. According to the ASCE 4-98 procedure, the equivalent soil spring stiffness constants are calculated. Basically 4 layers are used in walls and slabs of the concrete structures to accommodate the accurate flexural deformation of the wall and slabs.

Table 2.1. Parameters for numerical analyses

Factors	Cases	Remarks
Impact location	2	Spring-line or wall middle shown in Fig. 2.1
Damping ratio	2	0% or 5%
Soil conditions	5	Shear wave velocities 500,1000,1500,2000m/s and infinite
No of layers in wall and slab	1	1 - 4 layers

3. FREQUENCY ANALYSIS RESULTS

To understand the dynamic behaviour characteristics of the coupled system, i.e., reactor containment building-internal concrete structure-soil medium, the frequency analyses have been performed. Table 3.1 summarized the fundamental frequencies of the each coupled system. Some fundamental mode shapes are shown in Fig. 3.1 to Fig. 3.3. For fixed base model of which the shear wave velocity is infinite, the 1st and 2nd modes are x-directional and z-directional horizontal sway modes respectively. The 3rd and 4th modes represent that third (level 6) floor suspended on thick wall of the shield structure of internal concrete structure acts like cantilever. For shear wave velocity 500m/s, the 1st to 4th modes represent almost rigid body motions of 2 horizontal rocking, vertical and torsional motions of rigid body. And the 7th and 8th modes are corresponding to those of 3rd and 4th modes of fixed base model. For shear wave velocity 1,000 m/s, the 3rd mode shown in Fig. 3.3 is horizontal-rocking mode and the 4th mode is fully coupled modes of outer reactor building and internal structure. The 6th and 8th modes for this system is correspond to those of 3rd and 4th modes of fixed base model.

Table 3.1. Fundamental frequencies for each coupled systems (unit: Hz)

Modes	Shear wave velocity				Fixed base Model
	500m/s	1,000m/s	1,500m/s	2,000m/s	
1	1.4621	2.5188	3.1290	3.4589	4.0341
2	1.4632	2.5235	3.1397	3.4749	4.0640
3	2.3130	4.4327	6.0826	6.3567	6.3962
4	3.6534	5.8414	6.5004	6.9412	7.0519
5	3.6592	5.8532	6.9518	7.3458	7.3515
6	4.2834	6.4321	7.0153	7.4396	7.4406
7	6.3974	6.7890	7.2536	7.6588	7.7178
8	7.0686	7.1098	7.3546	7.6952	7.8180
9	7.3554	7.3603	7.4389	7.7237	8.8340
10	7.4408	7.4427	7.7178	7.8325	8.8838

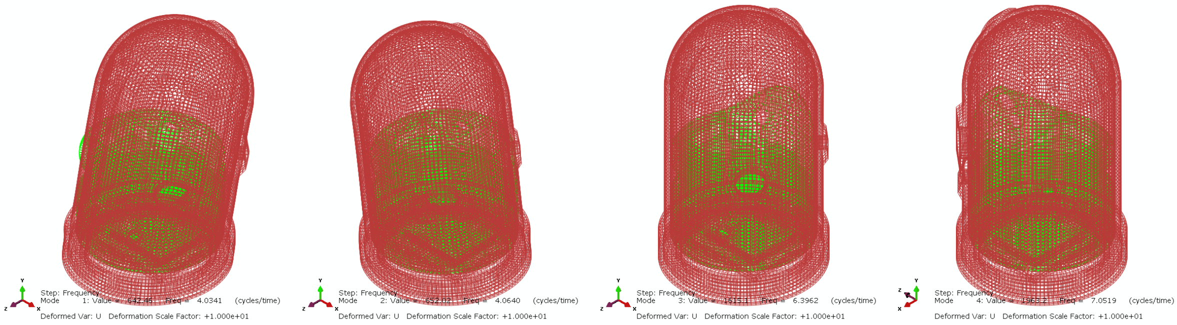


Figure 3.1. Mode shapes for fixed base model (1,2,3 and 4-th modes)

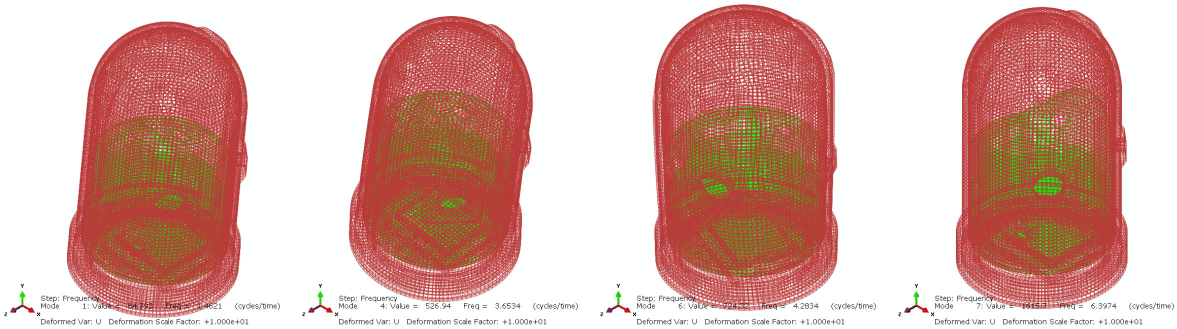


Figure 3.2. Mode shapes for shear wave velocity, Vs=500m/s (1,4,6 and 7-th modes)

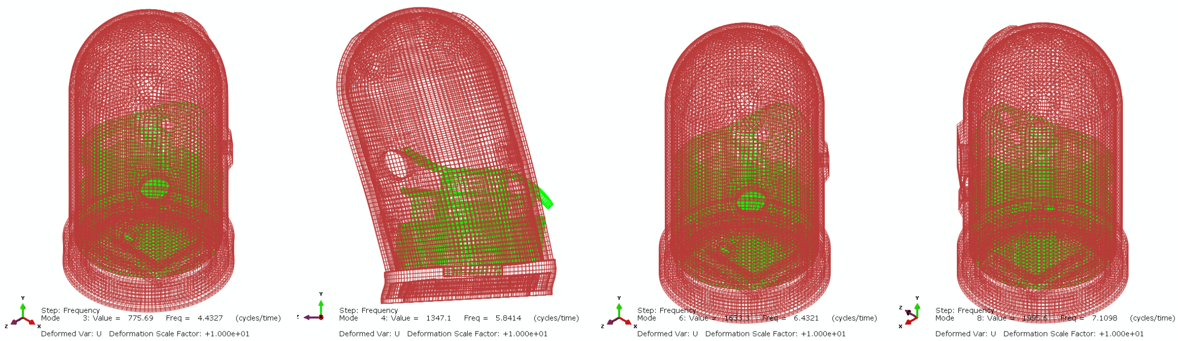


Figure 3.3. Mode shapes for shear wave velocity, Vs=1,000m/s (3,4,6 and 8-th modes)

4. RESPONSES OF NPP DUE TO AIRCRAFT IMPACT LOAD

4.1. Locations on Time History Outputs

Time history responses of total 35 points located in the reactor containment building and each floor in the internal concrete structure have been presented as shown in Fig. 4.1. The 5 points for outer reactor containment building are located on spring-lines, middle walls for both impact and opposite sides and top of the dome. Twelve points for each floor in the internal concrete structure also are located at the closest points to outer wall in impact and opposite sides as shown in Fig 4.1. Two or four points for each floor are located to measure the vibration responses of floor slab or internal wall.

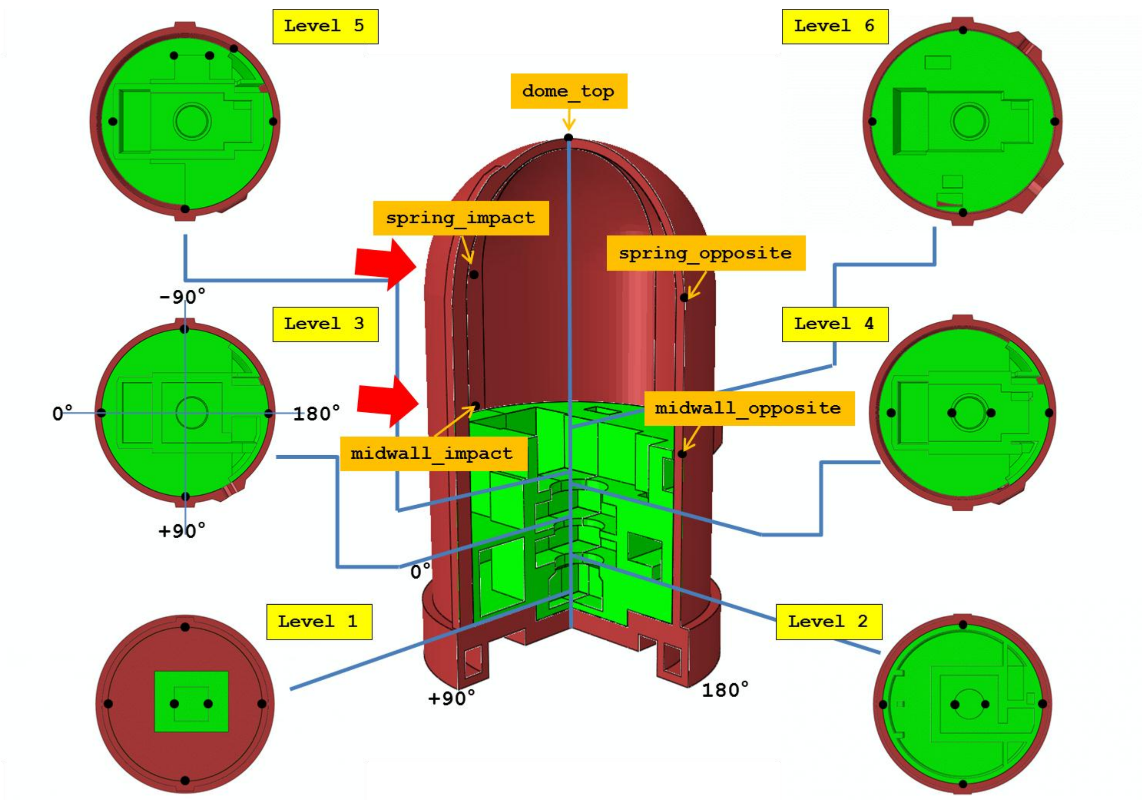
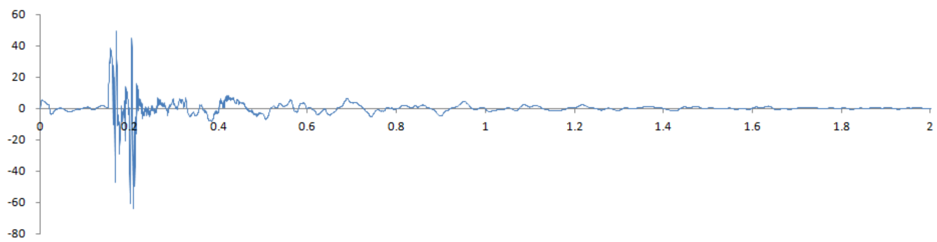


Figure 4.1. Time history output point locations and angles to impact point

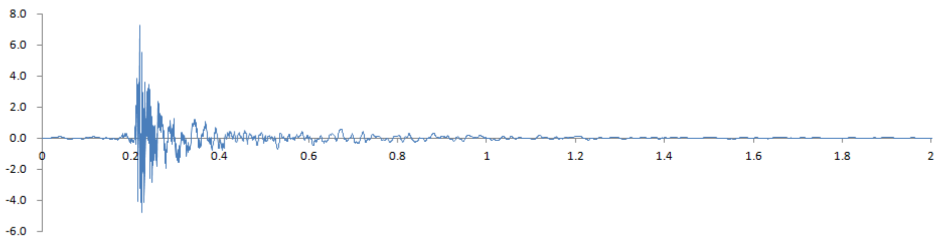
4.2. Analysis Results

4.2.1. Maximum accelerations

Table 4.1 summarized maximum acceleration responses at 5 points on reactor containment building in the cases of five soil conditions, i.e., shear wave velocities with 500m/s to infinite with damping ratio 5% and 0%, respectively, in each impact point cases. As shown in the tables, the levels of acceleration response at the output nodal points closest to the impact points are the highest, i.e. 30~100g. In the case of mid-wall impact, where the contact between the internal concrete structure and the reactor containment building occurred, while very high accelerations (1,000~1,500g), which may be numerically insignificant, were calculated, the displacements were not excessive.



(a) Wall middle



(b) Internal concrete structure (level 3)

Figure 4.2. Accelertaion time histories (A1, mid-wall impact, 5% damping, unit:g)

Fig. 4.2 shows acceleration time histories of a point on mid wall (midwall_impact) and a point on level 3 of internal concrete structure for the case of fixed base model.

Table 4.1. Maximum accelerations (A1, x-direction) of reactor containment building (unit: g)

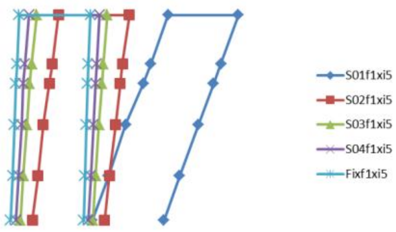
Location	Cases	Damping (%)	Shear wave velocities				Fixed base model
			500m/s	1,000m/s	1,500m/s	2,000m/s	
spring-line_ impact	Spring line impact	0	-40.18	-37.90	-38.10	-36.73	-35.95
		5	-38.59	-36.98	-42.30	-39.65	-36.57
	Mid-wall impact	0	-18.84	-18.74	-19.32	-19.80	-18.62
		5	-19.46	-18.93	-19.60	-19.77	-17.97
spring-line_ opposite	Spring line impact	0	-11.58	-12.87	-12.94	-13.19	-15.85
		5	-11.42	-11.36	-11.57	-11.99	-12.98
	Mid-wall impact	0	-9.38	-9.99	-9.87	-9.98	-8.71
		5	-8.12	-8.48	-8.54	-8.64	-7.88
midwall_ impact	Spring line impact	0	-23.30	-23.41	-23.98	-24.61	-23.79
		5	-22.52	-23.71	-22.44	-24.61	-22.54
	Mid-wall impact	0	-96.44	-102.87	-92.27	-101.54	-92.87
		5	-93.26	-91.20	-87.98	-93.42	-83.56
midwall_ opposite	Spring line impact	0	-15.48	-15.50	-15.23	-15.51	-16.48
		5	-14.13	-14.68	-14.27	-14.38	-15.03
	Mid-wall impact	0	-11.27	-10.71	-10.82	-10.56	-11.26
		5	-11.46	-10.98	-11.09	-11.51	-11.15
dome_top	Spring line impact	0	4.07	-4.24	4.03	4.00	-4.20
		5	3.93	-4.09	-4.32	-3.94	4.15
	Mid-wall impact	0	-4.34	-3.91	-3.93	-4.46	-4.56
		5	3.92	3.61	-3.76	-3.76	-4.48

Table 4.2. Maximum displacement (D1, x-direction) of reactor containment building (unit: mm)

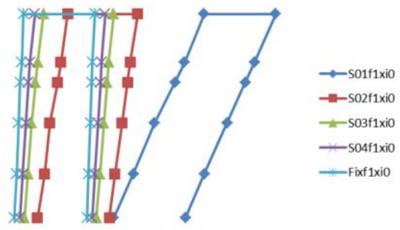
Location	Cases	Damping (%)	Shear wave velocities				Fixed base model
			500m/s	1,000m/s	1,500m/s	2,000m/s	
spring-line_ impact	Spring line impact	0	166.6	129.2	122.7	119.3	114.6
		5	147.7	123.6	118.2	115.3	111.3
	Mid-wall impact	0	117.1	72.5	66.3	63.7	60.7
		5	99.5	66.9	61.8	59.7	57.0
spring-line_ opposite	Spring line impact	0	96.2	49.7	37.9	33.5	29.2
		5	79.8	44.7	35.4	31.6	27.7
	Mid-wall impact	0	79.9	45.3	38.1	35.5	34.3
		5	66.0	40.7	34.8	32.6	30.5
midwall_ impact	Spring line impact	0	106.9	81.2	75.1	72.5	69.9
		5	91.1	75.1	70.0	67.8	65.5
	Mid-wall impact	0	178.3	164.4	160.2	158.2	155.5
		5	162.5	157.0	153.5	151.7	149.6
midwall_ opposite	Spring line impact	0	72.0	41.1	33.5	30.9	28.4
		5	55.5	37.5	31.1	28.7	26.3
	Mid-wall impact	0	63.1	37.4	31.3	32.0	32.1
		5	48.7	30.9	26.5	25.4	25.6
dome_top	Spring line impact	0	121.0	66.1	50.3	44.3	38.4
		5	100.6	59.5	46.7	41.7	36.3
	Mid-wall impact	0	109.4	62.9	49.3	44.9	44.2
		5	90.9	56.2	44.9	40.9	39.8

4.2.2. Maximum displacements

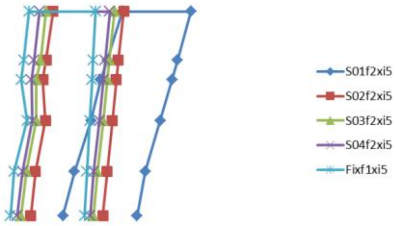
Table 4.2 summarized maximum displacements at 5 points on reactor containment building in the cases of five soil conditions, i.e., shear wave velocities with 500m/s to infinite with damping ratio 5% and 0%, respectively, in each impact point cases. In the cases where damping was ignored, as the response continued vibrating, the permanent displacements were computed only in the cases of 5% damping ratio. As shown in the tables, the maximum displacement occurred with level of 100~150mm locally at the output nodal points closest to the impact points. On the whole, however, the maximum displacements of reactor containment building were 20~50mm, and internal concrete structure 2~8mm for fixed base model. Fig. 4.3 and Fig. 4.4 show that the maximum displacements and accelerations of each floor in internal concrete structure in the cases of five soil conditions, i.e., shear wave velocities with 500m/s to infinite with damping ratio 5% and 0%, respectively. The points in the figures represent the nearest point to the impact side and the opposite side of impact.



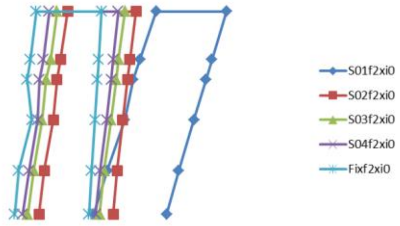
(a) Spring-line impact (5% damping)



(b) Spring-line impact (no damping)

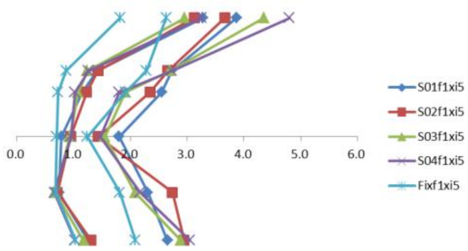


(c) Mid-wall impact (5% damping)

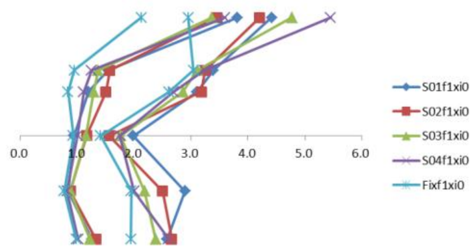


(d) Mid-wall impact (no damping)

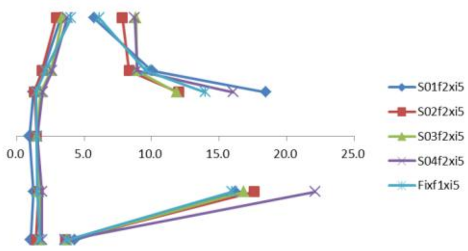
Figure 4.3. Graphical representative of displacements of each level in internal concrete structure



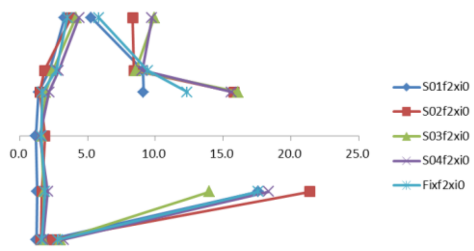
(a) Spring-line impact (5% damping)



(b) Spring-line impact (no damping)



(c) Mid-wall impact (5% damping)



(d) Mid-wall impact (no damping)

Figure 4.4. Graphical representative of acclerations of each level in internal concrete structure

4.2.3. Three-dimensional responses

In contrast to lateral loads such as seismic activity, the responses at each vertical level of internal concrete structure are three-dimensional. It means that, although the direction of lateral load x is main direction of the response, the accelerations, velocities and displacements of the orthogonal directions y and z are not negligible as shown in Fig. 4.5 and Fig. 4.6. Therefore, for the aircraft impact assessment on inner components, it is necessary to use three-dimensional model containing details.

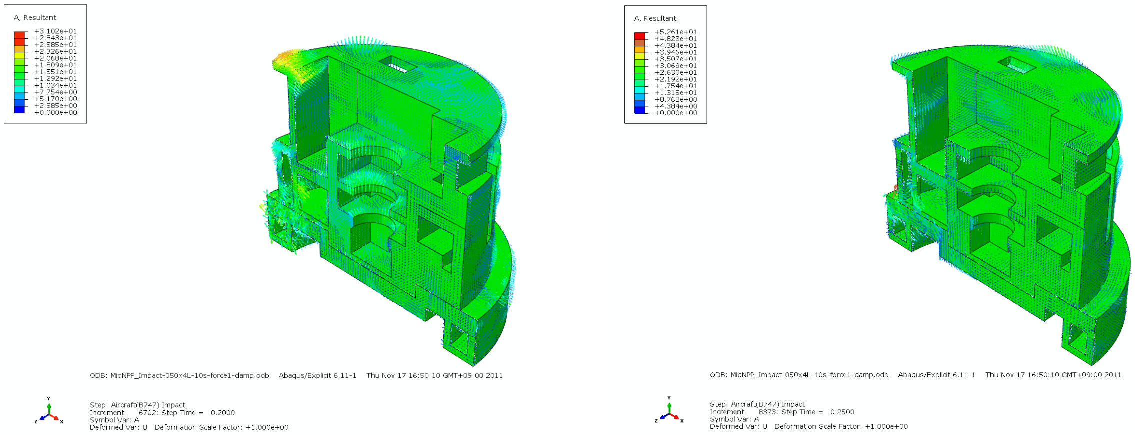


Figure 4.5. Acceleration vector (spring-line impact, 5% damping, 0.2 and 0.25s)

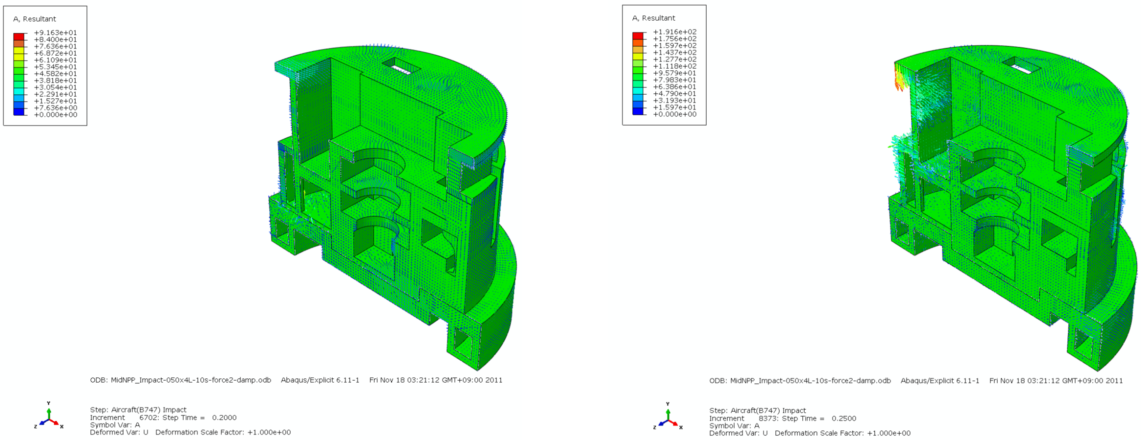
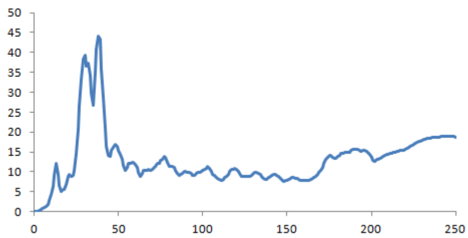


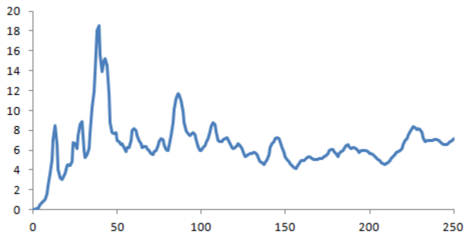
Figure 4.6. Acceleration vector (mid-wall impact, 5% damping, 0.2 and 0.25s)

4.2.4. Response spectrum

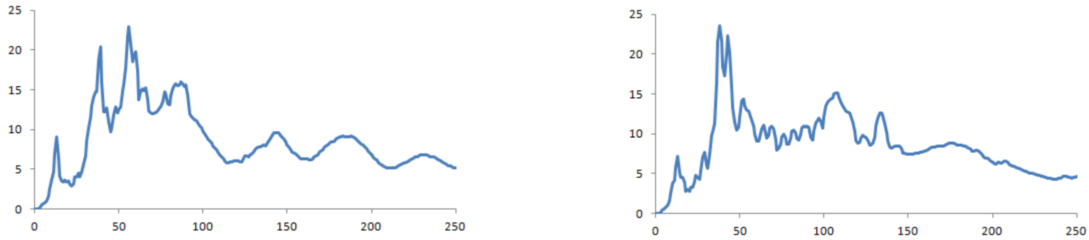
Fig. 4.7 shows acceleration response spectrum of typical case of damping 2%. Contrary to earthquake response, high frequency response component is dominant. A general tendency for the response spectrum is that in the response at 0° which is close to the impact point is dominated by 50Hz component, and at 180°, the opposite side of impact point, 100Hz component is also dominant. In the response spectrum at the ±90° with the impact point side, the two frequencies, i.e. 50Hz and 100Hz, simultaneously appeared. When acceleration response is extremely large, such as at the point where aircraft impact or contact between outer reactor containment building and internal structure occurred, it is difficult to find dominant frequency components of the response spectrum.



(a) 0°



(c) -90°



(b) 180° (d) 90°

Figure 4.7. Acceleration response spectrum at nodal points of internal concrete strcture (2% damping, level 6, mid-wall impact)

5. RESPONSE CHARACTERISTRICS OF NPP DUE TO AIRCRAFT IMPACT LOAD

5.1. Spring-line Impact Case

The impulses induced by aircraft impact load to the outer nuclear reactor containment building are transmitted to the internal structure through the exterior wall and the base slab. In the internal structure, the magnitudes of acceleration responses on the side close to impact sides are 1.35 to 2.6 times higher than those on side close to the opposite sides. The locations at ±90° to impact sides are alike or higher than those on side close to the opposite sides. And it is advisable that the safety examinations on the interior facilities due to aircraft crashes must be evaluated by 3 dimensional model including details. The maximum displacement responses of internal concrete structures are about 2mm in average sense. As the elevation level goes higher, the averaged displacement responses increases from 1.4 to 3.7mm. The permanent displacements of internal structures are generally 1mm. The permanent displacement is not due to the damage of internal structure, but due to the damages on base slab connected to the wall of the outer reactor containment building.

5.2. Mid-wall Impact Case

This case has the same transmitting path of the spring-line impact case. However, as physical contacts between the external wall and the internal structure occurs at time 0.2 to 0.25s after impact, there is much differences in acceleration responses compared to those of the spring-line impact case. Although the acceleration responses at the contact point or the same level are pretty much high value (1,500g or 1,000g), the absolute values of displacement is not high. The responses of same floor with same level show that the contact or impact between the external structure and internal structure is affecting on only the localized responses. And some damages are occurred at the region which the external structure and the internal structure contact.

5.3. Response Spectrum

From the results of response spectrum with 2% damping, high frequency responses, not expected in earthquake responses, above 50Hz arise. The general tendency show that the frequency contents on the impact sides are mainly 50Hz around while the frequency contents on the impact-opposite sides are mainly 100Hz around. The frequency contents on the locations at ±90° to impact sides show that two dominant frequencies of 50Hz and 100Hz exist. It is difficult to find the dominant frequencies on acceleration response spectrum in the aircraft impact regions or the contact region between the outer reactor containment building and the internal concrete structure because the computed accelerations are very high.

5.4. Damping Effects

Form the results of responses time histories of acceleration, velocity and displacement, the most responses will be reduced to zero four seconds after the aircraft impact in the case of considering 5%

critical damping. The effects of 5% critical damping in reactor containment building reduce the maximum responses to the level of 93~95%, while the effect of 5% critical damping in internal concrete structures reduce to the level of 75~80%. The effects of damping according to the elevation levels in internal structure are much higher.

6. CONCLUSIONS

Nonlinear dynamic analyses on a typical nuclear power plant against large civil aircraft crashes have been performed by using general purpose finite element analysis program. The responses such as the time histories of accelerations and displacements have been presented at the several points and levels on the NPP and the frequency characteristics on these responses have been studied by using the response spectrum.

Further studies will be required to evaluate the representative response spectrum of one elevation level which shows different response spectrum, also couple in each direction, from location to location at the same level. Also Proposal of cut-off frequency or high-frequency filtering methods also needs to be discussed. These would be closely related to the inherent safety evaluation of equipment, and should be presented as limitations on frequency ranges according to the safety evaluation methods considering the equipment properties.

It is needed to think considerably the effect of surrounding soil medium in the evaluation on vibration induced by aircraft impact.

Important equipment such as reactor vessel, steam generators and pressurizers may be considered in the safety evaluation of inner equipment. The internal pipelines passing through the walls on internal or the outer structures also need to be evaluated. The polar crane would fall down due to excessive displacement resulting from aircraft impact. It can be said that this preliminary study is available for the evaluation of these situations.

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