Seismic Analysis and Design of a Scaled Nuclear Fuel Assembly

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Objective of This Research

The main objective of this research is to design, analyze, and validate a scaled structure that is able to mimic the highly complex response of a full-scale nuclear fuel assembly during moderate to severe ground shakings. The first phase of the research, that is presented here, aims at:

1- Finding the relationship between the predominant periods of the scaled structure and the prototype fuel assembly.

2- Estimating the damping caused by the highly complex interaction between fuel rods and the surrounding fluid.

3- Designing a bracing structure that mimics the rigid nature of the container in the prototype fuel assembly.

4- Developing an accurate and efficient modeling approach to capture the salient features of the seismic response of this system considering the three-dimensional nature of the fuel assembly and the large number of details in such complex structure.

Background and Motivation

The catastrophic failure of Fukushima nuclear power plant due to the Tohoku Earthquake and Tsunami in 2011 and the subsequent release of substantial amounts of radioactive materials led to a world-wide awakening regarding the design and operation of nuclear power plants. Development of validated analysis methods that can be used to predict the seismic response of nuclear power plants is an important step toward preventing future catastrophic events.

Method and Approach

A scaled nuclear fuel assembly along with its bracing structure is designed and analyzed under seismic loading conditions. The design of the test section was assisted by a series of three – dimensional finite element analyses that considered various details of the complex structural system. The main variables of the analysis are ground motion characteristics, material used for the fuel rods, arrangement of spacer grids to hold the bundle of fuel rods and the method of modeling the bracing structure.

Fuel Rods Characteristics

Acrylic was selected as a surrogate for the fuel rod material. Tables 1 and 2 show the properties of acrylic rods and the real fuel rods (Zircaloy tubes containing Uranium), respectively.

Table 1. Material properties of Acrylic.

Acrylic		
Material Properties	Modulus of Elasticity (Pa)	3.30E+09
	Poisson's Ratio	0.4
	Density (kg/m^3)	1190
Geometry	Diameter (m)	0.01425
	Length (m)	4
	Distance between Rod Centers (m)	0.019

Table 2. Material properties of Zircaloy and Uranium dioxide.

Zircaloy and Uranium Dioxide			
Material Properties	Zircaloy	Modulus of Elasticity (Pa)	9.72E+09
		Poisson's Ratio	0.35
		Density (kg/m^3)	6570
	UO2	Density (kg/m^3)	10970
Geometry	Zircaloy	Tube OD (m)	0.0095
		Tube ID (m)	0.0082
		Distance between tube Centers (m)	0.0126

Fuel Assembly

The bracing structure is made of steel. The total height of the entire fuel assembly structure is 6.24 m, and fuel rods are 4.00 m long. Figures 1(a) and 1(b) show a real fuel assembly and a 3D rendering of the fuel assembly structure. Details of the spacer grids along the height of the fuel rods are shown in Figure 2.

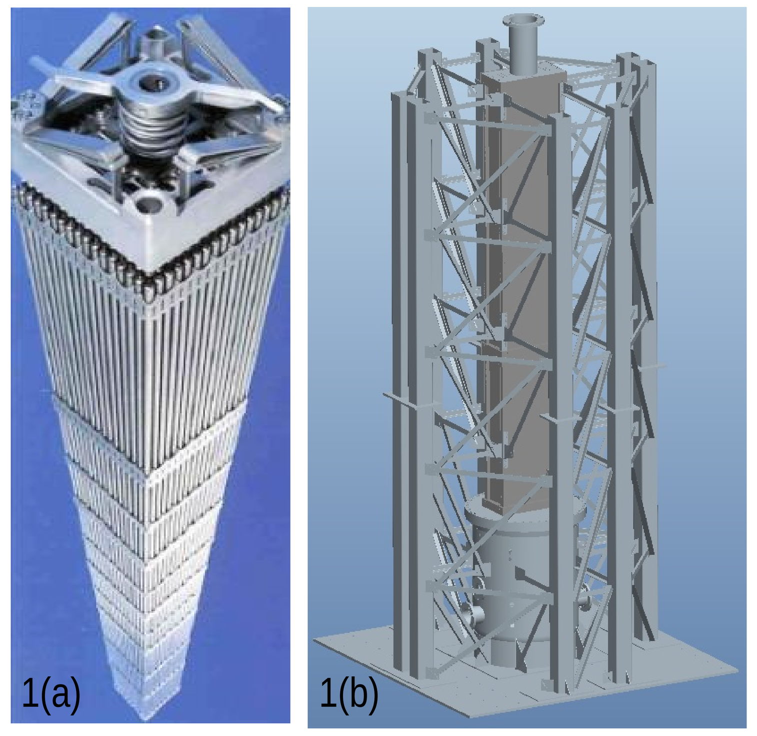


Figure 1. Fuel assembly.

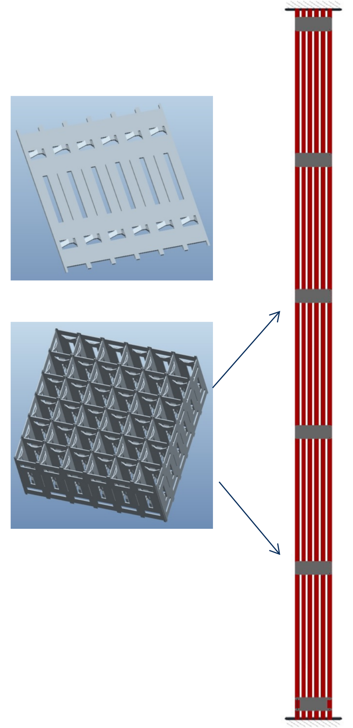
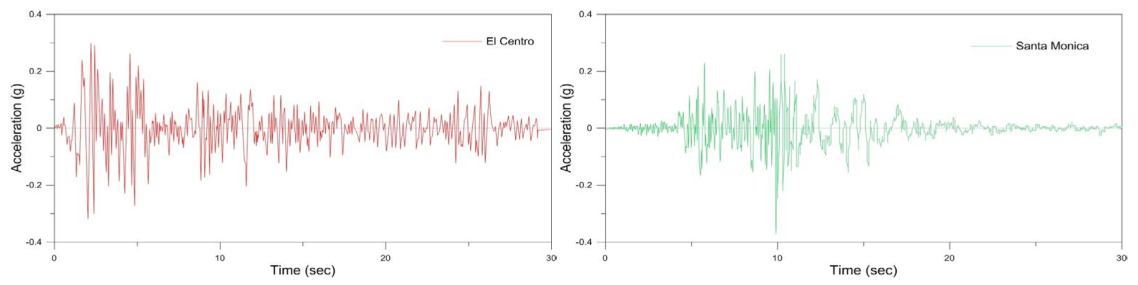


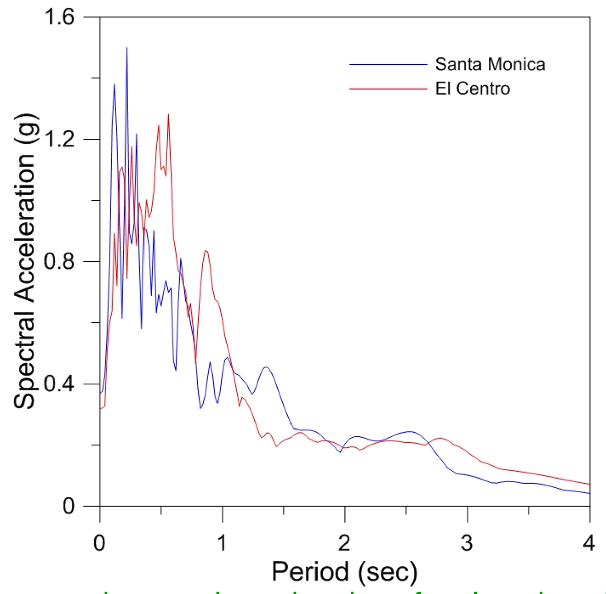
Figure 2. Spacer grids.

Ground Motion

Four different ground motions were used for dynamic analysis. Two sinusoidal motions with acceleration amplitudes of 0.15g and 0.30g and two real ground motions from El Centro and Santa Monica earthquakes. Acceleration time history and spectral acceleration of earthquake records are shown in Figure 3.



3(a). Acceleration time history.



3(b). Spectral acceleration.

Figure 3. Acceleration time history and spectral acceleration of real earthquakes.

Simulation Cases

Four cases were considered to assess the effects of the fuel rod material and the geometry and arrangement of spacer grids. Details of these cases are presented in Table 3.

Table 3. Simulation cases.

Case 1	Material of Rod	Acrylic
	Number of Spacer Grids	6
	Spacer Grid Height (m)	0.0571
	Distance between spacer grids (m)	0.75

Case 2	Material of Rod	Acrylic
	Number of Spacer Grids	8
	Spacer Grid Height (m)	0.0571
	Distance between spacer grids (m)	0.495

Case 3	Material of Rod	Zircaloy
	Number of Spacer Grids	8
	Spacer Grid Height (m)	0.038
	Distance between spacer grids (m)	0.508

Case 4	Material of Rod	Acrylic
	Number of Spacer Grids	7
	Spacer Grid Height (m)	0.0571
	Distance between spacer grids (m)	0.6225

Finite Element Modeling

The finite element simulations are conducted with models of various complexities. In one instance the fuel rods bundle was modeled as a group of vertical beam elements tied together at the elevations where spacer grids were located (simplified model). In a more detailed model, all fuel rods and their detailed interactions with the spacer grids were considered (sophisticated model).

Figure 4 shows some details of the sophisticated finite element model of the fuel assembly and its bracing structure.

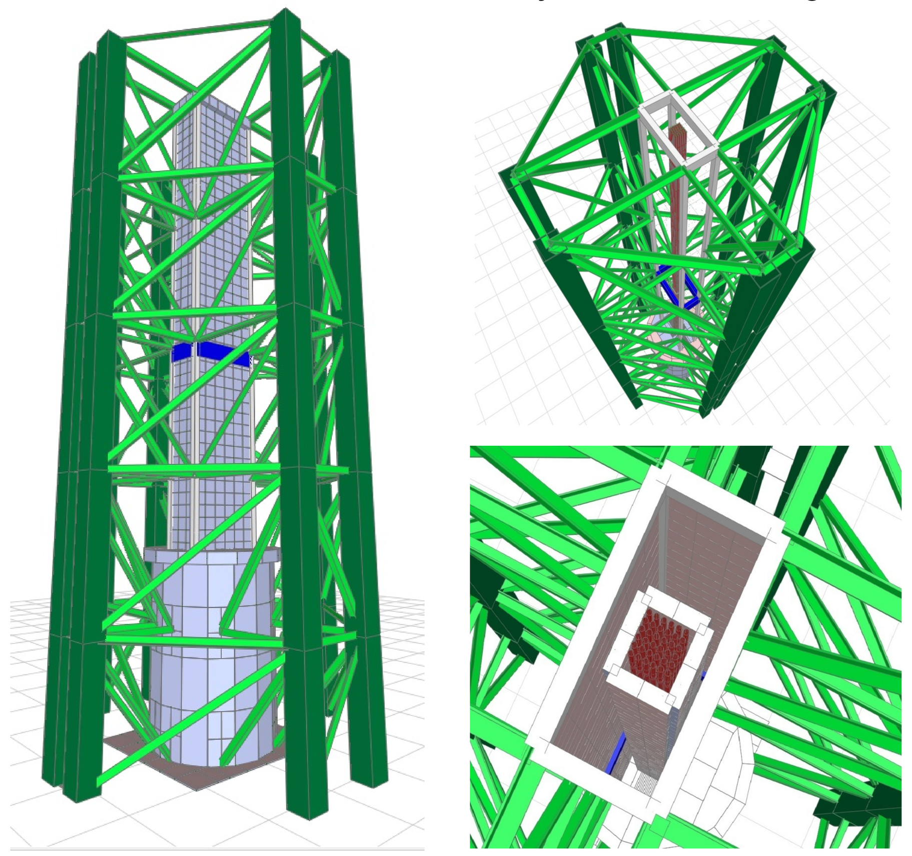


Figure 4. Finite element model.

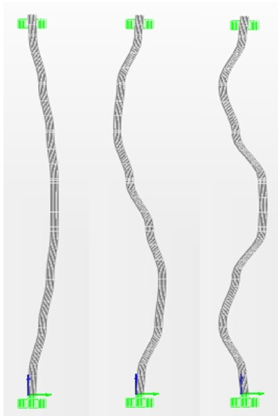
Results of Modal Analysis

Modal analyses of the four cases resulted in the predominant periods and frequencies presented in Table 4.

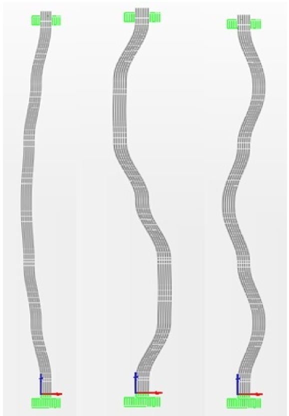
Table 4. Results of modal analysis.

	Case1	Case 2	Case 3	Case 4
Period (Sec)	0.354	0.216	0.276	0.288
Frequency (Hz)	2.826	4.630	3.618	3.472

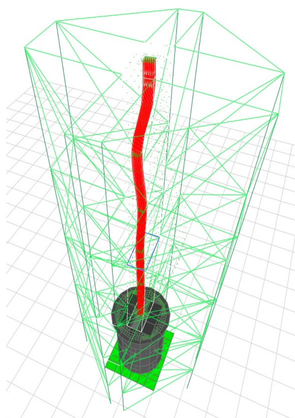
Figures 5(a) and 5(b) show the first three mode shapes of the structure for cases 3 and 4 in which the simplified model was used. Figure 5(c) shows a sample mode shape of fuel rods from analysis of the sophisticated finite element model.



5(a). Case 3.



5(b). Case 4.



5(c). Mode shape of sophisticated model.

Figure 5. Modal shapes.

Results of Seismic Analysis

The structural response is presented in terms of the maximum displacement of the structure under each seismic loading with 5 and 15 percent of damping ratios, respectively. The results are shown in Tables 5 and 6.

Results of Seismic Analysis

Table 5. Maximum displacements (mm) with 5% of damping.

Base Motion	Case1	Case 2	Case 3	Case 4
Sinusoidal (a=0.15g)	42.85	14.25	25.43	29.46
Sinusoidal (a=0.30g)	85.75	28.49	50.85	58.91
El Centro Record	27.04	9.25	17.22	17.28
Santa Monica Record	18.41	9.89	15.74	17.81

Table 6. Maximum displacements (mm) with 15% of damping.

Base Motion	Case1	Case 2	Case 3	Case 4
Sinusoidal (a=0.15g)	18.63	6.05	11.52	12.80
Sinusoidal (a=0.30g)	37.27	12.11	23.03	25.60
El Centro Record	17.82	7.24	12.02	13.11
Santa Monica Record	136.63	6.16	8.81	9.09

Figure 6 shows the effect of damping ratio on the lateral displacement of fuel rods at their mid-height under sinusoidal motion for case 3. Figure 7 compares the response of the structure under El Centro earthquake for cases 3 and 4 with 5% damping.

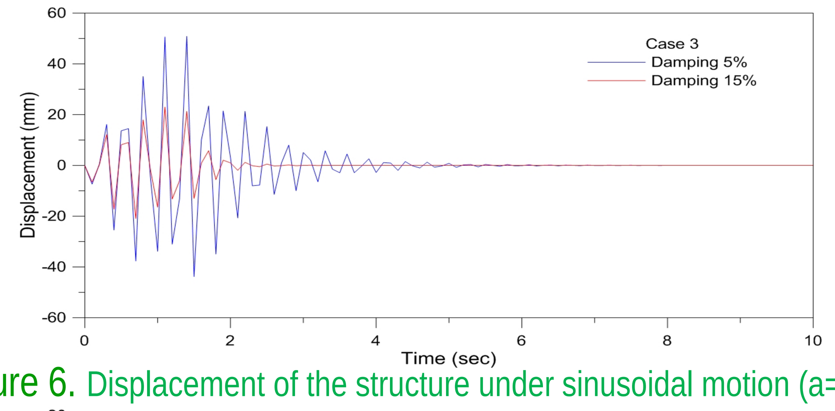


Figure 6. Displacement of the structure under sinusoidal motion (a=0.30g).

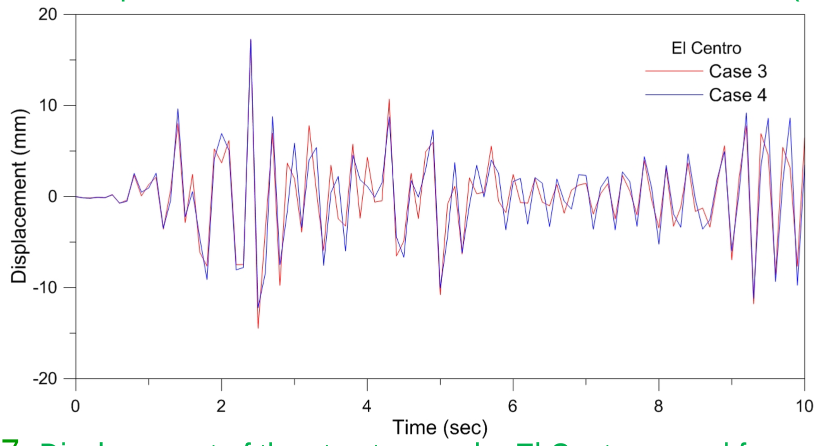


Figure 7. Displacement of the structure under El Centro record for cases 3 and 4 with 5% of damping.

Results of the modal and seismic analyses show that there is a good correspondence between responses of cases 3 and 4. Therefore, Acrylic rods with proper arrangement of spacer grids (case 4) are good replacements for Zircaloy tubes with Uranium Dioxide inserts (case 3).

Future Work

An extensive series of experiments is planned to assess the validity of the finite element simulation results and to observe the fluid-structure interaction in the scaled fuel assembly during various earthquake loading scenarios. Figure 8 shows some components of the test specimen and the bracing structure under construction on the shake table at VSTC.

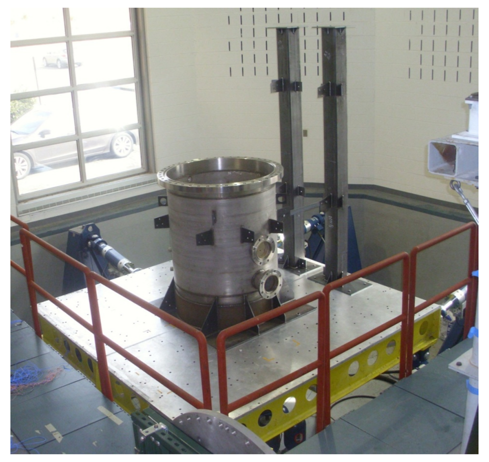


Figure 8. Test specimen under construction on the Shake table in the Earthquake Engineering and Structures Laboratory at Virginia Science and Technology Center.