SEISMIC STABILITY ANALYSIS FOR AN IN-BAY WORKTABLE FOR SPENT FUEL DRY STORAGE

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ABSTRACT

CANDU® reactors designed in Canada are built and operated worldwide to produce electricity economically with no emission of green house gases. In this paper, a seismic stability analysis for an in-bay stainless steel worktable for the spent fuel dry storage system of a CANDU® nuclear power plant is presented. A finite element model is developed to represent the structural behavior of the worktable. The seismic analysis is performed using the response spectrum method and accounts for the hydrodynamic effects of the surrounding water. Missing mass effect due to the truncation of high frequency modes is discussed. Various design loads and combinations are considered in the analysis. The overturning, sliding and the strength of the free standing worktable due to a Design Basis Earthquake are checked according to the current design codes. It is found that the design of the worktable is adequate under all loading conditions.

INTRODUCTION

The operation of CANDU® reactors yields spent fuel bundles that are removed from the reactor core by means of unique remote mechanisms. The purpose of the spent fuel dry storage facility is to provide safe, economical, reliable and retrievable medium term storage for spent fuel from CANDU® reactors. Spent fuel bundles coming out of the reactor are kept in the spent fuel bay for several years. By that time their heat production due to radioactivity has dropped sufficiently to allow moving them to specially designed and built concrete canisters for dry storage.

The spent fuel dry storage operations consist of removing the spent fuel bundles from the storage trays that are stacked in the spent fuel bay, placing them in stainless steel baskets, removing the baskets from the spent fuel bay, and transferring them to a shielded work station. Inside the shielded work station, the basket is dried and seal welded. It is then transferred to the storage site and placed in a concrete canister for storage.

The in-bay worktables are part of the spent fuel dry storage system. Figure 1 shows a sketch of the in-bay worktables. The function of the worktables is to provide a movable work surface and structural support to the equipment used in the basket loading operations (i.e., the fuel bundle tilter, the turntable, and the transfer table). It is necessary that the free standing underwater worktables maintain its structural integrity and stability under a severe earthquake. The objective of the analysis is to seismically qualify the stability and integrity of these free standing worktables under the Design Basis Earthquake (DBE). Since the worktables are submerged in water, hydrodynamic effects must be considered in the analysis to more accurately predict their structural behaviours. In addition, as the worktables are free standing type structures, care must be taken in the development of the finite element model and in the interpretation of the analysis results.

There are two adjacent worktables placed in the spent fuel bay. For the simplicity of presentation, only the analysis for one worktable is presented in this paper.

DESCRIPTION OF THE STRUCTURE

The worktable is made of stainless steel. The overall dimensions of the worktable are approximately 4 meters long by 2.5 meters wide by 1.2 meters high. The worktable is a free standing structure on the epoxy-coated spent fuel bay floor. It is constructed by two parts: a steel top plate to provide work surface; and a steel frame to support the top plate. The steel frame consists of steel single angles and stiffened plates. It includes six vertical legs, beams connecting the legs in two orthogonal horizontal directions at two different elevations, and knee braces and stiffened plates to strengthen the worktable. The steel frame is fabricated by welded connections. The top steel plate is bolted to the top of the steel frame at the leg locations. To lower the centre of gravity of the whole table and to mitigate the effect of overturning, solid steel bars are attached to the beams at the lower elevation of the frame.

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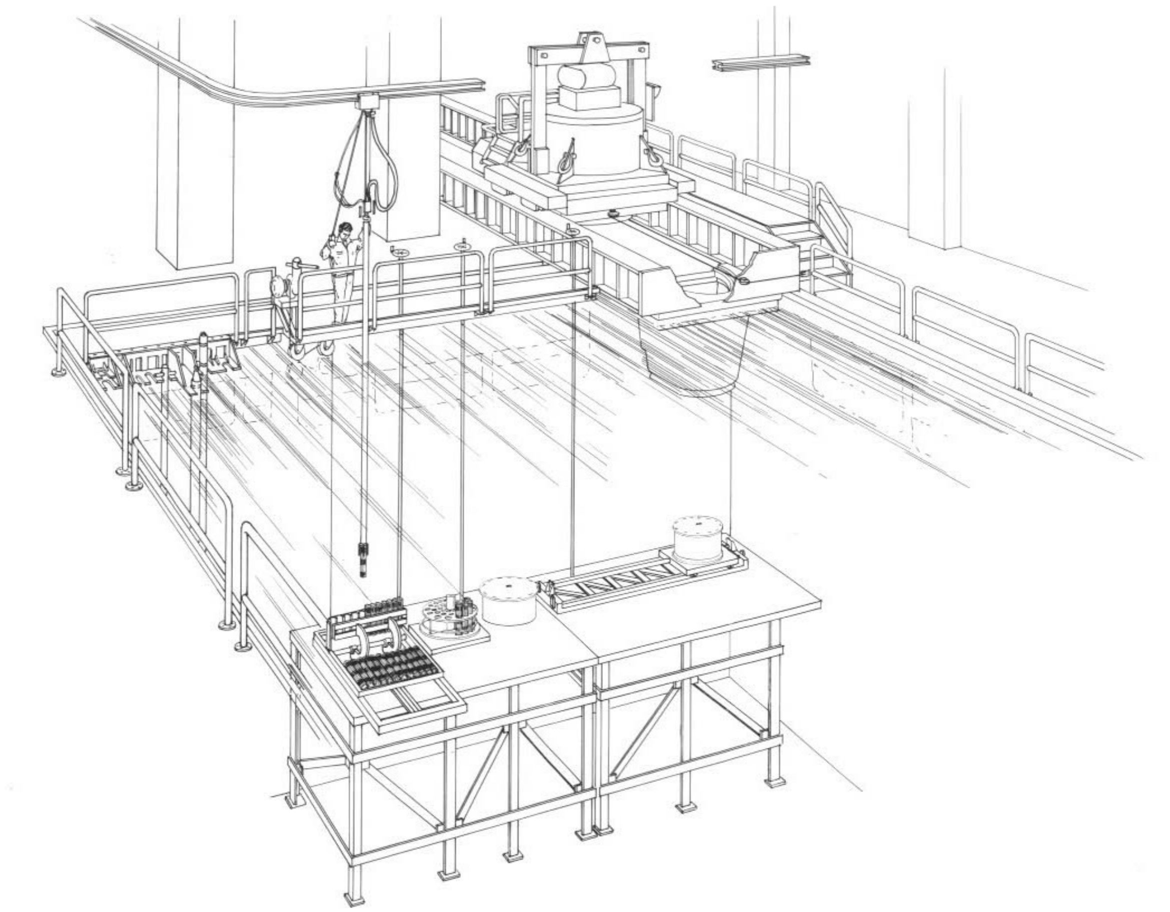

Figure 1 Sketch of In-Bay Worktables

FINITE ELEMENT MODEL

A finite element model for the worktable in the spent fuel bay is developed using the STARDYNE, a finite element software for seismic analysis. The finite element model is shown in Figure 2.

In the finite element modelling of the in-bay worktable, the followings are considered:

- Although the lower ends of the legs of the worktable are free standing on the epoxy-coated floor, they are assumed as pinned constraints for the purpose of analysis. This assumption is valid as long as the worktable does not move and the friction between the legs and the floor is big enough to resist sliding during an earthquake.
- The top steel plate is not welded to the worktable. It is bolted to the worktable at the leg locations. To include the stiffness contribution of the top plate, it is modelled as X-braces, assuming the sectional properties of a weightless plate strip. The weight of the top plate is distributed to the worktable legs separately.
- The triangular leg reinforcing plates are modelled as knee braces for the reason of simplicity.
- All connections are considered to be rigid due to the fully-welded construction.
- The origin is set to be at the bottom end of one of the corner legs, as shown in Figure 2 using a black dot. The horizontal axes are defined as X and Y, the vertical as Z.

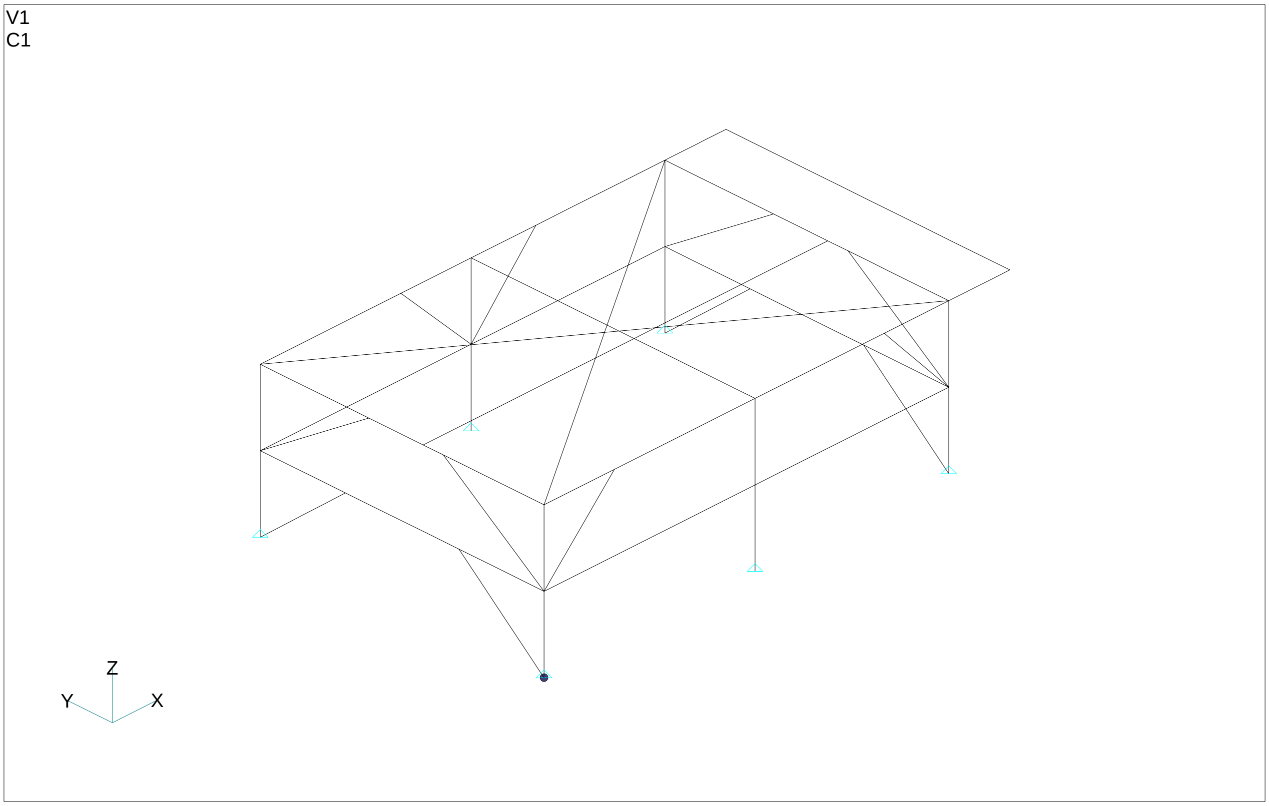

Figure 2 Finite Element Model of Worktable

DESIGN LOADS

1. Dead Loads (DL)

The design dead loads (DL) include the self-weights of the worktable, equipment permanently installed on the worktable, and the attached steel bars.

As the worktable is submerged in water, the hydrodynamic effects on the dynamic behaviour is considered as added mass of water attached to the worktable in the two horizontal directions. The attached added mass is not considered in the vertical direction because it is insignificant for lateral overturning and sliding. The added mass accounts for the inertial of the water affected by the accelerating worktable. As the worktable accelerates, the water surrounding the worktable must accelerate as well. The inertia of the affected water is the added mass. Added mass always decreases the natural frequency of a structure from that measured in a vacuum.

The added mass in this analysis is calculated using an approximate approach. This simplified approach assumes the weight of an equivalent cylindrical volume of water with a diameter same as the width of the member. The total amount of water attached to the worktable frame is then distributed to the adjacent nodes. Using the same approach, the amount of water attached to the equipment can also be calculated according to their approximate projected areas in the two horizontal directions.

2. Live Loads (LL)

The weights of the fuel bundles transferred in the spent fuel basket are considered as live loads (LL). Due to the uncertainty of the live load locations, 50% of these live loads will be added to each leg when checking the strength of the legs of the worktable.

According to the operation procedures of the spent fuel dry storage system, the probability of having an earthquake while performing the loading operation is very small. Therefore, the weights of the basket and the fuel bundles are not included in the seismic analysis.

3. Seismic Loads (E)

The worktable is analysed under the Design Basis Earthquake. Since the worktable is located close to the ground, the use of the existing floor response spectra is considered to be too conservative for this analysis. The seismic inputs in the two horizontal directions are therefore defined as the DBE ground response spectra for the specific site. The frequency and acceleration values are interpolated at 10% damping considering the hydrodynamic effects of the surrounding water.

The seismic inputs in the vertical direction are considered as two thirds of those for the horizontal directions according to CSA Standard N289.3 (Reference [1]). The worktable is found to be very rigid in the vertical direction and have the same vertical acceleration as the supports. Since the peak ground acceleration in this analysis is 0.2 g, the maximum vertical acceleration response is calculated to be 0.133g.

4. Load Combinations

In accordance with CAN/CSA-S16-01 (Reference [2]), the following load combinations are considered when checking the strength of the worktable. Seismic loads in the vertical direction (Ez) and the two horizontal directions (Ex and Ey) are combined by the Square Root of the Sum of the Squares (SRSS) method according to CSA N289.3 (Reference [1]).

Combination 1. 1.25 DL + 1.5 LL

Combination 2. $1.0\ \text{DL} + 1.0\ \sqrt{E_x^2 + E_y^2 + E_z^2}$

Combination 3. $1.0\ \text{DL} - 1.0\ \sqrt{E_x^2 + E_y^2 + E_z^2}$

As discussed above, the live loads are not included in the load combinations with seismic loads since the probability of having an earthquake while performing the spent fuel bundle loading operation is considered very low.

ANALYSIS

<u>Seismic Analysis</u>

A static STARDYNE analysis is performed for the finite element model described above to obtain the member forces and the reactions at each support due to dead loads. A dynamic STARDYNE analysis is then performed to obtain the frequencies and mode shapes of the worktable. All significant modes below 33 Hz are considered in this analysis according to CSA N289.3 (Reference [1]). The lowest three frequencies are found to be 17.1 Hz, 17.7 Hz and 32.6 Hz. The mode shapes for the lowest three frequencies are shown in Figure 3 for the lowest frequency (f_1), in Figure 4 for the second lowest frequency (f_2), and in Figure 5 for the third lowest frequency (f_3).

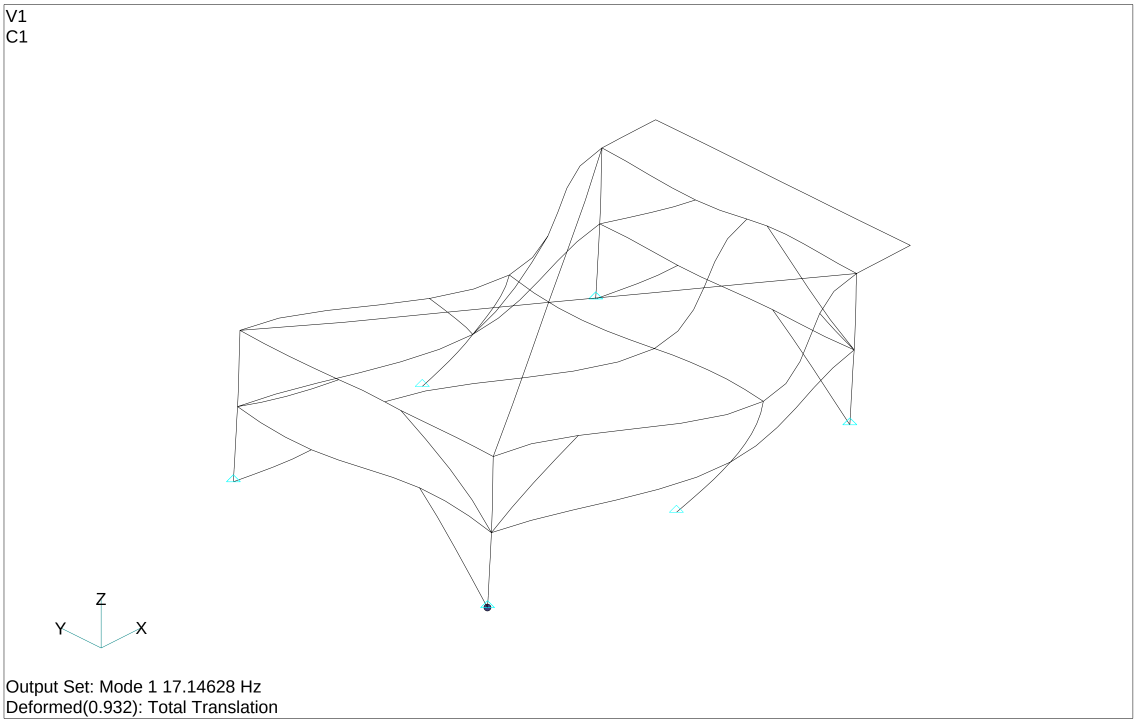

Figure 3 Mode Shape Corresponding to f_1 (17.1 Hz)

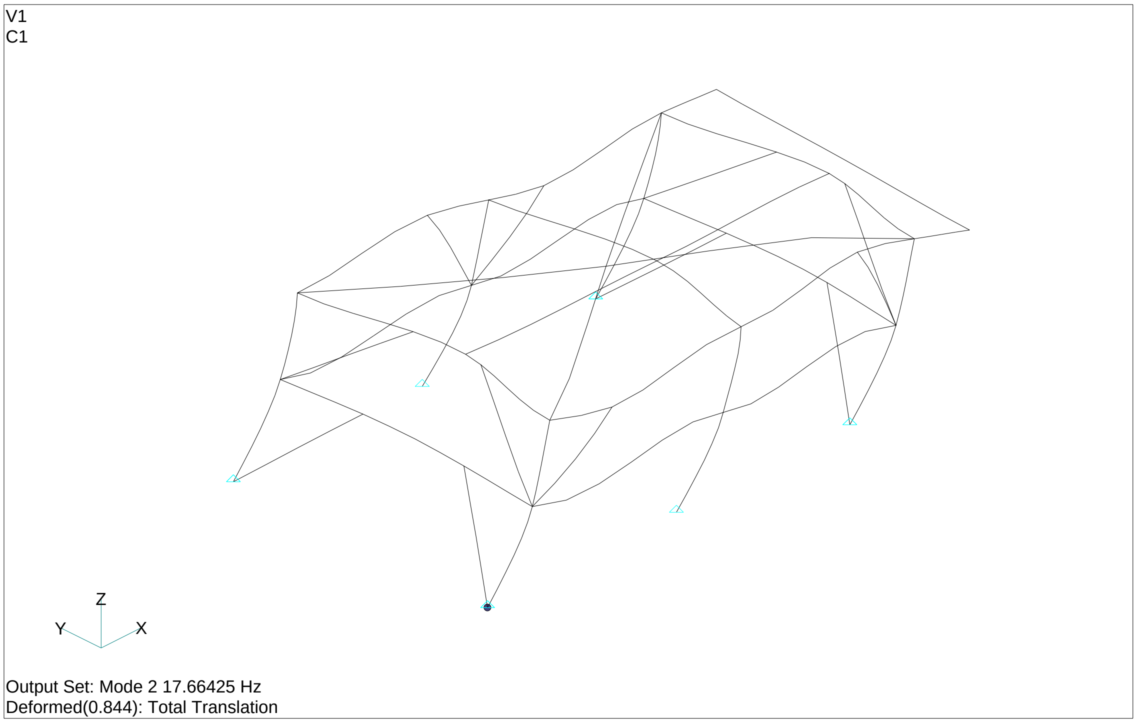

Figure 4 Mode Shape Corresponding to f_2 (17.7 Hz)

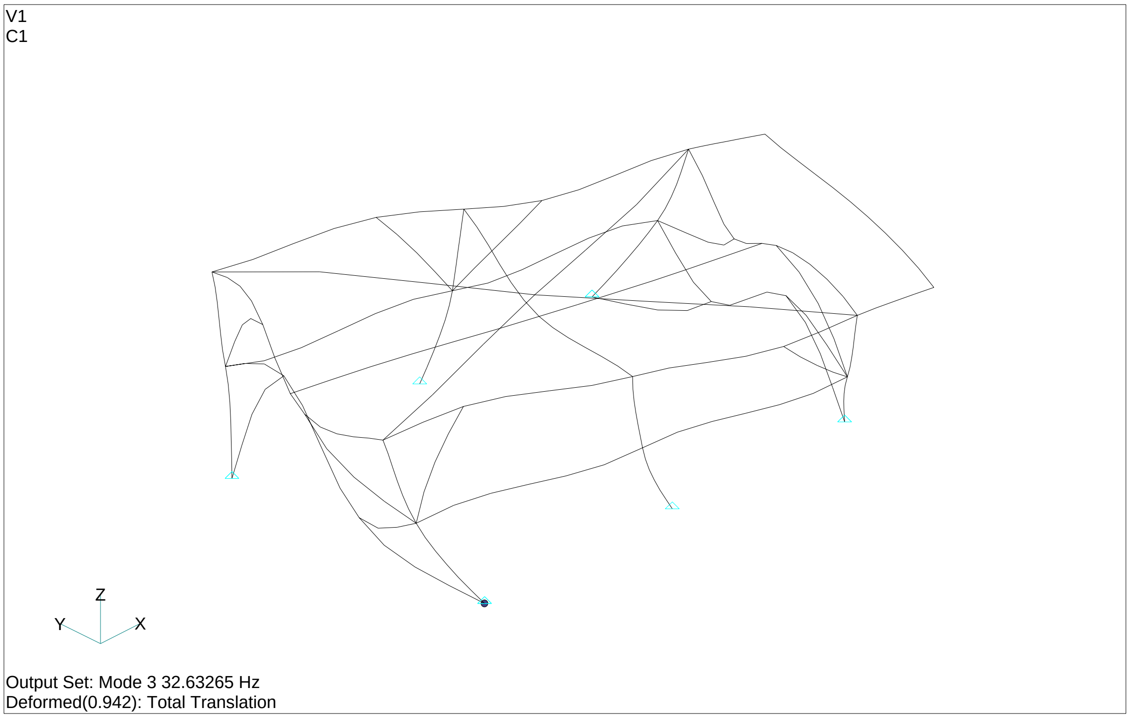

Figure 5 Mode Shape Corresponding to f_3 (32.6 Hz)

As seen in Figures 3 and 4, the mode shape corresponding to the lowest frequency f_1 is the dominant mode in the horizontal Y direction, while the mode shape corresponding to the second lowest frequency f_2 is the dominant mode in the horizontal X direction. This is explainable since the worktable has a configuration with two spans in the X direction and only one span in the Y direction, which makes the worktable stronger in the X direction than in the Y direction. The mode shape corresponding to the third lowest frequency f_3 is the dominant rotational mode in Plane XY as shown in Figure 5. The third lowest frequency f_3 is found to be 32.6 Hz and the rest of the frequencies are all above 33 Hz, which means the frequency corresponding to the dominant mode in the vertical Z direction is above 33 Hz and the worktable is considered to be very rigid in the vertical direction.

Having obtained the frequencies, the mode shapes, and the corresponding modal participation factors, the seismic response of the worktable is calculated using the response spectrum method. The most probable response is obtained as the square root of the sum of the squares of the response from the individual modes. Because the first two modes are closely spaced modes, i.e., their frequencies are within 10% of each other, their responses are combined by the absolute sum method, and then the combined response is combined with that of the third mode using the SRSS rule.

It is found that the acceleration responses of some of the key nodes of the worktable are below the zero period accelerations of the input spectra, especially in the vertical direction. This is due to the truncation of the high frequency modes and is known as the “missing mass” effect. This effect has been recognized in the available literature (e.g., Reference [3]) and many correction procedures are proposed. One of these proposed methods is given in Reference [4], in which the missing modes are considered by performing a static analysis using residual load vectors. The residual load vectors are obtained by manipulation of the modal vectors. The effect of the missing load vectors is then combined with the results obtained from the conventional method.

According to Reference [4], the “missing mass” effect can be corrected by considering a set of residual modes. In these residual modes the effects from high frequency modes are combined as follows:

$$R_j := 1 - \sum_{i=1}^{I} \left[\phi_{ji} \cdot \left(\Gamma_{xi} + \Gamma_{yi} + \Gamma_{zi}\right)\right] \tag{1}$$

where, R_j = residual mode of the j th degree of freedom,
ϕ_{ji} = eigen vector for the j th degree of freedom and the i th mode,

Γ_{xi}, Γ_{yi}, Γ_{zi} = participation factors in X, Y, and Z directions respectively,
I = number of significant modes.

The value of R_j should be positive and less than 1. The negative value of R implies that the rigid body floor acceleration is applied in a direction opposite to the direction of the floor motion that is considered unreal. If Eq. (1) gives a negative value of R_j, it has to be reset to zero. The maximum value of R_j should be 1 indicating a full correction. If Eq. (1) gives a value of R_j more than 1, it is reset to 1. Consequently the following condition is imposed on the value of R_j:

$$0 \le R_j \le 1.$$

The series R_j are separated into three vectors for the X, Y, and Z directions respectively. These vectors are denoted as

$\{R_{jn}\}$ = residual mode for the j th degree of freedom in direction n,
n = 1, 2, 3 representing X, Y, and Z directions respectively.

The residual acceleration vectors are obtained as

$$\{A_{jn}\} = \{R_{jn}\}\, a_n$$

in which a_n are floor accelerations in direction n. The residual inertial load vectors are obtained by multiplying the residual acceleration with the modal mass as follows:

$$\{P_{jn}\} = \{A_{jn}\, w_{jn}\}$$

where, P_{jn} = residual load vector for the j th degree of freedom in direction n,
w_{jn} = lumped mass for the j th degree of freedom in direction n.

In general, there are three residual load vectors, one for each of the three directions X, Y and Z. These three residual load vectors are intended to correct the “missing mass” effect. To obtain the corrected accelerations, the absolute values of the residual accelerations A_{jn} are added to the SRSS combination of the dynamic modes as follows:

$$a_j := \sqrt{\sum_{i=1}^{I} \left[\phi_{ji} \cdot \left(\Gamma_{xi} \cdot s_{xi} + \Gamma_{yi} \cdot s_{yi} + \Gamma_{zi} \cdot s_{zi}\right)\right]^2} + \left|A_{jn}\right| \tag{2}$$

The element forces and stresses from three residual load cases are combined with a SRSS procedure. The results are then combined with those of the SRSS combination of the dynamic modes as follows:

$$F_j := \sqrt{\sum_{i=1}^{I} F_{ji}^{\;2}} + \sqrt{\sum_{n=1}^{3} M_{jn}^{\;2}} \tag{3}$$

where, F_{ij} = the j th force for the i th dynamic mode,
M_{jn} = the j th force due to the n th residual load.

<u>Design Check</u>

With the static and seismic responses obtained, the structural integrity of the worktable is checked according to CAN/CSA-S16-01 (Reference [2]) by verifying the stresses induced in the structural components due to various load combinations. The combined responses are compared with the capacities of the steel members calculated according to the code. The structural integrity of the worktable is ensured as long as the combined responses are lower than the capacities. It is found that the design of the worktable is adequate to resist all of the loads, individually and combined.

Stability Check

Since the worktable is submerged in the water and is free standing on the floor of the spent fuel bay, the stability against uplifting, overturning and sliding must be checked. Also, if the stability of the worktable can not be ensured, i.e., if the worktable can uplift, overturn or slide during an earthquake, then the boundary conditions assumed in the finite element model are no longer applicable and all the analysis results will become questionable.

The uplifting and overturning of the worktable are checked by comparing the overturning moment due to the seismic loads and the restoring moment due to the self-weights of the worktable and the equipment. The overturning moment and restoring moment are calculated for different horizontal directions. If the restoring moment is larger than the overturning moment, then the worktable is considered not uplifting or overturning. In calculating the restoring moment, both of the vertical responses due to the seismic loads and the buoyancy effects due to the water are considered. It is found that the restoring moment is larger than the overturning moment and the worktable will not uplift or overturn during the Design Basis Earthquake.

The sliding of the worktable is checked by comparing the seismic shear forces at the lower ends of the legs and the friction between the legs and the supporting floor. If the total shear force due to seismic loads at the legs in any direction is smaller than the friction due to the self-weights of the worktable and the equipment, then the worktable is considered not sliding. In calculating the friction, the self-weights of the worktable and the equipment installed are reduced by the buoyancy forces and the vertical seismic inertial force. The friction coefficient between the legs and the epoxy-coated floor used in this analysis is based on the results from an AECL test report for the spent fuel bay steel structures. It is found that the friction between the stainless steel worktable and the epoxy-coated floor is larger than the total base shear force in any direction. Therefore, the worktable is considered not to slide during the Design Basis Earthquake.

Having checked the uplifting, overturning and sliding of the worktable, it is concluded that the boundary conditions used in the finite element model of the worktable are valid and the worktable is stable under the Design Basis Earthquake. It is noted that the above stability criteria is conservative. Even if the worktable is uplifting, and or sliding during an earthquake, the worktable may still be stable as long as it is not overturned, since the earthquake motion is transient in nature and may change its intensity or reverse its motion direction randomly.

CONCLUSIONS

In this paper, seismic qualification of a worktable in the spent fuel bay of a CANDU® nuclear power plant is discussed. A finite element model is developed to represent the structural behavior of the worktable. Because the worktable is submerged in the water, hydrodynamic effects are considered. Missing mass effect due to the truncation of high frequency modes is also considered. In addition, since the worktable is free standing on the epoxy-coated concrete floor and relies on its self-weight and friction to maintain the stability during a seismic event, the stability of the worktable is checked against uplifting, overturning and sliding. It is concluded that the design of the worktable is adequate for the given loads and the worktable is stable under a Design Basis Earthquake.

REFERENCES

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