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SEISMIC QUALIFICATION OF SPENT FUEL STORAGE STACKS

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ABSTRACT

CANDU reactors use short (0.5 meter) fuel bundles to facilitate on-power refueling. The spent (irradiated) fuel bundles are removed from the reactor during the re-fueling process and are transferred to the spent fuel (S/F) port by fueling machines. From there, the S/F bundles are loaded onto trays for storage in the S/F storage bay, where they are stacked on support structures. The leveled stack supports rest on the epoxy-lined concrete floor of the S/F storage bay. The S/F bay is filled with water designed for adequate shielding and cooling of S/F bundles. The S/F storage stacks are required to maintain their structural stability and integrity under a DBE (Design Basis Earthquake). The purpose of this paper is to present the seismic analysis techniques and the stability evaluations developed for the seismic qualification of the S/F storage stacks.

In the seismic qualification of the S/F storage stacks, models are developed in stages with two main objectives: (i) to accurately represent the structural behavior by a finite element method , and (ii) to simplify and reduce the model size by sub-structuring techniques (two level condensation). The reduced and simplified global models are of a spring-and-lumped-mass type. Also, in the three-directional time-history seismic analysis, off-set beams are implemented in the seismic model in order to capture the true combination of the overturning moments due to simultaneously applied horizontal motion and vertical motion. The total applied forces produced by the earthquake consist of the seismic inertia effects and the hydrodynamic pressure effects.

Stability and structure integrity are assessed for various design configurations of the S/F storage stacks. The stability evaluation involves checks against toppling and sliding based on defined stability criteria. Structural integrity is ensured by the stress analysis to have stresses within the acceptable limits. Both the stability evaluation and the stress analysis confirm that the design of the S/F storage stacks satisfy the design requirements.

1. INTRODUCTION

CANDU reactors offer very high capacity factor partly due to the on-power refueling capability. The spent (irradiated) fuel bundles are removed from the reactor and transferred to the spent fuel port by fueling machines. From there, the spent fuel (S/F) bundles are loaded onto S/F storage trays in the S/F storage bay. Trays filled with spent fuel bundles are stacked on support structures. The stack supports rest and are leveled on the epoxy-lined concrete floor of the S/F storage bay. In combination with safeguard covers at the top of the stacks (with seals for long-term monitoring of irradiated fuel bundles), the stack supports are connected in a 2x1 or a 2x2 arrangement, see Figs. 1 and 2 respectively. The S/F bay is filled with water for shielding and cooling of the S/F bundles.

Each storage tray can hold 24 fuel bundles in two rows. The tray is of stainless steel welded construction, and consists of two channel sections with a number of stiffener gussets and corner end plates, interconnected by a reinforced angle section at each side and a reinforced T-bar across the center. Figure 3 shows a finite element model of a tray. Contoured cradle trips are welded to the angle sections and the T-bar to support the fuel bundles. Each tray is provided with two tapered locating pins on the top channel end rails and two slots on the bottom channel end rails. The pins engage with the slots of the next-higher tray in the stack.

The design of the storage tray support ensures that the bay floor loading is not exceeded and that clearance is provided between the first row of fuel bundles and the bay floor to permit flow of water around the trays. Each support structure consists of two channels at the ends, a diagonally cross-braced steel frame and a reinforcing pipe running through the middle. Figure 4 shows a finite element model of a support structure. Each support is provided with 6 pads and feet on the bottom end rails of its channel sections for use in leveling. The channel sections on the ends are partially boxed-in together with gussets to provide additional strength. Two tapered locating pins on the top of the end channel sections locate the first tray in the stack.

The stacks are grouped into one of two arrangements by connecting the supports of the stacks by brackets: (a) two stacks grouped in a 2x1 arrangement as shown in Fig. 1, or (b) four stacks grouped in a 2x2 arrangement as shown in Fig. 2. The 2x1 grouped stacks are capped on top by a safeguard cover with tie rods, see Fig. 1 (a cover with seals for long-term monitoring of irradiated fuel bundles). A finite element model for such a cover is shown in Fig. 5. For 2x2 grouped stacks, the four supports are connected by brackets, and the two covers at the top are pin-connected.

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The S/F storage stacks are designed to a DBE (Design Basis Earthquake). The seismic qualification requirements include: (i) stresses in the structural components (trays, supports with connection brackets, and covers) are within the code allowable limits, and (ii) stability against toppling and sliding to avoid possible damage to the fuel bundles.

This paper deals with the following potential instabilities for the various design configurations of the S/F storage stacks under a DBE:

(1) Structural Configurations
- (a) 2x1 grouped stacks, with or without a cover
- (b) 2x2 grouped stacks, with or without covers (two covers are pin-connected).

The cases without safeguard covers are included to account for the possibility that an earthquake can occur during the stacking process before the covers are firmly tied by the tie rods.

(2) Stability Conditions
- (a) Toppling of tower of stacked trays at the top of the support structure
- (b) Toppling of the 2x1 or 2x2 grouped stacks at the concrete floor
- (c) Sliding of the 2x1 or 2x2 grouped stacks on the epoxy-lined concrete floor.

2. SEISMIC MODELS AND BOUNDARY CONDITIONS

2.1 Modeling Methodology (Sub-Structuring Technique)

The objectives of the seismic modeling have two folds:

- (i) to accurately represent the structural behavior (by finite element method)
- (ii) to make the seismic models simple and to reduce the model size (by sub-structuring -technique).

It has been observed that a simple stick model derived from the traditional beam theory to represent the stacked trays can be much stiffer than reality. This stiff beam model can wrongly and significantly reduce the amplification of the structural response to the earthquake excitation and lead to a non-conservative design. The finite element method is therefore adopted to accurately represent the structural behaviors. However, finite element models contain large degrees of freedom for the seismic analysis. Consequently, the sub-structuring technique is applied in the seismic modeling in order to reduce the degrees of freedom to a manageable size.

To achieve the above objectives, the seismic modeling process consists of 4 stages.

(a) Creation of a finite element model for each structural component (tray, support and cover), see Figs. 3, 4 and 5.
(b) Each finite element model is then condensed by the sub-structuring technique to a reduced stiffness matrix consisting of the minimum required nodes. The boundary nodes at this stage consist of nodes for attached masses and for contact with neighboring components.
(c) A single tower of trays (say 16, depending on the design) is formed by stacking the stiffness matrices of the trays with beams between trays to simulate the contact conditions between trays. A secondary condensation by the sub-structuring technique is then performed on a single tower of stacked trays. After the secondary condensation, the interior nodes and beams representing the contacts between trays are removed from the active degree of freedom. The active degrees of freedom retained for each tower consist of the mass nodes for each tray, the bottom nodes of the first tray and the top nodes of the top tray of the tower, see the towers shown in Fig. 6(a).
(d) Global models are then created from:
    (i) stiffness matrices and lumped masses of towers of stacked trays
    (ii) stiffness matrices and lumped masses of supports
    (iii) stiffness matrices and lumped masses of the covers
    (iv) beams representing connections between the above sub-structures, the tie rods for safeguard covers, the support connecting brackets and the off-set beams.

Figure 6 shows sketches of the global models for:

(a) 2x1 grouped stacks with or without cover
(b) 2x2 grouped stacks with or without covers (two covers are pin-connected).

2.2 Lumped Masses

The mass of each component is lumped at the representative global nodes. The total mass in the global seismic model consists of two parts:

(a) steel mass, including the structure members and the attached/mounted elements (e.g. bundles)
(b) added virtual water mass induced by vibration of submerged structure.

With the added water masses lumped together with the steel masses, the impulsive forces of the hydrodynamic effects are accounted and the stacks are then treated as if they were vibrating in the air during an earthquake.

2.3 Boundary Nodes

During the first condensation described in Section 2.1, boundary nodes are created as follows:

(i) Single Tray

(a) 10 nodes on the bottom end rails of the two channel sections, 5 on each channel section end rail.
(b) 10 nodes on the top end rails of the two channel sections, 5 on each side.
(c) 3 lumped-mass nodes, one on each angle section and the T-bar. If desired for refinement, more mass-nodes can be assumed on the angles and the T-bar (e.g. 3 masses on each member).

(ii) Single Support Structure

Same as for a tray, 10 nodes on the bottom and 10 nodes on the top channel end rails. Two mass nodes are assigned.

(iii) Single Cover (for 2x1 grouped stacks)

20 nodes for a cover to match the top nodes of a 2x1 grouped stacks. Two mass nodes are assigned.

During the second condensation in forming a tower of stacked trays, each tray is represented by a stiffness matrix. The connection conditions between the contacted nodes of two trays, i.e. between the top 10 nodes of the lower tray and the bottom 10 nodes of the next higher tray are:

(a) No separation in the vertical direction. This represents that there is no toppling/separation between trays. This stable condition will be verified later if the restoring moment is larger than the overturning moment.

(b) The two horizontal degrees of freedom between the contact nodes are relatively free except for the nodes at the pin location. This represents that the seismic shear forces will overcome the friction between contact surfaces, but the shear forces will be transmitted through the pins.

(c) Torsion moment degree of freedom is relatively free, based on the assumption that the seismic forces will overcome the friction between two trays, but the torsion moment will be resisted by the coupled pin shear forces.

(d) Bending moments about the two horizontal axes are transmitted between contact nodes due to the finite dimensions of the end rails of channels.

After the second condensation to form a tower of stacked trays, the active boundary nodes are reduced to (2*10 + n*m). The two 10 nodes occur respectively at the bottom and the top of a tower of stacked trays. The n*m comes from the m mass nodes for each tray in a single tower of n trays.

In the global model for each stack, the boundary nodes of the tower and its support (both are represented by reduced matrices) are connected by the same contact conditions as described above for two trays. The stacks are then grouped into 2x1 or 2x2 arrangement by connecting the supports with brackets and by capping the tops of stacks with covers and tie rods (for cases with safeguard cover), see Figs. 1, 2 and 6.

2.4 Boundary Conditions

The 2x1 or 2x2 grouped stacks and the seismic models as described above are free standing and supported by 6 feet for each stack on the epoxy-lined concrete floor. The finite dimensions of the foot may or may not provide the bending moment resistance on the floor. The boundary conditions at the bottom of the foot on the floor are assumed to be either fixed or hinged. For conservatism, their results are enveloped for the design. The no-uplift condition in the vertical direction will be verified if the stacks will not "tend" to overturn, i.e. if the restoring moment is higher than the overturning moment, see the stability criteria in Section 4.1. The horizontal restraint conditions will be verified if the horizontal shear (pushing) forces are fully resisted by the friction effects between the foot and the epoxy-lined floor, see the sliding stability criterion in Section 4.1.

3. SEISMIC ANALYSIS

The time-history method and the DYNRE1 module of STARDYNE computer program is adopted for the seismic analysis of the S/F storage stacks. A damping value of 7% is used and is considered conservative due to the following considerations:

(a) The whole structure is submerged in water.
(b) About 85% of the total mass comes from the bundles which are not structural members but attached elements (can roll in the cradle of the tray, like cable trays which usually has a damping value of 10% to 15%).
(c) Friction between trays and supports are not credited in the seismic model.

In the time-history seismic analysis, three directional input motions are applied simultaneously at the bay floor level. Off-set beams are created to capture the true combined overturning moments due to the horizontal and the vertical motion effects. The off-set beams are located at the bottom of each tower of stacked trays (for check of tower toppling stability) and at the concrete floor level (for the stability check against toppling and sliding of the grouped stacks) as shown in Fig. 6. The off-set from the center of gravity is equal to the moment arms of the overturning moments due to the vertical seismic force.

Seismic analyses have been carried out for:

(a) four models: 2x1 grouped stacks with or without cover, and 2x2 grouped stacks with or without covers.
(b) fixed and hinged boundary conditions of the foot support at the epoxy-lined concrete floor.

4. STABILITY EVALUATIONS

4.1 Stability Criteria

Stability evaluations are rated against the following criteria:

(a) Toppling

Safety Factor Against Toppling (T.F.) = (Restoring Moment) / (Total Overturning Moments)

If T.F. > 1.0, then the structure is stable and no uplift, or separation, will occur. Toppling stability is evaluated at the bottom of the tower of stacked trays (i.e. at the top of support) and at the concrete floor.

The restoring moment is provided by the net weight (Deadweight - Buoyant Force). The overturning moments at the bottom of the tower due to the horizontal and the vertical motion (the seismic inertia effects) are obtained from the off-set beams (Beam No. 173, 273, 373 and 473 in Fig. 6). The overturning moments of the grouped stacks at the concrete floor level are obtained from the off-set beam No. 80 shown in Fig. 6. The total overturning moments are due to the combination of the seismic inertia effects and the hydrodynamic effects on the submerged structure.

(b) Sliding

Sliding Factor (S.F.) = (Horizontal Applied Forces at Floor Level) /
(Deadweight - Buoyant Force - Vertical Seismic Force)

If S.F. < friction coefficient between the support foot and the epoxy-lined concrete floor, then the structure is stable against sliding.

The horizontal applied forces consist of the horizontal seismic inertia forces and the hydrodynamic forces acting on stacks. The horizontal seismic inertia forces at the floor level are equal to the beam-end shear forces of the off-set beam No. 80.

4.2 Results and Design

The seismic inertia loads obtained from the seismic analysis are combined with the deadweight loads, the buoyant forces and the hydrodynamic forces for the stability evaluations as described in Section 4.1. The total loads for stability evaluation are also used in the stress analysis for each component in order to ensure the structural integrity under earthquake. Both the stability evaluation and the stress analysis confirm that the design of the S/F storage stacks satisfy the design requirements.

5. CONCLUSIONS

Various design configurations of the S/F storage stacks are considered in the seismic qualification. In developing the seismic models, finite element models are created to accurately represent the structural behavior and then two levels of stiffness condensation by the sub-structuring technique are adopted in order to simplify and reduce the model size. The reduced and simplified seismic models are essentially of spring-and-lumped-mass type. Also, off-set beams are implemented in order to capture the true combined overturning bending moments due to the simultaneously applied horizontal and vertical earthquake motions.

Stability criteria are established for stability evaluations for toppling and sliding. The off-set beam concept simplifies the calculations of loads used in the stability evaluation. From the stability evaluations, it is concluded that toppling and sliding of stacks grouped in 2x1 or 2x2 arrangement will not occur under a DBE earthquake, for which both the seismic inertia effects and the hydrodynamic effects are considered. Also, the stress analysis confirms that the design of the S/F storage trays and supports meet the code requirements under a DBE earthquake.

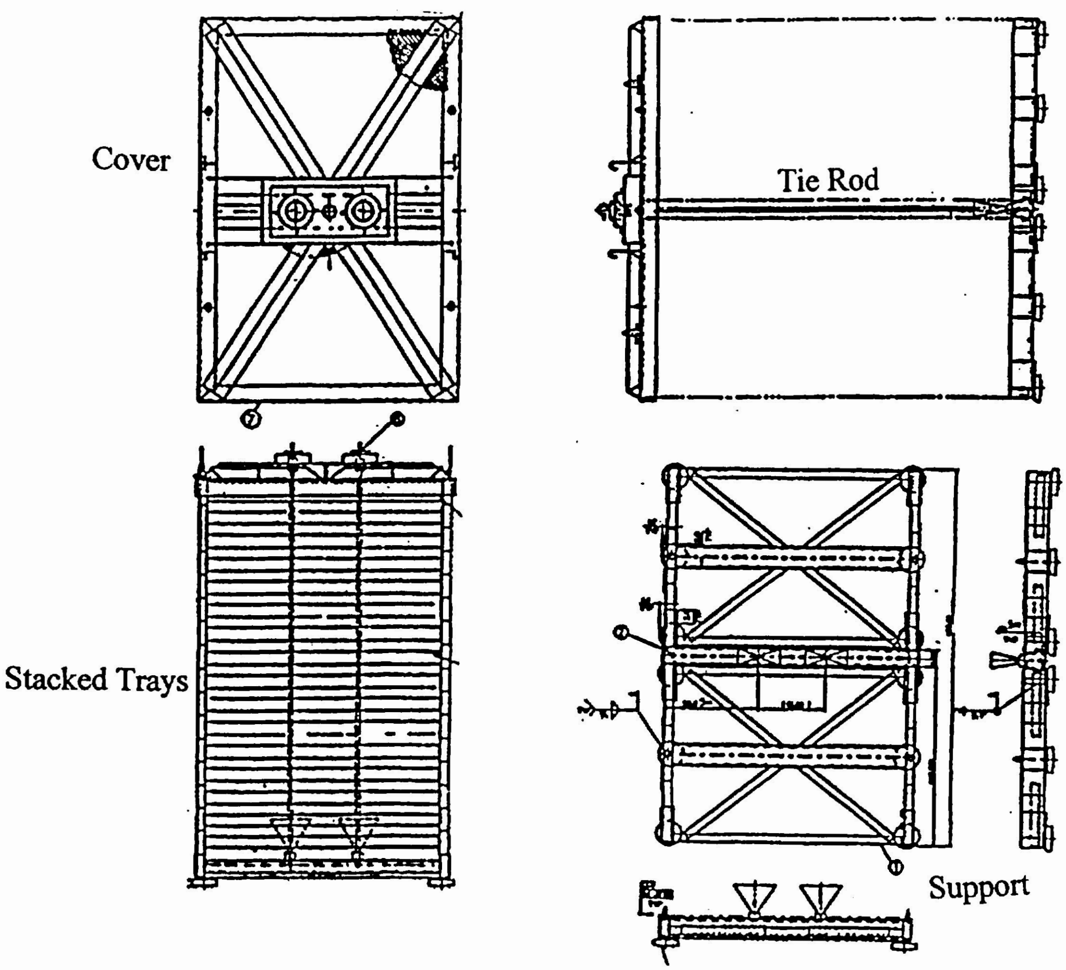


Figure 1: S/F Storage Stacks Grouped in 2X1 Arrangement

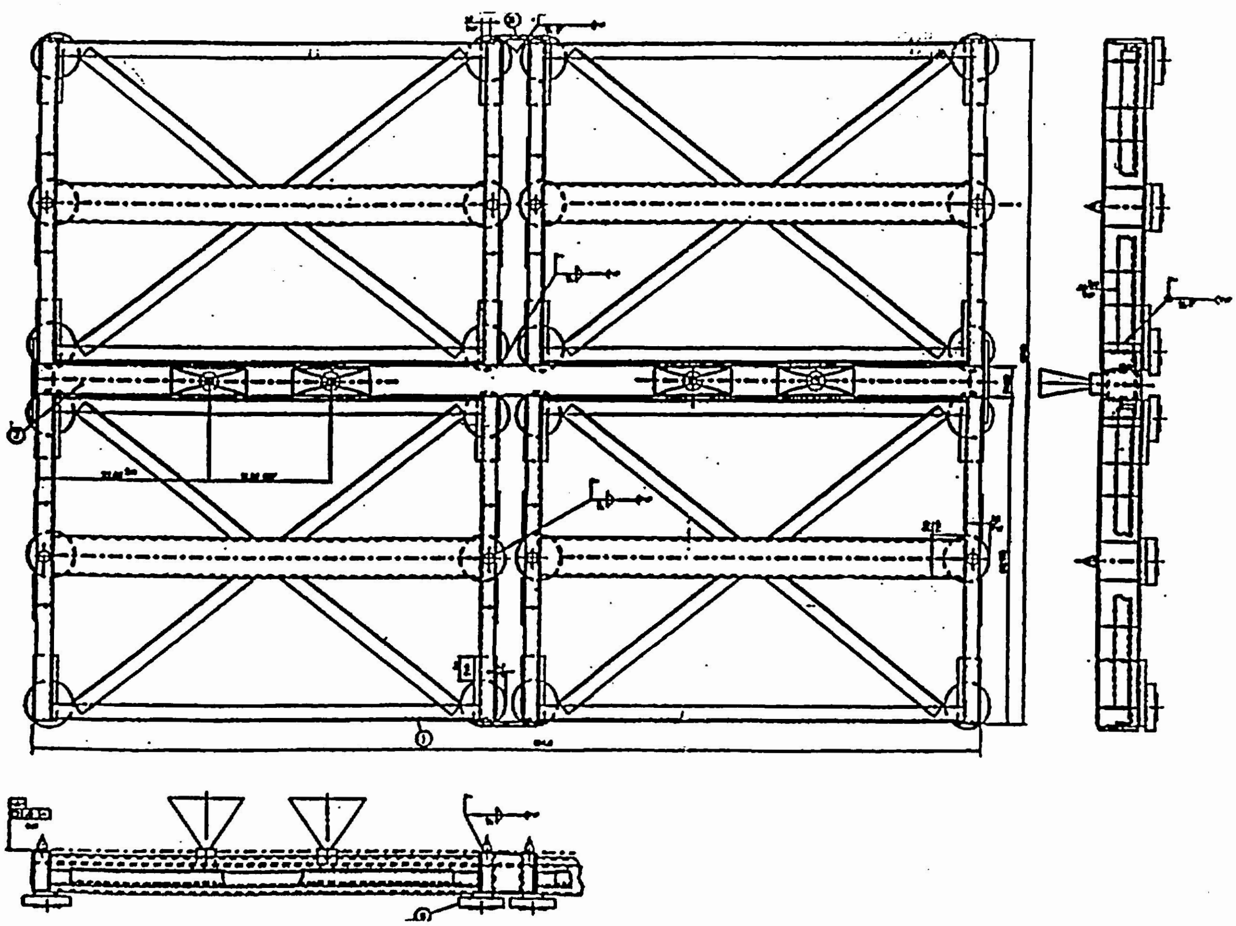


Figure 2: Tray Supports Connected in 2x2 Arrangement

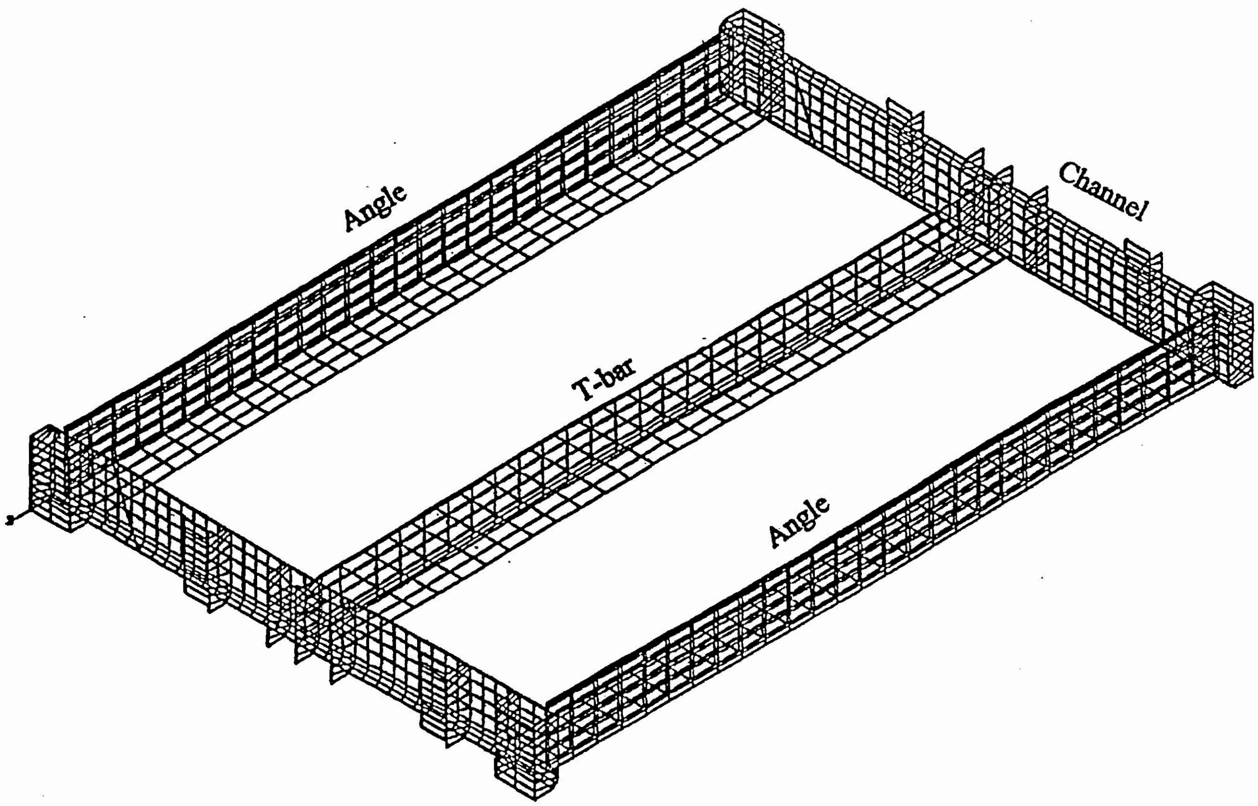


Figure 3: Finite Element Model for Spent Fuel Storage Tray

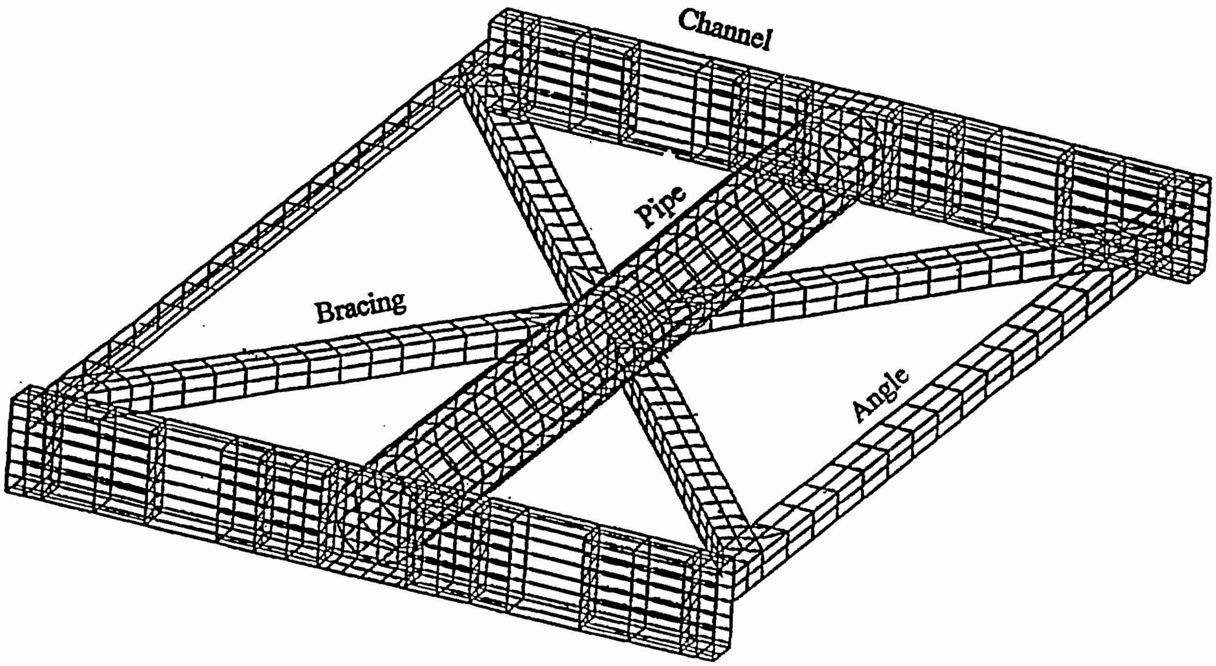


Figure 4: Finite Element Model for S/F Storage Tray Support

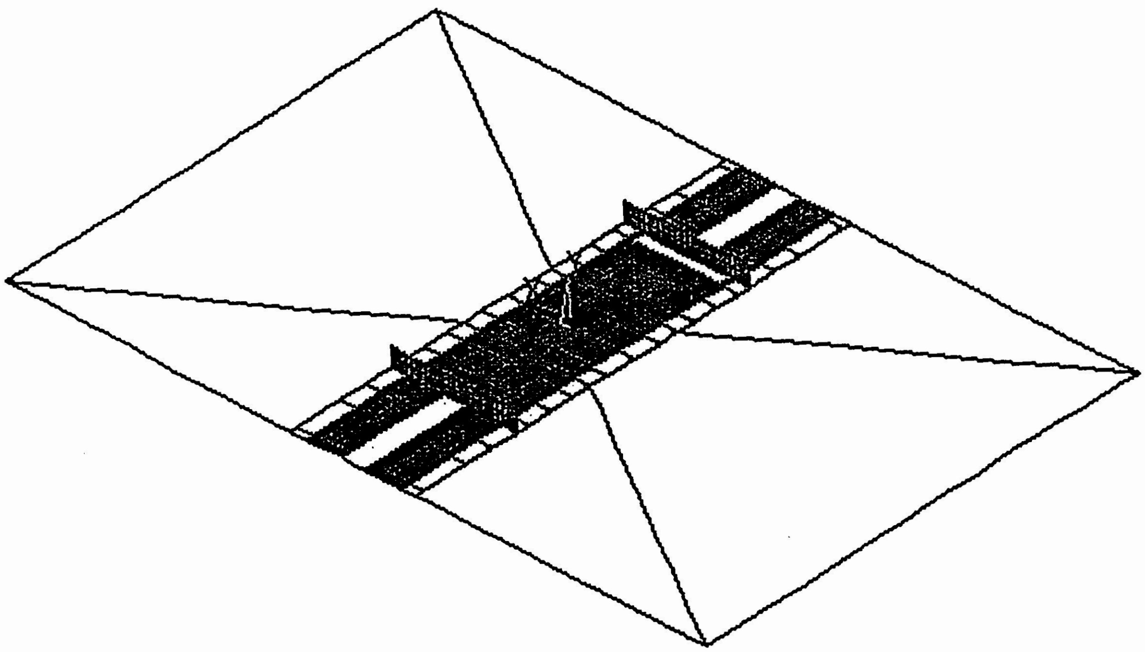
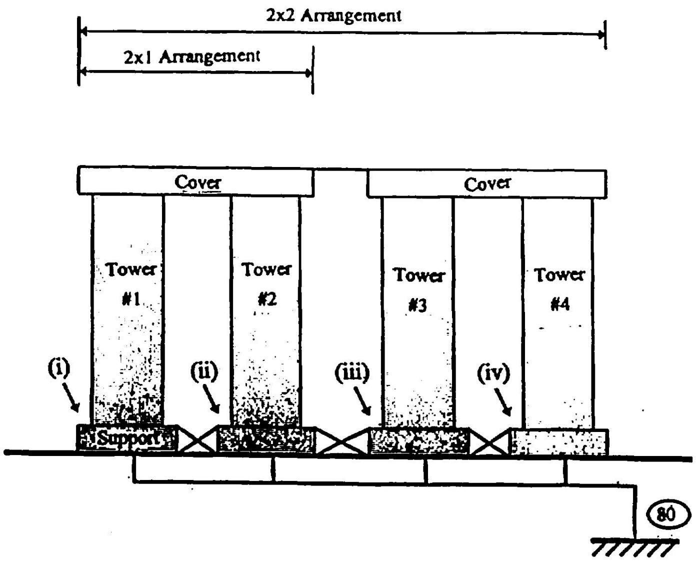
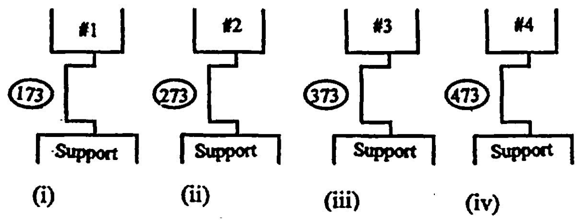


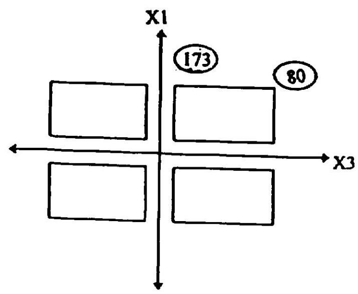
Figure 5: Finite Element Model for S/F Storage Cover



(a) Grouped Stacks



(b) Off-set Beams for Tower of Trays



(c) Off-set Beam No. 80

Figure 6: Global Seismic Model of 2x2 Grouped Stacks with Cover