STRUCTURAL ANALYSIS OF FUEL HANDLING SYSTEMS

by

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ABSTRACT
The purpose of this paper has three aspects: (i) to review "why" and "what" types of structural analysis, testing and report are required for the fuel handling systems according to the codes, or needed for design of a product, (ii) to review the input requirements for analysis and the analysis procedures, and (iii) to improve the communication between the analysis and other elements of the product cycle.

The required or needed types of analysis and report may be categorized into three major groups: (i) Certified Stress Reports for design by analysis, (ii) Design Reports not required for certification and registration, but are still required by codes, and (iii) Design Calculations required by codes or needed for design.

Input requirements for structural analysis include: design, code classification, loadings, and jurisdictionary boundary. Examples of structural analysis for the fueling machine head and support structure are given.

For improving communication between the structural analysis and the other elements of the product cycle, some areas in the specification of design requirements and load rating are discussed.

1. INTRODUCTION

Quite often the analysis part of the product cycle is hidden in the underworld or undervalued if not ignored, or is taken for granted. This paper reviews and highlights the main features involved in the structural analysis and hopefully promotes mutual understanding and appreciation among the analysis and other elements of the design-analysis-fabrication-installation-operation-and-maintenance product cycle of the fuel handling systems in a CANDU nuclear power plant.

2. WHY AND WHAT TYPES OF ANALYSIS AND REPORT

Why and what types of analysis and report are required or needed? As part of the Component Design Document (per CSA N285 series, References 1 to 4) or the Design Output Documents (per ASME Boiler and Pressure Vessel Code, Article NCA-3550, Reference 5), types of analysis, testing and report required for structural integrity achievement for fuel handling components and supports are summarized below:

(1) Certified Stress Reports for design by analysis (together with Certified Review of Design Report by the owner or his designee) are required for design registration for the following components and supports:

(a) Class 1, 1C and 4 components and their supports.

(b) Class 2 and 2C vessels designed to ASME NC-3200.

(c) Class 2 or Class 3 components designed to Service Loading greater than design loading.

Due to the early contract award requirements for some of the major fuel handling equipment a Provisional (Preliminary) Design Registration is usually applied and obtained when, at the time of application, the final Design Report or the final drawings are not completed. This allows for component fabrication or system installation to commence before a final design registration is obtained. In such a case, a Certified Provisional Report (or Base Design Report) may be substituted for a final design report. The Provisional Report only has to include the Design and Testing Conditions, not any Service (A, B, C and D) Conditions (see Section 4 for the design requirements). The purpose of the stress calculations is to show that primary stresses are within allowable limits to prove adequacy of material thickness.

(2) Certified Design Report Summary may be furnished in lieu of a Certified Design Report for standard supports (Class 1, 2, 3 or 4) designed by analysis (provided by the manufacturer).

(3) Design Reports not requiring certification and registration are required by the codes for:

(a) Class 2 and 2C non-standard support.

(b) Class 3 and 3C pressure-retaining systems and components.

(4) Load Capacity Data Sheet and catalogue for Class 1, 2, 3, 4 and 6 standard supports to be qualified by load rating method. The Load Capacity Data Sheet shall identify the tests and calculations used to establish the load capacity (per Article NCA-3551.2). This is important in order that the user (designer) can interpret correctly the load ratings used in the design and analysis (see Section 6 below). Also, it shall be certified by a Registered Professional Engineer for supports for Class 1 components, Class 4 vessels, and Class 2 vessels designed to NC-3200.

(5) Design calculations are needed for design and upon regulatory request are required for:

(a) Class 3 and 3C component supports.

(b) Class 6 pressure-retaining components and their supports.

(c) Design deviation due to fabrication errors (e.g. during post-order engineering).

(d) Modification of an existing design, e.g. change of configuration or material.

(e) Change of operating conditions, e.g. hot or ambient temperature F/M D_2O supply.

(f) Change of installation conditions, e.g. deviation of bolt pre-load torque, material substitute, layout change, etc.

(g) Item replacements or repairs due to fabrication discrepancy, actual or anticipated item failure (e.g. fatigue life shorter than the plant life).

(h) Conceptual design for firming up the member sizes.

(i) Others as needed, e.g. for intervening elements.

The Fueling Machine (F/M) Head Pressure Boundary is classified as Class 1 pressure-retaining component in CSA N285.0 and N285.1, and by reference, is designed to the requirements of the ASME Subsection NB. The Fueling Machine Support systems are usually composed of structural supporting elements and mechanisms which are classified as Class 1C supports in CSA N285.0 and N285.2, and by reference, are designed to the requirements of the ASME Code, Subsection NF Class 1 component support. The classification of 1C, instead of Class 1, component support in CSA N285.2 is because that there is no rules in the ASME code for mobile support. Portions of the F/M supports, (e.g. an elevating bridge and carriage, and a mechanism such as a ball screw and nut assembly) have a mobility not usually found in supports for pressure-retaining components. One important consequence of the CSA classification is that materials specified in CSA-N285.6.9 can be used, which otherwise may not be ASME NF material.

No matter why or what type of analysis and document is required, the essential purpose of analysis is to ensure the structural integrity and the adequacy of the product design under various service conditions.

3. CLASSIFICATION AND JURISDICTIONARY BOUNDARIES OF COMPONENTS AND SUPPORTS

Classifications of pressure-retaining systems, components, and their supports are stipulated in CSA N285.0. The jurisdictionary boundary consideration involves boundaries between components and their supports, attachments, intervening elements, and building structures. The boundaries for Class 1, 2, 3, 4 and their supports are shown in NB-1130, NC-1130, ND-1130, NE-1130 and NF-1130 respectively. The specific boundaries of jurisdiction between these structures shall be clearly defined, e.g. in the Design Specification.

For the purpose of defining the jurisdictional boundary between a component or piping support and the building structure, they should be shown in respective drawings (civil/structural drawings or support drawings). The key criterion for NF support structure is that they are installed and used for the "primary purpose" of supporting piping or components. In general, a bolted connection between the NF support structure and the building structure should be designed as part of the building structure. Whereas, if the means by which the NF structure is connected to the building structure is a weld, the weld shall fall within the jurisdiction of the NF support. One simple rule for determining whether the connection design belongs to NF can be that: the analysis of the connection design need not involve the design of the building structure, otherwise, the connection design should be part of the building structure.

An attachment is an element in contact with or connected to a component or support structure. It may have either a pressure retaining or nonpressure-retaining function and either a structural or nonstructural function. Structural attachment which has pressure retaining function or is in the support load path should be treated as part of that pressure-retaining component or the support structure.

Sometimes confusion may be caused by intermittent structural elements as to whether they should be treated as NF supports or Intervening Elements. Intervening Element by definition is a structural element in the support load path for a pressure-retaining component for which a major purpose is other than to "passively support" the component. It is noted that the "means" (bolted or welded) by which the component or piping support is connected to the intervening element shall fall within the jurisdiction of component or piping support. Intervening Elements are not registered, but when required by the regulatory authority, design criteria and supporting calculations shall be submitted.

4. DESIGN REQUIREMENTS AND ANALYSIS PROCEDURES

Input requirements for structural analysis must be provided before analysis can proceed. The design basis of plant and system operating and testing conditions is stipulated in NCA-2140 and is based on the system safety criteria and operability of components and supports. Based on the plant and system operating and test conditions, Design, Service (A, B, C and D), and Test Loadings are established; its criteria are explained in NCA-2142.4

The structural analysis is performed by a designer or analyst as an N Certificate Holder. The structural integrity and safety achievements are ensured and stipulated in the codes partly by:

(a) control of material.

(b) only certain types of design or construction are allowed, e.g., for welded and bolted flanged connections.

(c) acceptable stress analysis procedures and stress limits with safety margins which are compatible with the class of construction and specification of loadings.

On the other hand, the operability of components (whether the design works for the functional purposes), including leaking, seem not to be emphasized by the codes. The assurance of operability is up to the owner (or his designee) to define the appropriate limiting parameters. However, code rules apply to the operability of pressure relief valves.

4.1 Design Requirements

The rules for construction of Class 1, 2, 3 and 4 (MC) nuclear components and their supports are given in the ASME Code, Subsection NB, NC, ND, NE and NF respectively. The owner shall provide or cause to be provided the design requirements and a design verification report for intervening elements. Design requirements should be defined in documents, e.g. design specifications. Article NCA-3252 stipulates the required contents of Design Specification. As a minimum, the design requirements should include the following information:

(a) Design, including drawings, and material specifications including impact tests.

(b) Code classification of components.

(c) Jurisdictionary boundary.

(d) Loadings for Design, Service and Test Conditions.

The loading conditions that shall be taken into account in designing component or support are specified in Article NB-3111, NC-3111, ND-3111, NE-3111 and NF-3111 respectively for Class 1, 2, 3, 4 components and their support structures.

4.2 Analysis Procedures

The rules of analysis procedure for Class 1, 2, 3 and 4 (MC) nuclear components and their supports are given in the ASME Code, Subsection NB, NC, ND, NE and NF respectively. Requirements for acceptability of design are stipulated in Article NB-3211, NC-3211.2, ND-3300, NE-3211 and NF-3131. They can be demonstrated by analysis or experiment tests. The analysis method can be either design-by-analysis or by design rules (e.g. ND-3300). For design by analysis, the classical method and/or finite element method can be adopted depending on the complexity of the structure geometry, the load types (pressure, temperature or seismic loads, etc.) and the requirements of the code allowable stress limits (primary vs. secondary stress, allowable stress intensity vs. allowable maximum stress, etc.). Highlights of the considerations for structural analysis in accordance with Subsection NB and NF are given below.

Class 1 Components (NB)

(1) The design details shall conform to the general rules given in NB-3130, including the minimum required thickness of shells.

(2) The stress limits for Design, Service, and Test Conditions are based on the stress intensity (i.e. maximum shear stress theory). Fatigue evaluation shall be considered for Service Lever A, B and Test Conditions.

(3) Protection against nonductile fracture shall be provided.

(4) Buckling should be evaluated, e.g. under external pressures.

NF Support Structure

(1) Types of supports are given in Article NF-1212, NF-1213, NF-1214. Standard supports and catalog items are supplied by a Quality System Certificate Holder as material, including Certification of Load Capacity Data Sheets and Design Report Summary.

(2) Analysis procedure by: (i) design by analysis, (ii) experimental stress analysis, and (iii) load rating method.

(3) NF support needs not include thermal or peak stress, except for high cycle fatigue, n > 20,000 cycles, for Class 1 Linear Type support.

(4) Buckling should be evaluated, e.g. for beam type elements of F/M support bridge and columns.

(5) Protection against nonductile fracture for Class 1 component and piping support should be considered.

(6) There are three types of supports: (i) Plate-and Shell-Type support, (ii) Linear Type Support, and (iii) Load Rated Support. The stress limits for Class 1 Plate-and Shell-Type supports are defined by the design stress intensity (Sm) which is based on the maximum shear; others are defined in terms of the allowable stresses (S) which are based on the yield strength of material and the maximum stress (principal stress). For bolting, the limits are based on the yield strength and the ultimate strength.

5. ANALYSIS EXAMPLES

5.1 F/M and Support Structure Seismic Analysis

Earthquake loads are part of the loading conditions (as Level C Service loads) for the F/M head pressure boundary components and the support structure. They are also required for the interfacing systems, i.e., F/M process system, reactor structure, fuel channels, and feeders of the PHTS. Seismic analysis of the F/M and the support structure is therefore carried out to generate the seismic loads.

The seismic analysis methodology follows the requirements and procedures of the National Standard of Canada CAN3-N289.3-M81 (Reference 6). Seismic models have been constructed using beam and spring elements for various systems, e.g. the F/M, the support structure and the reactor. For examples, see Figures 1, 2, and 3. To account for various operation modes during the re-fueling process, seismic models representing various configurations have been developed:

(a) F/M attached or unattached to the reactor in the reactor vault area, with the F/M located at seven representative fuel channel locations (A11, E03, E20, K11, P02, S20, W11).

(b) F/M on the maintenance lock track, five configurations were considered: (i) unattached at centre of track, (ii) unattached at new fuel port location, (iii) unattached at spent fuel port location, (iv) attached to new fuel port, and (v) attached to spent fuel port.

For the F/M seismic analysis, the input earthquakes are the F/M support points motions, in terms of floor response spectra or acceleration time-histories, which are generated from the reactor building seismic analysis by the Civil design group. The input motions take into account the effects of the variation of soil conditions at the site and the sensitivity due to the uncertainties of the structural properties (frequencies). The seismic loads resulted from the seismic analysis are represented in terms of nodal accelerations, beam end loads and third-level floor response spectra. These seismic loads are then used in the seismic qualifications (by analysis or test method) of the affected systems.

5.2 Stress Analysis of F/M Head Pressure Boundary
The F/M head assembly consists of a number of major sub-assemblies: a snout assembly, a magazine assembly, a ram assembly and two separators. The housings for these sub-assemblies form the pressure boundary of the F/M head. Loads and load combinations for Design, Service Level A, B, C, and Test Conditions for the F/M head pressure boundary were defined in a design specification. Final detailed stress analysis and report was prepared and certified by the author and the third-party reviewer. It formed part of the submission for the final design registration in accordance with the requirements of References 1 and 5.

The methodology adopted in the stress analysis of the F/M head pressure boundary components makes use of an optimum combination of classical and finite element (FE) methods. The stress analysis is based on linear elastic static analysis except for some assemblies in which non-linear gap elements are used in the FE method to simulate the interaction behaviours under various loading conditions at the contacted face between two components.

In the finite element method, the trend is to utilize computer-aided capabilities for modeling and meshing. Ideally, the mechanical design automation tools used should able to provide direct interface between the design models, the drafting models and the analysis solid models. The analysis solid models are usually simplified to remove unnecessary details. Figure 4 shows such a FE model for the magazine housing, which was generated by using I-DEAS software package (by vendor SDRC).

5.3 Stress Analysis of F/M Support Structure
The F/M head assembly and the cradle assembly are supported from the F/M carriage. The carriage is suspended from rails on the bridge in the reactor vault area (Fig. 2) or on the track frame in the maintenance lock area. The F/M support structure is analyzed in accordance with the analysis procedures stipulated in Subsection NF (as described in Section 4.2) as:

(a) Beam (linear) type elements in the cradle assembly, the bridge and the columns.

(b) Non-beam type elements (plate and shell) in the cradle, the carriage, the bridge and the column assemblies.

(c) Load rated mechanisms of manufacturer's proprietary components in the carriage, and the bridge-elevator interface. There are 19 load rated components used in the F/M support structure as listed in Table 1.

6. INTERACTIONS BETWEEN ANALYSIS AND OTHER ASPECTS OF PRODUCT CYCLE

Various elements of the product cycle need the service of structural analysis (see Section 2) while the latter requires input from the former (see Section 3 and 4). Mutual understanding, appreciation, and efficient communication among them are important for a successful product. Experience indicates that some areas within the interfaces warrant improvements. Examples are given below:

(1) The required information for analysis should be provided "timely and adequately". This is vital in order to avoid repeated analysis. Prior to contract award, it is essential that the requirements (e.g. design specifications) be clear and available.

(2) Have a section on "Requirements for Analysis" included in the design specifications to provide specific instructions for analysis. Examples can be:

(a) The component can be defined as piping, while the analysis, for convenience, can be based on the requirements for vessel.

(b) Analysis can be optionally based on a higher class (usually means higher allowable limits) than the class of which the component is classified. In this case, the material requirements for the higher class shall be satisfied.

(3) For non-standard NF supports, do not specify (e.g. on drawings) the type of support, whether Plate- and Shell-Type or Linear-Type. The type of support to be assumed in the analysis should be determined by the analyst depending on the geometry complexity and the load distributions.

(4) Procedures for determining load ratings for Plate- and Shell-Type and Linear-Type support are provided in ASME NF-3280 and NF-3380 respectively. The

load ratings are defined for Level A, B and C (including seismic) Service Loading. The load ratings provided by the manufacturers, in terms of test reports, Load Capacity Data Sheets or catalogues, should be compatible with the NF definitions. For instance, the load ratings given in catalogue as "static" or "dynamic" can be determined by testing conditions and failure mechanisms which may be quite different from the required ASME NF testing procedures or the actual operating conditions. Similarly, the "capacity" rating given in some catalogues can be established based on the fatigue life while the load ratings stipulated in the ASME NF procedure are based on the ultimate load failure criterion. Any discrepancy in the compatibility of the definition between the ASME NF and manufacturer's can create confusion and mis-application for analysis.

(5) If a Provisional (Preliminary) Design Registration has been applied and obtained, see Section 2, therefore, component fabrication might have commenced before the results of the final structural analysis are completed. It can happen that the Service Conditions (considered in the final Design Report, but not in the Provisional Report), e.g. seismic loads or fatigue life, indicates that the preliminary design may not be adequate. This requires an extra effort on the structural analysis to remove any fictitious overstress that might result in order not to modify design during manufacture. Close coordination between the structural analysis, design, manufacturing and maintenance (e.g. item replacement due to short fatigue life) are vital in order to find an acceptable solution.

7. CONCLUSIONS

This paper describes the basic requirements and procedures for structural analysis in accordance with the codes. To satisfy the code requirements is necessary, however, to have the analysis work done in a cost effective manner is vital to the overall success of a project. This paper has highlighted some areas for the improvement of the work method, especially the interface between the structural analysis and the other elements of the product cycle.

8. REFERENCES

(1) National Standard of Canada CAN/CSA-N285.0, "General Requirements for Pressure-Retaining Systems and Components in CANDU Nuclear Power Plants".

(2) National Standard of Canada CAN/CSA-N285.1, "Requirements for Class 1, 2, and 3 Pressure-Retaining Systems and Components in CANDU Nuclear Power Plants".

(3) National Standard of Canada CAN/CSA-N285.2, "Requirements for Class 1C, 2C, and 3C Pressure-Retaining Components and Supports in CANDU Nuclear Power Plants".

(4) National Standard of Canada CAN/CSA-N285.3, "Requirements for Containment System Components in CANDU Nuclear Power Plants".

(5) ASME Boiler & Pressure Vessel Code, Section III, Subsection NCA, NB, NC, ND, NE and NF.

(6) National Standard of Canada CAN3-N289.3, "Design Procedures for Seismic Qualification of CANDU Nuclear Power Plants".

Table 1 NF-Grade Load Rated Components in F/M Support Structure

No.	F/M Support Structure	Load Rated Component
1	Cradle Trunnion Bearing (Fixed End)	Spherical Roller Bearing
2	Cradle Trunnion Bearing (Free End)	Cylindrical Roller Bearing
3	Cradle Ram Assembly Cam Followers	Rollerway
4	Carriage Wheel	Wheel
5	Carriage Wheel Bearing	Wheel Bearing
6	Carriage 'Z' Guide Cam Followers	Camrol Bearing
7	Carriage Cam Follower	Camrol Bearing
8	Carriage Fine 'Y'-Drive Screw Jacks	Screw Jack
9	Gimbal Roundway Bearing	Roundway Bearing

Table 1 (continued)

No.	F/M Support Structure	Load Rated Component
10	2" Gimbal Roundway	Roundway
11	Upper Gimbal Turntable Bearing	Sleeving Bearing
12	Carriage Seismic Clamp	Thrust Bearing
13	Carriage 'Z' Motion Drive	Hydraulic Cylinder
14	Elevator Roundway Bearing	Roundway Bearing
15	Elevator Roundway	Roundway
16	Bridge Ball Screw	Ball Screw
17	Bridge Screw Jack	Screw Jack
18	Bridge Screw Nut	Ball Nut Thrust Bearing
19	Bridge/Elevator Camrol Bearing	Camrol Bearing

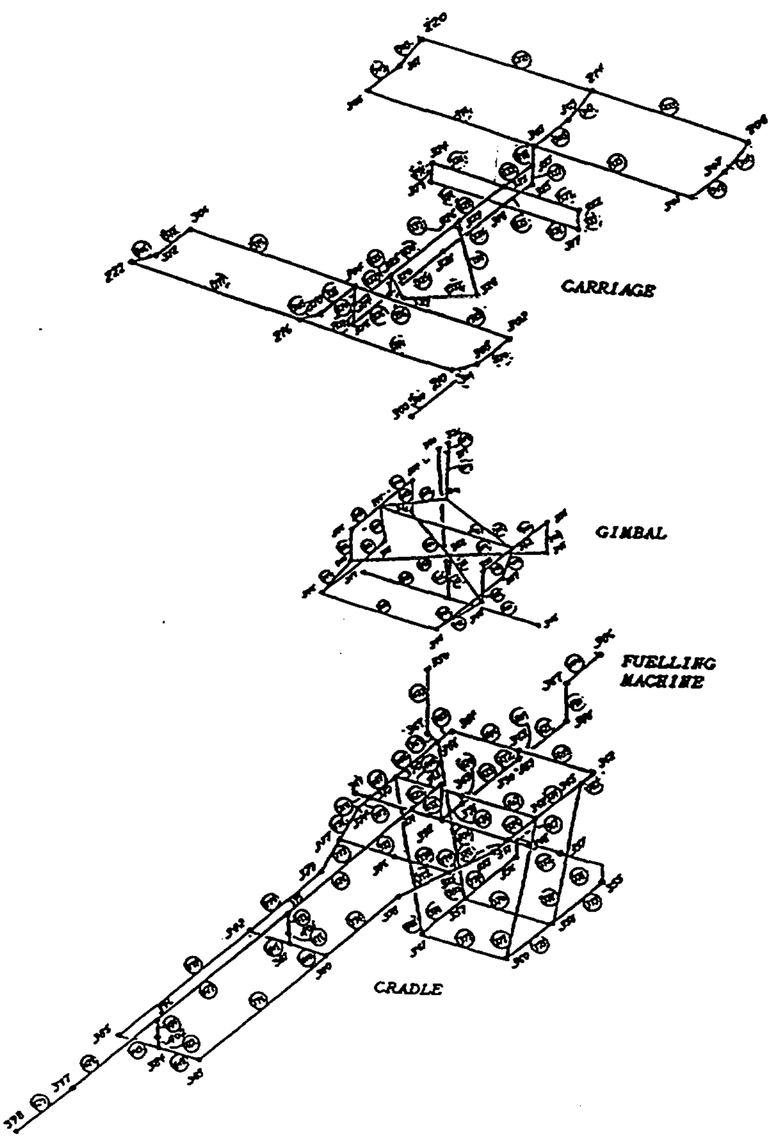


FIGURE 1 FUELING MACHINE AND CARRIAGE SEISMIC MODEL

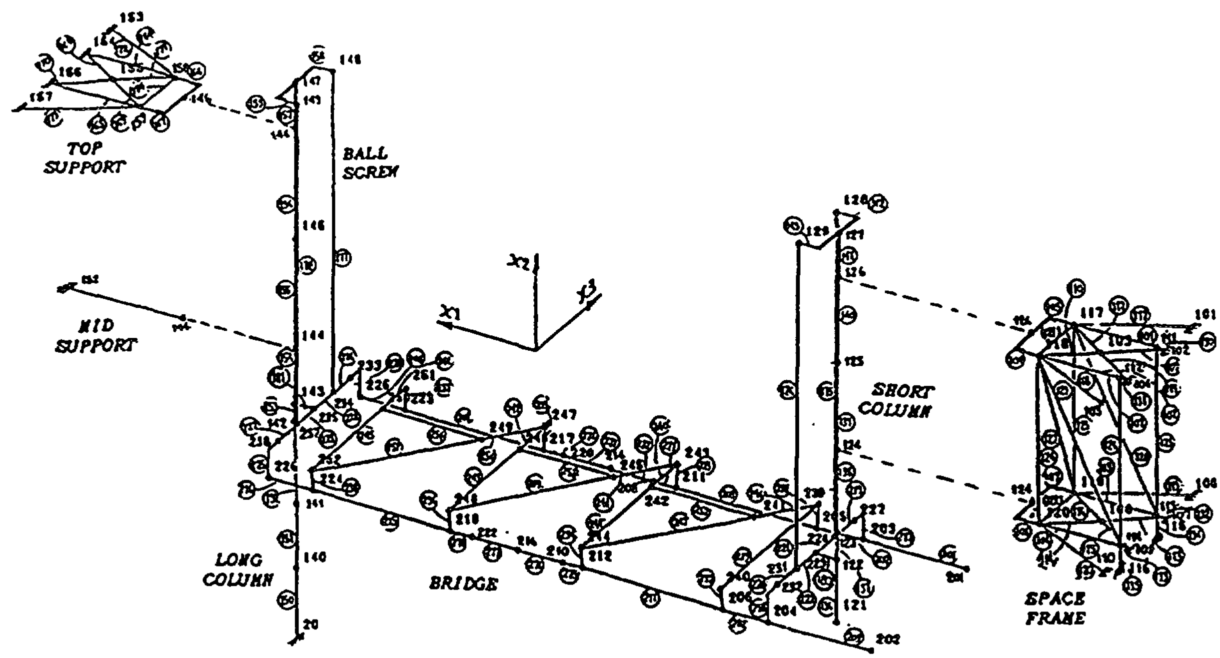


FIGURE 2 BRIDGE AND COLUMN SEISMIC MODEL (for Fuel Channel Location W11)

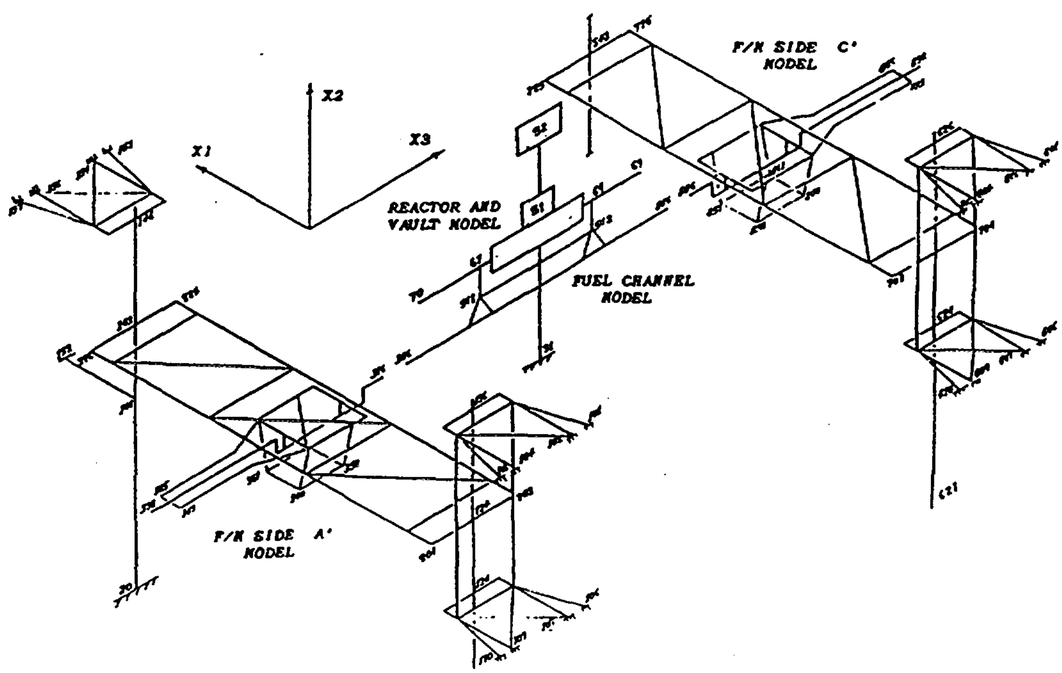
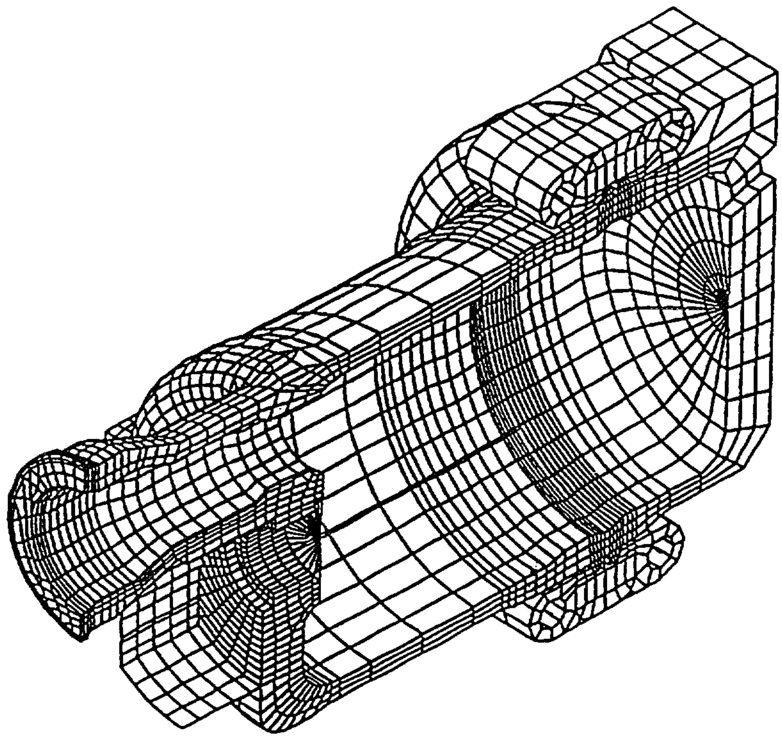
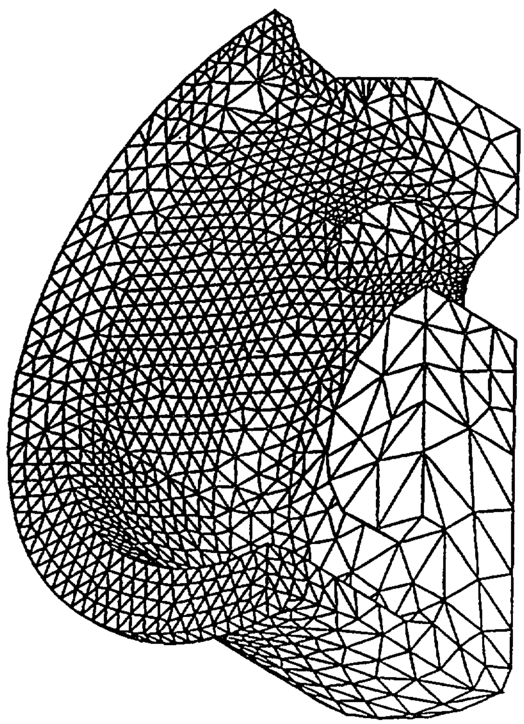


FIGURE 3 ATTACHED FUELING MACINE AND REACTOR SEISMIC MODEL



(a) Global Model



(b) Submodel of the End Cover

FIGURE 4 FINITE ELEMENT MODEL OF F/M MAGAZINE