Modal Analysis of Light Ion Beam Fusion Reactor Vessels

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ABSTRACT

Light ion beam inertial confinement fusion reaction vessels will be subjected to intense dynamic overpressure and heat flux from nuclear microexplosions. The conceptual design proposed consists of a cylindrical chamber with hemispherical ends. The shell structure is supported by a gridwork of ribs and stringers. Modal static deflections and stresses for panel and beam components are developed in parametric form. The dependence of modal dynamic load factors upon the pulse shape of the fireball blast wave are identified. Maximum DLF values are determined and characterized as functions of flexural frequencies for the various structural components. The dynamic response is determined by coupling the static results with the appropriate dynamic load factors.

INTRODUCTION

A conceptual design for a light ion beam fusion research facility has been developed by the University of Wisconsin Fusion Engineering Program[1]. Figure 1 is a schematic representation of the facility. The pulsed power system is based upon the PBFA-I driver of the Sandia National Laboratories. Marx capacitor banks are located in the outermost oil-filled annular region. In the intermediate water-filled annulus are the pulse forming lines and secondary storage capacitors. The central region contains borated water for radiation shielding. Within this also are the magnetically insulated lines which transmit power to the reaction vessel. This shell structure has a cylindrical chamber with a height and diameter of 6 meters; the ends are hemispherical caps. The target yield is 200 MJ in a cavity gas of xenon at 70 torr. Materials considered for the reaction vessel include Al 6061 and 5086, 304SS, HT-9, Ti-6Al-4V, Cu-Be C17200 and C17600. Of these, the aluminum alloys have the best combination of relevant characteristics: high strength to mass ratio, low cost, good induced radioactivity response and thermal shock resistance.

GENERAL STRUCTURAL DESIGN CONSIDERATIONS

One of the major influences on the mechanical design of the reaction chamber is the shock wave

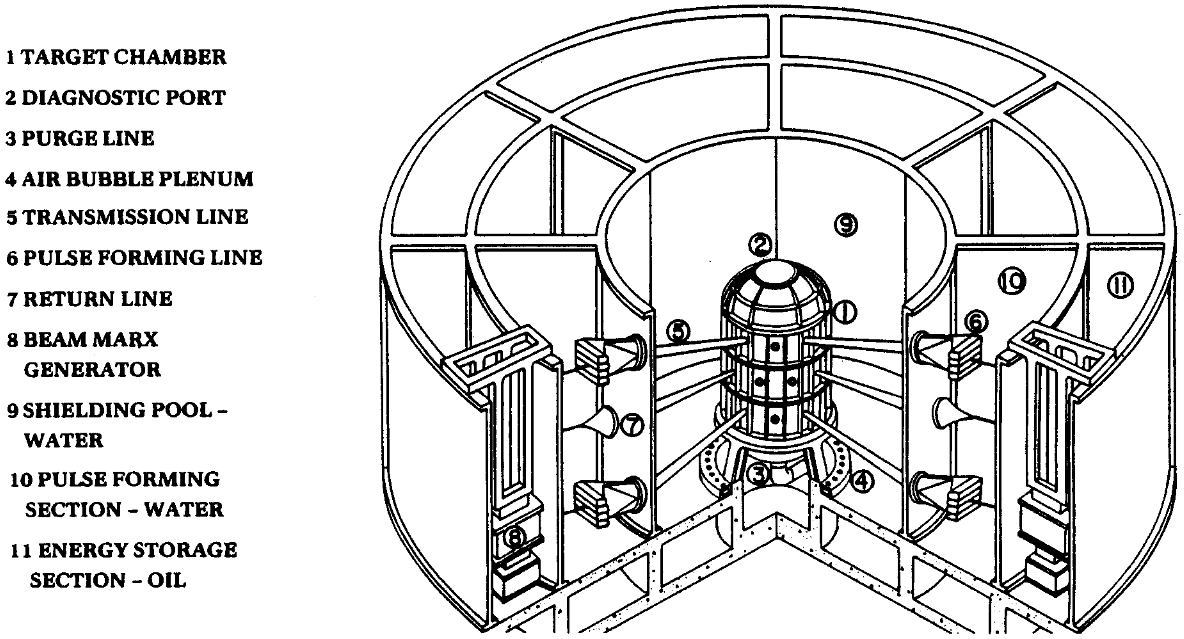

Figure 1. Conceptual Light Ion Beam Fusion Research Facility

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[1] Work supported by Sandia National Laboratories, Albuquerque, New Mexico.

generated by the fireball. This dynamic pressure is essentially uniformly distributed over the surface of the wall. If the wall structure is modelled as a perfect isolated thin cylindrical shell, then the radial pressure distribution will be sustained by uniform circumferential normal stress. In other words, such a concept is essentially a thin-walled tube in which the pressure generates circumferential stresses and complimentary axial normal stresses. Accounting for distributed mass and elasticity for this model will lead to dynamic response characterized by a breathing mode in which each cross section remains circular, expanding and contracting in simple harmonic motion following the mechanical shock.

However such an idealized state will not be realized in an actual chamber because of a variety of mechanical constraints including beam ports and external supports. Thus a more practical concept is a shell with a structural reinforcement system. Since the overall shape is cylindrical, a configuration with axial stringers and circumferential ribs is consistent. This is shown schematically in Figure 1. While the vertical stringers directly support the wall, the ribs either provide the same support or are offset, encircling the stringers and contacting only them. Consequently a fundamental component of the wall is considered to be a flexural plate element as shown in Figure 2, appropriately supported at some orientation and distance from the cavity center. For more general applications this could be a generic "building block" for other chamber geometries.

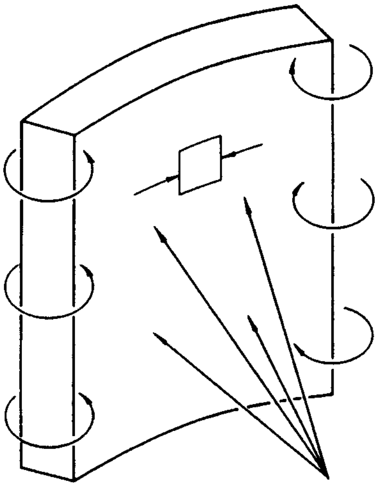

Figure 2. Dynamic Flexure of First Wall Plate.

PLATE MECHANICAL ANALYSIS

Wall response analysis for mechanical shock loading requires specification of a number of mechanical characteristics, including identification of plate support conditions. At a rib or stringer it is assumed that a plate edge is constrained. The geometric conditions implied by this are essentially the same for a substantial connection or for a continuous plate spanning many beams at those locations where it bridges such supporting members, i.e., rotations and relative edge deflections are negligible. Thus the unit analyzed is a rectangular plate with so-called "clamped" or "built-in" edges. This may be a single plate or it may be a subdivision of a large plate supported by a number of ribs and stringers.

Radial pressure applied to the plate surface facing the cavity produces circumferential normal stresses which are tensile at the edges and compressive in the central region as indicated in Figure 2. Axial normal stresses would vary in a similar manner in the vertical direction. The relative side dimensions of the plate (aspect ratio) affect the magnitudes of these stresses. Typical results are shown in Figure 3 for uniform pressure. Stresses vary as the relative side dimensions change but quickly approach constant values for aspect ratios greater than two. These limiting magnitudes can be used for practical design purposes.

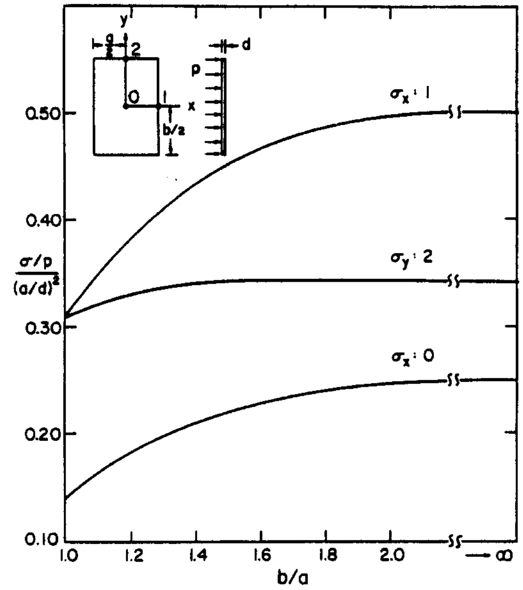

Figure 3. Dimensionless Static Stress vs. Aspect Ratio.

The dynamic analysis of the plate components can be developed by determining the quasi-static response and multiplying it by a dynamic load factor (DLF), or more accurately, a dynamic load function, to give the corresponding response. Deflections and stresses are proportional and therefore the dynamic load factor may be used in either case. Under uniform impulsive pressure, plate response can be adequately represented by a single degree of freedom system and thus the results for this model can be used to simplify the dynamic analysis.

In the discussion which follows, the dynamic loading exerted upon the plate is the product of an amplitude F_{max} and a time-dependent forcing function $f(t)$. The pressure pulse is modelled as a linear ramp with rise time t_r followed by an exponential function with a decay constant k. With damping, the dynamic load factors are rather complex and are reported in University of Wisconsin

Fusion Design Memorandum 478(1). The accuracy of the solution can be improved by including DLF's for as many modes as desired.

A sequence of computations is made in the design process. For example, it is necessary to determine natural frequencies; Figure 4 shows results as a function of thickness for candidate materials. Static deflections and stresses are found from design curves such as Figures 5 and 6. The dynamic load factors are determined for various frequencies and excitation parameters k and t_r. From these the maximum values are found. Generally these amplitudes are sensitive to the level of damping as indicated in Figure 7. Static deflections and stresses are then multiplied by the maximum DLF to obtain maximum dynamic deflections and stresses. Details of this procedure have been reported in

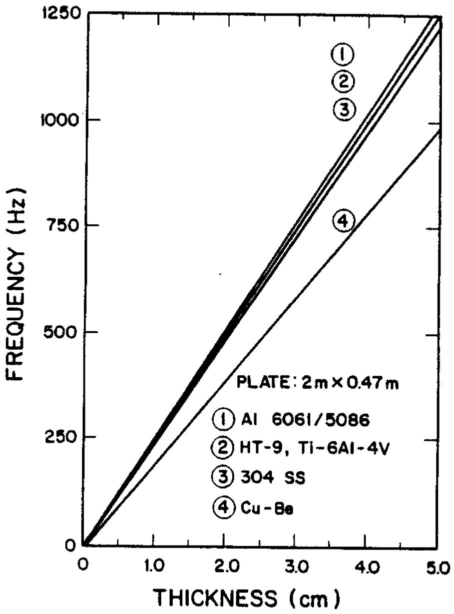

Figure 4. Fundamental Frequency vs. Plate Thickness.

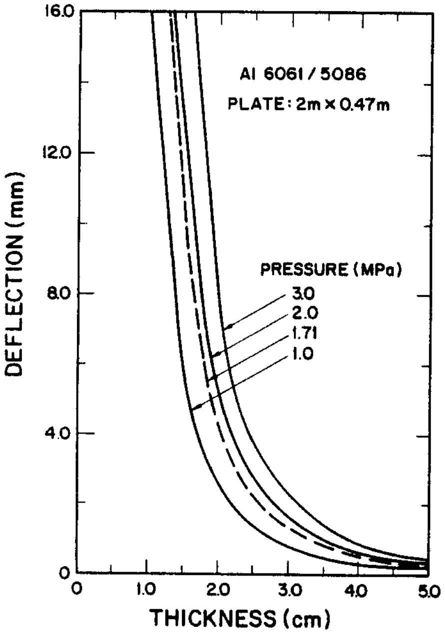

Figure 5. Midpoint Deflection vs. Plate Thickness.

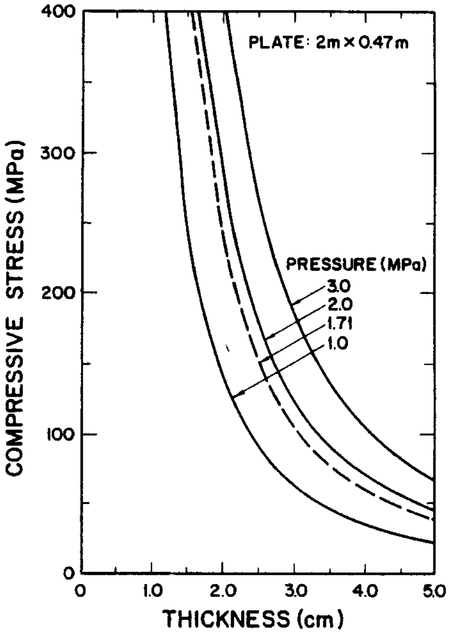

Figure 6. Flexural Stress vs. Plate Thickness.

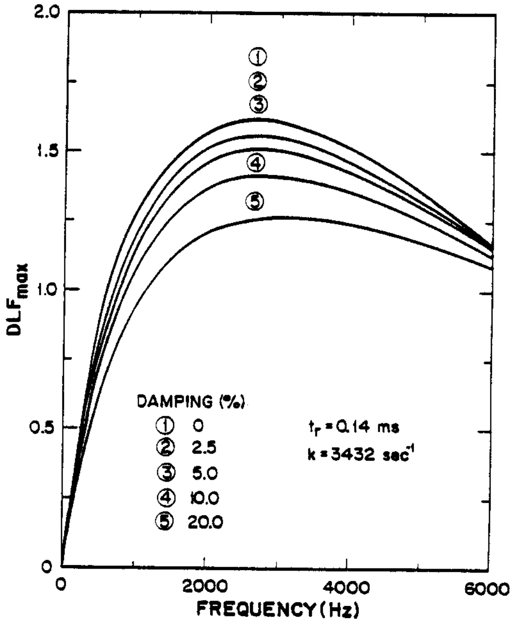

Figure 7. Maximum Dynamic Load Factor vs. Fundamental Frequency.

University of Wisconsin Fusion Design Memorandum 322(2). On the basis of the analysis, a computer code has been developed for the determination of frequencies, dynamic stresses and deflections for solid and hollow plates of various materials subjected to general time-dependent pressures. This program has also been coupled with a thermal stress program to produce the total stress history in a first wall plate.

PARTICULAR RESPONSE RESULTS FOR FIRST WALL PLATES

The plate is solid aluminum with 2.5% critical damping and a height, width and thickness of 200, 47 and 3 cm, respectively. The fundamental frequency of this component in flexure is 768.5 Hz (Figure 4). The 200 MJ target yield in 70 torr of xenon produces an overpressure of 1.71 MPa with t_r and k equal to 0.14 ms and 3432/sec, respectively. The corresponding equivalent static deflection and stress are 1.259 mm and 105.5 MPa (Figures 5 and 6). The maximum DLF was determined to be 1.088 (Figure 7) and thus the dynamic deflection and stress are 1.37 mm and 115 MPa. Figure 8 shows the circumferential normal stress profile across the horizontal midline of the cavity side of the plate. This distribution occurs during the first cycle of motion when the plate experiences its maximum outward radial displacement. For the same case the circumferential stress history is shown in Figure 9 for a point at the center of the plate surface facing the cavity. Note that compressive stress is plotted above the axis with the peak value corresponding to the midspan amplitude of Figure 8. This point was chosen for study since compressive thermal stress from the heat flux will add directly whereas flexural and thermal stress will counteract each other near the edges. The analytical form of the pressure pulse is superimposed to show its influence upon the response. It can be seen that initially the stress response follows the pulse and subsequently develops into free vibration.

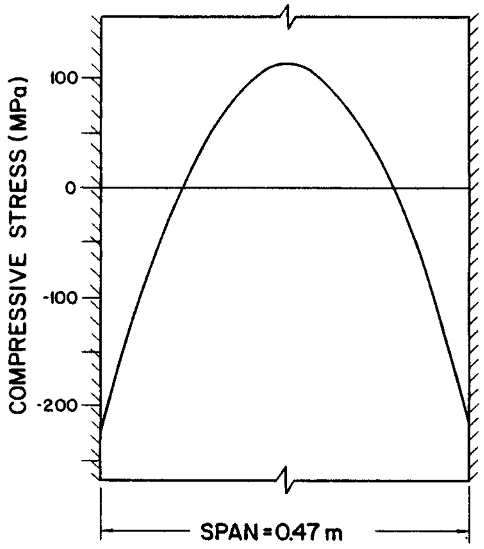

Figure 8. Flexural Stress Profile Across First Wall Plate.

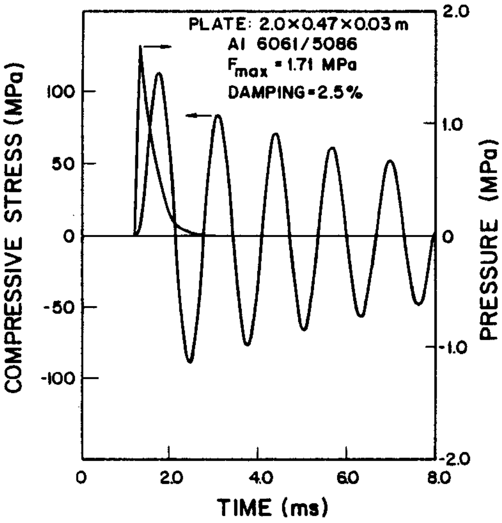

Figure 9. Pressure Pulse and Plate Stress vs. Time.

ANALYSIS AND DESIGN OF THE REINFORCING FRAMEWORK

The framework is modelled as a system of beams in which the curvature and hoop force capacity of the ribs are neglected. In addition, the plates are assumed to transmit the full strength of the overpressure without resistance from self-induced circumferential tensile stress. Such modelling will clearly lead to a conservative design.

The dynamic overpressure is taken as uniform over the plates and partitioned to the ribs and stringers as shown in Figure 10. The tributary

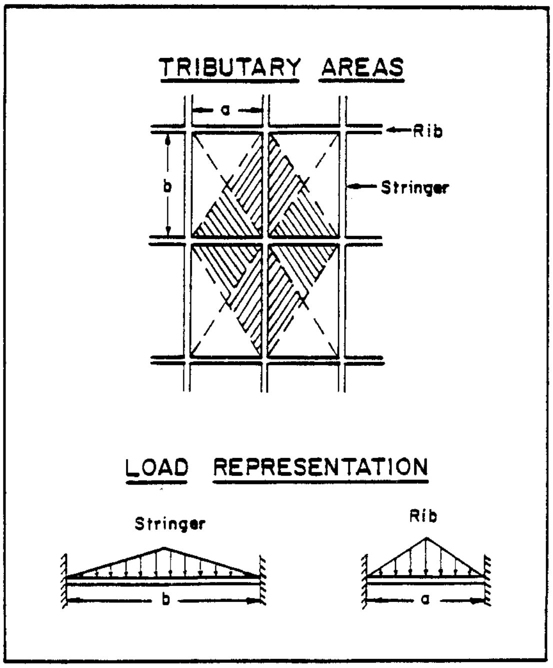

Figure 10. Load Partitioning to the Support Structure.

areas will produce uniformly varying line loads with maximum values pa and pb for stringers and ribs, respectively, where p denotes the maximum overpressure from the shock. The rib and stringer analysis is very similar to that used for the plates. The static response is first determined. This is subsequently modified by means of a Dynamic Load Factor (DLF) to account for dynamic effects. In this case, rib and stringer lengths have been chosen a priori. The design effort primarily involves the determination of cross section characteristics such that the mechanical stresses are within design limits and deflections are not excessive.

The analysis uses a prismatic beam element with uniform mass per unit length under a time-dependent loading which may be arbitrarily distributed but is eventually specialized to the profile shown in Figure 10. End conditions are characterized as "fixed," i.e., having negligible rotation. The effects of shear deformation, rotary inertia and damping are not included. It is necessary to calculate the natural frequencies and corresponding spatial mode shapes. These are used in a modal superposition method to determine the forced response. The deflection results are also used to compute the flexural moment (also a function of position and time) and thus the dynamic flexural stress.

QUANTITATIVE RESULTS FOR THE FRAMEWORK

A number of materials have been proposed for the wall panels and it would be practical to use the same alloy for the ribs and stringers. For these materials, the stringer and rib fundamental frequencies have been determined as functions of cross-sectional radius of gyration and are shown in Figures 11 and 12. It can be seen that the natural frequencies of ribs are approximately an order of magnitude greater than those of the stringers. This is an important design consideration since dynamic load factors are strongly influenced by the flexural frequency magnitudes.

The panel analysis was based on the loading from the 200 MJ target yield and this will be used for the frame as well, i.e., a maximum overpressure of 1.71 MPa at 1.32 ms, with t_r and k equal to 0.14 ms and 3432/sec, respectively. Thus the maximum DLF results of Figure 7 apply for these computations as well. Because of the relatively low frequencies of the stringers, the DLF will generally be less than unity but the rib DLF's will be substantially larger. The results have been used to develop design curves for dynamic flexural stress as a function of cross section modulus for both stringers and ribs. The overpressures cover a range of values and include the specific case of 1.71 MPa as shown in Figures 13 and 14. It should be noted that the stress graphs can be used for any elastic material under the given conditions. The design stress would be based upon both the yield characteristics of the material and the DLF. With this, the section modulus can be determined and thus the beam properties are established. In addition, deflections can be evaluated. For example in Figures 15 and 16, displacement is shown as a function of cross section moment of inertia for stringers and ribs.

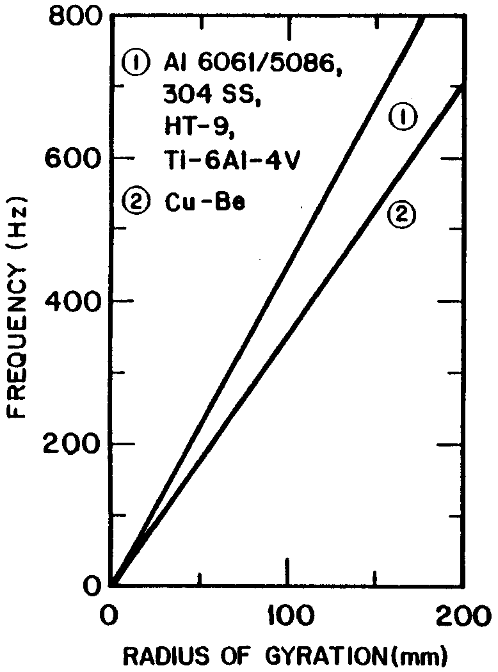

Figure 11. Stringer Fundamental Frequency vs. Cross-Sectional Radius of Gyration.

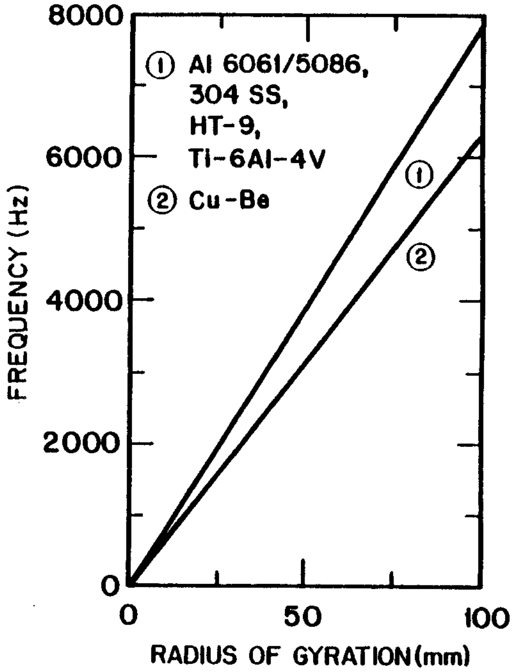

Figure 12. Rib Fundamental Frequency vs. Cross-Sectional Radius of Gyration.

NUMERICAL EXAMPLE FOR THE FRAMEWORK

A specific case is outlined here to illustrate the procedure. The material selected is aluminum 6061 with a yield stress of 276 MPa. The various design steps are summarized in Table 1 in which the following notation appears:

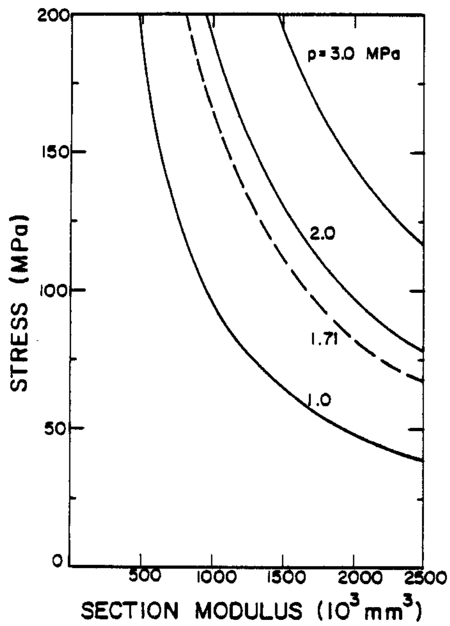

Figure 13. Stringer Flexural Stress vs. Section Modulus.

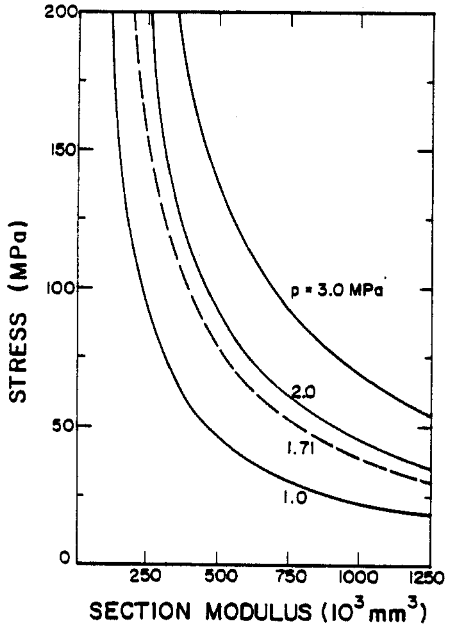

Figure 14. Rib Flexural Stress vs. Section Modulus.

I = major axis moment of inertia
S = major axis section modulus
r = major axis radius of gyration
ω = fundamental flexural frequency
σ = flexural stress
y = maximum transverse displacement

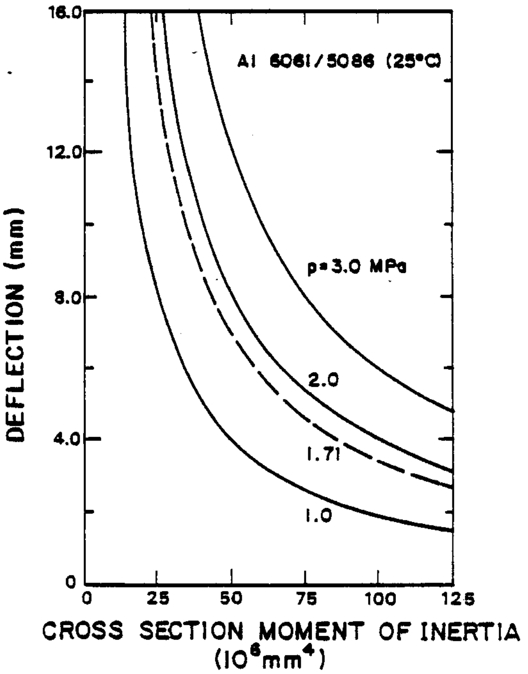

Figure 15. Stringer Deflection vs. Cross Section Moment of Inertia.

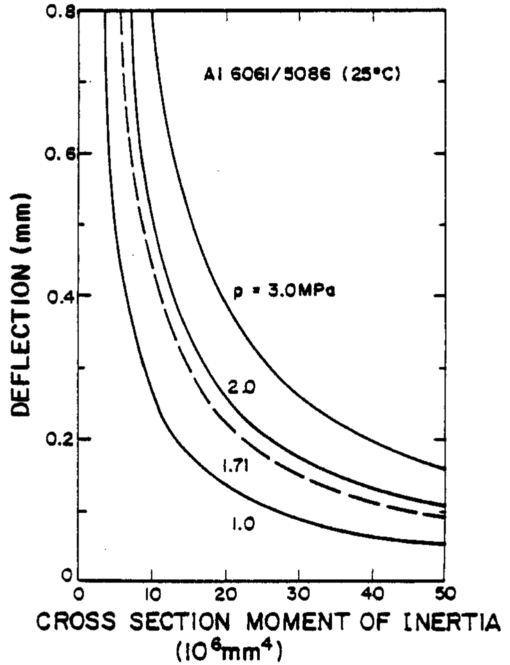

Figure 16. Rib Deflection vs. Cross Section Moment of Inertia.

Table 1. Structural Frame Design Example for Aℓ 6061/5086, Overpressure 1.71 MPa.

		STRINGER	RIB
1. STRUCTURAL TUBING DIMENSIONS FROM AISC MANUAL (IN.)		8×6×1/2	8×3×3/8
2. CROSS SECTION PARAMETERS FROM AISC MANUAL	I-in^4 (10^6mm^4)	103.0 (42.9)	51.0 (21.2)
	S-in (10^3mm^3)	25.8 (422.8)	12.7 (208.1)
	r-in. (mm)	2.89 (73.4)	2.64 (67.0)
3. STATIC RESPONSE FROM DESIGN CURVES	ω-Hz	330	5465
	DLF	0.65	1.27
	σ_s-MPa	391	187
	y_s- mm	7.94	0.21
4. DYNAMIC RESPONSE (UNDAMPED)	σ_d-MPa	254	238
	O.K.?	YES	YES
	y_d-mm	5.16	0.27
	O.K.?	YES	YES

It can be seen that the AISC manual has first been used to select the size of rectangular structural tubing. For each of these the relevant cross section parameters are listed. Next, the fundamental frequency is determined and consequently the DLF is established. Using the cross section modulus (S) and the moment of inertia, the static stress and deflection (σ_s and y_s) for each are found from the appropriate design curves. These in turn must be amplified by the DLF to give the corresponding dynamic response (σ_d and y_d).

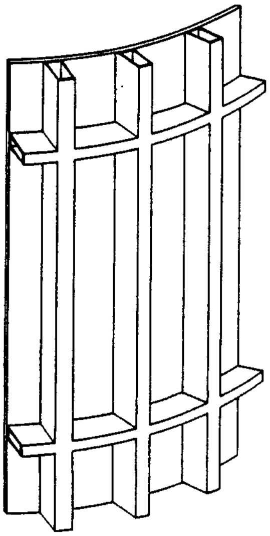

Figure 17. Conceptual First Wall Structural System.

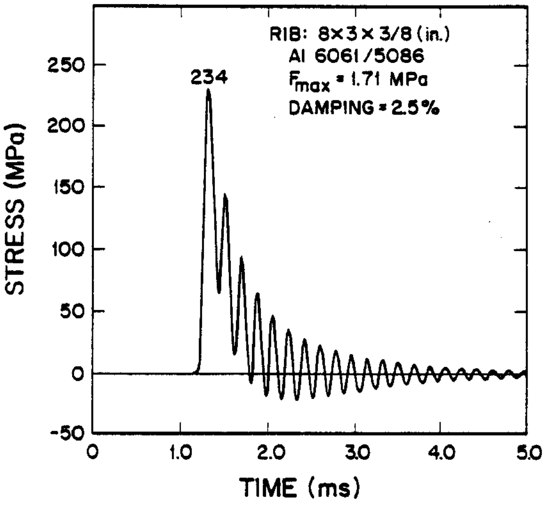

Figure 18. Rib Flexural Stress vs. Time.

From the sample calculations in the table it is observed that the stresses in the 8 inch tubing are below yield with acceptable deflections for both stringers and ribs. With these dimensions a section of the wall and frame has been drawn in proportion and is shown in Figure 17. Stress and deflection time histories have also been determined. For example, the flexural stress response of the rib shown in Figure 18 is necessary for an evaluation of the fatigue life of this structural component.

CONCLUSIONS

Modal analysis has been used to determine the response of reaction chamber structural components proposed for light ion beam fusion research systems. From the techniques developed, parametric data is generated for design purposes. The relationship is established between stress and deflection magnitudes and extreme values of Dynamic Load Factors. These, in turn, are shown to be primarily dependent on the natural frequencies of the wall and frame components, structural damping levels and the shape and amplitude of the dynamic overpressure. In particular it is shown that the shock from a 200 MJ target yield in 70 torr of xenon can be sustained at acceptable stress levels by a reaction chamber having a diameter of 6 meters and a 3 centimeter solid wall of 6061 aluminum.

REFERENCES

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(2) Engelstad, R. L. and Lovell, E. G., "First Wall Mechanical Design for Light Ion Beam Fusion Reactors," University of Wisconsin Fusion Engineering Program Report UWFDM-322, December 1979.