Stress Analysis of a Light Ion Beam Fusion Facility Target Chamber

R.L. Engelstad, E.G. Lovell
Department of Engineering Mechanics, University of Wisconsin, 1425 Johnson Drive, Madison, Wisconsin 53706, U.S.A.

Progress in inertial confinement fusion research and development will depend upon the availability of quality targets in significant numbers and variety. For this purpose a preconceptual design study has been initiated for a Target Development Facility (TDF) by Sandia National Laboratories in cooperation with the University of Wisconsin Fusion Engineering Program. This paper describes the preliminary design of the reaction chamber.

The major influence on the mechanical design of the chamber is the shock wave generated by the fireball. While theoretically the best shape for sustaining a uniform dynamic overpressure is a spherical geometry, practical considerations have led to a cylindrical configuration with removable end caps. An orthogonal gridwork of ribs and stringers reinforces the basic shell. Components of the wall are modelled as plates supported by flexural beams. The dynamic response of both systems is determined by modal analysis. This makes use of dynamic load factors which are calculated from the characteristics of the shock, the natural frequencies of the structural components and the damping level. Since the proposed chamber will be submerged in a water shield, the effect of the added mass of the liquid is also assessed. Dynamic stresses and deflections are determined from the maximum values of the dynamic load factors and the modal static response. In this form, parametric data is generated for a range of design variations.

Materials considered for the chamber include Al 6061 and 5086, 304 SS, HT-9, Ti-6Al-4V, Cu-Be C17200 and C17600. Of these, the aluminum alloys have the best combination of relevant characteristics for such a test facility: high strength to mass ratio, low cost, high thermal shock resistance and good induced radioactivity response for maintenance.

A particular numerical design is presented for a cylindrical shell with a height and diameter of 6 meters. A 200 MJ target yield in xenon cavity gas at 70 torr produces a shock wave at the wall with an amplitude of 1.71 MPa. It is shown that the maximum dynamic wall stress from flexure will be within design limits for a 3 centimeter thickness of Al 6061.

1. Introduction

Preliminary consideration has been given to the design of a light ion beam inertial confinement fusion target development facility (TDF) by Sandia National Laboratories. The facility is intended to serve for the development of targets in the 50 to 200 MJ yield range [1]. Quantified target characteristics sought include energy requirements, gain, yield, output spectra as well as fabrication technology. The TDF lifetime is estimated at 5 years with a target shot rate of approximately 10 per day and a facility shot rate approximately three times this value.

A schematic representation of the TDF appears in Fig. 1. The pulsed power system is similar to the PBFA-I driver of SNL. 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. The basic shell structure consists of a capped cylindrical chamber with a height and diameter of 6 meters. After lowering the water level, the top can be removed for convenient interior access. Materials considered for the reaction vessel include Al 6061 and 5086, 304 SS, HT-9, Ti-6Al-4V, Cu-Be C17200 and C17600 [2]. 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.

2. Chamber Structural System

The mechanical design is primarily influenced by the shock wave created by the fireball. The dynamic pressure can be expected to be nonuniform to the degree that the source is spherical and the chamber is cylindrical. Preliminary fireball calculations have shown the shock magnitude and rise time to be severe in general. In addition the wall would be structurally degraded by beam ports and diagnostic entries. Under such conditions a simple monocoque shell does not appear to be the most suitable configuration. A shell reinforced by circumferential ribs and axial stringers has been proposed as a more substantial system. With a large number of such members, the shell wall subsections can be modelled as flat plates in dynamic flexure. For more general applications, these could be considered as generic building blocks for other chamber geometries as well.

3. Analysis of Plate Response

Dynamic analysis of the plate response requires identification of mechanical characteristics including 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 Fig. 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 Fig. 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.

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 [3]. The accuracy of the solution can be improved by including DLF's for as many modes as desired.

Sequential calculations are made in the design process. The determination of natural frequencies is necessary; Fig. 4 shows results as a function of thickness for the various materials. The plate dimensions are the result of using two intermediate ribs and twenty stringers. The added mass of the shield water in contact with the wall can substantially reduce the flexural frequency, as shown in Fig. 5. Here ω_W and ω_V represent the fundamental frequencies for a plate in water and in a vacuum, respectively. To mitigate shock transmission from the wall through the water, an air bubble generation system has also been proposed. Fig. 5 shows the effect of the void fraction of the shield water on the wall frequency. Static deflections and stresses are found from design curves such as Fig. 6 and 7. The dynamic load factors are determined for a range of frequencies and various shock parameters k and t_r. For example, typical shock results from fireball code calculations appear in Fig. 8 [2]. With such particular values, maximum DLF's are determined, and as shown in Fig. 9, depend upon the level of damping in the system. 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 [4]. 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.

4. Particular First Wall Plate Response

The wall plate is solid aluminum with 2.5% critical damping and height, width and thickness of 200, 94 and 3 cm, respectively. The fundamental flexural frequency of this component in water is 76 Hz. For a 200 MJ target yield in 70 torr of xenon, the peak overpressure is 1.71 MPa with t_r and k equal to 0.14 ms and 3432/sec, respectively (Fig. 8). The corresponding equivalent static deflection and stress are 20.0 mm and 423 MPa (Fig. 6 and 7). The maximum DLF was determined to be 0.20 (Fig. 9) and thus the dynamic deflection and stress are 4.0 mm and 85 MPa. The circumferential stress history is shown in Fig. [10] for a point at the center of the plate surface facing the cavity. Note that compressive stress is plotted above the axis. 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. Initially the stress response will follow the pulse and subsequently develop into free vibration.

5. Shell Reinforcing System

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 Fig. 11. The tributary 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 [3]. Components with hollow rectangular cross sections were selected and characteristics are summarized in Table I. A schematic drawing of a portion of the wall system appears in Fig. 12 and a typical stress history for a rib is shown in Fig. 13.

6. Conclusions

A procedure based upon modal analysis and dynamic load factors has been used to develop design techniques for the first wall structural system of a preconceptual light ion beam target development facility. Particular calculations show that the overpressure from a 200 MJ target in 70 torr of xenon can be sustained by a reinforced aluminum chamber with a diameter of 6 m and a 3 cm solid wall.

7. References

[1] COOK, D. L., "Preliminary Conceptual Design and Engineering Aspects of a Light Ion Fusion Target Development Facility (TDF)," Proceedings 9th Symposium on Engineering Problems of Fusion Research, Chicago, Illinois, Oct. 26-29, 1981, pp. 664-671.

[2] PETERSON, R. R. et al., "Choice of First Wall Material in Light Ion Beam Target Development Facility," University of Wisconsin Fusion Design Memorandum 456, Feb. 1982.

[3] ENGELSTAD, R. L. and LOVELL, E. G., "Analysis and Design of ICF Target Development Facility First Wall Reinforcing Structures," University of Wisconsin Fusion Design Memorandum 478, July 1982.

[4] ENGELSTAO, R. L. and LDVELL, E. G., "First Wall Mechanical Design for Light Ion 8eam Fusion Reactors," University of Wisconsin Fusion Design Memorandum 322, Dec. 1979.

Acknowledgement

Support for this work has been provided by Sandia National Laboratories, Albuquerque, N.M.

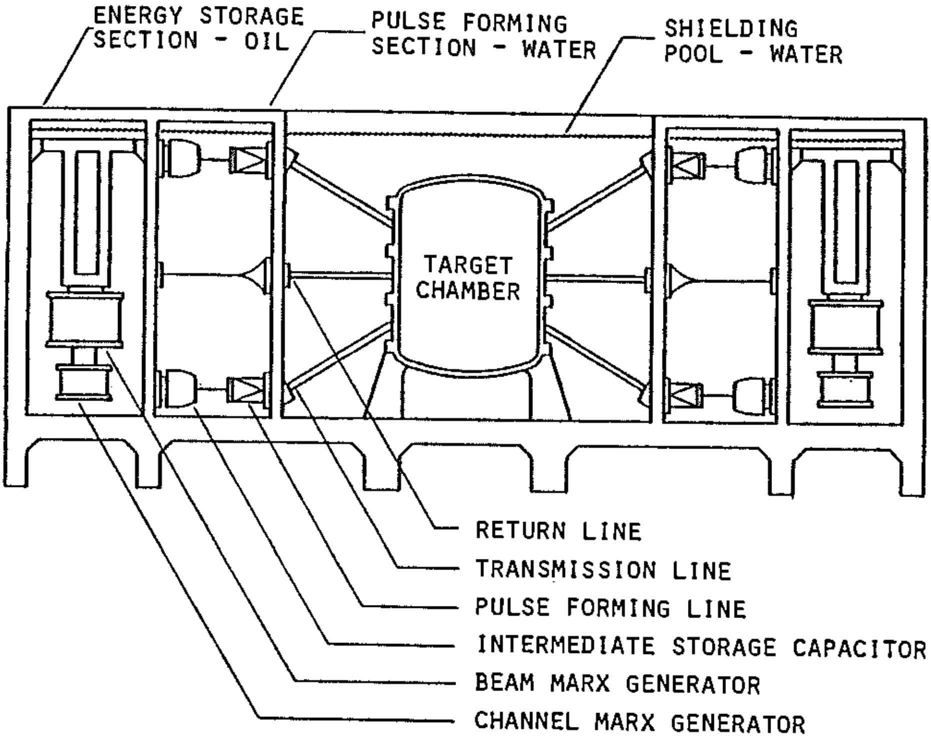

Fig. 1. Conceptual light ion beam target development facility.

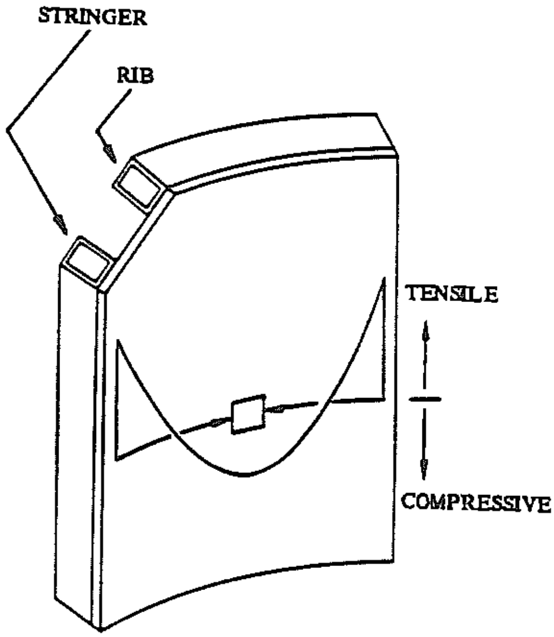

Fig. 2. Dynamic flexure of first wall plate.

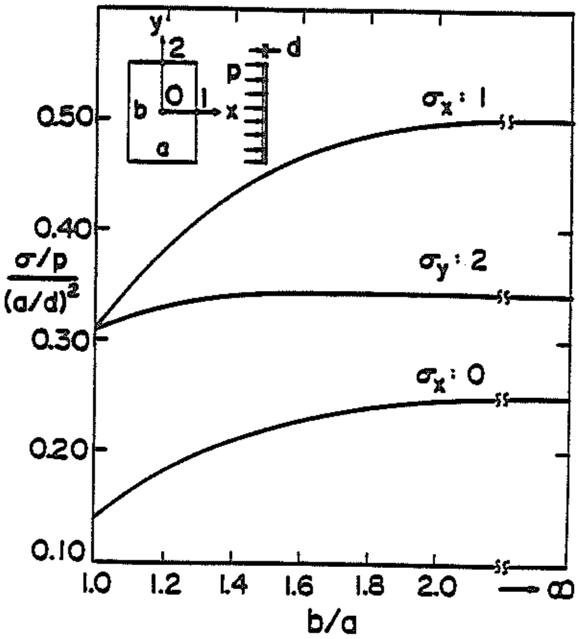

Fig. 3. Dimensionless static stress vs. aspect ratio.

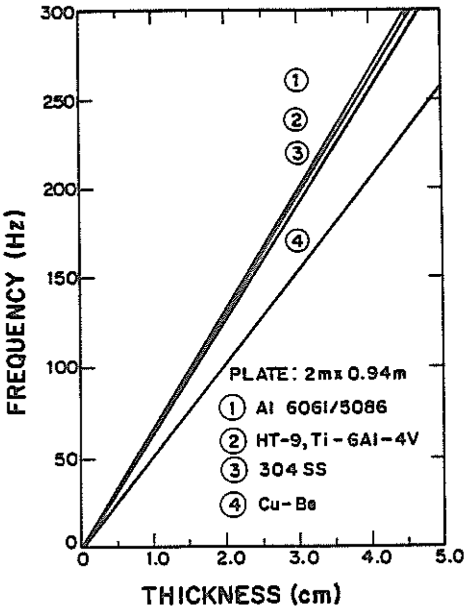

Fig. 4. Fundamental frequency vs. plate thickness.

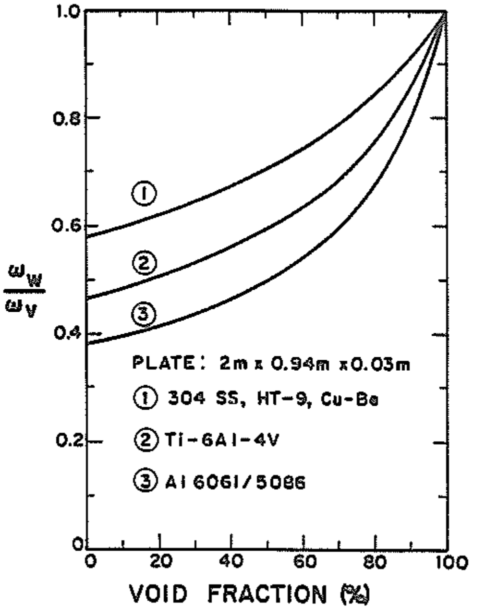

Fig. 5. Plate frequency in water and vacuum vs. void fraction of water.

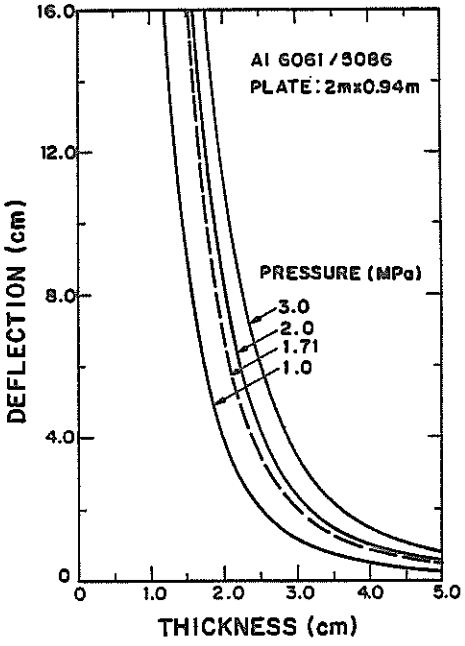

Fig. 6. Midpoint deflection vs. plate thickness.

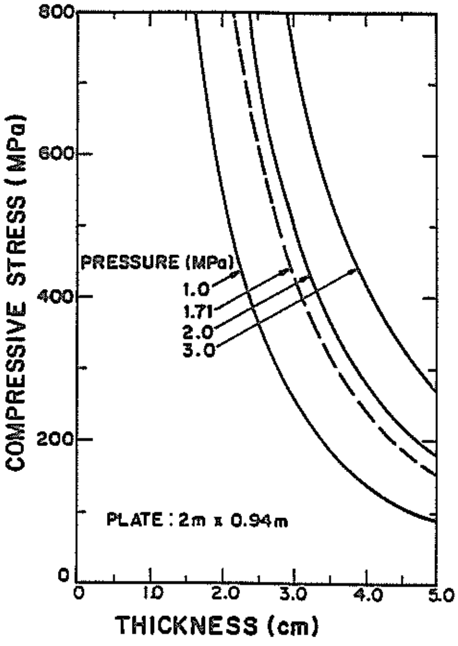

Fig. 7. Flexural stress vs. plate thickness.

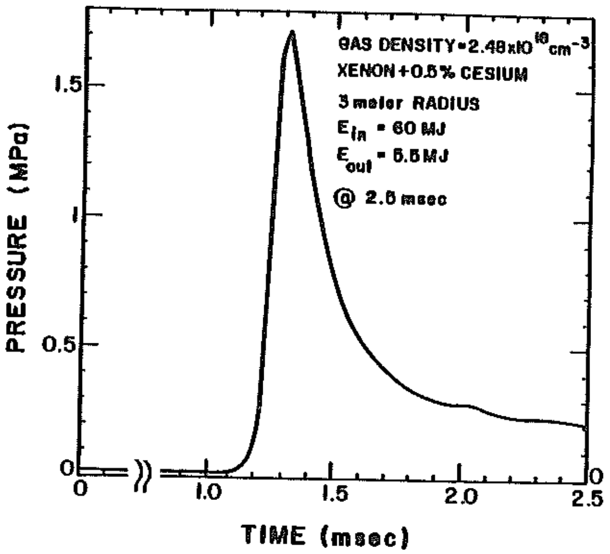

Fig. 8. Dynamic overpressure at the first wall.

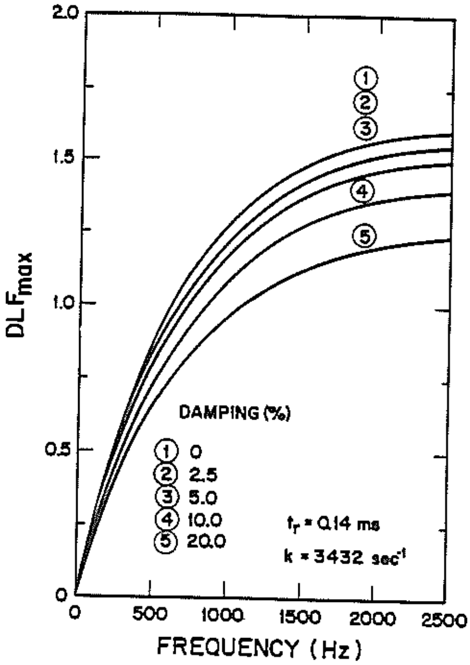

Fig. 9. Maximum dynamic load factor vs. fundamental frequency.

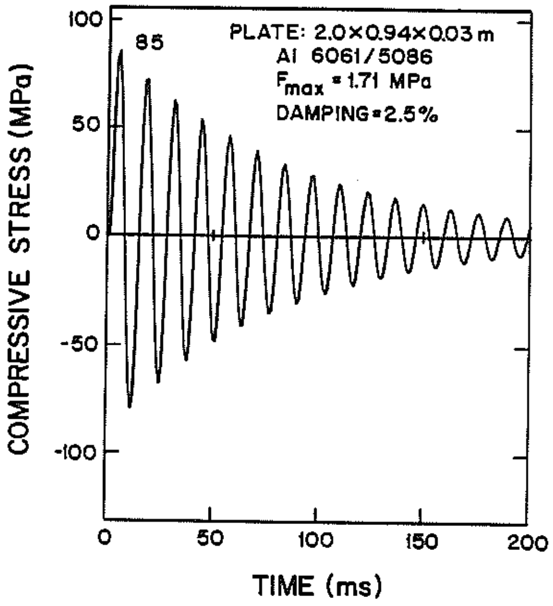

Fig. 10. Plate stress vs. time.

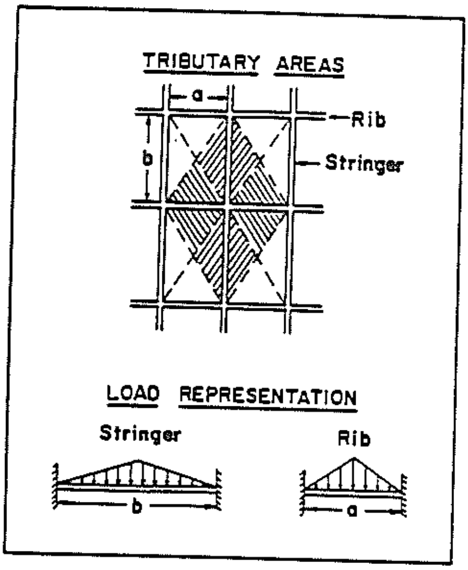

Fig. 11. Load partitioning to the support structure.

TABLE I - Reinforcing Structure Design Example

Al 6061 Overpressure = 1.71 MPa Damping = 2.5%

Structural tubing dimensions (in.)	8x8x5/8	8x8x5/8
Flexural frequency in vacuum (Hz)	338	1520
Flexural frequency in water (Hz)	220	988
Maximum dynamic load factor	0.45	1.22
Static flexural stress (MPa)	527	248
Dynamic flexural stress (MPa)	237	303
Maximum static deflection (mm)	10.7	1.1
Maximum dynamic deflection (mm)	4.8	1.4

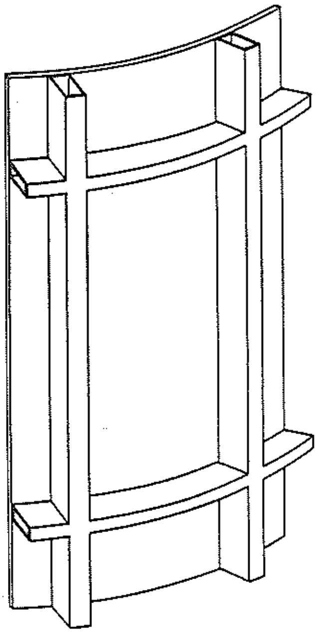

Fig. 12. Conceptual first wall structural system.

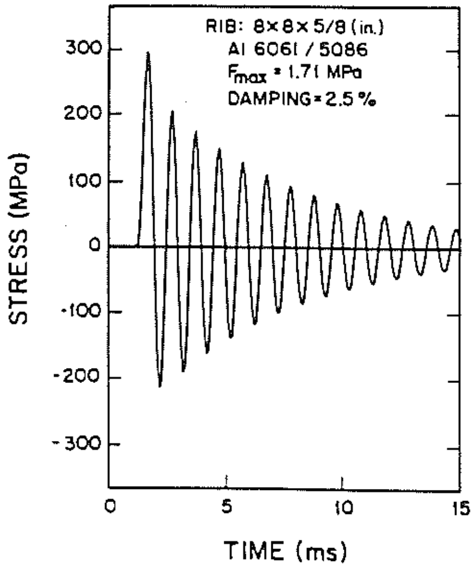

Fig. 13. Rib flexural stress vs. time.