SIMPLIFIED METHOD OF ANALYSIS OF SACRIFICIAL SHIELD WALL FOR PIPE WHIP RESTRAINT LOAD

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SUMMARY

The purpose of this paper is to analyze the sacrificial shield wall for the pipe whip load which is particularly important for the safety analysis and failure predictions of concrete reactor pressure vessel. The location of the shield wall makes it a very important structure for the support of the pipe whip restraints. The sacrificial shield wall is a composite structural steel and plain concrete, open-ended cylindrical shell structure stiffened by stiffening rings and vertical stiffeners.

In a previous paper, an energy balance procedure considering the energy absorbed by the pipe as well as the restraint has been presented. The restraint reaction time-history given by the energy balance method is a two-step pulse loading. The finite element methods can be used and have been used in analyzing the sacrificial shield wall. However, the finite element model of the shield wall is usually very large and the analysis is quite expensive.

The restraint reaction loads act over a small area and are assumed to be concentrated and local loads on the sacrificial shield wall. The response of the sacrificial shield wall to the restraint-reaction load is assessed in terms of local effects and overall structural response which can be treated separately but are interrelated in actuality. Due to the complex physical processes involved with the analysis, local effects are evaluated primarily by the application of ring theory and the overall structural response by the beam theory.

Local effects are evaluated considering a sector ($-45° \leqslant \theta \leqslant 45°$) of a ring of mean radius "a" and subjected to a concentrated (two-pulse loading) dynamic load of magnitude "F" at center ($\theta = 0°$). Overall effects are evaluated by considering a cantilever cylindrical beam of mean radius "a". An effective spring and effective mass are used to represent the most contributing ring mode from the ring analysis described earlier into the beam model.

The results of the simplified approach are compared with the results by the bending theory of thin shells. The "ASHSD" program developed by S. Ghosh and E. Wilson is used for shell analysis purpose. Two typical structural configurations namely, the ribbed section in which the presence of concrete is accounted for mass computations only and the concrete section in which the concrete serves as a structural material, have been considered for analysis purpose. The results of computations using the two methods are compared below for both the configurations.

Description	Thickness inches	Deflection in Inches for 600 kip Load	
		Simplified Method	Shell Analysis
Ribbed Section	16	0.048	0.0485
Concrete Section	24	0.14	0.16

The above comparison shows a reasonable agreement between the two methods. As can be seen from the table, this method provides comparable accuracy with considerably less expense and hence may be considered as an acceptable approach for preliminary design.

1. Introduction

The sacrificial shield wall is a composite structural steel and plain concrete, open-ended cylindrical shell placed around the reactor pressure vessel (RPV). The main function of the sacrificial shield wall is to act as a radiation and heat barrier between the RPV and the drywell wall. The steel portion of the shell is designed to carry all the loads imposed and the concrete portion of the shell satisfies the shielding requirements. Although the primary purpose of the sacrificial shield wall is for radiation shielding, because of its location, Figure 1, is also one of the most important structures for supporting equipment and piping loads as well as to resist pipe rupture, pressure, thermal and seismic loads. The effect of pipe rupture on the sacrificial shield wall mainly consists of jet impingement loads and pipe whip restraint loads. The U.S. Nuclear Regulatory Commission (NRC) requires that breaks be postulated in high-energy lines and that measures be taken to prevent consequent damage to essential equipment and structural components. The pipe whip restraint reaction loads are calculated by the use of energy balance procedure (Reference 1) considering the energy absorbed by the pipe as well as the restraint. Figure 2 shows a general restraint reaction time-history given by the energy balance method and Figure 3 shows a typical pipe whip restraint supported by the sacrificial shield wall.

2. Sacrificial Shield Wall

The sacrificial shield wall is a double-walled shell stiffened by stiffening rings and vertical stiffeners. General features of a typical reactor shield as illustrated in Figure 1 are as follows:

a. The outside steel shell is constructed of 1" plate with deep ring stiffeners and vertical stiffeners. This shell is designed to carry all of the loads that might be imposed on the shield.

b. The inside steel shell is constructed of 3/8" plate with stiffening rings and vertical stiffeners. This comprises the insulation support and concrete forming system. This support and forming system is designed to carry only the loads associated with the insulation and the concrete placement.

c. The plain concrete fill in between the two shells is needed only to satisfy the shielding requirements.

d. The shield structure is anchored to the concrete reactor support pedestal at the base and the top of the shield is supported from the containment wall by the stabilizer structure.

e. Major pipe penetrations are sealed around pipes by prefabricated steel door units which are designed to provide the required radiation shielding and resist transient pressure loadings within the shield annulus.

3. Loads on Pipe Restraint Support Structure

The effect of pipe whip due to blowdown thrust involves a dynamic analysis to calculate the restraint reaction load for use in the design of the supporting structure. The energy-balance method is used as the basis for pipe whip analysis.

The maximum response of an idealized model of the pipe-restraint system, shown in Figure 4, when subjected to a suddenly applied constant force is calculated. The essential feature of the method is that it incorporates a massless spring (restraint spring) between the pipe and the structure. The impact is assumed to be inelastic (no rebound) such that at the end of the impact, the external work done by the pipe break force is absorbed by inelastic deformations of the pipe (at idealized plastic hinges) and the restraint. The idealized model used in the analysis allows a hinge to form in the pipe at the restraint on impact, if the restraint is large enough. The restraint reaction time-history (Figure 2) given by the analysis is implied as a time-dependent force to the support structure.

4. Method of Analysis

The design of the support structures to resist the reaction loads requires determination of the dynamic response due to concentrated loads acting over a small area. The dynamic response is assessed in terms of local effects and overall structural response which can be treated separately but are interrelated in actuality. Due to the complex physical process involved with the analysis, local effects are evaluated primarily by the application of ring theory and the overall structural response by the beam theory.

4.1 Local Effects

Local effects are evaluated considering a sector ($-45^\circ \leq \theta \leq 45^\circ$) of a ring of mean radius "a" subjected to a concentrated dynamic load (two-pulse loading shown in Figure 2) acting at $\theta = 0^\circ$. The modal characteristic shapes are given by (Reference 3)

$$\phi_n(\theta) = \cos n\theta \quad (n = 2, 6, 10, 14 \ldots.) \tag{1}$$

The dynamic deflection, W, may be represented by the summation of the modal components:

$$W(t,\theta) = \sum^{n} A_n(t)\,\phi_n(\theta) \tag{2}$$

where A_n is the modal amplitude.

The equation of motion for the n^{th} mode is given by (Reference 4)

$$\ddot{A}_n + \omega_n^2 A_n = \frac{f(t) \int p_1(\theta)\,\phi_n(\theta)\,d\theta}{\omega_n^2\, m \int \phi_n^2(\theta)\,d\theta} \tag{3}$$

where f(t) is the load time-history function,

$p_1(\theta)$ is the load distribution along the circumference,

m is the uniformly distributed mass

The modal static deflection is defined by

$$A_{nst} = \frac{\int p_1(\theta)\,\phi_n(\theta)\,d\theta}{\omega_n^2\, m \int \phi_n^2(\theta)\,d\theta} \tag{4}$$

The modal response is given by

$$A_n(t) = A_{nst}\,(DLF)_n \tag{5}$$

where $(DLF)_n$ is the Dynamic Load Factor for the equivalent one-degree freedom system of the n^{th} mode.

For the case of a concentrated load, F, the numerator integral in the right hand side of equation (4) is replaced by

$$\int p_1(\theta)\,\phi_n(\theta)\,d\theta = \sum F\,\phi_n(0) = F \tag{6}$$

The denominator integral in the right hand side of equation (4) is given by

$$a\int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \phi_n^2(\theta)\,d\theta = a\int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \cos^2 n\theta\,d\theta = \frac{\pi}{4} \quad (\text{for } n = 2, 6, 10, 14 \ldots) \tag{7}$$

The modal static deflection is

$$A_{nst} = \frac{F}{m\pi a\,\omega_n^2} \tag{8}$$

The modal dynamic deflection at any point along the ring is

$$W_n = \frac{F}{m\pi a \omega_n^2} (DLF)_n \cos n\theta \tag{9}$$

The total deflection at any point along the ring is

$$W = \frac{F}{m\pi a} \Sigma \frac{1}{\omega_n^2} (DLF)_n \cos n\,\theta \tag{10}$$

The $(DLF)_n$ for the two-pulse loading is given in Figure 5. The frequency equation for the case of inextensional vibration with vibrations taking place in planes at right angles to the axis of the cylinder is given by (Reference 3)

$$\omega_n^2 = \frac{Eh^2}{3\rho(1-\nu^2)a^4} \frac{n^2(n^2-1)^2}{(n^2+1)} \tag{11}$$

where E is modulus of elasticity, ν is poisson's ratio, ρ is mass density of the material, h is the thickness and a is the mean radius.

4.2 Overall Effects

Using the restraint reaction time-history (Figure 2) as the input loading, the overall structural response can be obtained by performing a dynamic analysis of thin shell structures. However, the design of sacrificial shield wall is governed by both local and overall stresses and hence in most cases such a detailed shell analysis may not be necessary. Instead, overall effects are evaluated by considering a cantilever cylindrical beam (Figure 6) of mean radius "a". An effective spring and effective mass are used to represent the most contributing ring mode from the ring analysis described earlier into the beam model.

5. Numerical Example and Discussion

Two typical structural configurations namely, the ribbed section in which the presence of concrete is accounted for mass computations only and the concrete section in which the concrete serves as a structural material, have been considered for analysis purpose. It is first necessary to determine the local effects in accordance with the procedures described in Section 4.1. Tables I and II summarize the results for the "concrete" section and "ribbed" section, respectively. The results of this simplified approach are compared with the results by the bending theory of thin shells. The "ASHSD" program developed by S. Ghosh and E. Wilson (Reference 2) is used for shell analysis purpose. Axisymmetric shell model used for shell analysis is shown in Figure 7. Figures 8 and 9 show the variation of displacement along the circumference for "ribbed" section and "concrete" section, respectively and Figure 10 shows the variation of maximum displacement along the meridian for the "concrete" section. From Figures 8 and 9, it can be observed that the displacement pattern divides the entire section into four sectors thus verifying the assumption ($-45^\circ \leq \theta \leq 45^\circ$) made in Section 4.1. Figure 10 suggests that, for overall analysis, the shield wall structure can be modeled as a cantilever cylindrical beam with an effective spring and effective mass representing the most contributing ring mode portion. The effective spring and effective mass are calculated based on the results of local effects analysis. Figures 10 and 11 show the base moment and base shear variation along the circumference. The results of computations using the two methods are compared in Table III for both the configurations. The above comparison shows a reasonable agreement between the two methods. As can be seen from Table III, this approximate method provides comparable accuracy with considerably less expense and hence may be considered as an acceptable approach for preliminary design.

6. Acknowledgements:

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[1] V. K. Verma, M. Valathur, M. A. Salmon and H. Shah, "Pipe Whip Analysis, Restraint and Support Structure Design", Second ASCE Specialty Conference on Structural Design of Nuclear Plant Facilities, New Orleans, 1975, Vol. 1-B, pp. 1485-1511.

[2] S. Ghosh and E. Wilson, "Dynamic Stress Analysis of Axisymmetric Structures Under Arbitrary Loading", Report No. EERC 69-10, College of Engineering, University of California, Berkeley, 1969.

[3] A. E. H. Love, "A Treatise on the Mathematical Theory of Elasticity", Dover Publication, Fourth Edition, New York.

[4] J. M. Biggs, "Introduction to Structural Dynamics", McGraw-Hill, 1964.

TABLE I. LOCAL EFFECTS - CONCRETE SECTION

Data: Young's Modulus = 4000 ksi

Poisson's ratio = 0.17

Mass density = 4.65 lbs-sec^2/ft^4

Mean radius = 14 ft

Thickness = 2 ft

n	ω rad/sec	f cps	DLF	W_n inch
2	89.2	14.2	1.0	0.139
6	1148.2	182.7	2.0	0.001
		Deflection	=	0.14 inch

TABLE II. LOCAL EFFECTS - RIBBED SECTION

Data: Young's Modulus = 29,000 ksi

Poisson's ratio = 0.3

Mass density = 4.85 lbs-sec^2/ft^4

Mean radius = 14 ft

Thickness = 1.33 ft

n	ω rad/sec	f cps	DLF	W_n inch
2	155.0	24.6	1.1	0.048
6	1994.0	317.4	2.0	0.00001
		Deflection	=	0.048 inch

TABLE III. COMPARISON OF MAXIMUM DEFLECTIONS

Description	Thickness inches	Deflection in Inches	
		Simplified Method	Shell Analysis
Ribbed Section	16	0.0481	0.0485
Concrete Section	24	0.14	0.16

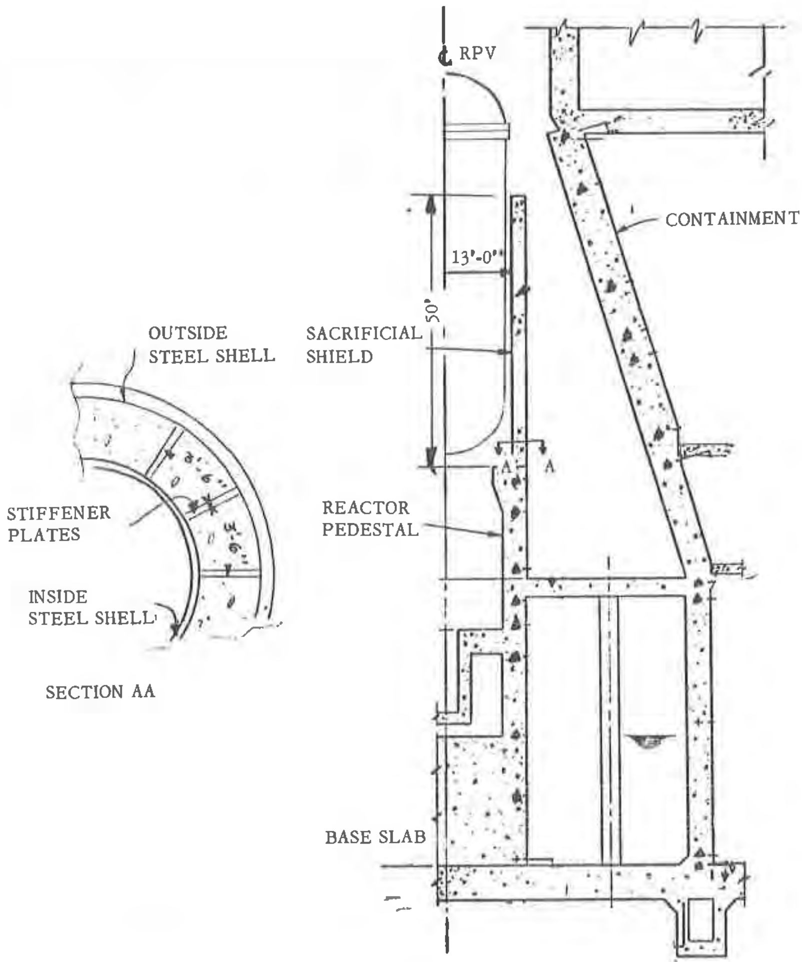

FIGURE 1 REACTOR CONTAINMENT

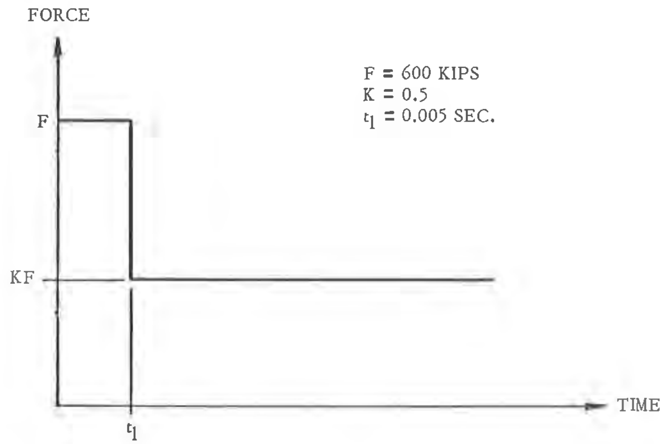

FIGURE 2

FORCE — TIME FUNCTION

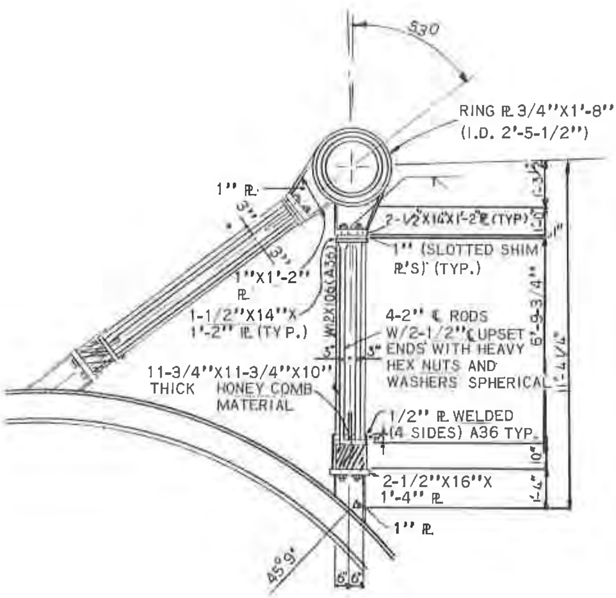

FIGURE 3

TYPICAL PIPE WHIP RESTRAINT

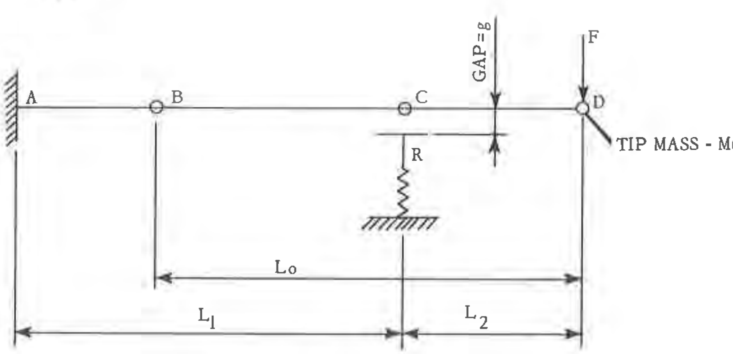

FIGURE 4

PIPE RESTRAINT SYSTEM

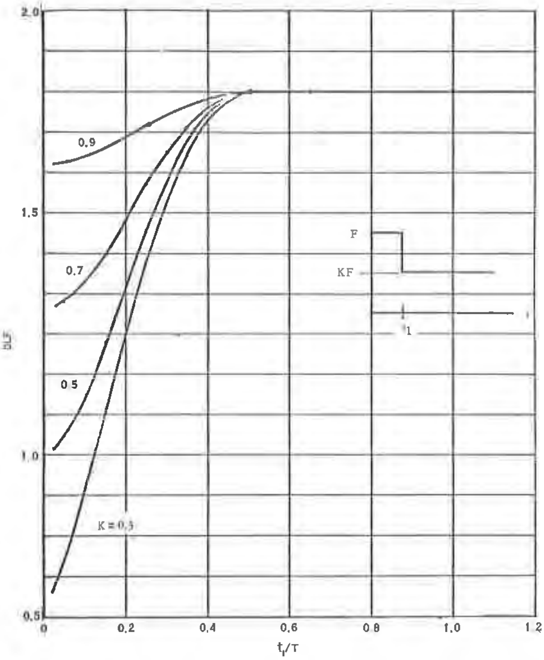

FIGURE 5

DYNAMIC LOAD FACTORS — 7% DAMPING

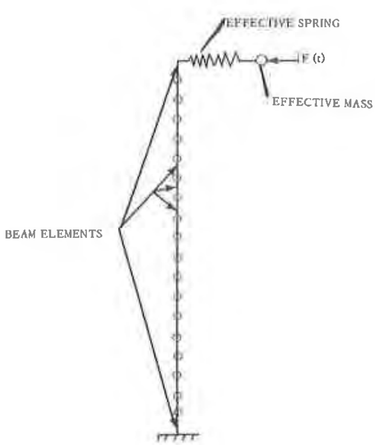

FIGURE 6

BEAM MODEL FOR OVERALL EFFECT

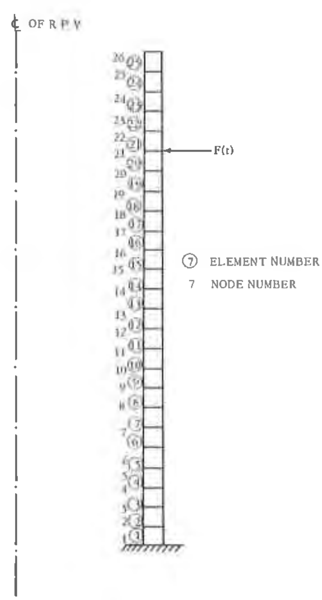

FIGURE 7

AXISGMMETRIC MODEL FOR SHELL ANALYSIS

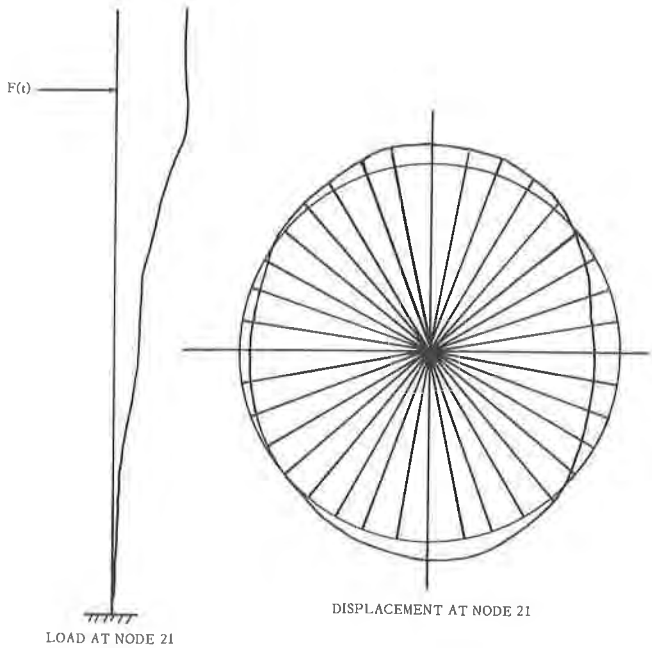

FIGURE 8

DISPLACEMENTS IN THE "RIBBED" SECTION

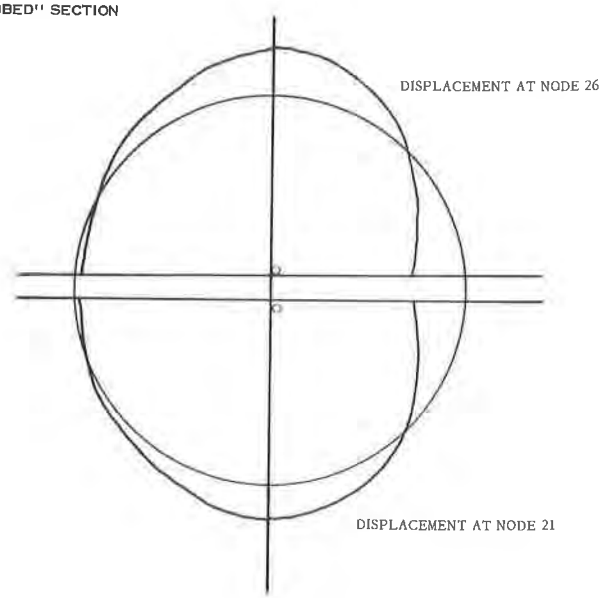

FIGURE 9

DISPLACEMENT IN THE "CONCRETE" SECTION FOR LOAD AT NODE 21

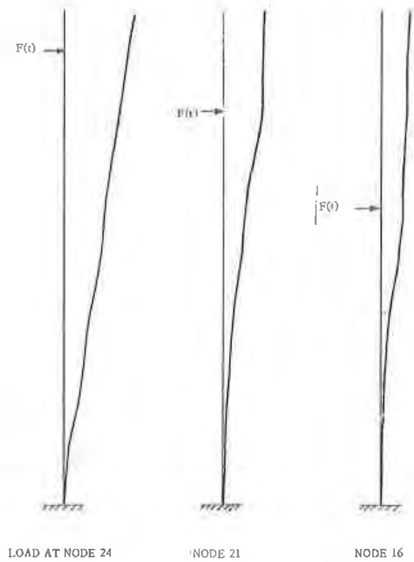

FIGURE 10

VARIATION DISPLACEMENT ALONG THE MERIDIAN FOR "CONCRETE" SECTION

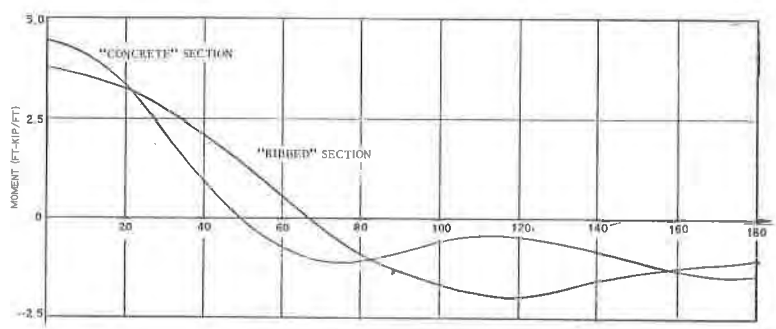

FIGURE 11

VARIATION OF BASE MOMENT

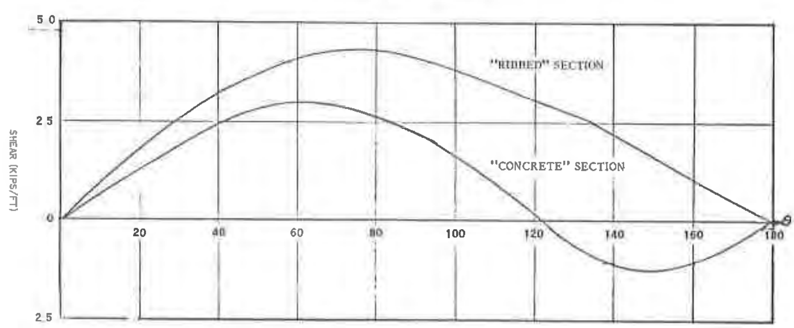

FIGURE 12

VARIATION OF BASE SHEAR