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Nonlinear Stability Analysis of Apollo Aft Heat Shield

by

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ABSTRACT

This report presents a study of the influence of geometric nonlinearities on the stresses and buckling pressures of both the original and the scalloped aft heat shield of the Apollo Spacecraft. This is the first successful nonlinear analysis of this structure. The results show that geometric nonlinearities are important when the load is applied over a large area. The calculated buckling loads are above those anticipated during water impact. The stresses in the face sheets are high but agree well with values measured experimentally. A paper pertaining to this research will be presented at the Air Force 2nd Conference on Matrix Methods in Structural Mechanics to be held at Wright-Patterson Air Force Base, October 15-17, 1968.

INTRODUCTION

The original version of the aft heat shield was of stainless steel honeycomb construction with face sheets of .008" thickness. However, structural damage was encountered during tank-testing and the heat shield was modified by scalloping as shown in Fig. 1.

In an effort to verify the structural integrity of the scalloped heat shield, Bell Aerosystems Company[1] and Stebbins[2] conducted analyses using the available finite element techniques. These included static, thermal, dynamic, and stability analyses. However, none of these analyses included the effects due to large deflections.

The Manned Spacecraft Center employed Budiansky and Sanders[3] to review the work of Bell Aerosystems Company and of North American Aviation and to make recommendations of further studies to verify the structural integrity of the aft heat shield during water impact. One of the recommendations was that the effects of large deflections be included, especially in the stability analysis.

As a result of this consultation the Manned Spacecraft Center placed a contract with Bell Aerosystems Company for a stability analysis using large deflection theory. The research was, however, unsuccessful and Dr. Stebbins of the Manned Spacecraft Center requested that Texas A&M University conduct the stability analysis under NASA Grant NGR 44-001-044. This report presents the results of the investigation.

THEORETICAL APPROACH

A paper[4] on this research has been accepted for presentation at the Air Force 2nd Conference on Matrix Methods in Structural Mechanics to be held at Wright-Patterson Air Force Base, October 15-17, 1968. Only an outline of the theory is presented here.

The displacements of a curved shell element are represented by polynomials in the meridional distance and a Fourier series in the circumferential angle[5]. For shells of revolution with symmetrical stiffness properties orthogonality of the Fourier terms results in the uncoupling of the various harmonics. However for shells with asymmetrical stiffness properties such as the

Apollo aft heat shield all harmonics are coupled. This gives rise to an element stiffness matrix of order 8N x 8N where N is the number of harmonics. Thus for seventeen harmonics, the maximum allowed in the computer code, the element stiffness matrix is of order 136 by 136. This element stiffness matrix is derived by evaluating the 8 x 8 stiffness matrix representing the coupling between any two harmonics. Then by an orderly interchange of the harmonic numbers and through sign changes to account for sine terms in the Fourier expansion the entire element stiffness matrix may be evaluated. The element stiffness matrix contains terms which must be integrated over the length of the element and around the circumference. The integrals over the meridional length of the element are evaluated numerically while the integrals around the circumference are evaluated exactly. This latter integration is performed by first expanding the shell thickness in a Fourier series. This expansion is independent of the expansion used for the deflections which allows a different number of terms to be used. The element stiffness matrices are combined in the usual way to obtain the stiffness matrix for the shell.

The nonlinear analysis follows the same procedure presented in Ref. 4. However, in this case the thickness of the shell depends on the circumferential angle and requires the evaluation of fourth order sine and cosine functions in the circumferential direction.

The solution procedure is quite similar to the predictor corrector method. The contribution to the generalized forces by the nonlinear terms is estimated by an extrapolation procedure and then iteration is applied until convergence occurs. Thus, the solution is obtained for a sequence of increasing loads.

The computer code was written primarily for the nonlinear stress analysis. However, buckling loads may be obtained as a limiting case. The program will continue to yield solutions for increasing loads until a load is reached where divergence occurs. This indicates that the iteration procedure is seeking a solution to the buckled shell. The actual buckling load is obtained by plotting the load-deflection curve and extrapolating to a load where the curve becomes horizontal.

RESULTS

Original Heat Shield

The original heat shield was idealized as a shallow spherical cap clamped at the bolt circle. The load was applied at 15° from the apex over a wetted area with a 20" radius.

Figure 2 presents a plot of the maximum meridional stress in the face sheets as a function of the pressure applied to the wetted area. The pressure encountered during water impact for this wetted area is estimated to be 150 psi.

Examination of Fig. 2 reveals that the maximum stress is not highly nonlinear for this particular loading. An examination of the stress values reveals, however, that the proportional limit of the stainless steel face sheets is exceeded at a rather low value of the loading. Similar results were obtained for other loadings.

Scalloped Heat Shield

As discussed in the introduction the original analysis was conducted by personnel at Bell Aerosystems Company. In that analysis it was assumed that linear theory applied for all loadings. This report presents results obtained when geometric nonlinearities are included.

During "splashdown" the pressures on the aft heat shield are very high at the edge of the wetted area and decrease towards the center. Further, the loads vary quite rapidly with time which implies significant dynamic forces. However, since the objective of this research is to ascertain the influence of geometric nonlinearities, it was decided that the actual loading may be approximated as a uniform static load over a specified wetted area. Further, this is the same approximation used by Bell Aerosystems Company.

The analyses were conducted for four different loadings. The first is for a center of impact at 15° from the apex and over a wetted area with a 20" radius. The other three are for a center of impact at 10° and with radii for the wetted area of 10, 20, and 40 inches respectively.

The results for the maximum displacements, maximum stress in the face sheets, and maximum transverse shear force are presented in Fig. 3-8. The buckling loads and stresses at the anticipated loading are summarized in Table 1.

Table I Buckling Pressures and Stresses for Scalloped Heat Shield

ϕ	Radius (in.)	Buckling Pressure (PSI) Gallagher[1] (Linear)	Buckling Pressure (PSI) Present Research (Non-linear)	Estimated Pressure (PSI) (MSC)	Maximum Absolute Face Sheet Stress At Estimated Pressure(PSI) Present Research)	Maximum Transverse shear at estimated Pressure (#/in) (Present Research)
15°	20	———	700	———	———	———
10°	10	1179	1100	273	123×10^3	1130
10°	20	396	300	151	150×10^3	1370
10°	40	210	100	80	125×10^3 104×10^3*	1100

*Linear Solution

Comparing the nonlinear results for the buckling pressures to those given by Gallagher based on linear theory, it is observed that nonlinearities are not significant when the pressure is applied over a small area but quite significant for a wetted area with a 40" radius. It is also noted that all calculated buckling pressures are above those anticipated during water impact.

In the linear analysis Gallagher assumed that geometric nonlinearities would reduce the critical pressure by 50%. The results in Table 1 shows that this estimate is conservative for localized loadings and approximately correct when the pressure is distributed over a large area.

The inclusion of dynamic forces will probably lower the buckling pressure whereas the actual load distribution will tend to increase the buckling load. Thus, the two effects tend to counteract each other. The effect of small initial imperfections is likely insignificant because of the rather large thickness of the aft heat shield.

The last two columns in Table I present the values of the maximum meridional stress and transverse shear force at the anticipated loads. The maximum transverse shear force occurred at the bolt circle in two cases. These shear loads are considered to be within the allowable values.

The maximum meridional stress in the face sheet occurs near the inboard edge of the wetted area. Thus for the 40" radius wetted area the maximum stress occurs near the apex. A face sheet thickness of .05" was assumed near the apex in the computation of stresses. It is noted that the maximum stress is high. However, it is below the allowable values and well within the range of values measured experimentally.

CONCLUSION

The recommendation of Budiansky and Sanders to investigate the effects of geometric nonlinearities has been followed. This effect is unimportant for localized loadings but quite significant for loads applied over a large area. It is concluded that the aft heat shield will not buckle under anticipated loads but that the large values of the computed stresses fully justify the extensive experimental program currently underway at the Manned Spacecraft Center.

REFERENCES

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3. Sanders, J.L., "Report on Apollo Shell Structure," Communications to NASA Manned Spacecraft Center, July 1965.

4. Stricklin, J.A., DeAndrade, J.C., Stebbins, F.J., and Cwiertny, A.J.,"Linear and Nonlinear Analysis of Shells of Revolution with Asymmetrical Stiffness Properties," Paper to be presented at Air Force 2nd Conference on Matrix Methods in Structural Mechanics, Oct. 15 - 17, 1968.

5. Stricklin, J.A., Haisler, W.E., MacDougall, H.R., and Stebbins, F.J., "Nonlinear Analysis of Shells of Revolution by the Matrix Displacement Method," AIAA Paper No. 68-177 (To be published in AIAA Journal).

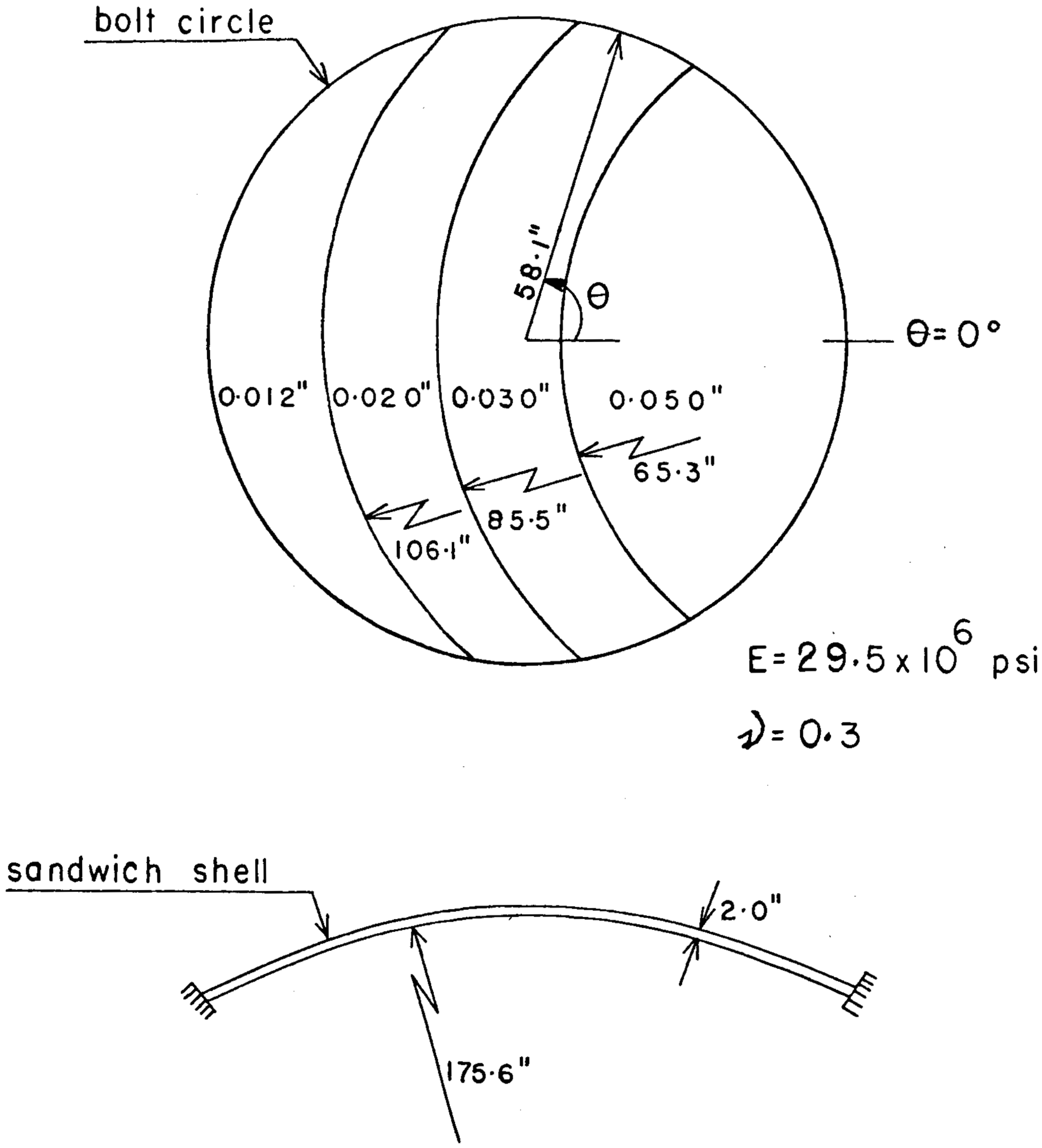

FIG.1 SCALLOPED APOLLO AFT HEAT SHIELD

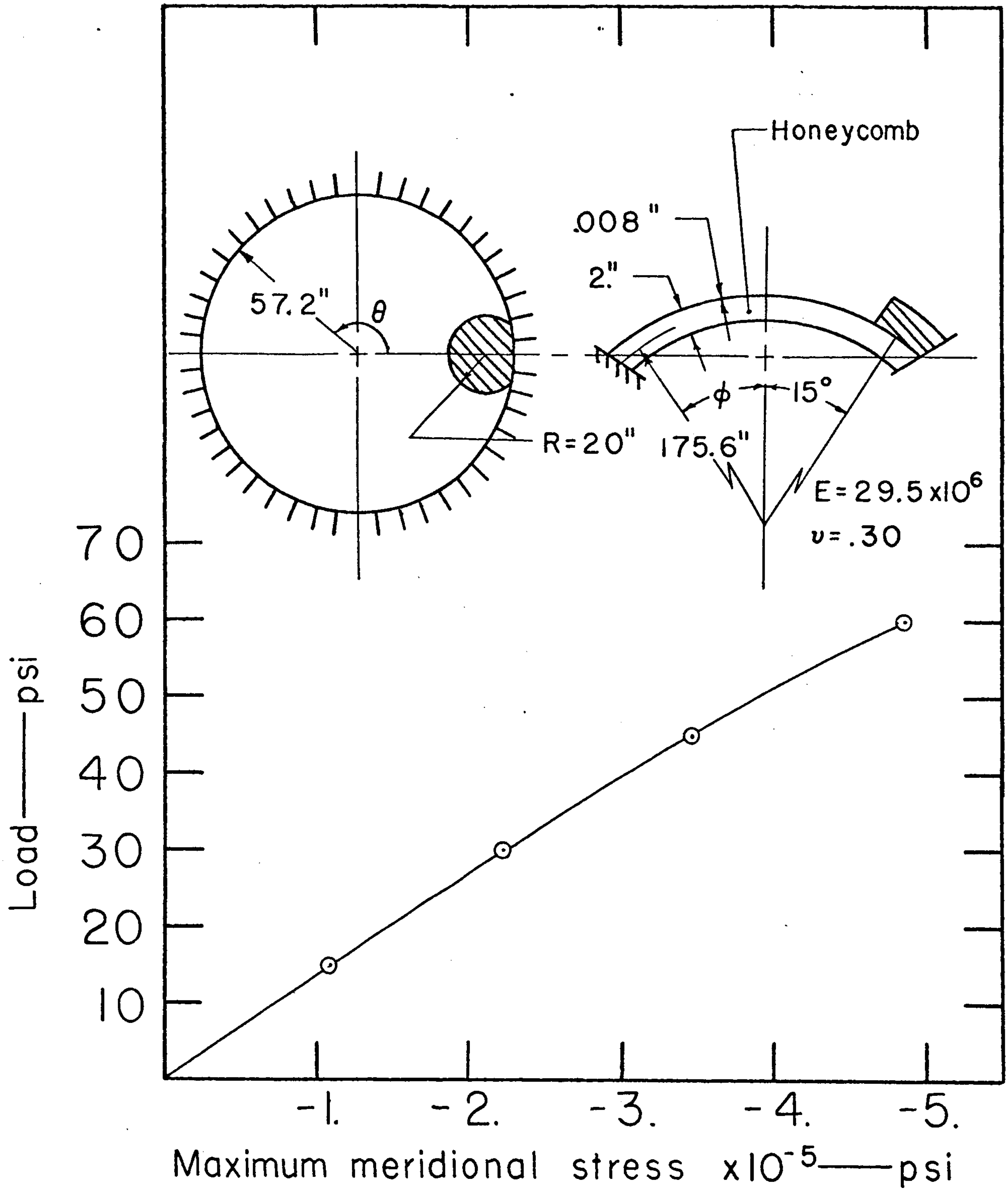

Fig. 2 PRESSURE LOADING VERSUS MAXIMUM MERIDIONAL STRESS

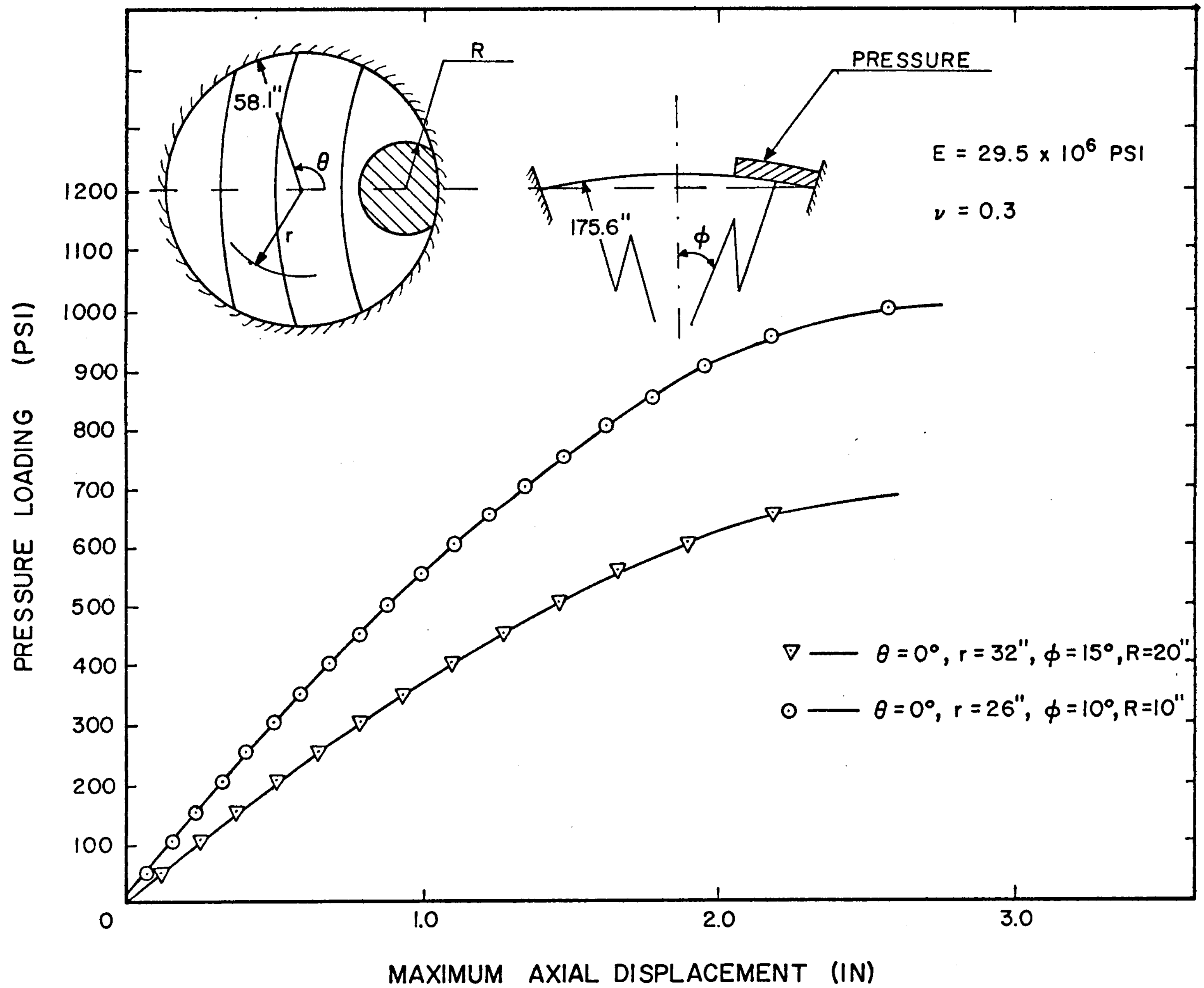

FIG. 3 MAXIMUM AXIAL DISPLACEMENT VERSUS LOADING

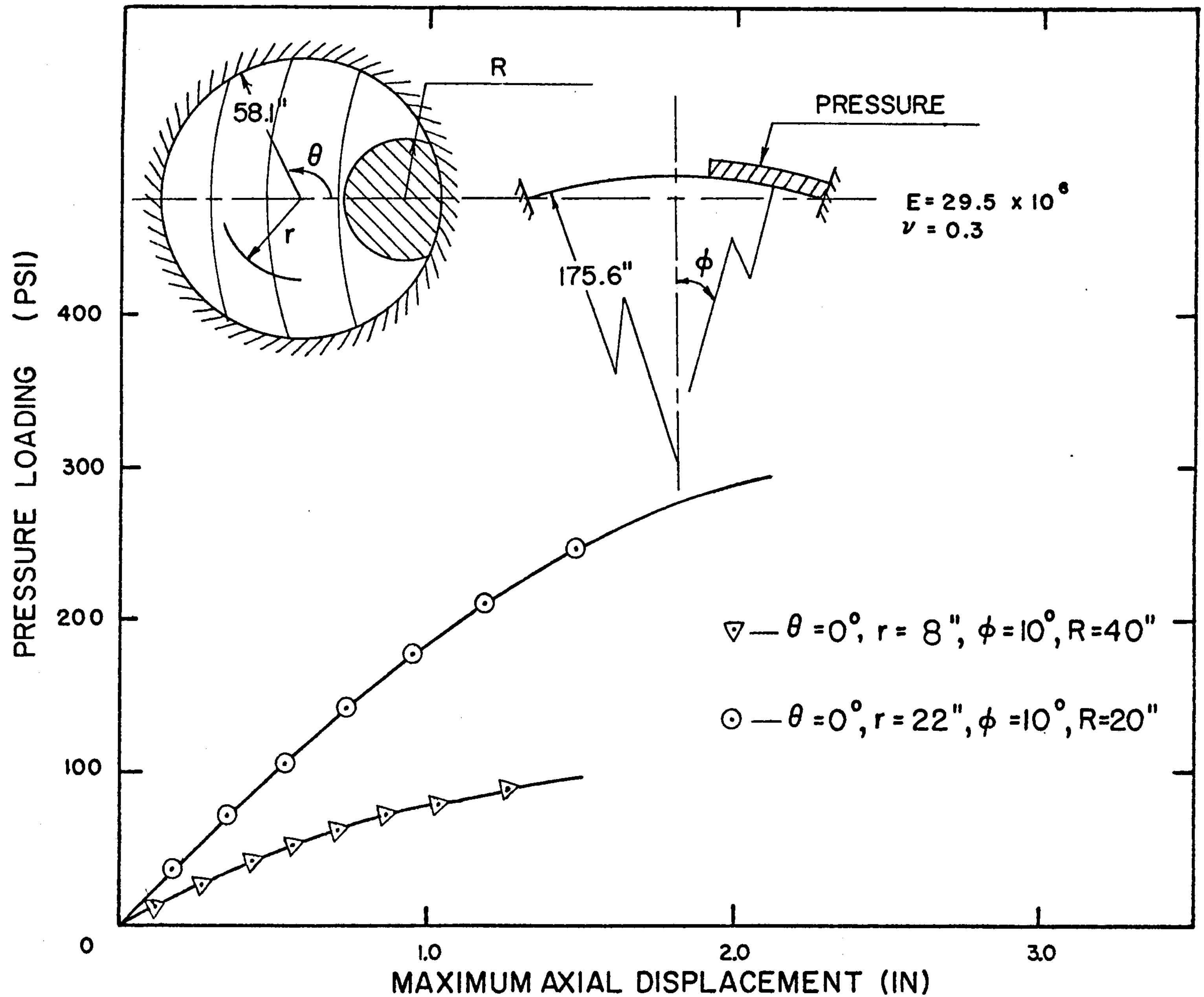

FIG. 4 MAXIMUM AXIAL DISPLACEMENT VERSUS LOADING

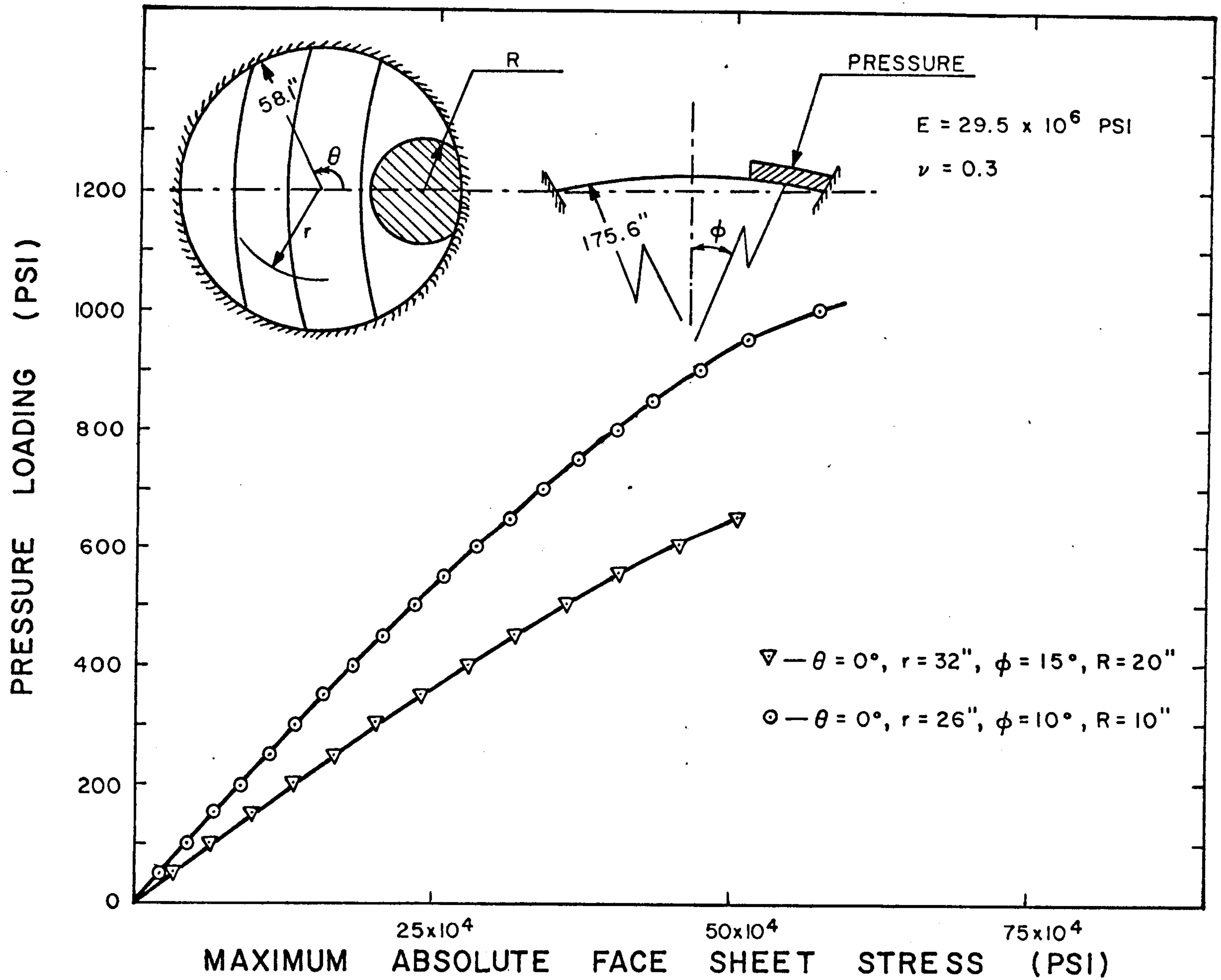

FIG. 5 MAXIMUM ABSOLUTE FACE SHEET STRESS VERSUS LOADING

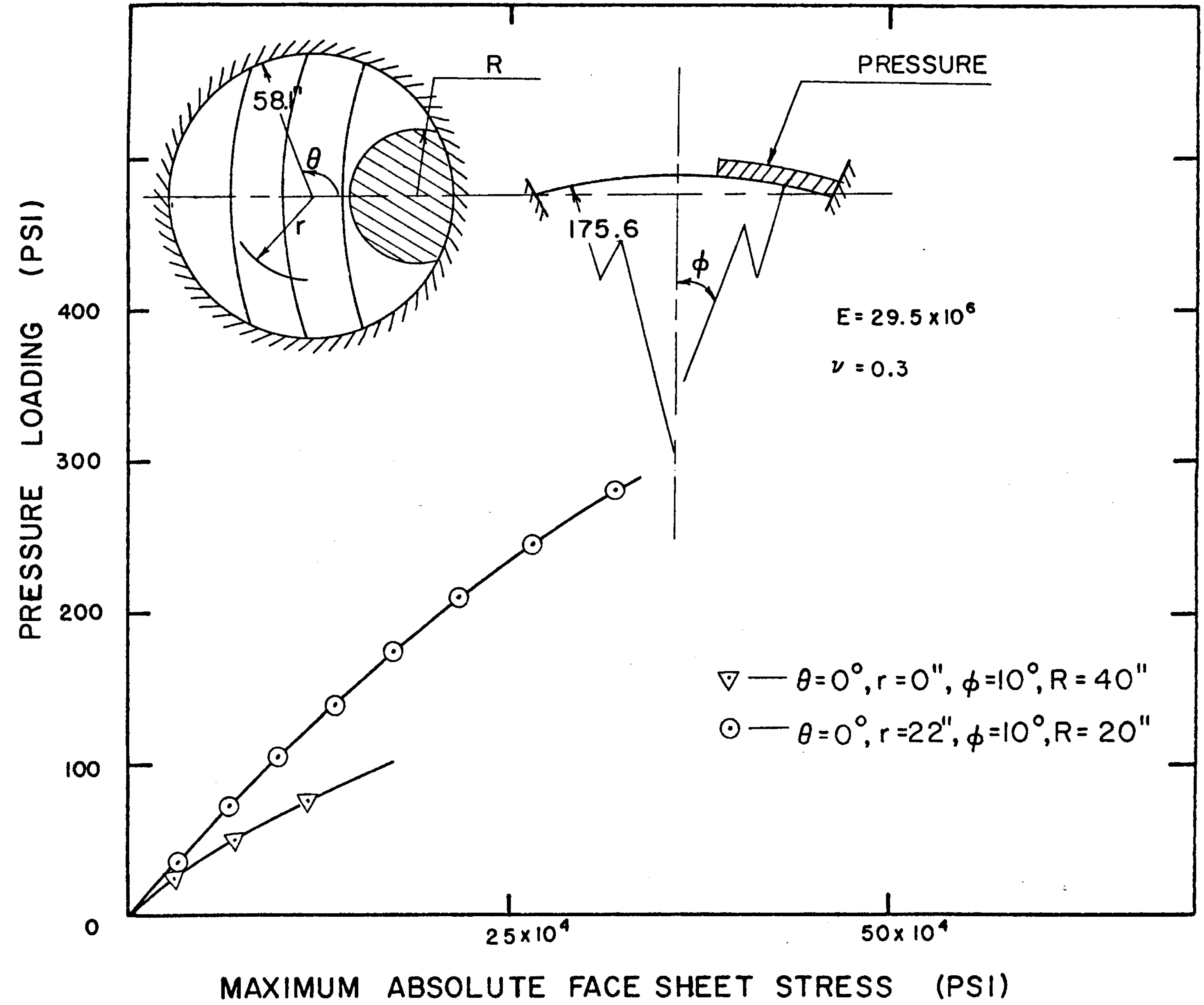

FIG. 6 MAXIMUM ABSOLUTE FACE SHEET STRESS VERSUS LOADING

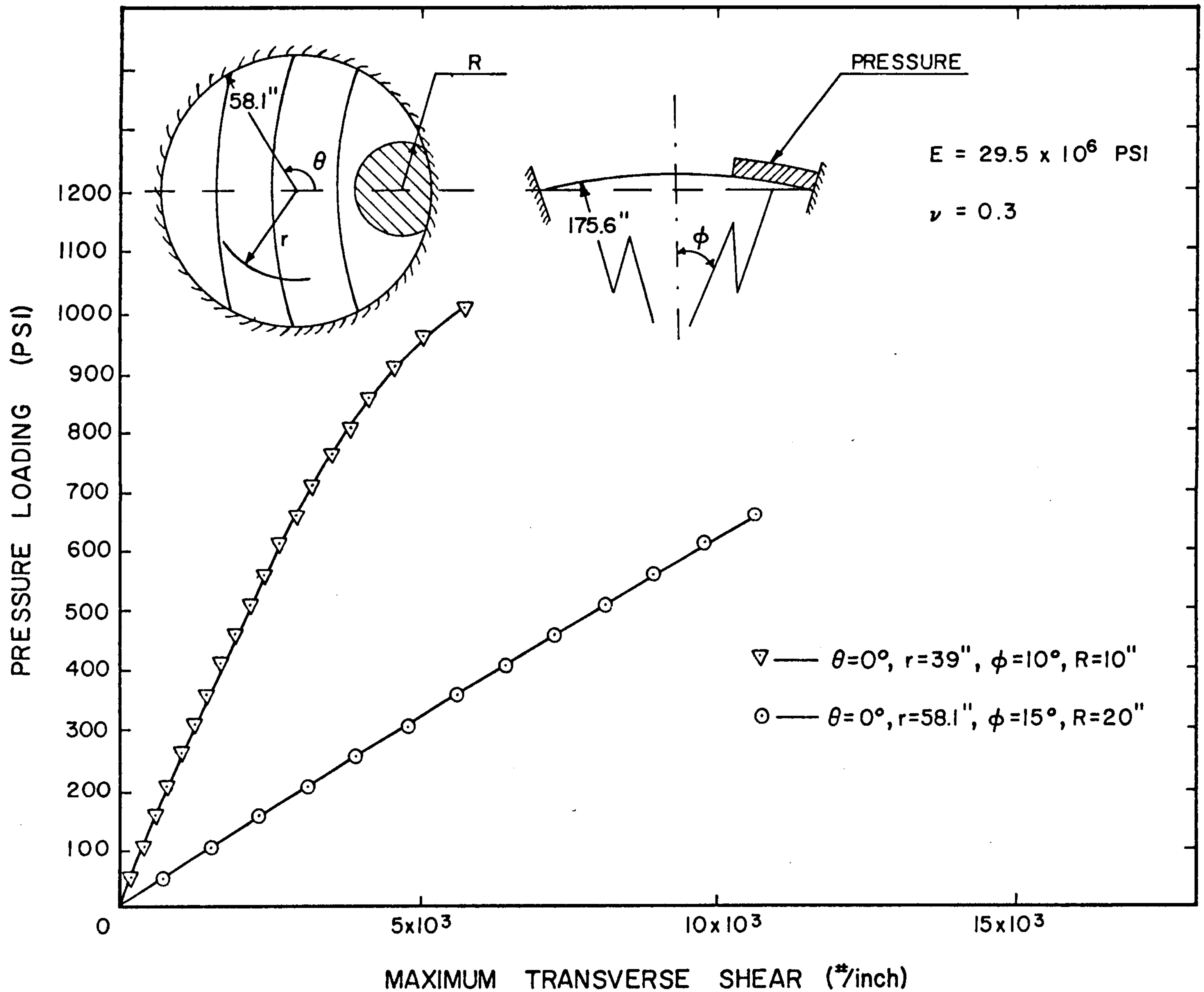

FIG. 7 MAXIMUM TRANSVERSE SHEAR VERSUS LOADING

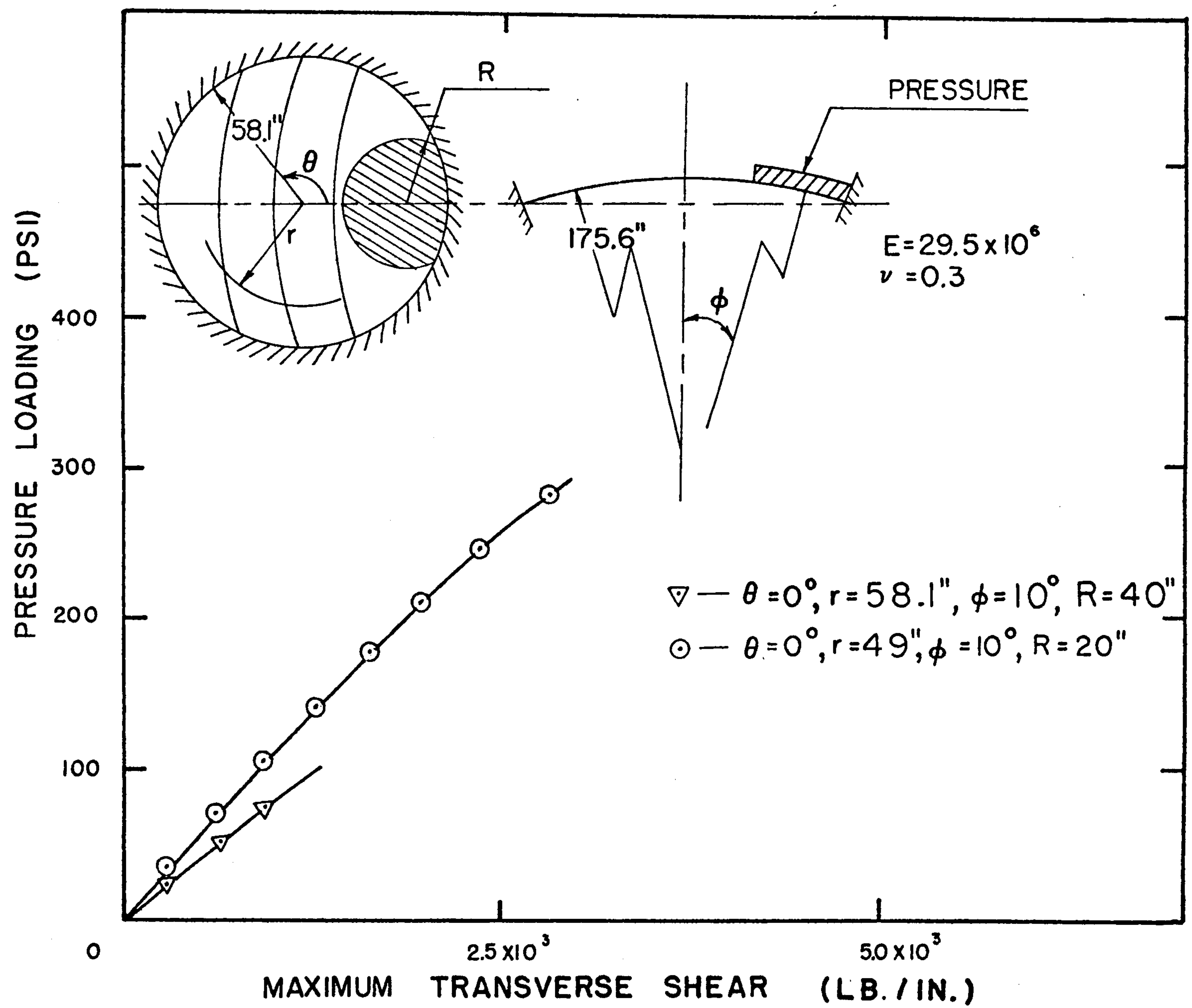

Fig. 8 MAXIMUM TRANSVERSE SHEAR VERSUS LOADING