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INVESTIGATION OF THE EFFECTS OF GEOMETRIC AND LOAD PERTURBATION TO BUCKLING IN MULTILAYERED TORISPHERICAL PRESSURE VESSEL HEADS

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ABSTRACT

The object of this paper is to investigate the effects of geometry and load perturbation to buckling in multilayered pressure vessel heads. The pressure vessel head in concern is thin walled torispherical geometry. Geometric and load perturbation can alter both the critical load for buckling and the buckled shape. Two and three layered torsispherical heads are considered. Two layered models include steel–aluminum and titanium–aluminum configurations and three layered models include copper–steel–copper configuration. Internally pressurized three-dimensional torispherical pressure vessel head model that is previously used in literature is constructed. As a first step eigenvalue solutions are obtained for each model. After this instability solutions with large deformation effects are conducted to obtain more realistic instability pressure values nonlinear. The solution is performed by finite element program ANSYS Workbench. In nonlinear analyses, perfectly plastic material model is used. It is concluded that geometric and load perturbations cause the instability pressure to decrease and cause the structure to buckle at a lower pressure value. It is also observed that for steel-aluminum configuration geometric perturbation is more critical than load perturbation whereas for aluminum-titanium the reverse is valid.

INTRODUCTION

Thin-walled torispherical pressure vessel heads have a wide usage area in industry.

One of the major problems that is faced during the operation of thin-walled structures is buckling. In buckling structural members collapse under compressive loads greater than the material can withstand. Torispherical pressure vessel heads are sensitive to geometric or load imperfections due to unstable post-buckling behavior. Finite element analysis is widely used in the design of these structures [1,2].

Extensive studies are presented on the buckling of pressure vessels [3-8]. Athiannan and Palaninathan presented experimental studies on buckling of thin-walled circular cylindrical shells under transverse shear. The buckling loads are also obtained from finite element models, empirical formulae and codes and are compared [9]. Godoy’s study deals with the modeling of shape deviations in thin-walled plates and shells using finite elements together with perturbation techniques [10]. Khan et al. presented an experimental technique for the buckling test of shells under external pressure to determine buckling load [11]. Miller worked on buckling criteria for torispherical heads under internal pressure which are especially outside the limits of ASME codes [12].

Layered structures are widely used in as diverse applications as in aircrafts, thin film deposition in semiconductor devices, heat exchangers, etc. Such structures are subjected to a variety of loading types with some of them being capable of causing buckling. Rutgerson and Botega’s study provides details about a wider study in to the elastic buckling behavior of circular panels for combination of temperature, external pressure and edge loading [13]. Guz and Dyshel studied loss of local stability in a cracked bimetal plate [14]. Muscat et al. proposed a criterion for evaluating the critical limit values and determining the plastic loads in pressure vessel design [15]. Blachut’s study presents results of a numerical and experimental investigation into static stability of externally pressurized layered hemispherical and torispherical domes. Buckling/collapse tests are also conducted on domes from various materials [16].

Mackenzie et al. made an extensive review on the descriptions of the EN13445 and ASME Boiler and pressure vessel code contents [17]. The ASME Twice Elastic Slope (TES), criterion uses an empirical procedure for calculating collapse loads in experimental stress analysis of pressure vessels. Mackenzie et al. considered small and large deformation effects and the geometry and load perturbations. Their study contains the formation of the gross plastic deformation mechanism in the models in relation to the elastic–plastic buckling response of the vessels. In their study both ASME TES and plastic work criteria (PWC) are considered. The PWC criterion requires a plot of load against normalized load-plastic work curvature [17].

The object of this paper is to investigate the effects of geometric and load perturbation to buckling in multilayered pressure vessel heads. Internally pressurized three-dimensional torispherical pressure vessel head model that is previously used in literature is constructed. For the solution finite element program ANSYS Workbench is used. First of all linear, buckling analyses are conducted prior to solving the nonlinear buckling shapes. Afterwards, nonlinear instability analyses are performed for no perturbation, geometric perturbation and load perturbation models. For all nonlinear analyses elastic perfectly plastic material model is used.

FINITE ELEMENT MODEL

Geometry

For the analyses of multilayered thin walled torispherical head, multilayered version of the geometry investigated previously by Miller et al. [18] and Galletly and Blachut [19] and Mackenzie et al. [17] is considered. The two layered configuration of geometry of torispherical head is given in Fig. 1. For two layered configuration thickness of each layer is set to be 3.29 mm, and the three layered configuration has layer thickness of 2.193 mm. In each case total thickness adds up to 6.58 mm.

Finite Element Model

Ansys Workbench version 14 is used for the finite element analyses [20]. In the finite element mesh 4-noded SHELL181 element is used for simulating multilayered torispherical head. SHELL181 may be used for layered applications for modeling laminated composite shells or sandwich construction. This element can be used for a wide range of thickness from thin to moderately thick geometry and supports Mindlin-Reissner shell theory. Each complete model is 3D and two layered model consists of 17345 elements and three layered model has 25977 elements (Fig.2).

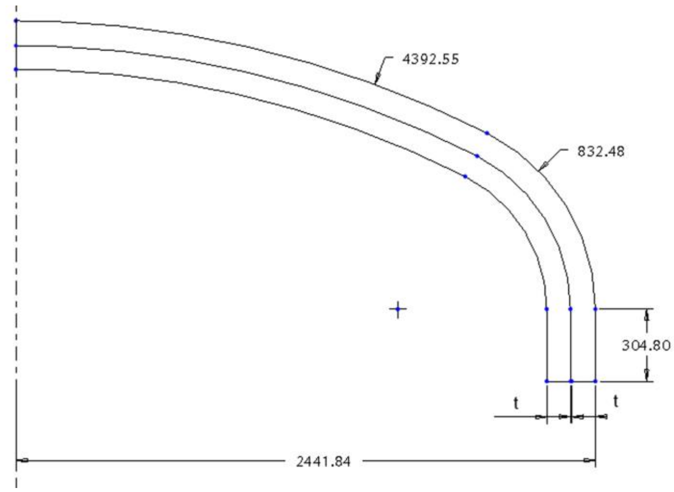


FIG. 1. TWO LAYERED TORISPERICAL HEAD GEOMETRY.

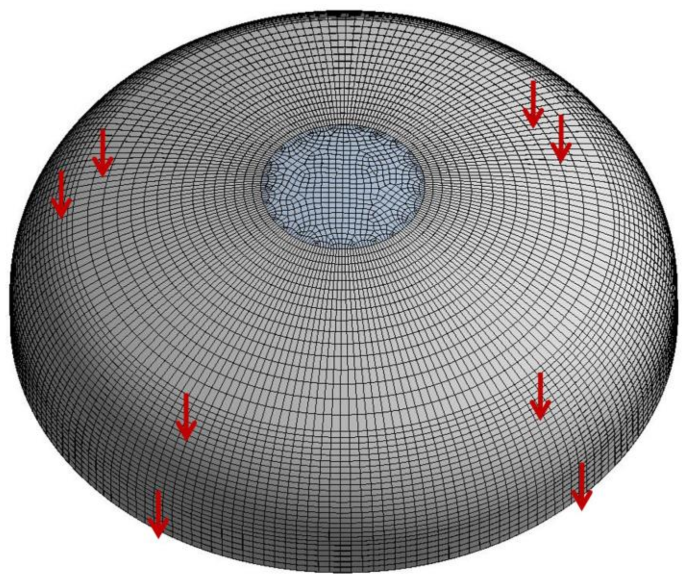


FIG. 2. FINITE ELEMENT MODEL AND PERTURBATION FORCES.

TABLE 1
MATERIAL PROPERTIES OF MULTILAYERED TORISPHERICAL PRESSURE VESSEL HEAD.

Material	Young's modulus (GPa)	Yield strength (MPa)	Poisson's ratio
Steel	210	350	0.3
Aluminium	70	300	0.3
Copper	120	70	0.3
Titanium	114	830	0.3

Material Properties

Elastic perfectly plastic material model is used for large deformation nonlinear analyses. Table 1 shows the material properties used in static analyses.

Multilayered Configurations

Taking the industrial usage into account several multilayered configurations are prepared. These are steel-aluminum, aluminum-titanium and copper-steel-copper. For two layered configurations the reverse options are also solved for. These are aluminum- steel and titanium- aluminum.

EIGENVALUE SOLUTION

It is useful to conduct a linear buckling analysis before solving a nonlinear buckling problem to observe the frequency content of the system [21,22]. Linear buckling (eigenvalue) analysis yields a 'classical' solution to a buckling problem. In spite of the fact that the critical load obtained by linear buckling is not conservative, linear buckling is important as the eigenvalue buckling yields an estimate of the critical load to induce buckling. Altough generally the calculated value is higher than the actual critical load, it presents a good starting point to observe the possible buckling mode shapes. The solution time for linear buckling analysis is less than the solution time for nonlinear post-buckling analysis.

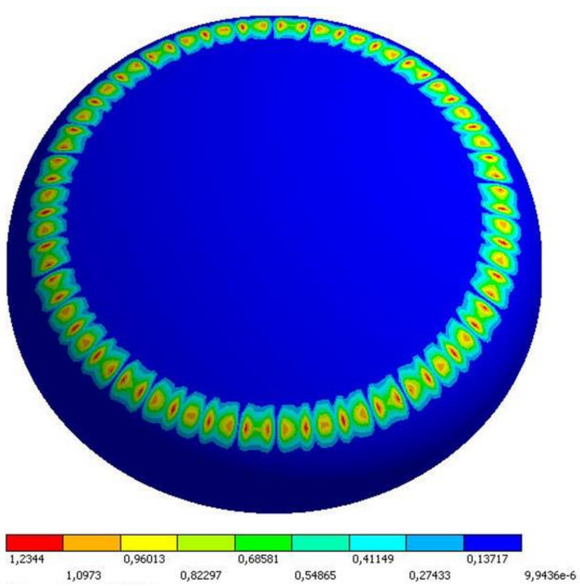


FIG. 3. FIRST BUCKLING MODE SHAPE FOR COPPER-STEEL-COPPER CONFIGURATION.

First buckling mode shapes for all two and three layered models are obtained using eigenvalue analysis. For all the eigenvalue solutions the internal pressure is kept constant at 0.1 MPa. The obtained critical pressure values are presented in Tables 2 and 3 for two layered and three layered structures respectively. In Fig. 3 first buckling mode shape for copper-steel-copper configuration is given.

TABLE 2
CRITICAL PRESSURE VALUES FOR TWO LAYERED STRUCTURES (EIGENVALUE SOLUTION).

Inside	Outside	Critical Pressure (MPa)
steel	aluminum	0.8462
aluminum	steel	0.8458
aluminum	titanium	0.5770
titanium	aluminum	0.5771

TABLE 3
CRITICAL PRESSURE VALUES FOR THREE LAYERED STRUCTURE (EIGENVALUE SOLUTION).

Inside	Middle	Outside	Critical Pressure (MPa)
copper	steel	copper	0.7780

PERTURBATION MODELS

For perturbation force model, similar to Mackenzie et al. [17], 2kN perturbation forces are used which are applied normal to the mid-section of the knuckle region of each quadrant, as shown in Fig. 2.

For geometric perturbation model, initial geometric perturbation corresponding to the first non-axisymmetric eigen buckling mode, shown in Fig. 3 is applied, with maximum displacement corresponding to half of the total shell thickness.

NONLINEAR INSTABILITY SOLUTIONS

Pressure vessel materials show linear elastic behavior up to yield point and thereafter the stress and strain increase in a non-proportional manner which means work hardening occurs. In a case like this to study the post-buckling behavior is important. As nonlinear buckling analysis approach is usually more accurate and realistic, it is recommended to use in design of structures. In this technique, a nonlinear analysis with gradually increasing loads is employed to search for the load level at which the structure turns to unstable state. Both material and load nonlinearity are considered in this problem. Large deformation effect is also the cause of nonlinearity. Newton-Raphson scheme is applied in ANSYS in solving nonlinear problems. In Newton-Raphson method, the load is subdivided into a series of load increments that can be applied over several load steps.

In this paper large deformation analysis are applied to geometric and load perturbation models and no perturbation model. The pressure deformation graph for no perturbation model which is also presented by Mackenzie et al. [17] is given in Fig. 4.

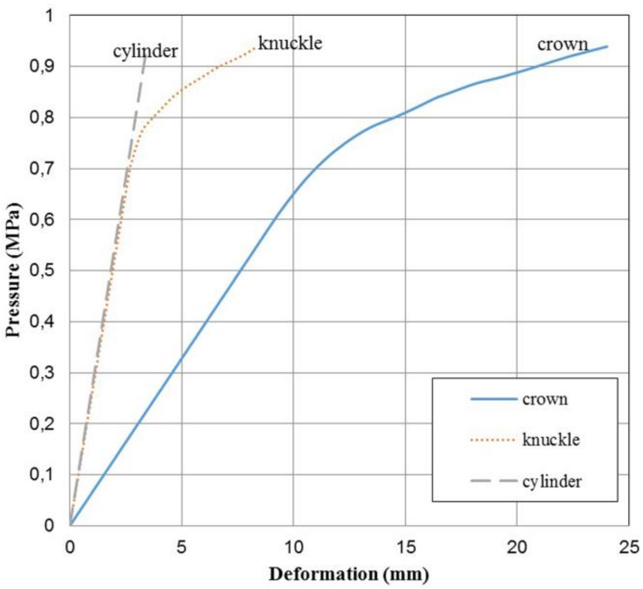


FIG. 4. PRESSURE DEFORMATION GRAPH [17].

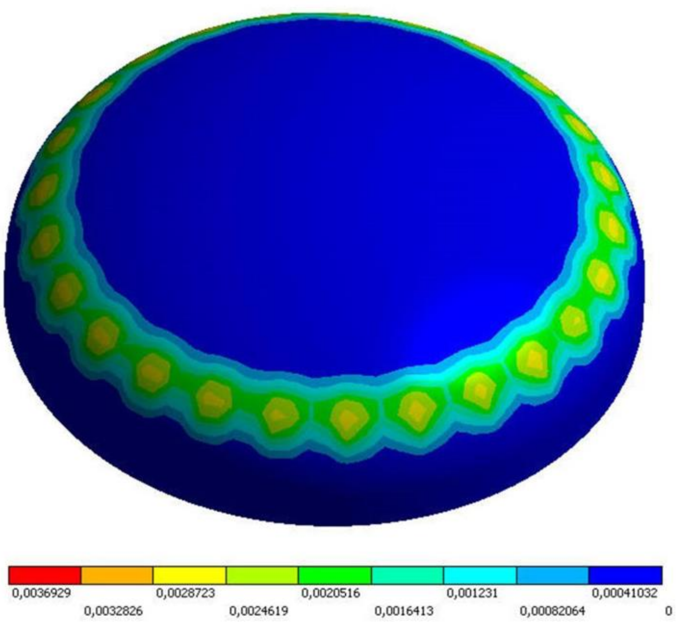


FIG. 5. EQUIVALENT PLASTIC STRAIN DISTRIBUTION AT THE ONSET OF BUCKLING FOR NO PERTURBATION MODEL (ALUMINIUM-STEEL CONFIGURATION) (INSTABILITY PRESSURE 0.929 MPA).

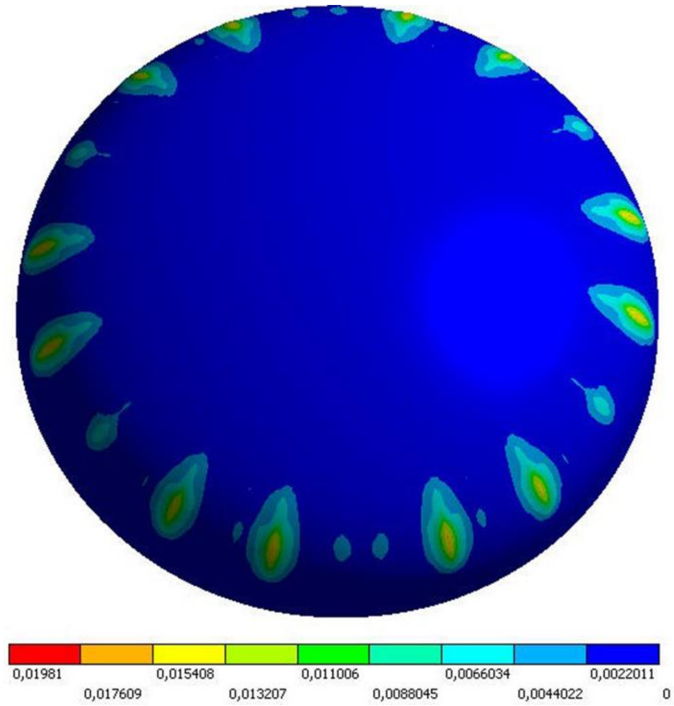


FIG.6. EQUIVALENT PLASTIC STRAIN DISTRIBUTION AT THE ONSET OF BUCKLING FOR GEOMETRICALLY PERTURBED ALUMINIUM-STEEL CONFIGURATION (INSTABILITY PRESSURE 0.765 MPA).

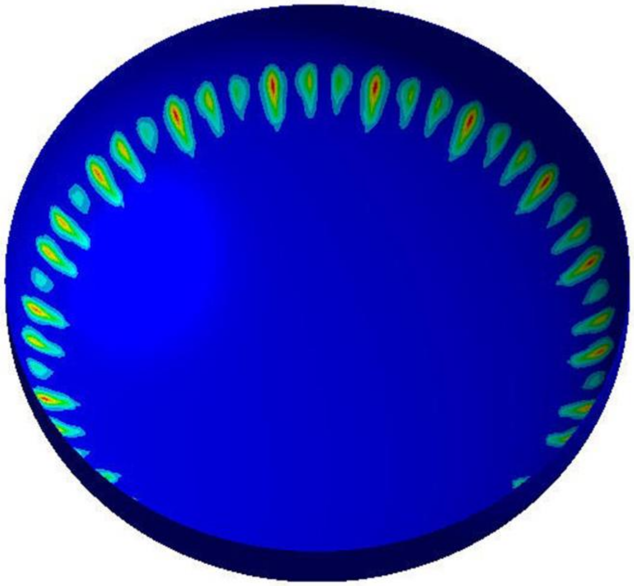
The equivalent plastic strain distribution at the onset of buckling for no perturbation model for aluminium-steel configuration is shown in Fig. 5. The equivalent plastic strain distribution at the onset of buckling for geometrically perturbed aluminium-steel configuration is shown in Fig. 6. When this shape is compared with no perturbation model presented in Fig. 5, the effect of geometric perturbation on the buckling shape can be easily observed.

In Fig. 7 the equivalent plastic strain distribution at the onset of buckling for geometrically perturbed aluminium-titanium configuration is shown. Different from the aluminium-steel configuration aluminium-titanium configuration has different shapes at the inside and outside of the torispherical geometry. In Fig. 8 the equivalent plastic strain distribution for steel-aluminium for load perturbation model is presented.

The instability pressure and corresponding equivalent plastic strain values obtained for two and three layered configurations are presented in Tables 4 and 5 respectively.

For steel- aluminium and aluminium-steel configurations the obtained instability pressure values are exactly the same whereas slight differences exist in plastic strain values. For aluminium-titanium and titanium-aluminium configurations differences exist in both instability pressure and plastic strain values.

a) Inside view



b) Outside view

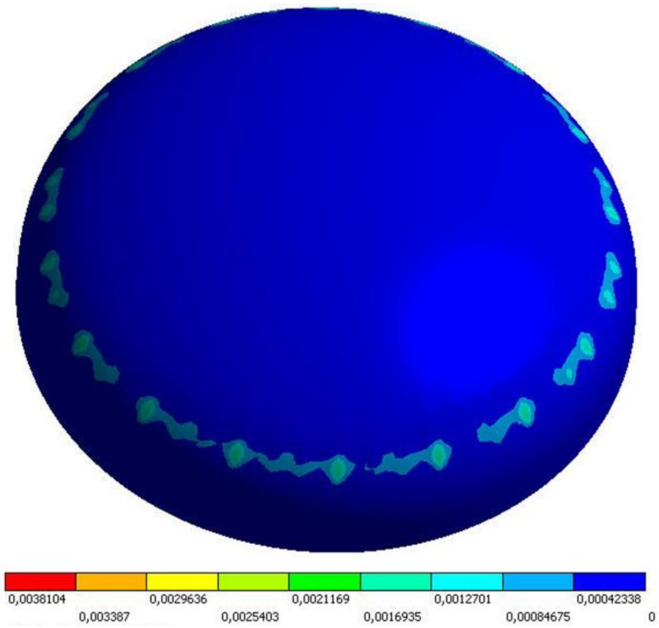


FIG.7. EQUIVALENT PLASTIC STRAIN DISTRIBUTION AT THE ONSET OF BUCKLING FOR GEOMETRICALLY PERTURBED ALUMINIUM-TITANIUM CONFIGURATION (INSTABILITY PRESSURE 0.944 MPA).

For both two and three layered structures it is obtained that geometric and load perturbations cause to decrease the instability pressure values. For steel-aluminum configuration geometric perturbation is more critical than load perturbation whereas for aluminum-titanium the reverse is valid.

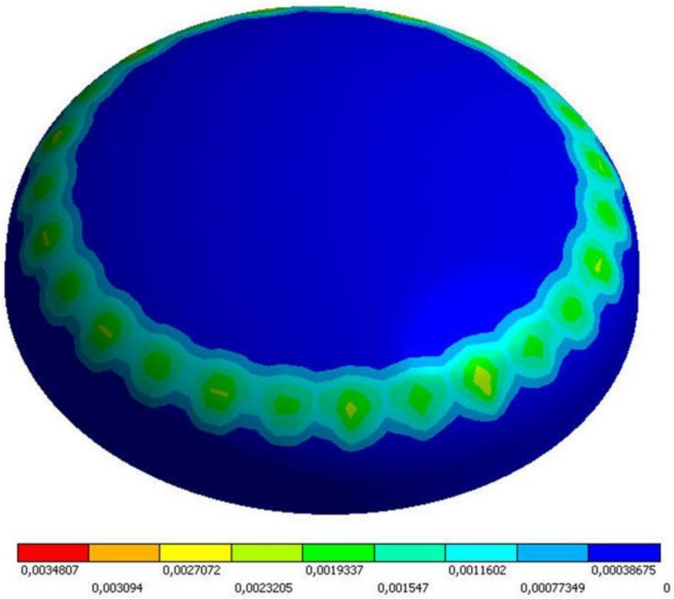


FIG.8. EQUIVALENT PLASTIC STRAIN DISTRIBUTION AT THE ONSET OF BUCKLING FOR LOAD PERTURBATION MODEL FOR STEEL-ALUMINIUM CONFIGURATION (INSTABILITY PRESSURE 0.923 MPA).

DISCUSSION AND CONCLUSIONS

The effects of geometric and load perturbation models to buckling for multilayered torispherical heads are investigated through this study. As a first step, eigenvalue analyses are conducted. The results of eigenvalue study yield the buckling shapes given in Fig. 3 and the critical pressure values are presented in Tables 2 and 3 for two and three layered configurations respectively.

As a second step, nonlinear instability analyses are conducted for each two and three layered configurations with geometric and load perturbation and with no perturbation options. It is concluded that geometric and load perturbations cause the instability pressure to decrease and cause the structure to buckle at a lower pressure value. It is also observed that for steel-aluminum configuration geometric perturbation is more critical than load perturbation whereas for aluminum-titanium the reverse is valid. The equivalent plastic strain values for two layered geometric perturbation models are higher than no perturbation and load perturbation results. For three layered copper-steel-copper configuration the obtained perturbation effect is found to be insignificant.

When the eigenvalue results are compared with nonlinear solutions it can be stated that nonlinear solutions do not yield the same deformation modes with eigenvalue solutions. Different from the single layered structure results, this work show that the critical pressure values obtained by eigenvalue solutions are lower than the instability pressure values obtained by nonlinear instability solutions.

TABLE 4

INSTABILITY PRESSURES AND CORRESPONDING EQUIVALENT PLASTIC STRAINS FOR TWO LAYERED STRUCTURES.

Inside	Outside	Perturbation	Instability Pressure (MPa)	Eq. Plastic Strain
		No	0.929	0.003725
steel	aluminum	Load	0.923	0.003481
		Geometric	0.765	0.019972
		No	0.929	0.003693
aluminum	steel	Load	0.923	0.003703
		Geometric	0.765	0.019810
		No	0.980	0.000407
aluminum	titanium	Load	0.944	0.000101
		Geometric	0.949	0.003810
		No	0.971	0.00030
titanium	aluminum	Load	0.942	0.000083
		Geometric	0.949	0.003785

TABLE 5

INSTABILITY PRESSURES AND CORRESPONDING EQUIVALENT PLASTIC STRAINS FOR THREE LAYERED STRUCTURE.

Inside	Middle	Outside	Perturbation	Instability Pressure (MPa)	Eq. Plastic Strain
			No	0.819	0.074741
copper	steel	copper	Load	0.816	0.057126
			Geometric	0.818	0.064558

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