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Parameters Affecting Load Diffusion in Cylindrical Shell Structures

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***Abstract*—Structural Qualification tests on Aerospace structures are carried out to study the behaviour and to qualify the structure to ensure the Ultimate load carrying capacity. The stresses and displacements on the test specimen are measured and assessed for this purpose. The load, being of very high magnitude is applied as concentrated loads by hydraulic jacks to simulate the real flight conditions. The concentrated loads applied by the hydraulic jacks have to be brought to uniformly distributed load as expected in flight of the launch vehicle. Load diffusers (Adaptors) are used for this purpose.**

Various fundamental parameters such as number of loading points, height, thickness, material, etc. affect the load diffusion.

Interface parameters like interface gaps machining tolerances, bolted joints etc also play additional role in load diffusion. These are to be quantified as a research element. The theoretical analysis using FEM software of the above parameters will be dealt in the present work.

I. INTRODUCTION

Static structural qualification tests form an important aspect in the realization of a structural component. These tests will help us to understand the behavior of the structures under external load. To ensure the authenticity of the test data the real flight boundary conditions has to be simulated. Real flight boundary conditions include loads and fixity conditions. The overall test setup readiness includes instrumentation, hydraulics etc. Instrumentation includes strain gauging displacement measurements using LVDT's, pressure measurement, load measurement, photo elastic coating, holography, data logging etc. Load application methods include use of hydraulic jacks (the most extensively used methods), dead weight loading, pressure loading on open components using rubber bellows with hydraulic or pneumatic loading, balancing systems etc. Hydraulic jacks are actuated by hydraulic power packs or manually operated hand pumps. The loads are transmitted through wire ropes or metallic links.

Types of components generally tested include open metallic structures, pressure vessels, pressure bottles, payload fairing etc. Tests include proof, structural, hydro proof tests, design development tests, design qualification tests, some of which are up to failure.

Static structural qualification tests are basically meant for the design qualification. The various types of loads that are considered are – Internal/External pressure, Axial load: Tension or Compression, Shear load, Bending moment, Low temperature simulation. The requirements that lead to the design of a test rig are:

- Simulation of flight boundary conditions
- Measurement of strain/displacements etc.

The qualification test should provide unambiguous and accurate data on the total load applied, accurate and reliable strain / displacement/ deflection data, determine safety margin, buckling and post buckling behaviour etc.

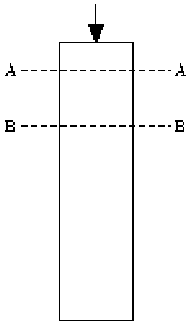
The different elements that constitute a test rig for qualification test are the loading modules, hydraulic jacks, load cells and adaptors.

Since the loads required for structural qualification tests are of very high magnitude, are applied as concentrated loads by hydraulic jacks. These loads have to be brought to uniformly distributed load as expected in flight of the launch vehicle. *Load Diffusers* are used for this purpose. The design of a Load diffuser involves determining the various parameters which ensures the real flight boundary conditions.

In the present work, we are concerned with the study of various load diffusion parameters on Cylindrical Shells (which is the general shape of Adaptors) using an FEA software like Ansys. The various parameters considered include:

- Effect of number of loading points on the shell
- Effect of thickness of the shell
- Effect of height of the shell
- Effect of diameter of the shell
- Effect of material of the shell
- Effect of gussets/ local reinforcement on load diffusion.

II. SAINT-VENANT'S PRINCIPLE [1] [2]



So far we have been dealing with point loads acting at the ends of beams. We have assumed that the stress is the same as $\sigma_{av} = P/A$. However, this is not true close to the point of application of the load. Saint-Venant's principle (by the French elastician Saint-Venant) states that the stresses remote from the point of application of the load are not affected by the precise behaviour of the structure close to the point of application of the load. In the drawing shown, this means that although the stress field at A-A might be hard to calculate, at B-B the stress can be approximated as P/A. S-V's principle is consistent with many years of experiment and analysis, but has not been proved.

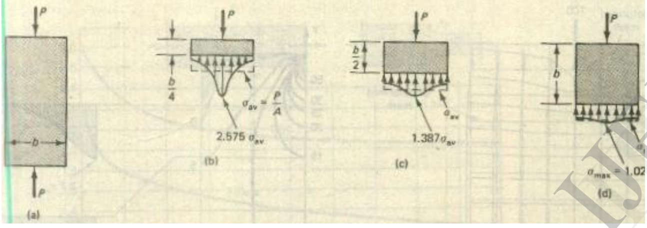


Fig No. 2 Stress distribution near a concentrated force in a rectangular elastic plate

A short block is shown in Fig No. 2(a) acted upon by concentrated forces at its ends. Analyzing this block for stresses as a two dimensional problem using the methods of theory of elasticity gives the results shown in Fig No. 2(b), (c) and (d). The average stress σ_{av} is also shown on these diagrams. For a purely elastic material the maximum stress theoretically becomes infinite right under the concentrated force, since a finite force acts on a zero area. In real situations, however, a truly concentrated force is not possible and virtually all materials exhibit some plastic behaviour; therefore the attainment of an infinite stress is impossible. It is important to note two basic aspects from this solution. First, the average stress for all cases, being based on conditions of equilibrium, is always correct. Second, the normal stresses at a distance equal to the width of the member are essentially uniform. The second observation illustrates the famed Saint-Venant's principle [1]. In common engineering terms it simply means that the manner of force application on stresses is important only in the vicinity of the region where the force is applied. This also holds true for disturbances caused by changes in cross section. Consciously or unconsciously this principle is nearly always applied in idealizing load carrying systems.

III. METHODOLOGY

Test adaptors are to be analysed for its structural adequacy to withstand the required loads and also to distribute the loads uniformly to the flight hardware. For this purpose cylindrical shells of different thickness, height and diameter were to be modelled and concentrated axial loads were applied at different points. The total axial load considered was 4800KN. The various load diffusion parameters have to be then studied using the FEA software ANSYS. The various parameters to be studied include:

- Effect of number of loading points on the shell
- Effect of thickness of the shell
- Effect of height of the shell
- Effect of diameter of the shell
- Effect of material of the shell

In all the above cases the height where the uniformly distributed load condition is achieved has to be measured from the ANSYS result interface.

A. *Finite Element Modelling*

The application of Finite Element methods to obtain the behaviour of the structure has reached a sufficient state of maturity so that the results obtained for this analysis can be accepted with high level of confidence.

The modelling of the cylindrical shell is carried out in Ansys itself. Four nodded shell elements are used for modelling the shell. Cylindrical shells of different thickness (12mm, 16mm, and 24mm), heights (2m, 3m, 4m and 5m) and diameters (2.8m and 4m) were modelled. Shells of different materials (Mild Steel, Aluminium and Cast Iron) were also modelled. As there is need to apply load and constraints at certain locations, the beam element is generated according to the requirements and revolved to get shell elements.

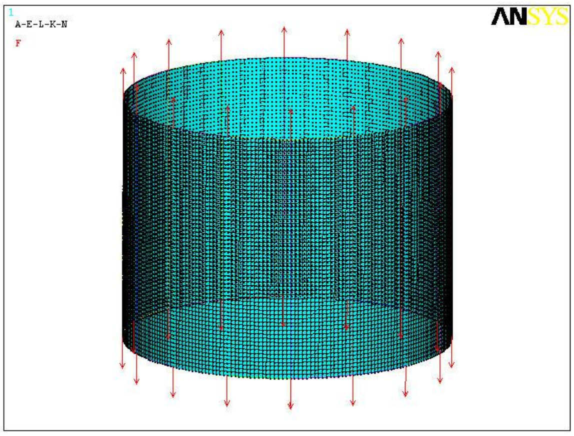


Fig No.3 Meshed model of a cylindrical shell element (4m dia, 3m high and 24mm thick) loaded at 16 points on both sides prepared in Ansys

B. *Finite Element Analysis*

Linear static analyses for the above modelled cylindrical shells are carried out independently. The analysis mainly consists of studying reaction/constant forces, element forces, displacement and axial stress distribution. Analysis is carried out for different cases of axial loading conditions (Tensile and Compressive) as well as for different sets of loading points (8 points, 12 points and 16 points). The loadings were provided on both ends of the cylindrical shells. About 40 models were analysed for different conditions of shell heights, shell thickness, loadings etc. The axial stress-distribution results are analysed to get the height where the load condition becomes that of uniformly distributed load (UDL).

Also, in the top adaptor modelled the reaction forces were calculated at the 16 locations that were restrained and its deviation from the applied force was studied and the percentage error calculated.

C. Theoretical Calculations

Here the total axial load considered for analysis purpose is P = 4800000 N.

So for 8 loading points each point should produce a load of $F_1 = P/8 = 600000$ N.

Then for 12 loading points each point should produce a load of $F_2 = P/12 = 400000$ N.

And for 16 loading points each point should produce a load of $F_3 = P/16 = 300000$ N.

Now, the average axial stress, $(\sigma_Y)_{avg}$ for a shell = P/A

where, A – Cross sectional area of the shell = $\pi \times D \times t$
where, D – Diameter of the shell
t – Thickness of the shell

- For a 4m diameter shell –
  A. For a shell thickness of 12mm, average axial stress, $(\sigma_Y)_{avg} = 31.831$ N/mm^2
  B. For a shell thickness of 16mm, average axial stress, $(\sigma_Y)_{avg} = 23.873$ N/mm^2
  C. For a shell thickness of 24mm, average axial stress, $(\sigma_Y)_{avg} = 15.916$ N/mm^2

- For a 2.8m diameter shell –
  A. For a shell thickness of 16mm, average axial stress, $(\sigma_Y)_{avg} = 34.105$ N/mm^2

Now we know that the region where the axial stress value becomes same as that of the average axial stress around the cross-section of the cylinder, the load becomes that of uniformly distributed load (UDL). But here as per the design requirement a 1% variation in this average axial stress is permissible. So, we now redefine the UDL region as one which falls within 1% variation of the average axial stress. Thus we have to define the range of average stress for the above conditions. They are:

- For a 4m diameter shell –
  A. For a shell thickness of 12mm, the range for $(\sigma_Y)_{avg}$ is (31.5127,32.1493)N/mm^2
  B. For a shell thickness of 16mm, the range for $(\sigma_Y)_{avg}$ is (23.5345,24.1119)N/mm^2
  C. For a shell thickness of 24mm, the range for $(\sigma_Y)_{avg}$ is (15.7563,16.0747)N/mm^2
- For a 2.8m diameter shell –
  A. For a shell thickness of 16mm, the range for $(\sigma_Y)_{avg}$ is (33.7636,34.4457)N/mm^2

Thus while plotting the result for axial stress in the cylinder in Ansys, we have to use non-uniform contour plot for specifying the above ranges for average axial stress. And from such a plot we can measure the height from either the top or bottom end of the cylinder where the UDL load condition is achieved.

IV. RESULTS AND DISCUSSIONS

A contour plot for the axial stress variation was plotted in Ansys for as many as some 40 cases based on the different conditions to be analysed. The height to the UDL condition i.e. where the loads diffuse to a uniform state in each of the shells modelled was measured in all these cases. These results were then tabulated. Also graphs were plotted for the variation of axial stress along the height of the cylindrical shells at the point of application of load. The contour plots for two of the conditions are given below.

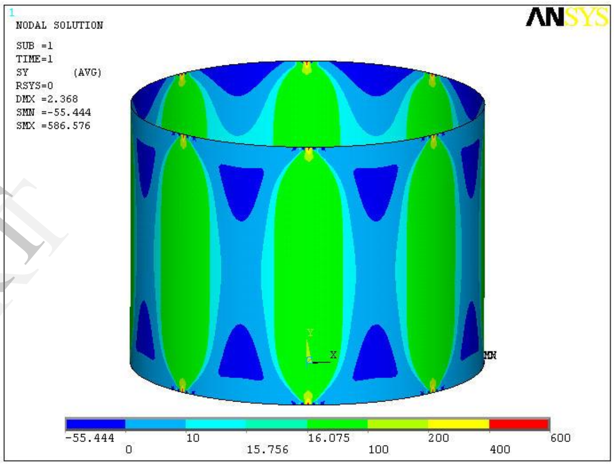


Fig No.5 Contour plot in Ansys showing variation of axial stress (σ_Y) along the height of the cylindrical shell (4m dia, 3m high and 24mm thick) loaded at 8 points on both ends

The above result is obtained by loading a cylindrical shell of the above mentioned dimensions at 8 loading points on either side. In the above plot we have used non-uniform contour to plot a range of stress between 15.765 N/mm^2 and 16.075 N/mm^2 in order to define the region of UDL. But it can be seen from the plot that no such UDL region is obtained at any cross-section of the cylindrical shell. So in this case we do not achieve the condition of UDL. A maximum variation of about 65% is observed in the stress values at the mid section of the shell when compared to the theoretical average stress value of 15.916 N/mm^2.

The result of another loading condition is shown next.

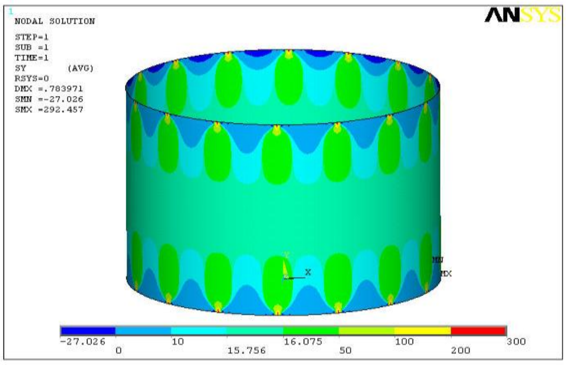


Fig No.6 Contour plot in Ansys showing variation of axial stress (σ_Y) along the height of the cylindrical shell (4m dia, 3m high and 24mm thick) loaded at 16 points on both ends

All the dimensions remaining the same, the above result is obtained by loading the cylindrical shell at 16 loading points on either side. Here the same range of stress as in Fig No.5 is used for plotting the axial stress using non-uniform contours. But here we can see that we obtain the region of UDL at a cross-section, at a distance of 950mm from either ends of the cylindrical structure. By comparing the above two results we can see that by increasing the number of loading points we can ensure faster load diffusion and thereby reduce the distance to the UDL region from the shell end.

Similar results were plotted in Ansys for the other conditions also. In those results wherein UDL condition was achieved, the distance from the shell ends to the UDL region was measured using geometry checking features in Ansys and these results were then tabulated. Graphs were also plotted to show the variation of the axial stress along the height of the cylindrical shell at the point of loading. These graphs give a good comparison between the various conditions considered for analysis.

TYPE OF AXIAL LOADING	DIAMETER OF CYLINDRICAL SHELL (mm)	MATERIAL OF CYLINDRICAL SHELL (mm)	HEIGHT OF CYLINDRICAL SHELL (mm)	NUMBER OF LOADING POINTS	PERCENTAGE VARIATION FROM AVERAGE STESS AT UDL OR MID SECTION REGION (DISTANCE)		
					FOR 12mm THICK SHELL	FOR 16mm THICK SHELL	FOR 24mm THICK SHELL
TENSION	4000	MS	2000	8	±209% (1000mm)	±190% (1000mm)	±155% (1000mm)
				12	±54.8% (1000mm)	±35.7% (1000mm)	±20.5% (1000m)
				16	±2.3% (1000mm)	±1.2% (1000mm)	±1% (1000mm)
			3000	8	±143% (1500mm)	±109% (1500mm)	±65.5% (1500mm)
				12	±3.6% (1500mm)	±1% (1400mm)	±1% (1300mm)
				16	±1% (1050mm)	±1% (1000mm)	±1% (950mm)
			4000	8	±76.5% (2000m)	±45.8% (2000mm)	±17.9% (2000mm)
				12	±1% (1500mm)	±1% (1450mm)	±1% (1350mm)
				16	±1% (1050mm)	±1% (1000mm)	±1% (950mm)
			5000	8	±30.1% (2500mm)	±11.6% (2500mm)	±1% (2400mm)
				12	±1% (1550mm)	±1% (1450mm)	±1% (1350mm)
				16	±1% (1050mm)	±1% (1000mm)	±1% (950mm)
		ALUMINIUM	2000	16	-	±1.2% (1000mm)	-
		CAST IRON	2000	16	-	±1.2% (1000mm)	-
	2800	MS	2000	16	-	700	-
COMPRESSION	4000	MS	2000	16	-	±1.2% (1000mm)	-

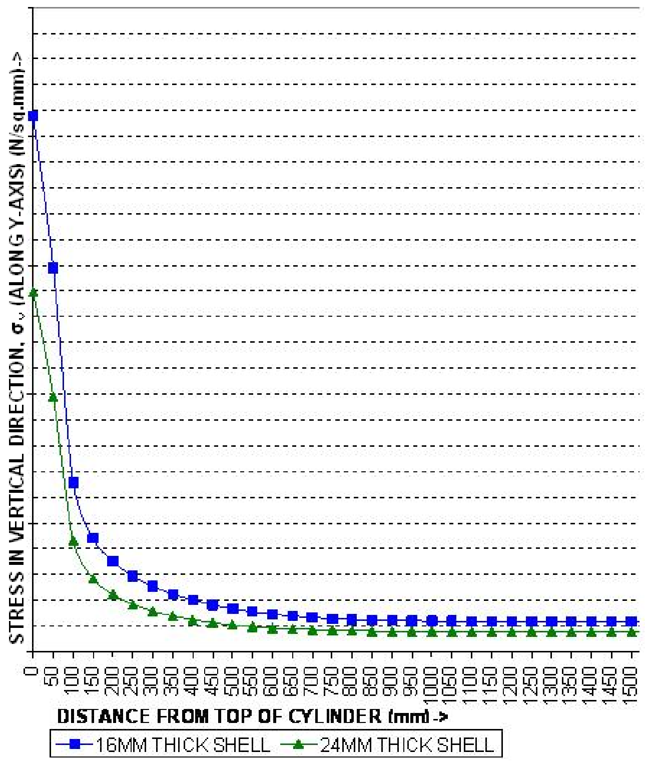


Fig No.7 Plot for variation of stress in a cylindrical shell 3m high, loaded in tension, axially at 16 points on both ends for various shell thickness along the loading point

The above plot shows that with the increase in shell thickness, the load diffuses faster and UDL condition is achieved early. The effect of various load diffusion parameters were better understood by plotting similar graphs comparing those parameters.

V. CONCLUSION

The following conclusions could be drawn from the analysis of the results in the table as well as from the graphs:

1. The increase in thickness of the cylindrical shell shows a reduction in the distance to the UDL region. This is due to the fact that when the thickness increases more cross-sectional area is available which leads to faster load diffusion.
2. With the increase in number of loading points there is again reduction in the distance to UDL region since the increased number of loading points replicates a closer condition of uniformly distributed load.
3. It is observed that the height of the cylindrical shell does not have much effect on load diffusion. So there is no point in increasing the height beyond a certain limit in the design of adaptors.
4. Since the material is considered to be perfectly elastic, no change is observed in the distance to the UDL region whether loading is tensile or compressive. There is only a change in sign of stress.
5. The effect of flange is to improve load diffusion, thereby reducing the distance to UDL region. Here more cross sectional area is available for faster load diffusion.
6. Stresses are geometry dependent within the elastic limit. Thus the distance to UDL region is independent of the material chosen. This is also evident from the relation for stress, where E value doesn't have any significance.

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