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Optimization of shrink fitted compound pressure vessel

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ABSTRACT

Two cylinders are shrunk into each other with different diametric interferences to form a compound cylinder. The shrinkage produces a residual stress distribution within the walls of the cylinders, which improves the cylinder behavior against the working pressure. When the magnitude of pressure approaches to the yield point of the material used, the thickness of cylinder to resist the load approaches infinity. The goal of the work is "To get optimum volume of compound cylinder subjected to the internal pressure equal to the yield stress of the material". Optimized volume is obtained using excel non-linear solver. Two layer compound cylinder considered for the study. Theoretical results of hoop stresses are verified with ANSYS Workbench results. Hoop Stresses are maximum at the inner surface of the inner cylinder; similar observations are found for aluminium and brass compound cylinders. Finally comparison of the volume of compound cylinder is done between steel, aluminium and brass. Volume of compound cylinder with steel material is less than volume of compound cylinders with aluminium and brass. Steel can handle more pressure with less volume as compared to aluminium and brass.

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I. INTRODUCTION

The compound cylinders are used for storing fluids at high pressure. Compound cylinders are classified into two types - Thin cylinder & Thick cylinder. For high pressure applications thick cylinders are used. When the magnitude of pressure increases and approaches the yield point of the material used, the thickness of cylinder to resist the load approaches infinity. If internal pressure is equal to the yield strength of the material used, thick cylinder fails. Therefore shrink-fitted compound cylinders are used. Compound cylinders can store the fluids at higher pressure closer to the yield stress of the material. Compound cylinder has wide applications in chemical, nuclear, fluid transmitting plants, power plants, gas storages, hydraulic presses and military equipment. Optimally designed compound cylinders have equal maximum hoop stress in both - the inner and outer cylinders. The value of this hoop stress is closer to the value of yield stress of the material used. Such compound cylinders can be used in future automobile and space vehicles for storing gaseous fuels. Majzoobi et al., 2003; Hojjati and Hassani, 2007; have analysed the autofrettaged cylinders, which are similar to compound cylinders [3]. Design of a shrink fit assembly is tricky and trial and error method is used in it. The compound cylinder consists of one innermost cylinder which is covered other cylinder by interference fit. The cylinders are manufactured such as to maintain the required interference. Then the inner cylinder is cooled to a very low temperature or the outer cylinder is heated to a high temperature depending on the interference value, and then both the cylinders are assembled together. After attaining normal room temperature, the inner cylinder expands or the outer cylinder shrinks, which keeps both the cylinders together due to the interference. This causes compressive stress in inner cylinder and tensile stress in outer cylinder. These stresses should be within the elastic limits of the material. When such compound cylinders are subjected to internal pressure, the compressive stress in inner cylinder is relieved first, and then tensile stress is developed. The tensile stress in outer cylinder is further increased due to internal pressure. Generally the three principal stresses in the cylindrical pressure vessels are – circumferential stress, radial stress and longitudinal stress. Out of these, the circumferential stress, also known as hoop stress, is maximum and it is the main cause of failure of pressure vessels. In case of open type of cylindrical pressure vessels, the longitudinal stress is absent. When the internal pressure is very high, almost close to its yield point stress, then designing the single cylinder pressure vessels would be very bulky and heavy. Then by using compound cylinders, compact and practicable pressure vessel design can be obtained.

In this work, the numerical optimization techniques, computer simulations are employed to predict the optimized parameters of a compound cylinder for a specific working pressure equal to the yield point stress of the material used for the cylinders. ANSYS Workbench is used to verify the optimum design stresses. Two layered compound cylinder is used for the study with steel, aluminium and brass material.

II. Analytical Approach

A two layered compound cylinder (Fig. 1) is made by press-fitting outer cylinder on the inner cylinder. The purpose is that to increase the pressure capacity of the cylinder.

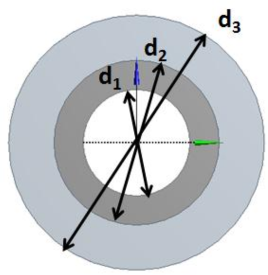

Fig.1 Two layered compound cylinder

In the classical design of pressure vessels, the thickness (t) of cylindrical shell is computed by using various formulae depending upon the type of material used. For ductile material and open type of pressure vessels, Birnie's equation as given below is used [8].

$$t = d_1 * \left[\sqrt{\frac{(\sigma_t + (1-\mu)P)}{(\sigma_t - (1+\mu)P)}} - \right. \tag{1}$$

When the compound cylinder is subjected to internal fluid pressure (P), it causes tensile (hoop) stress in both the cylinders, which can be computed by –

$$\sigma_t = P * \frac{d_1^2}{(d_3^2 - d_1^2)} * \left(1 + \frac{d}{d}\right. \tag{2}$$

The other stresses i.e. radial and longitudinal stresses are small as compared to hoop stresses. Hence they are not considered. The resultant maximum hoop stresses occur at the inner surfaces of both the cylinders and are given by –

At inside surface of inner cylinder (d=d1)

$$\sigma_{imax} = P * \frac{(d_3^2 + d_1^2)}{(d_3^2 - d_1^2)} - P_s * \frac{(2 * d_2^2)}{(d_2^2 - d_1^2)} \tag{3}$$

At inside surface of outer cylinder (d=d2)

$$\sigma_{omax} = P * \frac{(d_3^2 + d_2^2)}{(d_3^2 - d_1^2)} * \left(\frac{d_1^2}{d_2^2}\right) + P_s * \frac{(d_3^2 + d_2^2)}{(d_3^2 - d_2^2)} \tag{4}$$

The proper value of contact pressure will produce equal tensile stresses in both the cylinders. This value of contact pressure is given by-

$$P_s = P * \left(\frac{\left(\frac{c_2^2 * (c_1^2 - 1)}{c_1^2 * c_2^2 - 1}\right)}{\left(\frac{c_2^2 + 1}{c_2^2 - 1} + \frac{2 * c_1^2}{c_1^2 - 1}\right)}\right) \tag{5}$$

$$P_{s1} = P * \left(\frac{(c_2^2 - 1)}{(c_1^2 * c_2^2 - 1)}\right) + P_s \tag{6}$$

Interference at the interface diameter is given by-

$$\delta_1 = P_s * \frac{2 * d_1 * c_1[(c_1 * c_2)^2 - 1]}{[E * (c_2^2 - 1) * (c_1^2 - 1)]} \tag{7}$$

2.1 Optimum design of compound cylinder

The optimization problem can be defined as given the material of compound pressure vessel and internal diameter (dependent on the volume of fluid to be stored. Find the minimum values of internal diameter, outside diameter and diametral interference between the cylinders.

Mathematically it can be expressed as follows:

Given: Pressure – P $= \sigma_y$; $d_1 = (4V/\pi L)^{1/2}$

Optimize Volume: $V = \pi(d_3^2 - d_1^2)/4$

Subject to constraints: $\sigma_{imax} < \sigma_y, \sigma_{omax} < \sigma_y$, $\delta_1 > 0$

The inside diameter (d1) is considered as 100 mm. The material for both the cylinders is assumed to be linear isotropic with following properties for steel, aluminium and brass:

Steel:

Yield Stress = 250 MPa

Young's Modulus = 2.1 X 10^5 MPa

Poisson's ratio = 0.3

Aluminium:

Yield Stress = 90 MPa

Young's Modulus = 7.2 X 10^4 MPa

Poisson's ratio = 0.33

Brass:

Yield Stress = 124 MPa

Young's Modulus = 9.7 X 10^4 MPa

Poisson's ratio = 0.3

MS-Excel is a strong linear and non-linear solver. There are different techniques available to solve linear and non-linear problems in MS-Excel. One can formulate a problem with mathematical expressions. MS-Excel solver can be used to maximize or minimize the problem. The important terms are target cell and constraints. In tool bar main solver option is available. One can enter all constraints, variables and constants through cell references. Fig. 2 shows the dialogue box corresponding to this problem. Note that, the objective function in the target cell which is set to minimize. The other cell references are from constrains listed in these cells. Clicking the solve button solver will solve the problem. Compound cylinder optimization problem is solved by using a nonlinear solver available in MS-Excel and the results are as given below for steel material.

C_1=1.5522, C_2=1.556, δ1=0.108, d_1 = 100 mm.

We know that $C_1 = d_2/d_1$, $C_2 = d_3/d_2$. Using these equations we get d_2 = 155.22 mm, d_3 = 241.42 mm. Optimized volume is 37941 mm^3, Which is same for steel, aluminium and brass if we consider internal pressure equal to the yield strength of the respective material.

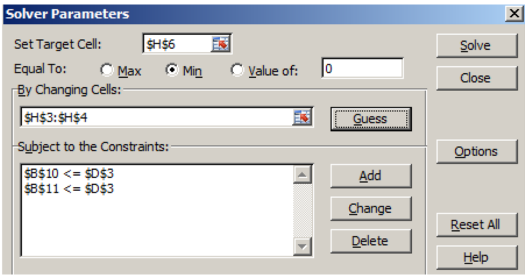

Fig. 2 MS-Excel Solver Parameters Settings

2.2 Steps of MS-Excel

Assume internal diameter of cylinder1 (d_1) say 100 mm.

Select the ratios C_1 andC_2, $C_1 = d_2/d_1$, $C_2 = d_3/d_2$

For the given internal pressure Pi, one can find contact pressure Ps & Ps1 in terms of ratios of C_1 andC_2.

Find the volume of compound cylinder using,

$$V = \pi(d_3^2 - d_1^2)/4$$

Minimize the volume subject to the constraints,

$$\sigma_{imax} < \sigma_y, \sigma_{omax} < \sigma_y, \ \delta_1 > 0$$

Optimized parameters C_1 andC_2 are used for the compound cylinder design.

III. Validation using ANSYS Workbench

Modelling and analysis of compound cylinder is done in ANSYS Workbench 12.1. Optimized dimensions from "MS-Excel nonlinear solver" are analyzed. Solid 186 elements are used for meshing (Fig. 3). Frictional contact is used between inner and outer cylinder with the interference. Internal pressure of 250 N/mm2 is applied on the inner face of the inner cylinder as shown in Fig.4.3. Applied pressure is normal to the surface. Outer face of the outer cylinder is axially constraint. It is free in radial and hoop direction as internal pressure will generate hoop stresses in inner and outer cylinder. Using direct solver in ANSYS Workbench, results are obtained. Results for optimized compound cylinder using are shown in Figures below and results for optimized compound cylinder using MS-Excel are tabulated in Table 1 and Table 2.

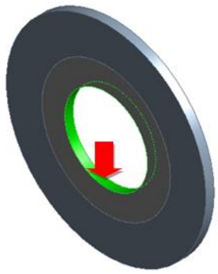

Fig.3 Pressure Applied Normal to Inner Surface

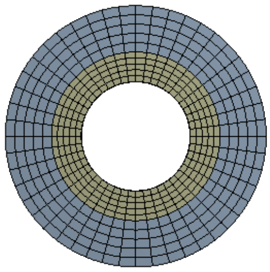

Fig.4 Mesh Details

3.1 Ansys Results for Steel-Steel Cylinder

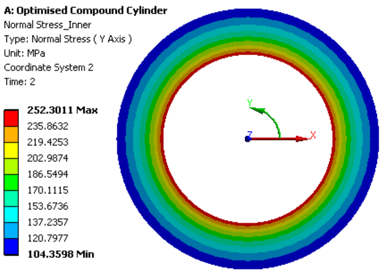

Fig.5 Hoop Stress in inner cylinder (Steel)

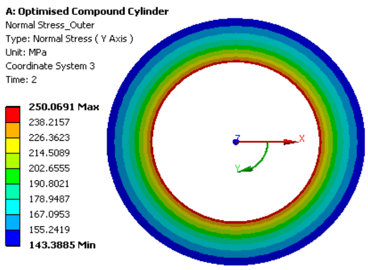

Fig.6 Hoop Stress in Outer cylinder (Steel)

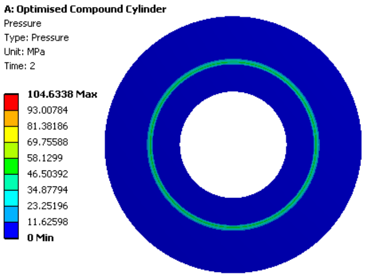

Fig.7 Contact pressure (Steel)

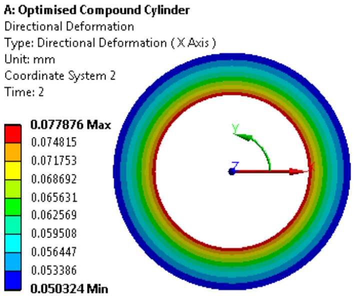

Fig.8 Radial Deformation of Inner Cylinder (Steel)

The inner and outer cylinders are modeled in Design Modeler of Ansys Workbench 12.0 with the computed dimensions. The model is meshed by using brick elements. The contact elements are generated at the interface. The inside surface of inner cylinder is subjected to a fluid pressure of 250 N/mm2. Here forces acting on the model are balanced. Compound cylinder exhibits maximum stress in hoop direction. Fig. 5 shows Hoop Stress in inner cylinder, the stresses are nearly equal to yield strength of the steel material. So optimum design is valid and it can sustain pressure of 250 MPa. Similar observations are made with outer cylinder. Radial deformation of inner cylinder with steel material is 0.07 mm.Steel shows less deformation of inner cylinder.

3.2 Ansys Results for Aluminium-Aluminium Cylinder

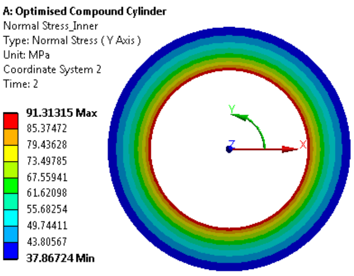

Fig.9 Hoop Stress in inner cylinder (Aluminium)

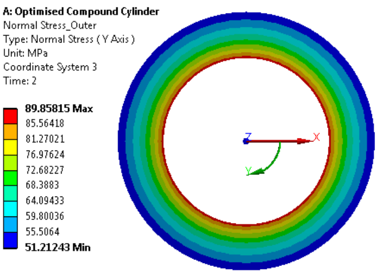

Fig.10 Hoop Stress in Outer cylinder (Aluminium)

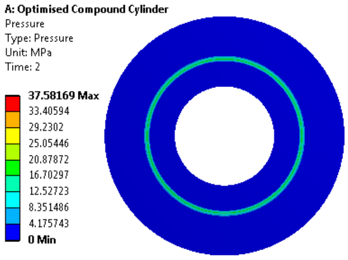

Fig.11 Contact pressure (Aluminium)

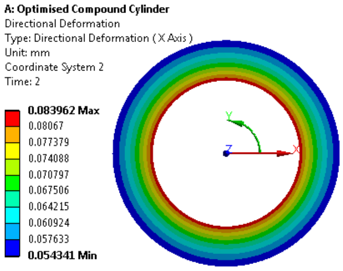

Fig.12 Radial Deformation of Inner Cylinder (Aluminium)

Aluminium inner and outer cylinders exhibit maximum stress in hoop direction, which is about 90 MPa. Fig. 9 and Fig.10 shows hoop stress of inner and outer cylinder respectively, the stresses are about yield strength of the steel material used. Theoretical and FEA results are matching, for comparison refer Table 2. Radial deformation of inner cylinder with aluminium material is 0.083 mm.

3.3 Ansys Results for Brass-Brass Cylinder

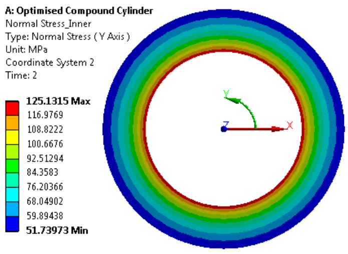

Fig.13 Hoop Stress in inner cylinder (Brass)

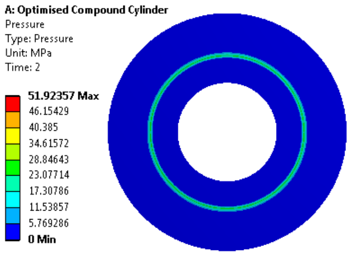

Fig.14 Contact pressure (Brass)

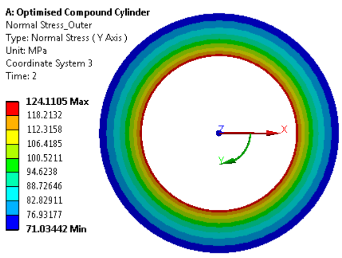

Fig.15 Hoop Stress in Outer cylinder (Brass)

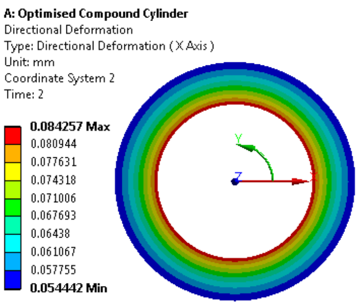

Fig.16 Radial Deformation of Inner Cylinder (Brass)

The yield strength of the brass is 124 Mpa. Fig.13 and Fig.15 shows hoop stress of inner and outer cylinder respectively, the stresses are about yield strength of the material used. This are optimized parameters result. The optimized parameters are listed in Table 4.1, and compared with FEA in Table 2. Radial deformation of inner cylinder with brass material is 0.08 mm.

Table 1
Optimized Parameters

Steel				
Parameters	d_1	d_2	d_3	δ_1
Unit (mm)	100	155.22	241.42	0.108
Aluminium				
Parameters	d_1	d_2	d_3	δ_1
Unit (mm)	100	155.37	241.42	0.113
Brass				
Parameters	d_1	d_2	d_3	δ_1
Unit (mm)	100	155.37	241.42	0.116

Table 2
Maximum Hoop Stress and Contact Pressure

Steel			
Method	**Maximum hoop stress (Mpa)**		**Contact Pressure (Mpa)**
	Inner Cylinder	**Outer Cylinder**	
Theoretical	250	250	104.63
FEA	252.3	250.07	104.63
Aluminium			
Method	**Maximum hoop stress (Mpa)**		**Contact Pressure (Mpa)**
	Inner Cylinder	**Outer Cylinder**	
Theoretical	90	90	37.28
FEA	91.31	89.85	37.58
Brass			
Method	**Maximum hoop stress (Mpa)**		**Contact Pressure (Mpa)**
	Inner Cylinder	**Outer Cylinder**	
Theoretical	124	124	51.36
FEA	125.13	124.11	51.92

IV. CONCLUSION

Compound cylinder is designed for optimum volume with stresses in inner and outer cylinder as a constraint. Optimum dimensions are computed for the internal pressure equal to yield stress of the material used. Optimum dimensions are calculated using non- linear solver available in MS-Excel.

2. FEA was carried out for the optimum dimensions Using ANSYS Workbench 12.1. Finite element analysis results and theoretical results are having good match.

3. Steel material can handle maximum pressure with less volume as compared to aluminium and brass.

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