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Numerical and Experimental Stress Analysis of Stiffened Cylindrical Composite Shell under Transverse end Load

J. Arashmehr, G. H. Rahimi, S.F.Rasouli

***Abstract*—**Grid composite structures have many applications in aerospace industry in which deal with transverse loadings abundantly. In present paper a stiffened composite cylindrical shell with clamped-free boundary condition under transverse end load experimentally and numerically was studied. Some electrical strain gauges were employed to measure the strains. Also a finite element analysis was done for validation of experimental result. The FEM software used was ANSYS11. In addition, the results between stiffened composite shell and unstiffened composite shell were compared. It was observed that intersection of two stiffeners has an important effect in decrease of stress in the shell. Fairly good agreements were observed between the numerical and the measured results. According to recent studies about grid composite structures, it should be noted that any investigation like this research has not been reported.

***Keywords*—**Grid composite structure, Transverse loadings, Strain measurement, Finite element analysis

I. Introduction

COMPOSITE materials are desirable in lightweight structures due to their high specific stiffness and strength. These materials have great importance in aerospace and aircraft industries. The main reason leads to success of the use of composite materials. In the aerospace industry is high performance versus weight ratios that it is possible to achieve using these materials and on the necessity to lower the weight of the aircraft as much as possible to enhance its efficiency [1]. Grid Composite Structure is made of stiffeners and skin. The stiffening structures either on the inner, outer or both sides of the skin. Use of stiffeners significantly increases the load resistance of a cylinder without much increase in weight [2]. Based on kind of Application, these structures may undergo different loads like axial load, bending, transverse load etc. It should be noted that more of the recent research about these structures have been concentrated on the axial loading. However some investigations about grid composite structures subjected to transverse loads have been done. [3], [4].

This investigation tries to study about grid composite cylindrical shell under transverse end load, experimentally and numerically. In recent years some investigations about grid composite cylindrical shell by G.H.Rahimi have been done [5], [6],[7]

J.Arashmehr is with the Department of Mechanical Engineering, Tarbiat Modares University; e-mail: m.arashmehr@ yahoo.com).

GH.Rahimi is a professor of mechanical engineering in Department of Mechanical Engineering, Tarbiat Modares University (e-mail: rahimi_gh@modares.ac.ir).

S.F.Rasouli is with the Department of Mechanical Engineering, Tarbiat Modares University (Rasouli.s.f@gmail.com).

In this present study, stress analysis of the structure under Clamped-Free boundary condition subjected to transverse end load experimentally and numerically has been carried out. Also a finite element analysis for the test has been carried out. Because the complex structures usually require finite element analysis models to capture the details of their behavior.

II. Experimental Studies

A. Fabrication Process

The specimen in this research was fabricated using an especially-designed filament winding machine designed and built in Tarbiat Modares University shown in figure 1. This machine executes a continuous procedure to fabricate the specimen, in which the ribs are first made and then immediately the skin is wound, and then the specimen is cured. This process ensures solid fusion of the ribs to the skin. E-glass fibers and a room-temperature-curing resin epoxy matrix were used materials for the fabrication. Nominal mechanical properties of the material are presented in table 1. [5]

TABLE I
NOMINAL MATERIAL PROPERTIES

Material properties	Symbols	Unit	E-glass/Epoxy
Longitudinal modulus	E_{11}	Gpa	36
Transverse modulus	E_{22}	Gpa	5.8
Transverse modulus	E_{33}	Gpa	5.8
Shear modulus	G_{12}	Gpa	3.22
Poisson's ratio	ν_{12}		0.3

TABLE 2
GEOMETRICAL PROPERTIES OF STIFFENED COMPOSITE CYLINDRICAL SHELL

Geometrical Properties	Value
Length	31 cm
Diameter	14 cm
Number of Ribs	6
Cross Section's Dimensions of Ribs	6×6 mm
Thickness of Shell	0.8 mm

Figure 1 shows the fabrication process of the specimens. As it mentioned the filament winding method applied for fabrication. In all specimens, there were 3 clockwise and 3counter-clockwise helical ribs. The cross-section area of all ribs was quadrangle with the area of 36 mm^2.

Fig. 1 Fabrication Process with filament winding method

It should be noted that the effect of the cross section of stiffeners can be important [8].

Fig. 2 Fabricated specimen

B. Testing

For strain measurement, 120 Ω strain gauges were used. The strain gauges were attached to the top face of the shell at four points (Three strain gauges at each point) as rosette arrangement. It is shown in figure 2. An INSTRON test machine was used to apply the load in a displacement-controlled procedure with a rate of 1 mm/min. The loading was carried on until the structure failed from clamped end and underwent local buckling in the fixed end.

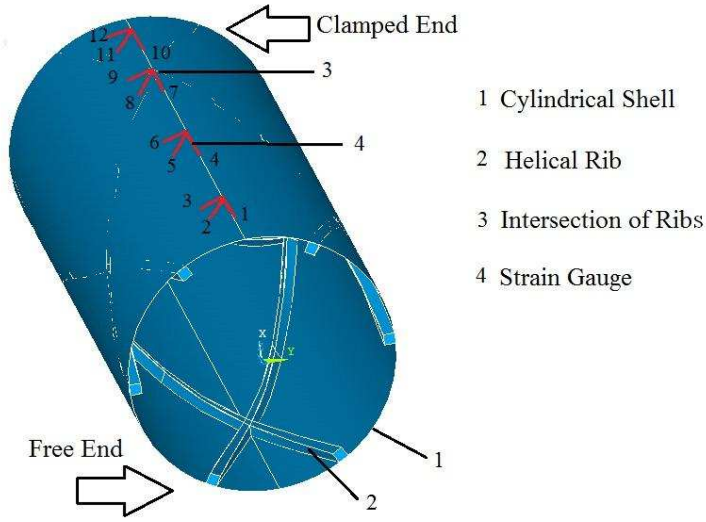

Fig. 2 Plan of attachment of strain gauges on the top of the specimen

To mount the specimen on the testing machine, two steel sheets were attached to both ends of the specimen by creating a circular groove in each sheet and then filling it up with resin and placing the edge of the specimen into the groove. These sheets provided distribution of the load on the circumference of the edge of the shell and prevented local damages due to concentrated load. The stiffened shell was tested under clamped-free boundary conditions, with the load transversely exerted on the free end as presented in figure 3.

Fig. 3 The specimen under experiment

III. Finite Element Modeling

ANSYS 11.0 software was employed to make a 3-D model of the structure. The structure was modeled as a whole and symmetries were not used. The shell was modeled as a surface and the ribs as volumes. The stiffeners were meshed using 20-node layered solid elements, SOLID191. Since the fibers are unidirectional within the ribs, the number of the layers would not make any difference in the results; therefore the ribs were assumed to have one layer. 8-node layered shell element, SHELL99 was used to mesh the shell [9]. It was found to be adequate to assume the shell as a 20 ply laminate after a divergence test. The ribs were meshed using hexahedron and the shell with quadrilateral shaped elements. The sizes of the meshes were obtained by a convergence check on mesh size. The nodes of the shell and the rib elements within a tolerance of 0.6 millimeters were coupled together in order to provide the sticking of the shell and the ribs. All degrees of freedom of all nodes in one end of the cylinder were locked. To model the applied force, a mass element was first created at the center of the other side's cross-section. Then all nodes of the structure on the latter side were coupled to the mentioned nodes using rigid region command, which uses rigid links to connect the nodes. Static analysis was conducted to extract the strains and stresses along the top face of the shell .The created FEM model is presented in figure 4:

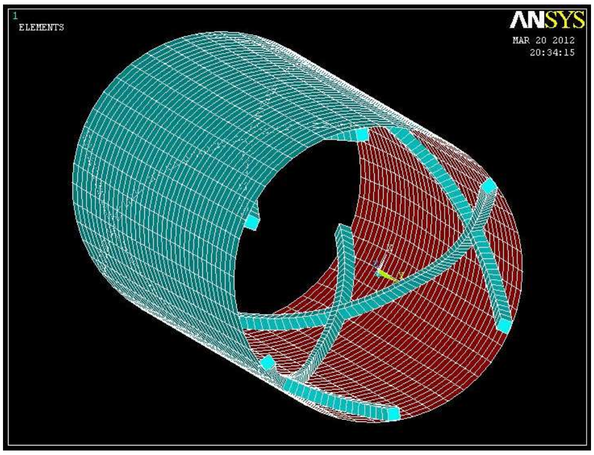

Fig. 4 The FEM modeling

IV. Results

A. Stress analysis

Considering that the strains gauges show the strains in the outer layer of the shell, and the fact that the shell is wound in a 75 degrees angle, a coordinate system transformation should be done prior to using stress-strain relations.

The stress-strain relations in an arbitrary coordinate system for a lamina of an orthotropic material under plane-stress are expressed In Eq. (3) [10].

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{bmatrix}=\begin{bmatrix}\overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16}\\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26}\\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{bmatrix} \quad (1)$$

Where $\overline{Q}_{ij}$ is transformed reduced stiffness. It should be noted that the stresses have been calculated in 400N. Based on load-deflection curve, in 400N the structure is still in linear zone.

B. Experimental vs. Finite Element Result

Generally fairly good agreements were observed between the numerical and the measured results.

The comparison of variation of σ_x versus the distance from the free end, between experimental and finite element results is shown in figure 5.

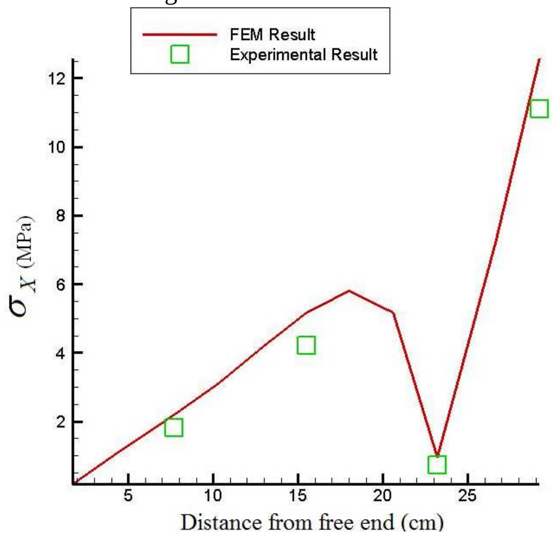

Fig. 5 σ_x - Finite element vs. experimental result in 400 N

Fig 7 shows that the intersection point of two ribs have a considerably lower σ_x than other points.

Also the comparison of variation of σ_y versus distance from free end, between experimental and finite element results is shown in Fig.6.

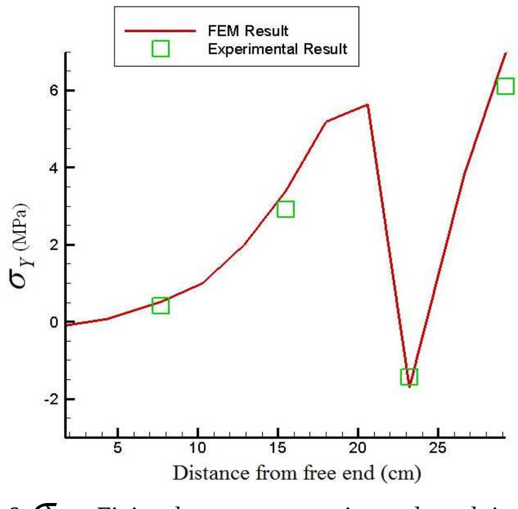

Fig. 6 σ_y - Finite element vs. experimental result in 400N

According to figure 6, σ_y increases as the distance from free end increases. Yet in intersection point of two ribs, σ_y declines and transforms to compressive stress from tensile stress. The comparison of variation of τ_{xy} versus distance from free end is shown in Fig.7.

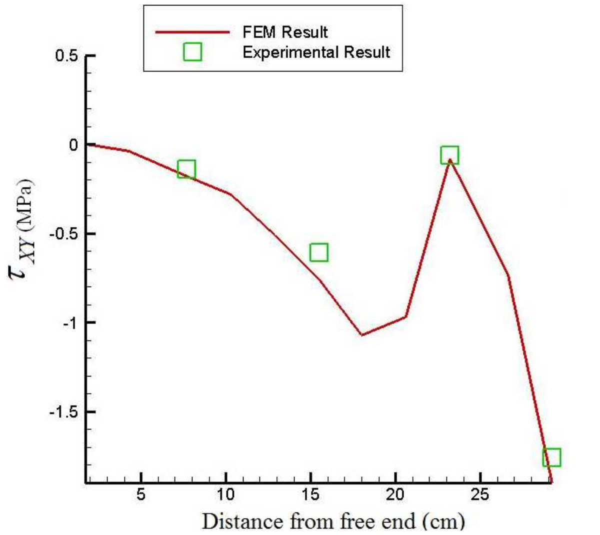

Fig. 7 τ_{XY} - Finite element vs. experimental result in 400N

The intersection point of two ribs causes a decrease in τ_{XY} as seen for normal stresses.

The Vonmises equivalent stress for plane-stress is obtained by the following equation:

$$\sigma_{vonmises} = \sqrt{\frac{(\sigma_x - \sigma_y)^2 + \sigma_x^{\ 2} + \sigma_y^{\ 2} + 6\tau_{xy}^{\ \ 2}}{2}} \tag{2}$$

Figure 8 show that the equivalent Vonmises stress predictably has a sensible decrease in the intersection point of two ribs.

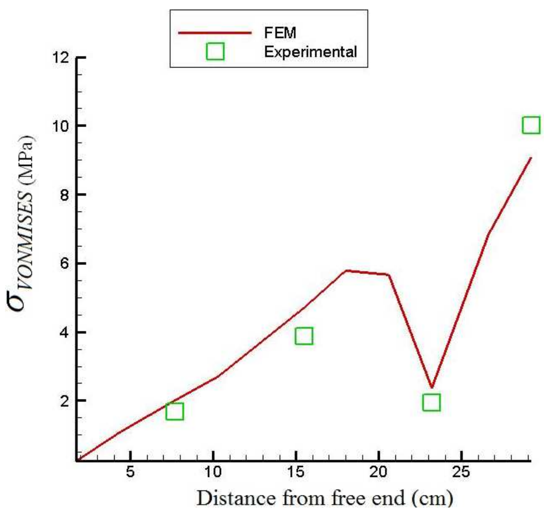

Fig. 8 $\sigma_{VONMISES}$ - Finite element vs. experimental in 400N

C. Stiffened Shell vs. Unstiffened Shell Result

In this section is, the obtained FE results are compared to the results of an unstiffened shell under the same boundary and loading conditions. Therefore, a finite element model of an unstiffened composite shell with the same material properties was built. Figure 9 shows the comparison of variations of $\sigma_{vonmises}$ between stiffened shell and unstiffened shell in same boundary and loading conditions.

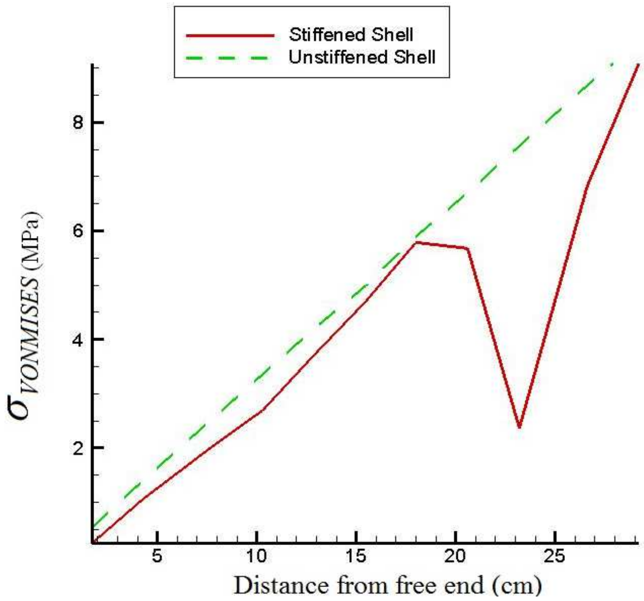

Fig. 9 $\sigma_{VONMISES}$ - Stiffened vs. Unstiffened composite shell in 400N

According to the result, it is observed that there is not a huge difference in stresses between stiffened composite shell and unstiffened composite shell in similar boundary and loading condition. Aside from the fact that the value of stresses in stiffened shell is a little lower compared to unstiffened shell, it is concluded that the main advantage of stiffened shell is the point of intersection of two ribs on the shell. As it was shown, in this point the stresses decrease sensibly despite the increase of bending moment near clamped end.

V. Conclusions

The general observations of experimental part of the present paper show that stiffened composite cylindrical shell in clamped-free boundary condition under transverse end load will finally fail from clamped end. It was not observed any other kind of collapse in stiffeners or separation between ribs and skin. In clamped-free boundary condition and transverse end load, there is not a considerable difference in load capacity between stiffened composite shell and unstiffened composite shell. But it was concluded that effect of intersection of two ribs can decrease the stresses sensibly. This conclusion can be useful specially somewhere stress concentration exists.

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