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Design and Analysis of Grid Stiffened Fuselage Panel withrounded Stiffeners

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Abstract. Designing and analyzing grid stiffened panel to understand the effect of stiffeners on stiffness of the panel is crucialin designing grid stiffened cylinder for fuselage application. Traditionally only straight stiffeners were used due to limited manufacturing capabilities and in recent years GSS with curved stiffeners have become a reality. The present work ison flat grid stiffened panel and the focus is to realize the change in stiffness by converting straight stiffeners in an isogrid panel to curved stiffeners. An isogrid stiffened panel is identified from literature for which experimental results were available and was considered for replacing straight stiffeners with curved stiffeners. Defining and designing the curve for curved stiffeners which can be used to replace straight stiffeners in isogrid pattern is crucial. FE model of the grid stiffened fuselage panel with isogrid pattern identified from the literature for which experimental data was available was developed and evaluated for stiffness. For the same panel, curved grid pattern to enhance stiffness of the panel was designed following existing design procedure. FE model of the grid stiffened fuselage panel with designed curved stiffeners was developed and evaluated for stiffness. It is established that the stiffness of panel can be increased by minimum of 2.82% to maximum of 11.93% by using curved stiffenersof particular curvature as a replacement for straight stiffeners in isogrid pattern with a slight mass penalty.

INTRODUCTION

Metal designs of fuselage structures have reached a high degree of perfection. Therefore extraordinary weight and cost savings are unlikely in future metal structures, whereas composite material structures are promising. Grid Stiffened Structures (GSS) are the structures supported by grid/lattice of stiffeners. GSS have the potential to replace semi-monocoque and honeycomb sandwich fuselage structures. Typically these stiffeners run in two to four directions forming a repeated pattern. Any pattern/grid in presently seen practical Grid Stiffened Structures (GSS) can be recognized as Orthogrid, Isogrid or Anisogrid. Composite materials are suitable for isogrid type of structures becausethe typical stresses generated in the ribs are directional along the rib length [2]. In composite material, it is easy to getthe directional strength and stiffness by directing the fibers in the required direction. To convert conventional complexfuselage structure to a grid stiffened cylinder, there are huge number of parameters to be decided to design a Grid Stiffened Cylinder such as layup sequence of skin, cross-sectional dimensions of stiffener, pattern of stiffeners, stiffener cross-sectional shape, etc. Considering all these parameters, designing a grid stiffened cylinder to replace fuselage in a single step is very difficult task. Hence understanding the relation between each parameter and the behavior of overall structure will be crucial.

The main competitor for composite GSS is honeycomb sandwich composite structures. GSS have proven to possess better impact resistance and redundancy in load path compared to honeycomb sandwich composite structures.One advantage of GSS is that, the stiffeners can be directed/steered based on the strength or stiffness requirements.

There are numerous ways to achieve stiffness of the panel because there are several parameters which affect the panel stiffness. The stiffness of these panels can be varied by three ways, namely geometrical parameters, material parameters and combination of both. Geometrical parameters are like grid pattern, grid density, stiffener cross-section, stiffener dimensions etc. Material parameters are like fiber selection, fiber orientation, matrix selection, lay- up sequence etc.

Traditionally only straight stiffeners were used and curved stiffeners were out of reality due to limited manufacturing capabilities. However, with the advent of automated fiber placement technique, curved stiffeners have become reality. This technique places fiber reinforcements on molds/mandrels in automatic fashion and uses a number of small width pre-impregnated tows. Better accuracy is maintained in this technique. This new manufacturing technique has led to many researchers to carry their researches on GSS with curved stiffeners in recent years. Curved stiffeners have proven to be useful over straight stiffeners in some applications for achieving better structural and weight efficiency. Considering this, the present work is intended at converting straight stiffeners of a flat grid stiffened panel to curved stiffeners with an aim to realize the benefits of curved stiffeners.

Problem Formulation

Curved stiffeners have proven to be useful over straight stiffeners in some applications for achieving better structural and weight efficiency. The use of straight stiffeners leads to a very limited design space, whereas using curved stiffeners increases the design space for GSP [3]. Particularly, for multi-axial loading condition, panels with curved stiffeners have better stability than panels with straight stiffeners [5]. These findings from the literature have prompted to explore the possibility of utilizing curved stiffeners for fuselage application to enhance the stiffness. Hence the aim of the study was to design and analyze the grid stiffened panel with curved stiffeners to enhance the stiffness for fuselage application.

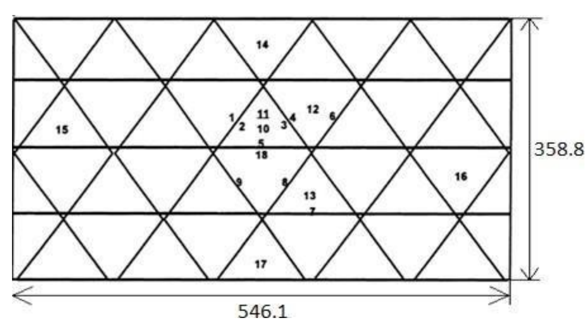
An isogrid stiffened panel is identified from literature for which complete details of design, manufacturing and experimental test data were available. The identified isogrid panel was fabricated from carbon fiber reinforced epoxy in the form of pre-preg tow and unidirectional tape. The carbon fiber and resin used were 'Hercules IM7' and 'toughened epoxy (977-2) respectively. The applications of the identified panel are found in fuselage shell, fuselage floor panel, wing panel and wing box.

The first objective of the study is to develop Finite Element (FE) model of the identified Isogrid Stiffened Panel (ISP) to evaluate stiffness of the identified ISP and validate with the available experimental results. The next step is to design the curved stiffener pattern following existing design procedure. The final objective is to develop the FE model of the grid stiffened fuselage panel with designed curved stiffeners and evaluate the stiffness. Thus, the final goal is to assess the effect of converting straight stiffeners to curved stiffeners in an isogrid panel.

FE Analysis of the Identified Isogrid Stiffened Panel

Identified Isogrid Stiffened Panel

The identified ISP considered for study is shown in Fig. 1. Complete details of design, manufacturing and experimental results are available for the identified ISP [1]. The ISP was fabricated from carbon fiber reinforced epoxyin the form of pre-preg tow and unidirectional tape. The carbon fiber and resin used were 'Hercules IM7' and 'toughened epoxy (977-2) respectively. The properties of IM7/977-2 are 00 Tensile Modulus (E1) = 173 GPa, 900 Tensile Modulus (E2= E3) = 7.6 GPa and Shear Modulus = 5.5 GPa.



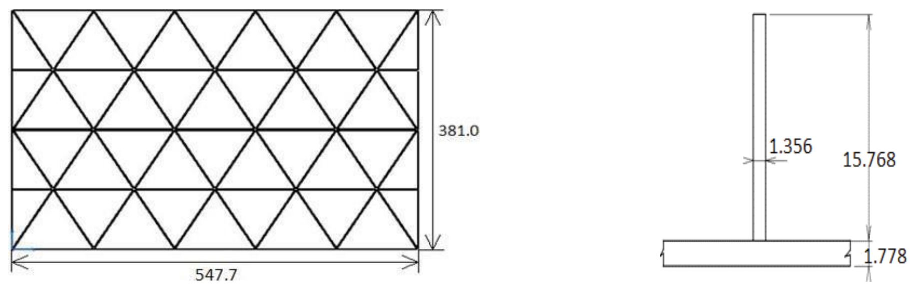
All dimensions are in mm

FIGURE 1. Configuration of Identified ISP with location of strain gauges (1 to 18) employed for experimental study [1]

The panel consists of three horizontal stiffeners stretching between left and right edges, 12 angled stiffeners, 6 of them oriented towards right edge and another 6 towards left edge. The panel was subjected to uni-axial compression test. The compression test fixture was designed to simulate the simply supported condition. The panel is mounted with18 strain gauges fixed on the panel at various locations as shown in Fig. 1 to record the strains.

Geometric Modelling of Isogrid Stiffened Panel

In an isogrid pattern, at intersection of stiffeners three times the fibers will cross-over resulting in increased thickness. To reduce this thickness build-up at intersections, the intersection of angled stiffeners is made to offset fromthe horizontal stiffener in the identified literature as shown in Fig. 1. But in an ideal isogrid pattern, all the stiffeners intersect at a common point. The dimension of the identified ISP (546.1 × 358.8 mm) is modified to 547.666 × 381.061mm to achieve an ideal isogrid pattern and to facilitate design of curved stiffeners and the same is shown in Fig. 2 (a). Same cross-sectional dimensions of the stiffener used in the identified ISP were used in modelling as shown in Fig. 2 (b).

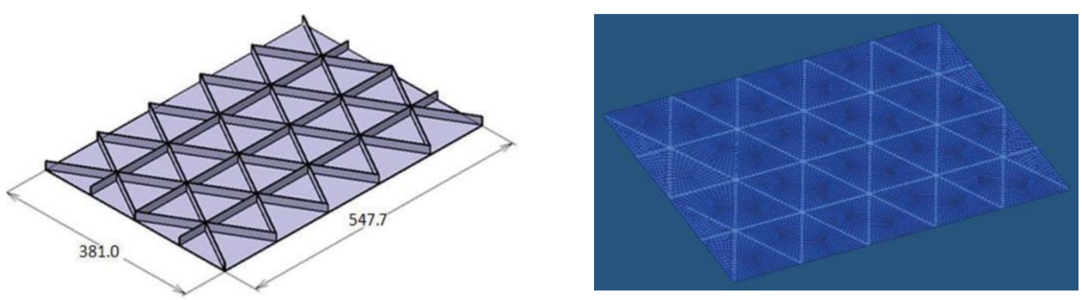


(a) (b)

All dimensions are in mm

FIGURE 2. (a) Modified Isogrid Stiffened Panel (b) Stiffener and skin dimensions

The panel was modeled using commercial solid modeling software CATIA and the image of the developed geometric model of ISP is shown in Fig. 3 (a).



(a) (b)

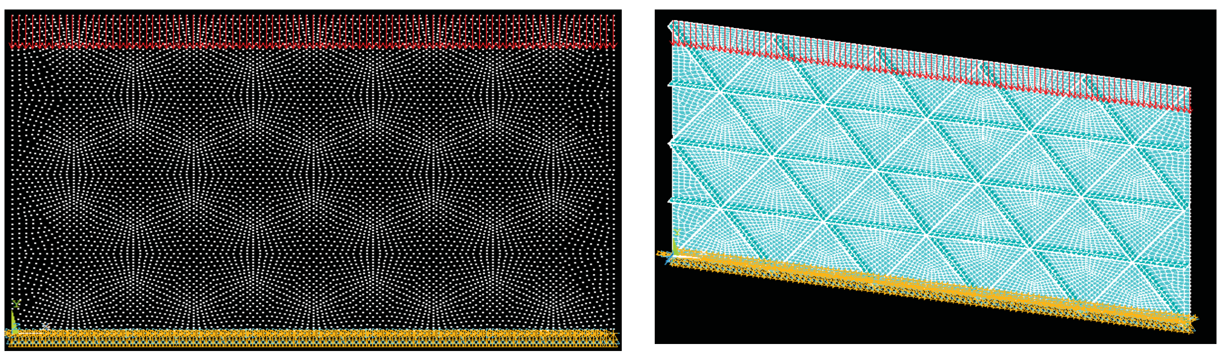
FIGURE 3. (a) Isometric view of the ISP model in CATIA (b) Meshed model of the ISP

Meshing of Isogrid Stiffened Panel

The ISP model was meshed using HyperMesh software. Skin of the model was meshed using shell 181 element and the stiffeners with beam 188 element. To ensure the stiffener-skin connectivity, nodes at the interface of skinand stiffener were made common. Meshing was done for various element sizes. All the meshed models with various element sizes were analyzed for same load and boundary conditions as that used in experimental study. The strains against load curves of all the meshed models were compared with experimental results. The meshed model with highest accuracy was found to be, the model with element size 6 mm. Further analysis and study was carried out using the meshed model of element size 6 mm and without biasing. Skin of the panel was assigned with thickness by defining it as a laminate of 12 plies with appropriate material properties to simulate the experimental test. Themeshed model employed for final analysis is shown in Fig. 3 (b).

FE Analysis of ISP and its validation

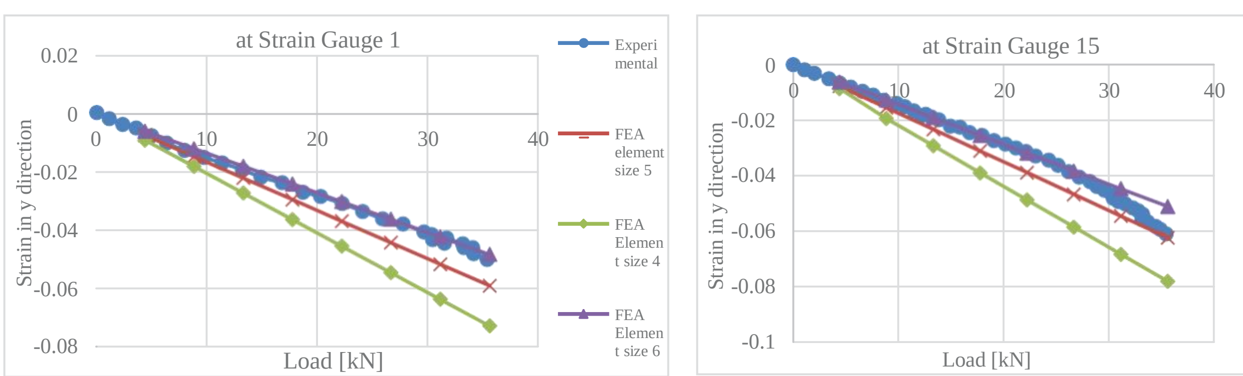
The analysis of the panel is carried out using Mechanical APDL software (ANSYS). All the material properties and boundary conditions in experimental test were maintained same in Finite Element (FE) Analysis. Top most line of nodes of the panel was subjected to vertical force and bottom most line of nodes are constrained in all degrees of freedom (DOF) with zero displacement to simulate the experimental test. Throughout the study the analysis of all thepanels was carried out for nodal solution of total mechanical strain in y direction.



(a) (b)

FIGURE 4. (a) Load and boundary conditions applied on nodes of the FE model of ISP, (b) Oblique view of the boundary conditions applied on FE model of ISP

Validation of the FE model



(a) (b)

FIGURE 5. (a) Validation of FE model at Strain Gauge 1 location, (b) Validation of FE model at Strain Gauge 15 location

Validation study was conducted at all the strain gauge locations for all the meshed models. Strain against load curve at all the strain gauge locations are found to be having similar trend as that of experimental results, but with varying accuracy. Validation study results for strain gauges 1 and 15 are shown in Fig. 5 (a) and Fig. 5 (b). Extent of deviation from the experimental results for all the strain gauge locations is shown in Fig.6.

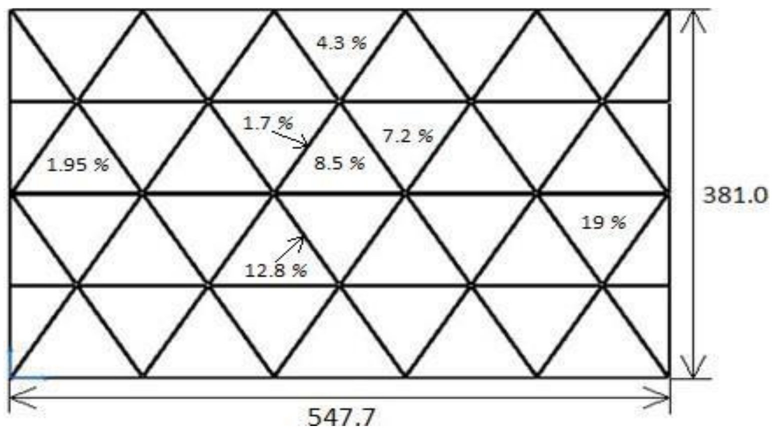


FIGURE 6. Extent of deviation of FE results from experimental results at various strain gauge locations

Design of curved stiffeners

The shape of the curve employed for curved stiffeners is defined in terms of two angles i.e. tangential angle of a simple curve at the start θ_1 and tangential angle of a simple curve at the end θ_2 [4]. Three designs were created with adopted optimum values of θ_1 and θ_2 from the literature [4] in which the focus is on buckling optimization of isogrid stiffened square panel by using curved stiffeners. The three designs considered are with θ_1 values of 150, 200 and 300 and θ_2 maintained constant at 750 for all the three designs. The curves of all these three designs are as shown in Fig. 7.

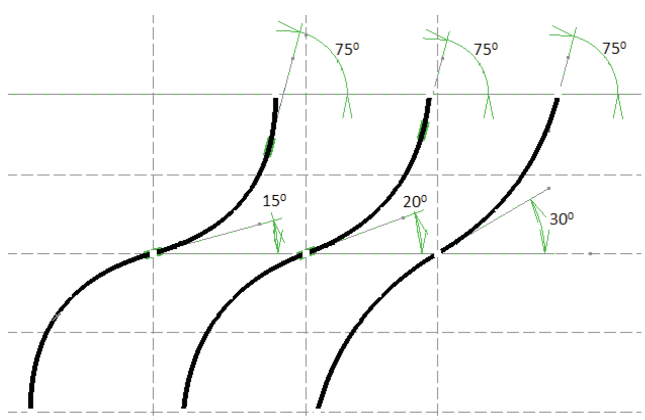
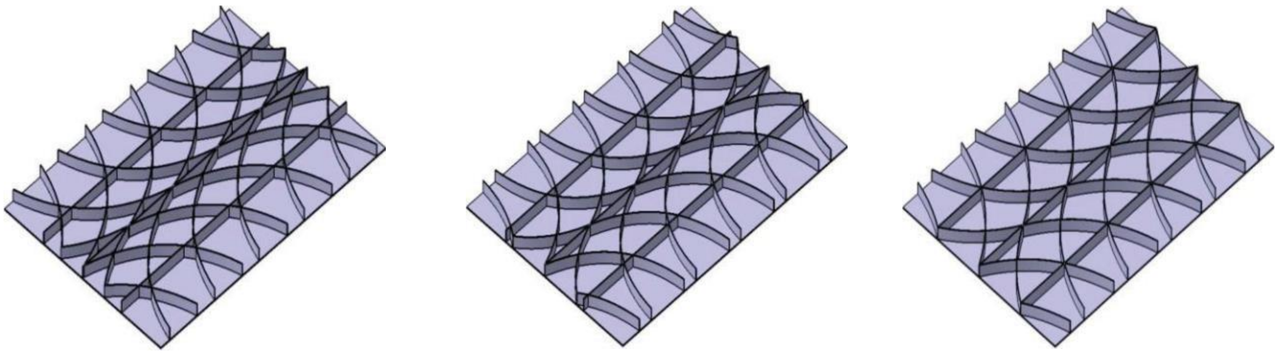


FIGURE 7. Three designs of curved stiffeners considered for the study

Three different panels with curved stiffeners with three different values of θ_1 were created. The panels are namedbased on the value of θ_1 like 15 degree panel, 20 degree panel and 30 degree panel.

FE Analysis of Panels with Curved Stiffeners

The FE analyses of panels with curved stiffeners were carried out using same procedure and applying same boundary conditions as that of FE analysis of ISP. Geometric models of the three different panels with curved stiffenersdeveloped in CATIA are shown in Fig. 8.

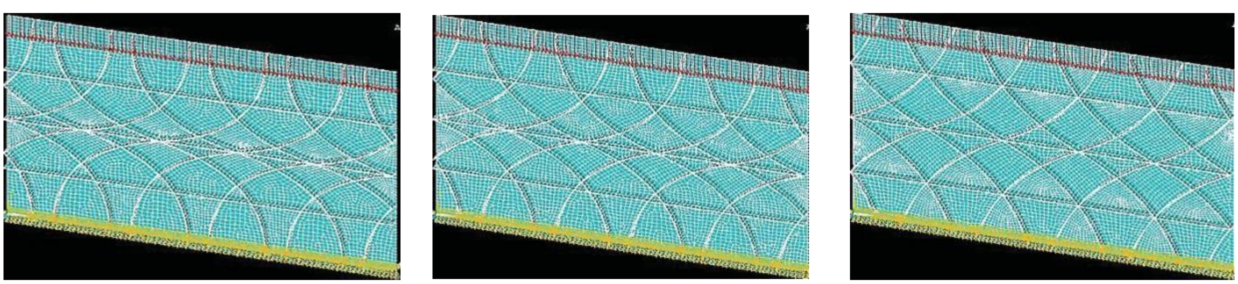


(a) (b) (c)

FIGURE 8. Geometric models of three different panels (a) 15^0 Panel, (b) 20^0 Panel and (c) 30^0 Panel

Meshing and analysis of all the three panels with curved stiffeners were carried out using same procedure as that in ISP. Meshing procedure and elements used for all panels with curved stiffeners were same as that of isogrid stiffened panel. The quality of the mesh was maintained within limits by carefully altering the shape of selected elements.

Figure 8 shows the FE models of the three designs. After developing the FE model, the panels with curved stiffeners are analyzed by applying same boundary conditions and material properties as that of isogrid stiffened panel.



(a) (b) (c)

FIGURE 9. FE models of three different panels with curved stiffeners (a) 15^0 Panel, (b) 20^0 Panel and (c) 30^0 Panel

Results and Discussions

In order to assess the effect of curved stiffeners on the stiffness of the panel, all the three panels with curved stiffeners and the ISP are compared on the basis of strain at various locations obtained from FE analysis.

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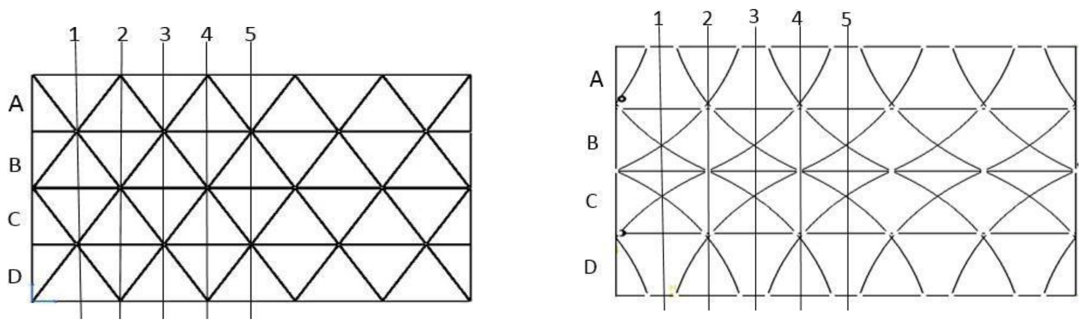

(a) (b)

FIGURE 10. Naming of locations (a) in ISP, (b) in panels with curved stiffeners

Considering symmetry, comparison of panels can be done only with half of the panel symmetric along the vertical line named as line 5. The locations on the panel were named by dividing the panel into sections namely A, B, C and

D. Three horizontal stiffeners divide the panel into these four sections. In every section, results were compared alongfive lines namely 1, 2, 3, 4 and 5. Strain values are extracted from the FE results exactly at half of the height of sectionsA, B, C and D and along the lines 1, 2, 3, 4 and 5.

The results of strain at locations in sections A, B, C and D along lines 1, 2, 3, 4 and 5, are used to compare the stiffness of different panels. It was found that 20 degree panel was stiffer than other two panels at several locations. Hence 20 degree panel is considered among the three panels to compare with ISP in order to assess the stiffness. Thiscomparison has lead to the comparison of an ISP with a corresponding panel with curved stiffeners. Further it was observed that, at sections A and D, boundary condition/application of load have an effect on the local stiffnessof panel. Considering this, the effect of stiffener pattern on stiffness of the panel can be more accurately compared in sections B and C. Hence comparison of panels with straight and curved stiffeners is made at sections B and C as shownin Fig. 11 and 12.

Figure 11 shows the variation of strain at section B along the locations 1 to 5. It is clearly indicated that all along the section B the strain values are lower for panel with curved stiffeners in comparison with ISP. The extent of reduction in strain values along with change mass of the panel are summarized in Table-1.

Similarly, Fig. 12 shows the variation of strain at section C along the locations 1 to 5. Here also, it is indicated thatall along the section C the strain values are lower for panel with curved stiffeners in comparison with ISP. The extentof reduction in strain values along with change mass of the panel are summarized in Table-2.

From the results summarized in Tables 1 and 2, it is observed that stiffness can be increased by minimum of 2.82

% and up to a maximum of 11.93 % by replacing straight stiffeners in isogrid pattern with curved stiffeners with a slight increase in the mass of 3.13 %. This clearly establishes the advantage of replacing straight stiffeners by curvedstiffeners in a grid stiffened panels.

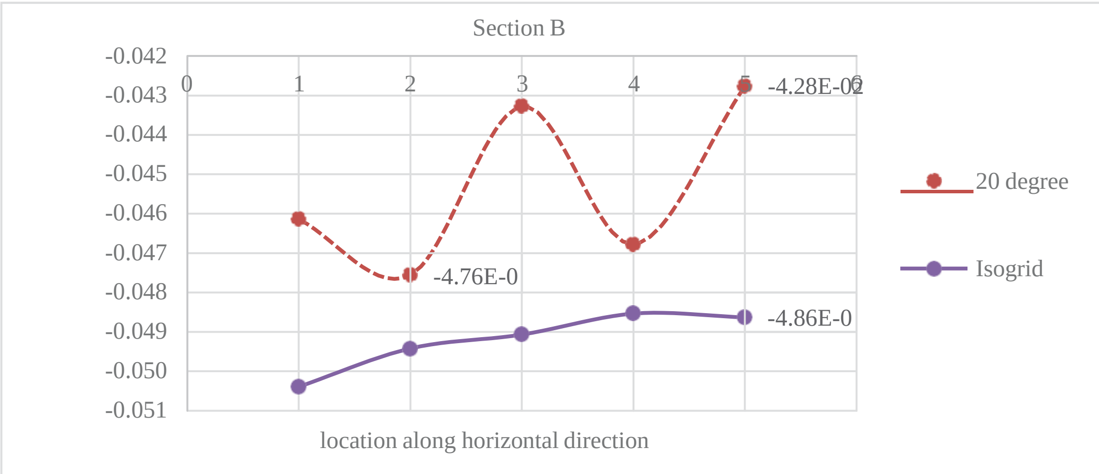

FIGURE 11. Comparison of panels with straight and curved stiffeners at section B

TABLE 1. Comparison of panels with straight and curved stiffeners at section B

	Straight Stiffener	**Curved Stiffener**	**Difference instrain**	**Percentage reduction instrain**	**Difference inmass**
Strain at B2 (least difference is at B2)	-0.0494	-0.0476	-0.0018	3.64 %	3.13 %
Strain at B5 (maximum difference at B5)	-0.0486	-0.0428	-0.0058	11.93 %	3.13 %

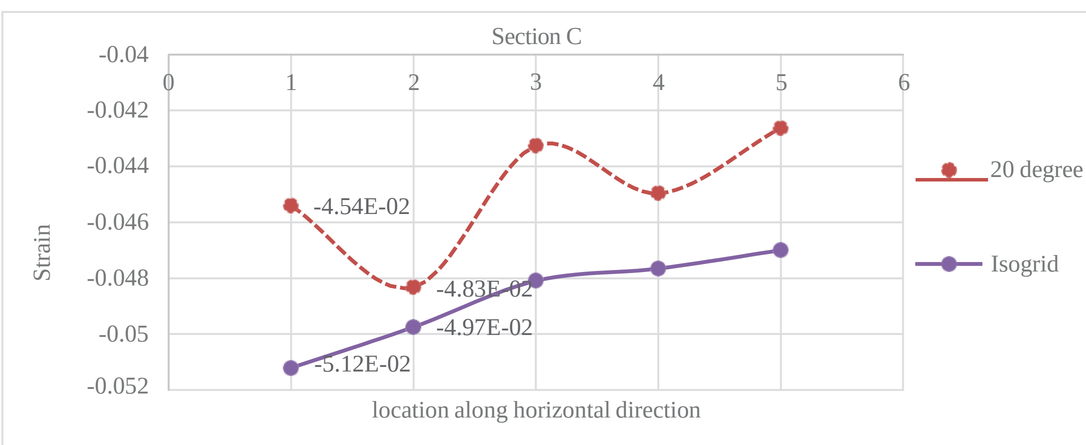

FIGURE 12. Comparison of panels with straight and curved stiffeners at section C

TABLE 2. Comparison of panels with straight and curved stiffeners at section C

	Straight Stiffener	Curved Stiffener	Difference instrain	Percentage reduction in strain	Difference inmass
Strain (least difference C2)	-0.0497	-0.0483	-0.0014	2.82 %	3.13 %
Strain (maximum difference C1)	-0.0512	-0.0454	-0.0058	11.33 %	3.13 %

CONCLUSIONS

The study focused on assessing the effect of converting straight stiffeners to curved stiffeners in an isogrid stiffenedpanel on the overall stiffness of the panel. An isogrid stiffened panel identified from literature for which experimental results were available was considered for replacing straight stiffeners with curved stiffeners. The design of curved stiffeners was carried out following the procedure available in the literature to suit the requirementsof selected isogridpanel. Three different panels with curved stiffeners were designed and incorporated into selected panel, analyzed through FE procedure to evaluate the best suitable curvature. From the FE results it was found that stiffness of panel can be increased by a minimum 2.82 % up to a maximum of 11.93 % by using curved stiffeners of particular curvature(20 degree panel) instead of isogrid stiffeners with a mass penalty of 3.13 %. Experimental investigations on GSS with curved stiffeners are required to validate the results of FE analysis.

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