Buckling analysis of a ring stiffened hybrid composite cylinder

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Abstract. This study aims to understand the response of the ring stiffened cylinders made up of hybrid composites subjected to buckling loads by using the concepts of Design of Experiments (DOE) and optimization by using Finite Element Method (FEM) simulation software Ansys workbench V15. Carbon epoxy and E-glass epoxy composites were used in the hybrid composite. This hybrid composite was analyzed by using different layup angles. Central composite design (CCD) was used to perform design of experiments (D.O.E) and kriging method was used to generate a response surface. The response surface optimization (RSO) was performed by using the method of the multi-objective genetic algorithm (MOGA). After optimization, the best candidate was chosen and applied to the ring stiffened cylinder and eigenvalue buckling analysis was performed to understand the buckling behavior. Best laminate candidates with high buckling strength have been identified. A generalized procedure of the laminate optimization and analysis have been shown.

Keywords: FEM, Buckling, Composite Shells, Ansys, Response Surface Optimization.

1. Introduction

Use of fiber-reinforced composites (FRP) materials has been increasing over the past few decades in aircraft structures due to their high specific stiffness and strength properties. The superior characteristics of the composite materials, the tailorability of the stiffness, strength properties and substantial reduction in weight offered by such materials are some of the primary reasons for their increased use in the aerospace industry. However, the major problem with these types of materials is that traditional manufacturing cannot be used to manufacture them. A laminate consists of different plies in which the strength properties of the plies depend upon the fiber angle and fiber material embedded inside the lamina. Generally, the fiber angles in the traditional laminates are limited to 0^o, 90^o, and $\pm45^o$ angle template. By using such type of the fixed angle templates, the designer is unable to unleash the full potential of a composite laminate system. Nowadays with the advent of automated fiber placement machines, it is possible to place the fibers in a different orientation rather than the conventional angles templates. Inter-lamina hybrid composites are those, which are designed with different plies made up of different materials. Such type of Hybridization process allows higher control of the properties of the composite laminate. Buckling is a phenomenon, which occurs mainly in slender structures and this phenomenon also tells us about the stability of a structure, for this reason, the buckling phenomenon has to be studied.

ZhongYue et. al., [1] Conducted numerical simulation of different types of composite CNG cylinders using ANSYS software. He used the top-down modeling approach to model cylinders and reported that insufficient strength of the liner material and unreasonable structure are the primary causes of defects in the cylinders. L. Weiß et. al., [2] Characterized the shape as well as the magnitude of the composite cylinder’s deformation experimentally. They noticed that the shell bending beside expansion and contraction is the cause, which contributes to the overall deformation of the composite cylinder. Mustafa Akbulut et. al.,[3] proposed an optimization procedure to minimize the thickness of the laminated composite plates which are subjected to in-plane loading they used “direct search simulated annealing” algorithm as the optimization technique. M. Azuma et. al., [4] described the safety design of a composite cylinder, including compliance with regulations, the influence of vibrations, and safety verification in case of a collision Saullo G.P. Castro et. al., [5] Presented semi-analytical models for the linear buckling analysis of the composite cylinders and cones with flexible boundary conditions. He used the classical laminated plate theory and the first order shear deformation theory for the development of these models. Saullo G.P. Castro et. al., [6] Presented a semi-analytical model to predict the non-linear behavior of the unstiffened cylinders and cones considering initial geometric imperfections and various loads and boundary conditions by applying Classical Laminated Plate Theory (CLPT) and Donnell’s equations. Payal Desai et. al., [7] presented an accurate and simplified semi-analytical-numerical model for investigating the behavior of a cylinder of finite length subjected to partly bending load by considering a laminated cylinder under symmetric load as 2-D plane strain problem. C. Furtado et.al., [8] presented an experimental study on the effect of ply-level hybridization on the tensile un-notched, notched response of composite laminates and showed ply-level hybridization can be used to improve the notched response of the composite laminates. Gyeong-Chan Lee et. al., [9] used optimization to increase the design load of the composite sandwich cylinders under external hydrostatic pressure and suggested that both the buckling and the static material failure should be considered in the design of the composite sandwich cylinder. Mayank Nirbhay et. al., [10] conducted a comprehensive study for predicting the behavior and failure of CNG cylinders under various loading conditions using ANSYS software by using glass/epoxy and carbon/epoxy separately with different patterns of helical and hoop windings. Mohammad Rouhi et. al., [11] developed A multistep design optimization procedure to get the maximum potential improvement in structural performance of the cylinders. He also investigated the effects of radius, aspect ratio, as two structural parameters, on the structural improvement of the variable stiffness cylinders. G.H. Rahimi et. al., [12] analyzed the buckling behavior of thin-walled GFRP cylindrical shells with triangular lattice patterned reinforcements formed by helical and circumferential ribs under axial force by using ANSYS software. The ratio of buckling strengths to weight parameters was calculated for each model and was compared to results that were obtained from other models.

2. Problem modelling

2.1. Problem Objective

The objective of the present work is to optimize a hybrid laminate by varying the orientation of the plies made up of different composite materials. Hybrid laminates with different ply angles were designed and best laminate candidates have been identified based on the least inverse reserve factor (IRF) which denotes the strength of a laminate. Then the laminates were applied to the ring stiffened cylinder which is subjected to the buckling loads and then buckling modes were identified. Using the CCD technique design of experiments were conducted and different design points were generated and then solved. From the design of experiments, a kriging type of response surface was generated and it was improved by the use of different verification points. After response surface generation was done, multi-objective genetic algorithm (MOGA) technique was used to optimize the ply angles of the laminate. Three best candidates for which the IRF was the least were identified. For these layup cases, Eigen value buckling analysis was performed are shown in table.2

2.2 Geometry

The geometry of the laminate is a thin sheet of the dimensions is 100mm X 50 mm and the geometry of the ring-stiffened cylinder is taken as the thin shell [12]. The dimensions of the cylinder shell are length= 260mm, inner diameter = 139 mm, thickness = 3 mm, thickness of each layer = 0.5mm. For both geometries, the composite layup was performed using the Ansys ACP pre post module.

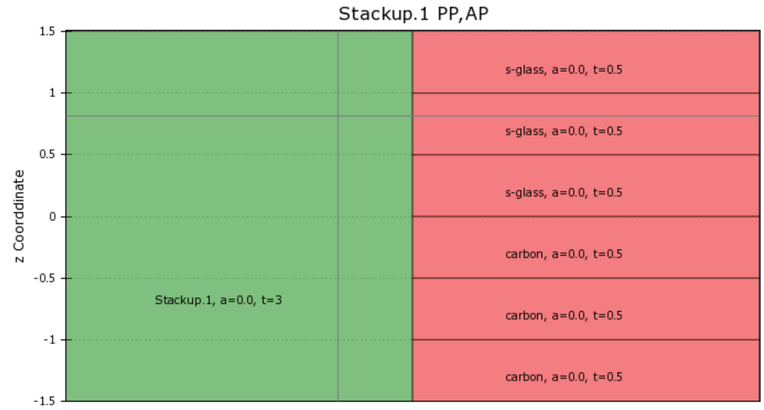


Figure 1. Initial lay-up of the laminate

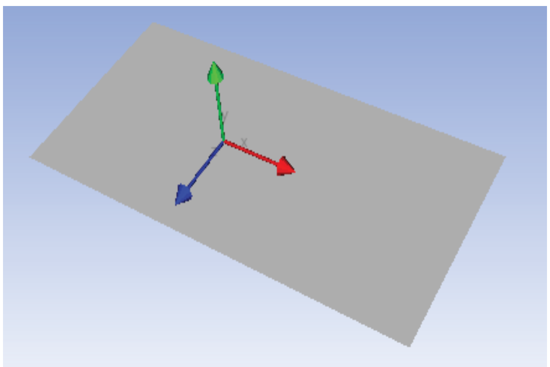


Figure 2. Shell model of the laminate.

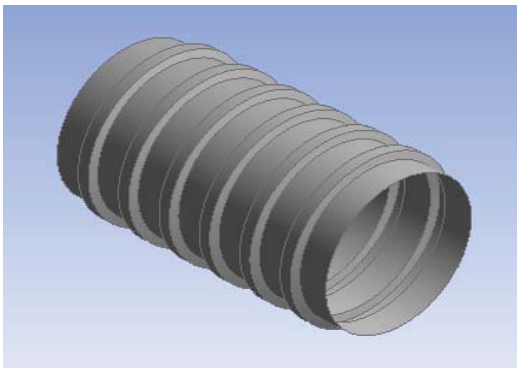
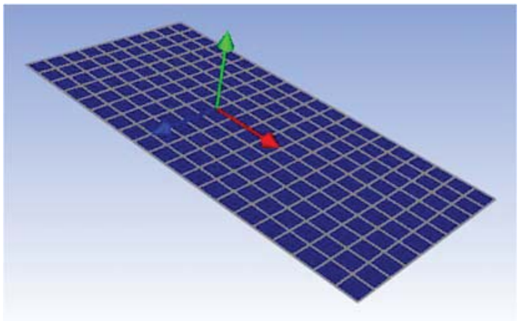


Figure 3. Shell model of the ring stiffened cylinder.

2.3 Finite element meshing

It is the process of converting geometrical entities into finite element entities [13]. Shell element was used for both geometries of the laminate and the cylinder as well. 8 node finite strain element is known as shell 281 in Ansys software which was used to mesh the geometries. The meshed geometries of the laminate and cylinder are shown in Figure 4. & Figure 5.



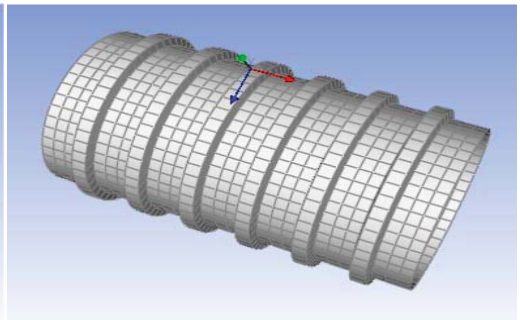
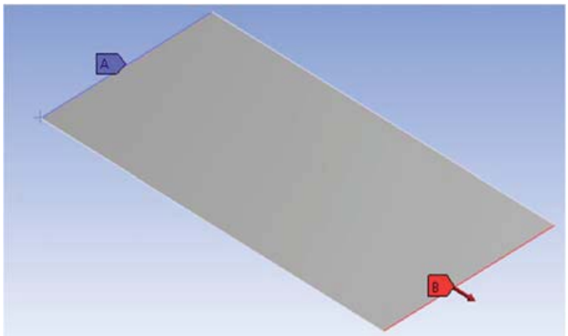


Figure 4. Meshed model of the laminate. **Figure 5.** Meshed model of the ring stiffened cylinder.

2.4 Loads and Boundary Conditions



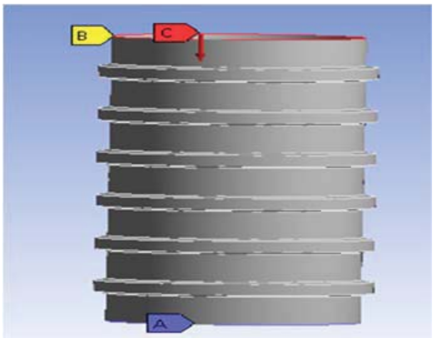


Figure 6. B. C's for Laminate Shell. **Figure 7.** B. C's for Stiffened Cylinder.

For the laminate, one end is fixed and a force of 1000 N has been applied as shown in Figure 6. One end of the cylinder is fixed, other end the displacement in the y and z -direction are constrained, and a force of 10 KN is applied in such a way as to simulate the fixed –fixed buckling condition as shown in Figure 7.

2.5 Materials Properties of the ply materials

A hybrid laminate was designed which consists of the 6 plies. Each ply has a thickness of 0.5 mm. The materials used for the plies are carbon epoxy and s-glass epoxy composites. The lay-up of the laminate is shown in Figure 1. The material properties of the CFRP and S-glass epoxy composites are given in Table 1.

Table 1. Material Properties.

Property	Units	Epoxy/Carbon	Epoxy/S-Glass
E_1	MPa	209000	50000
$E_2 = E_3$	MPa	9450	8000
$G_{12} = G_{13}$	MPa	5500	5000
G_{23}	MPa	3900	3846.3
ν_{12}	MPa	0.27	0.3
ρ	Kg/m^3	1540	2000

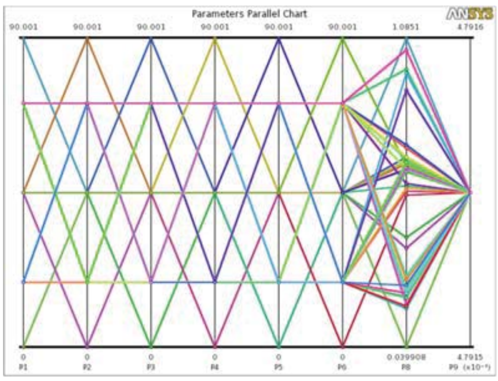
All the material properties that are shown in Table.1 have been calculated using the analytical equations in the MATLAB software. The properties of the epoxy, S-glass, carbon fibers are the inputs and the material properties of the composites are the output.

3. Results & Discussions

The design of experiments analysis, response surface generation, and response surface optimization have been performed using the design exploration modules present in the ANSYS workbench V16 software.

3.1 Design of Experiments

The design points were taken from the design of experiments analysis, which uses the procedure of central composition design method (CCD). A Central Composite Design (CCD) is a five-level fractional factorial design that is suitable for calibrating the quadratic response of a model. A CCD consists of a single center point, 2*N axis points located at the –a and +a positions on each axis of the selected input parameter, 2^ (N-f) factorial points which are located at the -1 and +1positions along the diagonals of the input parameter space that is selected. A parameters parallel chart shows the variation of different output parameters w.r.to input parameters for the cases generated in D.O.E, which is shown in Figure 8. Charts have been plotted to show the variation of the IRF for the laminate for different ply angles at different design points, which lets us identify the feasible solutions. In this case, we find the angle at which low IRF is obtained and then fix the ply angles for each ply in the laminate. Figure 9. shows the design point vs parameter chart plotted using Ansys workbench V16.



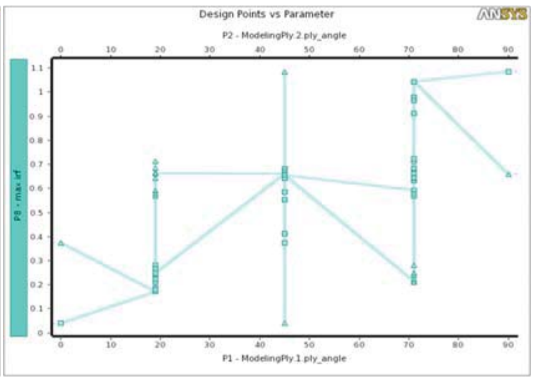


Figure 8. Parameters parallel Chart. **Figure 9.** Design Points Vs Parameters Chart.

3.2 Response Surface optimization (RSO)

Response surface optimization was performed from the response surface that was generated using design points obtained from the design of experiments (DOE) using the kriging method. Kriging is a multidimensional interpolation combining a polynomial model similar the standard response surface, which provides a “global” model of the design space plus local deviations are determined so that the Kriging model interpolates the DOE points. The response surface generated through this method will always have a high goodness of fit metric. Figure 10 shows the goodness of fit metric chart, which shows that the values obtained from the response chart, and the values of the verification points obtained by solving the model are in good correlation. Figure 11 shows the response surface obtained from the design points created from the D.O.E.

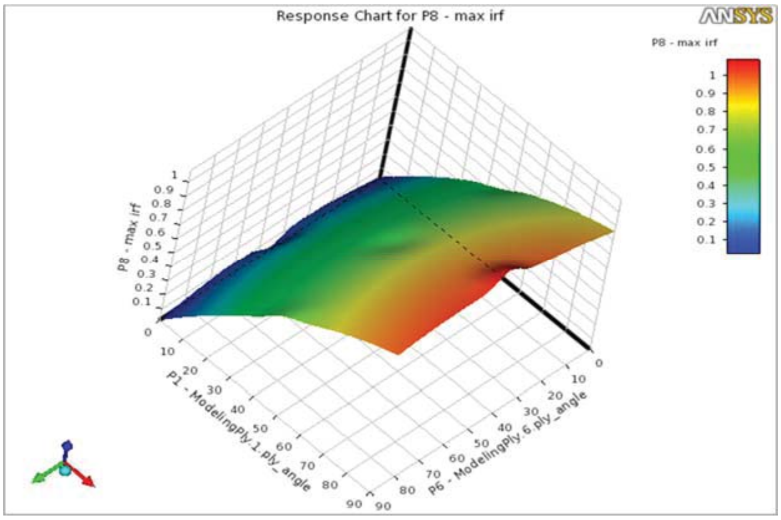


Figure 10. Goodness of fit Chart

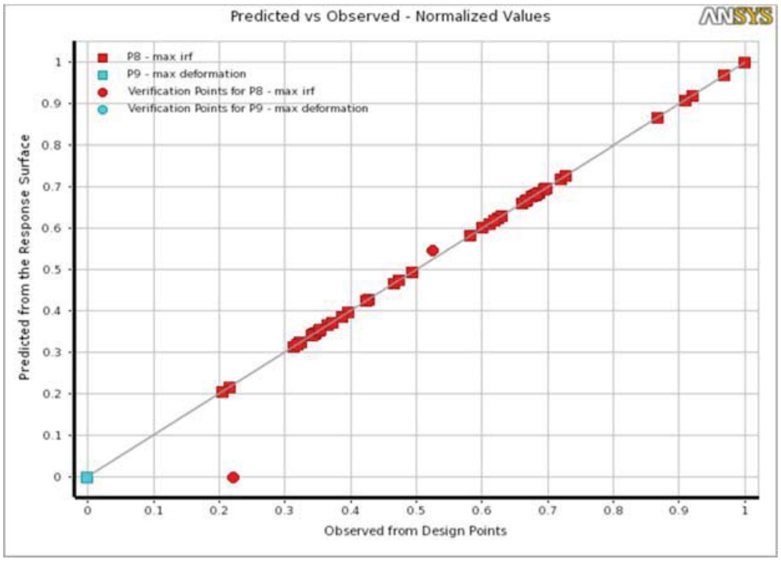


Figure 11. 3-D Response Surface Generated from D.O.E.

The objective of the optimization is to identify the candidates, which have very low IRF and low deformation, which are related to the stiffness and strength of the laminate. Multi-objective genetic algorithm (MOGA), an iterative algorithm which provides a more refined approach to optimization was used. It goes through several iterations retaining the elite percentage of the samples through each iteration allowing the samples to genetically evolve until the best Pareto front has been found ideally suited for calculating global maxima/minima. It will be used to generate an initial population of 100-design point and then solve until the convergence occurs. If convergence criteria are not met then the population is again evolving. The three best candidates that were identified from the optimization are denoted with candidates no: 2, 3, 4 which are shown in Table 2.

Table 2. Candidates generated from the optimization (2, 3, 4).

Candidate number	Ply Angle					
	1st	**2nd**	**3rd**	**4th**	**5th**	**6th**
1	0º	0º	0º	0º	0º	0º
2	1º	90º	4º	40º	6º	6º
3	0º	86º	3º	45º	65º	4º
4	1º	85º	0º	42º	28º	3º
5	90º	90º	90º	90º	90º	90º

3.3 Buckling Analysis

Eigenvalue buckling analysis was performed to find the buckling modes for the ring-stiffened cylinder. Lancoz solver was used and the buckling analysis was performed. Buckling load factors were obtained for all the different laminate layup candidates. The boundary conditions that were used for the analysis were shown in Figure 6. Five cases were performed in which each case consists of the same laminate layup but the ply angles were different and are provided in Table.2.

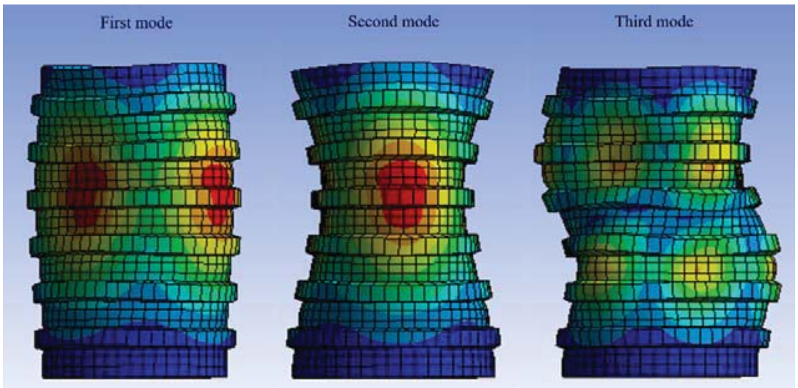


Figure12. shows the first three buckling modes for the first candidate laminate layup.

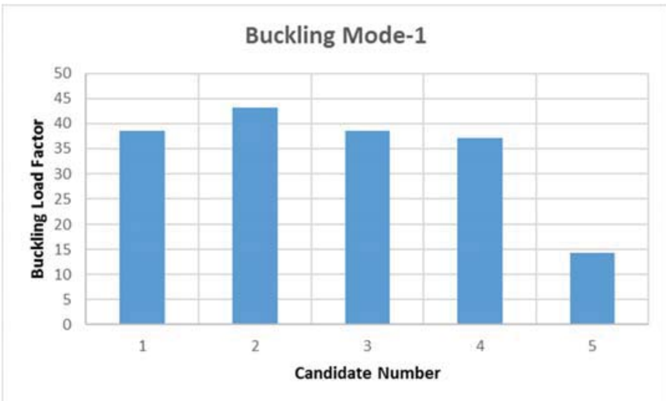


Figure 13. Buckling load factors for different candidates for mode-1.

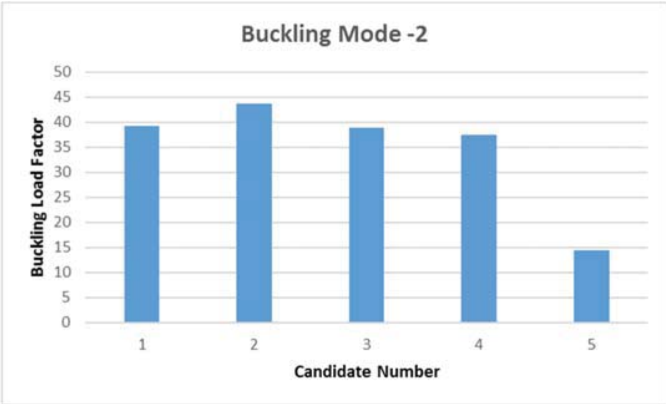


Figure 14. Buckling load factors for different candidates for mode-2.

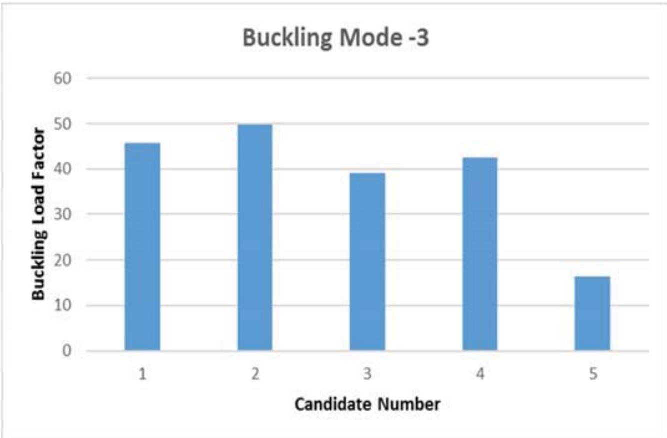


Figure 15. Buckling load factors for different candidates for mode-3.

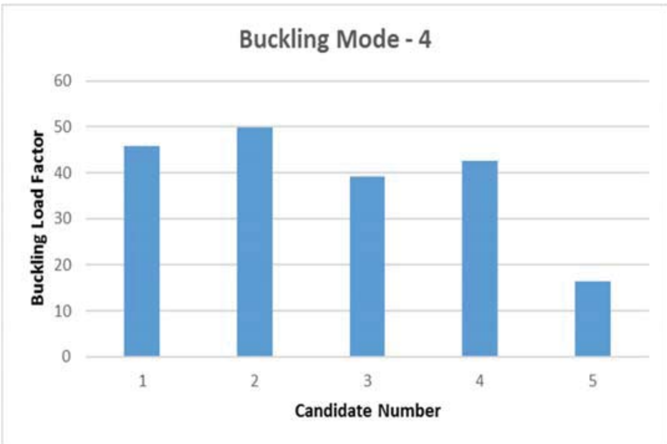


Figure 16. Buckling load factors for different candidates for mode-4.

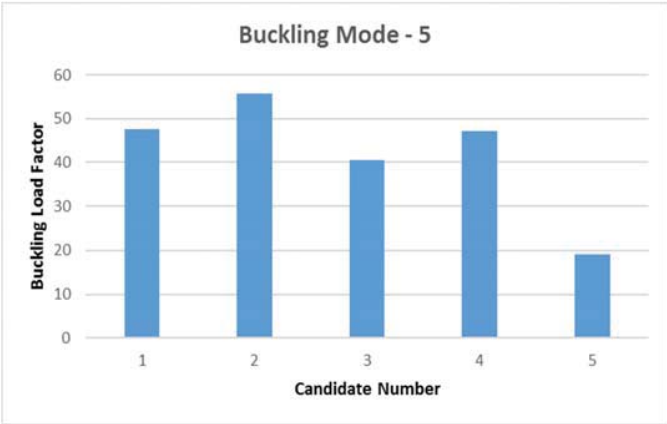


Figure 17. Buckling load factors for different candidates for mode-5.

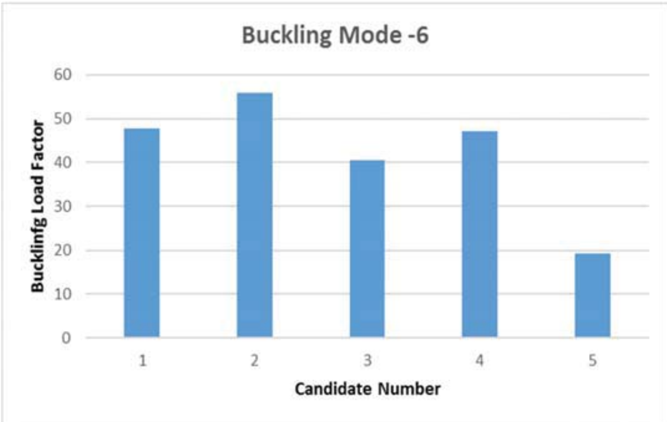


Figure 18. Buckling load factors for different candidates for mode-6.

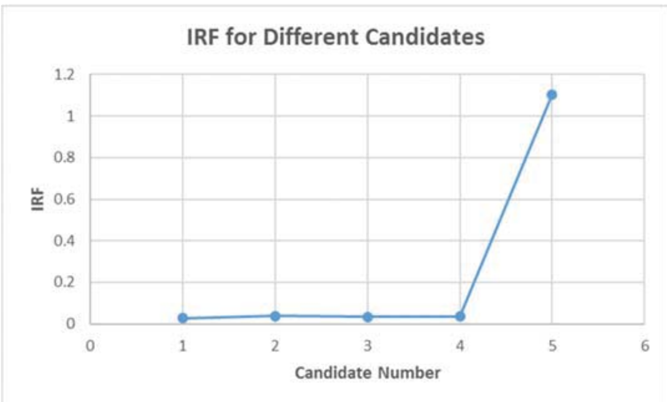


Figure 19. IRF for Different configurations.

The above Fig. 13, 14, 15,16,17,18 shows the comparison of the buckling factors for the 6 different modes for different candidates obtained from the eigenvalue buckling analysis performed on the ring stiffened cylinder. From the figures, we can say that the highest buckling load factor occurs for the laminate layup consisting of the candidate 2 ply angles and lowest buckling load factors occur for the laminate layup consisting of the candidate 5 ply angles. From the Figure 19, the highest IRF is for the laminate with candidate 5 ply angles and lowest for the laminate with candidate 2 ply angles.

The inverse reserve factor should as low as possible to say that the strength of the laminate is high as there is an inverse relation between the laminate ultimate strength to the inverse reserve factor and the buckling load factor should be high so that the laminate will bear more amount of load before it buckles. So from the above we can say that the laminate with candidate 2 ply angles is the best choice.

4. Conclusions

Successful optimization using the response surface optimization procedure for a hybrid laminate has been performed. Buckling analysis of the ring-stiffened cylinder subjected to buckling loads was performed with designed laminate for which the ply angles were optimized successfully. From the optimization, we have obtained three different laminate candidates with optimized ply angles for which have high strengths. From the IRF and buckling analysis, we can say the candidate 2 ply angles are the best. A procedure for optimizing laminates using the multi-objective genetic algorithm in ansys workbench was shown. The ply angles obtained from the optimization can be made only if the composite material is manufactured using automated fiber placement machines as the obtained fiber angles are not from the standard angle templates that are already used in the industry.

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