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Numerical Investigation of Effect of Reinforcements on Circular Cutouts in Composite Ribs

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Abstract

Cut-outs in aircraft structural components such as wing spars and ribs are commonly encountered in practice. Cut-outs are often necessary for lightening holes, passages for wire bundles, hydraulic and fuel pipes, control linkages, accessibility for final assembly and maintenance inspections. For a given circular cut-out areas, loading and laminate construction, various reinforcement configurations are attempted, based on linear analysis. This study considers a shear loaded square panel representing a segment of a composite rib containing a reinforced circular cut-out. Numerical studies have been conducted to investigate the effect of reinforcements around cut-outs on the stress concentration under in plane shear load and buckling behavior under in plane shear, compression, combination of shear and compression loading on a carbon/epoxy composite panel. Also, Tsai- Wu failure criterion is applied and the failure indices are calculated for all the configurations.

1. Introduction

An introduction of new technology follows the development and use of modern materials. Today, composite materials are the subject of an intensive development and use. The amount of composite materials in modern aircraft constructions is increasing. For example, fifty per cent of new Boeing 787 structure is made from composites. These materials have significantly better mechanical and other characteristics than their constituent elements. The problems of stress concentration and bucking behavior due to cut-outs in laminated composite plates have been studied by a number of researchers. There have also been considerable research efforts devoted to shear-loaded panels with cutouts. However research in the cut-out reinforcement is very limited.

The numerical study of stress concentration and stability of shear loaded plates with cut-outs Pandey [1] et al adopted the idea of flanged cutouts for composite panels. The performance of the reinforced composite panel was numerically simulated and compared with an aluminum counterpart of the same cut-out size and weight. The authors found that the composite plates showed significant dividends in reducing stress concentration and increasing buckling loads, and therefore composite ribs with flanged cutouts could provide weight savings and better load-carrying capabilities[1]. S.J. Guo [2] conducted numerical and experimental studies to investigate the effect of reinforcements around cut-outs on the stress concentration and buckling behavior of a carbon/epoxy composite panel under in-plane shear load. Four different types of cut-out reinforcements made of a range of materials were evaluated. Study shows that double ring reinforcement results into better reduction of stress concentration and increase in critical buckling load [2].

The objective is to present the results of a study of carbon/epoxy composite square panels with cutouts that are reinforced in order to reduce the stress concentration and enhance the stability. Therefore, the reinforcement types such as rings or flanges, which have been widely adopted for metallic structures and had some success with composite plates, are considered for the shear, compression and combined-loaded(Shear + Compression) composite panels. Finite element method has been employed to analyse reinforced cut-outs and various laminate stacking sequences. In this study the commercial FE code MSC PA TRAN NASTRAN is employed as the numerical tool. In all numerical cases, constant shear stress was applied at the panel's loading edges, for linear static analysis.

2. Problem Definition

A simply supported plate of size of 300 mm X 300 mm X 2 mm is used in the study. A uniform in-plane shear loading of 20 N/mm along all the outer edges is considered in the linear static analysis and for buckling analysis compression loading as well as combined loading of 20 N/mm cases also considered. The

Composite Material used has the following material properties:

E_{11}=130000 MPa; E_{22}=10000 MPa; ν_{12}=0.35; G_{12}=5000 MPa; G_{23}= 3270 MPa; G_{13}= 5000 MPa; X_t = 1200 MPa; X_c = 1000 MPa; Y_t = 40 MPa; Y_c = 246 MPa; S = 65 MPa; ρ = 1.8 g/cc. The laminate used has 16 layers each of 0.125 mm thickness and is symmetrically laid across mid plane with stacking sequence of $[-45/45]_s$.

The reinforcement types considered for analysis are: Unreinforced cut-out and cutouts with various reinforcements like ring reinforcement, flange reinforcement, flange with lip reinforcement and flange with ring reinforcement respectively shown in below figures.

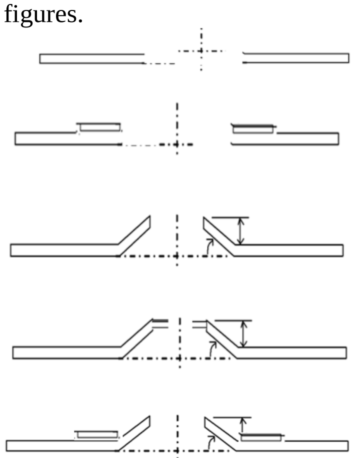

Fig [1] Types of Reinforcements [1,2]

3. Reinforcement Dimensions

The reinforcement dimensions considered for analysis are as indicated in below table while maintaining the plate thickness of 2mm for all the cases of analysis.

Reinforcement type	Flange height, h(mm)	Lip width, b(mm)	Ring width, w_r(mm)	Ring thickness, t_r(mm)	θ
Unreinforced	0	0	0	0	0
Ring	0	0	30	2	0
Flange	8	0	0	0	45
Flange with lip	8	5	0	0	45
Flange with lip	4	0	30	2	45

Table [1] Reinforcement Dimensions

4. Convergence Studies

An isotropic square plate of size 300 mm X 300 mm X 2 mm with 20 mm diameter cut-out is used for the validation of element formulation, mesh density, etc. Four different meshing schemes are used for this purpose under uni-axial tension. Tensile loading of 20 N/mm is considered in the convergence analysis. E=70000 MPa, ν=0.3; ρ = 2.7 g/cc. Here SCF is stress concentration factor and BLF is buckling load factor.
Below table shows the deviation of obtained results from the actual results.

Meshing Schemes	Total elements around cut-out	Total elements	Obtained SCF	Actual SCF Ref [3]	% of error
1	32	1280	2.735	2.807	2.56
2	40	1600	2.753	2.807	1.92
3	48	1920	2.763	2.807	1.57
4	56	2240	2.763	2.807	1.57

Table [2] convergence studies

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5. Validation Studies

The same plate as used for the convergence studies is used for validation purpose but with shear loading of 20 N/mm is applied. The table of SCF with obtained result.

Element geometry	Elements around cut-out	Loading	SCF (present)	SCF(Ref1)	% error
CQUAD4	48	1920	3.834	3.898	0.87

Table [3] SCF validation

The validation for BLF prediction is done by using isotropic plate as considered in above analysis for shear loading with the same dimensions but cut-out of 60mm, below is the table of BLF.

Element geometry	Elements around cut-out	Loading	BLF (present)	BLF(Ref1)	% error
CQUAD4	48	1920	1.944	1.949	0.26

Table [4] BLF validation

From the above studies it can be concluded that the methodology of mesh refinement employed, type of mesh selected for FE analysis and the element length chosen for FE modelling are giving accurate results and hence the same methodology of FE modelling can be applied for the problem under study.

6. Parametric Studies

The effect of variation in flange height for various cut-out diameters on the SCF and BLF is studied for the flange with ring reinforcement type configuration using composite material. Also Tsai-Wu failure criterion is applied and failure indices are calculated for all the cases.

7. SCF

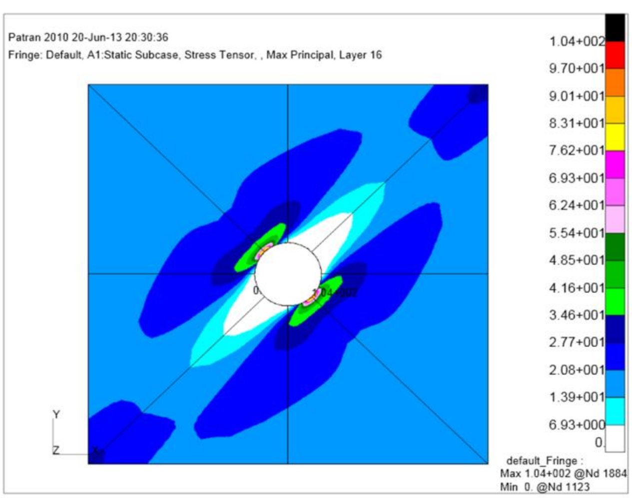
For the all above reinforcement types, SCF for 50-mm cut-out is calculated for composite rib under uniform shear load of 20 N/mm. The results are tabulated below in table.

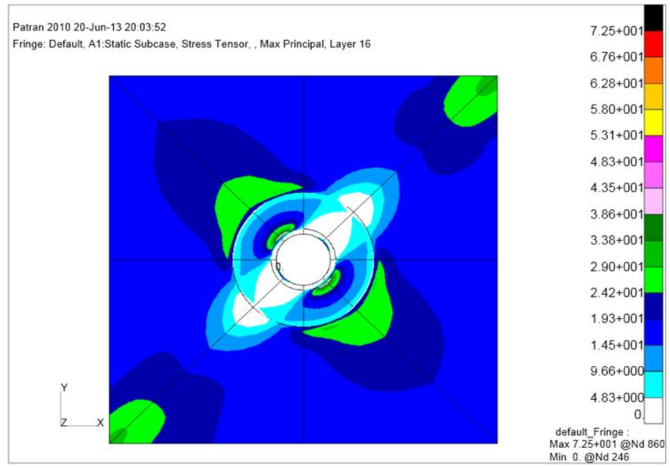
Table [5] SCF for various reinforcements

Reinforcement type	Flange height, h(mm)	Lip width, b(mm)	Ring width, w_r(mm)	Ring thickness, t_r(mm)	θ	SCF
Unreinforced	0	0	0	0	0	8.667
Ring	0	0	30	2	0	6.950
Flange	8	0	0	0	45	7.147
Flange with lip	8	5	0	0	45	7.581
Flange with lip	4	0	30	2	45	6.235

Stress concentration values are larger in composite rib and are due to the combined effect of material orthotropy, layup sequence, eccentricity and the compatibility requirement.

Below are the fringe plots of SCF for composite rib for the unreinforced cut-out and flange with ring





reinforcement.

Fig [2] fringe plot for unreinforced cut-out
Fig [3] fringe plot for flange-ring cut-out

Below graph shows the variation in SCF for various reinforcement methods employed herein.

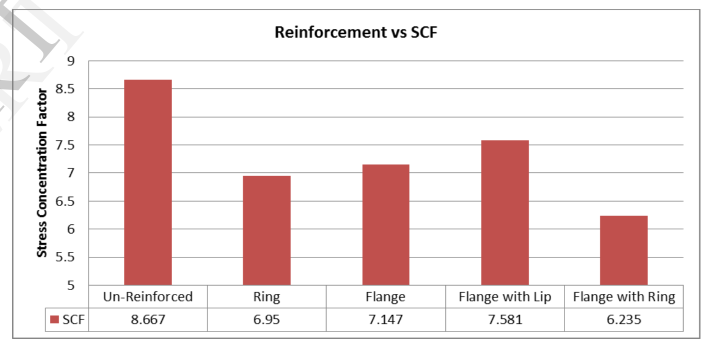


Fig [4] Graph for SCF with reinforcements

It can be observed that for the Ring type of reinforcement the decrease in SCF is comparatively higher than the flange type, however the gain in reduction is not very high(3%). The maximum stress value is higher in case of Ring reinforcement because of its orthotropic nature, lay-up sequence, and eccentricity and compatibility requirement. The lip attached to the flange does not give much improvement, but it is required to avoid delamination, at the end of flange and other manufacturing considerations.

8. Parametric studies for SCF

Parametric study is carried out for flange with ring reinforcement. Three different cut-out diameters; 50mm, 80mm and 110mm are considered for three different values for flange height 'h'

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(4mm,6mm,8mm). The width of the ring, ring thickness and flange angle are kept constant at 30mm, 2mm and 〖45〗^0 respectively for all the cases.

The results are tabulated below in table.

Cut-out size (mm)	Flange height (mm)	SCF
50	4	6.235
50	6	6.139
50	8	6.021
80	4	7.114
80	6	7.146
80	8	6.946
110	4	7.656
110	6	7.878
110	8	7.691

Table [6] SCF parametric studies

Below graph shows variation of SCF for various cut-out diameters with different flange heights.

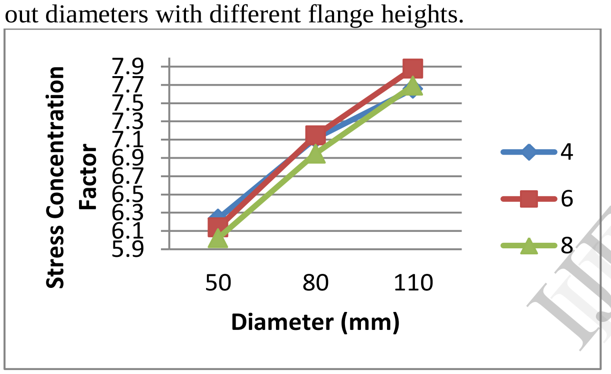

Fig [4] SCF vs Diameter

It is clear from table and graph, that increase in h results in a decrease in SCF but the gain is not very significant. It is also evident that the SCF value increases with the increase in cut-out diameter, which is in accordance with the classical theory. The increase in the value of SCF with cut-out diameter for any particular value of h is quite significant.

9. Failure Indices

For the all above reinforcement types, Tsai-Wu failure indices are calculated for composite rib of 50-mm cut-out under uniform shear load of 20 N/mm. The results are tabulated below in table.

Reinforcement type	Flange height, h(mm)	Lip width, b(mm)	Ring width, w_r(mm)	Ring thickness, t_r(mm)	θ	Tsai-Wu failure indices
Unreinforced	0	0	0	0	0	0.173
Ring	0	0	30	2	0	0.135
Flange	8	0	0	0	45	0.132
Flange with lip	8	5	0	0	45	0.138
Flange with lip	4	0	30	2	45	0.114

Table [7] Failure Indices

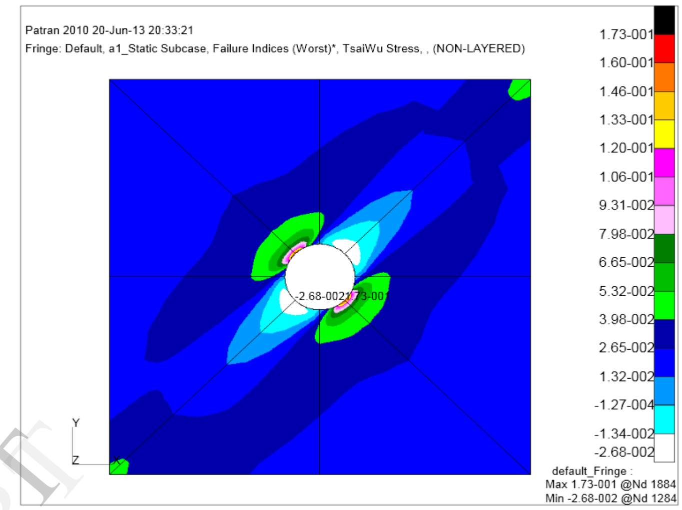

Fig [6] failure index for unreinforced cut-out

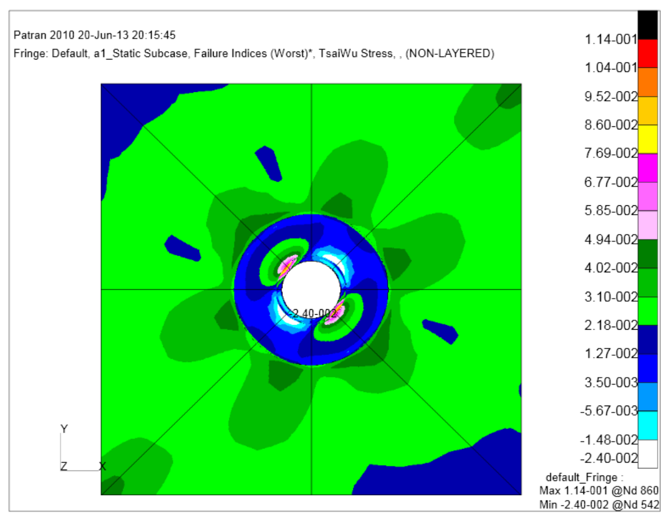

Fig [7] failure index for flange-ring cut-out

Below fig shows failure indices for various reinforcement methods studied herein.

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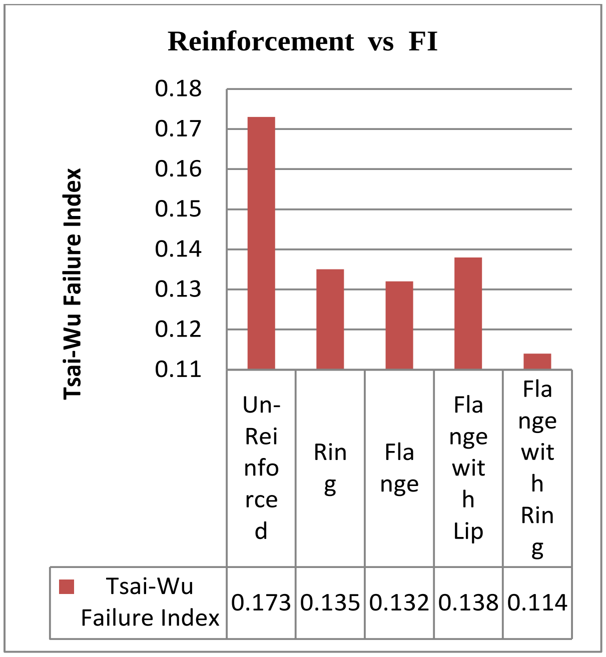

Fig [8] Reinforcement vs Failure Index

Parametric study is conducted on flange with ring configuration for various diameters and for different flange heights and results are tabulated in below table.

Cut-out size (mm)	Flange height (mm)	Tsai-Wu failure indices
50	4	0.114
50	6	0.110
50	8	0.107
80	4	0.149
80	6	0.147
80	8	0.141
110	4	0.188
110	6	0.188
110	8	0.181

Table [8] failure indices for Parametric study

From the above table and graph we can conclude that increase in reinforcement around the cut-out decreases the failure index and there is increase in the Strength Ratio. It is clear that increase in flange height results in decrease in Failure Index and an increase in the Strength Ratio. Large cut-out causes increase in the Failure index and reinforcement around the cut-out is necessary to reduce these effects. Reinforcement in the plates is more efficient in plat with larger cut-outs.

9. BLF

Below table represents values for various reinforcement methods adopted here for the composite rib. The loading conditions are compression, shear and combination of both compression and shear loading. The dimensions are as the same as used for the above study.

Reinforcement type	Compression BLF	Shear BLF	Compression + Shear BLF
Unreinforced	0.8855	1.5658	0.6831
Ring	1.1565	2.4980	0.9911
Flange	1.0303	2.0333	0.8308
Flange-Lip	1.0310	2.1058	0.8383
Flange-Ring	1.1619	2.4818	0.9976

Table [9] BLF for various Reinforcements

Below are the figures showing buckling load factors for flange- ring reinforcement.

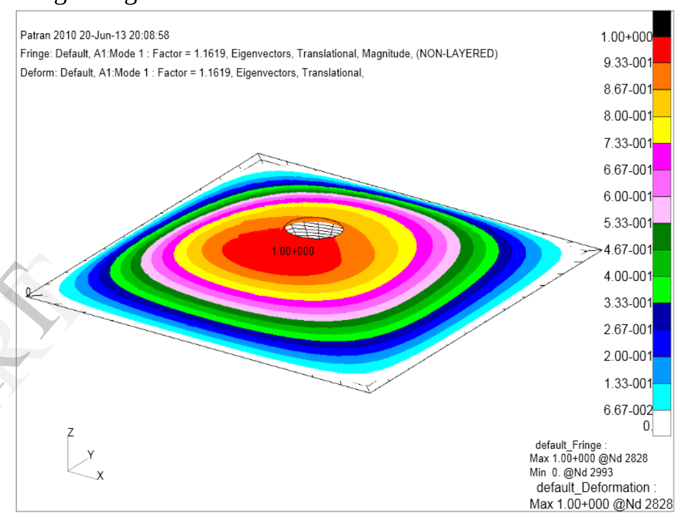

Fig [9] BLF for compression loading

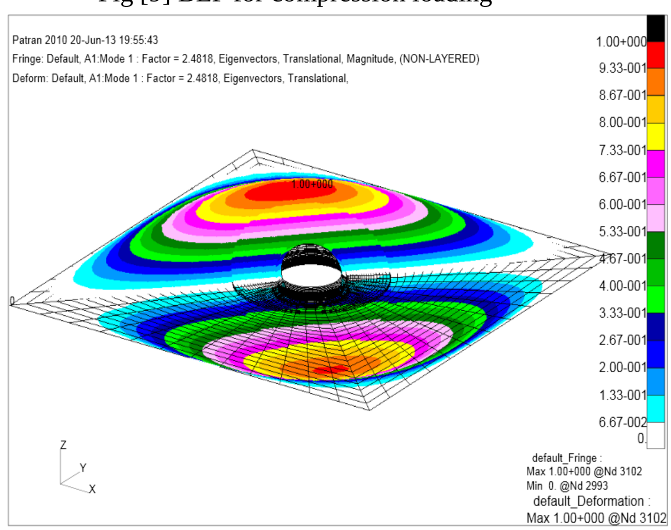

Fig [10] BLF for Shear loading

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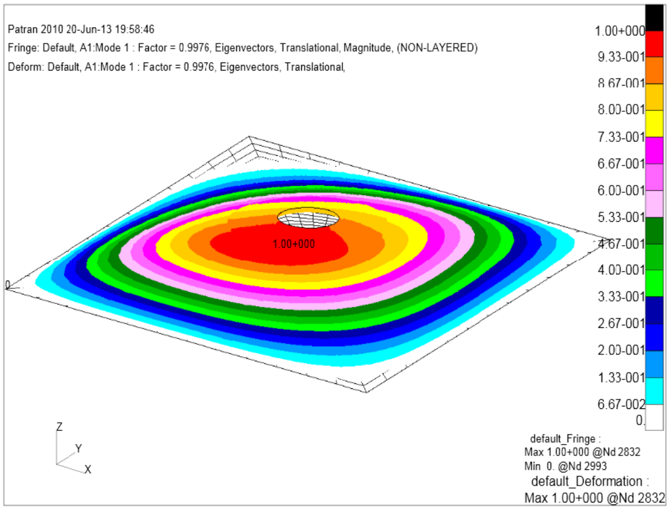

Fig [11] BLF for Compression- Shear loading

Parametric study is conducted on flange- ring configuration for various diameters with different flange heights. The results are tabulated as below.

Cut-out size (mm)	Flange height (mm)	Buckling Load Factor		
		Compression	Shear	Compression + Shear
50	4	1.1619	2.4818	0.9976
50	6	1.1685	2.4835	1.0047
50	8	1.1707	2.4838	1.0074
80	4	1.2908	2.9292	1.1042
80	6	1.3171	2.9610	1.1357
80	8	1.3306	2.9747	1.1518
110	4	1.4814	2.7186	1.1934
110	6	1.5534	3.0622	1.2894
110	8	1.5987	3.3289	1.3454

Table [10] BLF for parametric studies

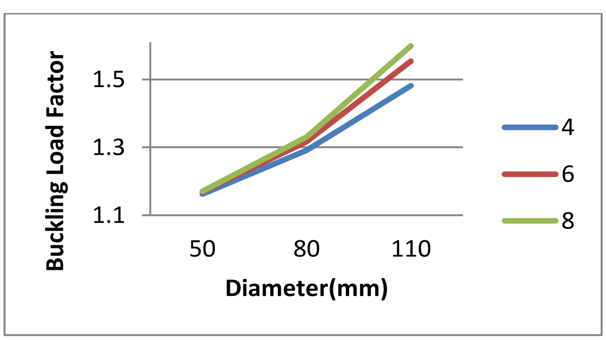

Fig [12] BLF vs Diameter

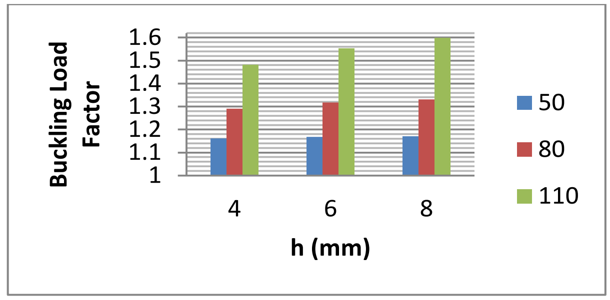

Fig [13] BLF vs Flange height

BLF increases with addition of reinforcement. This can be attributed to fact that the reinforcements results in the reduction in the effective aspect ratio of the plate. Substantial gains can be had in shear-buckling loads by the addition of flanges with the holes. Increasing the flange height leads to increase in buckling loads.

10. Conclusions

Stress concentration factor in the case of composite plate is decreases for various reinforcements adopted herein and the gain is not very substantial for larger diameters. Reinforcements are more effective in case of shear loading than compression and compression-shear loading case. Future studies can be done for different stacking sequences and cut-out sizes.

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11. References

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