BEHAVIOUR OF FRP COMPOSITE PANEL SUBJECTED TO IN-PLANE LOADING

S. Kumar
Research Scholar (PhD), Department of Civil Engineering,
Indian Institute of Technology (BHU) Varanasi, India

R. Kumar
Professor, Department of Civil Engineering,
Indian Institute of Technology (BHU) Varanasi, India

S. Mandal
Professor, Department of Civil Engineering,
Indian Institute of Technology (BHU) Varanasi, India

ABSTRACT

This paper deals review of the research on buckling behaviour of stiffened panels, which has been conducted in recent years by using finite element method (FEM) analysis, analytical method and experimental work. The review paper also deals post-buckling behaviour of fiber-reinforced polymers (FRP) stiffened panels with delamination-damage under compression and shear. Many experimental and analytical studies have been performed on the pre-buckling and post-buckling behaviour on laminated composite panels under axial compression. Most of the researchers have worked on the composite panel by using blade type, I section, T section and hat stiffeners. A very few literature are available on trapezoidal type stiffener of panels with respect to the specific depth of stiffeners but a variation of depth of stiffener has not been included in parametrical studies on buckling behaviour of composites panel by 3D-FEM. Non-linear finite element (FE) model has been used to perform parametrical studies on debonding between skin and stiffeners.

Keywords: Stiffened Panel, Laminated Composite, Pre-Buckling, Post-Buckling, FEM Analysis

Cite this Article: S. Kumar, R. Kumar and S. Mandal, Behaviour of FRP Composite Panel Subjected to in-Plane Loading, International Journal of Civil Engineering and Technology, 9(6), 2018, pp. 1324–1332.
http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=9&IType=6
1. INTRODUCTION
The design of laminated composite panel should be such that it can achieve better performance with specific strengths per unit weight. Shear force, compressive load and their combination are applied on stiffened panels to check its stability. In stiffened panels, generally, local buckling, global buckling and collapse occur under shear, compression and their combination. The failure of stiffened panel initiates from the interface between plate and stiffeners due to stress induced by damage to plate and stiffeners after the local buckling. Influence on buckling strength of the stiffened panel with variation of the thickness of plate and stiffener can be studied using analytical method, FEM and experimental work.

2. METHOD FOR BUCKLING ANALYSIS OF COMPOSITE STRUCTURE
Recently researchers to find a more efficient solution of laminated composite stiffened panel have conducted many different methods. Xu et al. [1] presented the detail studies on buckling of laminated composite stiffened structures under different loading conditions. The review has been done on the basis of different method of analysis on the composite panel. Ni et al. [2] presented a broad recent research done on the buckling behaviour of different stiffened structures. The review has been done on the basis of two aspects, application of FEM and experimental work with different loading conditions.

2.1. METHOD DEVELOPMENT
Chen and Soares [3] presented reliability assessment of the post-buckling capacity of composite structures subjected to axial compression. The post-buckling capacity structure was predicted by a progressive failure analysis (PFA). Parametric studies were performed on composite stiffened panels to find out the post-buckling capacity improvement with increasing thickness of panels. Yang et al. [4] presented the reliability assessment of the buckling capacity of top-hat stiffened panels under uniaxial compressive load. A reliability method is used to design the laminated stiffened panel as shown in fig. 1. Riccio et al. [5] proposed novel numerical methodology, by which the compressive response of composite panels with skin-stiffener separation was predicted successfully. The same methodology was used to test single stiffener composite panels. Response of buckling of the stiffened panels with debonding between skin-stiffener was confirmed by comparisons with a load-displacement curve and debonding size at failure. Romano et al. [6] used PFA methodology for the post-buckling analysis of damaged composite panels and studied its final failure response. In addition, its collapse load was also calculated accounting damage at different locations. Mallela and Upadhyay [7] used artificial neural network (ANN) to obtain an analytical tool for the prediction of the buckling capacity of laminated composite stiffened panel under shear load. The results of ANN were in good correlation with FEM results of shear buckling of stiffened panels.

Figure 1 Configuration of stiffened panel with hat stiffeners [Yang et al. [4] from Marine Structures]
2.2. APPLICATION OF ANALYTICAL METHOD

Loughlan and Delaunoy [8] analyzed the buckling of stiffened panels under edge loads, shear and combination of compression-shear load using finite strip technique. It has been also analyzed the buckling strength of stiffened panel by considering parameters like pitch length, stiffener size, and fiber orientation. Barbero et al. [9] investigated laminated composite plates and presented a numerical analysis of the connection between them. The orthotropic surface of FRP materials was modeled by using two-friction coefficients (orthogonal) and applying the constitutive law. Hadi and Matthews [10] studied to predict the buckling load of a sandwich panel with FEM. Parametric studies have been presented by the analytical method and compared with symmetric angle-ply laminated faces, anisotropic faces and (00/core/00) of sandwich panels. Guo et al. [12] studied the buckling response of stiffened panels under uniaxial compression by using a layer-wise FE formulation. Parametric studies of stiffened panels were presented for skin thickness to length ratios, ply configuration, stiffener depth to skin thickness ratios and panel aspect ratios. Bisagni and Vescovini [13] used T-shaped stiffeners in the composite panel as shown in fig. 2, to study its local buckling and the post-buckling analysis by using an analytical method.

![Figure 2](image_url)

**Figure 2** Configuration of stiffened panel with T-shaped stiffeners [Bisagni and Vescovini [13] from Thin Wall Structures]

Ruocco and Fraldi [14] presented an analytical method for prediction of the buckling of plates with mixed boundary conditions. Separation of variables method was adopted to solve the partial differential equation by introducing the displacement field. Exact buckling load was determined due to biaxial compressive loads with mixed boundary condition. Dung and Hoa [15] presented the effect of impact number and stiffeners dimension on the buckling and failure strength of cylindrical shell structures due to torsion by using an analytical method. Numerical formulations are derived with an application of classical shell theory and smeared stiffeners technique. Girish and Ramachandra [16] presented numerical results of symmetric $0^\circ/90^\circ/0^\circ$ and antisymmetric $0^\circ/90^\circ$ cross-ply laminated panels subjected to edge loads, temperature field and initial imperfection. Dey and Ramachandra [17] derived the governing partial differential equations describing the post-buckling response of sandwich panel with the application of minimum total potential energy. Numerical results were also exhibited for both flat panels and cylindrical sandwich panels under various non-uniform in-plane edge loading. Liu et al. [18] investigated the influence of cohesive parameters on the post-buckling pattern of composite structures subjected to compressive load by 3D FE analysis. The delamination behaviour was studied using parameters of cohesive strength, cohesive shape, and cohesive element thickness.
2.3. EXPERIMENTAL WITH COMPUTATIONAL

Kong et al. [19] studied analytically and experimentally on the two-laminated composite panel using blade-shaped stiffeners, and I-shaped. Detailed study was carried out to show the influence of ply orientation and stiffener shaped on buckling strength and failure load of the stiffened panels. Giannopoulos et al. [20] presented the numerical study on an IPC pedestrian bridge and correlated corresponding deformation with experimental results. Broekel and Prusty [21] conducted experimental study on laminated composite structures subjected to uniform transverse loading and compared with FE analysis results. Bisagni and Cordisco [22] carried out experimental work on buckling and post-buckling for cylindrical shell panels. Shell panels were designed with different ply orientation and skin thickness for post-buckling application. Zimmermann et al. [23] performed experimentally on buckling behaviour of stiffened panels with different skin thickness and a number of I-shaped stiffeners. The experimental results are compared with computational results obtained from ABAQUS. Pevzner et al. [24] proposed an extended effective width method to study the torsion, bending and buckling of curved stiffened panels with T-shaped and J-shaped stiffeners. Also, finite element result was found in good agreement with experimental work. Orifici et al. [25] conducted experimental work and numerical investigations on collapse behaviour of stiffened structures for damage growth between skin and stiffeners. The pre-damaged panels are manufactured by changing adhesive between skin and stiffener with a full-width Teflon strip. Undamaged panels were studied to predict the collapse load with the application of ply failure degradation model and global-local approach. Elaldi [26] studied composite stiffened panels through experiments and compared post-buckling capacity of structural efficiency of hat-shaped and J-shaped stiffened panels. Perret et al. [27] studied post-buckling analysis to predict the numerical models of composite fuselage panel by experimental work. Two Digital Image Correlation systems were placed on both the sides of the panel to obtain out of plane displacement that was aimed to correlate between numerical and experimental results. Falzon and Faggiani [28] presented genetic algorithms and numerical results with ABAQUS for optimization of the global-local modeling of the I-shaped stiffened panel. Global buckling and post-buckling results were validated by experimental results. The solution of the global buckling was used to derive the local model to predict the debonding between skin and stiffeners. Takeda et al. [29] presented buckling behaviour of carbon-FRP stiffened panel subjected to compressive loading by using FBG sensors and strain gauges. Blazquez et al. [30] studied the buckling response of stiffened panel with an effect of the thickness, ply orientation and shape of the stringers. A FEM model has been developed by ABAQUS software to predict the pre-buckling behaviour of the panel with the application of solid elements for modeling of adhesive layers between skin and stiffeners. Buckling mode shape 2 to 30 modes are taken for analysis of stiffened panel. Boni et al. [31] developed a validated procedure of modeling strategies. Pre-buckling and post-buckling simulation are done by the commercial software ABAQUS. The strains from FEM are compared to the strain gauge readings at mid-bay between the stiffeners and the buckling phenomena are identified by strain-load curves. Reinoso et al. [32] used ABAQUS software with a local-global approach for comparing sub-modeling and shell-to-solid modeling techniques, and for global modeling of panels with shell element, typology was applied. Liu et al. [33] performed an experimental study of buckling behaviour and failure mode of the stiffened panel with M-type stiffeners subjected to compressive loading. Numerical simulation was used for predicting buckling and post-buckling behavior of the panel and it was compared with experimental results. Zhu et al. [34] conducted experimental work to study the buckling load and failure load of I-section composite laminated stiffened panel subjected to compressive loading. For this study, stiffened panels were manufactured with different plates and stiffeners. The effect on buckling strength of stiffened panels were studied and compared with FEM results by varying the plate
and stiffener thickness. Riccio et al. [35] presented inter-lamina damages propagation in composite stiffened structure. The delamination growth between skin-stringer in the stiffened panel was investigated in ABAQUS using cohesive elements parameters under compressive load. Borrelli et al. [36] investigated kinematic coupling approaches for Finite element simulation of the buckling behaviour of laminated stiffened structures. Stress distributions have been compared at domains interfaces with the results obtained from the model with mesh continuity and merged modes. Wang et al. [37] studied to find out their buckling and ultimate load carrying capacity of I-shaped stiffened panel. The deformed shape of the first buckling mode is shown in fig. 3 with six buckling waves situated in the part of the skin of the panel.

![Figure 3](image-url) The deformed shape of 1st mode buckling of stiffened panel [Wang et al. [37] from Composite Structures]

2.4. APPLICATION OF FINITE ELEMENT METHOD
Kalyanaraman and Upadhyay [38] discussed the behaviour of FRP box girders and proposed a computationally efficient method to study the single cell FRP box-girder bridges made with angle-shaped, T-shaped or blade-shaped stiffened panels using FEM based software ANSYS. Mallela and Upadhyay [39] performed a parametric study of the laminated stiffened panel under in-plane shear. Models were analyzed using FEM based software ANSYS and a database was provided for various skin-stiffeners combination. Few parameters are identified based on the buckling response of stiffened panel. Rahimi et al. [40] analyzed the buckling response of shell structure due to stiffeners subjected to axial compressive load by ANSYS software. Tserpes et al. [41] presented numerical buckling analysis of stiffened panel under compressive load and determined state of strain of the stiffened panel. The stiffened panel was modeled by using ANSYS SHELL63 element. Fiber sensors were engrained into the stiffened panel to capture the developed strains during delamination of stiffened panel under compressive load, hence reducing the risk of fiber damage. Huang et al. [42] computed the performance of stiffened panels using FE technique and arbitrated the accuracy of proposed model. Parametrical studies were performed to assess influence of skin thickness, stiffener spacing and stiffener depth on the buckling strength of grid panels. Fathallah et al. [43] studied the optimization of ply orientation and number of layer of composite structure with T700/5505 Born and others laminated composite materials to find the minimum buoyancy factor for composite elliptical submersible pressure hull. ANSYS software was used to perform the analysis and optimization of laminated composite structures. SudhirSastry et al. [44] performed the analysis of buckling of laminated stiffened panels using ABAQUS based on FEM with carbon fiber and others composite materials. Square stiffened panel was fabricated with 8 layers of plate and 16 layers of different shaped of stiffeners. The variation of the numerical results of stiffened panels were analyzed and correlated with the experimental results. The linear buckling analysis (pre-buckling analysis) as the eigenvalue problem was estimated by SudhirSastry et al. [44] as:

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\[(\mathbf{K}_0 - \lambda \mathbf{K}_p) \{x\} = 0\]

where, \([K_0]\) is stiffness matrix, \([K_p]\) is geometrical stiffness matrix, \(\lambda\) is critical loads and \(\{x\}\) is eigen-vector. Yetman et al. [45] studied the hat-stiffened panel to provide an efficient structure and observed debonding between stiffener and plate. It was found that the position and debonding size influences the mode of damage of stiffened panel significantly. Buckling capacity of top-hat-stiffened structures was computed considering debonding between the skin and the stiffener. A non-linear FE model was implied to work out parametric studies on influence of both delamination and failure modes of the geometry of panel. Farooq and Myler [46] studied failure prediction of laminated composite panel with damage due to low velocity impact by using ABAQUS software. Known damaged size and shape was inscribed at different positions in the laminated panel to predict buckling load on the basis global-local buckling approach with mixed-mode buckling. The buckling load was predicted for eight, sixteen and twenty-four ply laminated composite panel with considering failure and ply level strength.

3. CURRENT STATUS OF KNOWLEDGE

From the above review of literature, it has been observed that the substantial research work has been conducted on panels, which are manufactured with laminated composite materials and stabilized with different shape of stiffeners to attain lightweight structures with superior buckling and stiffness capacity. Due to need of clarity on the computation of buckling strength and failure load of stiffened panel, the guidelines for design of FRP panel is not available. Therefore, it is assumed to give emphasis on parametric studies (ratio of smeared extensional stiffness of stiffener to that of skin, stiffener depth to plate thickness, panel aspect ratio and ply orientations) for determination of buckling capacity and failure load of stiffened panel.

Most common failure pattern in laminated structures is delamination of plies and skin-stiffeners. In recently, many researchers have dedicated their study on the delamination of skin-stiffeners and failure pattern of laminated composite structures. This is due to their delamination of inter-laminar interfaces, debonding between skin-stiffeners and low bucking capacity under shear and compression. Local damages of the composite structure gradually increase due to delamination with increase in the buckling deformation and buckling modes subjected to compression, shear and their combination. Load carrying capacity and stability of composite structure reduce due to delamination damage. Delamination is more significant for the stiffened panel under compression since the reducing of stiffness lead to the collapse of the stiffened panel.

4. APPLICATIONS

A lightweight structure is an ongoing task for the engineering community. Fiber-reinforced polymers (FRP) meet this requirement to some extent since its development in 1960s. FRP has been used extensively in defense, aircraft, and automobiles area and now it is currently employed in structural applications. FRP stiffened panels are being used as the load shared walls of the compressive member of structures, which possess load carrying strength after initial buckling until the ultimate strength of the composite material is achieved. Composite panels are also used in multi-storey building to reduce the dead load of the structure. FRP laminated panels are currently used in heritage building for retrofitting due to its high strength and aesthetic appearance.
5. CONCLUSIONS

This paper reviewed the existing research works on the behaviour of FRP stiffened panels with I-section, T-section, hat-stiffener, and Blade-type stiffeners. It has been observed that buckling load and collapse load of panels don’t increase with unnecessarily increase the depth of I-section, T-section and blade-type stiffeners of composite panels. A non-linear FE model is implied to work out parametric studies on the influence of the delamination and failure modes of the panel’s shape.

Most of the researchers have worked with I-section, T-section, hat-stiffener and Blade-type stiffeners of the stiffened panel. A very few literature are available on trapezoidal-type-stiffener of panels. In all above-mentioned literature, the effect of variation of depth of trapezoidal stiffener on buckling behaviour has not been included. On the basis of literature review and problem description, the following parametrical studies have been considered for experimental and FEM analysis of FRP stiffened composite panels.

- Influence on buckling capacity with a bond length between skin and trapezoidal-type-stiffener of the panel.
- Optimum stiffener orientation of hat-stiffened panel for maximum buckling load under compression load on the panel.
- Effect of different ply configurations of the panel on buckling load for given stiffener depth and bonding between skin and stiffeners.

REFERENCES

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