Mechanical Behavior of CFRP Stiffened Panel under Uniaxial Compressive Loading

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Declaration

I declare that this written submission represents my ideas in my own words, and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

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This thesis entitled Mechanical Behavior of CFRP Stiffened Panel under Uniaxial Compressive loading by Madhava Ramesh Babu Yarlagadda is approved for the degree of Master of Technology from IIT Hyderabad.

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iii

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Dedication

Dedicated to God, family and teachers

Abstract

The present work focuses on the experimental and finite element analysis of Carbon fiber reinforced polymer (CFRP) stiffened panels with two blade stiffeners. The buckling behavior of the CFRP stiffened panels with and without cutouts between the stiffeners is investigated under compression loading. In this study, stiffened panels are fabricated in-house starting with the both stiffeners individually fabricated using vacuum infusion (VI) process and later co-bonded to the skin is of quasi isotropic stacking sequence $[-45^0/45^0/90^0/0^0]_s$. End blocks are cast at the transverse edges of the stiffened panel for applying uniform load whereas the longitudinal edges are left free. Whole field non-contact optical technique called digital image correlation (DIC) is used in the experimental study to estimate the whole field displacement and strain over the stiffened panel, being loaded under a uniaxial compressive load. The buckling parameters such as initial axial stiffness, critical buckling loads, post buckling axial stiffness obtained experimentally are compared for panel with and without cutout. Experimental results are compared with the finite element predictions for validation. In case of panel with cutout a circular hole is introduced at the center of the skin between the stiffeners. In this study all the buckling parameters are compared with the experimental results obtained for the same panel configuration without any cutout.

Nomenclature

DIC	Digital image correlation
VI	Vacuum infusion
FEM	Finite element method
CFRP	Carbon fiber reinforced polymer
cp	Centipoise
Q	Volume rate of resin flow
K	Permeability of the material (a measure of the ease that resin can flow through the material
A	Area of the cross section through which the resin is flowing
Δp L	Pressure difference across a section of laminate whose length is
μ	Viscosity of the resin (dynamic)
t	Distance the resin has to travel
a	Distance between the flange edge and panel free edge
d	Diameter of the circular cutout at the mid of panel in between the stiffeners
f	Width of flange
h	Height of flange
L	Total length of the panel
W	Width of the panel

Contents

References

Chapter 1

Introduction and literature review

1.1 Introduction of composite stiffened panel

Aerospace and automobile sectors are multi-million dollar industries in this modern era. Both sectors have significant impacts on environment as they are releasing pollutants in to the environment. They are driven by the quest to make the transportation more efficient by reducing the weight of their products. When it comes especially to aerospace industry fuel costs are very high. There is a huge demand for innovation to make the aircrafts lighter along with rigorous quality requirements. Lighter aircrafts have the advantages on greater fuel savings, low maintenance costs and also by being environmental friendly. Weight reduction of aircraft's fuselage leads to the requirement of smaller lift which needs only smaller wings. This lowers the required thrust as the drag force is reducing. This ultimately leads to smaller weight engine and reduction of fuel reserve which lowers the ultimate weight. All these factors have motivated the aerospace industry for the extensive application of efficient materials along with the efficient structures in aircrafts to make them lighter in weight.

In the beginning aircrafts are made using wood. Later wood is replaced by traditional metals like aluminum alloys, steel, titanium etc. to reduce the maintenance costs in the modern aircrafts. The invention of the composite materials has been a boon for the modern aerospace industry in reaching its goals to make the aircrafts lighter and efficient. A composite material is the resultant of the macroscopic scale combination of two or more distinct materials differ in terms of physical and chemical properties. The resultant material is superior to all the individual constituents in several aspects. The major constituents of a composite material are matrix and reinforcement. Reinforcement is embedded in the matrix. Composites are beneficial in terms of stiffness to weight and strength to weight ratio, resistance to corrosion when compared to traditional metals. The designer can also have the flexibility to tailor the properties by varying the ply orientations and stacking sequence of the laminate to suit the loading situation. These qualities are attracting the major aircraft manufacturers like Airbus, Boeing to replace the metallic structures like wing, fuselage with composite structures made out of Carbon fiber reinforced polymer (CFRP). There has been a gradual increase in the usage of composites in commercial aircrafts started in 1950's with 2% of Boeing 707 made of fiber glass. In 1980's Airbus also started with composites usage by manufacturing 5% of A310-300 using composites. With the advancement of technologies in composite manufacturing, industries succeeded to have fuselage, wings and in most of the other airframe components made mostly out of composites. It accounts for about 50% of Boeing 787 Dreamliner and 53% of A350XWB built using CFRP [1]. Utility of composite materials in Boeing 787 Dreamliner aircraft is illustrated in Figure 1.1. [2]. Boeing 787 Dreamliner is one of the most fuel efficient passenger aircrafts because of significant use of composites to make it lighter in weight.

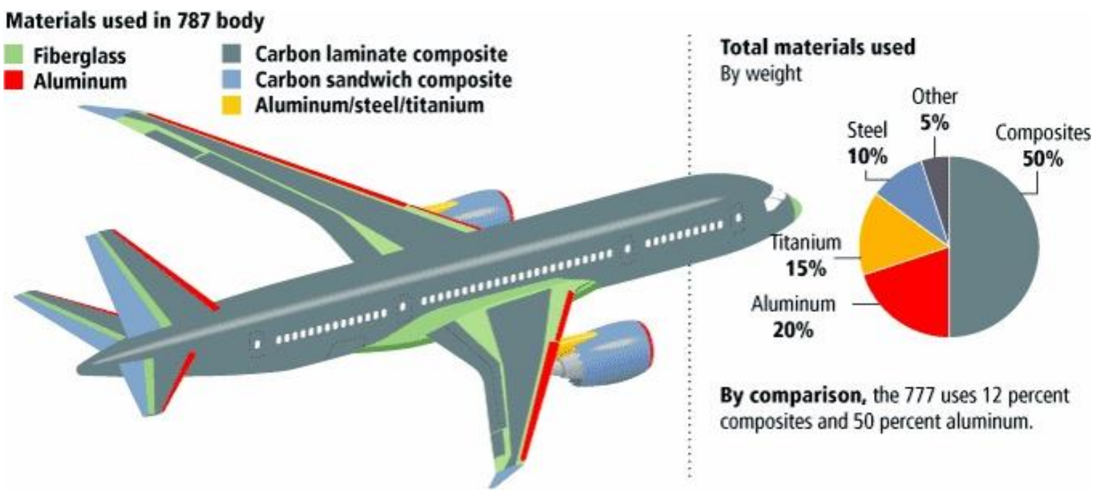


Figure 1.1: Contribution of various materials in Boeing 787 Dreamliner's construction [2]

CFRP has the superior mechanical properties such as low density combined with higher strength, stiffness. So, the strength based design leads to thin skin and is prone to buckling phenomenon. Stiffeners, simply the columns attached to skin longitudinally help to improve the buckling load capability with a relatively less weight penalty by increasing the second moment of area of skin locally. The composite stiffened panels are thus combining material and structural efficiencies. Structures like wing, fuselage in modern aircrafts comprise of CFRP stiffened panels. Utility of composite hat stiffened panel in Boeing 787 Dreamliner aircraft fuselage is illustrated in Figure 1.2. [3].

Figure 1.2: Disassembled fuselage section of Boeing 787 Dreamliner [3]

1.1.1 Types of stiffeners

The stiffener attached to the skin longitudinally improves the load carrying capacity of the overall structure especially under compressive and bending loads. The required property of the stiffener is to make cross sections with larger moment of inertia. There are several cross-sectional shapes available for the stiffeners in practice such as "L", "C", "Z", "T", "I", "J", "Hat" [4]. Different cross-sectional configurations of stiffeners are illustrated in Figure 1.3.

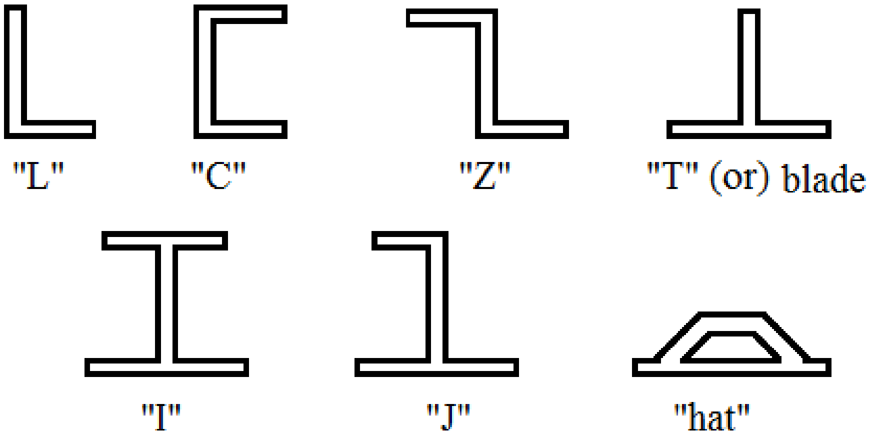


Figure 1.3: Different cross-sectional configurations for the stiffener

1.1.2 Cutouts in fuselage

Cutouts are unavoidable in fuselage for the purpose of windows, wiring, visual inspection etc. which can act as stress raisers and affect the load carrying capability. Their profiles are designed to have rounded corners, circular or oval to reduce stress concentration. Aircraft's fuselage having circular window cutouts is shown in Figure 1.4.

Figure 1.4: De Havilland Comet having circular cutouts in fuselage [5]

1.2 Literature review

Composite stiffened panels can reduce the overall aircraft weight as discussed before because of its material and structural efficiencies. Its load carrying capability even after getting buckled has attracted several researches because it helps to further reduce the weight of aircrafts. It made them to focus on improving manufacturing methods to fabricate integrated structures comprised of composite stiffened panels. They also worked to understand the failure mechanisms in post buckling region of loading in the composite stiffened panels. Since experimental studies on full scale fuselage representative composite stiffened panels are expensive, researchers worked on geometrically scaled composite stiffened panels for their experimental investigations.

Wenli Liu [6] detailed about the fabrication procedure of the two and three blade Carbon fiber reinforced polymer (CFRP) stiffened panels using prepeg tape. He performed experiments by loading the stiffened panels in compression which are pasted with strain gauges and validated the experimental results with FEA results. Rouse and Asaadi [7] conducted experimental studies to compare the structural response and failure characteristics of geometric scaled graphite-epoxy flat stiffened panels loaded in compression. They validated the experimental results by comparing with the results of nonlinear FEA.

Barbero [8] demonstrated the modelling of composites, Eigen and nonlinear buckling analysis of composites in ANSYS. Leong and Hogg [9] conducted the stiffener pull-off tests to evaluate the bond quality between skin and stiffener. They fabricated the co-cured composite blade stiffened panels using vacuum infusion (VI) and resin transfer molding (RTM). They compared the effects of different materials at skin-stiffener interface and manufacturing methods on the skin, stiffener bond strength. Adrien et al. [10] detailed about the experimental techniques for compressive testing of a composite stiffened panel and validating with the numerical results. They also briefed about the machining requirements of the specimen after casting with resin end blocks on two loading ends to avoid the misalignments of specimen for accurate loading. Charlotte et al. [11] explained about the mechanisms for skin-stiffener detachment and also the influence of damage introduced at the interface on those mechanisms. Shuart et al. [12] explained about different modern and automated fabrication technologies for high performance polymer composite manufacturing. Huang [13] conducted stiffener pull-off tests on co-cured blade stiffened panels made out of woven fabric tape of Cytec fiber to see the effects of the radius of tool which is used as mold for stiffener fabrication. He optimized the radius of tool and length of flange based on the debonding strengths observed from the stiffener pull-off tests. Bloodworth et al. [14] used DIC to find local strain fields at skin stiffener interface qualitatively. They used these results to correlate these strain data with the failure initiation and propagation at skin stiffener interface. Luca Lanzi [15] conducted experimental and numerical investigations on the composite stiffened panels into post-buckling regime by measuring the initial geometric imperfections in the specimens and modelling these imperfections in FEM. He found that these imperfections are affecting initial stiffness and first buckling load moderately but having relevant role on post-buckling behavior. Ma et al. [16] conducted experimental investigations to study the influence of various processing methods and parameters on the quality of CFRP blade stiffened panels, manufactured using carbon fiber/epoxy resin prepeg with cobonding autoclave process. Bisangi and Davila conducted experimental investigations usind 3D-DIC to study the postbuckling behavior and failure mechanism on CFRP co-cured single hat stiffened element. They also focussed to evaluate the postbuckling response and the effect of an embedded defect on the collapse load and the mode of failure.

1.3 Motivation, scope and objectives

Composite stiffened panels are playing a very significant role in the modern aircrafts for structures like wings; fuselages to reduce the aircraft over all weight and also to withstand very high aerodynamic forces during flight. Being a very complicated structure, stiffened panel loaded in compression results in different types of initial independent buckling modes occurring such as skin local buckling, stiffener local buckling or even panel global buckling. Local buckling modes do not lead the structure to fail catastrophically like panel global buckling mode. Thus structure comprised of stiffener continues to carry more loads even after the occurrence of the initial buckling occurs until the final failure happens. Initial skin local buckling mode in between stiffeners prevents the panel to buckle as a whole and help stiffeners to retain their axial load carrying capability [4]. The main aspect that limits the maximum load in the post buckling region is skin stiffener separation. Systematic study on the pre buckling and post buckling behavior of the stiffened panel under compressive loading and the effects of cutouts on its behavior is necessary.

One way of understanding the buckling behavior of the stiffened panel is through fabricating the panel and conducting proper experimental studies on it under gradually increasing compressive loading. Fabrication of stiffened panel itself is a big challenge and it needs to be pursued diligently towards perfect fabrication of the panel outside out of clave process. As CFRP panels are not in withstanding compressive loads compared to tensile loads. Therefore, buckling study is of primary importance for practical structural applications. Whole field non-contact optical technique called digital image correlation (DIC) can be used in the experimental study to estimate the whole field strain, axial as well as out-of-plane displacement of the stiffened panel being compressive loaded. Further one can also use finite element analysis (FEA) to predict the buckling behavior of the stiffened panel under compressive loading and compare it with the experimental results. For proper experimentation, one needs to fabricate stiffened panels without any flaws using available manufacturing process. Further loading fixture needs to be designed and developed for carrying out the experimental study. The objectives of thesis are outlined as follows:

1. To establish a standard procedure for fabricating the CFRP blade stiffened panels.
2. To establish a standard procedure for conducting proper experimental studies on the buckling behavior of the CFRP stiffened panels.

3. To design and manufacture the required fixtures for the purpose of fabrication as well as testing them.
4. To validate the experimental results by comparing it with the results obtained from FEA study.

1.4 Thesis layout

This section discusses about the layout of the thesis.

Chapter 1 gives the brief introduction to composite stiffened panel and its utilities along with literature review, motivation and objectives of the thesis.

Chapter 2 explains the fabrication aspect of CFRP stiffened panels along with the process parameters. The conceptualization and the design of the fixture for the purpose of fabrication and testing of the stiffened panel is dealt in with detail

Chapter 3 covers the finite element study on the buckling behavior of the composite stiffened panel along with the validation studies on the buckling analysis.

Chapter 4 deals with the experimental aspect of testing of CFRP stiffened panel under uniaxial compressive load. Further exploitation of whole field DIC technique for such buckling study is established. Buckling analysis on it and results obtained from DIC are compared with FEA prediction for validation.

Chapter 5 contains conclusions of the thesis work and future recommendations.

Chapter 2

Fabrication of blade stiffened CFRP panel

2.1 Introduction

The main objective of the entire thesis is to perform systematic experimental studies on the mechanical behavior of the CFRP stiffened panels under gradually increasing compressive loading. The accomplishment requires proper fabrication of the CFRP stiffened panel by following a standard procedure. A fixture for casting the resin end blocks at loading edge of the panel needs to be developed. In case of the experimental study towards proper applying of load, the specimen needs to be held in an appropriate fixture towards better gripping and load transfer from the test equipment. This chapter focusses on the procedure for the fabrication of the CFRP stiffened panel. It contains the design and fabrication of the above mentioned fixtures. For completeness the practical challenge one faces in all these manufacturing process are summarized at the end.

2.2 CFRP stiffened panel fabrication

A CFRP stiffened panel can be fabricated in several different ways. The methods differ by based on the fiber form which can be either in a dry form or as a prepeg (preimpregnated fiber) which decides the cost and quality of the final output. The complexity of the shape of the stiffener also plays a main role in choosing the suitable method to fabricate the CFRP stiffened panel.

The present work aims in manufacturing a CFRP blade stiffened panel from dry Carbon fibers in which fabrication of a perfect blade stiffener is the bottleneck in the process. A blade stiffener's cross section typically looks like an inverted 'T' as shown in Figure 2.1. The vertical portion of the blade stiffener is called web and horizontal portion of it is called flange which helps to bond the stiffener to skin.

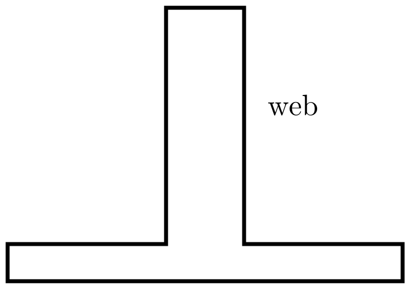


Figure 2.1: Cross section of a blade stiffener

It is very convenient to fabricate the blade stiffener by considering it as two mirrored L's glued to each other. Entire cross section is divided in to web, right flange and left flange. Web usually have symmetric stacking sequence so that plies in the right half of the web section continues in to the right flange and remaining plies in the left half of the web section continues in to the left flange. Vacuum resin infusion process, being an easier and cost effective method is chosen to fabricate the CFRP blade stiffener.

2.2.1 Vacuum resin infusion process

Vacuum resin infusion (VRI) or vacuum infusion (VI) or vacuum assisted resin transfer molding (VARTM) is a process of using vacuum pressure to facilitate the flow of resin mixture in a controlled manner in to the fiber layup packed with in a mold tool, covered by a vacuum bag. Later the resin mixture solidifies results the assembly of fibers and resin mixture in to a unified rigid composite material.

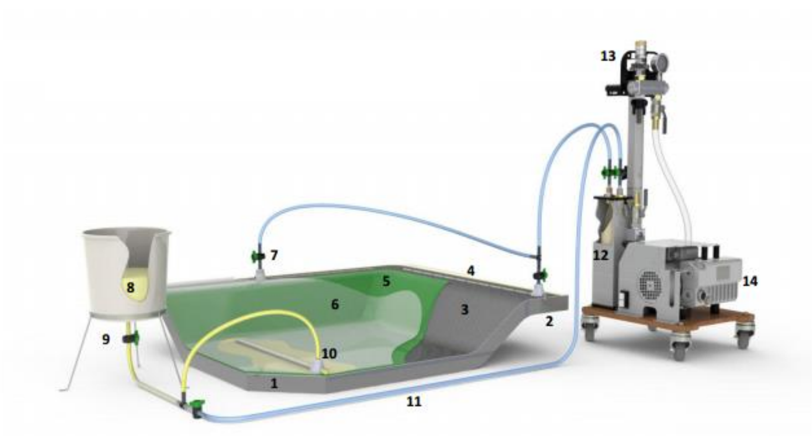
The key part of the process is the evacuation of fibers which are packed in the desired sequence in an air tight envelope using a vacuum pump. This envelope comprised of molds pretreated with the mold releasing agent tightly packed in a vacuum bagging cover. Vacuum bagging sealant tapes made out of synthetic rubber are generally used to seal the cover to mold to avoid air leaks in to the envelope during and after evacuation. After checking for any possible leakages, an appropriate quantity of resin has to be taken by considering the weight of dry fibers, quantity of consumables and length of tubes used for infusion. Resin after mixed with the required ratio of hardener after degassing is allowed to infuse by using the spiral tubes. Spiral tubes assist for moving the resin front in a straight line. Using of appropriate tube sizes helps to achieve the flow rate of the resin mixture so as to impregnate all the dry fibers with resin mixture. A high permeability flow medium generally called infusion mesh is used for the effectiveness of the process. It helps to spread the resin mixture uniformly across the surface of the preform. This assists in wetting of all layers of dry fibers. A peel ply is used in between fibers and infusion mesh. Peel ply is a polyester cloth which helps to separate the rest of consumables from the cured laminate because of its special quality of not sticking to epoxy resin while curing. As the name suggests it can be easily peeled off from the cured laminate. The surface of the laminate which is in contact with peel ply while curing of epoxy resin mixture have a textured finish similar to the weave of peel ply. It helps for the further bonding processes on this surface to be effective. After infusing the degassed resin mixture in to fibers, vacuum pressure has to be maintained during curing phase. Finally, the cured laminate has to be taken out of the mold which has to be further processed. A typical vacuum infusion setup is shown schematically in Figure 2.2.

2.2.1.1 Process parameters

Vacuum infusion process is mainly driven by five process parameters. They can be manipulated to overcome the issues that can occur in the process and also to optimize the outcomes. The relation of these process parameters to the Vacuum infusion method is explained by Darcy's law. This applies well for the flow of epoxy resin through the dry fibers. Equation 2.1 shows the mathematical form of Darcy's law.

$$Q = \frac{K\, A\, \Delta p}{\mu\, t} \tag{2.1}$$

As from the equation 2.1 the rate of flow of resin mixture through dry stack of fiber laminate in VI process is inversely proportional to its dynamic viscosity. In general, the viscosity ranges of the resin used for VI lies between 200-500 cps at 20°C.It should be noted that slight variations in temperatures can cause significant effects on the viscosity changes of the fluids. Thus temperature of the resin has the direct role on the flow rate of the resin in VI process [18].



Key

1	Mould, leak tight and pre-treated with mould release	7	Vacuum control valve(s). May be just a clamp on the vacuum tube
2	Sealing flange. Typically 75 mm (3") to 150 mm (6") wide	8	Resin (normally positioned below the part)
		9	Resin control valve. May be just a clamp on the resin feed tube
3	Laminate materials. Placed in mould in DRY state		
4	Permeable vacuum line under the bag	10	Resin entry point(s)
5	Disposable materials (typical). Peel ply above the laminate and flow medium above the peel ply	11	Optional vacuum line for pre-evacuation
		12	Resin trap with internal catchpot
6	Vacuum "bag". May be nylon (disposable) or a reusable film such as silicone rubber	13	Vacuum controls
		14	Vacuum pump

Figure 2.2: A schematic of typical vacuum infusion setup [18]

Volume flow rate of resin in VI is directly proportional to pressure differences along the path. In VI, vacuum is created at one end of the path of resin flow and the resin is driven in the path by the atmospheric pressure from the other end. Pressure losses should also be considered along the path in the form of friction in the tubes. Resin flow rate is also affected by the leakages of air in to the vacuum bag. Resin flow rate is also affected by the static pressure head i.e. the position of resin supply source with respect to the VI setup [18].

Use of infusion mesh which has higher permeability for the resin flow compared to the dry fibers alters the flow path of the resin. It spreads the resin uniformly over the surface with which it is associated and makes the resin to flow across the dry fiber laminate in the thickness direction. Thus, it is improving the impregnating of the fibers during the resin infusion [18].

2.2.2 Fabrication of stiffener

For fabricating the stiffener using VI process, a split mold is needed to hold the dry fibers in the inverted T mode. Wood is used to save the machining cost and time so as to have the flexibility to work with different sizes of the stiffeners. Mold is made to the dimensions so as to have machining allowance for the cured specimen. The fabrication of the stiffener starts with the cutting of dry Carbon fiber plies from the unidirectional roll of Carbon fibers having areal density of 200 grams per square meter and stitching them in the required stacking sequence as shown in Figure 2.3. In general fibers are to be cut by keeping the machining allowance in mind. Machining is required for the cured specimen because the hand stitching of the plies may cause misalignments along the borders.

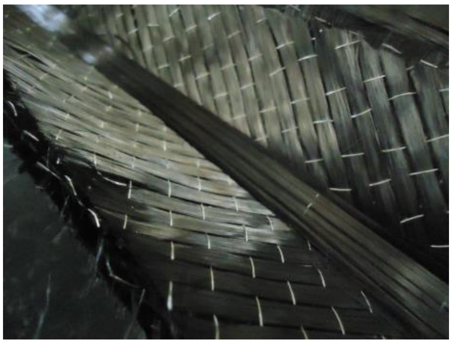
(a)

(b)

Figure 2.3: Preparing the dry fiber laminate: (a) cutting of plies using surgery blade first and then scissors, (b) stitched laminate.

After applying mansion wax polish, mold is wrapped in perforated release film to ease the removal of the cured stiffener at the end. Folds should be avoided for the film while wrapping to maintain the good finish on the cured stiffener surfaces as shown in Figure 2.4(a). Stitched dry fiber laminate is packed in between the two mold halves to take the shape of T. The Bermuda triangle region is filled with separated zero degree fibers to avoid voids as shown in Figure 2.4(b) by keeping the entire setup inverted.

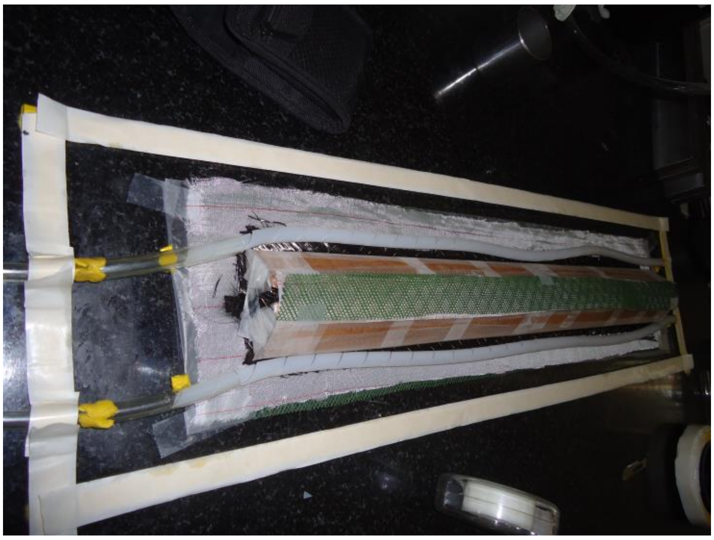
(a)



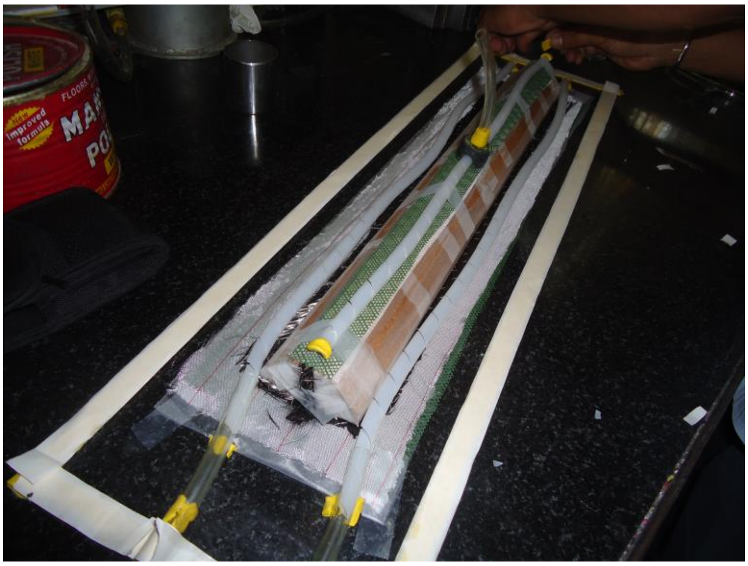
(b)

Figure 2.4: Preparing the preform: (a) mold wrapped in the release film; (b) filling Bermuda triangle region of setup with zero degree fibers.

Infusion mesh, peel ply and perforated release film are cut to required size according based on the mold dimensions. The entire setup of VI for fabricating the blade stiffener needs a flat surface with perfect finish. Granite table located in-house serves the purpose. Sealant tape is applied on the granite surface to create a portion of area for placing the entire setup and to pack them. Mansion wax polish is applied on the entire portion of area after sealant tape to avoid the interactions of tape and wax. Mansion wax polish serves as mold release agent as explained before to ease the removal of the cured laminates. Peel ply, infusion mesh and perforated release film, are to be placed on one another respectively on the inverted mold with packed fibers. Peel ply should be covering the left and right flanges and the zero degree fibers. Now the entire mold packing along with the consumables kept on it is placed on the granite surface which is pretreated with wax already. Now the perforated release film is made to be at the bottom to ease the removal of entire setup from the granite surface. Spiral tubes are cut to place along the full length on either sides of the mold on the longitudinal edges of the right and left flanges of the dry fiber laminate preform. It is desired for the resin to flow against the gravity for the uniform flow of the resin front in the web portion. Ref. [25]. To facilitate the uniform vacuum pressure peel ply and infusion mesh are placed on the mold at its top along with a spiral tube as shown in Figure 2.5.



(a)



(b)
Figure 2.5: Setup of VI procedure: (a), (b) different stages of VI setup

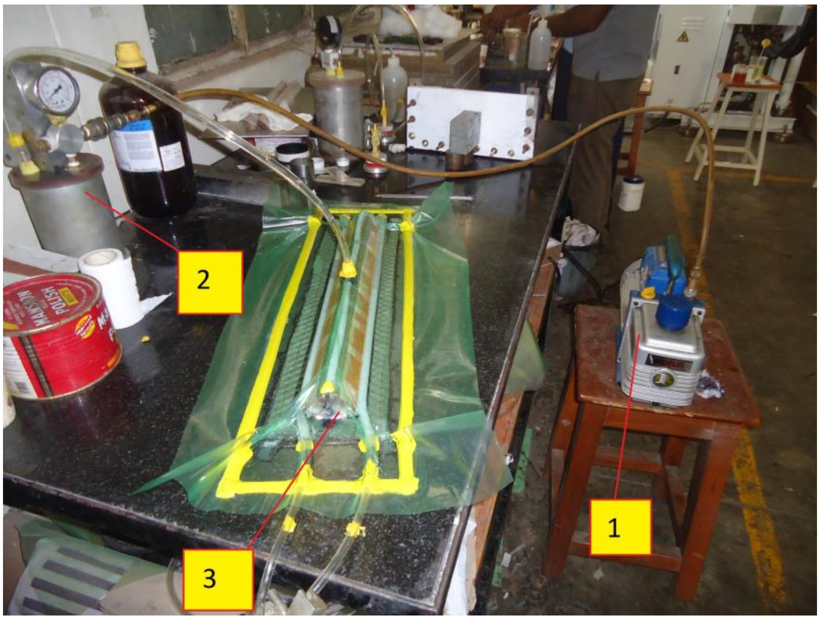
One end of the spiral tubes at bottom are connected to the plastic tubes which are the inlets of the resin mixture. Spiral tube placed at top is slightly extended manually to promote the distribution of uniform vacuum at the top of mold for effective sucking of resin throughout the length of the setup. A plastic tube is connected from top to the spiral tube placed at top as shown in Figure 2.5 (b). Free ends of all the spiral tubes are closed using the infusion tape, which is soft in texture so as to avoid the tearing of vacuum cover after applying vacuum pressure. This step is very important in the setup and is shown in Figure 2.6.

(a) (b)
Figure 2.6: Closing of spiral free ends: (a) upper spiral tube (b) lower spiral tubes

The entire setup is sealed and vacuum bagged.The bagging cover is loosely packed so as to avoid expansion of it after applying vacuum. This way of packing as shown in Figure 2.7 avoids the stresses in the cover, which effectively prevents the air leakages in to the bagging of VI setup.

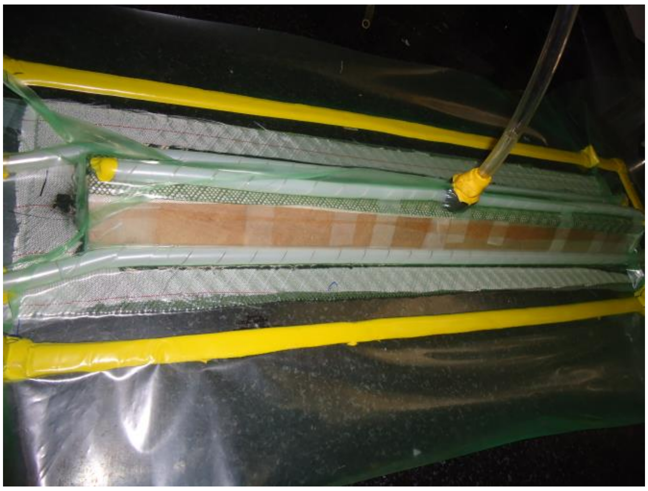
Figure 2.7: Sealing to the entire VI setup in vacuum cover

The inlet tubes connected to the lower spiral tubes are closed. The outlet tube connected to the upper spiral tube is also connected to the resin trap at the other end. Vacuum pump which is connected to resin trap helps to apply vacuum pressure from the top of the mold. This step is shown in Figure 2.8.



(1) Vacuum pump (2) Resin trap (3) Packing of VI setup

(a)



(b)

Figure 2.8: Applying vacuum pressure in VI process using vacuum pump: (a) entire setup, (b) zoomed view of the setup compacted in the vacuum cover.

Air leakages are checked and closed properly. Required quantity of resin has taken by considering the weight of dry fibers, volume of resin to be consumed by all the tubes and amount of resin absorbed by consumables like infusion mesh, peel ply. Resin used for the infusion process is Araldite ® CY230.It is degassed after heating to eliminate the voids in the cured laminate of the stiffener. Degassing is done by placing the resin beaker in the degassing vessel and evacuating it by connecting it to a vacuum pump. This allows the trapped gases in the epoxy resin to escape by expanding and floating them in the form of bubbles. Later, the degassed resin is mixed with hardener in the ratio of 10:1 by weight of the resin and the hardener respectively. The hardener used is Aradur ® HY951.

Infusing the resin is a critical step in the process. As observed in several industry manufacturing procedures by VI process, resin is taken in a very large quantity and allowed to flow till it reaches the resin trap. It literally needs very high quantities of resin and to bear large amount of wastage of resin. Instead, to avoid the wastages it is slightly modified to infuse the resin, taken only in the limited quantity as explained before. Gauge pressure is slightly reduced from full vacuum to -85 kPa and pump has to be disconnected from resin trap. This is done to slow down the resin flow slightly so as to allow it to wet all the layers effectively throughout the thickness of the dry laminate. Resin is allowed to flow in a controlled by opening the valves slightly, which close the inlet tubes. It can be observed that the resin comes out from the spiral tubes only after filling them entirely. The infusion mesh distributes the resin throughout its surface uniformly and aids to wet the dry fibers which are in direct contact with the peel ply. After sending the entire resin mixture in to the inlet tubes, the valves at the entry of the resin mixture are fixed closed tight to prevent the flow of air. Vacuum pump is then connected to resin trap which can now suck the resin from bottom to top through the plies in the web. It takes about twenty to thirty minutes for the resin to reach the top of the web. It is inevitable because allowing the resin to flow against the gravity enables the resin to flow slow and in a straight front. The lower spiral tubes also act as reserve of the resin mixture. After the resin mixture reaches the outlet tube as shown in Figure 2.9, pump has to be disconnected from the resin trap and switched off. On the safe side, the outlet tube also should be closed to avoid the escape of the resin from wet fibers to resin trap.

Figure 2.9: Resin filling the outlet tube

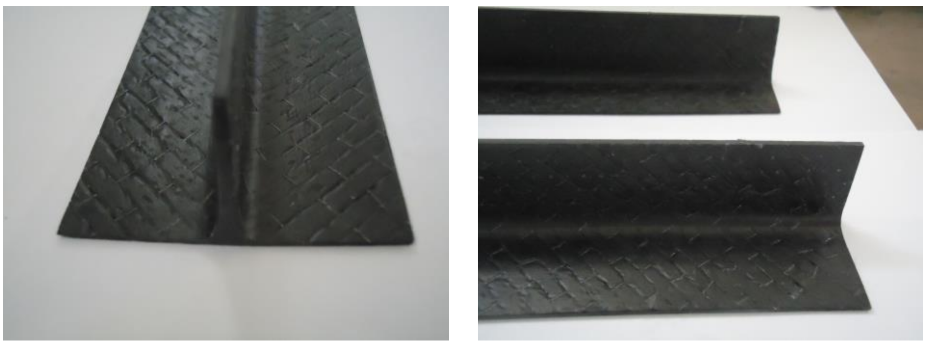
After leaving it for about twenty four hours the cured stiffener can be obtained by carefully separating it from other consumables and the mold. This step is shown in Figure 2.10.

(a)

(b)

Figure 2.10: Cured stiffener: (a) removing from mold (b) stiffener from top and bottom view

The stiffener thus fabricated is machined to the required dimensions. Final finishing of the edges is done by grinding with the emery sheet. The final stiffeners thus fabricated are shown in Figure 2.11.



(a) (b)

Figure 2.11: Finished stiffener in zoomed view: (a) front view, (b) side view.

2.2.3 Bonding of stiffener to the skin

The stiffened panel can be fabricated by bonding the stiffener to the skin either by secondary bonding or co-bonding techniques. In the secondary bonding method, the pre-cured separate composite parts are bonded together by using adhesive at their interface. The adhesive at the interface of the separated parts gets cured and bonds them in to an integrated structure. Careful surface preparation of the pre-cured composite parts is necessary for the bonding to be perfect. The aligning and clamping of the parts together is the critical step for the success of this method.

In the co-bonding method, a fully cured composite element is bonded to an uncured part while curing of the latter. It requires careful surface preparation of the pre-cured composite part before clamping. Adhesives can also be required at their interface depending upon need.

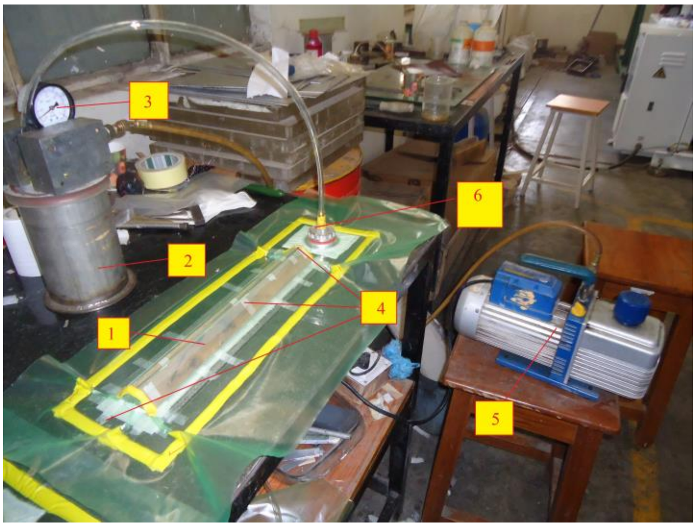
As a part of the thesis work, the CFRP stiffened panels are fabricated by using of both the above mentioned methods.

2.2.3.1 Secondary bonding

Secondary bonding is used in the fabrication of the single stiffened panel specimen. The steps involved in the method of bonding the stiffener to pre-cured CFRP flat panel are shown in Figure 2.12.

(a)

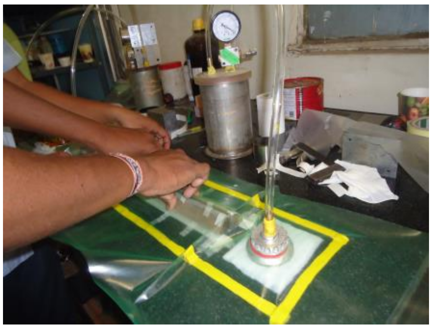
(b)



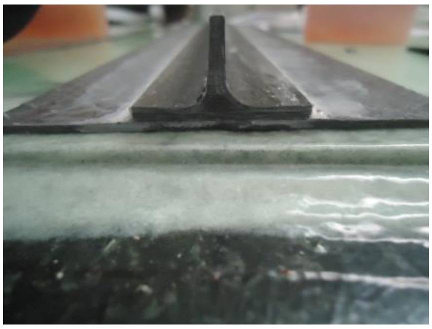
(c)

(1)Wooden mold (2)Resin trap (3)Vacuum gauge (4)clamping setup (5)Vacuum pump

(6) Valve



(d)



(e)

Figure 2.12: Steps involved in secondary bonding: (a) setting of guides to align the stiffener on the surface prepared skin; (b) applying adhesive at the interface; (c) vacuum bagging setup; (d) holding the mold while applying vacuum to apply uniform pressure throughout length; (e) stiffened panel front view after the stiffener bonded to skin.

The pre-cured skin is fabricated by vacuum bagging process and is machined to the required dimensions (see section 2.2.3.2 for detailed explanation). The required portion of its surface is prepared for the secondary bonding by grinding with the emery paper. Similar preparation is also to be done over the stiffener flange on its bottom surface. Guides are attached on the skin as shown in Figure 2.12(a) so as to place and align the stiffener in the perfect required position. Adhesive used in the process is Araldite ® 2015. It is available in the form of two-part paste and is applied uniformly over the bonding region of the skin as shown in Figure 2.12(b).

Stiffener is placed in the guides along with the wooden mold. This wooden mold helps in applying uniform compaction over the length of the stiffener. The entire setup is packed in the vacuum bagging setup as shown in Figure 2.12(c). After checking for the leaks, vacuum is maintained till the adhesive gets cured. Usually it takes twenty-four hours for it to get cured at room temperature and to obtain the perfect bonding. Figure 2.12(e) shows the front view of the bonded stiffener to the skin in the CFRP single stiffened panel obtained by this method.

2.2.3.2 Co-bonding

Co-bonding is used in the fabrication of the CFRP panel having two longitudinal stiffeners. The steps involved in the method of co-bonding the stiffener to an uncured skin towards fabricating the CFRP double stiffened panel are shown in Figure 2.13. This method is relatively complicated as compared to the secondary bonded technique. No adhesive is used at the interface and the stiffener is allowed to bond to the skin by itself by compacting it against the uncured skin during the curing process.

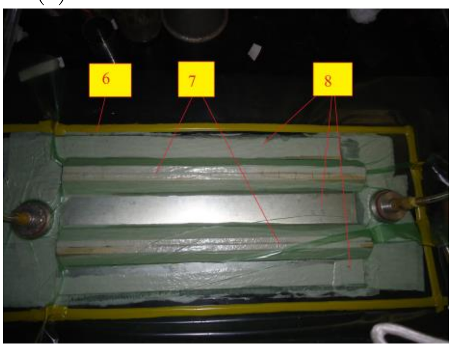
(a)

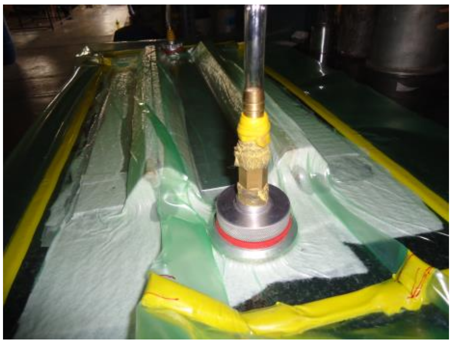
(b)

(c)

(d)

(e)





(f) (g)

(1) Vacuum gauge (2) Resin trap (3) Valves (4) Vacuum pump (5) Clamping setup

(6) Sealant tape (7) Stiffener placed using wooden mold (8) Metallic caul plates.

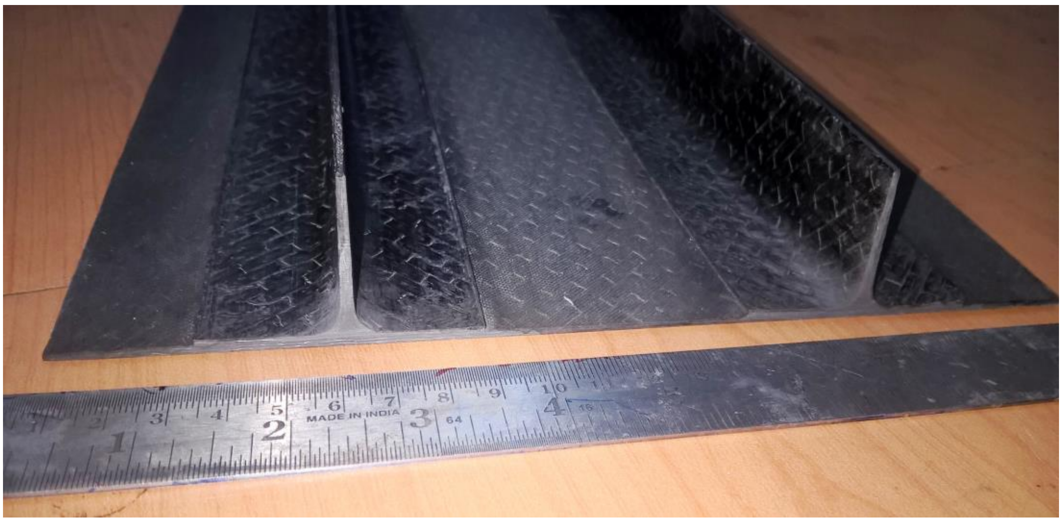
(h) (i)


(j)


(k)


(l)


(m)



(n)

(o)

Figure 2.13:Steps involved in co-bonding method: (a)surface preparation for flat mold;(b)sealant tape;(c)mold preparation;(d)tape applied to stiffener;(e)complete setup;(f),(g)zoomed view of the setup;(h)disassembling;(i)cured panel;(j)cutting to approximate dimensions;(k)aligning of panel for machining in milling machine;(l)machining;(m)making cutout;(n)side view of the final stiffened panel;(o)top view of the final stiffened panel.

The fabrication of the stiffened panel requires a cleaned flat mold. Sealant tape is applied around the region of the flat surface which is estimated according to the size of the panel to be fabricated as shown in Figure 2.13(b). Later, the flat surface is carefully applied with mansion wax polish (mold release agent) to avoid any interactions between tape and the wax. Release film is then wrapped around the wooden molds in order to avoid sticking of the molds to stiffener in case of spreading of the resin at their interface as shown in Figure 2.13(c). Temporary surface protection tape is applied to the flange so as to preserve the finish in case of any resin spread out. Dry plies are laid in the required stacking order along with manual impregnation of the resin mixture as shown in Figure 2.13(d). The entire setup is packed under vacuum bagging as shown in Figures 2.13(e). Figures 2.13(f) and 2.13(g) shows the zoomed view of the packing. Figures 2.13(h) and 2.13(i) show the disassembling and the cured stiffened panel respectively. The longitudinal edges of the stiffened panel are trimmed to the approximate dimensions by using the abrasive grinding wheel to reduce the final machining time as shown in Figure 2.13(j).The stiffened panel is thus aligned and machined by using the high speed carbide composite cutting end mill of 16 mm nominal diameter. Machining is done at the speed rate of 1400 rpm and feed of 40 mm/min with the depth of cut 0.5 mm(for every feed). This cutter is different from that of conventional metal cutters and is specially designed for composite by the manufacturers in order to avoid delamination in the laminate by compressing the material inward while machining. Figures 2.13(k) and 2.13(l) shows the sequence of machining process carried over the longitudinal edges of the stiffened panel specimen. Figure 2.13(m) describes the later process of introducing the cutout for the second specimen which requires the cutout. To introduce the cutout in the designed portion without error, the bed of the milling machine is moved soas to align it with repect to the milling head, so as to match the tip of the centre bit to align with the marked centre on the panel. Later the cutout is introduced using 16 mm carbide end mill with the same speed rate. The finally obtained CFRP stiffened panel having the required dimensions is shown in Figures 2.13(n) and 2.13(o).

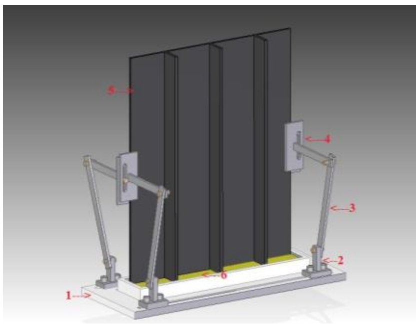
Out of the two above explained methods to bond stiffener to skin, it is observed that the secondary bonding method is advantageous because of its simplicity. It has also the advantage of accessing the surface of the skin. It helps to place guides to assist in aligning the stiffeners relatively, in order to bond it perfectly.

2.3 Development of fixture for casting resin end blocks

The success of an experimental study depends mainly on the visualization of practical challenges while testing and preparing the specimen so as to meet the loading requirements. Based on several experimental studies given in the literature, it is must to cast epoxy resin end blocks at the loading edges the CFRP stiffened panels. This procedure helps to prevent brooming of ends of the stiffened panel while loading in compression as mentioned in Ref. [6].Epoxy resin end blocks helps in uniform load distribution throughout the width of the stiffened panel. They also help in applying clamped boundary conditions at two loading edges of the stiffened panel. This casting has to be done after the stiffened panel is fabricated and machined to required dimensions as illustrated in section 2.2.

2.3.1 Conceptualization and design

The epoxy resin end blocks to be casted at the transverse edges of the stiffened panel are such that they should assist in aligning the longitudinal geometric centroid axis of the panel with the loading axis of the machine to avoid eccentricity of the load and any other possible misalignments. The main purpose of the fixture is to hold the composite stiffened panel perfectly without getting disturbed until the epoxy resin pour at the transverse edge gets cured. For the CFRP stiffened panel machined to final dimensions, being lighter in weight it is easy to hold it in the required position while casting at the first transverse edge. After finishing for the first transverse edge, the same process has to be repeated for the second (opposite) transverse edge of the stiffened panel. The fixture should be capable of withstanding the weight of the first end block while fixing the panel for casting on the second transverse edge. The fixture should also be flexible for varying the design of the stiffened panels. It should suit for single or double stiffened panels along with different aspect ratios of them. It should also allow varying laminate stacking sequences and stiffener dimensions by accommodating the panels of different thicknesses. To meet all the requirements, a fixture is specially designed after considering various designs of the composite stiffened panels from literature. It can hold the stiffened panel specimen of length varying from 200-500 mm and width 100-400 mm. The CAD model of the fixture modelled using Solid Edge- ST7 (academic version) is shown in Figure 2.14.



1. Base plate 2.Stand to hold links 3.Rotating link 4.Rotating arm 5.Stiffened panel 6.Resin pool

Figure 2.14: Assembled CAD model of fixture for casting resin end blocks with different orthotropic views

As from Figure 2.14, fixture is designed to have rotating links so as to have flexibility for usage and design of the stiffened panels. The base plate is a 500 x 120 mm rectangular plate, made using Perspex sheet so as to avoid sticking of epoxy resin to the base plate while curing. Its surface is machined flat. Two slots running throughout the length are cut on the base plate so as to allow the fixture assembly to hold the stiffened panels of different widths as explained before. A 'T' shaped stand is aimed to give support to the rest of mechanism containing a rotating link and a rotating arm to hold the panel firmly. For the rotating arm, a rectangular plate of 100 x 40 mm is welded. It supports the panel to stand straight and perpendicular to the base plate by holding the panel against to the similar rotating arm on its opposite which also supported by the same type of rotating mechanism. Four sets of stand, link and arm comprise the assembly along with the base plate so as to hold the panel. The 'T' stand can be moved in the slot of the base plate and then clamped using two pairs of nut and bolt. After placing the panel at approximate center of the base plate aligning the stiffened panel in the required manner i.e. perpendicular to the base, all the links should be tighten using spanner to arrest their rotation. This helps to keep the panel in the desired position, undisturbed.

2.3.2 Application and challenges

The fixture described in the previous section accomplishes the desired task. The fixing of the stiffened panel specimen in the fixture needs to be done attentively and it requires minimum two persons to align it perpendicular to the base and to tight all the bolts using spanner. Parallel blocks serves good to hold the stiffened panel perfectly perpendicular to the base plate. After confirming the position the panel to fix on the base plate, all the four 'T' stands have to be clamped to the base plate by tightening their nuts against the slot of the base plate. After confirming the alignment of the stiffened panel, all the rotatable links have to be brought to the desired angles to hold the stiffened panel firmly using the rectangular plates of the pair of oppositely placed rotating arms as described before. All the rotations of these links have to be finally arrested by tightening the nuts using spanner carefully.

A flat CFRP panel is fabricated prior to the CFRP stiffened panel and is attempted to cast the epoxy resin end blocks at its transverse edges to find out any short comings and all the practical challenges. It is planned to create a rectangular pool of the desired size, based on panel dimensions and machining requirements using Perspex sheets bonded using chloroform. Clay is also applied at the interface of the base plate and Perspex sheets to avoid the leakages. Mansion wax, which acts as an effective mold releasing agent is to be applied to avoid sticking epoxy resin after getting cured. The base plate has to be placed horizontally to avoid taper at the upper edge of the resin end block, which can affect the loading of the panel. This position of the base plate needs to be confirmed using by using spirit level. Later the epoxy resin mixed with hardener is filled in the pool up to the height of 35 mm. The entire setup is kept undisturbed till all the epoxy resin gets cured. Lot of fumes are observed during curing of the resin which is an exothermic reaction. It is observed that the temperature reached up to 120° C. The elevated temperatures and the contractions of the epoxy resin while curing twisted the panel and created imperfections in the panel which are not desired for a proper experimentation.

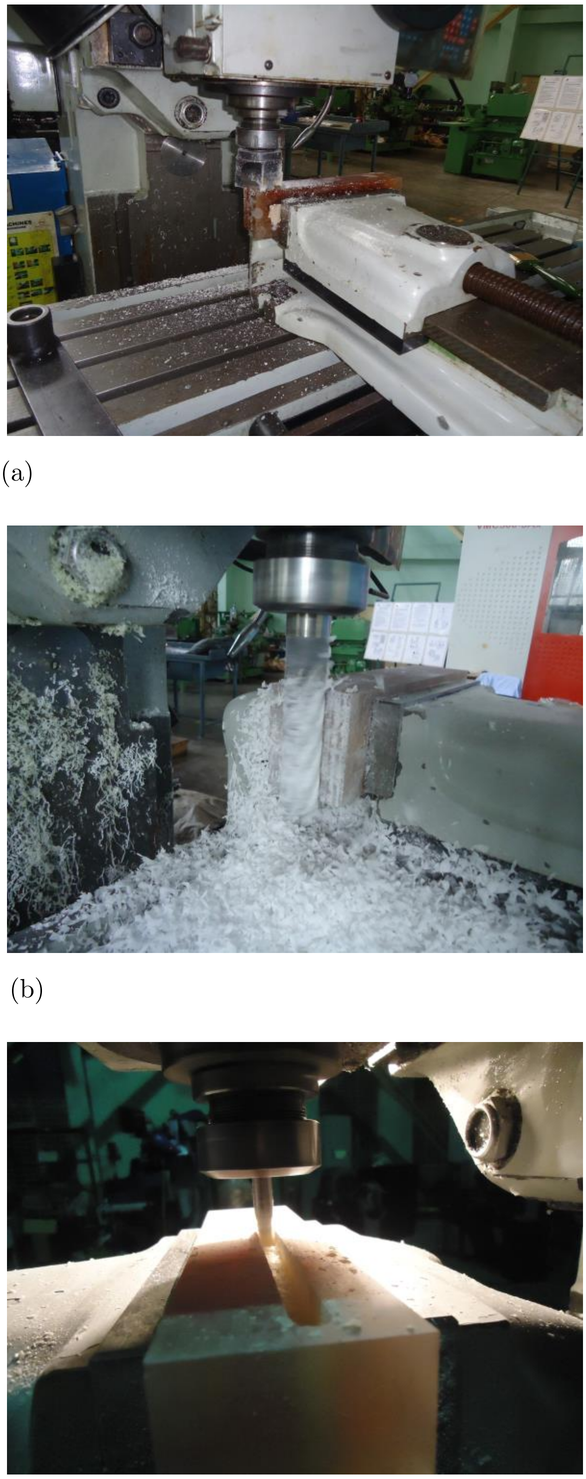
After observing all these practical challenges it is believed that too much increasing in temperatures and large amount of contractions are happening because of the very large amount of resin taken in the pool entirely and is set to cure in a single cycle. It is believed that the imperfections on the stiffened panel can be avoided if only a very small amount of resin is allowed to cure while casting at the panel's transverse edge.

A new approach is taken to cast the epoxy resin block in a metal mold to the dimensions as required according to the stiffened panel design. These dimensions are to be taken by also considering the machining allowance and contractions of the entire epoxy resin blocks while curing.

(a) (b)

Figure 2.15: Casting of epoxy resin block using metal mold: (a) resin in mold while curing, (b) Cured resin block

Initial step of casting epoxy resin block is shown in Figure 2.15. For the stiffened panel of skin width 226 mm and stiffener height 30 mm approximately, a rectangular mold of 270 x 150 mm is made. Mansion wax polish is applied to all the inner walls of the mold as mold releasing agent. Required amount of epoxy resin LY556 mixed in the ratio of 10:1 by weight with hardener *Huntsman®* HY951 is filled in the mold up to height of 40 mm. The solidified resin block is about 260 x 140 x 38 mm because of contractions of resin while curing. It is cut in to two halves using vertical sawing machine resulting in two solid blocks of 260 x 70 x 38 mm each. This is followed by machining of the resin blocks and cutting slot in it using universal milling machine. Figure 2.16 shows the machining of the solid epoxy blocks in the universal milling machine. After machining, the block is made into perfect cuboidal shape. The end block should also assist in aligning the geometric centroid of the cross section of the stiffened panel with the centroids of the cross section of loading platens. This helps in aligning the longitudinal geometric centroid axis of the panel with the loading axis of the machine to avoid eccentricity as mentioned before. Slotting is done using 10 mm HSS slot cutter in the solid block similar to the stiffened panel cross section. It should allow the stiffened panel to sit in it and allow the adjustments to align the geometric centroid of both the cross sections of the stiffened panel and epoxy resin block. There should be some clearance to fill the remaining slot, after placing the stiffened panel in it with same type of resin mixture as that of entire block.



(a)

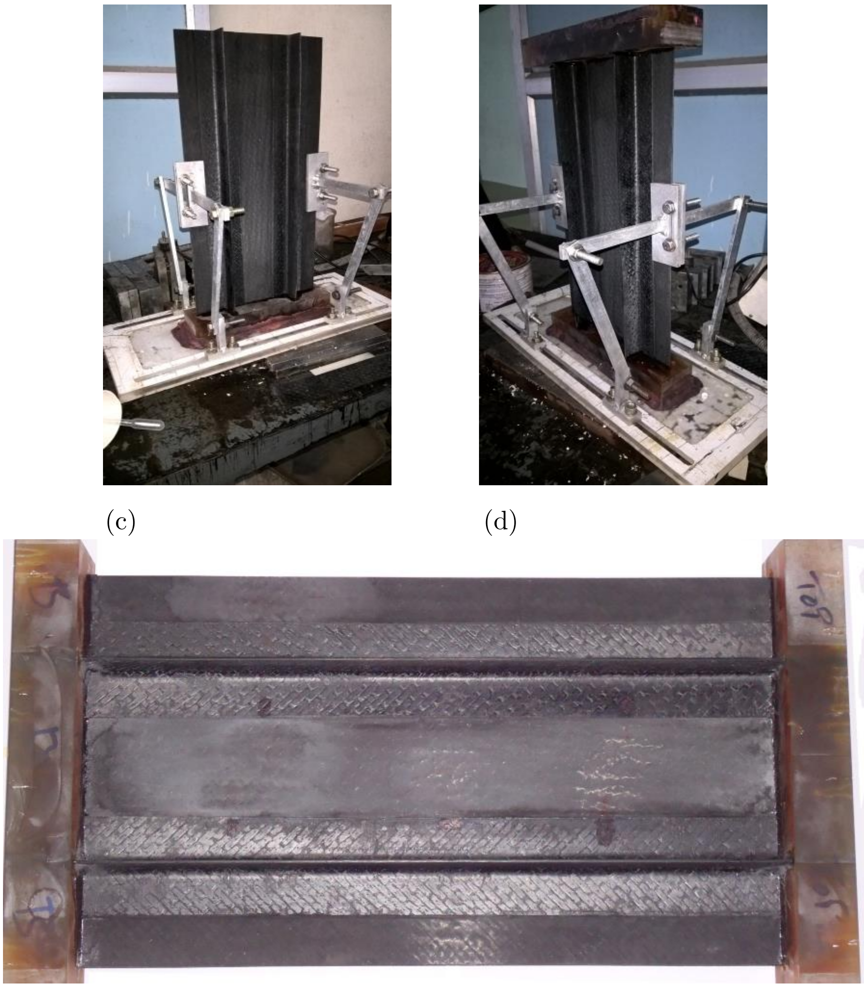
(b)

(c)

Figure 2.16: Machining of solid resin block in universal milling machine: (a) face milling, (b) end milling, (c) slot cutting.

The base plate is applied with the mansion wax polish after checking its level using spirit level. The slotted resin end block is placed on the base plate along with the stiffened panel. The stiffened panel should sit in the slot of the resin block. The stiffened panel is aligned perpendicularly according to the upper surface of the resin block using parallel blocks. Now the entire clamping procedure of the panel using the rotating links is finished as explained earlier. After confirming that the panel is exactly perpendicular to the upper surface of the resin end block, the resin end block is such that the geometric centroid of the stiffened panel's cross section should exactly coincide with the centroid of the cross section of resin end block. Later synthetic clay is applied at all the bottom edges of the resin end block to prevent its displacement and also to avoid leaking of resin which can flow from the bottom. Now the slot is filled with the resin and hardener mixture completely using a plastic dropper. The entire setup is left without disturbing till the resin in the slot get hardened. The entire procedure is repeated for the other transverse edge. The sequence of steps to cast the resin end block to a double stiffened panel is shown in Figure 2.17.

(a) (b)



(c) (d)

(e)

Figure 2.17: Steps to cast the resin end blocks to the stiffened panel: (a) checking the level of base plate by using the spirit level, (b) filling the slot with resin using dropper, (c) fixture assembly while casting at first transverse edge of the stiffened panel, (d) fixture assembly while casting at second transverse edge of the stiffened panel, (e) stiffened panel with resin end blocks on both ends.

2.4 Buckling test fixture for the stiffened panel

A fixture is specially designed and fabricated in-house to carry out the experimental studies on the stiffened panels which are fabricated according to the procedures given in the previous sections 2.2 and 2.3.

2.4.1 Conceptualization and design

The fixture to be designed should be able to grip the specimen firmly so as to transfer the load from the machine frame affectively. MTS machine load frame is contained with an internal threaded slot, so as to have the flexibility to assemble different types of fixtures as required according to the experiment. The fixture can be assembled to the load frame with the help of a stud having the similar threading configuration to that slot. The most important requirement of the fixture is to align the geometric centroid of the cross section of the specimen to the loading axis of the machine. It also should be capable of withstanding higher loads without any deformation, as it can affect the load distribution within the specimen. Taking all these considerations in to account and with reference to the previous experimental studies Ref. [10] and [17], a fixture is specially designed. The CAD model of the fixture made using Solid Edge ST7 (academic version) is shown in Figure 2.18.

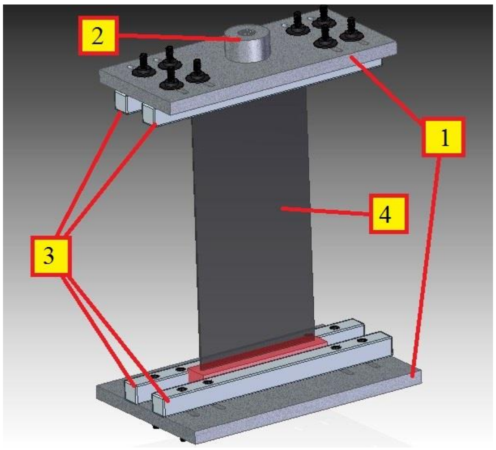


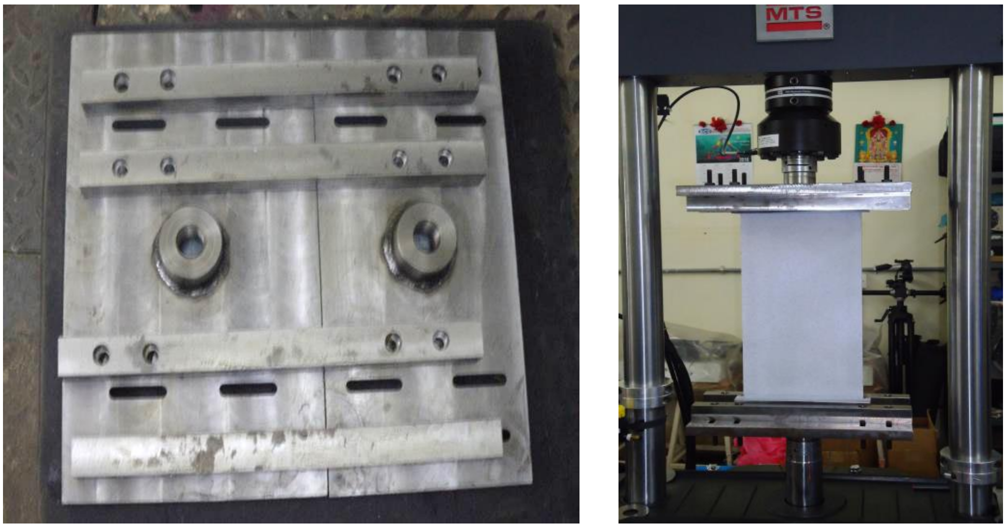
Figure 2.18: CAD model of the buckling test fixture

(1) Loading platens. (2) Internal threaded hollow cylinder. (3) Grips. (4) Specimen.

The fixture is designed to have loading platens at top and bottom which can be assembled to the machine load frame with the help of internal threaded hollow cylinders fastened to the loading platens at their centre. By having the similar threading as that of given for the loading frame, it can be fixed easily to the frame by using an external threaded stud. The fixture is required to hold the stiffened panel specimen with several different stiffener configurations. The slots cut along the transverse direction in the platens, can allow the grips to adjust their position according to the specimen to be clamped in the fixture. These grips can also assist to place the specimen so as to align the geometric centroid of its cross section to that of the loading platen. This in turn aligns the geometric centroid of specimen's cross section with the loading axis of the machine frame. The thickness of each platen is designed to be of 20 mm after taking the load considerations and the length of each platen is 400 mm.

2.4.2 Manufacturing and application

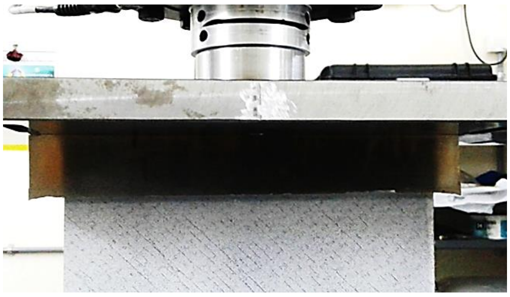
The fixture is fabricated in-house using CNC five axis milling machine for making slots and surface milling for the loading platens. The loading platens are then surface grinded and are clamped to the hollow cylinders with internal threads by using Allen bolts tighten using a torque wrench.



(a) (b)

Figure 2.19: Fabricated fixture: (a) individual elements; (b) assembled fixture

Figure 2.19 shows the in-house fabricated loading fixture being mounted to the test equipment along with the clamped CFRP stiffened panel. The resin end blocks of the specimen have to be machined carefully such that parallelism is ensured soas to avoid the mis alignments. This helps in transmiting the load uniformly over the panel loading edges. The specimen to be clamped in the grips of the fixture should be positioned according to the reference markings given on the fixture as shown in Figure 2.20. The loading platens of the fixture should be protected from the surface corrosion by applying the anti-corrosive spray on its surfaces.



(a)

(b)

Figure 2.20: Specimen alignment: (a) top platen; (b) bottom platen

2.5 Micrograph of stiffener crosssection

To access the quality of the fabricated CFRP stiffened panels, cross section of the sample element is examined using digital electron microscope. The micrographs captured at different regions of cross section is shown in Figure 2.21. The obsevations from this study shows the presence of very slight amount of voids at this cross section. This suggests for the need of Non-destructive testing (NDT) methods to evaluate the quality of the entire specimen.

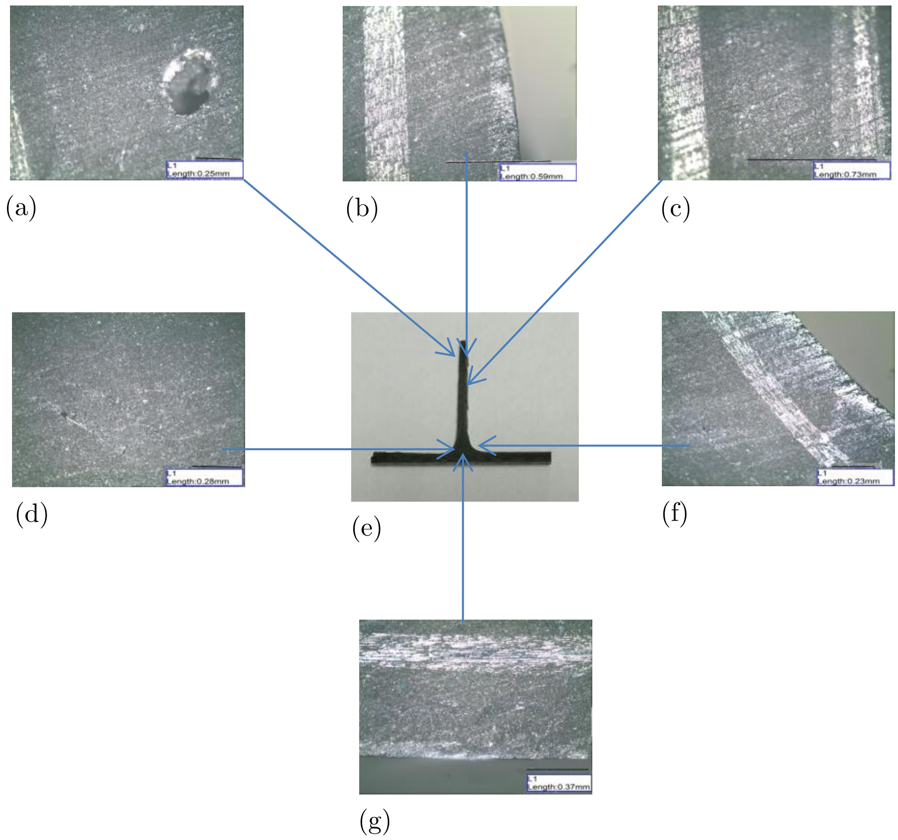


Figure 2.21: Micrographs at different regions of stiffened panel cross sction; (a) void zone; (b) web tip; (c) mid of web; (d) Bermuda triangle zone; (e) full section of element; (f) curvature; (g) skin-flange interface.

2.6 Closure

This chapter mainly focused on the fabrication of CFRP stiffened panel. Firstly, the stiffeners are fabricated separately and are co-bonded to the skin using vacuum bagging. The process parameters for the resin infusion are established. Further fixture for end block casting is also designed and established. Later loading fixture designed for applying the uni-axial compressive load is conceptualized and fabricated successfully. Final machining has to be done for the resin end blocks so as to ensure parallelism at their ends and also to align the geometric centroid of the stiffened panel cross section to coincide with the loading axis of the machine after clamping in the loading fixture. It is recommended to opt for the secondary bonding method in case of stiffened panel fabrication by, bonding the existing stiffener to the existing skin using an adhesive.

Chapter 3

Finite element analysis

3.1 Introduction

Finite element analysis is an efficient and faster way to validate the results obtained from any experimental study. Preliminary analysis is also necessary before any experimental study so as to fabricate the test specimens in some cases to assess their critical buckling and failure loads which needs to be well within the machine's maximum loading capacity. For the present problem which is the buckling analysis of a CFRP stiffened panel, it is required to analyze the specimen model by varying laminate stacking sequence and dimensions either separately or simultaneously. ANSYS APDL provides the flexibility to allow the user to analyze his model by varying different parameters related to the study.

3.2 FE modelling of CFRP stiffened panel

This section is mainly focused to explain the modelling aspect of the CFRP stiffened panel in ANSYS software.

3.2.1 Modelling of stiffened panel in ANSYS Structural

The blade stiffener looks like an inverted 'T'. Its vertical portion is called web and contained with flanges on either side of it at its bottom. In general, the stiffener is bonded to the skin at the flange bottom surface. Therefore, the portion of the stiffened panel where the flange attached to the skin can be modelled as a single plane for the simplicity. That in-turn leads to combine the layups of skin and flange in the single element. Corresponding planes of skin and stiffeners web are also modelled and are glued accordingly to form the continuity of the structure so as to replicate the actual geometry of the stiffened panel. The mostly used design method in literature is to maintain the distance between the longitudinal edge and nearby stiffener edge as half the distance between the adjacent stiffener edges. Basic dimensions of the two blade stiffened panel are taken from Ref. [20]. Figure 3.1 shows the finite element model of the stiffened panel.

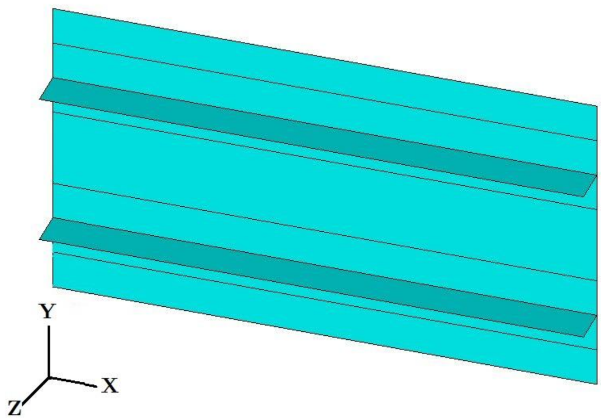


Figure 3.1: Stiffened panel modelled in ANSYS structural

The skin is chosen to have quasi-isotropic layup $[-45°/45°/90°/0°]_s$ .The stiffener web is having the layup $[-45°/45°/90°/0°/45°]_s$. The appropriate stacking sequences for shell elements are assigned separately to those areas corresponding only to skin, to skin with bonded flange and to web using mesh attributes. Shell-281, an 8 noded planar element is chosen because of its capability to save computational time when compared to the solid elements. It has six degrees of freedom at every node and is very efficient to analyze from thin to moderate thick shell structures [19]. Shell-281 being a two dimensional layered element, a reference plane should replace the three dimensional components of the model. The thickness can be modelled in finite element analysis program as the property of the shell element. The reference plane for the elements at the web portion is chosen at its mid plane and for the skin section top plane is chosen. Element size is chosen to be 4 x 4 mm after mesh convergence studies.

For the stiffened panel with cutout, a structured mesh is created around the hole with in a square region of 50 x 50 mm with 40 elements around the circumference of the hole. Figure 3.2 shows the finite element model of the stiffened panels with and without cutout.

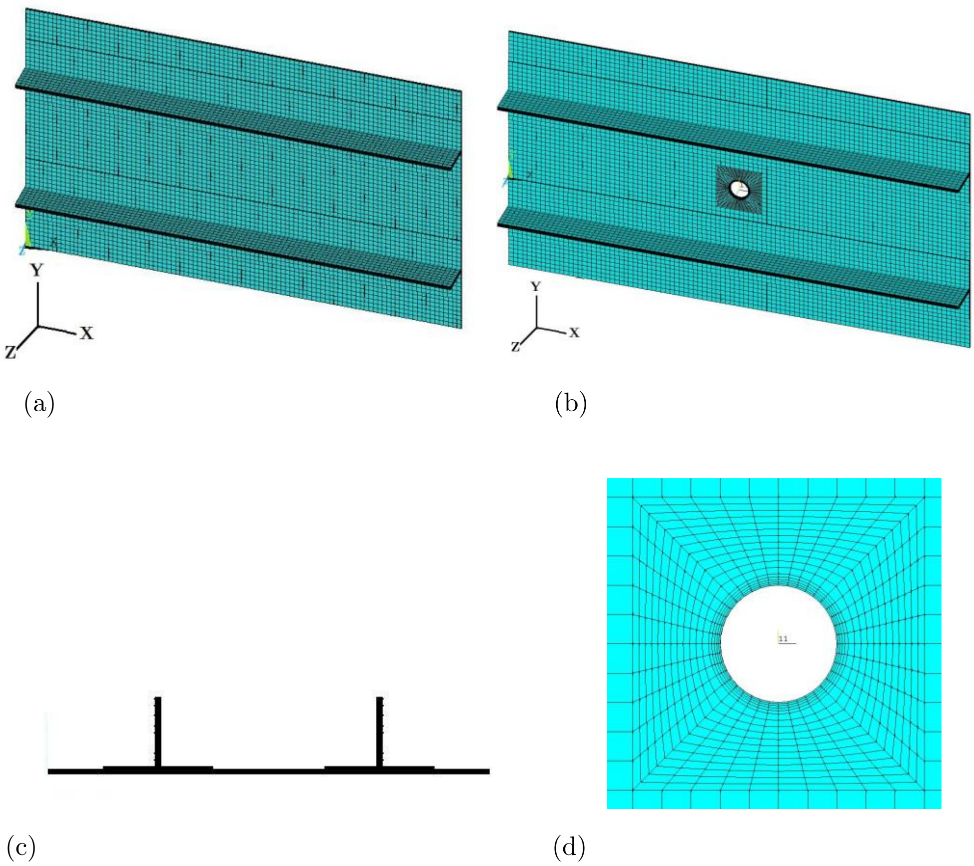


Figure 3.2: Finite element model: (a) without cutout; (b) with cutout; (c) sectional view; (d) zoomed view of the cutout region

3.2.2 Material properties

Material properties of CFRP composite laminates are obtained from Ref. [22] and are given as the input for the ANSYS Structural to ensure the appropriate correlation with the results to be obtained from the experimental studies. For fabricating the specimens in the current thesis work, unidirectional Carbon fiber mat having a density of 200 grams per square meter is used as the reinforcement and CY-230 epoxy resin mixed with HY-951 hardener in a weight-ratio of 10:1 is used as the matrix. The elastic properties are listed in Table 3.1.

Table 3.1: CFRP material properties Ref. [22]

Material properties		Value
Longitudinal Modulus	$\boldsymbol{E_{11}}$	98.41 GPa
Transverse modulus	$\boldsymbol{E_{22}}$	6.3 GPa
In-plane shear modulus	$\boldsymbol{G_{12}}$	1.53 GPa
Out-plane shear modulus	$\boldsymbol{G_{23}}$	1.91 GPa
In-plane Poisson's ratio	$\boldsymbol{\vartheta_{12}}$	0.23
Out-plane Poisson's ratio	$\boldsymbol{\vartheta_{23}}$	0.30

3.2.3 Loading conditions

The transverse edges are casted with resin end blocks and are loaded in actual experiment. To replicate the same boundary condition, all nodes representing the fixed edge in the experiment are subjected to clamped boundary conditions by constraining all degrees of freedom. All nodes at the loading edge are coupled to a master node in the axial direction (u) and compressive load is applied there are. The degrees of freedom $v, w, \theta_x, \theta_y, \theta_z$ of are constrained along the loading edge. The applied boundary conditions for the panel without cutout are shown in Figure 3.3.

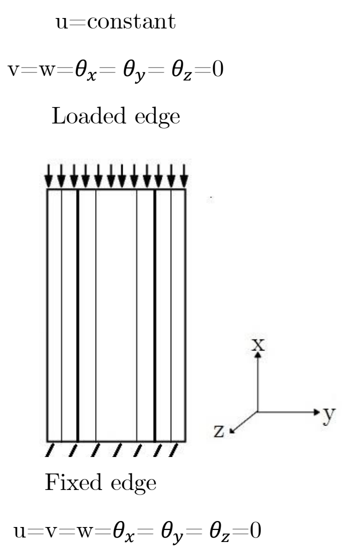


Figure 3.3: Boundary conditions of two blade stiffened panel

3.3 Eigen buckling analysis

Linear buckling is the most basic form of buckling analysis in FEA. To predict the theoretical buckling strength of any ideal elastic structure in FEA, Eigen buckling analysis is done. In this analysis, external loads are applied. Pre-buckling stress analysis is performed to extract the stress state of the structure as a resultant of the applied load. After the pre-buckling analysis, the critical load factor is estimated with the help of this stress state. The external applied load is multiplied with the critical load factor to obtain the critical buckling loads. The buckling mode shapes, scaled to an arbitrary factor can also be obtained from the solution of Eigen buckling analysis. (see Ref. [23])

3.3.1 Buckling loads

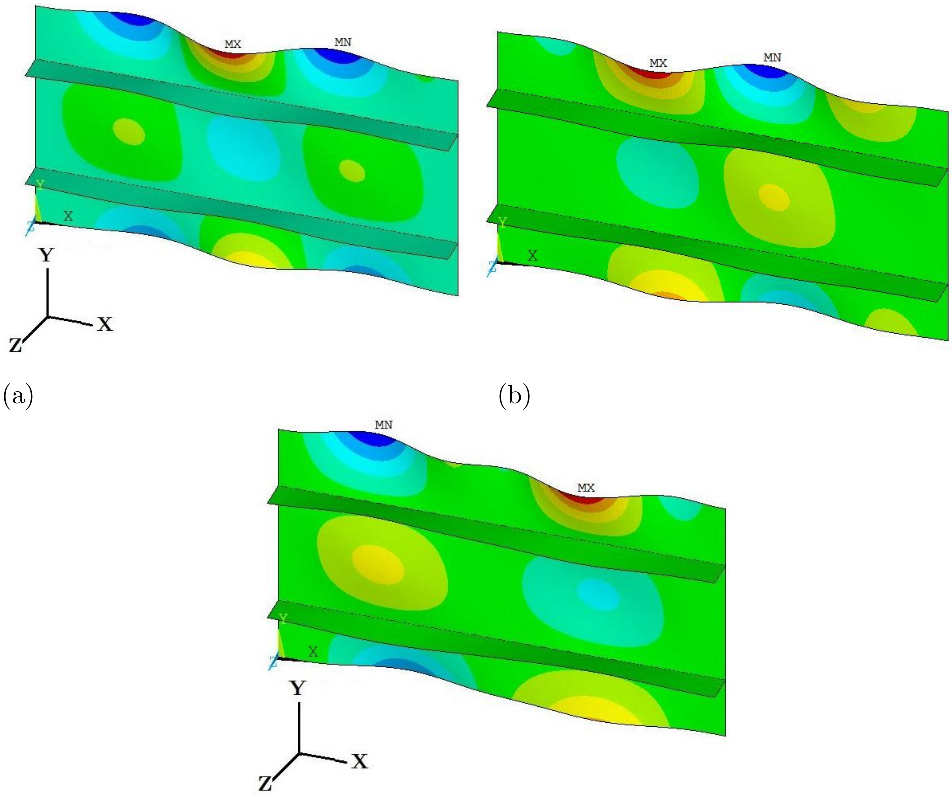
For the current buckling analysis as a part of this thesis work, an external load of 1 kN is applied and pre-buckling analysis is done. It is followed by Block Lanczos mode extraction method to compute the critical load factors. The first three buckling loads obtained are listed in Table 3.2 and are observed to be close.

Table 3.2: CFRP material properties

Buckling load	Value (kN)
First	34.38
Second	34.57
Third	36.53

3.3.2 Buckling mode shapes

Mode shapes obtained from linear Eigen buckling analysis are plotted for first three buckling loads in Figure 3.4. It can be observed that the number of half sine waves on the longitudinal edge of the stiffened panel have increased progressively from three to five for the first three critical buckling loads. There is also a shift from the three to two half sine waves at the mid bay of the stiffened panel for the first three critical buckling loads.



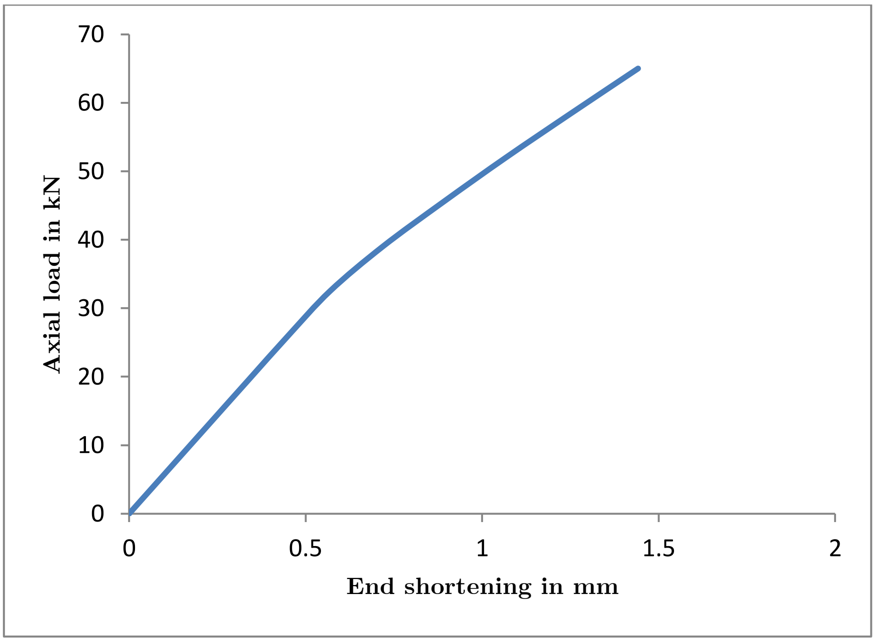
(a) (b) (c)

Figure 3.4: Different mode shapes obtained from Eigen buckling analysis: (a) first at 34.38 kN; (b) second at 34.57 kN; (c) third at 36.53 kN.

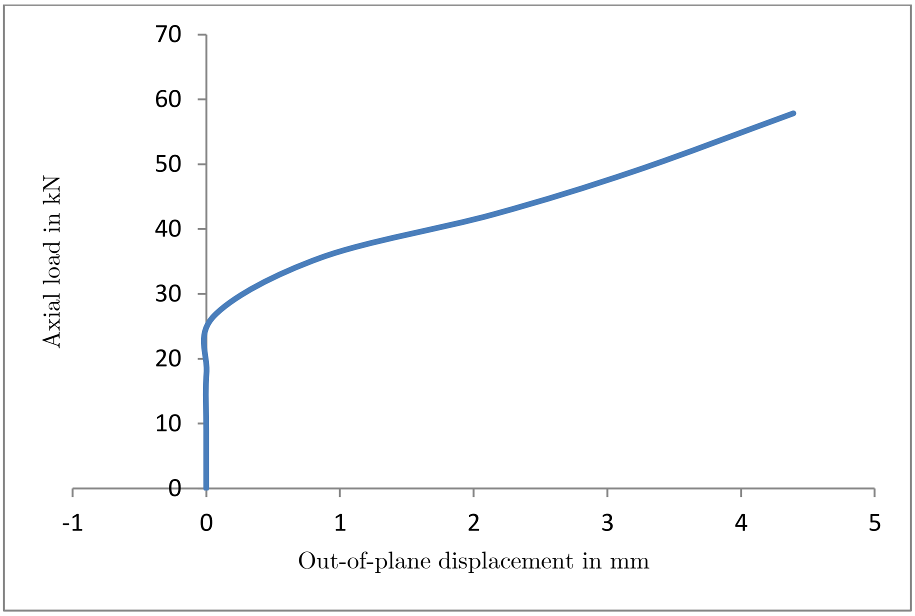
3.4 Post-buckling analysis

The theoretical critical buckling loads obtained from the Eigen buckling analysis can be notably higher for some structures for what they encounter in real. This is mainly because of imperfection sensitivity and it is very critical in case of thin shell structures when considered. Linear buckling analysis assists only to find critical buckling loads. It is not capable of predicting the behavior of the structure after reaching the critical loads. Nonlinear post-buckling analysis can be done by incrementally loading the structure in order to extract the load vs end-deflection behavior of the structure so as to study the reduction of stiffness of the structure after buckling. It also traces out-of-plane deflection, in-plane displacement and stress distributions of the entire panel at each load step with respect to the increasing load. It is expected in the real structure, say CFRP stiffened panel tested for this thesis study to have initial imperfections because of tolerances in manufacturing, mishandling, operating conditions etc. An initial imperfection in geometry or a small lateral load is necessary to initiate the instability of the structure which leads to buckling. The general strategy is to use the first mode shape obtained from the Eigen buckling analysis as the imperfection. It is scaled so as to replicate the expected imperfections in the real structure, after the tolerances in manufacturing and operating conditions are considered. In the current thesis work, the first mode shape from Eigen buckling analysis has been used as the initial imperfection with a scaling factor of 10% of the thickness of the skin of the stiffened panel structure. In the current study, Newton-Raphson method with automatic load stepping option was chosen to perform the post-bucking analysis.

Figure 3.5 shows the plots of load vs end shortening and load-maximum out of plane displacement for the CFRP double stiffened panel obtained based on FE analysis



(a)



(b)

Figure 3.5: Pre buckling and post buckling behaviour from non-linear buckling analysis :
(a) Load vs end shortening plot; (b) load vs maximum out-of-plane deflection plot.

The first critical buckling load for the double stiffened panel obtained from Eigen buckling analysis is 34.38 kN. Looking at the load vs end shortening plot obtained from non-linear analysis to capture the post buckling behavior for it, a significant reduction of axial stiffness can be observed. From the load vs out-of plane-deflection plot, it can be concluded that the panel is under pure compression until to 25 kN and no significant out-of-plane deflection is observed. Later one can see significant rise in out of plane displacement value suggesting occurrence of post-buckling phenomenon.

It is recommended to compute the first three buckling mode shapes from Eigen buckling analysis and to use their combination to model the initial imperfection for the non-linear analysis. Ref. [17]. Above recommendation is mainly valid where closer critical load factors exist between various buckling modes because the imperfection sensitivity may be varied a lot in-between various buckling modes . (see Ref. [23]).

3.5 Closure

The CFRP double stiffened panel has been modelled and analyzed using FEA. The numerical buckling loads have been determined followed by analyzing the post buckling behavior of the panel. The buckling mode shapes for the panel are extracted using the Eigen buckling analysis and mode shapes have been presented. Load vs end shortening load vs out of plane displacement plots are obtained using non-linear buckling. An initial imperfection corresponding to the first Eigen buckling mode scaled by 5% of skin thickness is assumed and given as input for the nonlinear buckling analysis. A reduction in the axial stiffnes has been observed for the stiffened panel in its post buckling regime by 38.4 %.

Chapter 4

Experimental studies

4.1 Introduction

The primary aim of the current thesis work is to conduct the experimental studies to have a proper understanding of the pre buckling and post buckling behaviour of the CFRP stiffened panels. It is also meant that the results obtained from experiments helps us to reassert the quality of the fabricating procedures. Experimental studies are conducted on two CFRP double stiffened panels with and without cutout in their mid-bay. Whole field non-contact optical technique called digital image correlation (DIC) is used for all experimental studies to estimate the whole field strain, axial as well as out-of-plane displacement of the panels subjected to uniaxial compressive loading. Experimental results are compared with the results obtained from FEA for validation.

4.2 Double stiffened panel testing

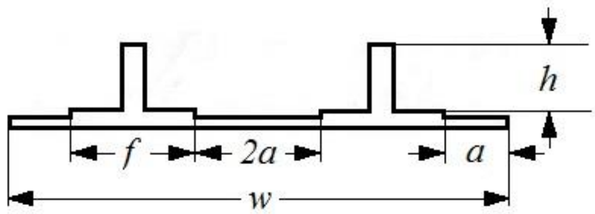
Comparative study of CFRP double stiffened panel with and without cutout is conducted to investigate the impact of it on their buckling and failure behavior under uniaxial compressive loading. As part of all the experimental work the reinforcement for all the CFRP specimens is cut from unidirectional Carbon fiber mat having a density of 200 grams per square meter. Matrix is composed of Araldite ® CY-230 Epoxy resin mixed with Aradur HY-951 hardener in a weight-ratio of 10:1.

4.2.1 Panel design

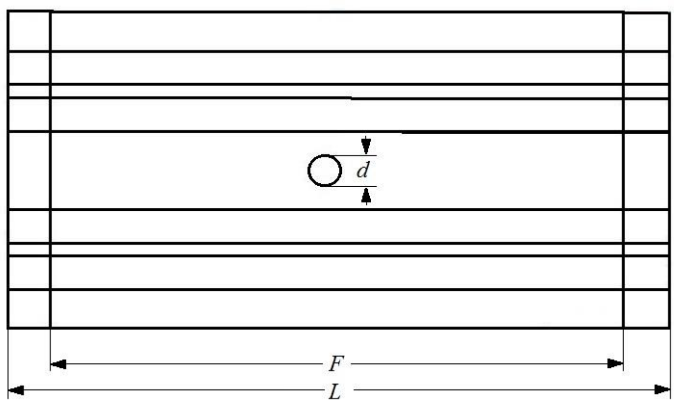
Basic dimensions of the two blade stiffened panel are taken from Ref. [20]. There are certain guide lines to be followed while choosing the laminate stacking sequence. Ref. [6].

1. In order to prevent the direct loading of matrix in other directions, there should be 10% of 90° plies to be maintained in both the stiffener and skin laminates.
2. In order to maintain the homogeneity in the laminate stacking sequence and to prevent edge splitting, stacking of more than three plies of same configuration together should be avoided.
3. There should be ±45° orientation for the outer plies in both stiffener as well as skin to consider damage tolerance aspects under compressive loading.

The layup of the skin is chosen to have balanced and symmetric with quasi isotropic stacking sequence $[45°/-45°/90°/0°]_s$ .The layup of the stiffener is having the laminate stacking sequence $[45°/-45°/90°/0°/45°]_s$. These layups are chosen to reduce the coupling effects of shear and bending with the extension. The size of the cutout for the second specimen is designed to be of diameter 16 mm. ($w/d = 14$). Stiffened panel geometry is shown in Figure 4.1 and the dimensions are given in Table 4.1.



(a)



(b)

Figure 4.1: Stiffened panel geometry: (a) cross section of panel geometry; (b) geometry of panel with cutout.

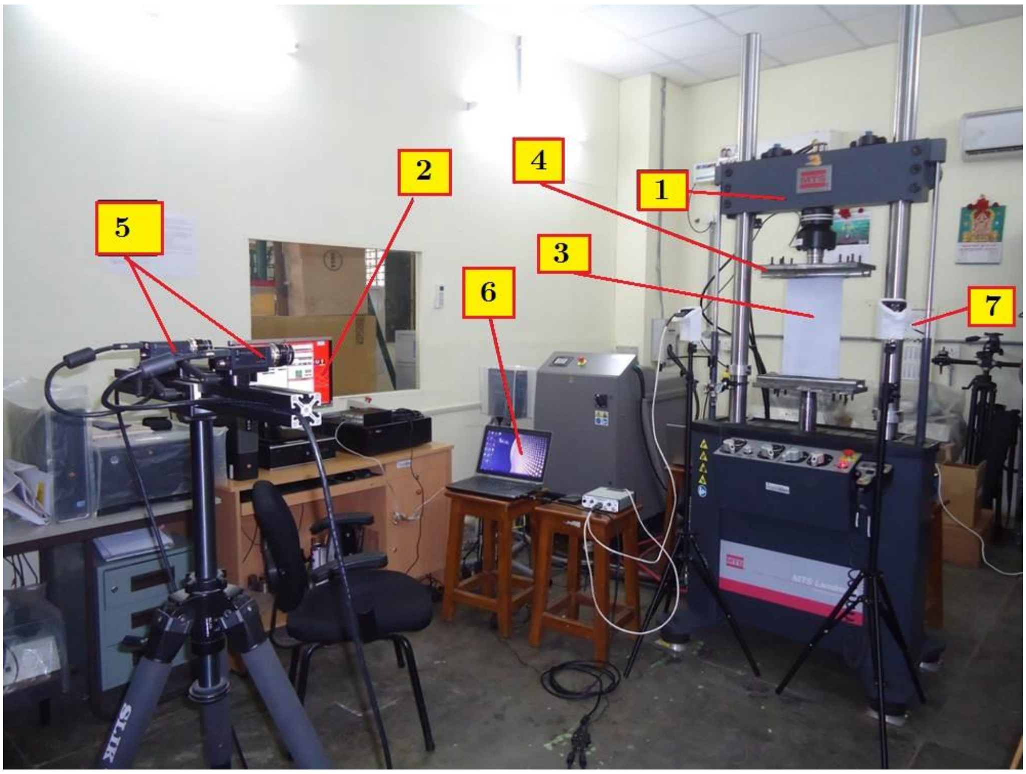
Table 4.1: Stiffened panel dimensions

Dimensions	Values (mm)
a	28
d	16
F	400
f	56
h	28
L	470
w	224

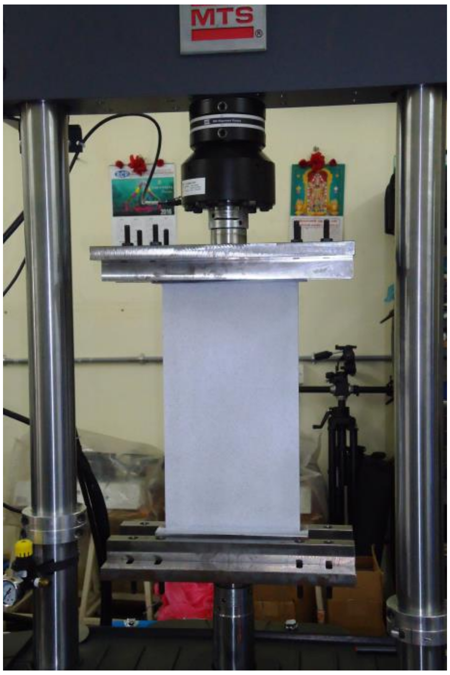
The geometry and layup sequence are similar to those panels mentioned in the previous chapter.The double stiffened panels with and without cutout are fabricated starting with the stiffeners fabricated using VI process as explained in the section 2.2.2 and co-bonded to the skin as discussed in the subsection 2.2.3.2. The final dimensions of the stiffened panels have slightly deviated from the intended dimensions as one has to do the manual grinding using the emery sheet along the transverse edges of the stiffened panels resulting to the dimension of the free length of 396 mm instead of 400 mm.

4.2.2 Experimental setup

MTS servo-hydraulic cyclic testing machine of 100 kN capacity is used to load the specimen. Panel is carefully clamped in the grip such as to align the centroid of the specimen cross section to coincide with the loading axis of the machine's actuator. Specimen is loaded under displacement control mode at the rate of 0.25 mm/min. Skin is painted with a random black and white speckle pattern over the rear side of the panels for DIC measurement. 3D-DIC setup is used which comprises of Vic-Snap software which captures the images of the loaded panel at the rate of 5 Hz using two grass hopper CCD cameras (Point Crey-Grass-5055M-C) having a spatial resolution of 2448 x 2048 pixels. Experimental setup for buckling test of CFRP stiffened panels is shown in Figure 4.2. Strain gauges are pasted on the front side of the stiffened panel specimen as shown in Figure 4.3.

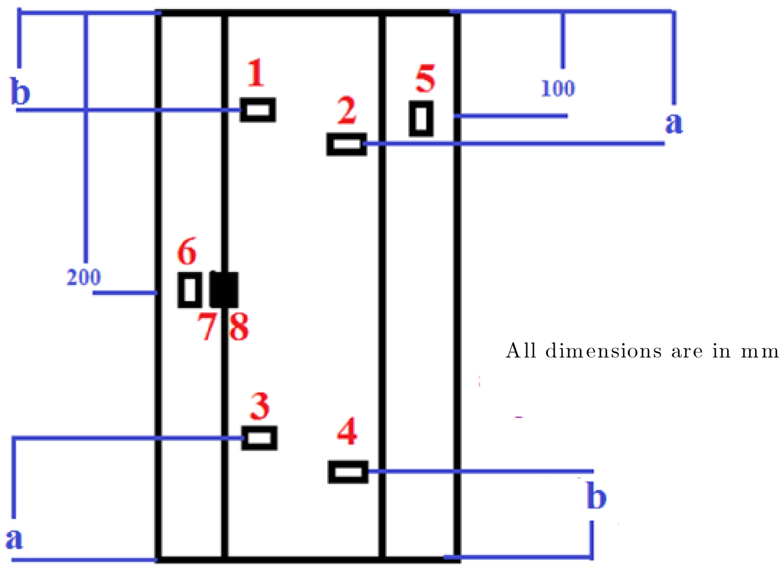


(a)
(1) 100 kN MTS frame (2) User interface (3) Specimen (4) Fixture (5) CCD cameras
(6) Image grabbing PC (7) Light source



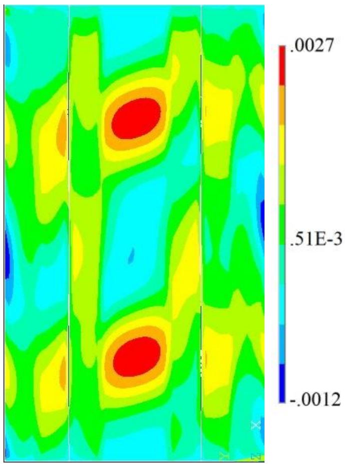
(b) (c)

Figure 4.2: Experimental setup for buckling test of CFRP stiffened panels:(a) Entire experimental setup; (b) zoomed view of clamped specimen; (c) Strain readers



a=100, b=85 for the panel without cutout. a=110, b=100 for the panel with cutout

(a)



(b)

Figure 4.3: Position of strain gauges pasted to the stiffened panels: (a) Strain gauged panel geometry; (b) contour showing critical regions of debonding at skin-stiffener interface

Strain gauges 1-4 are pasted in the transverse direction. Their position is chosen so as to measure the critical transverse strains at their regions during skin-stiffener separation. It is proposed in the literature Ref. [11, 14] that the skin stiffener debonding is the critical failure along with the with the surface ply splitting. So, the critical regions associated with the maximum intra-laminar peel-strain (ε_{yy}) are selected from the contour plots obtained from FEA to paste the strain gauges 1-4. Strain gauges 5-8 are pasted to find the axial strain at different regions. Strain gauges 7, 8 are bonded back to back to the web of the stiffener so as to identify the onset of buckling phenomenon. Contour of ε_{yy} obtained from non-linear analysis showing the relatively critical region in the whole panel for the stiffener debonding from skin is shown in Figure 4.3.

4.2.3 Post-processing

Post processing of all the images captured during the entire experimentation has been done using commercially available Vic 3-D software from Correlated Solutions. Whole surface of the stiffened panel rear side skin is taken as region of interest. Subset size is defined as 41×41 pixels and step size is taken 5 pixels.

4.2.4 Experimental results and discussion

This section specifically focusses on the observations from the conducted experimental study to investigate the buckling behavior of the CFRP double blade stiffened panel and the effect of cutout on it.The experimental DIC results obtained after the post-processing of all the experimental outcomes are compared for the double stiffened panels with and without cutout. The comparison of the axial displacement contours at different load levels for both the panels, with and without cutout is shown in Figure 4.4.

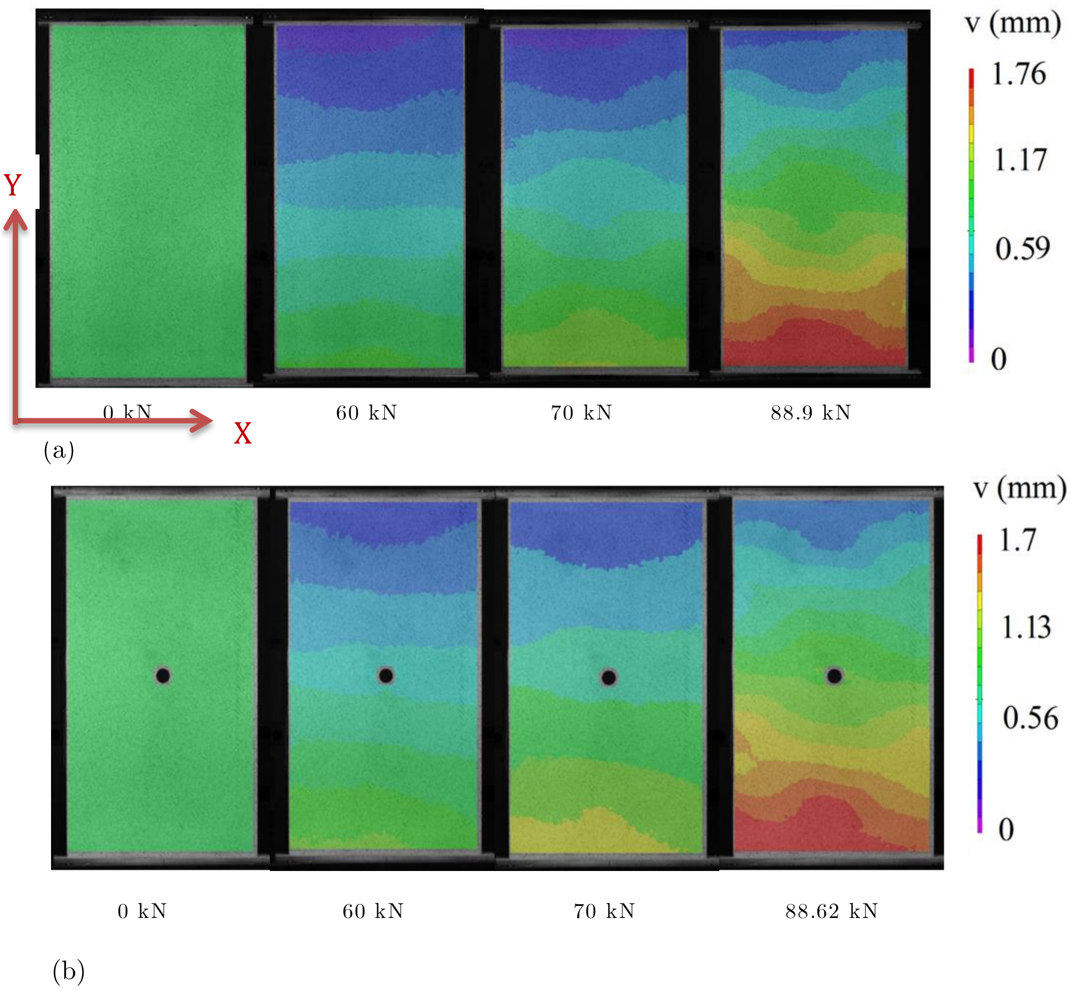


Figure 4.4: Axial displacement contours at different load levels extracted from DIC (a) panel without cutout; (b) panel with cutout.

A similarity in the axial displacement trends with increasing load levels for both the panels can be observed. The evolution of the mode shape at different load levels for the stiffened panels with and without cutout is compared in Figure 4.5.

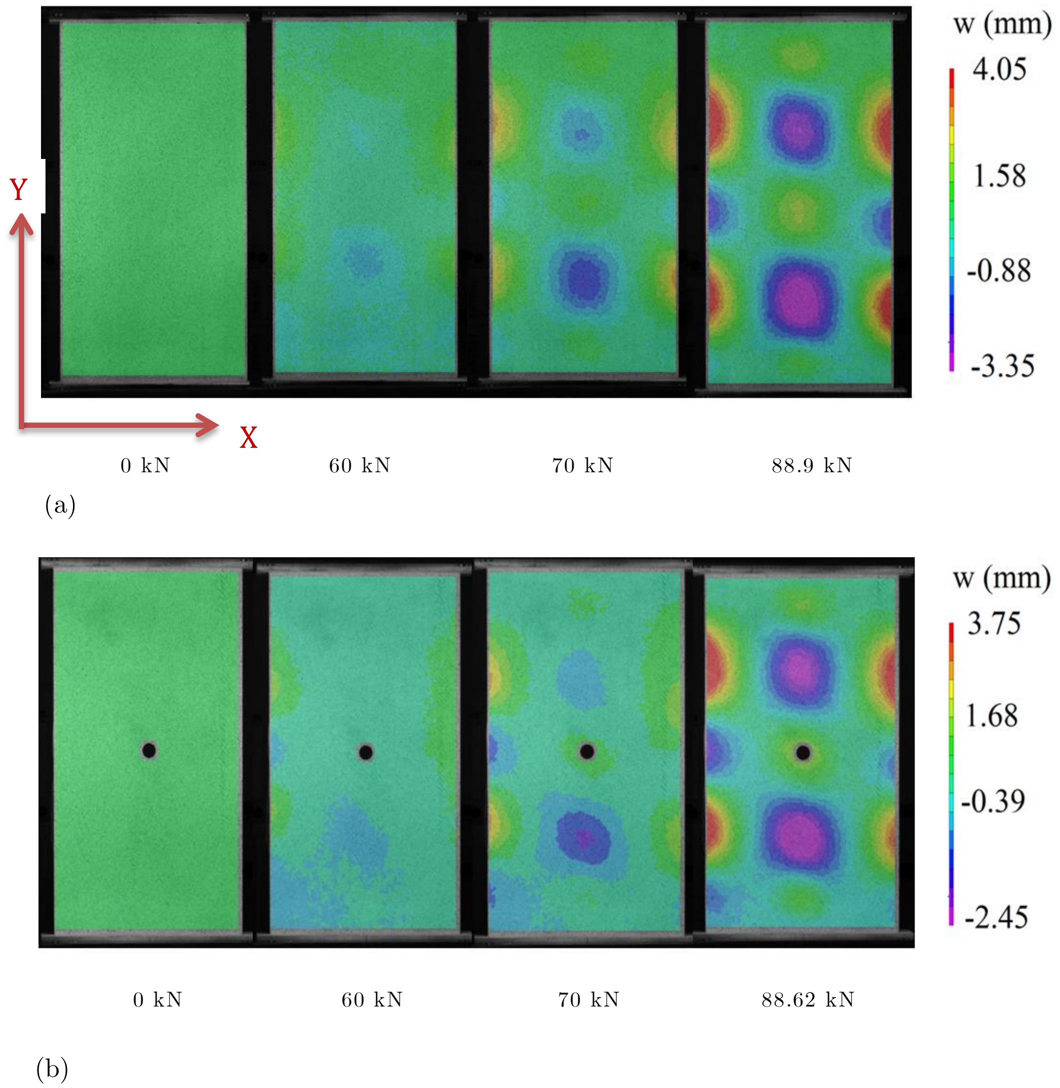


Figure 4.5: Out-of-plane displacement contours at different load levels extracted from DIC: (a) panel without cutout;(b) panel with cutout.

A similarity in the trends of the contours for both the panels can be observed from DIC contours. The perfect symmetric mode shape observed from the DIC contours for both the panels can assure the uniform loading because of the resin end blocks and the way the panels are held in the grips of the specially designed buckling test fixture. The transition in to post-buckling regime is progressive. It is not possible to exactly identify the critical buckling loads from whole field DIC contours. The shear and transverse strain contours obtained from DIC at different load levels for the stiffened panel without cutout is shown in Figure 4.6.

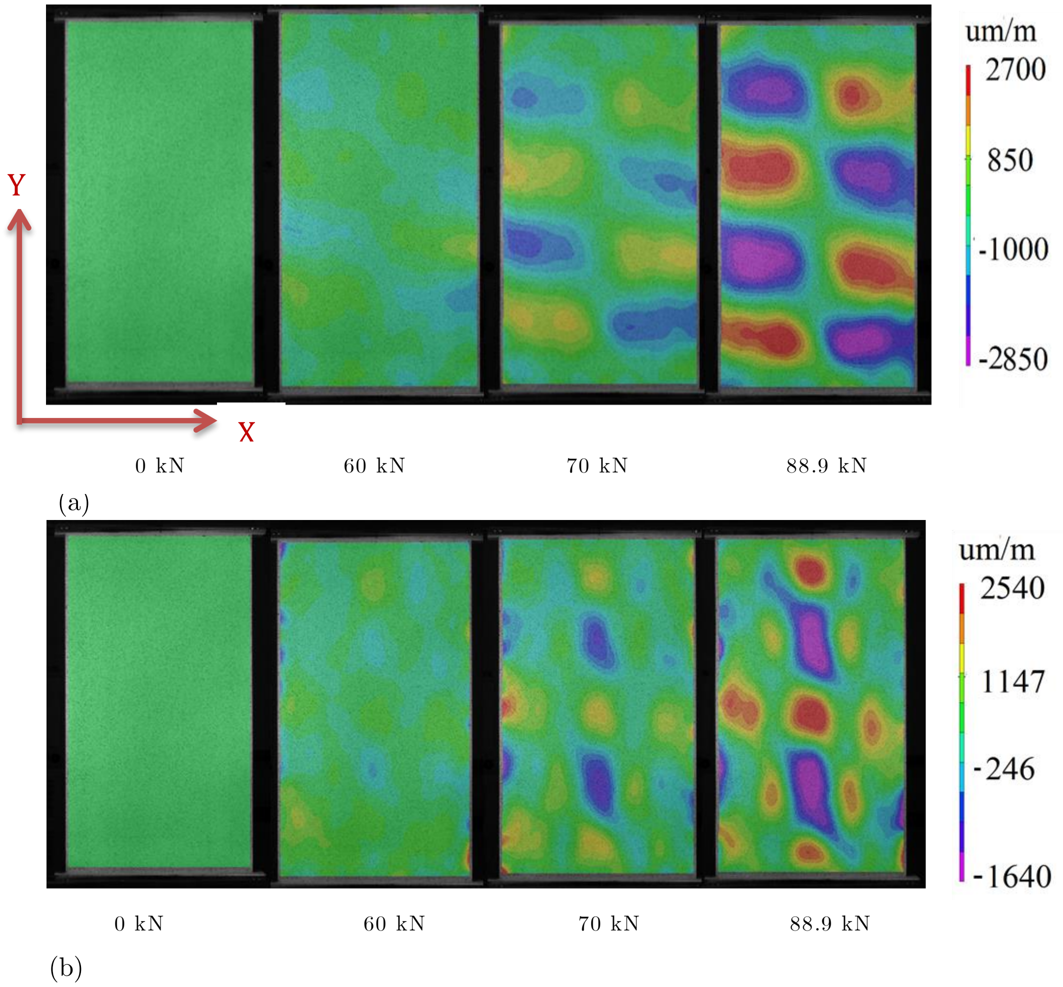


Figure 4.6: Strain contours at different loads extracted from DIC for the panel without cutout (a) shear strain ;(b) transverse strain.

The shear and transverse strain contours obtained from DIC at different load levels the stiffened panel with cutout is shown in Figure 4.7.

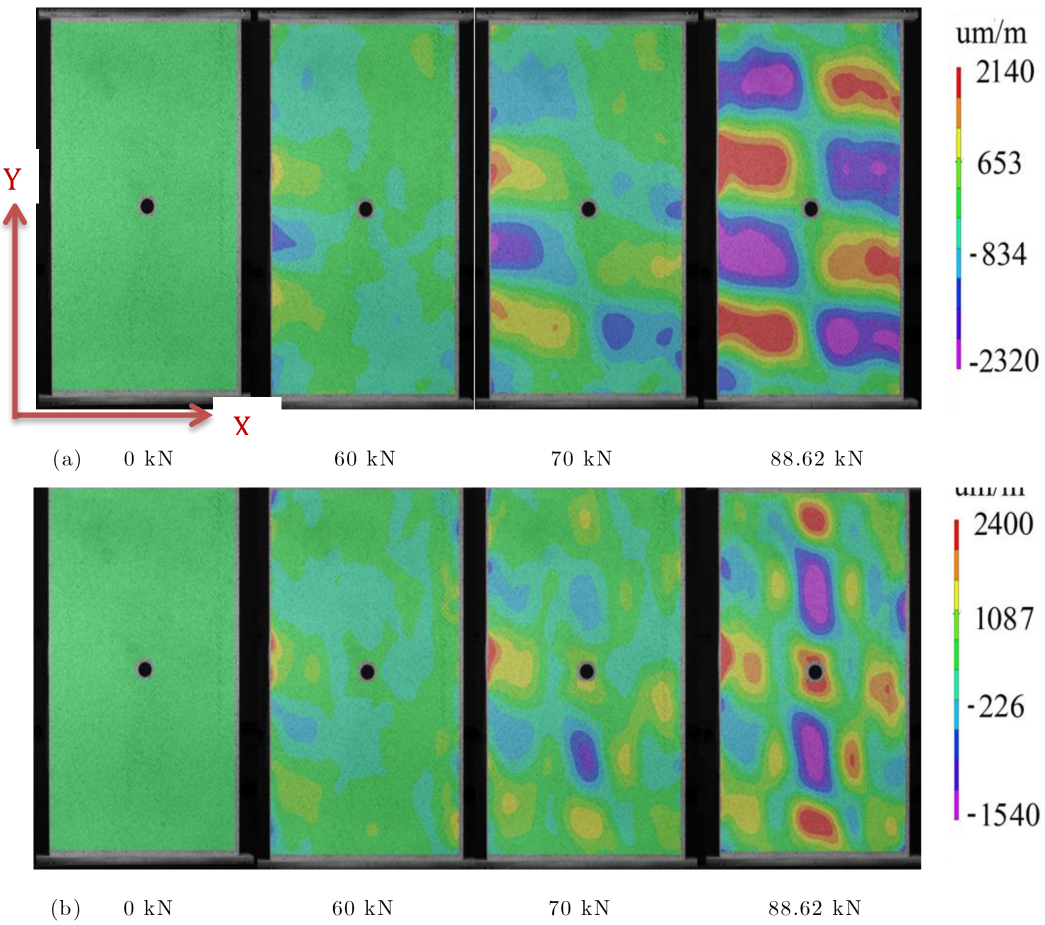
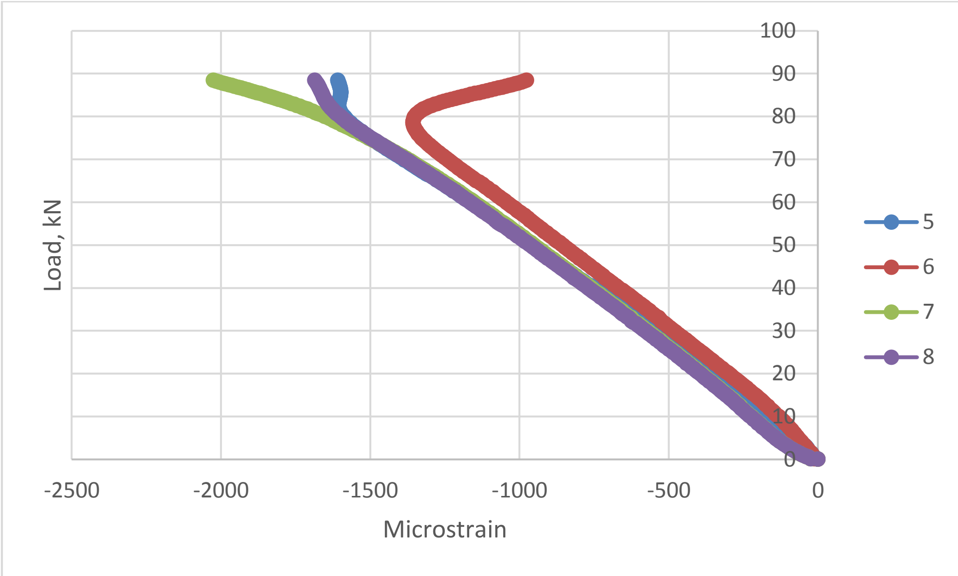


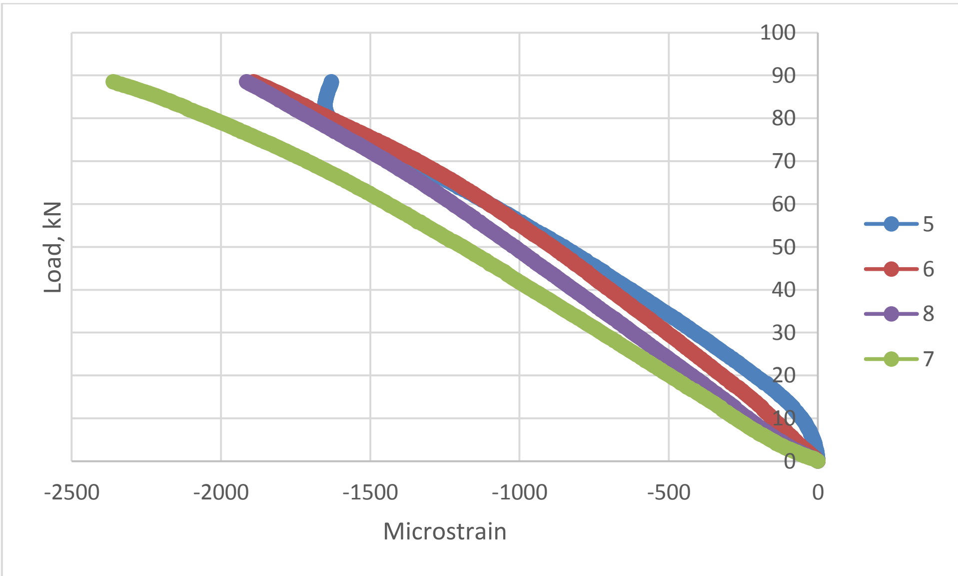
Figure 4.7: Strain contours at different loads extracted from DIC for the panel with cutout (a) shear strain ;(b) transverse strain.

4.2.5 Observations from strain measurements

The onset of buckling of the stiffened panel can be captured by looking at the strain gauge readings located on skin and web. The corresponding axial micro strain measured by the strain gauges 5-8 while loading the panel is plotted with respect to load in kN since the loading has started. The divergence in the readings of the strain gauges 7, 8 which are attached back to back to the stiffener is observed around axial load of 78 kN approximately. Figure 4.8 shows the strain measurement plots of strain gauges 5-8 with respect to Load.



(a)



(b)

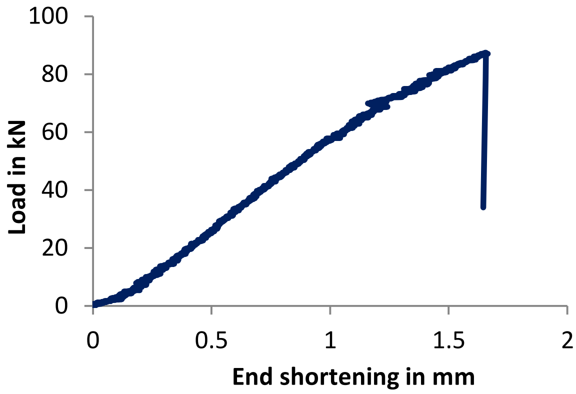
Figure 4.8: Strain measurement plots (a) panel with cutout; (b) panel without cutout.

There is no much significance made by the cutout on the strain measurements recorded at similar locations for both the panels till failure. This data also confirms the similarities in case of two stiffened panels in the aspect of strain behaviors which assures the repeatability of the manufacturing and testing procedures.

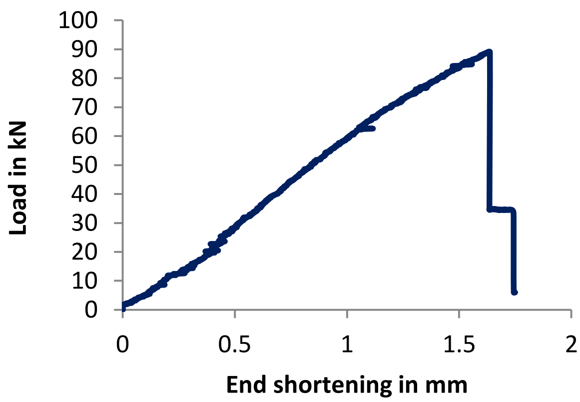
Incase of the stiffened panel without cutout, the observations from the transverse micro strain measured by the strain gauges 1-4, it is found that the strain gauge 4 failed first to read the strains after showing the relatively higher reading as +4203 microstrain. It suggests that the failure of the panel started with the debonding of stiffener from the skin occurred near to it. This observation agrees well with the phenomenon of debonding of stiffener from skin discussed in the subsection 4.2.2.

4.2.6 Axial stiffness

The load vs end shortening plots obtained from the experimental data is shown in Figure 4.9. There is no much significant influence of the cutout on the panel stiffness. The axial stiffness calculated is 62.65 kN/mm in the case of the panel without cutout and 61.83 kN/mm in the case of the panel with cutout.



(a)

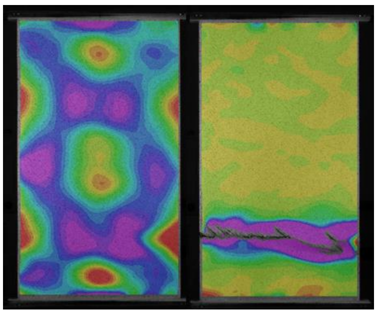


(b)

Figure 4.9: Load vs end shortening plots: (a) panel without cutout; (b) panel with cutout.

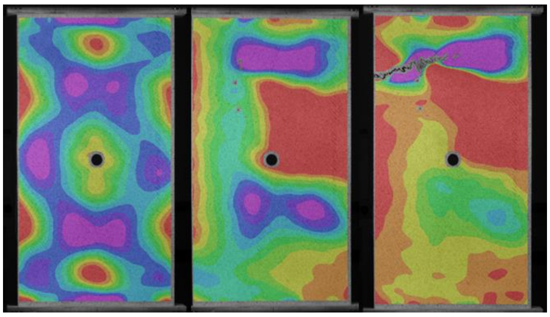
4.2.7 Failure in the panels

The preliminary analysis done from FEA shows that there is no much significance of the cutout on the buckling behavior of the CFRP double stiffened panel and it is well agreed from the observations of the experimental studies. The cutout is expected to play a major role initiating the damage in the form of stiffener debonding from skin near to the cutout. The damage mechanism observed from the experiment is in the good agreement with the prediction. For the stiffened panel without cutout, collapse occurred suddenly as skin-stiffener interface debonded followed by crippling of both the stiffeners. This failure mechanism is in well agreement with the previous experimental results observed from literature.[17]. The crippling of the stiffener can be characterized by a fracture across the entire stiffener width, perpendicular to the stiffener.(see Fig. 4.11 (b)) For the stiffened panel with cutout, skin-stiffener debonding occurred near the cutout for the left stiffener followed by crippling of it. Panel still continued to carry load and later it collapsed after the right stiffener debonded and crippled. There is a slight reduction of the stiffness before collapse and it can be observed from the load vs end shortening plot (see figure 4.9). Axial strain contour plots shown in Figure 4.10 is for the immediate images captured at the moment of panel failure.



89.07 kN After failure

(a)



89 k 34.5 kN 31.9 kN

(b)

Figure 4.10: Axial strain contours at the failure of the panels: (a) without cutout;(b) with cutout.

The observation from the above figure signifies the failure mechanism which occurred catastrophically with a loud sound for the panel without cutout. For the panel with cutout, the load carrying capacity suddenly decreased but still managed to carry load with the support of the right stiffener. The delamination and its growth can be observed from the contours of the above figure.

Figure 4.11 shows the images of the collapsed panel without cutout.

(a)

(b)

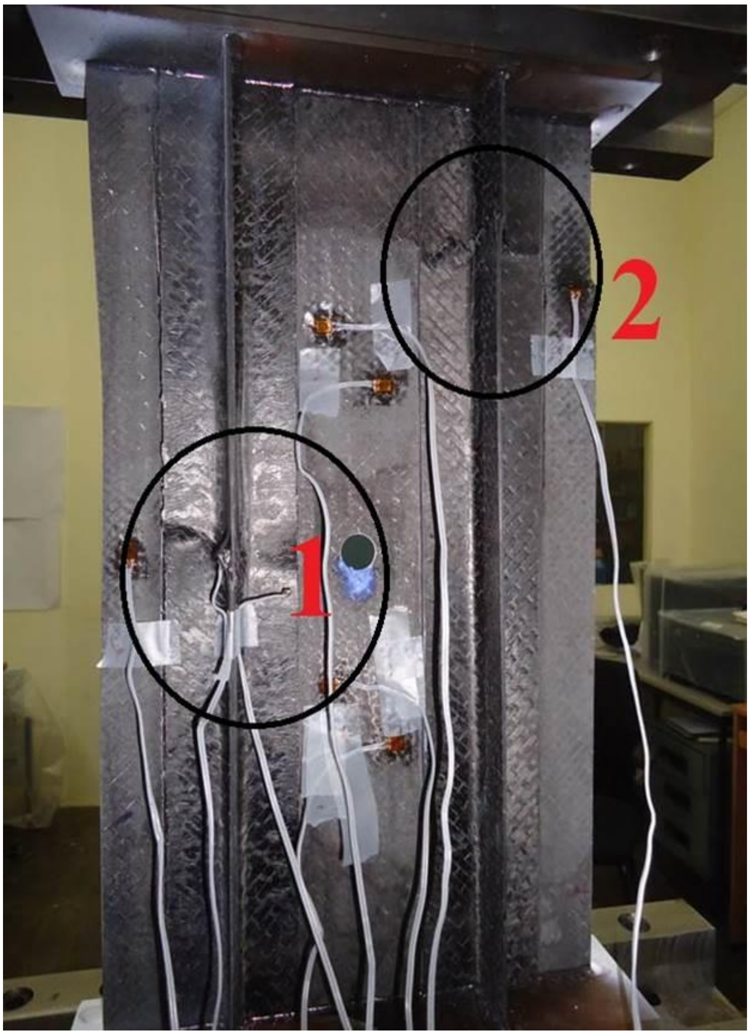
Figure 4.11: Images of the collapsed panel without cutout: (a) zoomed view of failure region.; (b) entire panel

From the above figures, it can be observed that the failure propagated across the width of the panel. One cannot pinpoint the origin of the failure from the captured images. The images of the collapsed panel clearly show that the stiffener has failed because of its web crushing. It happens due to the the local buckling of the stiffener where initial stiffener debonding has taken place. So, it can be concluded that the crushed region of the stiffener is the region where initial skin-stiffener debonding has occured. It is also observed that the site of the skin- stiffener debonding is well in agreement with the earlier prediction made based on the contours of intra laminar peel strain.

Figure 4.12 shows the images of the collapsed panel with cutout.

(a)

The skin-stiffener debonding started at the vicinity of the cutout as it is evident from the stiffener fracture as described above. The panel finally collapses as the second stiffener debonded and crippled. The crushed region of the stiffener is also well in agreement with the prediction based of the intra-laminar peel strain.

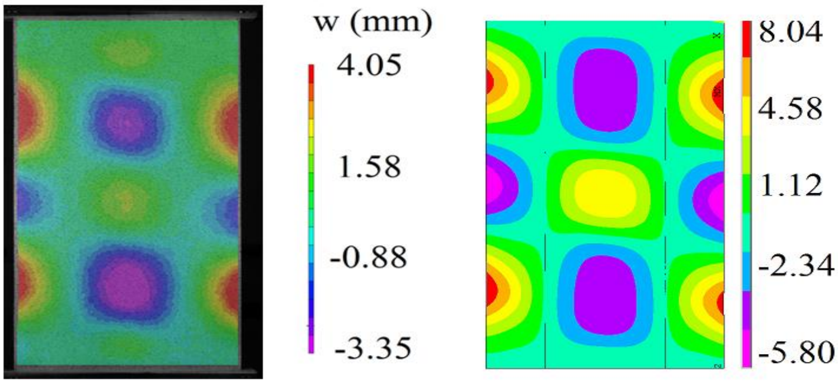


(b)

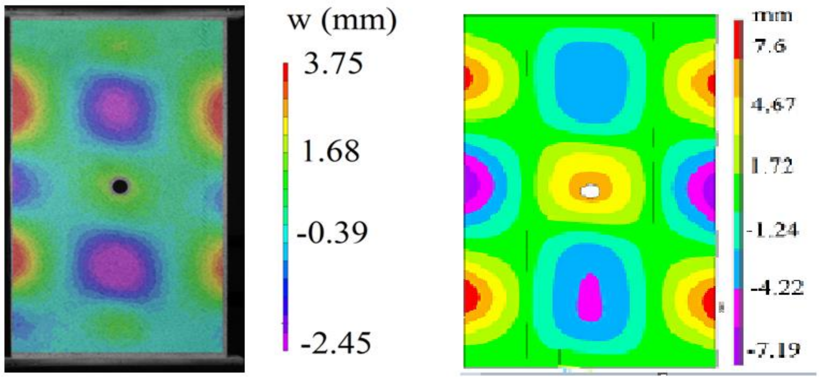
Figure 4.12: Images of the collapsed panel with cutout: (a) side view showing the skin-stiffener delamination ;(b) front view with marked sequence of failures.

4.2.8 FEA validation

FEA has done using commercially available ANSYS software. The procedure for the buckling and post-buckling analysis is already discussed in the Chapter. 3. In this section, displacement contours of DIC are compared with the contours of FEA at the maximum load (approximated to 89 kN) just before its collapse



(a)



(b)

Figure 4.13: Out of plane deflection contours from DIC compared with FEA respectively: (a) panel without cutout ;(b) panel with cutout.

It can be observed that the number of half sine waves along the longitudinal edge is in good agreement for both DIC and FEA contours in the case of both the panels from the figure 4.13. The mid bay is observed to have five half sine waves as from DIC contours. It is in contrary to contours from FEA in which only three half sine waves are observed. The maximum out of plane deflection obtained from FEA is approximately double to that of the deflection observed from the experimental studies.

Similarly the comparison of the axial displacement contours obtained from FEA and DIC for both the panels is shown

The upper edge of the panel is fixed and axial compressive loading is applied in the displacement control mode to its lower edge. The trend observed to be similar for DIC and FEA contours from .

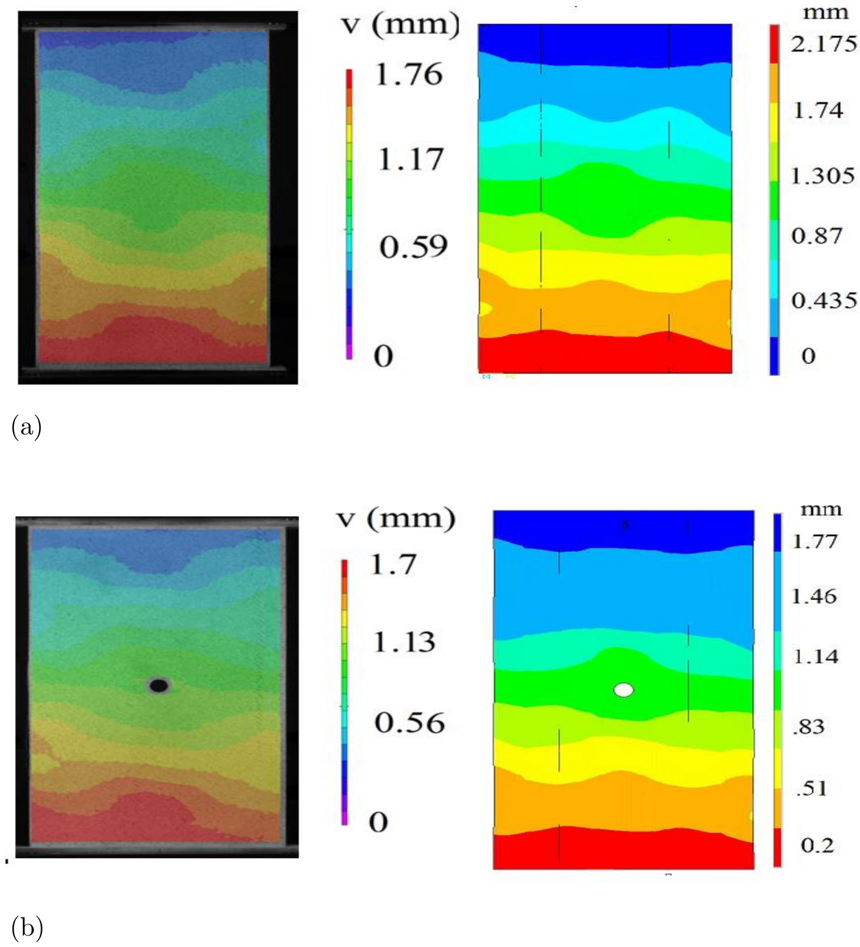


Figure 4.14: Axial displacement contours from DIC compared with FEA respectively: (a) panel without cutout ;(b) panel with cutout.

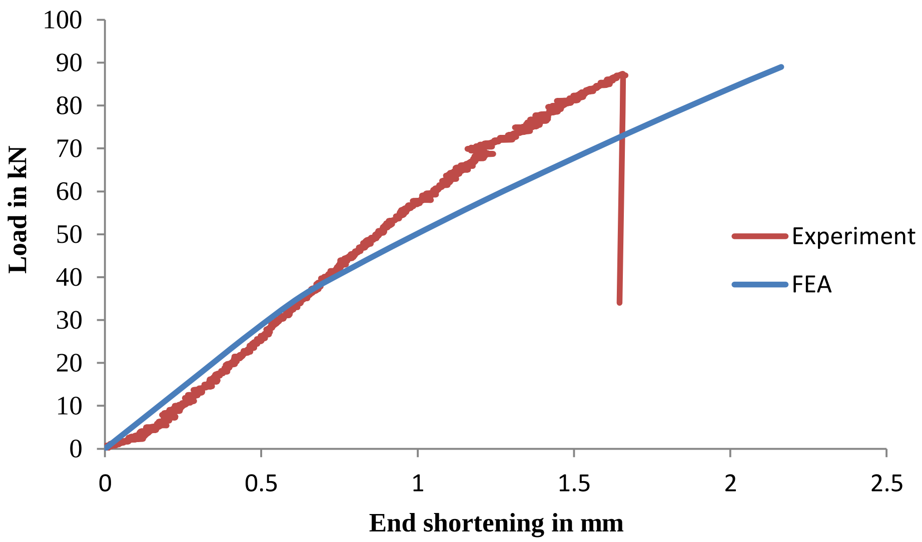
4.2.8.1 Stiffness comparison

The pre-buckling stiffness of both the stiffened panels, with and without cutout calculated by using the experimental data from DIC is compared with their respective pre-buckling stiffness obtained by the non-linear post buckling analysis using FEA in Table 4.3.

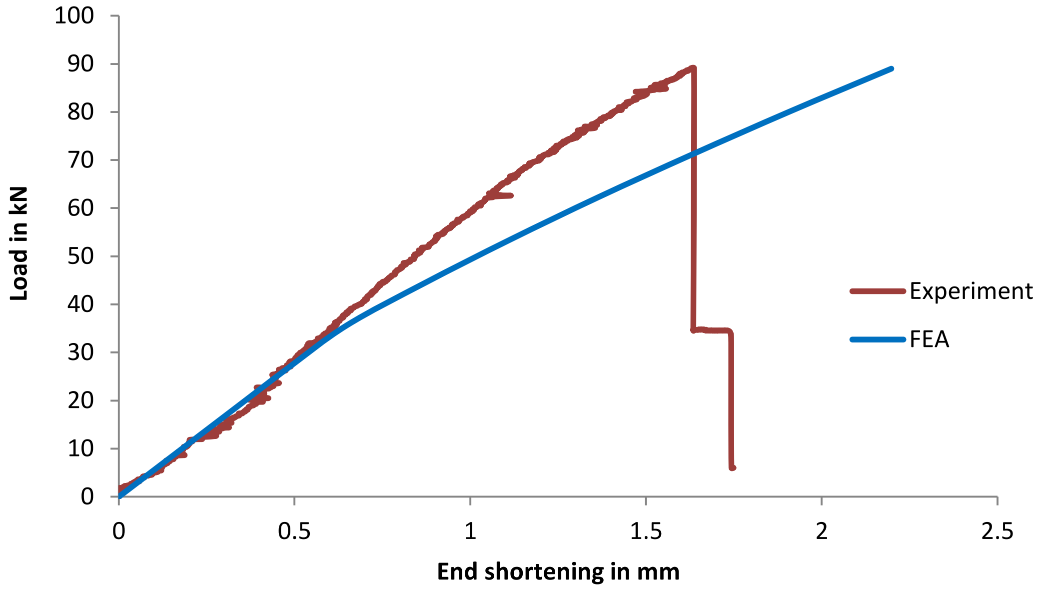
Table 4.3: Comparison of pre-buckling axial stiffness from FEA and DIC

Panel	FEA (kN/mm)	DIC (kN/mm)
Without cutout	**56.86**	**62.65**
With cutout	**55.07**	**61.83**

The circular hole introduced at the center of the skin between the stiffeners is showing a similar amount of reduction in the initial axial stiffness for a CFRP double blade stiffened panel in both FEA and experimental results. Stiffness predicted by FEA for both the panels is slightly lesser than their respective stiffness obtained from the experimental study. The comparison of FEA predicted load vs end shortening plots with the actual plots obtained from the experiments for both the panels is shown in Figure 4.15.



(a)



(b)

Figure 4.15: Load vs end shortening plots compared from FEA and experiment (a) Panel without cutout ; (b) Panel with cutout.

4.3 Axial strain contour

The divergence in the readings of the strain gauges 7, 8 which are attached back to back to the stiffener, at its midlength is observed around -2000 micro strains approximately as discussed in the subsection 4.2.5. The predicted load from the nonlinear buckling analysis for having the local axial strain value range to match with -2000 mico strain at similar location of the stiffener is 48.95 kN. The corresponding contour is shown in Figure 4.16.

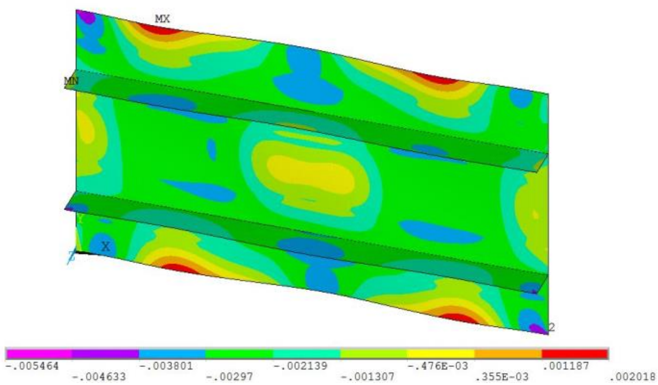


Figure 4.16: FEA contour with matching local strain value of -2000 $\mu\varepsilon$ *at* stiffener midlength

4.4 Closure

Experimental studies are conducted to investigate the effects of a cutout on the buckling behavior and failure mechanism of a double stiffened panel under axial compressive loading. Specimens are fabricated in-house starting with the stiffeners fabricated by VI process and later co-bonded to the skin. DIC is used in the experimental study. The experimental results obtained from DIC are compared to FEA. It is observed that the failure mechanism for the panel without cut out is in good agreement with the literature. Though the cutout hasn't made any significant effects on the pre-buckling and post-buckling behaviors, it is observed that the skin-stiffener debonding followed by the crippling of the stiffeners initially occurred in the vicinity of the cutout. The critical buckling loads obtained from FEA for both the panels are close. It is not possible to exactly identify the buckling loads of the Panels experimentally , since the transition in to post-buckling regime is progressive in DIC contours of both the panels. The stiffness is not greatly affected by the cutout.

Chapter 5

Conclusion and future recommendation

5.1 Conclusion

The current thesis work is focused mainly to establish the standard in-house fabrication and testing procedures for the CFRP blade stiffened panels by following the literature. In this process, fabricating the blade stiffener using vacuum infusion is the toughest challenge to overcome. By varying the different flow parameters for infusing the resin and by overcoming all the practical difficulties, a standard procedure is established to fabricate the blade stiffener of any required dimension. An appropriate fixture is designed and fabricated in-house to assist in the process of casting the resin end blocks. Further a buckling test fixture for applying uniaxial compressive loading of the stiffened panels is also designed and fabricated in-house. Later, experiment studies are carried out for understanding the pre and post-buckling behavior of the CFRP double blade stiffened panels. Finite element study is also done using the commercially available FEA package ANSYS. Linear buckling analysis followed by non-linear post buckling analysis is done to obtain the critical loads, buckling mode shapes, all the associated displacements and strains over the complete panel using FEA. Following it 3D-DIC technique is used to obtain the experimental results, so as to validate it with the results obtained from FEA. The influence of a small cutout ($w/d = 14$) on the buckling behavior of a double stiffened panel seems to be of not much significance. Bigger the hole size diameter, greater it might influence. Cutout showed a significant role in the failure mechanism occurred in the stiffened panel while collapsing. For the stiffened panel without cutout, collapse occurred suddenly as skin-stiffener interface debonded followed by crippling of both the stiffeners.The crippling of the stiffener can be characterized by a fracture across the entire stiffener width, perpendicular to the stiffener. For the stiffened panel with cutout, skin-stiffener debonding occurred near the cutout for the left stiffener followed by crippling of it. Panel still continued to carry load and later it collapsed after the right stiffener debonded from skin and crippled. The failure mechanisms observed in the tested panels are in good agreement with the literature. This assures the manufacturing and testing procedures followed as a part of this thesis work is of required standard. Comparison of out of plane deflection contours from FEA and DIC showed a significant difference, while the axial displacement contours have shown good similarities in between them.

5.2 Recommendations for future work

Current study has established a standard procedure to fabricate the stiffened panel. Attempts are made to validate the quality of the stiffeners, by observing voids in a microscope. NDT can create a good platform to assure the quality of the fabricated panels. The process parameters can also be further modified to see their effects on the quality of the specimens. As the imperfections are not avoidable while fabricating, machining and due to operating conditions, it is advised to measure the imperfections of the whole panel before testing using co-ordinate measuring machine (CMM). This data can be used to model these imperfections in FEM to study the significance of these imperfections. Further FEA analysis need to be improved for exactly capturing the experimental behavior. It would be beneficial to compute the first three buckling mode shapes from Eigen buckling analysis and to use their combination to model the initial imperfection for the non-linear analysis. Above recommendation is mainly valid where closer critical load factors exist between various buckling modes because the imperfection sensitivity may be varied a lot in-between various buckling modes. Since the fabrication of huge CFRP panels takes lot of time and cost element level tests like stiffener pull off tests have to be focused. Progressive damage modelling on FEA would give a deep insight of the failure mode and propagation in the experimental study.

Appendix A

Buckling study of CFRP single stiffened element

A.1 Introduction

Prior to the testing of the double stiffened panels, an experimental study is conducted on a single stiffened element to sort out any practical challenges in the process of making panels and testing them. 3D-DIC setup is used to determine the mode shape, in-plane stiffness, out-of-plane deflection and other buckling behaviors. Experimental results are compared with the finite element predictions for validation.

A.2 Element geometry and fabrication

The geometry details of the single stiffened element are summarized in Table A.1 and FigureA.1 below.

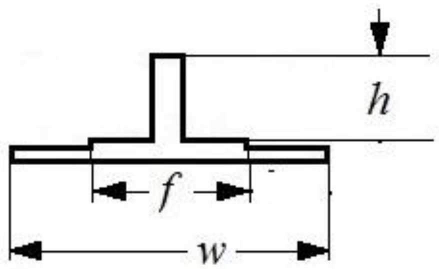


Figure A.1: Geometry of single stiffened element

Table A.1: Single stiffened panel dimensions

Dimensions	Values (mm)
f	32
h	14
w	90

The stiffener fabricated by VI technique is secondary bonded to the skin pre-cured by vacuum bagging method as detailed in the section 2.2.3.1. The layup of the skin is chosen to have balanced and symmetric with quasi isotropic stacking sequence $[45°/-45°/90°/0°]_s$. The layup of the stiffener web is having the laminate stacking sequence $[45°/-45°/90°/0°/45°]_s$. The layup of stiffener flange web is having the laminate stacking sequence $[45°/-45°/90°/0°/45°/[45°/-45°/90°/0°]_{2s}]$. Thickness of each ply is approximately 0.225 mm.

A.3 Experimentation

The single stiffened element is prepared as according to the procedures explained in chapter 2. Final machining is done for the resin end blocks so as to ensure parallelism at their ends and also to align the geometric centroid of the stiffened panel cross section to coincide with the loading axis of the machine after clamping it in the loading fixture.

The experimental setup is same as described in the subsection 4.2.2. Uniaxial compressive loading is applied on the element in displacement control mode at the rate of 0.5 mm/min. Images of loaded panel are taken at the rate of 5 Hz using 3D-DIC setup and are post processed as explained in the section 4.2.3.

A.4 Result and discussion

Axial displacement contour for the element while loading has been obtained from DIC to verify the uniform loading condition of the fixture at 10 kN in Figure A.2.

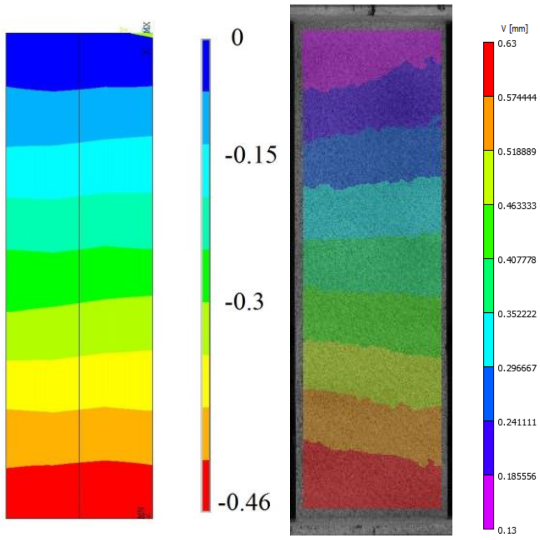


Figure A.2: Finite element (FEA) and experimental (DIC) comparison of in plane axial displacement at 10 kN

A.4.1 Mode shapes

Eigen buckling analysis predicts the first critical load for the single stiffened element to be 30 kN. Experimental mode shapes are extracted using 3-D DIC at a particular load and compared with FEA mode shapes at 32 kN in post buckling regime and is shown in Figure A.3.

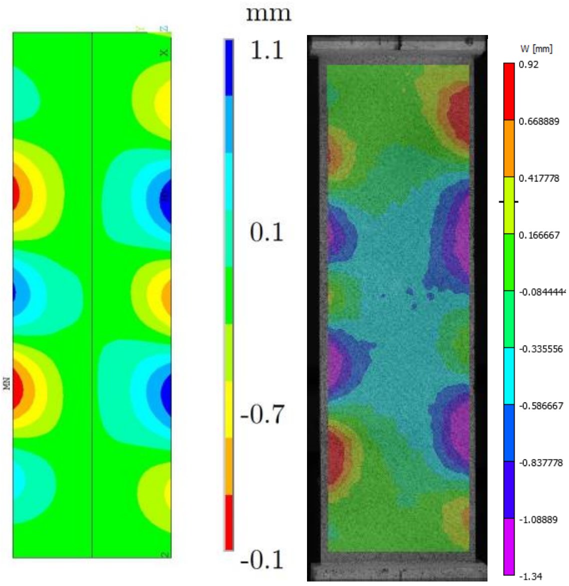


Figure A.3: Finite element (FEA) and experimental (DIC) comparison of out-of-plane deflection at 32 kN

A.4.2 Initial axial stiffness

Load vs end shortening plot obtained from the experiment is compared with the plot predicted in nonlinear buckling analysis for the single stiffened element and is shown in Figure A.4.

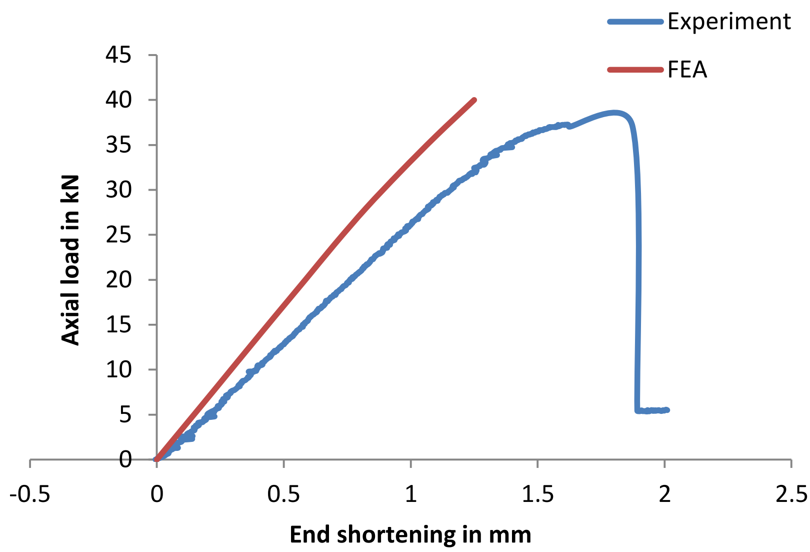


Figure A.4: Finite element (FEA) and experimental (DIC) comparison load vs end shortening plots

Initial axial stiffness obtained in the experimental study is 26 kN/mm whereas the predicted axial stiffness from the non-linear post buckling analysis using FEA is 32 kN/mm.

Dissertation Outcomes

Conference paper submitted based on this research

Proceedings of First Structural Integrity Conference and Exhibition (SICE-2016), Bangalore
July 4-6, 2016

Experimental Study on Buckling Behavior of CFRP Stiffened Panels Involving Digital Image Correlation

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Abstract

The present work focuses on the experimental and finite element analysis of carbon fiber reinforced polymer (CFRP) stiffened panels with two blade stiffeners. The buckling behavior of the CFRP stiffened panels with and without cutouts between the stiffeners is investigated under compression loading. In this study, stiffened panels are fabricated in-house starting with the stiffeners fabricated using vacuum infusion (VI) process and later co-bonded to the skin. End blocks are cast at the transverse edges of the stiffened panel for uniform loading whereas the longitudinal edges are left free. Whole field non-contact optical technique called digital image correlation (DIC) is used in the experimental study to estimate the whole field strain, axial as well as out-of-plane displacement of the stiffened panel being loaded

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under compressive load. Experimental results are compared with the finite element results for validation. Subsequently investigations are carried out by introducing a circular cut-out in between the stiffeners, where all the buckling parameters are compared with the experimental results obtained for the same panel configuration without any cutout.

Keywords: Stiffened panel,Digital image correlation,Buckling.

1. Introduction

Composites are beneficial in terms of stiffness to weight and strength to weight ratio, resistance to corrosion and also the designer can have the flexibility to tailor the properties. These qualities are drawing the attention of automobile and aerospace industries to replace the metallic structures like wing, fuselage with composite structures. So the strength based design leads to thin skin and is prone to buckling phenomenon. Stiffeners, simply the columns attached to skin longitudinally help to improve the buckling load capability with a relatively less weight penalty by increasing the second moment of area of skin locally. The composite stiffened panels are combining material and structural efficiencies which can assist in light weight aerospace structures thus drawing the attention of several researchers. Being a very complicated structure, stiffened panel loaded in compression results in different types of initial independent buckling modes occurring such as skin local buckling, stiffener local buckling or even panel global buckling. Local buckling modes do not lead the structure to fail catastrophically like panel global buckling mode. Thus structure comprised of stiffened panels continues to carry more loads even after initial buckling occurs until the final failure happens. Initial skin local buckling mode in between stiffeners prevents the panel to buckle as a whole and help stiffeners to retain their axial load carrying capability [1]. The main aspect that limits the maximum load in the post buckling region is skin stiffener separation. Current research is also going on to improve the manufacturing techniques of monolithic integrated stiffened panel.

Adrien et al. [2] detailed about the experimental procedure for testing of a composite stiffened panel and validating with the numerical results. Charlotte et al.

[3] explained about the mechanisms for skin-stiffener detachment and also the influence of damage introduced at the interface on those mechanisms. Leong et al. [4] conducted the experiments to test the bond quality of stiffened panels by comparing specimens manufactured by vacuum infusion (VI) and resin transfer molding (RTM) using different materials at skin-stiffener interface. Shuart et al. [5] explained about different modern and automated fabrication technologies for high performance polymer composite manufacturing. Huang [6] conducted studies on co-cured blade stiffened panels by experimenting with varying the radius of tool. Bloodworth et al. [7] used DIC to correlate local strain rates with the failure initiation and propagation at skin stiffener interface.

Cut outs are unavoidable in wings and fuselage for the purpose of windows, assembly, fuel access, wiring, visual inspection etc., which can act as stress raisers and affect the load carrying capability. Their profiles are designed to have rounded corners to reduce stress concentration. In this work a comparative study is done to see the effects of a simple round cut out on the buckling performance and mode shapes of a fuselage representative flat stiffened panel. Investigations are carried out by introducing a circular cut-out in between the stiffeners, where all the buckling parameters are compared with the experimental and FEA results obtained for the stiffened panel with the same configurations without any cutout. 3-D DIC, a non-contact optical technique is used to measure the out of plane displacements, whole field strain, and axial displacement in experiments.

Nomenclature

a	distance between the flange edge and panel free edge
d	diameter of circular cut out at the mid of panel in between the stiffeners
F	free length of the panel
f	width of the flange
h	height of the stiffener
L	total length of the panel

w width of the panel

---

2 Stiffened panel fabrication

2.1 Specimen design

The present work aims in investigating the effects of cutouts in buckling behavior of a two blade stiffened CFRP panel. So comparative experimental studies need to be done on the panels having the same configuration with and without cutouts. The mostly used design method in literature is to maintain the distance between the longitudinal edge and nearby stiffener edge as half the distance between the adjacent stiffener edges.

Basic dimensions of the two blade stiffened panel are taken from Ref. [9] and the stacking sequence for it is obtained according to guidelines given in Ref. [10].The skin is chosen to have the quasi-isotropic layup $[45°/-45°/90°/0°]_S$. The stiffeners web is having the layup $[45°/-45°/90°/0°/45°]_S$.With reference to our previous experimental works potting length was taken 35 mm instead of 50 mm resulting in a panel of 470 mm length and 224 mm width. For the panel with cut out the same dimensions and stacking sequence is considered with a hole of diameter 28 mm at its midpoint placed in between the stiffeners. Panel geometry is shown in Fig. 2 and the dimensions are given in table 1.

b)

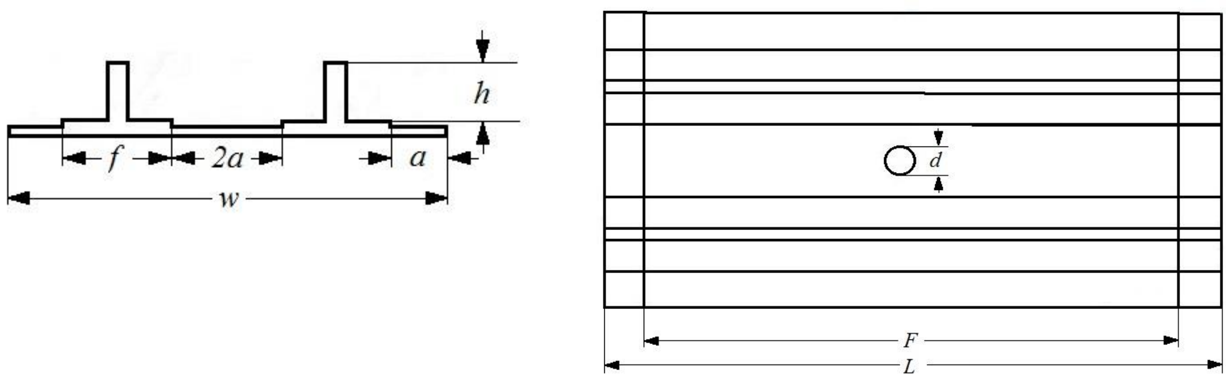
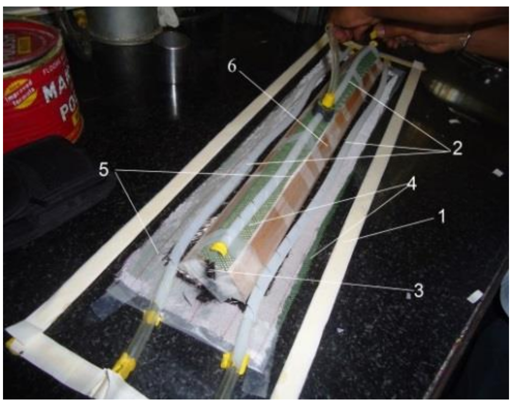


Fig. 2 Stiffened panel geometry (a) Cross section of panel geometry; (b) Geometry of panel with cut out.

2.2 Specimen fabrication

The specimen fabrication starts with cutting of the carbon fiber plies of required size and angles from a 200 gsm unidirectional carbon fiber roll and fabricating stiffeners using VI process. In this process vacuum pressure is used to facilitate the resin flow in a controlled manner through spiral tubes into a dry fiber preform. Dry fiber layers are stitched in the required stacking sequence and packed within a mold tool covered by a vacuum bag. After checking for leaks at maximum possible vacuum pressure the degassed resin and hardener mixture is made to flow through the fiber preform at reduced pressure of -80 kPa. The resin used in the entire process is Araldite® CY230 and the hardener is Huntsman® HY951 mixed in the ratio of 10:1 by mass of resin and hardener respectively. It is allowed to cure for 24 hours under maximum possible vacuum pressure and cured part is removed from the bagging. Final machining brings it to the required dimensions. The same process is repeated for all the stiffeners. Later, the skin is bonded to the stiffeners by appropriately placing the cured stiffeners above the wet skin plies having the required stacking sequence. Later these are cured by vacuum bagging setup. Fig. 3 shows the sequential steps involved in fabrication of stiffener using VI process. The entire setup takes 24 hours for curing. Finally the integrated panel is machined to required dimensions.

a)



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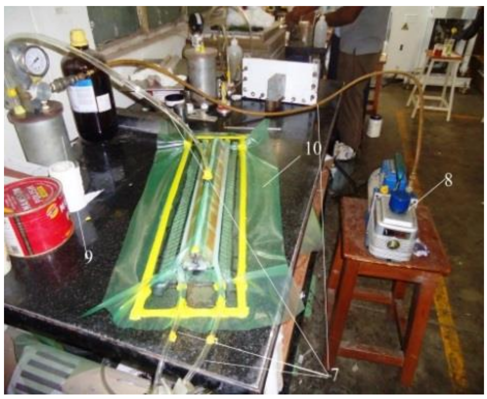


1-Synthetic tape 2-Spiral tubes 3-Dry fiber Preform 4-Resin Infusion mesh 5-Peel ply 6-Wooden mold 7-Tubings for applying vacuum and resin infusion 8-Vacuum pump 9-Catch pot 10-Vacuum cover.

Fig. 3. Stages of making a stiffened panel, (a)vacuum infusion setup before bagging along with connectors to vacuum pump;(b)final setup of vacuum infusion for fabricating the stiffener.

Later, resin blocks are casted at loading ends of the panel and are machined to ensure their flatness, parallelism [2].Machining also helps in aligning the centroid of the specimen's cross section with the centroid of the resin end blocks. This procedure avoids any possible misalignments and helps in uniform distribution of the applied load throughout the width of the panel. The drilling operation is performed on the second stiffened panel by using special purpose diamond coated drill bit to introduce the cutout. Skin is painted with a random black and white speckle pattern on its back side to the panel in order to carry out experiment using 3-D DIC. so as to have randomly distributed grey levels to employ

3 Experimental setup

Experimental setup is shown in Fig. 5.MTS servo-hydraulic testing machine of 100 kN loading capacity is used to load the specimen in displacement control mode. The specimen is loaded at the rate of 0.5 mm/min. Specimen is carefully clamped in the grip such as to align the centroid of the specimen's cross section to coincide with the loading axis of the machine's actuator [6]. Images are captured using two grasshopper CCD cameras (Point Crey-Grass-5055M-C) having a spatial resolution of 2448 x 2048 pixel at the rate of 2 images per second. Vic snap software is used to capture the images and are post-processed using Vic-3D software obtained from correlated solution to get the whole field displacement and strain contours.

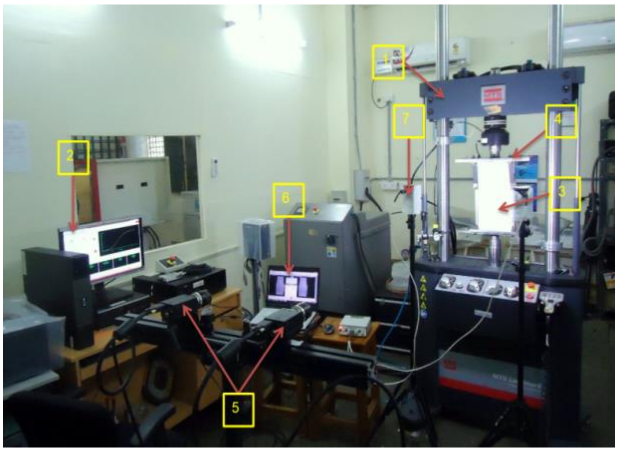


Fig. 5 Experimental setup DIC system coupled with MTS loading machine

1. 100 KN MTS frame, 2. User Interface , 3. Plate under compression load , 4. Fixture, 5. CCD Cameras , 6. Image grabbing PC, 7. Light Source.

4 Finite element analysis

4.1 Material properties

Material properties for CFRP laminate which are obtained according to ASTM standards are shown in Table 2.

Table 2. Material properties for CFRP

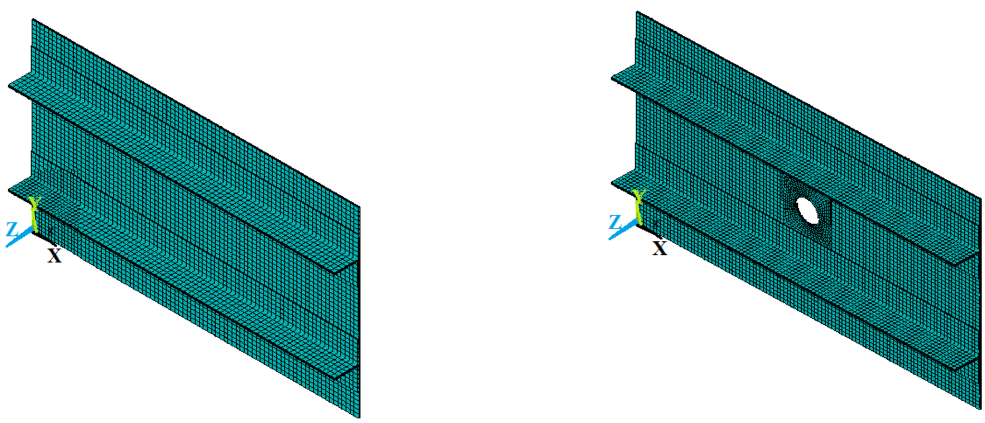
Material properties		Values
Longitudinal Modulus	E_{11}	98.41 GPa
Transverse modulus	E_{22}	6.3 GPa
In-plane shear modulus	G_{12}	1.53 GPa
Out-plane shear modulus	G_{23}	1.91 GPa
In-plane Poisson's ratio	ϑ_{12}	0.23
Out-plane Poisson's ratio	ϑ_{23}	0.30

4.2 Modelling of stiffened panel in Ansys

Numerical buckling loads are found using commercial FEA package Ansys. Shell 281, a planar 8-noded element is used for the modelling. Blade stiffener looks like an inverted T. It contains web and flanges on either side of web so as to bond it to the skin. For simplicity the entire panel is modelled by creating corresponding planes of skin, skin with flange and stiffeners web individually and separately gluing them. The appropriate stacking sequences for shell elements are assigned separately to those areas corresponding only to skin, to skin with attached flange and to web using mesh attributes. Material properties obtained by characterization are shown in table. 2 and they are given as input to the model. Shell 281 being a two dimensional element, a reference plane should replace the three dimensional components of the model. The reference plane for the elements at web portion is kept at its mid plane and for the skin section is kept at its top plane. Element size is chosen to be 4 x 4 mm after mesh convergence studies resulting in 21945 nodes and 7200 elements in total.

For the stiffened panel with a cutout, a structured mesh is created around the hole with in a square region of 56 x 56 mm as shown in Fig. 9.(c).The meshed model of the stiffened panel has got 23042 nodes and 7396 elements in total.

b)



c)

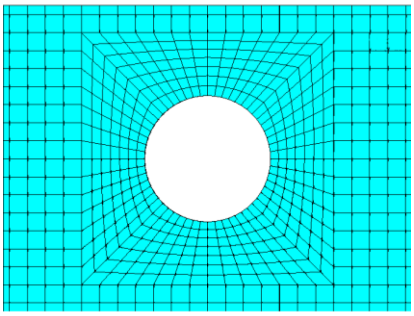


Fig. 9.Finite element model (a) without cutout ;(b) with cutout;(c) zoomed view of the cut out region.

4.3 Loading Conditions

The transverse edges are casted with resin end blocks and are loaded in actual experiment. All nodes at x=0 are applied with clamped boundary conditions by constraining all degrees of freedom. All nodes at x=400 are coupled to a master node where the loadings will be given here. The$U_y, U_z, \theta_x, \theta_y, \theta_z$ of them are constrained. The applied boundary conditions are shown in Fig. 10 shown for panel without cutout and the same boundary constraints are applied for the panel with cutout.

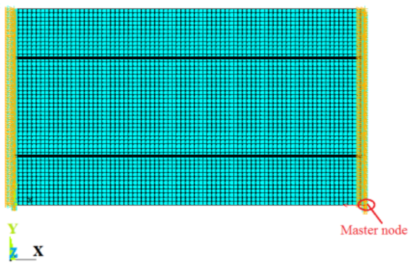


Fig. 10. Finite element model along with the boundary conditions

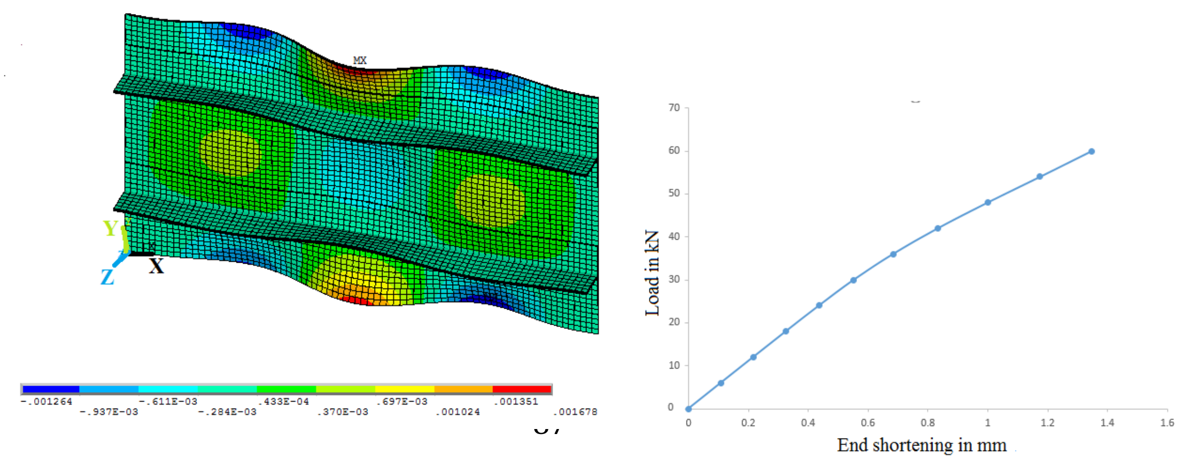
4.4 Results in Finite Element Analysis

Prebuckling analysis is done followed by the Eigen buckling analysis to obtain the critical loads and the mode shapes. The critical load for the panel without cutout is obtained as 36.95 kN and for the panel with cutout is obtained as 36.02 kN. The first three numerical buckling loads of two panels obtained from FEA are shown in table 3.There is a very slight differences that cutout is causing on these buckling loads obtained from FEA. To predict the behavior of the panel with response to the increasing load non-linear analysis is done to obtain the load versus axial displacement plot. Since, it is impossible for a perfect panel to deflect out of plane with increasing load, out of plane displacement obtained for first critical load is taken as initial imperfection by scaling it to 5% of thickness of skin for the nonlinear analysis. Load is applied in discrete steps to capture the response of the panel gradually. The master node at x=400 mm is used to capture the end shortening of the panel with load. The mode shapes ,the load versus end shortening plots and maximum out of plane displacement plots obtained for panels without and with cutout are shown in Fig. 11 and Fig. 12 respectively.

Table 3. Comparison of first three buckling loads

Buckling Load	Panel without cutout (kN)	Panel with cutout (kN)
First	36.95	36.02
Second	37.20	37.43
Third	38.78	38.22

a) b)



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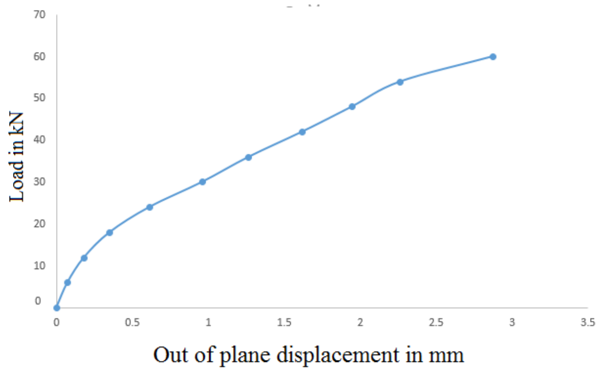
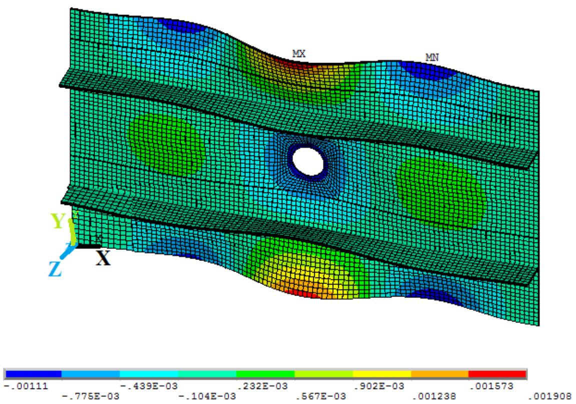


Fig. 11.Mode shape, end shortening and maximum out of plane displacement plots obtained from FEA study in case of stiffened panel without cutout. (a) mode shape at critical loading of 36.95 kN;(b) load versus end shortening plot;(c) load versus maximum out of plane displacement plot

a)



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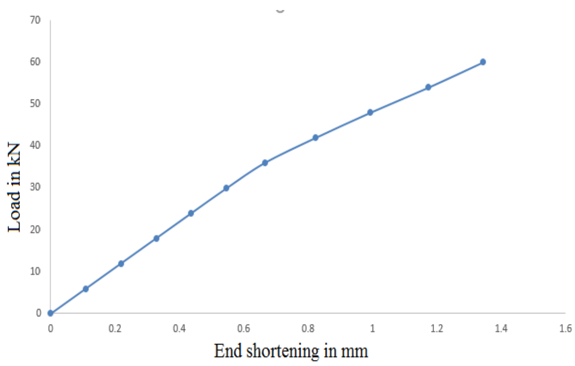

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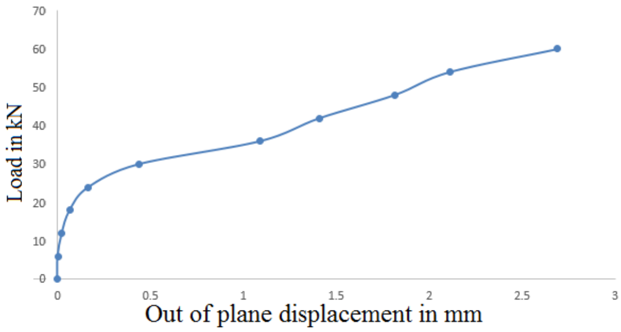

Fig. 12.Mode shape, end shortening and maximum out of plane displacement obtained from FEA study in case of stiffened panel with cutout. (a) mode shape at critical loading of 36.02 kN;(b)) load versus end shortening plot;(c) load versus maximum out of plane displacement plot

After reaching the critical load one can observe the change in the stiffness from the load versus end shortening plot, but the panel is still capable of taking loads since local skin buckling mode occurred as discussed before. This study shows that cutout has negligible effect on initial stiffness in the linear zone and on the critical loads. As a result of discontinuity, high stiffness variations near the cutout are observed. By observing the contour, one can predict the separation of skin and stiffener going to begin near the cutout, since it acts as high stress raiser which may lead to debonding of stiffener from the skin. So it is the critical region of failure in case of stiffened panel with hole.

5 Conclusion

The first three buckling loads obtained from FEA are close for both stiffened panels with and without cutout. Therefore, one can conclude that cutout is not making a significant effect on the critical loads. The obtained FEA results will be validated by comparing it with the DIC results and currently authors are working in that direction. The cut out plays a major role in initiating the damage as the debonding of stiffener from skin is predicted to begin near them. This debonding mechanism will be confirmed later from the damage mechanism observed from the experiment.

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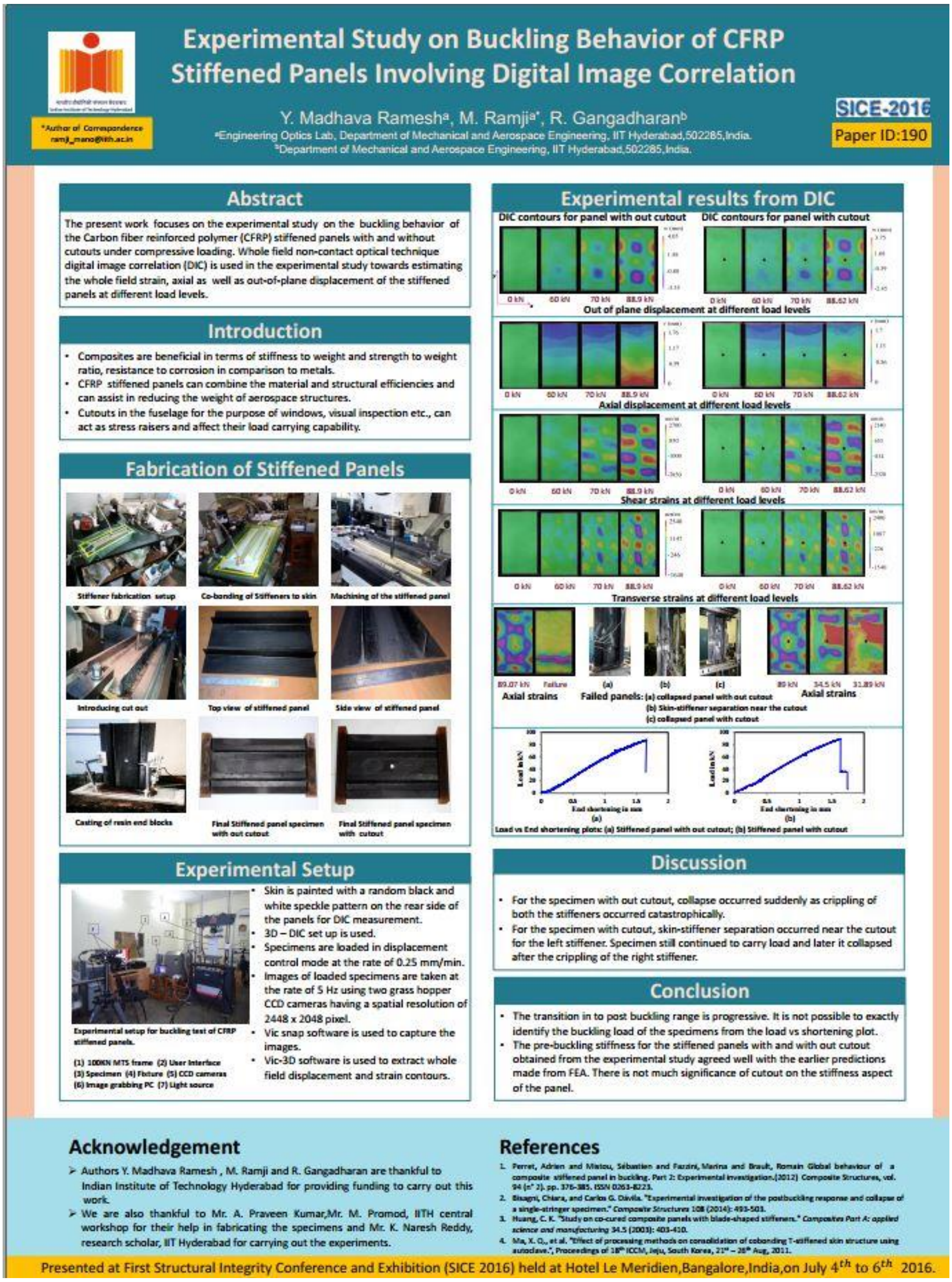

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