Stress Analysis of a Stepped-Lap Bonded Repair Joint in Composite Laminate under Compressive Loading

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Abstract

With increasing the usage of advanced composite materials in aircraft structures, it is required to have a suitable repair technology for composite airframe. One of the primary requisites of the repair in such structures is that the repaired surface should not affect the aerodynamic contour. Adhesively bonded repair joints are generally preferred over mechanically fastened repair joints to avoid the stress concentration and achieve smooth aerodynamic surface. Significant numbers of research works have been carried on interface stress distributions for lap, butt and scarf adhesive repaired joints under the static tensile loading. However, the behavior of stepped-lap adhesive joints under compressive loading has not been fully understood and there are not many literatures available on this subject. The present work focuses on stress analysis of a laminate that is repaired through a stepped-lap joint repair scheme. The stress analysis has been carried out and stress distributions in the laminate, patch and adhesive were studied. In order to establish and validate the FE approach for analysis of stepped-lap repair joint subjected to compression, an experimental study also has been carried out. The strains from the analysis have been compared with the strains obtained from the test at important locations. Both the results have shown good agreement.

1.0 INTRODUCTION

As fiber-reinforced composites are gaining wide acceptance in different industry especially in aerospace, it is essential to have suitable repair-techniques for composite airframe. Externally bonded or bolted patches in repair are only suited for lightly loaded structure that are not aerodynamically critical. For structure repair, generally adhesively bonded joint are favored over the bolted joints to avoid stress concentration. There are different types of bonded joints such as; single lap joints, scarf joints, tapered joint and stepped-lap joints [1]. However, single lap joints leaves a step on the surface that may be detrimental to aerodynamic performance and is suitable when low thick laminates are joined [2]. For thick laminate, scarf or stepped-lap bonded joint repair methodologies are preferred. A scarf joint repair is defined by the removal of the damaged area and the process of tapering the perimeter of the undamaged portion of the composite. A patch is then cut and scarfed to match the opening and then bonded in place. A step-lap joint is basically the same as scarf joint except that the step-lap joint is not a simple taper but it is having a series of uniform steps that form the taper. Both scarf and stepped-lap bonded repair techniques are typically expensive and time consuming to accomplish, hence it is necessary to understand the load transfer behaviors of these repair scheme before implement to structure. A stepped-lap bonded joint is widely used in composite structure of thickness more than 4mm, as the load transfer through step-lap joint is more uniform through shear [3]. There are lots of literature are available in stepped-lap repair joints behavior under tension loading and very less work are available for structure repaired with step-lap repair scheme under in-plane compression loading [4]. The present study shows the stress analysis of laminate under in-plane compression loading repaired with step-lap joint repair scheme. The 3D FE model is developed to simulate the stepped-lap repair in composite there by understanding the behavior of laminates subjected to compression loading. The 3D analysis has been carried out to capture the detailed stress variations at the joint location. The FE model has been validated with results obtained from an experimental work. The FE model will be used to study the strength of the repair through an extension of the present work.

2.0 PROBLEM STATEMENT

In present study, a carbon fiber composite (CFC) laminate is subjected to uniaxial compression loading. The dimension of the square CFC laminate is of 150mm X 150 mm having a thickness of 4.08 mm. The size of damage in the laminate is 50mm diameter and it is repaired with stepped-lap bonded joint repair scheme as shown in Fig 1. A stepped-lap repaired laminate consists of six steps with 5^0 slopes along the interface. Thickness of the adhesive between laminate and patch is 0.20 mm. Both the laminate and the patch are made of CFC. Equal lay-up sequence $(45,-45, 0, 90)_{3s}$ is maintained for the laminate and the patch. Mechanical properties of CFC material and adhesive are given in Table 1 and Table 2 respectively.

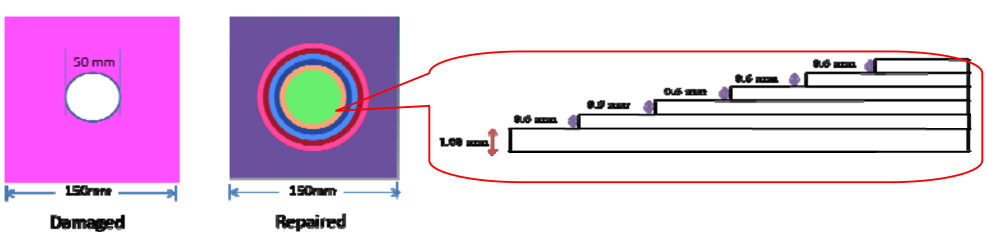

Fig. 1: Typical damage configuration and it's repair scheme

Table 1: Mechanical properties of UD Carbon/Epoxy composite materials

Young's modulus along fiber direction E_{11} [GPa]	130
Young's modulus along matrix direction E_{22} [GPa]	8
E_{33} [GPa]	8
In plane shear modulus G_{12}	3
G_{13} [GPa]	3
G_{23} [GPa]	3
In plane Poisson's ratio ν_{12}	0.32
N13	0.30
N_{23}	0.30

Table 2: Mechanical properties of adhesive materials

Young's modulus along fiber direction E_{11} [GPa]	3
In plane Poisson's ratio ν_{12}	0.33

3.0 FINITE ELEMENT MODELLING AND BOUNDARY CONDITIONS

Three dimensional finite- element modeling has been carried out in ABAQUS software using C3D8R elements. The adhesive between the laminate and patch is also modeled with three dimensional hexagonal elements to capture the stress distribution through the thickness. Due to axis-symmetry conditions, one quarter of plate is only modeled to reduce the size of the model and solving time. The FE-model consists of 69240 elements and 77958 nodes. Ten elements are used through the each steps thickness in laminate and patch. Four elements are used through the thickness in adhesive layer. Equivalent material properties are considered for each step thickness of plate and patch due to modeling constraints. The FE model of repaired laminate is shown in Fig.2. Appropriate boundary conditions have been used to simulate the symmetry conditions at the edges as shown in Fig.3.

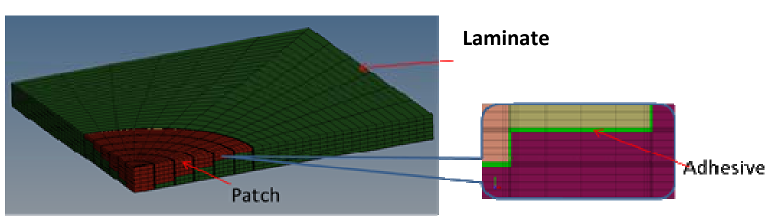

Fig. 2: Three dimensional FE-model of stepped-lap bonded laminate

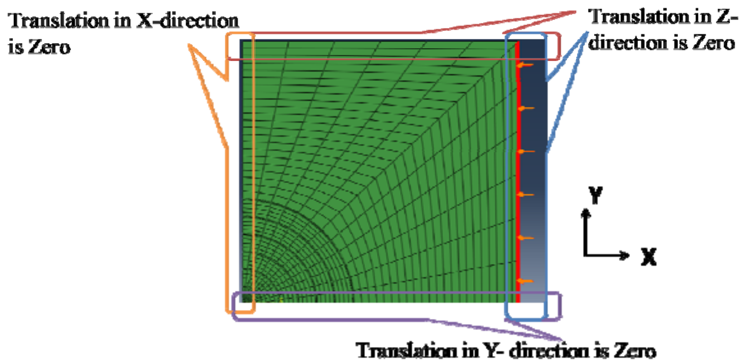

Fig. 3: Boundary conditions in Finite-Element model

4.0 RESULTS AND DISCUSSIONS

Finite element stress analysis is carried on repaired laminate with increasing the compressive loads till failure load of 108 KN and analysis is requested with stress, strain and displacements for full laminate. Failure-load is the load at which a repaired laminate of the same geometry and configuration failed in a test. Stress variations in all the parts of repaired laminate like patch, laminate, adhesive are studied at failure load. Distribution of in-plane compressive stress in repaired laminate is shown in Fig.4. Uniform compressive stress is observed on the repaired laminate except in the adhesive and its interface. There is stress concentration observed at the interface of the laminate and the patch. This stress concentration is due to steps and presence of unlike materials at interface. Right angle corner of each step in laminate and patch is also getting highly stressed as shown in Fig.5 and Fig. 6. Compressive stress in the direction of loading and in plane-stress in the adhesive is also shown in Fig.7. Vertical steps in the adhesive are more stressed as compared to horizontal steps for both compressive and in-plane shear stress, because of less thickness presence in loading direction.

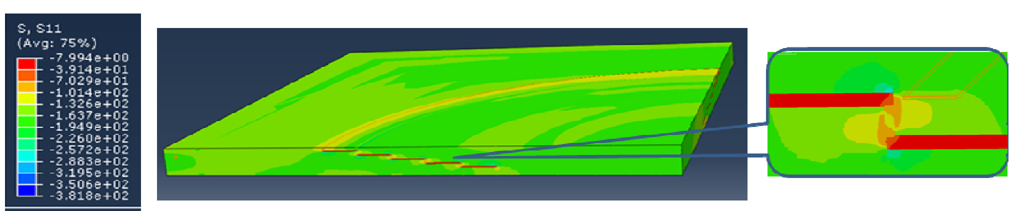

Fig. 4: Compressive stress distributions in Repaired laminate

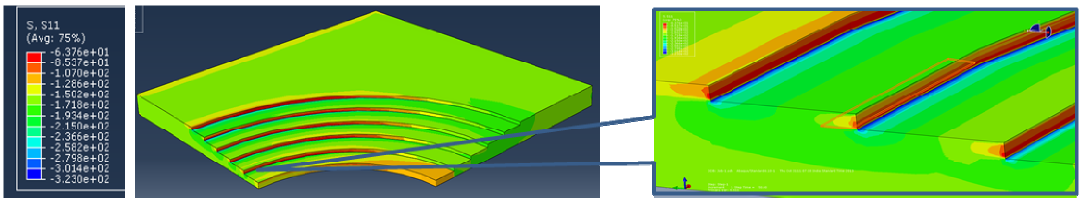

Fig. 5: Compressive stress distributions in laminate interface

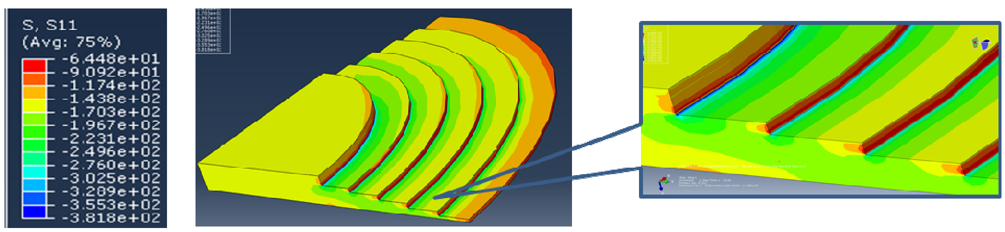

Fig. 6: Compressive stress distributions in patch interface

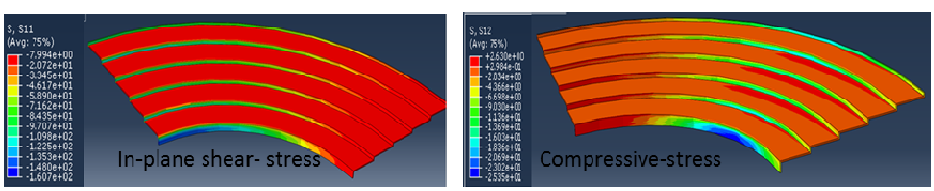

Fig.7: Compressive stress and In-plane shear stress distributions in adhesive

To establish and validate the FE-analysis methodology of stepped-lap repaired bonded joints, experimental studies also have been carried out on repaired laminates. For this, six different locations of strain gauge position are selected as shown in Fig. 8. Strain-gauge positions 1, 3 and 5 are on the patch (front) and strain-gauge positions 2, 4 and 6 are on the laminate (back). Directions of all strains gauge are in loading directions. Finite-element strains and experimental strains are plotted with the increasing the loads in the interval of 20 KN till the failure load (108KN) and strains are compared at all six locations. FE and experimental strains at location 1(front) and 2(back) are compared in Fig. 9 and it is found that both the strains are correlating well. Maximum variation in strain in this location is 5 %. FE and experimental strains at locations (3, 4) and locations (5, 6) are compared in Fig.10 and Fig. 11 respectively and it is observed that both the strains trends are correlating but variation in strains in these locations are 5 % at 20KN to 45 % at failure loads. Most probable reasons for increasing the variation in strains is local buckling in the test specimen or de-bonding in laminate in that area.

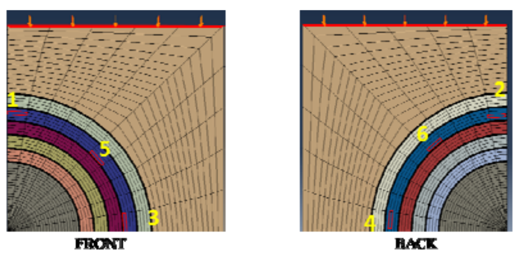

Fig. 8: Location of Strain- gauges in repaired laminate

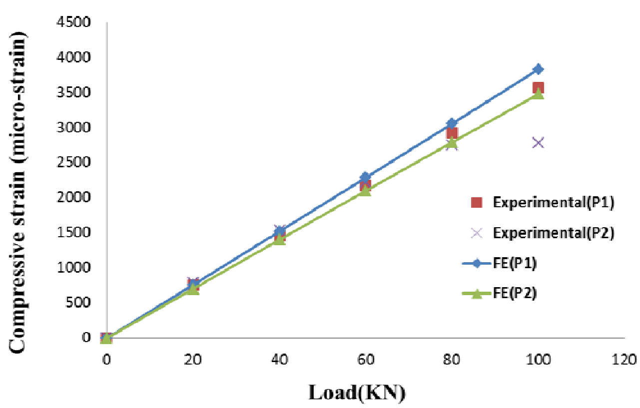

Fig. 9: Comparison of FE and experimental strain in repaired laminate at positions (1 and 2)

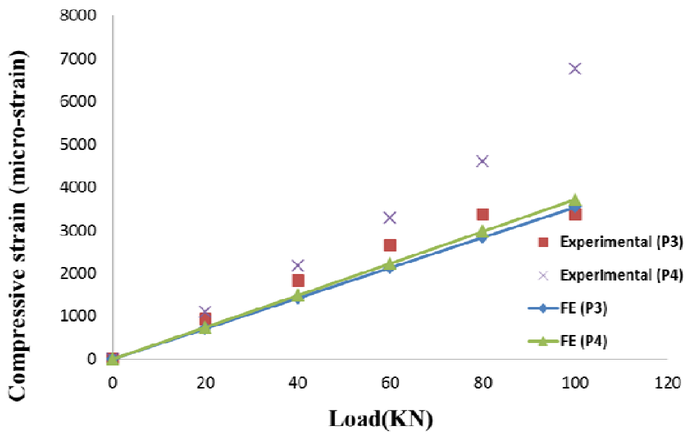

Fig. 10: Comparison of FE and experimental strain in repaired laminate at positions (3 and 4)

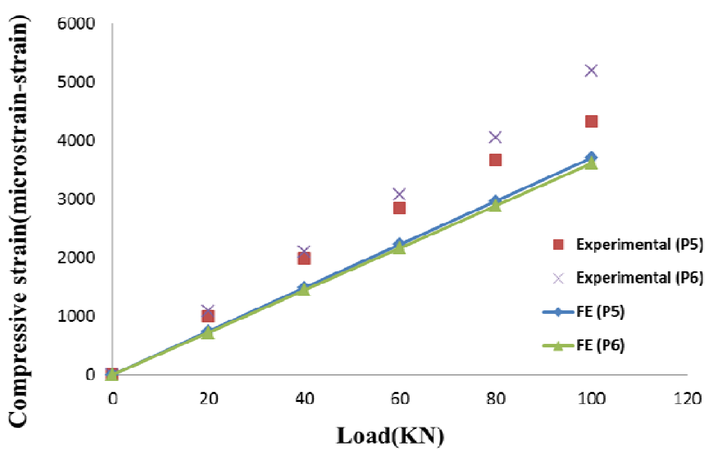

Fig. 11: Comparison of FE and experimental strain in repaired laminate at positions (5 and 6)

5.0 CONCLUSION

The study has brought out the stress behaviors of stepped-lap repaired joint laminate subjected to compressive loading. Based on stress distribution, critical area in each part of laminate, adhesive and patch is investigated. There are high stress concentration observed at the interface of laminate and patch specially at the corner of each steps. In case of adhesive, vertical steps is getting more stressed than horizontal steps for both in-plane normal and shear stress.

To establish and validate the analysis approach, finite-element and experimental strains are compared. In most locations there is a good agreement between the FE and the test results and the difference is within 5%. At one location there is a difference of 45% between FE and test strains. This could be mostly due to local buckling happened in the test. However, the trends of both the strains are same. To decrease the variation of strains and study the local buckling behaviors in laminate, it is required to model the layer wise three dimension modeling in composite parts and two dimensional modeling in adhesive parts. The present model can be used further for prediction of strength and study the failure of stepped-lap repair in laminate.

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