International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:11, No:10, 2017

# Design Modification of Lap Joint of Fiber Metal Laminates (CARALL)

Shaher Bano, Samia Fida, Asif Israr

***Abstract*—**The synergistic effect of properties of metals and fibers reinforced laminates has diverted attention of the world towards use of robust composite materials known as fiber-metal laminates in many high performance applications. In this study, modification of an adhesively bonded joint as a single lap joint of carbon fibers based CARALL FML has done to increase interlaminar shear strength of the joint. The effect of different configurations of joint designs such as spews, stepped and modification in adhesive by addition of nano-fillers was studied. Both experimental and simulation results showed that modified joint design have superior properties as maximum force experienced stepped joint was 1.5 times more than the simple lap joint. Addition of carbon nano-tubes as nano-fillers in the adhesive joint increased the maximum force due to crack deflection mechanism.

***Keywords*—**Adhesive joint, carbon reinforced aluminium laminate, CARALL, fiber metal laminates, spews.

## I. INTRODUCTION

FIBER METAL LAMINATES (FMLs) are basically a deployment of composite materials with a slight difference of idea of using two materials to produce a hybrid material. Conventional composites have a problem of fatigue cracking and low impact strength. Use of FMLs showed a visible difference in fatigue strength and impact strength [1]. FML is a hybrid structure composed of metal layers stacked in a layer-by-layer manner with a polymeric layer thus forming a sandwich structure. FMLs are made by joining metal or alloy sheets with polymeric reinforced plies. Metal sheets mainly used are of aluminium and titanium.

The combination of two different materials is advantageous in many ways such as combatting corrosion and excellent impact strength unlike metals. The development and progress of FMLs usage in various applications is a gradual process and started with, first, replacement of monolithic metallic aluminium sheets with thin sheets of aluminium, then improvement of the adhesive strength between the fibers, followed by usage and optimization of excellent mechanical properties of different types of reinforcement fibers [2]. In 1978, at University of Delft, experiments were conducted in order to enhance the fatigue strength of aluminium alloys and the scientists came up with an entirely new idea of combining two different materials in a form of a hybrid structure, with extraordinary fatigue strength. The very first FML was achieved by combining aluminium with aramid fibers and named ARALL [3]. After few years, carbon fibers were introduced to the aluminium laminates and CARALL was obtained. These laminates have carbon epoxy prepregs, when compared with ARALL, i.e. aluminium reinforced aramid fibers, give greater specific modulus values [4]. Third type of FML is GLARE. This FML is composed of glass fiber reinforced epoxy and aluminium layers (0.2-0.5 mm) [5]. GLARE is said to possess higher resistance to compressive load as compared to ARALL, moreover the adhesion between the glass fiber is better than aramid fibers in ARALL [6]. Production of FML involves mainly the autoclave process for the polymeric materials and majorly comprises of a couple of basic steps in manufacturing composite FMLs. Such as, pre-treatment of the metal sheets by some chemical reagents, e.g. acid, to improve the adhesion ability of the sheets followed by deposition of material by lay-up technique mainly, then curing and eventually post stretching of the FML in an autoclave in order to diminish the residual stresses from them. Last but not the least, inspection is carried out by a non-destructive testing technique to investigate cracks and flaws in the assembly of FMLs [5]. Moreover, two major types of lap joints are adhesively bonded lap joints and mechanically bonded lap joints. We will only discuss adhesively bonded lap joints.

Adhesive bonding is a widely used technique not only in the production of FMLs but also in aircraft and automobile production units. Adhesive bonding is preferred over mechanical fastening techniques due to its low damage tolerance, over-all reduction in the production cost and considerable reduction in the structural weight of the components. Mechanically bonded structures are more prone to corrosion than adhesively bonded structures. The adhesive layers act as crack dividers when cracking phenomena occur. This can help in the reduction of fatigue crack growths [7]. It should be noted that adhesive bonding process also requires some pre-treatment or surface modification in order to improve the surface roughness and adhesive bonding. These processes involve chemical, electrochemical, and mechanical treatments such as chemical degreasing, sand blasting, grit blasting. These mechanical and chemical processes enhance the macro-roughness of the surface and results in good wettability for adhesives. The conventional aluminium based parts of aircrafts are being replaced by the FMLs mainly because of the high fatigue tolerance and minimal crack growth rate during failure. Airbus A380 is the major example

Shaher Bano is with Institute of Space and Technology, Islamabad Highway, Islamabad 44000, Pakistan, as Research Assistant, Pakistan (phone: +92 332 5046068; fax: +92-51-9273310, e-mail: shaherbanoo@gmail.com).

Samia Fida, is with Institute of Space and Technology, Islamabad Highway, Islamabad 44000, Pakistan, as a Teaching/Research Associate, Pakistan (e-mail: samiafida902@gmail.com).

Asif Israr is with the Mechanical Engineering Department, Institute of Space and Technology, Islamabad Highway, Islamabad 44000, Pakistan, as Head of the Department, Pakistan (e-mail: asif.israr@ist.edu.pk).

of the use of FMLs in the aerospace industry for structural applications. ARALL is used in the fabrication of lower wing skin panels and cargo doors. Moreover, GLARE is in under testing for the application of main floorings of an aircraft [8]. It has also been reported that GLARE is used in the main fuselage skin of the Airbus A380 CARALL [1] is used in various aerospace applications like impact absorbers for helicopter struts [9].

Damage propagation in adhesive joints can be modelled and simulated using cohesive zone modelling CZM with the help of extended finite element XFEM analysis methods. CZM is not a physical entity rather it is a cohesive force that exists between two matting surfaces joined with any adhesive having material properties [10]. This method has been used in early 60s to predict damage under static loading relating relative displacement between opposing surfaces and force per unit area also termed as traction [11]. ABAQUS has been used in various researches to evaluate and analyzed the delamination and damage along adhesive bond lines using CZM. As in one approach, adhesively bonded single and double lap joints of aluminium adherends with overlap length of 5 mm and 20 mm have been simulated to compare the behavior and strength of both joints [12]. The mechanical properties under tensile loading of different single lap joint configurations both numerically and experimentally have also been studied by Gültekin et al. [13]. Similarly, in another study, the impact of adherend recessing at edges on the rigidity of single lap joint bonded using brittle adhesive was analyzed [14].

## II. MATERIALS AND METHODS

The materials were purchased from a local vendor in desired forms. Aluminum 2024 alloy sheets were in T3 condition with 0.5 mm thickness. Carbon fiber prepreg 3K 200 g has a thickness of 0.3 mm. EPOKUKDO YD-128 was used as adhesive with resin and hardener ratio of 65/35.

The different design configurations were first simulated in ABAQUS 6.10 then samples of FML of Al/Carbone fiber/Al stacking were prepared using carbon fiber UD pregreg and aluminium sheets of 0.5 mm thickness using compression molding technique.

## III. EXPERIMENTATION

### *A. Modelling and Simulation*

ABAQUS 6.10 was used to model and simulate the three different joint configurations. Cohesive zone modelling was carried out using 2-D modelling 4 node cohesive COH2D4 elements. The damage behaviour was simulated by implementing triangular traction separation law. The composite lamina was modelled using continuum shell elements. Cohesive elements were defined between the overlapped regions with a bond length of 25.4 mm and tie constraints was used to connect each layer of carbon fibre and aluminium. Fig. 1 represents the lay-up of the whole model was metal/composite/metal for each joint configuration with dimensions in accordance with ASTM D5868 standard.

TABLE I
PROPERTIES OF MATERIALS USED IN STUDY

| Properties | Carbon Fiber Prepreg | Aluminium 2024 | Epoxy | CNTs |
|---|---|---|---|---|
| **Transverse Elastic Modulus** | 142 GPa | 71 GPa | - | - |
| **Longitudinal Shear Modulus** | 8.8 GPa | - | - | - |
| **Transverse Shear Modulus** | 4.2 GPa | - | - | - |
| **Poisons ratio υ12** | 0.27 | 0.32 | - | - |
| **Poisons ratio υ21** | 0.21 | - | - | - |
| **Tensile strength** | - | - | 100 MPa | - |
| **Hardness** | - | | 105 M Rockwell | |
| **Average diameter** | - | - | - | 11 nm |
| **Average length** | - | - | - | 10µm |
| **Purity** | | | | >95% |
| **Thickness** | 0.3 mm | 0.5 mm | - | - |

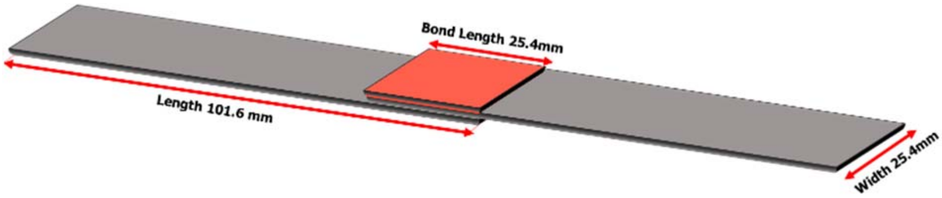

Fig. 1 Single Lap Joint dimensions according to ASTM D5868

Fig. 2 Layup of each FML for single lap joint

For experimentation, ten samples of simple lap joint, and the one in which carbon nanotubes were incorporated in adhesive were prepared according to ASTM D5868 standard.

### *B. Sample Preparation*

The experiment to conduct tensile test using UTM was completed in following stages:

1. Preparation of AL Sheets

Cutting of 0.5 mm thick Al 2024 sheets into 1 by 1 ft. sheets. Washed with detergent and grinded using 1200C sand paper of surface of each sheet, finally cleaned in acetone solution. The sheets were then immersed in 11 wt.% NaOH solution for 15 min.

2. Anodizing of AL Sheets

Al sheets were then anodized in electrolytic bath using platinum cathode to create a porous aluminium oxide layer on surface of the sheets for better adhesion with each other and the prepreg. The electrolyte was 12 wt.% phosphoric acid solution prepared in distilled water at an operating voltage of 12 V for 20–25 min at room temperature as shown in Fig. 3.

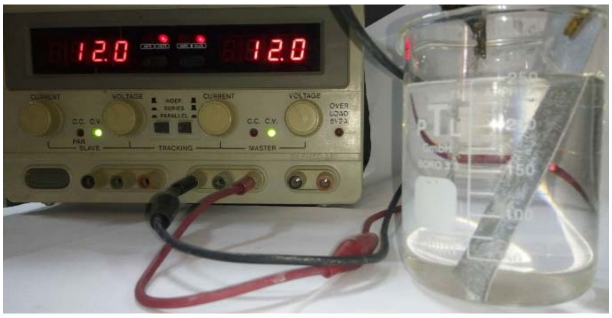

Fig. 3 Anodizing of Aluminium in 12 wt.% Phosphoric acid at 12V

### *a. Preparation of FML*

The anodized sheets were then attached with Carbon fibre fabric prepreg cut in same dimensions. The FML was then placed between two aluminium sheets of 3 mm thickness and tightened with the help of nut and bolts creating a compression mould for FML for better dimensions and avoid distortion. This mould was placed in an oven for 1hour at 150 °C to cure prepreg.

### *b. Preparation of Lap Joints*

Finally, the FML was cut into desired strips of 25.4*101.6 mm using MetaCut and lap joint was formed of bond length of 25.4 mm for all samples using epoxy with 65% epoxy and 35% hardener as adhesive. For spew joint configuration, 2 mm fillets were made using MetaCut. CNTs incorporated samples were prepared by first functionalizing CNTs, then 0.5 wt.% CNTs were dispersed in epoxy using sonication for an hour. After dispersion hardener was added to the epoxy, and overlap was formed using CNTs containing epoxy. The cured samples were subjected to tensile test on Universal Testing Machine (UTM).

## IV. RESULTS AND DISCUSSIONS

For the three different configurations modelled in ABAQUS 6.10 using CZM, variation in failure loads and stresses for each design was observed. The mesh sized was decreased for the cohesive region to simulate better results despite of the difference in stress at the edges of joint than the other areas. The model was subjected to tensile loading by keeping one edge fixed and applying displacement on the other end. A rigid body with a reference point was connected to the model on both ends to apply boundary conditions.

a. Simple Lap Joint
b. Stepped Joint
c. Spew Joint

As the presence of nano-fillers does not affect the design of the joint and modulus of adhesive, so it was not modelled in ABAQUS. But, all other three configurations were modelled by varying joint design to study the effect of adherends' shape on strength of the single lap joint. The variation in experimental and simulated results was observed for each design configuration. However, the trend of changes in maximum strength and force was the same in both experimented and modeled results. All of the simulated curves of load followed a bilinear triangular cohesive law of traction separation suggesting the exact implementation of cohesive law. The presence of adhesive on both faces of overlap after failure also confirmed cohesive failure of joints.

For simple lap joint configuration, it can be seen from Figs. 4 (d) and (e) that the value of maximum stress and loads stress and load was far less than the tensile strength of adhesive (epoxy). It is due to the sharp edges present in a simple lap joint configuration which can act as stress raiser resulting in failure at lower loads. In case of spew joint configuration, the rounded corners decreased the stress concentration and material failed at a load higher than simple lap joint in evident from both modelled and experimental results presented in Figs. 5 (d) and (e). The stepped lap joint with three steps of equal length failed at the maximum load and stress as the load displacement curve in Figs. 6 (d) and (e) shows failure of steps one after another providing two different values of force at which each step failed. Simulated curve of stepped joint provided three values of steps for each step unlike experimental results where only two values were obtained due to a number of constraints. The stepped configuration provides better strength as upon failure of each step another step exists to bear the load till the last step fails.

Simple lap joint incorporated with CNTs, was not modelled due to constraint of properties but it was subjected to tensile test. The results showed the highest maximum failure loads as compared to all three design configurations. By incorporation of nano-fillers, the strength of the adhesive increased from 80 MPa to 97 MPa due to crack arrest mechanism resulted from presence of nano-fillers in adhesive. This shows that incorporation of CNTs or other nano-fillers increases the strength of adhesively bonded joint; however, this method is somehow economical as it involves cost of nano-fillers.

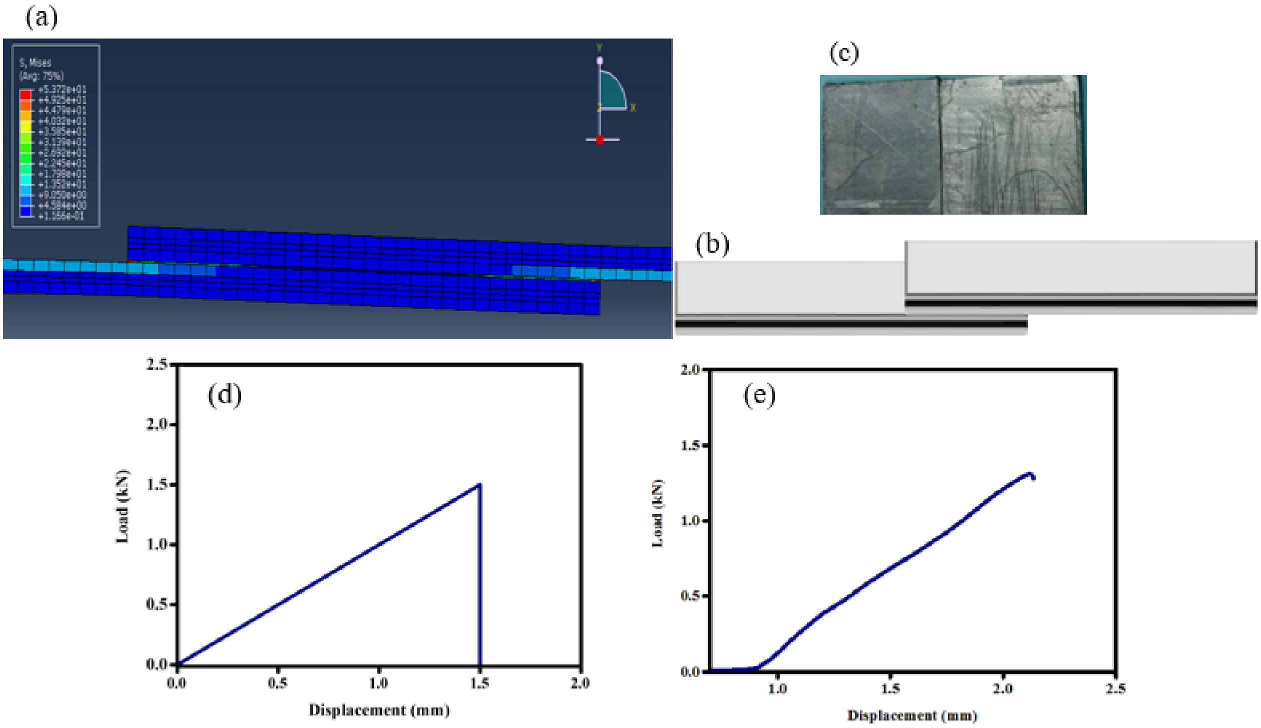

Fig. 4 (a) Simulated simple lap joint, (b) Simple lap joint design (c) Sample after testing showing cohesive failure. Load vs displacement curve of (d) simulated (e) experimented.

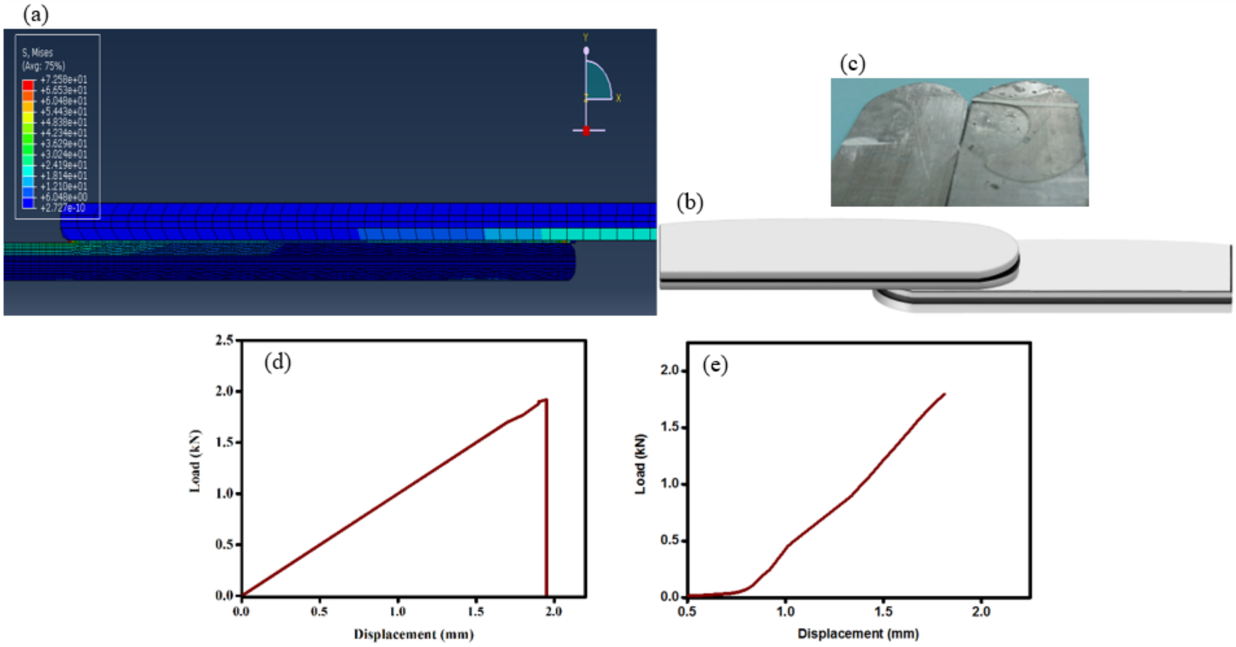

Fig. 5 (a) Simulated spew lap joint, (b) Spew lap joint design (c) Sample after testing showing cohesive failure. Load vs displacement curve of (d) simulated (e) experimented.

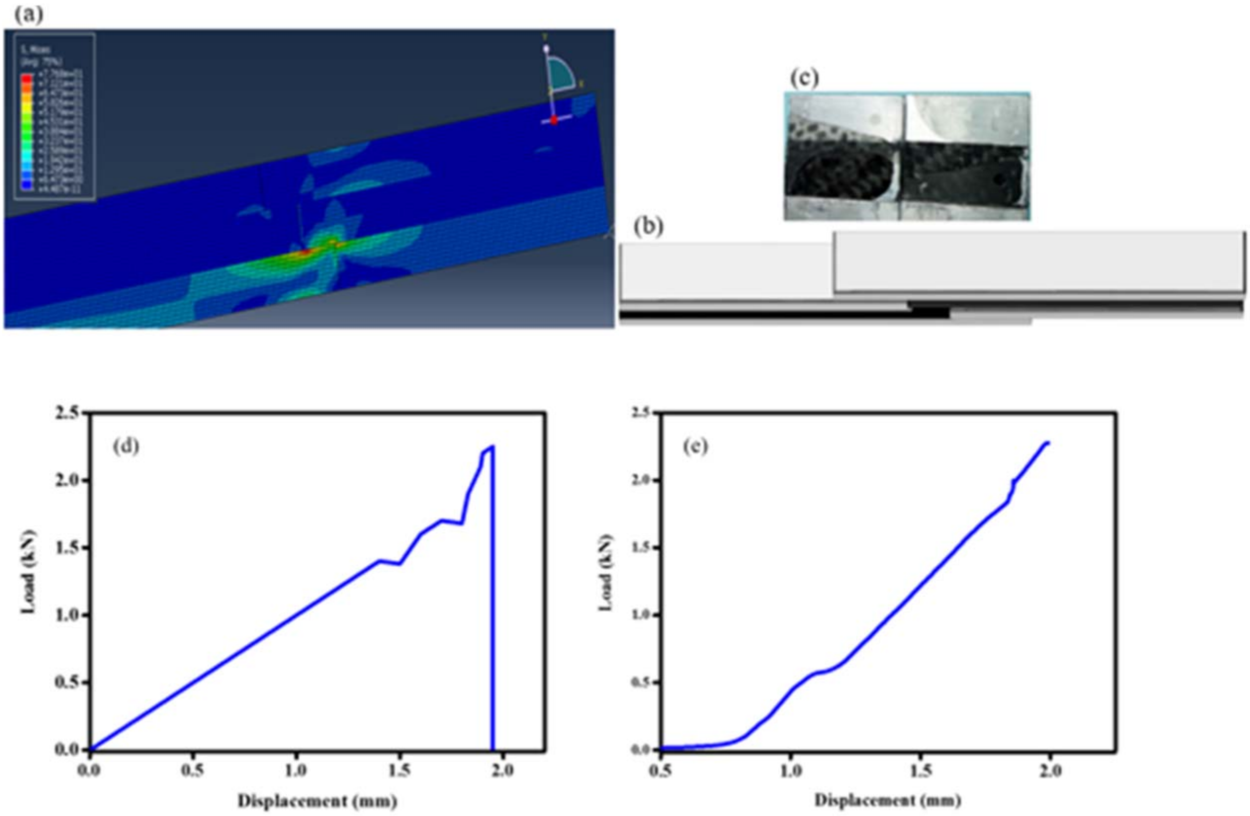

Fig. 6 (a) Simulated stepped lap joint, (b) Stepped lap joint design (c) Sample after testing showing cohesive failure. Load vs displacement curve of (d) simulated (e) experimented

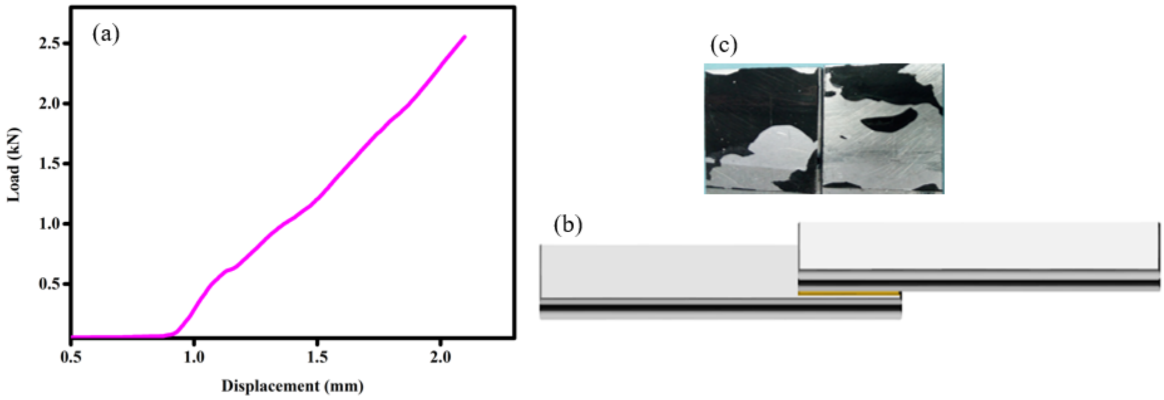

Fig. 7 (a) Load vs. displacement curve of lap joint with CNTs incorporated along the bond line subject to tensile loading, (b) lap joint containing CNTs design (c) Sample after testing showing cohesive failure

.

TABLE II
COMPARISON BETWEEN MAXIMUM LOAD AND STRESS OF ALL DESIGN CONFIGURATIONS MODELLED AND EXPERIMENTED

| **Design Configurations** | **Max. Force, kN** | | **Max. Stress, MPa** | |
|---|---|---|---|---|
| | **Simulated** | **Experimental** | **Simulated** | **Experimental** |
| **Simple Lap** | 1.5 | 1.3 | 53 | 47 |
| **Spew Joint** | 1.9 | 1.79 | 72 | 70 |
| **Stepped Joint** | 2.25 | 2.19 | 77 | 75.7 |
| **CNTs** | -- | 2.4 | -- | 97.9 |

The experimental and numerical results presented in Table II suggest that stepped joint is the best design configuration as it failed at higher loads and has maximum stress compared to the other configurations. The variation in experimental and simulated results is approximately ±2 for simple lap joint, ± 0.11 for spew joint and ± 0.06 which is least for stepped joint configuration. The variation in simple lap joint is more due to experimental conditions and higher stress concentration during experimentation.

## V. CONCLUSION

Adhesively boned lap joint was modified by varying design configurations and incorporation of CNTs along the bond line. All the tree design configurations were modelled and prepared experimentally to compare the maximum force to failure and stress under tensile loading. The comparison showed that stepped joint has maximum force to failure compared to the other loads and is more durable as upon failure of one step another step is still intact to bear the loading. The simple lap joint incorporated with CNTs was not modelled as there is no change in modulus of adhesive or design of overlap but was tested experimentally under tensile loading. It was revealed that the CNTs acted as barriers for propagation of crack and hence failed at highest load as compare to other three configurations.

## ACKNOWLEDGMENT

Extend gratitude to the Mechanical Department of Institute of Space and Technology.

## REFERENCES

[1] Shim D. J., Alderliesten R. C., Spearing S. M., and Burianek D. A., 2003, “Fatigue crack growth prediction in GLARE hybrid laminates,” Composites Science and Technology, 63(12), pp. 1759–1767.

[2] Schijve J., van Lipzig H. T., van Gestel G., and Hoeymakers A. H., 1979, “Fatigue properties of adhesive-bonded laminated sheet material of aluminum alloys,” Engineering Fracture Mechanics, 12(4), pp. 561–579.

[3] Srivastava V. K., 2011, “Effect of carbon nanotubes on the strength of adhesive lap joints of C/C and C/C–SiC ceramic fiber composites,” International Journal of Adhesion and Adhesives, 31(6), pp. 486–489.

[4] Moussavi-Torshizi S. E., Dariushi S., Sadighi M., and Safarpour P., 2010, “A study on tensile properties of a novel fiber/metal laminates,” Materials Science and Engineering: A, 527(18), pp. 4920–4925.

[5] Botelho E. C., Silva R. A., Pardini L. C., and Rezende M. C., 2006, “A review on the development and properties of continuous fiber/epoxy/aluminum hybrid composites for aircraft structures,” Materials Research, 9(3), pp. 247–256.

[6] Asundi A., and Choi A. Y. N., 1997, “Fiber metal laminates: An advanced material for future aircraft,” Journal of Materials Processing Technology, 63(1-3), pp. 384–394.

[7] Lin C. T., Kao P. W., and Yang F. S., 1991, “Fatigue behavior of carbon fiber-reinforced aluminium laminates,” Composites, 22(2), pp. 135–141.

[8] Alderliesten R., 2009, “On the development of hybrid material concepts for aircraft structures,” Recent Patents on Engineering, 3(1), pp. 25–38.

[9] Lin C. T., and Kao P. W., 1995, “Effect of fiber bridging on the fatigue crack propagation in carbon fiber-reinforced aluminum laminates,” Materials Science and Engineering: A, 190(1-2), pp. 65–73.

[10] Khoramishad H., Crocombe A. D., Katnam K. B., and Ashcroft I. A., 2010, “Predicting fatigue damage in adhesively bonded joints using a cohesive zone model,” International Journal of fatigue, 32(7), pp. 1146–1158.

[11] Liljedahl C. D. M., Crocombe A. D., Wahab M. A., and Ashcroft I. A., 2006, “Damage modelling of adhesively bonded joints,” International journal of fracture, 141(1), pp. 147–161.

[12] Campilho R. D., Banea M. D., Pinto A. M. G., da Silva L. F. M., and Jesus A. M. de, 2011, “Strength prediction of single-and double-lap joints by standard and extended finite element modelling,” International Journal of Adhesion and Adhesives, 31(5), pp. 363–372.

[13] Gültekin K., Akpinar S., and Özel A., 2014, “The effect of the adherend width on the strength of adhesively bonded single-lap joint: Experimental and numerical analysis,” Composites Part B: Engineering, 60, pp. 736–745.

[14] Pinto A. M., Campilho R., Mendes I. R., and Baptista A. P., 2014, “Numerical and experimental analysis of balanced and unbalanced adhesive single-lap joints between aluminium adherends,” The Journal of Adhesion, 90(1), pp. 89–103.