Use of Nomex Honeycomb Composites for Secondary Structures in Aircraft Industry

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Abstract. Composites are extensively used in the aeronautical industry for secondary structures like aircraft part that include galleys, sidewalls, ailerons, flooring and ceiling as well as in the manufacture of aircraft seats. An emerging class of such composites comes under the name of Fiber Metal Laminates (FML). Traditionally, they comprise of thin metal sheets with fibrous reinforcement layers embedded in a suitable resin. ARALL – Aramid Fiber Reinforced Aluminum Laminates was the first class of FML's that was developed for the fuselage of the airplane. ARALL is composed of two constituent's i.e. Kevlar in the middle with Aluminum on both of its ends. Further studies in this subject led to the assembly of two other variants known as GLARE and CARALL. GLARE and CARALL consists of glass fiber and carbon fiber in place of KEVLAR respectively.

In recent times use of carbon fiber composites is increased enormously in Formula 1 Cars, Rockets, satellites and especially in aero planes. For example Boeing 787 has about 50% of its structure made of Carbon Fibers Composites. But the issue is that it is brittle in nature and unrepairable. To improve these features innovative specimens made of carbon fiber reinforced hybrid sandwich honey comb structure were prepared and tested. This is similar to CARALL but it includes Nomex Honeycomb at the center along with Carbon Fibers, altogether acting as core between two Aluminum sheets. Four Point Bending tests were used to study the improvement in properties followed by DIC (Digital Image Correlation) method that was used to find the point of fracture. The results were compared with CARALL and both models were simulated on Abaqus. A good correlation between experiment and simulation was found.

Keywords— Composite Structures, Carbon Fiber, Nomex Honey Comb, Aluminum, Four point bending, Digital Image Correlation

1. Introduction

Knowledge and understanding of the uses, strengths, limitations, and other characteristics of structural metals is vital to properly construct and maintain any equipment, especially airframes. In aircraft maintenance and repair, even a slight deviation from design specification, or the substitution of inferior materials, may result in the loss of both lives and equipment. The use of unsuitable materials can readily erase the finest craftsmanship. The selection of the correct material for a specific repair job demands familiarity with the most common physical properties of various metals.

Aluminium has been the standard material used in aircraft for more than a century - even the Wright brothers' famous first flight in 1903 used an aircraft made partially from the metal. And still Aluminum is one of the most widely used metals in modern aircraft construction. It is vital to the aviation industry because of its high strength to weight ratio and its comparative ease of fabrication. The outstanding characteristic of aluminum is its light weight. Aluminum melts at the comparatively low temperature of 1,250 °F. It is nonmagnetic and is an excellent conductor. High strength Aluminum alloys are used widely in fuselage skins as well as in upper and lower wing skins [1]. But the 'aluminium age' could be about to end - with the delivery of the first large-scale commercial aircraft made using 50 per cent 'composite materials' including plastics and carbon fibre.
Composite materials are now widely used in aircraft structures because of the extensive useful properties that they exhibit. ARALL CARALL and GLARE are most widely used their construction is shown

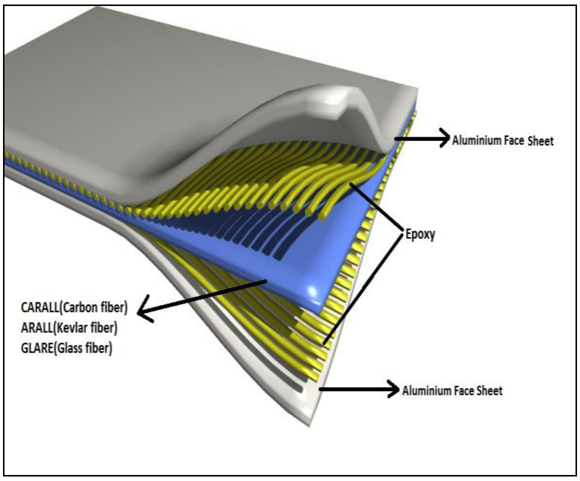


Figure 1: Materials are combined together to enhance the properties exhibited by its constituents

This rapid composite repair technique offers temporary repair capability to get an airplane flying again quickly, despite minor damage that might ground an aluminum airplane. All these special properties have also enabled engineers to think about innovative designs.
Such innovative materials and reinforcement matrices have been developed that enable us to choose from a vast array of properties allowing improved characteristics and exceptional performances. Different sets of properties can be achieved by altering parameters such as the type of alloy used, the orientation of the fiber, stacking sequence, number of layers of the materials etc. Among these GLARE and CARALL is most widely used in aerospace. As shown in the figure below:

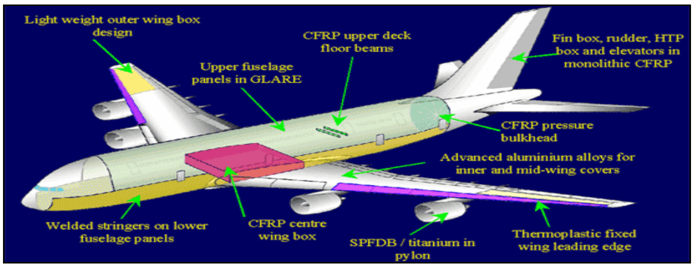


Figure 2: Upper fuselage shell of the A380 airplane using GLARE as the main composite

The most important set of features of composite structures are the weight saving that they bring into use. Instead today's latest planes like Boeing's 787 Dreamliner and Airbus's A350 rely on lightweight carbon fibre composites. Each kilogramme cut means a saving of roughly $1m (£603,000) in costs over the lifetime of an aircraft, he calculates - and the use of such composites can reduce the weight of an aircraft by up to 20%. A lot of research is going for modelling of new industrial designs and materials related to carbon fibers. One development of this research has been the trailing edges of the wing of Airbus's latest plane, the A350 and fuselage of Boeing 787.

2. Materials

A. Aluminum 2014 T3 Alloy

For the fabrication of ARALL, Aluminum alloy from 2XXX series[2], comprising of Copper and Magnesium as its major alloy was chosen. The alloy was preferred over other options0 because of the edge that it has in its fatigue properties. The type 2014 T3 refers to solution heat treated, cold worked and naturally aged alloy. The solution heat treatment involved three major stages. Initially, a super saturated solution of Copper in Aluminum was made by heating the mixture to about 500Oc, which was later cooled rapidly so that copper does not get time to precipitate out of the solution becoming a part of the crystal. After some time the copper is separated from the solution in the form of copper rich compounds. The resulting formation of the compounds results in the alloy being stronger and harder than before. Aluminum sheets used for the ARALL composites were chosen to not exceed 0.5 mm.

B. Carbon Fiber

To produce Carbon fiber the carbon atoms are bonded together in crystals that are more or less aligned parallel to the long axis of the fiber as the crystal alignment gives the fiber high strength to volume ratio, making it stronger for its size. Several thousand carbon fibers are bonded together to make a tow, which may be used by itself or woven into a fabric. Some of the properties that make them extremely useful in the aircraft industry include their high stiffness, high tensile strength, low weight, high chemical resistance, high thermal tolerance and low thermal expansion.

C. Nomex Honeycomb

Phenolic Resin Honeycomb is manufactured from NOMEX aramid fiber sheet. A thermosetting adhesive is used to bond these sheets at the nodes, after expanding to the hexagonal or OX-Core configuration. The geometry of honeycomb structures can vary widely but the common feature of all such structures is an array of hollow cells formed between thin vertical walls. The cells are often columnar and hexagonal in shape. A honeycomb shaped structure provides a material with minimal density and relative high out-of-plane compression properties and out-of-plane shear properties.

Man-made honeycomb structural materials are commonly made by layering a honeycomb material between two thin layers that provide strength in tension. This forms a plate-like assembly. Honeycomb materials are widely used where flat or slightly curved surfaces are needed and their high strength-to-weight ratio is valuable. They are widely used in the aerospace industry for this reason, and honeycomb materials in aluminum, fiber glass and advanced composite materials have been featured in aircraft and rockets since the 1950s. They can also be found in many other fields, from packaging materials in the form of paper-based honeycomb cardboard, to sporting goods like skis and snowboards

D. Adhesive System

For the bonding of the major constituents, Araldite LY5052 epoxy resin and Aradur 5052 hardener is used. Curing time is 24 hours at room temperature however the cured resin should be post cured at 100OC to optimize extent of cross linking and hence the composite properties.

3. Methodology

At the outset of the whole process Aluminum sheet of 2024 T3 alloys were mechanically and electrochemically prepared before actual composite fabrication, in order to make it mechanically stable. For the purpose, surface preparation was carried out in order to obtain contamination free surface with roughness and enhanced wet-ability. The processes involved are mentioned below:

A. Surface Preparation

For the formation of bonds on the surface it is essential that dirt, debris and grease are removed. The surface is both mechanically and chemically treated. For the purpose degreasing of the surface and surface abrasion later on is carried out. Solvent degreasing only removes grease and debris but doesn't provide the surface conditions necessary for durable bonding. In order to make the bonding reliable chemical pretreatment is employed at the end of surface preparation in order to avoid from future contamination. [3]

For the purpose of bond formation between the alloy of Aluminum and carbon fiber sheet the following steps were taken:

1) Alkaline cleaning

Aluminum sheets were mechanically prepared as described earlier. The sheets were immersed in 11 percent per weight of NAOH solution (15minutes).

2) Abrasion

This was done by using sand paper of sizes of 300C, 600C, 800C, 1000C and 1200C.

3) Deoxidation

Clean Aluminum alloy sheets were immersed in a de-oxidant at 80oC for 25 minutes, which had the composition of 10 wt% Sodium dichromate, 30 wt% Sulphuric acid and 60 wt% distilled water.

4) Anodization

Sheets were then anodized in 12wt% Phosphoric acid solution in distilled water at an operating voltage of 12V for 20-15 minutes.

Surface treatment method [4] anodizing is an electrochemical process in which a protective layer of oxygen is developed on the surface of aluminum. Aluminum is immersed in an electrolyte as an anode and current is made to flow between the two electrodes. Cathode is usually of Carbon or Stainless Steel and it stays neutral in the entire process. Electrons are disassociated from the metal surface and ions are left behind to travel through the electrolyte to react with water to produce hydrogen gas at the cathode.

The selection of the electrolyte plays the most important role in the development of the film that is grown on the material's outer side. It is selected keeping in view the rate of disbanding of the oxide layer, which should be lesser than the deposition of the oxide layer, for the oxide layer to grow.
Depending on the electrolyte, porous and barrier are the two kinds of film which can be made to grow on the surface of the metal. Porous layer exhibits better interfacial properties. The layer is made by acidic baths such as those with phosphoric and sulphuric acids. In aerospace industry Phosphoric acid is used to grow porous oxide layer on metal surface to facilitate laminate bonding. Dissolution/disbanding process of the film takes place alongside the deposition process, resulting in the pore formation in the oxide layer. Chemical representation of the dissolution of the oxide layer is given below [5]:

$$Al_2O_3(s) + 6H^+ \rightarrow 2Al^{3+}(aq) + 3H_2O$$

All the above mentioned steps were performed using ASTM D3933 standard. In the end, the sheets were primed to save the oxide layer from reacting with the environment. Thickness of the porous Aluminum oxide layer is increased by increasing the time of the anodizing process which may exhibit adverse effects on its adhesion properties.

Figure 3: Surface treatment process for adonization of Aluminum

B. Pressing and Post curing

The specimen is then pressed in a mold for proper bonding between epoxy, aluminum and carbon fibers. The mold has weights and nuts for tightening. A settling time of 24 hours is given for specimen to settle in the mold. After this remove the specimen for post curing.

The specimen when removed from mold is placed in the furnace for half hour. Temperature of the process is 90°C. When a sample is placed in the heated environment of furnace the crosslinking between and carbon fibers occurs. There is transition temperature for post curing. When crosslinking is done at room temperature the transition temperature is increased and even if there are unreacted parts the reaction still slows down at room temperature.

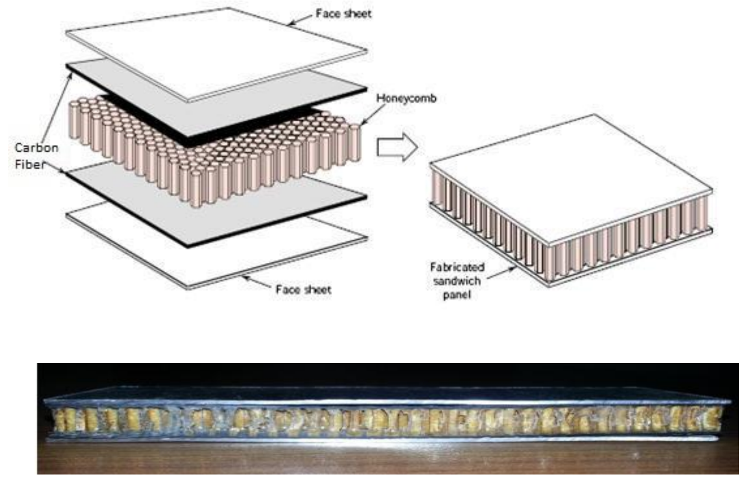


Figure 4*:* Assembling elements

Now in the post curing as the temperature is increased the crosslinking increases at elevated temperatures. If the specimen is heated above actual value of transition temperature the agglomeration of the particles may occur and there will be an increase in chain mobility and hence the electric properties are changed.

C.Four Point Bending

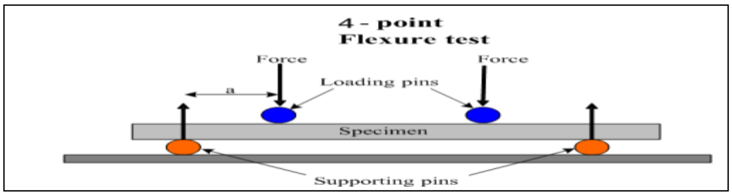


Figure 5 – Schematic showing individual forces in a 4 Point Flexture Test

ASTM Standard C393 was followed for performing four point bending test of structural composite (sandwich structure) on Material Test System 810. Two types of specimens were prepared i-e Honey Comb Sandwich and CARALL. Six specimens were prepared for each type. Their peak load and displacement were compared. The specimens were mounted on MTS and distance between load span and supporting span were set according to standard

Our specimens has the following dimensions

Honey Comb Sandwich:		
Length =120 mm,	Width =38 mm,	Depth = 12 mm
Carall:		
Length =120 mm,	Width =38 mm,	Depth = 4mm

According to the dimensions of our specimens, the following test specifications were used in the testing of our specimens.

Length of load span = 38 mm Length of support Span = 76 mm

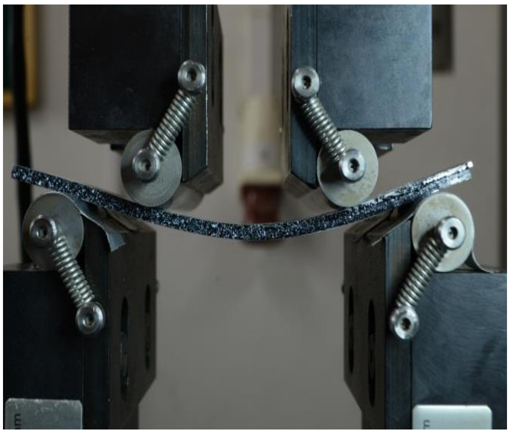


Figure 6 – Four Point Bending Test carried on honey comb specimen (Zero Load)

Figure 7 – Four Point Bending Test carried on honey comb specimen (max load)

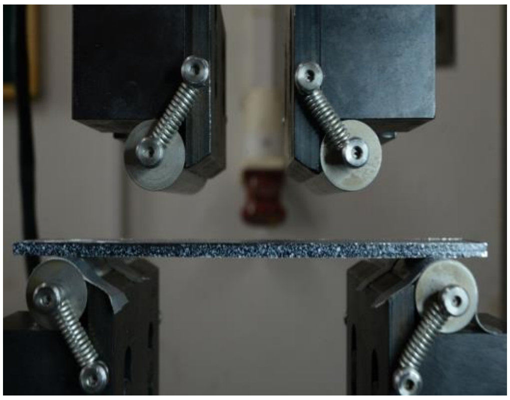


Figure 8 – Four Point Bending Test carried on CARALL specimen (Zero Load)

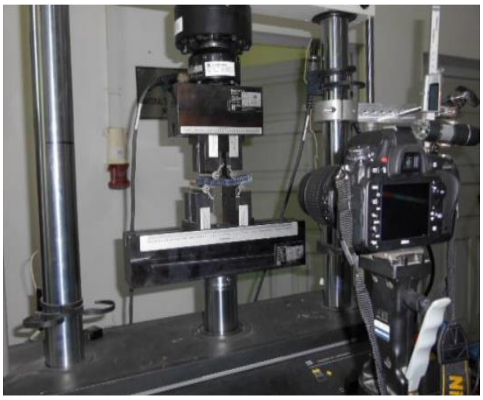


Figure 9 – Four Point Bending Test carried on CARALL specimen (max load)

D. Digital Image Correlation

DIC is an easy to use optical method which measures deformation on an object's surface. The method tracks the changes in gray value pattern in small neighborhoods called subsets during deformation. Digital Image Correlation has repeatedly proven to be accurate when compared to valid FEA models. The commercially available VIC-2D and VIC-3D systems from Correlated Solutions utilize this advanced optical measurement technology.

Calculating the transformation parameters for images under different loading conditions, both the displacement vector and deformation for each facet can be deter-mined. With the help of high speed camera images were taken and then with the help of Matlab images were correlated and required values of force at beginning of delamination were calculated.

Figure 10: High resolution camera taking various snapshots

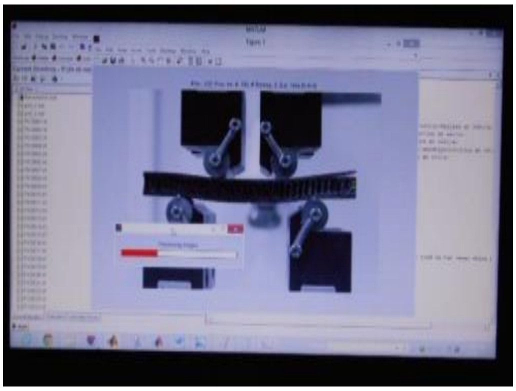


Figure 11: Digital Image Correlation Process in MATLAB

4. Results and Discussion

Four point bending test with monotonic loading was performed at both types of specimens. Load was plotted both against displacement to compare the peak load and brittleness behavior of both specimens.

Following parameters were selected for test.

- Crosshead speed was 0.1mm/sec
- Data points was 50 per second

The peak load for both specimens are found to be

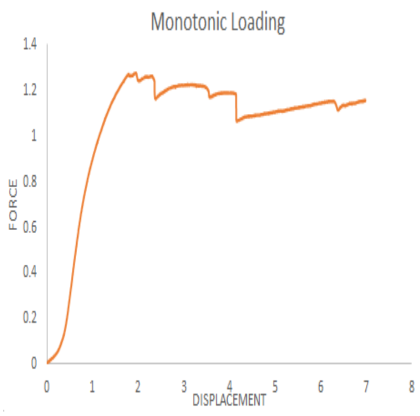
- Honey Comb Sandwich has a peak load of 1.2KN
- CARALL specimen has a peak load of 0.9kN.

Initially the rise of force response of CARALL was more linear than HONEY COMB specimen. But then there was abrupt decrease in force in case of CARALL. This is due to the brittle behavior of carbon fibers as we know this from previous research. In case of HONEY COMB specimen there was no abrupt decrease in force it shows more ductile behavior. This is because of HONEY COMB characteristic that it does not break at once.

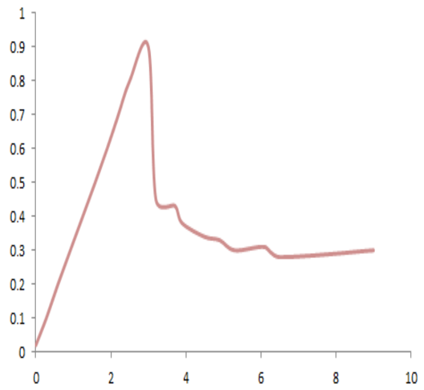
The peak load for HONEY COMB specimen was more than the CARALL. This is due to the property of HONEY COMB that it has very compression resistant.

Figure 12: Honeycomb Structure (Delaminated)

The final results of testing are shown below:



F-s graph: Honey Comb



F-s graph: CARALL

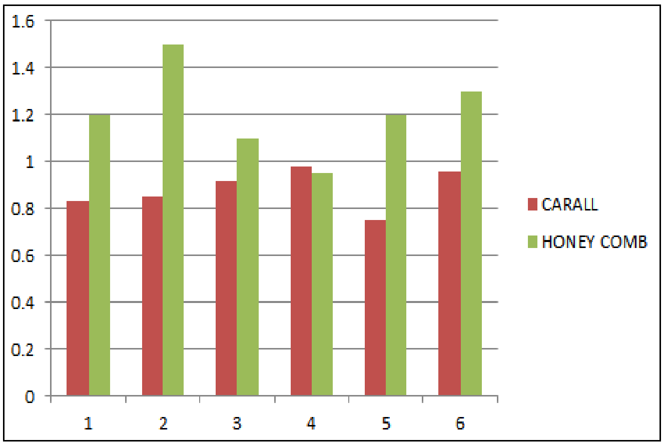


Figure 13: Comparison of experimental results of CARALL and HONEY COMB

4. Simulation

Simulation was done on ABAQUS 6.10 and following steps were involved:

- Creating the Part Geometry
- Defining the Material
- Creating and Assigning the Section
- Defining the Boundary Conditions
- Creating the Load
- Meshing the Geometry
- Creating and Submitting the Job for Results

The final results of simulation are shown below:

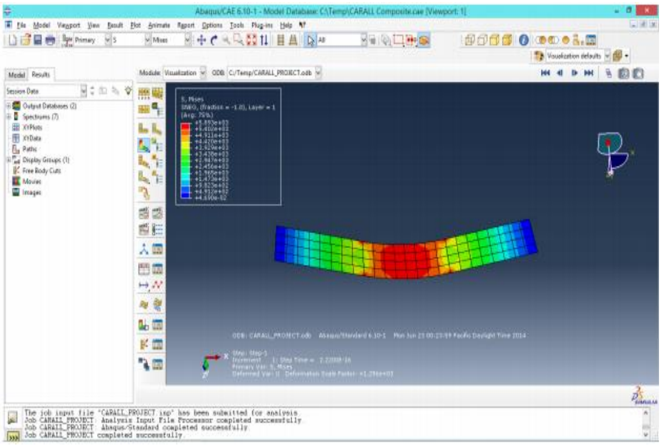


Figure 14: Simulation result of CARALL

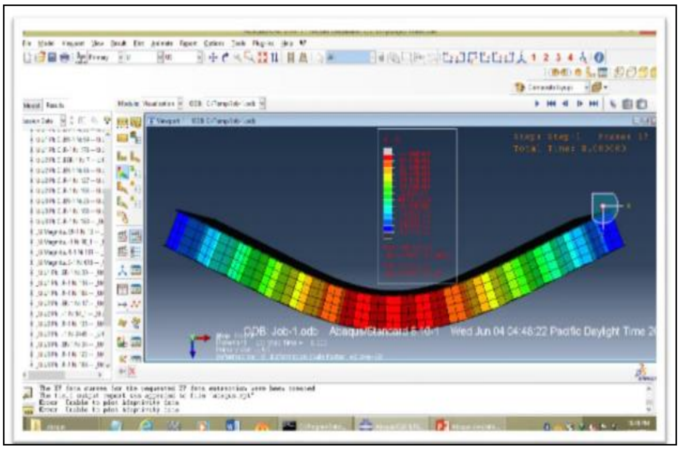


Figure 15: Simulation result of HONEY COMB

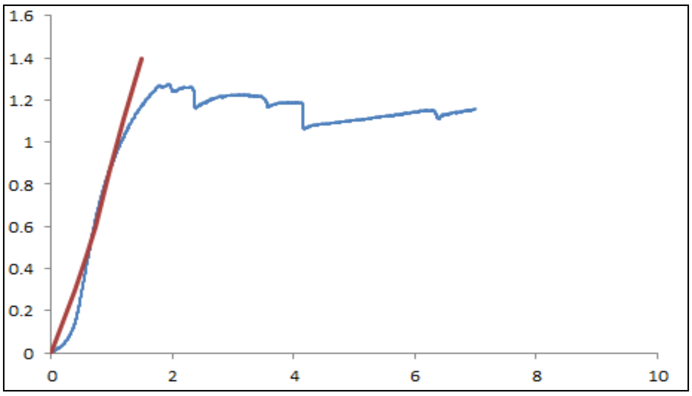


Figure 16: Comparison of experimental and simulation results for Honey Comb

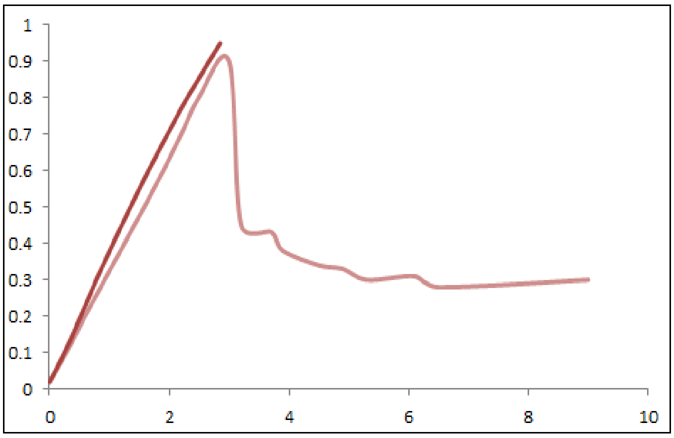


Figure 17: Comparison of experimental and simulation results for CARALL

Multiple tests were being carried out however numerical simulation was carried out for averaged force displacement curves only. Top face sheet was modeled and given the properties of Aluminum. The material model used for the Aluminum is an incremental plasticity model for aluminum 2024 T3 AL clad with E=72.4 GPA and σ=345 MPa. The epoxy properties were also defined. Carbon fiber was modeled as homogeneous material with E=5GPA. The mesh consists of CPE8 (An 8-node biquadratic plane strain quadrilateral elements) with an average size of 1 mm. Applying the boundary conditions, the results are as follows.

4. Conclusion and Recommendations

The characteristics improving scheme presented in this paper related to CARALL shows that the peak load bearing can be improved by inserting a HONEY COMB structure as a core between two face sheets of CARALL. The brittle behavior of Carbon Fibers can also be overcome by using NOMEX HONEY COMB because it has a very good compression force and also due to the cell configuration of HONEY COMB it does not break at one giving CARALL a ductile behavior which is very necessary in air craft wings and many other applications.

Honey comb specimens delaminated earlier than CARALL. This delamination can be improved by using different epoxies. And also advanced pressing techniques can be employed such as VARTM or AUTOCLAVE. This is left as future work.

Acknowledgments
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