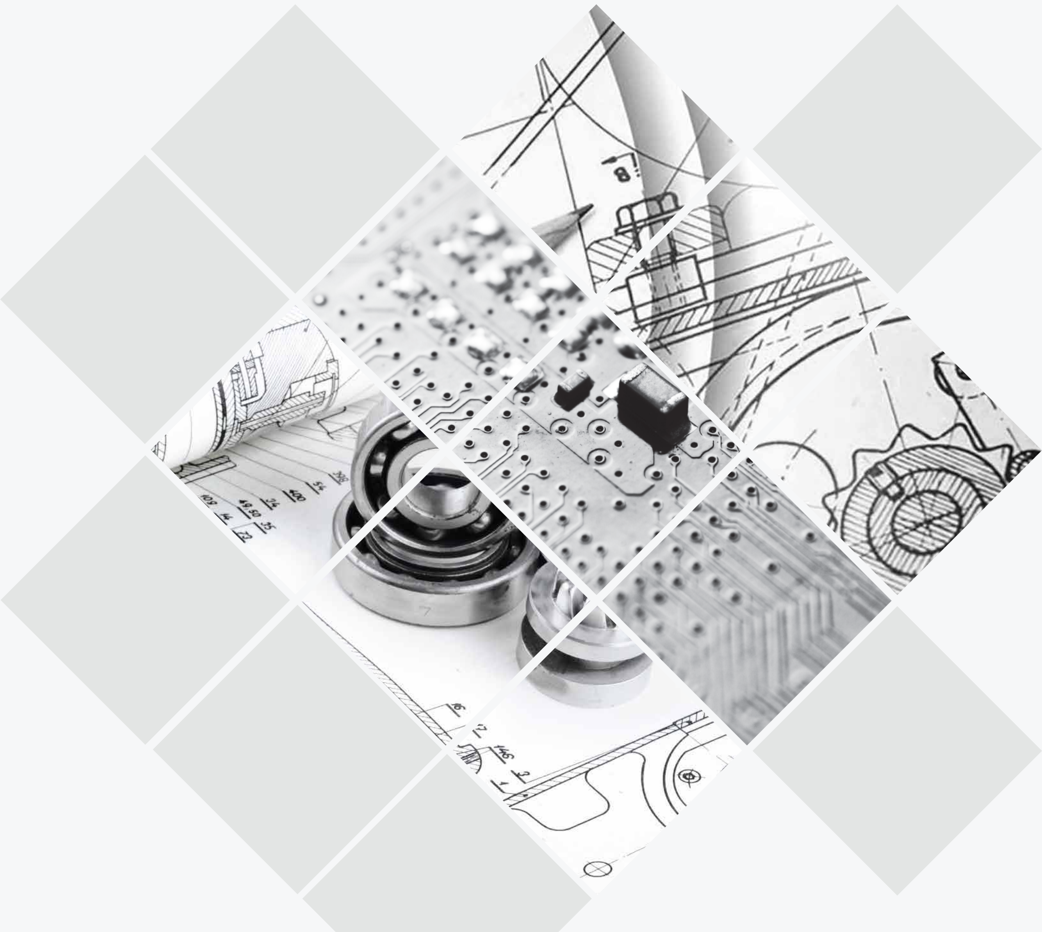
numerical analysis of metal-composite hybrid joint subjected to static loading

Composites are an integral part of structural design in the areas of Aerospace, Automotive, Marine, Construction, Manufacturing, etc. Due to high strength to weight ratio and at times, they are also replacing metallic structures.



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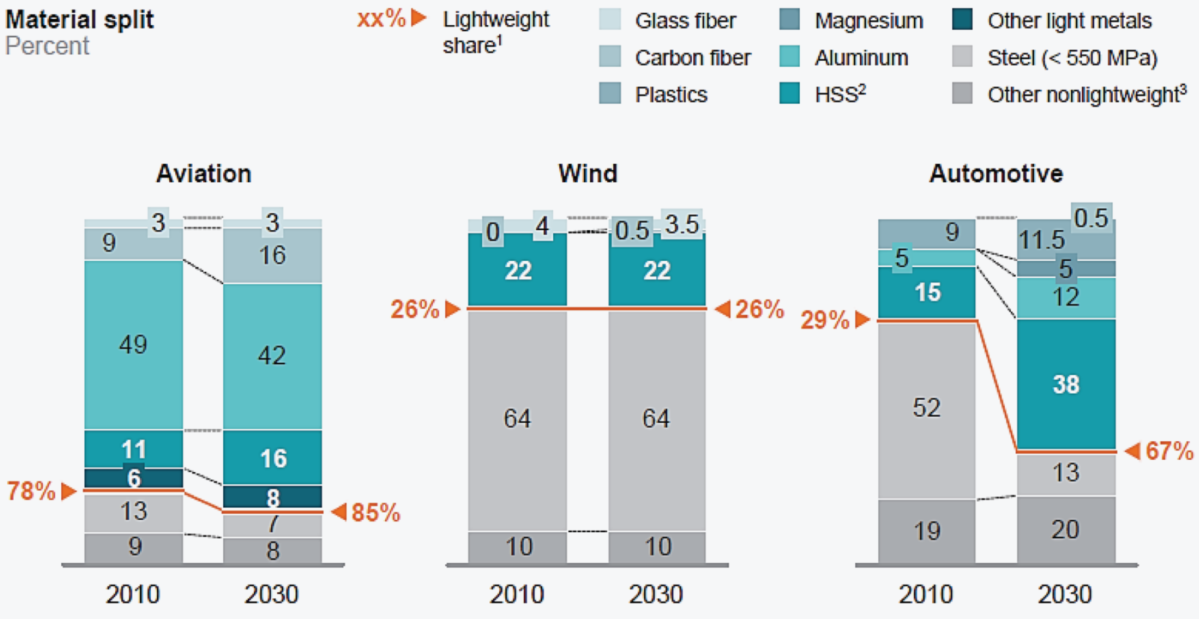
Abstract

Composites are an integral part of structural design in the areas of Aerospace, Automotive, Marine, Construction, Manufacturing, etc. Due to high strength to weight ratio and at times, they are also replacing metallic structures. However, these materials are not typically applied in isolation due to insufficient stiffness and ductility of the FRP compared to traditional metallic structures. There are many instances where metal and composite structures need to be connected together. This is primarily achieved with mechanical (bolted or fastened) or bonded joints. Various parameters which dictate the selection of type of joints are such as surface finish required, join weight, structure thickness, moisture penetration, sensitiveness to peel or tensile forces, stress concentrations or vibration damping. The behaviour of metal-composite joints needs to be assessed for their load carrying capacity, mode of load transfer and failure mechanisms. Focus of the current study is static loading of bolted joints with GFRP and Aerospace grade Aluminium 2014. Numerical analysis is being carried out using MSC NASTARN & MSC PATRAN. The mechanical properties are obtained commercially available 'The Laminator' software which uses resin and fibre properties. The peak stresses are found at the hole in the composite laminate at Layer 2.

Introduction

Light-weight structures consume fewer raw materials and less fuel, thus having less environmental impact. Light-weighting could be achieved by modifications in Materials, Design or Manufacturing methods. Any drastic changes in the design may not be always viable for a given structure/system. Hence, focus on Materials and manufacturing methods could be the best alternatives to achieve lightweighting. Although the lightweight share in the industry is currently highest in the aviation with almost 80%, automotive sector is massively increasing its share from 30-70% within next 15 years as shown in Figure 1. High-strength steel, composites are some of the best alternatives to achieve adequate strength, stiffness along with weight-savings.



1 HSS, aluminum, magnesium, plastics (beyond current use), glass/carbon fiber
2 High-strength steel (> 550 MPa)
3 Mainly other metals, glass, fluids, interior parts for automotive, etc.

SOURCE: McKinsey

Figure 1: Materials usage forecast for various industries [Light weight, Heavy impact; McKinsey & Company, 2012]

Literature Review

Advanced materials are essential for boosting the fuel economy of modern automobiles while maintaining safety and performance. A 10% reduction in vehicle weight can result in a 6%-8% fuel economy improvement. By using lightweight structural materials, vehicles can carry additional advanced emission control systems, safety devices, and integrated electronic systems without increasing the overall weight of the vehicle. The transport sector accounts for a significant environmental impact. However new technologies such as new lightweight materials have already begun to make smart travel possible and can contribute even more as the technology improves. The technology to make automobiles of composites is still relatively expensive, but still the people are putting efforts to achieve it.

There has been a progressive increase in the number of metal parts and Structures replaced by composite materials. Airbus A380 aircraft shows a composite content of 23%, and Boeing 787 & Airbus A350 have around 53% of Composite material [Fink and Kolesnikov 2005]. As the usage of composites is increasing day by day it is obvious that focus on metal–composite hybrid joints is widespread in the structure. In naval vessels, concerns over (stainless steel) cost, weight, stealth and corrosion have led designers to look at advanced materials for hull-form construction. Aluminium, although lightweight, corrosion resistant and non-magnetic, is prone to fatigue failures. In light of these concerns, advanced composite materials have emerged as a viable alternative to the conventional hull construction methods.

In aircrafts (Airbus A380) composite and metal hybrid joints are used in Leading edge and trailing edge attachements, D-nose,Tipfalse stub, Inner false stub also in stub rib. The current study describes the method of load transfer in metal/Composite hybrid joints. One of the easiest and best non-destructive methods of joining two materials is mechanical fastening which has the advantage of no special surface preparations, easy disassembly and inspection. Table 1 shows the parameters to be considered during the selection of bolted/bonded joints.

Property	Mechanical (Bolted) Joining	Adhesive (Bonded) Joining
Time to make the joint	Several steps, joint assembly rapid	Few steps, long cure
Surface Preparation	Minimal	Excessive, Critical
Thin sections	May not be possible	Can be done carefully
Join weight	Heavy	Light
External surface aspects	Protrusions	Can be smooth
Temperature limitations	Limited by laminate	Limited by adhesive
Laminate fibre damage	Can be important	Not important
Ability to Inspect	Easy	Difficult
Environmental issues	Can have galvanic corrosion	Solvent sensitivity
Moisture penetration	No resistance	Self-sealing
Stress concentrations	Significant	Can be very low
Long term loads	Relaxation and fatigue effects, creep	None
Sensitivity to peel forces	Resistant	Susceptible
Sensitive to tensile forces	Susceptible	Resistant
Vibration dampening	No damping	Inherent damping
Health and Safety	Cutting, drilling, thermal dangers	Solvent, thermal dangers

Table 1: Difference between bonded and bolted joints

Factor of safety (FOS) is the ratio of structural capacity to actual applied load which is also a measure of the reliability of a particular design. A structure with a FOS of exactly 1.0 will support only the design load and no more. FOS of ground heavy machineries are high (8.0-12.0); however the FOS for Civil structures are around 5.0-8.0; for automobiles it will be nearly 3.0 and for Aerostructures it is around 1.2-1.5. For safety requirement, the aircraft must be designed to withstand these load factors without structural damage. As the Factor of safety of these structures is low, the load transfer mechanism and failure modes for these materials have to be analysed very carefully.

Faruk Sen and Kemal Aldas [2011] numerically studied (with 3D-FEA) the effects of stresses on a hybrid adhesively bonded and pinned joint where four metal plates were used: Aluminium, Steel, Titanium and Copper along with GFRP Composite.

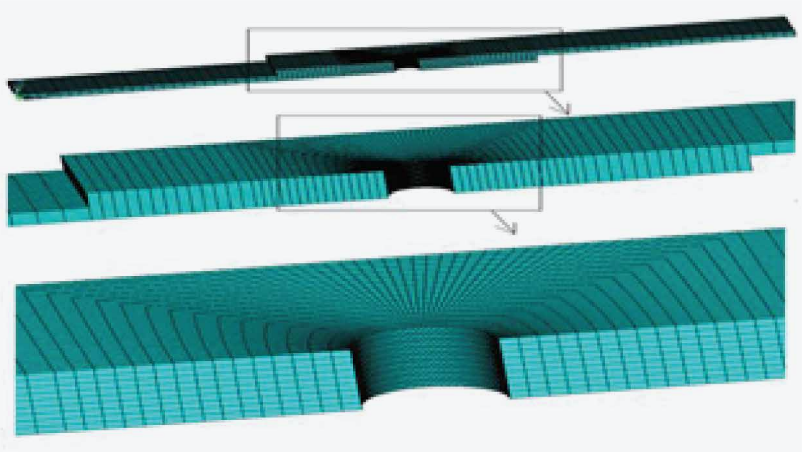


Figure 2: FEM structure of hybrid joint with details [Faruk and Kemal, 2011]

The results showed that the Composite-Titanium posed lesser risk with lower stress values and Composite-Steel joints had higher stresses. This behaviour was similar for both normal and shear stresses. As expected, the stresses were concentrated around the pin hole, which was seen as very critical.According to ASTM D5961, failure mechanisms occur in a fastened joint due to the effect of bearing or bearing-bypass.Kolesnikov et al. [2008] found that by embedding thin titanium layers in between the CFRP enhanced the structural efficiency of bolted and riveted joints. Experimental studies were carried out [Matsuzaki et al. 2008] to determine the joint strength of co-cured hybrid bolted joint (GFRP/Aluminium) which showed that the hybrid joints have 1.84 times higher maximum shear strength and a quarter of the standard deviation compared with conventional co-cured joints. Furthermore, less stress concentration and undamaged glass fibres in the hybrid joints contribute to much higher fatigue strength than that of the bolted joint.

Numerical Study

FE Modelling

The study is carried out according to the guidelines of ASTM D5961. Aluminium (2014 series, Table 2) and GFRP panel were mechanically fastened using Titanium bolts. GFRP laminate stacking sequence is presented in Table 3. The GFRP layup consists of 4 DB layers, 4 WR layers and 4 UD layers, symmetricalabout neutral axis. The composite & metallic panel joint (hybrid lap joint) model used in the analysis as per ASTM D5961 is shown in Figure 3.

Figure 3: Specimen-Hybrid Lap joint

2014 Aluminium alloy is presented in Table:

Hardness, Brinell	135
Hardness, Vickers	155
Ultimate Tensile Strength	483 MPa
Tensile Yield Strength	414 MPa
Elongation at Break	13%
Modulus of Elasticity	72.4 GPa
Compressive Modulus	73.8 GPa
Notched Tensile Strength	414 MPa
Ultimate Bearing Strength	889 MPa
Bearing Yield Strength	662 MPa
Poisson's Ratio	0.33
Fatigue Strength	124 MPa
Fracture Toughness	19 MPa-m½
Machinability	70%
Shear Modulus	28 GPa
Shear Strength	290 MPa
Density	2.8gm/cc

Table 2: Aluminium 2014 Material Properties [ASM Aerospace Materials]

Lamina No.	Layer	Fibre Direction	Fibre Weight (gsm)	Lamina Thickness
Mould Surface				
1	WR	0° / 90°	300	0.3
2	DB	±45°	300	0.3
3	UD	0°	300	0.2
4	DB	±45°	300	0.3
5	WR	0° / 90°	300	0.3
6	UD	0°	300	0.2
7	UD	0°	300	0.2
8	WR	0° / 90°	300	0.3
9	DB	±45°	300	0.3
10	UD	0°	300	0.2
11	DB	±45°	300	0.3
12	WR	0° / 90°	300	0.3
Laminate Thickness				**3.2**

Table 3: Laminate Stacking Sequence for Composite panel

- As per the geometry, a numerical model was created using Catia V5 modelling software, converted to IGES format and imported to MSC PATRAN
- Pre and Post-processing was done using MSC PATRAN whereas MSC NASTRAN was used as a solver
- Implicit Non-linear analysis (SOL 600) was used to study the response of the hybrid joint subjected to Ten equal load increments

FE model (Figure 4) for the hybrid lap joint have been created for the study of metallic & composite joints failures under progressive loading and comparisons have been between metal and composite joint strength.

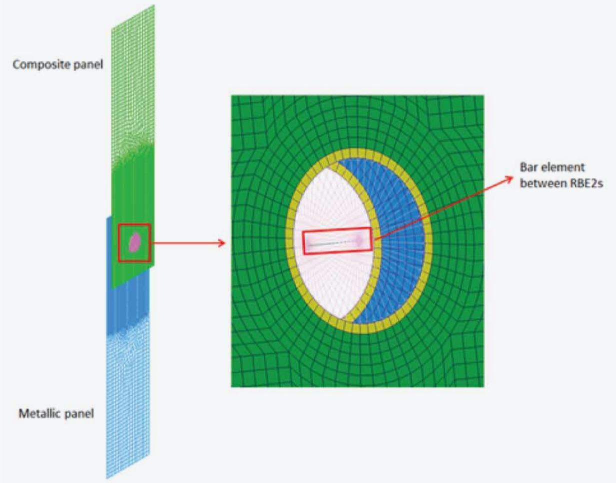


Figure 4: FE Model of hybrid lap joint

2014 Aerospace grade Aluminium was used in the study. Table 4 shows the mechanical properties of the composite laminate used. Three different fabrics were used: Double bias (DB ±45°); Unidirectional (UD 0°), Woven Roving (WR). It was assumed that the specimens were manufactured using Vacuum Infused Resin Transfer Moulding (VARTM).The mechanical properties are obtained from resin/fibre manufacturer commercially available 'The Laminator' version 3.7,software. The properties are derived based on Classical Laminate Plate Theory (CLPT) using fibre (E-glass) and resin (Epoxy) properties.

Property	**DB**	**UD-0**	**WR**	**Laminate**
E_{11} (MPa)	10080	39310	19155	23560
E_{22} (MPa)	10080	8552	19155	16920
E_{33} (MPa)	7532	7532	7532	7532
Å$_{12}$ (MPa)	0.354	0.28	0.27	0.291
G_{12} (MPa)	6385	3724	3724	6523
S_{11T} (MPa)	118	604	334	N/A
CTE *E-6	0.404	7.02	8.83	N/A

Table4: Material properties for composite panel – E-glass and Epoxy

Modelling of hybrid joint was carried out by using shell elements, represented as CQUAD element. Connection of composite panel with the metallic panel is through protruded head Titanium bolt which is idealised as bar element in the FE model. Table 5 shows the details of the FE mesh parameters used in the current study.

Number of grid points (Nodes)	15180
Number of CQUAD4 elements	14763
Number of CBAR elements	1
Number of RBE2 elements	2

Table 5: FE Model Summary for hybrid single lap joint

Joint between the two panels was done by connecting rigid bar elements around the holes and a bar element at the centre between the rigid elements as shown in Figure 4. The primary focus of the current study is to analyse the stresses at the bolted joint as well as predicting the location of initial failure due to bearing stresses.

Boundary Conditions

FE model is constrained at the doubler plate location on composite panel in all 6DOFs (1, 2, 3, 4, 5, 6) and 4DOFs (1, 3, 4, 5) at the metallic doubler plate as shown in Figure 5. (1, 2 & 3 are the translations in x, y and z directions; 4, 5, & 6 are the rotations in x, y, and z directions respectively). Detailed boundary conditions are shown in Figure 5. Implicit nonlinear analysis has been carried out for the hybrid lap joint FE model. The loading was provided in 10 equal increments to obtain the detailed Load-Deflection plot.

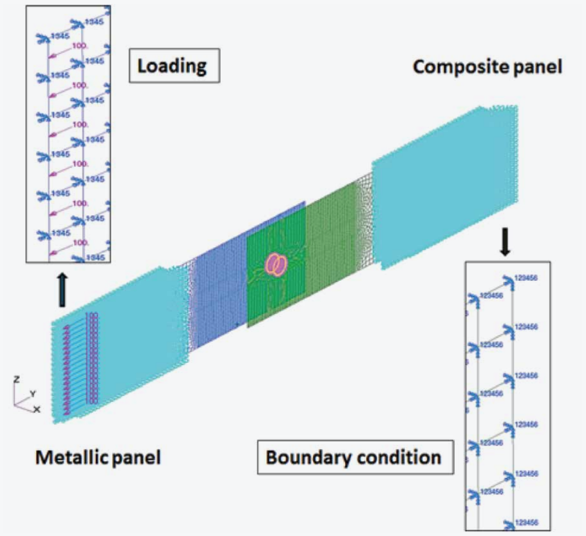


Figure 5: Loading & boundary condition for hybrid lap joint

Results

The current study is part of a larger study about experimental and numerical investigation of the behaviour of hybrid bolted joints subjected to static and impact load with progressive failure analysis.Load vs. Deflection plot is obtained along with the maximum stress plots for the failure case. Yield strength is considered as failure parameter for Metal panel and in-plane tensile strength for composite panel.Figure 6 shows the Maximum tensile stress plot for first ply failure. The first failure occurred at layer 2(DB ply) where the limiting stress value is 118 MPa.

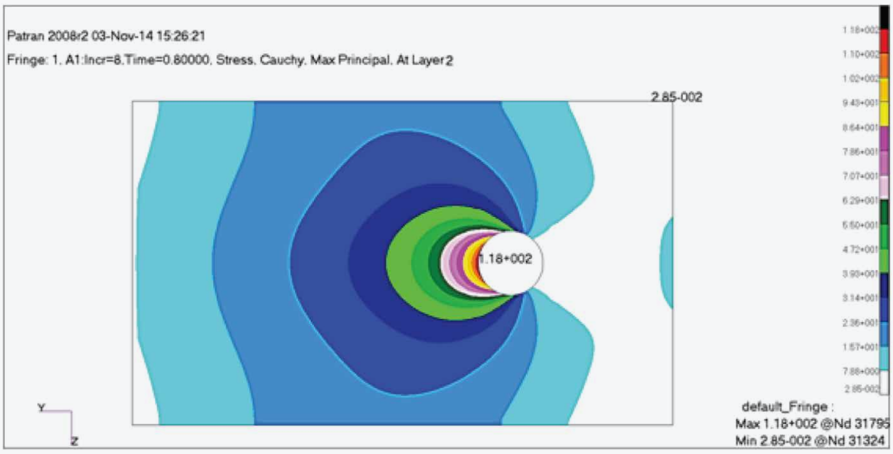


Figure 6: Maximum tensile stress plot for first ply failure (composite panel)

Figure 7 shows the Maximum von Mises stress plot for metallic panel

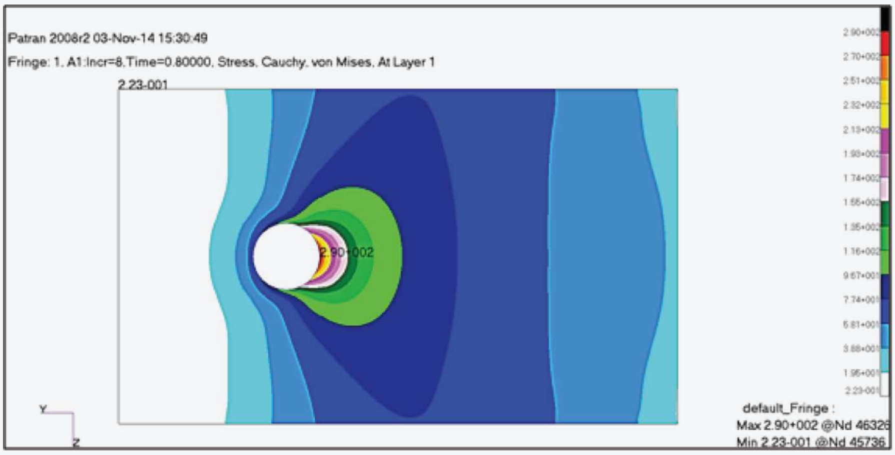


Figure 7: Maximum von Mises stress plot for metallic panel

Calculation: Distributed load of 100N is applied over length of 36mm and is applied in 10 steps with 10% increment of load in each step i.e. total load = 36 X 100 = 3600 (100%)

But first failure occurs at layer 2 (DB) at 80% loadi.e., 3600 X 0.8 = 2880 N Max Principal Stress = 118 MPa and Yield stress for DB is also 118 MPa

At 2880 N:

Max Von mises stress in metallic plate is 290 MPa which is below yield stress (414MPa) As per the design of the joint, the failure is supposed to be occurring to be in bearing (allowable=662MPa) FOS for bearing is 662/290 = 2.28

Thus means metal is safe but composite panel fails in bearing before metal. The stresses in the Titanium are very less compared to its yield strength.

Figure 8 shows Load vs Deflection plot of the hybrid joint.

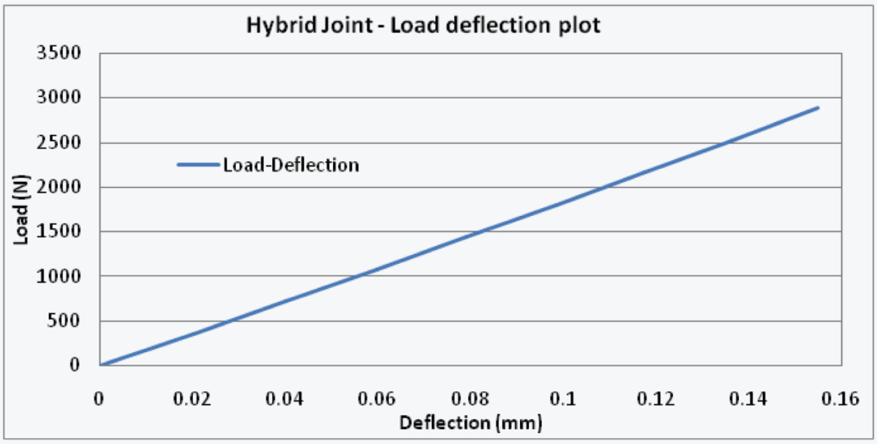


Figure 8: Load vs Deflection plot

Conclusions

A non-linear static analysis of Metal-Metal and Composite-Metal hybrid single lap joint is done in this study using MSC NASTRAN with Marc SOL600 solver. Detailed stress distribution around the hole is determined. Location of first failure is found to be at secondlayer (DB) of Composite specimen.

Future Work

- Composite specimen layup optimisation
- Progressive failure analysis until final collapse
- Experimental investigation till first failure and FE model validation
- Experimental Progressive failure analysis along with NDE testing
- Hybrid joint impact simulation and Experimental validation

References

i) ASM Aerospace Specification Metals Inc. for Aluminium 2014-T6: http://asm.matweb.com/search/ Specific Material .asp?bassnum= MA2014T6

ii) Faruk Sen and Kemal Aldas (2011). Effects of Using Different Metal Materials on Stresses in Metal-Composite Hybrid Joints. Chankaya University Journal of Science and Engineering, 8(1):1-13.

iii) Fink A. and Kolesnikov B (2005). Hybrid titanium composite material improving composite structure coupling. Proceedings of the European Conference on Spacecraft Structures, Materials and Mechanical Testing 2005 (ESA SP-581). 10-12 May 2005, Noordwijk, The Netherlands.

iv) Kolesnikov B, Herbeck L, Fink A. (2008). CFRP/titanium hybrid material for improving composite bolted joints. Composite Structures, 83(4):368-380.

v) Lightweight, heavy impact – How carbon fibre and other lightweight materials will develop across industries and specifically in Automotive, McKinsey & Company (2012).

vi) Matsuzakia R, Shibatab M, Todorokib A. (2008). Improving performance of GFRP/aluminum single lap joints using bolted/co-cured hybrid method. Composites Part A: Applied Science and Manufacturing, 39(2):154-163.

vii) Vehicle Technologies Office: Lightweight Materials for Cars and Trucks; Office of Energy Efficiency & Renewable Energy, USA.

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Fatigue and Damage Tolerance; Hybrid Structures; Structural Dynamics

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