

Finite Element Simulation of Aluminium/GFRP Fibre Metal Laminate under Tensile Loading

M N M Merzuki¹, M R M Rejab¹, N K Romli^{1*}, D Bachtiar¹, J Siregar¹, M F Rani²,
Salwani Mohd Salleh¹

¹Structural Materials & Degradation Focus Group, Faculty of Mechanical Engineering,
Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

²Faculty of Engineering, DRB-Hicom University of Automotive Malaysia, 26607 Pekan,
Pahang, Malaysia

Email : khaleedaromli@gmail.com

Abstract. The response of a fibre metal laminate (FML) model to the tensile loading is predicted through a computational approach. The FML consisted with layers of aluminum alloy and embedded with one layer of composite material, Glass fibre Reinforced Plastic (GFRP). The glass fibre and aluminium alloy 2024-0 was laminated by using thermoset epoxy. A compression moulding technique was used in the process of a FML fabrication. The aluminium has been roughen by a metal sanding method which to improve the bonding between the fibre and metal layer. The main objective of this paper is to determine the failure behaviour of the FML under the tensile loading. The responses on the FML under the tensile loading were numerically performed. The FML was modelled and analysed by using Abaqus/CAE 6.13 version. Based on the experimental and FE data of the tensile, the ultimate tensile stress is 120 MPa where delamination and fibre breakage happened. A numerical model was developed and agreed well with the experimental results. The laminate has an inelastic respond to increase the tensile loads which due to the plasticity of the aluminium layers.

1. Introduction

A fibre metal laminate (FML) or also known as a hybrid laminate contains metal layers and composite materials [1]. The combination of the metal layers and composite fibres produce superior characteristics such as fatigue and fracture. Besides that, the substitutions of both materials are to reduce weight of the aircraft structures and saving in oil consumption [2]. The Glare and Arall are members of fibre metal laminates. The fibre metal laminate started and applied in military application after the Second World War [3]. From the positive feedbacks of the application, the fibre metal laminate began the application widely in aircraft structures such as fuselage and wings [4]. The example of the application is in the Airbus A380 due to the improvement in fatigue, resistance to corrosion and impact and weight reduced nearly 794 kg [5].

An autoclave commonly used in manufacturing of fibre metal laminates or curing process at a high pressure. The curing temperature should be maintained as well [6]. The FMLs need to be processed up to 120°C as to avoid damage on the aluminium alloy 2024-T3. The temperature will allow excess of resin flow out and reduced its viscosity. The pressure will press and consolidate the plies then suppress the voids [7]. The shear thickening fluid is a combination of hard metal oxide particles which suspended in the liquid polymer. The STF can lead the laminates to improve resistance from ballistic impact damage [8].

The debonding process between a sheet metal layer and composite fibre layer, delamination of the composite layers, fracture due to a plasticity behaviour of a metal are commonly happened to a fibre metal laminate structure which because of the impact of a load and depended on the layup configurations [9]. The process of curing by using an autoclave will take long hours of processing and required intensive of labour cost for the whole production [10].



The purpose of this paper to investigate the failure behaviour of the fibre metal laminate modeled by using the Abaqus/CAE version 6.13 under uniaxial tensile stress. In this analysis will be more focused on the method of the analysis.

2. Experimental work

The tensile experiment was conducted by using an Instron 3369 series Universal Testing machine. The FML specimens were prepared with sample. The experiment was conducting at a displacement rate which 5 mm/min. The FML specimens were prepared through a compression moulding technique. The configuration layup of the FML was 2/1. A thermoset epoxy was mixed with hardener in a ratio 2:1 for laminating process. A moderated load was placed on the laminate for a consistent pressure application. The specimen was cured at a room temperature for 24 hours. The aluminium surface was treated with a metal sanding method to rough the metal surface and increase the bonding between the fibre and sheet metal layer. A type of sand paper, 80 grit has been used for the metal sanding.

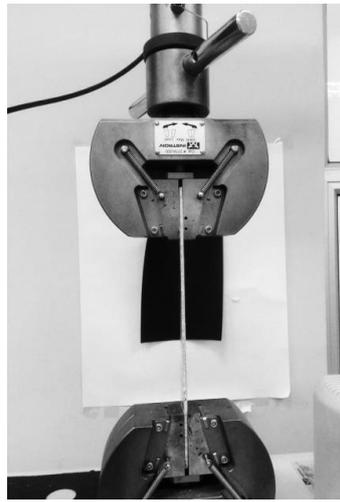


Figure 1. Setup for the FML in tensile test.

3. Computational modelling

The alternative way to predict experimental result is by using numerical analysis. Study of numerical analysis on fibre metal laminate was become crucial as to know impact behaviour of it. The process of simulation could be done by adding the properties material used such as the Young's modulus, Poisson's ratio, density of the materials and so on. The simulation process required reasonable numbers of structural tests for a validation process. The previous researchers were combined two theories of failure criteria and plasticity as to simulate the degradation behaviour of plate and study the behaviour of nonlinear numerical model. The damage of an impact was controlled by degradation of the stiffness and fracture was because of energy releases which aimed to delamination growth. The simulation of deformation process of 3D FE model involved sensitivity of strain-rate and large changes in transverse compression. The damaged of composite plies cannot be used directly in Abaqus [11].

The Abaqus/Explicit was used to develop a numerical simulation of the FML under the quasi-static loading. The FML consisted with two different of constituent materials; 2024-0 and woven GFRP. The failure of the FML depended on the ductility of the materials.

3.1 Modelling of the 2024-0 by using Isotropic Material

The aluminium alloy 2024-0 was modelled by using an isotropic elasto-plasticity to predict elastic and plastic behavior either as a rate-dependent or rate dependent model and it has a simple form.

3.1.1 Elasticity.

A model of isotropic linear elasticity was generated for the elastic respond for a material in a numerical analysis. The material that performed linear elastic behaviour, the total stress defined through this an equation:

$$\sigma = D^{el} \varepsilon^{el} \quad (1)$$

Where σ the total stress, D^{el} is the fourth order of an elasticity tensor and ε^{el} is the total elastic strain. From the Equation (1) the stress-strain relationship of isotropic linear elasticity strain

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{(1-2\nu)}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{(1-2\nu)}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{(1-2\nu)}{2} \end{bmatrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{12} \\ \varepsilon_{13} \\ \varepsilon_{23} \end{bmatrix} \quad (2)$$

The symbol of E is a Young's modulus and ν is a Poisson's ration. These have been defined in the equation above. The inverse relationship defined as an equation below:

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{12} \\ \gamma_{13} \\ \gamma_{23} \end{bmatrix} = \begin{bmatrix} \frac{1}{E} & \frac{-\nu}{E} & \frac{-\nu}{E} & 0 & 0 & 0 \\ \frac{-\nu}{E} & \frac{1}{E} & \frac{-\nu}{E} & 0 & 0 & 0 \\ \frac{-\nu}{E} & \frac{-\nu}{E} & \frac{1}{E} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{bmatrix} \quad (3)$$

G is a shear modulus; $G = \frac{E}{2(1+\nu)}$

The elastic material in the properties of aluminium 2024-0 was used in the numerical modelling. The properties were taken from experimental results. The value of Young's modulus, $E = 70.6$ GPa and the Poisson's ratio is $\nu = 0.3$.

3.1.2 Yielding.

An isotropic yielding is applied to a von Mises yield surface. The surface is assumed that yielding of a metal is independent where the observation was confirmed by an experimental works. The metal was applied under a positive pressure stress. When the metal applied in that kind of situation which high pressure stress, it may be inaccurate because voids can nucleate and grow in the metal.

3.1.3 Plasticity.

Beyond the yield point is a permanent deformation or called as plastic behaviour of the aluminium. The plastic behaviour is defined in an isotropic hardening. To describe the isotropic hardening, the yield stress, σ^0 which given in a plastic strain tabular function. The interpolation of the yield stress at any plastic strain rate can be done from the table of data. The data will remain constant when it reached to the last value that have been given in the table. Decomposition of the total increment of strain defined as below:

$$d\varepsilon = d\varepsilon^{el} + d\varepsilon^{pl} \quad (4)$$

For rate-dependent of material the relationship of the equivalent plastic strain rate, $\dot{\varepsilon}^{pl}$ followed by the uniaxial flow rate definition as:

$$\dot{\varepsilon}^{pl} = \varphi(q, \bar{\varepsilon}^{pl}, \theta_r) \quad (5)$$

φ known as function, q is the von Mises equivalent stress, $\bar{\varepsilon}^{pl}$ is an equivalent of the plastic strain and θ_r is the temperature.

3.2 Failure Criteria

The development of damage and failure of ductile material are used in Abaqus/Explicit to model the damage behaviour of the aluminium. *SHEAR FAILURE and *TENSILE FAILURE or a combination of both are two material failure

models will offer in the Abaqus to account the damage and failure in a ductile metal. To calculate the failure, shear and tensile failure models can use an equivalent of the plastic strain and hydrostatic cut-off stress respectively. If the failed meshes removed from the meshes it may for both failure models.

3.2.1 Damage for Ductile Metals.

There are two mechanisms for the ductile metals will be used in this study; ductile damage and shear damage models. The ductile fracture or ductile damage are initial criterion for predicting the onset damage which due to nucleation, growth and the voids. This model will active when the following condition is satisfied:

$$\omega_D = \int \frac{d\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_D^{pl}(\eta, \dot{\varepsilon}^{pl})} = 1 \quad (6)$$

ω_D is a state variable that increase monotonically with plastic deformation. The model is assumed that the equivalent plastic strain at the onset of damage, $\bar{\varepsilon}_D^{pl}$ is a function of triaxiality, $\eta = -p/q$, and the equivalent of plastic strain, $\dot{\varepsilon}^{pl}$. Note that p is the pressure stress and q is the Mises equivalent stress. The shear damage model is a fracture which due to shear band localisation in the ductile metals. The model will active when the following condition is satisfied:

$$\omega_s = \int \frac{d\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_s^{pl}(\theta_s, \dot{\varepsilon}^{pl})} = 1 \quad (7)$$

ω_s is a state variable that increases monotonically with plastic deformation and is relative to the incremental change in equivalent plastic strain, $\bar{\varepsilon}^{pl}$. The model is assumed that the equivalent plastic strain at the onset of damage, $\bar{\varepsilon}_s^{pl}$ is a function of the shear stress ratio, $\theta_s = (q + k_s p)/\tau_{\max}$ and the equivalent plastic strain rate, $\dot{\varepsilon}^{pl}$. Note that τ_{\max} is the maximum shear stress k_s is a material parameter ($k_s = 0.3$ for the aluminium alloy) [12].

3.3 Modelling of composite by Hashin damage criterion

The Hashin damage criterion is based on works of Hashin and Rotem and Hashin [13, 14]. This criterion is unlike other criteria like Tsai-Hill and Tsai-Wu [15]. Those criteria purposed an equation to predict damage initiation. The Hashin damage presents four failure modes with four corresponding indexes (a) breakage of fibre from the tension (F_f^t), (b) buckle of fibre from the compression (F_f^c), (c) crack of matrix from the tension (F_m^t) and (d) crush of matrix from the compression (F_m^c). There are four equation that applied to those failure modes respectively:

$$(F_f^t) = \left(\frac{\sigma_{11}}{S_{t1}} \right)^2 + \alpha \left(\frac{\sigma_{12}}{S_{12}} \right)^2 \leq 1.0 \text{ and } \sigma_{11} \geq 0 \quad (8)$$

$$(F_f^c) = \left(\frac{\sigma_{11}}{S_{c1}} \right)^2 \leq 1.0 \text{ and } \sigma_{11} < 0 \quad (9)$$

$$(F_m^t) = \left(\frac{\sigma_{22}}{2S_{s23}} \right)^2 + \alpha \left(\frac{\sigma_{c2}}{2S_{s23}} \right)^2 \leq 1.0 \text{ and } \sigma_{22} \geq 0 \quad (10)$$

$$(F_m^c) = \left(\frac{\sigma_{22}}{2S_{s23}} \right)^2 + \left[\left(\frac{S_{c2}}{2S_{s23}} \right)^2 - 1 \right] \frac{\sigma_{22}}{S_{c2}} + \left(\frac{\sigma_{12}}{S_{12}} \right)^2 \leq 1.0 \text{ and } \sigma_{22} < 0 \quad (11)$$

σ_{11} , σ_{22} and σ_{12} are applied stresses while α is a coefficient of the shear stress σ_{12} which contributed in fibre breakage by a tension criterion. In the Abaqus, the criterion of Hashin could be implemented in a conjunction with a damage evolution law. The law based on a specification of four fracture energy values G_f . The values corresponded to the material degradation in each mode. The values constituent in an implementation of the Hashin-based and analysed with the damage evolution in the Abaqus. The damage variable for fibres d_f , matrix d_m and shear d_s were assessed by this expression [16]:

$$d = \frac{\delta_{eq}^f (\delta_{eq} - \delta_{eq}^0)}{\delta_{eq} (\delta_{eq}^f - \delta_{eq}^0)} \quad (12)$$

δ_{eq}^f is an equivalent of a displacement in a FE when the stress reached to zero in a stress-displacement while δ_{eq}^0 is an equivalent of a displacement when the damage initiated. δ_{eq} is an equivalent of a displacement in FE for the given applied strain [16].

4. Results and Discussion

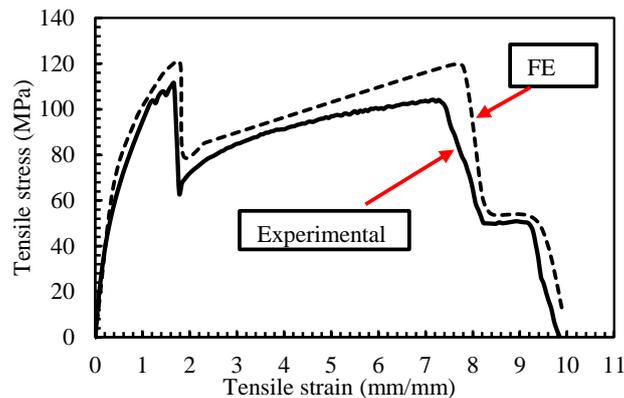


Figure 2. Graph tensile stress against tensile strain for aluminium/glass fibre laminate.

Based on the figure 2 the aluminium/glass fibre was subjected to an uniaxial tensile loading. There were a few transverse cracks as well as the delamination of the fibre and sheet metal layer. When the FML was applied and pulled by a higher loading, it was resulted in a composite structure which glass fibre degradation. This degradation was happened at the first stage. At this stage, the degradation was started by a matrix cracking which visible in the structure and continued with a delamination. Normally the matrix cracking happened at the lowest load applied. As the load increased, the delamination in the middle area was occurred as well as the delamination between metal and fibre layer. A transverse crack of the polymer composite occurred at the second stage. The matrix cracks was contained with two constituents, epoxy (matrix) and fibre. The epoxy characterised as brittle and has low resistance to a crack propagation. There are two types of matrix cracking; cracks which caused of bending and shearing. These cracks happened during high transverse shearing stress.

The 2/1 FML model based on aluminium and glass fibre was predicted through a finite element method; Abaqus/CAE. The numerical analysis was done as to evaluate the failure behaviour of the FML model under the uniaxial tensile stress. The specimen was modelled as a single layer solid which consisted with the aluminium alloy 2024-0 and glass fibre. The finite element analysis focused on a tensile behaviour. The simulation just focused on the model deformation, not the debonding and delamination. The element C3D8R was applied to the FML model. The C3D8R consisted of 8-node linear brick, reduce integration and hourglass control. The theoretical of the modelling, Young's modulus was used to determine the deformation of the FML. The mechanical properties of the FML could be predicted by the volume fraction which based on basic of the laminate theory. The model was analysed by applying Displacement/Rotation at x -axis and the other side will be fixed by a boundary condition type which called as a Encaster.

The failure mechanism of the model was recorded. The FE model became successful when at the perforation stage of the impact event. The failure area of the FML increased when the deformation have been applied increasingly. The FML exhibited and appeared with little plastic deformation at the impact location. The plastic deformation was in aluminum and there was a fracture on the composite ply. The results based on the stiffness of the material. The number of elements for the FML were with 750 elements which consisted of 250 element for each ply of 2/1 FML.

The experimental compared with finite element result which in order to verify the FE modelling approach used, FE stress and strain results. The results of both were validated and showed in the figure 3. The stress and strain relation were obtained from both, numerical analysis and experimental up to the final fracture. The failures of the FML in the numerical analysis when isotropic and Hashin damage criteria were applied to the aluminium and glass fibre, respectively. In meanwhile, the result of the FML in experimental slightly differ and lower than FE because the manufacturing process of the FML also effect to the structure.

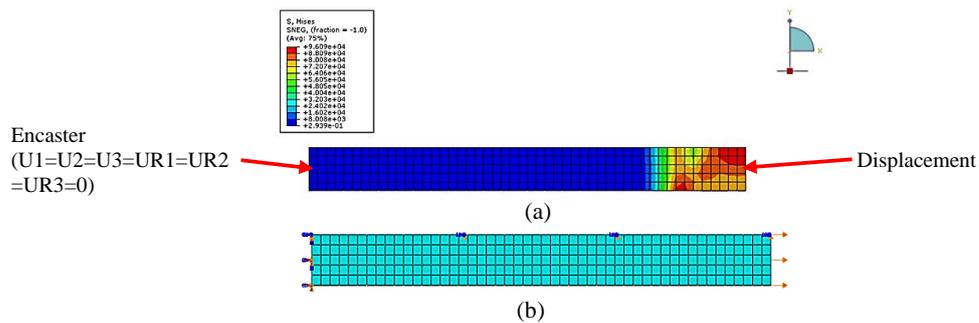


Figure 3. (a) FML analysis (b) Meshing of FML

Conclusion

The work was presented for uniaxial stress behavior and damage characterisation of a fibre metal laminate with the glass fibre. The influences of the tensile loading on the fibre metal laminate were found by the valuable information of the damaged composite structures. The damage mechanism was connected to the internal degradation of the composite material which it was a plastic behaviour of the fibre metal laminate. The failure behavior was started by a matrix cracking and followed by a delamination of the glass fibre. The delamination was a critical damage mode where found at the interface of the metal-composite in the fibre metal laminate. The plastic behavior normally happened in the metal layers. The damage of the material based on the type of the material used. The prediction of failure behaviour on the 2/1 FML was done by using the finite element analysis and were presented in details. The theoretical and calculation were considered in the analysis but adhesive strength was not involved in the analysis. The FMLs is suitable to be evaluated for the impact resistance which for automotive industry.

A numerical model was developed and agreed well with the experimental results. A glass/epoxy composite layer in the aluminium/glass laminate exhibited in a linear elasticity under a tensile loading. This show that, the laminate has an inelastic respond to increase the tensile loads which due to the plasticity of the aluminium layers.

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