Numerical Studies on Mode I Delamination and its Effect on the Vibrational Characteristics in Fibre Metal Laminates

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Abstract. Fibre metal laminates (FMLs) afford the notable advances over ongoing composite materials for aerospace and automotive applications due to their low weight and outstanding mechanical properties. Nevertheless, FMLs are prone to damages during manufacturing and loading conditions. Double cantilever beam (DCB) and vibration test are the commonly used tools to assess fracture energy values and the level of damage influence on the material properties respectively. Therefore, this paper aims at correlating the numerical validation of mode I delamination with already published experimental data by Y.Pan et.al and study the influence of delamination under free vibration analysis of Magnesium (Mg AZ31) alloy based fibre metal laminates. For the presented model, the numerical values showed good acceptance with the experimental values of DCB test. It was also further observed that there is significant reduction in natural frequency due to delamination in the fibre metal laminates.

Nomenclature
FMLs= fibre metal laminates,
CZM= cohesive zone method,
DCB= double cantilever beam,
Gc= fracture energy,
δfail= the point at which the elements fail completely,
Knn, Kss, Kn= stiffness parameters,
Nmax, Smax, T_max= strength parameters,
GIC, GIIc = the mode I and mode II fracture energy values respectively,
ΔLc= characteristic length,
OMF =Over meshing factor.

1. INTRODUCTION

Fibre metal laminates (FMLs) are the hybrid composite materials in which metal and fibre layers are arranged, alternatively. In recent years, the fibre metal laminates applicability is increasing rapidly in aerospace and automotive applications due to their low weight, fatigue resistance, outstanding mechanical properties, damage resistance and good energy absorbing capacity [1][2][3]. The first fibre metal laminates (ARALL) materials were originated at the Delft University of Technology (DUT) in the year of 1978 [4]. Even though Aluminium alloy based fibre metal laminates are exhibiting
excellent performance in structural applications but when it comes to weight reduction in structures; the magnesium alloys may be the alternative material to aluminium alloys due to its light weight [5]. Magnesium alloy based FMLs provide corrosion resistance, damage resistance, and higher damping properties over the GLARE[6][7]. The lower stiffness of the magnesium alloy limits the structural applicability but offer good mechanical properties over monolithic magnesium alloy when integrated with the higher stiffness fibres like carbon/glass [8].

Fibre metal laminates are prone to damages during manufacturing and loading conditions. So among all damages, it has been stated that delamination is the most impact failure in the FMLs [9]. It not only reduces the stiffness but also decreases the load bearing capacity of the material [10]. In specific, the delamination may occur at the interface region of the composite material [11]. In materials the delamination may propagate in three modes namely mode I, mode II, mode III. In general, there may be a chance of occur mixed mode behaviour. DCB, ENF and MMB tests are available as the standard tests to evaluate the these modes [12]. Non-destructive methods are accessible to assess the influence of damage levels on the mechanical behaviour of FMLs. Vibration analysis is the commonly method to understand the behaviour of the material under loading conditions among all non-destructive methods [13].

Finite element (FE) analysis is nowadays alternative technique to the experimental work to capture the behaviour of fibre metal laminates closely and efficiently, due to time and cost involved in fabricating and testing the fibre metal laminates in laboratory is a tedious process [14]. VCCT, CZM are frequently used numerical techniques to simulate the delamination behaviour in composite materials [15]. CZM, unlike VCCT, is independent of mesh size, time step and it is the efficient method to predict the delamination behaviour in the materials [16][17]. One more advantage of CZM compared to VCCT is that it can forecast the new crack initiation and propagation of existing crack. All these advantages make CZM, the mostly using method to understand the delamination behaviour in the interface region[18].

It can be observed from the literature that numerical modelling of delamination in magnesium alloy (Mg AZ31) based fibre metal laminates has not been discussed in detail. Therefore, in the present study, numerical validation of mode I delamination in AZ31 magnesium alloy-based fibre metal lamination is discussed using cohesive zone method (CZM) and influence of delamination on vibration characteristics of these laminates also studied under free vibration analysis.

2. Methodology

2.1 Modelling of cohesive layer and its strength parameters

Cohesive zone method (CZM) is implemented using either cohesive element or cohesive surface methods. The applicability of both the methods is different but they are mostly similar and follow the same rules. The cohesive surface method is suggested in the case of insignificant thickness of cohesive layer compared to metal or fibre layers, whereas cohesive elements are recommended when there is a failure observed in the adhesion region. Therefore, the modelling of delamination using CZM is nowadays getting popular because propagation of delamination can be easily defined in the front portion of the crack tip. In the numerical modelling the cohesive elements are defined in the delamination path and these elements are controlled by the traction-separation law principle [19].
The traction-separation law is shown in the Figure 1 and it can be noticed from the law that before damage initiation the cohesive elements are obeying the linear behaviour and this behaviour is controlled by the stiffness parameters $K_{nn}$, $K_{ss}$, $K_{tt}$. Once the law reaches to strength parameters $N_{max}, S_{max}, T_{max}$ then the curve starts to decrease gradually to zero. After damage initiation the behaviour of the curve rely on the softening laws (linear or exponential). The point at which the curve reaches to zero stiffness value of elements then the area under the curve is called fracture energy ($G_c$) and $\delta_{fail}$ is the point at which the elements fail completely. Therefore, all these stiffness, strength parameters can be calculated using following equations.

\[ K_{nn} = \frac{2G_{IC}}{\delta_{fail}^2} \]  
(1)

\[ K_{tt} = K_{ss} = \frac{2G_{IC}}{\delta_{fail}^2} \]  
(2)

\[ N_{max} = \frac{2G_{IC}}{\delta_{fail}} \]  
(3)

\[ T_{max} = S_{max} = \frac{2G_{IC}}{\delta_{fail}} \]  
(4)

Where, $\delta_{fail}$ = Penalty factor $x\Delta L_C$ and $\delta_{ratio} = \frac{\delta_{init}}{\delta_{fail}}$

Over meshing factor (OMF) = \frac{\text{structural mesh}}{\text{cohesive mesh}} \text{ region mesh} \]  
(5)

$G_{IC}, G_{IIIC}$ are the mode I and mode II fracture energy values respectively and over meshing factor (OMF) plays a crucial role in calculating $\Delta L_C$. Generally the structural mesh size is five times greater than cohesive mesh size [20]. In stiffness and strength parameters calculation initially the penalty factor can have assumed to be 0.05. This value can be assumed high for non-convergence and very low for convergence problems. $\delta_{ratio}$ value of 0.5 is recommended by Diehl et al [21]. In general, $\delta_{ratio}$ will not affect the parameters during simulations. Cohesive elements are generally controlled by
stress-strain methods for damage initiation and energy laws for evolution. In the present study Benzeggagh and Kenane (B-K) energy law is used with $\mu=1.4$ to model the damage evolution and for damage initiation, the quadratic normal stress criteria is used shown in Equation 6 and 7 [22].

$$G_{IC}^+ (G_{IIC}^+G_{IC})^{\frac{\mu}{2}}=G_T$$  \hspace{1cm} (6)

$$\left(\frac{N}{N_{\text{max}}}\right)^2 + \left(\frac{S}{S_{\text{max}}}\right)^2 + \left(\frac{T}{T_{\text{max}}}\right)^2 = 1$$  \hspace{1cm} (7)

2.2 Natural frequency (Eigen value) extraction method

Free vibration analysis is performed numerically to observe the influence of delamination on natural frequency response of the AZ31 magnesium alloy-based fibre metal laminates. Cantilever beam is modelled for analysis and linear perturbation with Lanczos Eigen solver is used to extract the natural frequency (Eigen values) during analysis. Therefore, ABAQUS/CAE provides a method to extract the natural frequencies during analysis as follows.

$$(-\omega^2 M^{MN} + K^{MN})\phi^N = 0,$$

Where

- $M^{MN}$ is mass matrix (symmetric and positive);
- $K^{MN}$ is stiffness matrix
- $\phi^N$ is eigen vector
- $M, N$ degree of freedom values.

When $K^{MN}$ is positive and definite then all eigenvalues are positive. Due to instabilities and rigid body modes, $K^{MN}$ is become indefinite. The instabilities will produce negative eigenvalues when initial stress values are included and zero eigenvalues due to rigid modes.

3. Geometrical modelling of AZ31 magnesium alloy-based fibre metal laminates

Double cantilever beam (DCB) and rectangle beam embedded with cohesive layer are modelled with six AZ31 magnesium alloy layers and seven carbon fibre prepreg (T800/5228) layers as shown in Figure 2. The dimension of the beam is taken as per the reference standards i.e., 130x15x2.36 mm with the pre-crack length of 45mm as shown in Figure 3. In both the models cohesive layer is modeled in the mid plane as shown in Figure 3 and Figure 4 with the mode I, mode II fracture energies 0.23 KJ/m$^2$ and 5.81KJ/m$^2$ respectively [23]. The properties of constituent layers are presented in Table.1. During numerical analysis 3D stress (C3D8R), continuum elements (SC8R) are selected to model the AZ31 magnesium alloy and T800/5228 carbon fibre prepreg layers respectively. 3D cohesive elements (COH3D8) are used to model the cohesive layer in the interface region. Recent literature suggests that cohesive layer thickness may be taken around 0.01 and 0.02 mm [24][25][26]. So, 0.02mm cohesive thickness has been used in the present study. Mesh sensitivity analysis has been done to improve the accuracy and saving time during analysis. During analysis one side of the beam is entirely fixed and displacement load is applied at another end of the beam as shown in the Figure 5.
**Table 1.** AZ31 magnesium/Carbon fibre prepreg layer mechanical properties[23].

| Materials                  | E (GPa) | ρ(g/cm³) | σ_{tensile} (MPa) | t_{thickness} (mm) |
|----------------------------|---------|----------|-------------------|-------------------|
| AZ31 Magnesium             | 45      | 1.78     | 230               | 0.2               |
| T800 C/5228 epoxy resin    | 125     | 1.53     | 1600              | 0.2               |

**Figure 2.** AZ31 magnesium alloy and T800/5228 carbon prepreg ply lay-up[23]

**Figure 3.** Schematic view of DCB model
4. Results and Discussion

In the present study, numerical analysis of DCB test for AZ31 magnesium alloy and T800/5228 carbon fibre prepreg based fibre metal laminates is performed to validate the experimental load-displacement curve. Cohesive zone method (CZM) is used to analyse the DCB test results numerically. The numerical results are in the order of experimental results presented by Y. Pan et al [23] and are as shown in Figure 6 and further, these cohesive layer properties are used in the free vibration analysis. From the curve, it may be depicted that linear behaviour till the damage initiation point (peak load in the curve) and after that there is a gradual decrease in the curve during propagation of delamination. The delamination propagation is also shown in the in Figure 7.

It is observed from the Figure 8 that there is a significant reduction in the natural frequency due to delamination in the FMLs. It may be due to the high reduction in the stiffness compared to the mass of
the fibre metal laminates. Approximately 51%, 84%, 55%, 65%, 61% are the percentage reductions observed in the natural frequency shifts of respective modes from mode 1 to mode 5. The lowest and highest percentage reductions corresponding to mode 1 and mode 2 respectively. Therefore, it is observed that reduction in natural frequency shifts may be depends on the mode shape and number.

**Figure 6.** load vs displacement curve

**Figure 7.** Delamination propagation during DCB test
5. Conclusions

This research paper investigated the numerical validation of mode I delamination using DCB test and studies the influence of delamination under free vibration analysis of Magnesium (Mg AZ31) alloy-based fibre metal laminates. After summarizing all the results obtained from this study, it can be depicted that for the presented model, the numerical values showed good acceptance with the experimental results and the natural frequency is sensitive to the delamination damages present in the fibre metal laminates. The lowest and highest percentage reductions corresponding to mode1 (51%) and mode2 (84%) respectively. Therefore, further it may be observed that reduction in natural frequency shifts are depends on the mode shape and its number.

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