Effect of shape mode and crack length on stress distribution in fiber metal laminates

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Abstract. Fiber metal laminates (FMLs) are widely used in various fields such as automotive and aerospace due to their high stiffness and strength to weight ratios. Moreover, they are also high fatigue resistance. In some applications such as aircraft structures, it is crucial to do a dynamic analysis in the FMLs structure. This research aims to investigate the effect of shape mode and crack length on stress distribution in fiber metal laminates. Numerical analysis is performed in this study to evaluate the stress distribution. Ten initial mode shape and crack length of 5 mm, 10 mm, and 15 mm are used as the environmental conditions of the FMLs. The results indicate that the mode shape will change the stress distribution and the maximum stress position. Besides, the crack will propagate when it received tensile stress and in opening mode.

Keywords: fiber metal laminates, shape mode, crack length, natural frequency, stress distribution

1. Introduction
Composites are combinations of two or more materials or phases simultaneously to produce a new material with new material properties [1]. Composites were used by the ancient Egyptians to build a house or boats where they combine mud and straw to produce strong and durable properties. Nowadays, composite materials are developed by utilizing plastic materials. However, plastic materials cannot provide sufficient strength, so a reinforcing material is needed as an addition to increase the stiffness and strength.

This research is using Fiber Metal Laminates (FMLs), where fiber is used as a reinforcement. The FMLs have excellent mechanical properties such as strength-to-weight ratio and stiffness-to-weight ratio compared to pure metal and polymer composite laminates. Based on the type of fiber, this material can be divided into three types, namely glass laminate aluminum-reinforced epoxy (GLARE), carbon-reinforced aluminum laminate (CARALL), and aramid-reinforced aluminum laminates (ARALLs) [2].

Glass laminate aluminium-reinforced epoxy (GLARE) is the most popular fiber metal laminates. GLARE is mostly applied in the production of aircraft structural components such as aircraft fuselage, which allows dynamic loading such as turbulence wind loading. Therefore, the vibrational characteristics such as natural frequency and shape mode of the structure are interested in analyzing. Natural frequency and material properties relationship can be seen in equation 1 [3].
\[
\omega_n^2 = \frac{\pi^4 D K}{a^4 \rho N}
\]

Where \( \omega_n \) is natural frequency, \( D \) is flexural rigidity (N m\(^2\)), \( \rho \) is density (kg m\(^{-3}\)), \( a \) is length (m), \( K \) is form function, and \( N \) is frequency coefficient (2.25 for fully clamped). Crack in FMLs can occur due to variations caused, including manufacturing and stress concentration, which can significantly change the properties of the FMLs plate such as reduce the stiffness, reduce the strength, and change the natural frequency. To analyze this phenomenon, stress and strain relationship and crack opening modes are essential concepts to understand the mechanics of materials and fracture mechanics, respectively. The value of stress and strain can give the mechanical properties of a material which is given a specific load [4]. For example, a material is stiff when the strain is small, even though it is subjected to large loads. The relationship between stress and strain can be seen in the following equation 2 [5].

\[
\sigma = E \varepsilon
\]

Where \( \sigma \) = stress (N m\(^{-2}\)), \( E \) is Young’s modulus (N m\(^{-2}\)), and \( \varepsilon \) is strain.

When vibration applied on the FMLs plates, three types of opening modes may occur (Figure 1). However, Mode 1 has a high possibility of occurring and lead the crack to propagate. Equations 3 and 4 show the stress that occurred perpendicularly to the crack in Mode 1 [6].

\[
\sigma = \frac{K_I \cos(\theta/2)}{\sqrt{2\pi r}} \left[ 1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right]
\]

(3)

where \( K_I = \sigma \cos^2(\theta) \sqrt{\pi a} \)

(4)

Where \( \sigma \) is applied stress (N m\(^{-2}\)), \( K_I \) is stress intensity factor (MPa\(\sqrt{m}\)), \( a \) is crack length (m), \( r \) is the distance from the crack tip (m), and \( \theta \) is the crack angle (°). Several kinds of research, such as analyzing the effect side-to-thickness ratio on the natural frequency of Glare fiber metal laminates with three layers of aluminium alloy (0.3 mm thick) and two layers of composite glass fiber (0.2 mm thick) with the simply-support has been done by Shooshtari [7]. The effect of the orthotropic plate and crack length on vibration characteristics has also been analyzed previously by Joshi [8]. In the study of Yang, vibration characteristics are analyzed by varying the applied stress on an isotropic plate [9]. However, these studies have not yet explained the effect of crack length, which
can affect the vibration and stress characteristics of FMLs. Because of that, it is necessary to have further research on the relationship of shape mode and crack length on stress distribution in fiber metal laminates.

2. Methods
A numerical method was used in this study by performing a software based on the finite element method (FEM). Ten initial mode shape and crack length of 5 mm, 10 mm, and 15 mm are used as the environmental conditions of the FMLs. The natural frequency and stress distribution that occurs in the crack tip area is obtained in each environmental condition. The geometry of the plate is shown in Figure 2. The fiber orientation is 0°/90°, and an epoxy adhesive is used to bond the aluminium and the fiber-reinforced polymers (FRPs). The loading is in the form of vibrations with 1 to 10 shape modes. The specimen is fully-clamped on the edges. Crack is modelled by using the seam method.

![Figure 2. The geometry of fiber metal laminates (in mm).](image)

The aluminium is assumed as bilinear isotropic hardening material, where the material properties are listed in Table 1. FRPs are assumed as an orthotropic material where the material properties are listed in Table 2. Table 3 shows contact interaction properties between aluminium and FRPs.

| Table 1. Material properties of aluminium |
|------------------------------------------|
| Property                   | Value |
| Young’s modulus (GPa)        | 68    |
| Yield stress (MPa)           | 85    |
| Ultimate tensile strength (MPa) | 105   |
| Poisson’s ratio              | 0.33  |
| Density (kg m⁻³)             | 2780  |
Table 2. Material properties of fiber-reinforced polymers

| Property                 | Value |
|--------------------------|-------|
| Density (kg m\(^{-3}\)) | 2200  |
| Transverse (MPa)         | 12    |
| Longitudinal (MPa)       | 12    |
| Transverse (MPa)         | 12    |
| Longitudinal (MPa)       | 12    |
| Tensile Modulus (GPa)    | 80    |

Table 3. Contact interaction properties

| Property                  | Value |
|---------------------------|-------|
| Contact stiffness (GPa)   | \(10^3\) |
| Normal (MPa)              | 1.2   |
| Shear in X direction (MPa)| 3.65  |
| Shear in Y direction (MPa)| 3.65  |
| Thickness (mm)            | 0.05  |

3. Results and discussion

3.1 The natural frequency

Table 4 shows the natural frequency for different shape mode and crack length obtained from the numerical results. It can be seen that the natural frequency decreases with increasing the crack length. Following equation 1, where the increase of the crack length will reduce the stiffness of FMLs, which will reduce the natural frequency. Besides, the different shape modes will change the natural frequency.

Table 4. Natural frequency (Hz) for different shape mode and crack length.

| Shape mode | Crack length (mm) | 5     | 10    | 15    |
|------------|-------------------|-------|-------|-------|
| 1          |                   | 52.523| 52.511| 52.498|
| 2          |                   | 106.72| 106.71| 106.70|
| 3          |                   | 106.76| 106.74| 106.72|
| 4          |                   | 157.09| 157.02| 156.95|
| 5          |                   | 190.50| 190.49| 190.46|
| 6          |                   | 191.46| 191.43| 191.40|
| 7          |                   | 238.65| 238.63| 238.57|
| 8          |                   | 238.75| 238.67| 238.60|
| 9          |                   | 303.49| 303.41| 303.26|
| 10         |                   | 303.54| 303.47| 303.44|
3.2 Stress distribution for various shape mode
Since the vibration is applied in the XZ plane, the stress in Y direction (normal to XZ plane) distribution is observed. There are three observed surfaces in this study, namely outer aluminum, inner aluminum, and FRPs. The stress is taken at the node in front of the crack tip. Table 5 summarized the displacement and stress in Y direction distribution of the FMLs with a crack length of 5 mm.

Table 5. The displacement and stress in the Y direction of the FMLs with a crack length of 5 mm

| Shape mode | Displacement | Stress in Y direction (MPa) |
|------------|--------------|----------------------------|
| 1          | ![Image]     | ![Image]                   |
| 2          | ![Image]     | ![Image]                   |
| 3          | ![Image]     | ![Image]                   |
| 4          | ![Image]     | ![Image]                   |
| 5          | ![Image]     | ![Image]                   |
| 6          | ![Image]     | ![Image]                   |
Figure 3. The highest stress in front of the crack tip on the outer surface of aluminium for different shape mode.
Table 5 informs that the deformation in each shape mode is different. However, the deformation on the outer surface of aluminum, the inner surface of the aluminum, and the FRPs remain the same. The red color represents the maximum value of the displacement and the stress in Y direction while the blue color represents the minimum value or passive vibration region. The positive stress value shows the tensile stress and the negative value shows the compressive stress. The highest stress in front of the crack tip on the three surfaces present in Figure 3-5.

![Figure 4.](image-url) The highest stress in front of the crack tip on the inner surface of aluminium for different shape mode

![Figure 5.](image-url) The highest stress in front of the crack tip on the FRPs surface for different shape mode.
Figure 3-5 shows a similar pattern though the stress value on the three surfaces is different. Since the vibration produces a similar loading condition as a bending load, the closest part with the neutral axis will have lower stress. In this study, the FRPs surface has the lowest stress compare to the inner and outer surface of the aluminium. Besides, the stiffness of the FRPs also plays an important role in this phenomenon. Another finding in Figure 3-5 is that each shape mode caused a different effect on the stress in front of the crack tip. Shape mode 3, 4, 8, and 9 have a low stress value. This condition indicates that the crack is not in opening mode, so the crack will not propagate.

As summarized in Table 5, the vibration form of 3, 4, 8, and 9 is symmetrical to the crack line or the center horizontal line of the plate. In this pattern, the crack line has a shallow stress value because the crack line is located in the middle horizontal line of the plate. On the contrary, the vibration form of 1, 2, 5, 6, 7, and 10 is symmetrical to the vertical axis so that the crack tip area has a high-stress value due to crack opening in mode 1 is dominant. The stress in front of the crack tip increase when the crack length is higher due to the stress concentration is increased. This is in accordance with equations 4 and 5, which show the relationship between crack length and stress value. The crack length is directly proportional to the stress value. Another unique phenomenon occurs in shape modes of 1 and 6. As shown in Figure 3-5, the highest stress value in front of the crack tip occurs in the crack length of 5 mm instead of 15 mm. It can be seen that the highest stress distribution occurs in the crack site. It will lead to relieve the stress near the crack. As shown in Figure 6, the maximum stress is decreasing while the crack length is increased.

**Figure 6.** The stress distribution for shape mode 1 on the outer surface of aluminium with the crack length of (A) 5 mm, (B) 10 mm, and (C) 15 mm.

**Figure 7** shows the stress distribution on the outer surface of aluminum, the inner surface of aluminum, and the FRPs surface with the crack length of 5 mm in the shape mode 1. The aluminium stress is relatively high compare to FRPS. The stress in front of the crack tip on the outer surface of aluminum, the inner surface of aluminum, and the FRPs surface are 127.285 MPa, 94.589 MPa, and 88.739 MPa, respectively. This is due to the FMLs plate has a rectangular cross-section so that the neutral axis is located in the middle of the FRPs, which means that the outer surface of the aluminum has the farthest distance to the neutral axis and the FRPs surface has the closest distance to the neutral axis.
Figure 7. The stress distribution for shape mode 1 at the crack length of 5 mm on (A) the outer surface of aluminium, (B) the inner surface of aluminium, and (C) FRPs surface.

4. Conclusions
With the proposed model, it is found that increasing the crack length will reduce the natural frequency of the plate but will increase the stress in front of the crack tip. The stress in front of the crack tip varies in different shape modes which are affected by different crack opening modes. Besides, the maximum to minimum stress distribution occurs on the outer aluminium surface, the inner aluminium surface, and the FRPs surface, respectively.

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6. References
[1] Askeland, Donald R., Pradeep P. Fulay, and Wendelin J. Wright. (2010). “The science and engineering of materials” 6th edition. Boston: Cengage Learning.
[2] Chadrasekar et al. (2018). “Fibre metal laminate” BioResources 13, 5725-5739.
[3] Leissa, Arthur W. (1969). “The vibration of plates.” Washington, D.C.: National Aeronautics and Space Administration.
[4] Ugural, Ancel C. (1993). “Mechanics of materials.” New York: McGraw-Hill.
[5] Popov, Egor P. (1990). “Engineering mechanics of solids”. Englewood Cliffs: Prentice-Hall.
[6] Gere, James M. & Stephen P.T. (1996). “Mechanics of Materials”. English: PWS Publishing Company.
[7] Anderson, T.L. (2005). “Fracture mechanics fundamentals and applications” 3rd edition. Boca Raton: Taylor & Francis Group.
[8] Shooshtari, A., and S. Razavi. (2010). “A closed-form solution for linear and nonlinear free vibrations of composite and fiber metal laminated rectangular plates.” Composite Structures 92: 2663-2675.
[9] Joshi, P.V., N.K. Jain, and G.D. Ramtekkar. (2014). “Analytical modeling for vibration analysis of partially cracked orthotropic rectangular plates.” European Journal of Mechanics A/Solids 50: 100-111.
[10] Yang, Nian et. all. (2016). “A unified solution for vibration analysis of plates with genera stress distributions.” International Journal of Naval Architecture and Ocean Engineering 8: 615-630.