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# Fracture Characteristic of Natural Fiber Metal Laminates

**Hitesh Raiyani [1], H. S. Patil [2], C. K. Desai [3]**

[1]*Ph.D. Research Scholar, Gujrat Technological University. Assistant Professor, Mechanical Engineering Department L J Institute of Engineering and Technology, L J University, Ahmedabad, India*
[2] *Professor and Head, Mechanical Engineering Department, GIDC Degree Engineering College, Abrama, Navsari, India*
[3]*Associate Professor and Head, Mechanical Engineering Department, C.K. Pithawala College of Engineering and Technology, Surat, India*

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**Abstract -** *Fiber metal laminates (FMLs) are innovative hybrid composite materials formed by laminating metal alloy sheets with composite layers, aimed at improving mechanical properties and fracture resistance. This study focuses on the development of FMLs, specifically exploring the influence of thickness variations on their mechanical properties and fracture behavior. The research examines the impact of size effects on the nominal strength and fracture characteristics of Natural Bamboo Fiber Metal Laminates (NB-FMLs). FMLs were initially fabricated with a thickness of 1.8 mm to assess their mechanical properties, and then a reduced thickness of 1.5 mm was used to analyze the effect on strength. 2D scaled specimens were prepared with size ratios of 1:1, 1:2, and 1:4, with rectangular samples of 25 mm, 13 mm, and 6 mm in width, and corresponding lengths of 178 mm, 127 mm, and 101 mm, respectively, for the different scale ratios. A double notch was introduced at the center of each specimen to study the fracture characteristics in relation to size effects. The nominal tensile strength of the Natural Bamboo reinforced Fiber Metal Laminates, created by alternating layers of Al-2024-T3 and bamboo-epoxy composite, was evaluated for each scaled model. The size effect parameter was determined by comparing the nominal strength across specimens. The tensile strength of the NB-FMLs was obtained using a Universal Testing Machine, following ASTM D 3039 standards. This paper provides an analysis of the tensile test results to determine the nominal strength of FMLs and evaluates the size effect parameters, including the length of the fracture process zone (FPZ) and fracture energy, to predict the material's fracture behavior.*

***Key Words***: Fiber Metal Laminates, Mechanical Properties, Nominal Tensile Strength, Effect of changing Thickness Size Effect Law, Fracture Characteristics

## 1.INTRODUCTION

Fiber metal laminates (FMLs) have been recently developed using diverse materials and fibers to enhance mechanical properties, such as high strength, superior fatigue resistance, and improved fracture characteristics, to meet the demands of the automation and aerospace industries, which require lightweight structures with enhanced mechanical and fracture properties [1]. To address these needs, hybrid FML structures have been created by alternating metal and composite layers [1, 2, 3]. Materials like aluminum alloys (e.g., Al-2024-T3, [3,4,5] Al-7475-T6 [6,7,8]), titanium [2,9,10,11], magnesium [12,13], and reinforced fibers (such as glass, aramid, and carbon) are commonly used to fabricate FMLs. Recently, there has been a shift towards the development of eco-friendly FMLs by substituting natural fibers for traditional glass or carbon fibers. Epoxy resins, typically mixed with hardeners at a 10:1 ratio, are employed to form composite layers and as adhesives to bond metal and composite layers together [13,14].

The hybrid structure of FMLs is formed through adhesive bonding of metal alloy sheets and composite layers [3,15,16], making the surface treatment of aluminum sheets crucial to improving FML strength. Surface preparation techniques, such as mechanical abrasion, alkaline treatment, anodizing, and etching, are commonly employed to enhance the bonding properties between layers [3, 13, 16]. In addition, alternative manufacturing methods, such as autoclave processing and resin transfer molding, have been adopted over traditional hand-layup techniques for FML production. The mechanical properties of FMLs depend on factors such as the thickness of the aluminum sheets, composite layers, resin-to-fiber ratio, and overall laminate thickness. The overall mechanical properties of FMLs can be predicted using two methods: Metal Volume Fraction (MVF) [9,11,17] and Classical Laminate Theory (CLT) [8,18]. While CLT provides more detailed predictions, MVF is a simpler method for estimating properties like tensile strength and modulus of elasticity.

Standard FMLs typically consist of thin metal alloy sheets (0.2 to 0.5 mm) and thin composite layers (0.2 to 0.3 mm) with various fiber orientations. However, a significant challenge in FML development is the lengthy resin curing process. Additionally, during the cutting of FMLs, the possibility of delamination between layers can occur. Cutting methods such as water jet cutting, wire cutting, and laser machining are commonly used. Water jet cutting is particularly effective for FMLs containing non-conducting materials, as laser and wire cutting methods may struggle with such materials. However, water jet cutting can cause more delamination than the other methods, requiring optimization of parameters like water jet flow and nozzle distance to minimize this effect.

The size effect is another important consideration in the design of FMLs, referring to how changes in specimen dimensions influence their nominal strength. A significant size effect is observed in composite materials, as the fracture energy release is influenced by the presence of the fracture process zone near the crack tip. In 1984 and 1993, Bazant proposed that for quasi-brittle composite materials, the size effect transitions from plasticity in the absence of a size effect to linear elastic fracture mechanics as the size effect becomes more prominent. The nominal strength is defined by the failure stress of crack-free or notch-free specimens. The relationship between size effect and nominal strength for geometrically similar specimens is described by the equation:

$$\sigma_N = B f_u (1+\beta)^{-1/2} \text{ where } \beta = \frac{D}{D_0}$$

Where β is relative structure size, $D_0$ is the constant depending on both fracture process zone and specimen geometry, D is characteristic dimensions, B is constant according to plastic limit theory, $f_u$ is reference strength of material to make B dimensionless. This size effect law applies to both 2D and 3D geometrical similarities. In 1D and 3D scaling, tensile strength decreases as scaling size increases due to more delamination, while in 2D scaling, tensile strength increases as the size grows, as the delamination effect is more significant at smaller scales. Furthermore, mechanical properties generally improve with an increase in specimen width. Size effect parameters have been measured to calculate the effective length of the fracture process zone and the fracture energy of materials [19].

## 2. LITERATURE REVIEW

The development of FMLs for aerospace applications is advanced for better strength and fracture toughness compared to monolithic materials. FML's development with monolithic aluminum Al-2024-T3 has better fracture toughness and fracture characteristics than pure monolithic aluminum Al-2024-T3. The crack growth of monolithic aluminum Al-2024-T3 rapidly increases, while GLARE and ARALL FML's crack growth are slower and almost constant slow crack growth [1]. Mechanical properties of Zn-Al-based FML were tested using a CMT5205 electronic UTM machine, considering the extensometer's span length of 25mm to measure deformation. Zn-Al-based FML's strength is 103% compared with the original magnesium alloy [12]. The effect of using alternative metal material, magnesium instead of aluminum, is studied, and it observed that magnesium is 1.55 times less heavy than aluminum with minor differences in tensile strength, bending strength and impact toughness. So, magnesium is better than aluminium for FML's development in the application where less weight is required by compromising slight strength [4].

Tensile-strength prediction of titanium-based FMLs with different fiber orientations between 0° to 90° with a 15-degree difference in fiber orientation is carried out by tensile testing. It is predicted that as the fiber orientation angle increases, tensile strength decreases. FMLs with 0-degree fiber orientation give higher tensile strength, while FMLs with 90° fibber orientation give lower tensile strength of FMLs [18].

FMLs with continuous film stacking have better properties than monolithic steel plates with 0.8 mm thickness. FMLs with 2 mm thickness archive 29% weight reduction compared with the steel plate of 0.8 mm [20]. It is better to use FMLs for lightweight structures. However, the scaling also affects the strength of FMLs. The size of FMLs varies in 1D, 2D and 3D and compared the normalized stress of all specimens. The normalized stress increases in 2D with increases in the size factor, while in 1D and 3D, normalized stress decreases with increases in the size factor [21].

## 3. STRENGTH OF FMLS

The test specimens of FMLs were prepared following the ASTM D-3039 standard [31] using the manufactured FMLs sheets. The specimens were extracted from the FMLs sheets through a water jet machining process. As per the ASTM D-3039 standard, rectangular specimens with dimensions of 250 mm (L) x 15 mm (W) x 1.8 mm (t) were cut from the FMLs sheet for the 0° fiber orientation, while specimens measuring 175 mm (L) x 25 mm (W) x 1.8 mm (t) were cut for the 90° fiber orientation, both using water jet machining [16,22].

Quasi-static tensile tests were performed at a constant crosshead displacement rate of 1 mm/min [6, 23, 30, 31] to evaluate the specimens, which had gauge lengths of 138 mm (for the 0° specimen) and 125 mm (for the 90° specimen). These tests were conducted in accordance with the guidelines and recommendations outlined in ASTM D3039 [16,22] to assess the mechanical properties.

**Table -1:** Tensile strength (0° specimen)

| Specimen Type | Yield Stress | Max Load | Modulus of Elasticity (E) | Ultimate Stress |
|---|---|---|---|---|
| 0 degree (Specimen 1) | 187.98 MPa | 7413.10 N | 14.241<br>G Pa | 260.00<br>M Pa |
| 0 degree (Specimen 2) | 190.22 MPa | 7903.08 N | 15.174<br>G Pa | 277.30<br>M Pa |
| 0 degree (Avg.) | 189.10 MPa | 7658.09 N | 14.707<br>G Pa | 268.65<br>M Pa |

**Table -2:** Tensile strength (90° specimen)

| Specimen Type | Yield Stress | Max Load | Modulus of Elasticity (E) | Ultimate Stress |
|---|---|---|---|---|
| 90 degree (Specimen 1) | 131.522 MPa | 8419.69 N | 4973.97 MPa | 168.39 MPa |
| 90 degree (Specimen 2) | 165.999 MPa | 8399.95 N | 8297.29 MPa | 167.99 MPa |
| 90 degree (Avg.) | 148.76 MPa | 8409.82 N | 6635.63 MPa | 168.19 MPa |

Two specimens were prepared and tested to ensure greater accuracy. The load-deflection and stress-strain curves were recorded for all specimens until failure occurred. Mechanical properties, including tensile strength and modulus of elasticity, were determined from the results of the tensile tests.

From the tensile test results, The Nominal strength of 268 MPa, Yield Stress of 189 MPa, and Modulus of Elasticity of 14708 MPa were recorded for the 0° fiber orientation specimen as shown in table 1 and the nominal strength of 168 MPa, Yield Stress 148 MPa, and Modulus of Elasticity 6635 MPa were recorded for 90° fiber orientation as shown in table 2. These tests were conducted in accordance with the guidelines and recommendations outlined in ASTM D3039 [16,22] to assess the mechanical properties as mentioned in Table 3.

## 3. THICKNESS EFFECT OF NATURAL BAMBOO FMLS

The total thickness of FMLs changed to 1.8 mm to 1.5 mm by reducing the layer thickness of Al-2024-T3 from 0.4 mm to 0.3 mm. The changing thickness effect on FMLs is carried out by testing of rectangular specimens with dimensions of 250 mm (L) x 15 mm (W) x 1.5 mm (t) were cut from the FMLs sheet for the 0° fiber orientation as shown in Fig-1, while specimens measuring 175 mm (L) x 25 mm (W) x 1.5 mm (t) were cut for the 90° fiber orientation as per the ASTM D-3039 standard, using water jet machining [16].

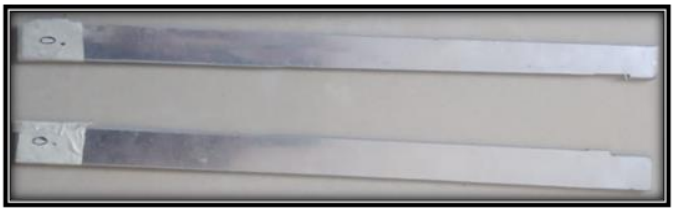


**Fig -1**: Specimen (0°fiber direction)

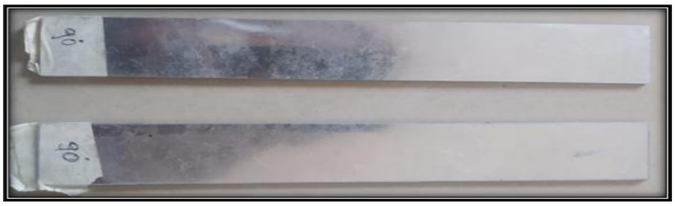


**Fig -2**: Specimen (90°fiber direction)

The Nominal strength, Yield Stress, and Modulus of Elasticity were recorded for the 0° and 90° fiber orientation specimen as shown in table 3 and comparison of different thickness as shown in table 4

**Table -3:** Tensile strength (1.5 mm Thickness)

| Specimen Type | Tensile Strength | Yield Stress | Max Load | % Elongation |
|---|---|---|---|---|
| 0 degree (Specimen 1) | 267.577 MPa | 214.062 MPa | 7.345 KN | 2.12 % |
| 0 degree (Specimen 2) | 255.161 MPa | 209.247 MPa | 7.119 KN | 4.12 % |
| 90 degree (Specimen 1) | 190.069 MPa | 152.015 MPa | 8.471 KN | 1.81 % |
| 90 degree (Specimen 2) | 201.728 MPa | 161.352 MPa | 9.223 KN | 2.76 % |
| 0 degree (Avg.) | 261.369 MPa | 211.654 MPa | 7.232 KN | 3.12 % |
| 90 degree (Avg.) | 195.898 MPa | 156.68 MPa | 8.847 KN | 2.29 % |

**Table -4:** Tensile strength Comparison (1.5 mm and 1.8 mm Thickness)

| Thickness (mm) | Fiber Orientation (degree) | Yield Stress (MPa) | Tensile Strength (MPa) |
|---|---|---|---|
| 1.5 | 0 degree | 211 ± 8.60 | 261 ± 8.60 |
| 1.8 | 0 degree | 189 ± 6.42 | 268 ± 6.42 |
| 1.5 | 90 degree | 156 ± 6.30 | 195 ± 6.30 |
| 1.8 | 90 degree | 148 ± 4.16 | 168 ± 4.16 |

The thickness effect of FMLs evaluated from comparison of FMLs specimens test results as shown in Table 4 it shows that the better yield stress in 1.5 mm thickness in both 0°fiber direction and 90°fiber direction with 1.5 mm total FMLs thickness as compare with FMLs with total 1.8 mm thickness.

## 4. SIZE EFFECT OF NATURAL BAMBOO FMLS

Fiber metal laminates (FMLs) are hybrid composite materials composed of alternating layers of thin metal alloys and fiber-reinforced composites. In this investigation, the stacking sequence of the FMLs is arranged as follows: Al-2024-T3 / Bamboo-epoxy Composite / Al-2024-T3 / Bamboo-epoxy Composite / Al-2024-T3. Three rectangular specimens were fabricated with the following dimensions: 25 mm × 178 mm × 1.8 mm (SE-1), 13 mm × 127 mm × 1.8 mm (SE-2), and 6 mm × 101 mm × 1.8 mm (SE-3), corresponding to 1, ½, and ¼ scale models, respectively. All the FML specimens were precision-cut using water jet machining. A double-notch was introduced at the center of each specimen using a 1 mm hand grinder to examine the fracture behavior of the natural bamboo Fiber Metal Laminates. Figure 1 depicts the specimen with a central double-edge notch. The double-notch was fabricated according to the relationship a=B/16 [23], where a is the length of the notch and B is the width of the specimen. The nominal tensile strength of the scaled FML specimens was evaluated as following ASTM D 3039 [23, 25,27-32] standards with crosshead speed kept at 1mm/min for all specimens [24,25,26] and gauge length of all specimens kept the same as 38mm using an Instron Universal testing machine.

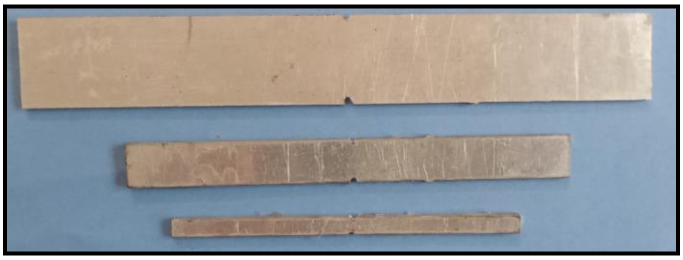
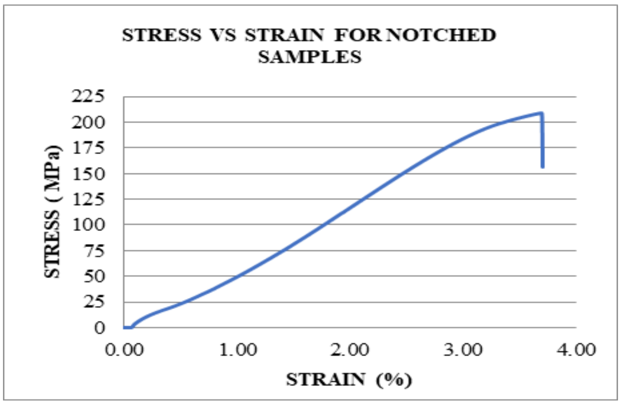
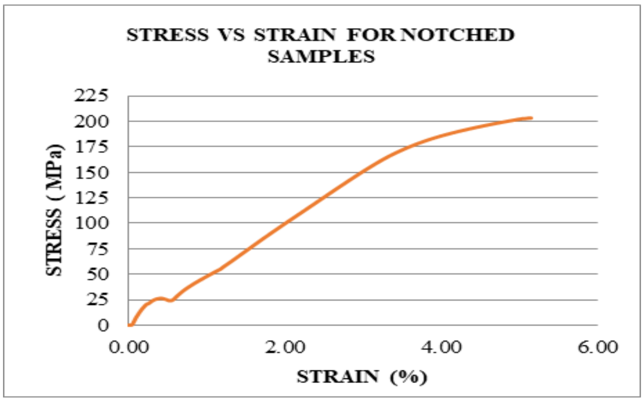


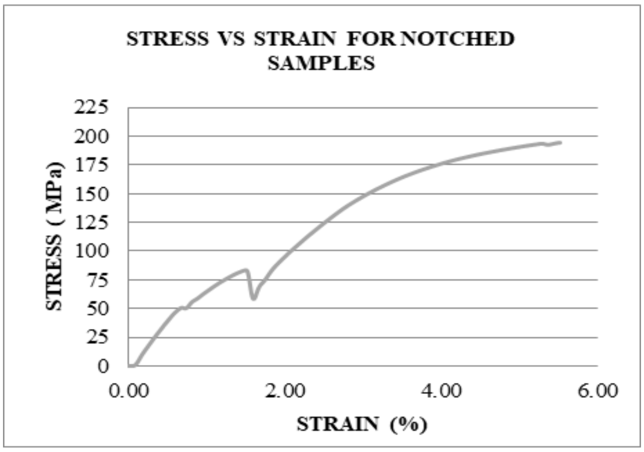
**Fig -2**: specimen with center double-edge notch



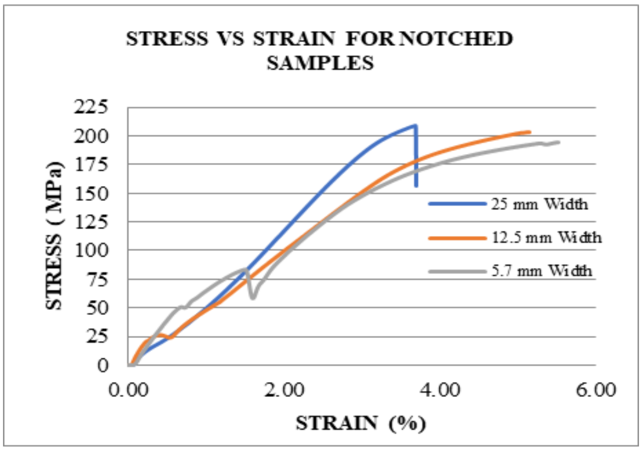
25 mm width specimen



12.5 mm width specimen



5.7 mm width specimen



Combine all specimens

**Chart -1**: Stress (MPa) vs Strain (%)

Chart 1 shows the experimental results obtained from the tensile test. The stress-strain diagram for large specimen dimensions behaves like brittle material while the small-size specimens behave like ductile materials. The size effect parameter for Natural Fiber Metal Laminates was calculated based on the nominal tensile strength obtained from tests conducted on specimens of varying sizes. This parameter was determined through a regression analysis of the data derived from the tensile testing. In calculating the size effect parameter, the size effect law, as represented by Equation 1, was applied, with the following considerations incorporated into the regression analysis process [23].

$D = X$

$\sigma_N = Y^{(-0.5)}$

$Y = \sigma_N^{-2}$ (GPa$^{-2}$

$Bfu = A^{-0.5}$

$D_0 = A/C = 1/(C\,(Bfu)^2\ )$

Linear regression equation obtained for the size effect law in equation 1 based on the above consideration.

$Y = A + CX$

A regression analysis plotted Y versus X in Chart 2 by using Minitab for geometrically similar specimens.

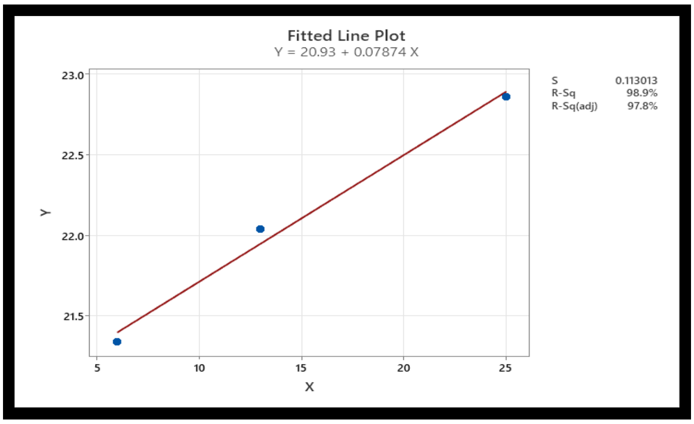


**Chart -2**: Regression Analysis

A regression equation Y = 20.93 + 0.07874 X was obtained by Plotting Y versus X or fitting the result data with the size effect law based on nominal strength. The value of A = 20.93 which is the vertical intercept and C = 0.07874 which is the slope, were obtained by comparing standard linear regression equations. The size effect parameter $D_0$ and Bfu determine by using equation 2. The parameter of size effect obtained as follows: $D_0$ = 265.81 mm and Bfu= 218.58 Mpa.

## 5. FRACTURE CHARACTERISTICS BASED ON MEASURED SIZE EFFECT

The failure of Natural fiber metal laminates containing cracks or notch shows a significant size effect. This size effect gradually converts from strength criteria to linear elastic fracture mechanics with increases in size. In 1990, Bazant and Kazemi reported the size effect law in terms of the nondimensionalized energy release-rate g (α) and obtains fracture energy of material ($G_f$) and effective length of fracture process zone ($C_f$) as follows [2].

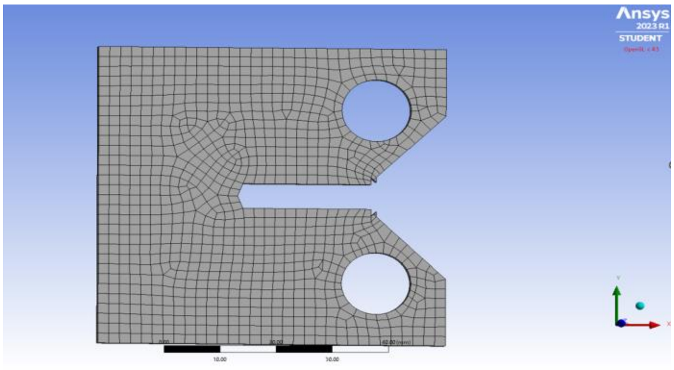
$$G_f = \frac{(Bf_u)^2}{(C_N)^2 E} D_0 \; g\,(\alpha_0)$$

$$C_f = \frac{g\,(\alpha_0)}{g'\,(\alpha_0)}$$

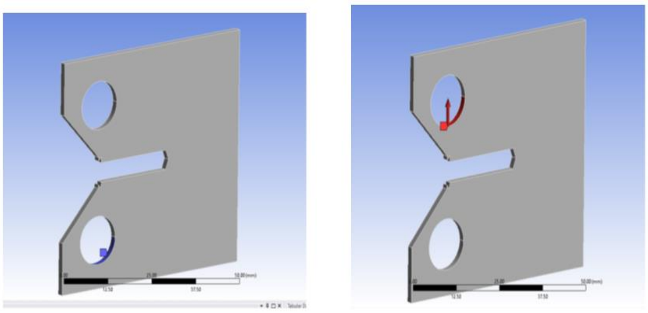
Where $\alpha_0 = 0.2 = \frac{a_0}{B}$, $a_0$ is initial crack length, $C_N$ value kept 1, and modulus of elasticity E = 15174.654 Mpa obtained from tensile test. Fracture characteristics in terms of fracture energy of material and effective length of fracture process zone can obtain by using the measured size effect parameter. We obtain fracture characteristics as $G_f$ = 0.99088 MJ/m$^2$ and $C_f$ = 31.52 mm for double notched natural Fiber Metal Laminates.

## 6. FRACTURE ANALYSIS

Numerical Fracture Testing carried out with CT specimen for stress intensity factor of FMLs. Fig -3 Shows the boundary condition and results obtain from numerical analysis.

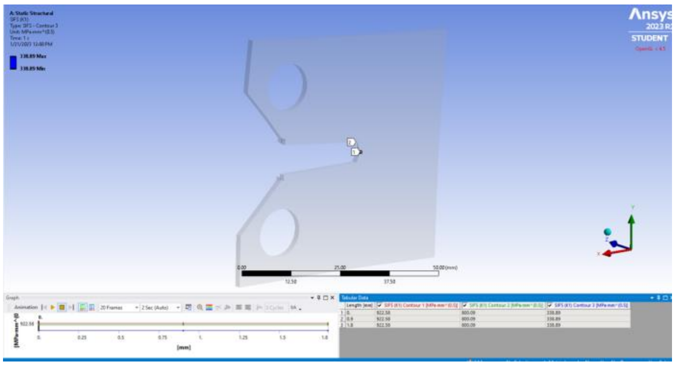


Meshed CT specimens



**Fixed Support** **Load : 2500 N**

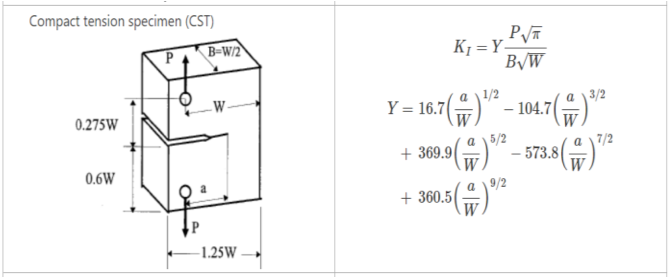
Boundary Conditions



SIFS ($K_1$): 338.89 Mpa $mm^{0.5}$

**Fig -3**: Boundary condition and SIFS ($K_1$)

Stress intensity factor 338.89 Mpa mm^ (0.5) is obtain by numerical analysis and analytical critical stress intensity factor by using $K_1$ formula as shown in Fig – 4, is calculated as 519.729 Mpa mm^ (0.5).



$$K_I = Y\frac{P\sqrt{\pi}}{B\sqrt{W}}$$

$$Y = 16.7\left(\frac{a}{W}\right)^{1/2} - 104.7\left(\frac{a}{W}\right)^{3/2} + 369.9\left(\frac{a}{W}\right)^{5/2} - 573.8\left(\frac{a}{W}\right)^{7/2} + 360.5\left(\frac{a}{W}\right)^{9/2}$$

**Fig -4**: CT Specimen Dimensions

Crack propagation takes place when the stress intensity factor, $K_1$, exceeds or equals the critical stress intensity factor, $K_{IC}$. In the current analysis, since $K_1$ is lower than $K_{IC}$, crack growth does not occur in the fabricated FMLs.

## 7. CONCLUSIONS

The tensile strength of Fiber Metal Laminates (FMLs) with a 0° fiber orientation was found to be 59.52% higher than that of FMLs with a 90° fiber orientation, while the yield strength of FMLs with a 0° fiber orientation was 27.70% higher compared to those with a 90° orientation. Additionally, the modulus of elasticity for FMLs with a 0° fiber orientation was observed to be more than twice that of FMLs with a 90° fiber orientation. The material's tensile strength in natural fiber metal laminates represents an optimal value compared to the individual strengths of aluminum (Al-2024-T3) and the composite material. It was noted that both tensile strength and modulus of elasticity decrease as the fiber orientation angle increases, making the 0° fiber orientation preferable for achieving superior strength. Moreover, fiber orientation parallel to the applied load direction results in higher tensile strength than fiber orientation perpendicular to the load direction. The longitudinal elasticity of natural bamboo fiber metal laminates was found to be more than twice the transverse elasticity.

Furthermore, the yield stress observed in FMLs with a thickness of 1.5 mm, regardless of fiber orientation (0° or 90°), was higher than in FMLs with a total thickness of 1.8 mm. This is attributed to the fact that larger thicknesses tend to result in greater delamination within the FMLs. The size effect on the nominal strength of natural fiber metal laminates was examined by testing three geometrically similar specimens. The stress-strain behavior of large specimens mimics that of a brittle material, whereas smaller specimens display ductile characteristics. Notably, a larger notch in a larger specimen reduces the material's ductility, causing it to behave more like a brittle material. The analysis revealed that as the specimen size increases, the size effect transitions from a strength-based criterion to linear elastic fracture mechanics.

The size effect method for calculating fracture characteristics is advantageous due to its simplicity, as only the maximum load needs to be considered. The size effect parameters derived from regression analysis can be utilized to determine fracture properties such as fracture energy and the effective length of the fracture process zone. These parameters are essential in assessing the fracture behavior of FMLs, especially in structures with micro-cracks. Additionally, crack propagation occurs when the stress intensity factor, $K_1$ , reaches or exceeds the critical stress intensity factor, $K_{IC}$ . In this study, as $K_1$ remains below $K_{IC}$, crack growth does not occur in the fabricated FMLs.

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