Investigation of the Structural Behaviour of Fibre-Reinforced Metal Laminates by Finite Element Analysis

Terry P. Crouch

The University of New South Wales at the Australian Defence Force Academy

Fibre-reinforced metal laminates are considered a suitable option in aerospace applications due to their superior mechanical properties, and high strength-to-weight and stiffness-to-weight ratios. The requirements for aerospace to have more weight sensitive structures have produced more interest in structural applications of fibre-reinforced metal laminates. Variations of parameters can influence the final properties of the fibre reinforced laminates. This research investigates the development and application of fibre reinforced metal laminates in the aerospace industry and the effects of a variety of parameters on the structural behaviour using numerically modelling technique.

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I. Introduction

The demands on composite laminates presently used in aerospace structures are driven by the market which seeks the production of new levels of performance and efficiency. The optimisation of initial and life cycle costs, time-to-market, and the overall performance of the platform are identified as areas of interest. Customers’ demands for reliability and price performance and a continuation with the increase in the capital returns for the investors, require ongoing advancement of technologies within the aerospace industry (Cantor, Grant, & Assender 2001). Optimisation of composite laminates will improve the platform’s performance and reduce the life cycle costs of the structure.

The client brief which outlined the objectives and deliverables of this thesis are in Appendix A. Appendix B lists the components of the tasks which were addressed. Appendix C is a Gantt chart outlining the predicted time frames for each individual task to be completed. Appendix D is a milestone chart of the major achievements within the research and their expected finish date.

The FRMLs which will be examined are Glass-reinforced Aluminium Laminate (GLARE) currently used extensively in aerospace industry, Central reinforced Aluminium (CentrAL) and Hybrid Titanium Composite Laminates (HTCL), also referred to as Titanium Graphite (TiGr). Both of the latter show strong signs of promise to become dominate FRMLs for aerospace applications in the future.

The aim of this research is to investigate the development and application of fibre-reinforced metal laminates currently used in aerospace structures, and through a process of numerical modelling, the influence of specific parameters on deflection and stress behaviour of the FRML will be determined, in order to provide designers information and references for an innovative composite laminate. Finite Element Analysis (FEA), with the assistance of an engineering computer software tool, ANSYS, which will be used for numerical modelling of the FRMLs. The key parameters to be considered are the volumetric fibre content of fibres present in each layer of
epoxy, the thickness of each individual layer of epoxy, the orientation of the fibres within the epoxy layers, and the configuration of the lay-up of the FRML.

II. Composite Laminates

There are many different types of composite materials such as fibre-reinforced composites, aggregate composites, and natural fibre reinforced composites (Shackelford 2005). Initially, aerospace structures predominately used advance composites due to their resistance to fatigue. With development over time composites have now become more attractive. Advanced composites offer advantages in additional areas such as fire resistance, impact resistance, and damage tolerance. The fatigue, corrosion, and high strength-to-weight ratio properties of composites are more attractive than metal alloys. When compared to metal alloys used in aerospace the disadvantages of advanced composites are their moisture absorption and lack of fracture toughness (Bothelo, Silva, Pardini & Rezende 2006).

Composite laminates are materials that involve some combination on a macroscopic scale of two or more different primary structural engineering constituents such as polymers, metals, ceramics and glasses. These combined materials are created to provide a final useful composite laminate which usually incorporates the best qualities of the individual constituent’s mechanical properties. The formation of composite laminates can improve some properties including the strength, stiffness, corrosion resistance, wear resistance, weight, fatigue life, temperature-dependant behaviour, thermal insulation and conductivity, and acoustical insulation (Jones 1999).

FRML composites are advanced composites which consist of fibre reinforcements and matrices. A stiffer and stronger fibre is used to reinforce the matrix material, which are relatively weak and possess lower specific stiffness. The combination produces a material which possesses significant improvements in some or all properties including high strength-to-weight and stiffness-to-weight ratios, fatigue resistance, residual strength impact resistance, blast impact resistance, and fire resistance properties. The materials used in both the fibre reinforcements and matrices can be metal, polymer, or ceramic materials. (Vogelesang & Volt 2000).

A. Fibre Reinforcements

Fibre reinforcements are generally produced in three forms: continuous fibres, whiskers, and woven fabric. The direction in which the fibres are aligned influence the strength and modulus (Guocai & Yang 2005). Continuous fibres are made from organic materials such as aramid fibres which contain carbon hydrogen and nitrogen long chain molecules or they can be produced from light elements. Examples of such light elements include the compounds silicon oxide (silica-based glasses and silica), silicon nitride, silicon carbide, carbon and boron. Whiskers are short and ultra-strong and stiff fibres which in general are difficult to incorporate into composites with a high degree of alignment and orientation. The limited use of whiskers is due to their high manufacturing costs. Technology advances over the years have allowed the development of special reinforcing fabrics comprising a single fibre or a combination of continuous fibres which are woven together as a composite reinforcement (Barker, Dutton & Kelly 2004). Material properties of some fibres used in composite materials for aerospace are shown in Table 1.

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Tensile Modulus (GPa)</th>
<th>Tensile Strength (GPa)</th>
<th>Density (g/cm³)</th>
<th>Specific Modulus (10⁶ m²/s²)</th>
<th>Specific Strength (10⁶ m²/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E Glass</td>
<td>69</td>
<td>2.4</td>
<td>2.54</td>
<td>27</td>
<td>1.0</td>
</tr>
<tr>
<td>R/S Glass</td>
<td>85</td>
<td>4.5</td>
<td>2.52</td>
<td>35</td>
<td>1.8</td>
</tr>
<tr>
<td>Aramid</td>
<td>125</td>
<td>3.6</td>
<td>1.45</td>
<td>85</td>
<td>2.5</td>
</tr>
<tr>
<td>Boron</td>
<td>400</td>
<td>3.5</td>
<td>2.6</td>
<td>155</td>
<td>1.4</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Based</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultrahigh Modulus</td>
<td>725</td>
<td>2.2</td>
<td>2.185</td>
<td>336</td>
<td>1.02</td>
</tr>
<tr>
<td>Intermediate Modulus</td>
<td>310</td>
<td>5.2</td>
<td>1.8</td>
<td>170</td>
<td>2.9</td>
</tr>
<tr>
<td>Medium Modulus</td>
<td>235</td>
<td>3.8</td>
<td>1.8</td>
<td>130</td>
<td>1.2</td>
</tr>
</tbody>
</table>
B. Matrices

The purpose of the matrix in addition to forming the components’ shape are to transfer the load into and out of the fibres, to provide a type of protection against environmental reactions, and to protect other fibres from failure if a surrounding fibre has failed, resulting in a restriction of the propagation of brittle cracks. Matrix dominated properties of the composite material are the shear strength, the transverse tensile strength, the resistance to temperature and environment, and the longitudinal compressive strength. Matrix materials in composites include polymers, metals, and ceramic (Callister 2003). Matrices generally have a lower stiffness than the fibres constituents which results in the fibre layer with a low shear modulus (Van Rooijen, Sinke, DeVries & Van Der Zwaag 2004). Polymers such as epoxy and bismaleimide resins have excellent mechanical properties. Metals such as titanium alloys, aluminium, and magnesium offer several advantages including tolerance of higher service temperatures. Ceramic matrices use silica-based glass to produce matrices that have an increase in toughness and operating temperatures (Barker et al. 2004).

C. Types of Composites Laminates

There are two main types of composite laminates; polymer matrix composites, also known as Carbon Fibre Reinforced Plastics (CFRP), and non-polymer composite systems. The main interest of the current research is the non-polymeric composites systems which are composites such as metal-matrix composites, particulate composite materials, ceramic matrix composites, and hybrid metal/polymer matrix composites. The hybrid metal/polymer matrix composites, also known as FRMLs, are seen as the composite having the most potential for future improvements to be incorporated in aerospace applications. Thus FRMLs is the main subject of this investigation.

III. Development and Application of Fibre Reinforced Metal Laminates Composites in Aerospace Industries

A. Fibre Reinforced Metal Laminates

Figure 1 shows a typical lay-up of FRMLs consisting of the combination of composite material layers of fibre reinforced polymer composite adhesively bonded to thin metal sheet layers (Afaghi-Khatibi, Lawcock, Ye, & Mai 2000). The capacity to produce many different types of FRMLs composites can be achieved due to the variety of metal alloy, matrix resins, thickness of each layer, number of layers, and fibre orientations which can be used in the configuration process. Table 2 shows the different properties of different metals, and different alloys. The theory of being able to create various configurations for specific applications promotes FRML as a good option for numerous specialised applications, especially in the aerospace industry (Sinke 2006). The material combinations which have been discussed for development because of their flexibility properties are a combination of aluminium and glass fibre/epoxy, or steel and glass fibre/epoxy, or even a combination of aluminium, steel and glass fibre/epoxy layers (Khalili, Mittal & Kalibar 2005). The variations of the combinations of these three materials produced a number of composite laminates with varying degrees of mechanical properties. Theoretically therefore, there is an FRML that is suitable for almost any application. It was also shown that an improvement in one area may also produce an increase in the undesirable properties of the laminate. However, the combinations available for FRMLs are not infinite. There are some considerations to keep in mind when developing new FRMLs, for example, the potential for galvanic corrosion to occur with the combination of particular constituents (Sinke 2006).

FRMLs when compared to metals have many advantages in damage tolerance in areas such as resistance to corrosion, fatigue, impact, residual strength, fire and lightning strike. In addition, their fracture toughness, durability, high blast resistance, and impact properties are greater than traditional materials, making them a more attractive alternative for aerospace applications. Another factor which needs to be taken into account when examining the feasibility in changing from metal alloy materials to FRMLs is the limited investment costs involved in the manufacturing process. There are disadvantages, which include their limited stiffness, the lack of feasibility of every combination, and the expense and time involved with the introduction of new FRMLs (Khalili et al. 2005).
Table 2  Metals Properties (www.matweb.com/index.aspx)

<table>
<thead>
<tr>
<th>Type</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Modulus E (GPa)</th>
<th>Density (g/cm³)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7475-T761</td>
<td>517</td>
<td>70.3</td>
<td>2.81</td>
<td>0.33</td>
</tr>
<tr>
<td>2024-T3</td>
<td>483</td>
<td>73.1</td>
<td>2.78</td>
<td>0.33</td>
</tr>
<tr>
<td>2324-T39</td>
<td>475</td>
<td>72.4</td>
<td>2.77</td>
<td>0.33</td>
</tr>
<tr>
<td>7075-T651</td>
<td>572</td>
<td>71.7</td>
<td>2.81</td>
<td>0.33</td>
</tr>
<tr>
<td>7178-T651</td>
<td>607</td>
<td>71.7</td>
<td>2.83</td>
<td>0.33</td>
</tr>
<tr>
<td>8090-T651</td>
<td>510</td>
<td>77.0</td>
<td>2.54</td>
<td>0.33</td>
</tr>
<tr>
<td>Titanium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti 15-3-3-3</td>
<td>790</td>
<td>82</td>
<td>4.76</td>
<td>0.33</td>
</tr>
<tr>
<td>Ti-6AL-2Sn-4Zr-2Mo</td>
<td>1010</td>
<td>120</td>
<td>4.54</td>
<td>0.32</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>1035</td>
<td>105</td>
<td>4.42</td>
<td>0.310</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9000 Series Steel</td>
<td>770</td>
<td>200</td>
<td>7.85</td>
<td>0.290</td>
</tr>
<tr>
<td>8000 Series Steel</td>
<td>530</td>
<td>187</td>
<td>7.85</td>
<td>0.29</td>
</tr>
<tr>
<td>6000 Series Steel</td>
<td>670</td>
<td>205</td>
<td>7.85</td>
<td>0.29</td>
</tr>
<tr>
<td>Magnesium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MA1 Sheet Hard-Rolled</td>
<td>240</td>
<td>45</td>
<td>1.77</td>
<td>0.35</td>
</tr>
<tr>
<td>Magnesium ZM21-H24 Sheet</td>
<td>248</td>
<td>45</td>
<td>1.79</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Common FRMLs which are currently used or are being developed for use in the aerospace industry are Aramid Reinforced Aluminium Laminate (ARALL), GLARE, carbon/aluminium laminates also named as CARbon Reinforced Aluminium Laminates (CARAL) (Barker, et al. 2004), and HTCL which consists of graphite fibres reinforcing titanium sheets (Johnson, Hammond 2008).

ARALL which consists of Kevlar fibres reinforcing aluminium sheets is applied in many aviation applications. It has been used as the rear door on the C-17, the T38 dorsal covers, missile load platform (Sandia), and early F100 crack stoppers. GLARE which consists of glass fibres reinforcing aluminium sheets has been applied in situations such as bulk cargo floors on Boeing 777, United Airlines Boeing 737 and 757 aircraft, and all Boeing aircraft at QANTAS. It is also employed in Midwest Express DC9; explosion hardened LD3 containers, Lear Jet 45 forward bulkhead, AT&T aircraft electronics cabinets, and the fuselage on the A380 Airbus (Laiberte, Poon, Straznicky, & Fahr 2000; Bernhardt, Ramulu & Kobayashi 2007).

A combination of composites such as Carbon Fibre Reinforced Plastics (CFRP) and GLARE used in conjunction with other materials is now used in commercial aircraft such as the A380 Air bus as shown in Figure 2. Another type of FRML which is also considered quite attractive and promising for space applications due to its high strength and stiffness combined with good impact properties is CARAL, which consists of carbon fibres reinforcing aluminium sheets (Bothelo et al. 2006).

![Figure 2 Metal/fibre applications in A380 airplane from Airbus (Bothelo et al. 2006).](image-url)
B. A Brief History of Composite Laminates in Aerospace

During the 1970’s, composites and metal combinations, although quite expensive, were being studied in the U.S. and Great Britain. NASA Langley research centre realised that the combination of metals and composites reduced the weight of the structures when compared to the same aluminium structures, and at a lower cost than using full composite option. Early development research carried out by Delft University of Technology identified the two major concerns with the FRML as being the crack growth and the de-lamination of the laminate. Optimisation of FRMLs required a balance between these two concerns. Continuation of FRML optimisation in 1980 at Delft resulted in a lay-up of aluminium layers between 0.3 mm or 0.4 mm and aramid fibre layers. This material, now known as ARALL was first applied in a project funded by the Netherlands Agency for Aerospace Programmes to an F-27 aircraft to determine its suitability in a real scenario. The ARALL wing panels of a F-27 were exposed to 270 000 flights, three times the design life of the F-27. The research identified minor cracks occurring at the fingertips, but this result enabled successful use of ARALL as a wing structure, giving increased safety level and achieving a 33% weight reduction when compared with the equivalent aluminium wing structure. ARALL was tested and developed for further applications such as a ballistic material when combined with a ceramic outer tile, and a modified ARALL for high temperature applications of space structures and supersonic transports by replacing the aramid fibres with carbon and replacing the aluminium layers with titanium. ARALL with such promise in the beginning was only used in secondary structures such as lower wing skins, lower flap skins, and on the C-17 military transport aircraft due to an excess weight problem in the rear. The rear door for the C-17 was manufactured from ARALL, but due to the complexity of production and the size of the rear door the cost factor became even more significant and consequently only thirty rear cargo doors were produced (Vermeeren 2003).

C. Glass Reinforced Aluminium Laminate

The observation of the failure of aramid fibres at some loading conditions initiated research into the area of using glass fibres to replace the aramid fibres in 1986. This research is what led to the development of a new FRML GLARE (Laiberte et al. 2000; Sinke 2006). As with ARALL, the initial studies on GLARE were done in wing structures, and the viability of the material depended on its ability to be applied to fuselage and other structural applications. The requirement of the fuselage to be able to withstand internal pressures in the presence of large cracks led to the development of GLARE 3, the cross-plied variants of the unidirectional laminates of GLARE 1 and GLARE 2. The introduction of cross plied GLARE variants made it a more suitable applicant for the fuselage panelling in aircraft. There are now six major variants of GLARE, each with a variation of their main beneficial characteristic as shown in Table 3 (Bothelo et al. 2006).

Table 3 Standard GLARE grades (Bothelo et al. 2006)

<table>
<thead>
<tr>
<th>GLARE grade</th>
<th>Sub</th>
<th>Al sheet thickness</th>
<th>Prepeg orientation in each fibre layer</th>
<th>Main beneficial characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLARE 1</td>
<td>-</td>
<td>0.3-0.4 (7475-T761)</td>
<td>0/0</td>
<td>Fatigue, strength, yield stress</td>
</tr>
<tr>
<td>GLARE 2</td>
<td>GLARE 2A</td>
<td>0.2-0.5 (2024-T3)</td>
<td>0/0</td>
<td>Fatigue, strength</td>
</tr>
<tr>
<td></td>
<td>GLARE 2B</td>
<td>0.2-0.5 (2024-T3)</td>
<td>90/90</td>
<td>Fatigue, strength</td>
</tr>
<tr>
<td>GLARE 3</td>
<td>-</td>
<td>0.2-0.5 (2024-T3)</td>
<td>0/90</td>
<td>Fatigue, impact</td>
</tr>
<tr>
<td>GLARE 4</td>
<td>GLARE 4A</td>
<td>0.2-0.5 (2024-T3)</td>
<td>0/90/0</td>
<td>Fatigue, strength, in 0° direction</td>
</tr>
<tr>
<td></td>
<td>GLARE 4B</td>
<td>0.2-0.5 (2024-T3)</td>
<td>90/0/90</td>
<td>Fatigue, strength, in 90° direction</td>
</tr>
<tr>
<td>GLARE 5</td>
<td>-</td>
<td>0.2-0.5 (2024-T3)</td>
<td>0/90/90/0</td>
<td>Shear, off-axis properties</td>
</tr>
<tr>
<td>GLARE 6</td>
<td>GLARE 6A</td>
<td>0.2-0.5 (2024-T3)</td>
<td>+45/-45</td>
<td>Shear, off-axis properties</td>
</tr>
<tr>
<td></td>
<td>GLARE 6B</td>
<td>0.2-0.5 (2024-T3)</td>
<td>-45/+45</td>
<td></td>
</tr>
</tbody>
</table>

The development of GLARE over the years has improved its mechanical behaviour and it has been applied to more areas of an aircraft. Originally used in the forward bulkhead of the Lear Jet 45 business-jets by Shorts of Northern Ireland in 1996, it was later applied as replacement stiffeners in aircraft used to transport seafood in Indonesia, cargo bay doors on C-17 military aircraft (Vermeeren 2003), and as shown in Figure 3, used for the first time in commercial airlines as a structural application on the upper fuselage skin structure panels in the A380 Airbus (Guocia & Yang 2005). The use of GLARE over the years since its initial development has increased on both commercial and military aircraft.
The aerospace industry’s need for greater weight savings in aircraft has encouraged development of the use of FRMLs in the wing structures. Considering the lower wing skins are constructed with 2000 series aluminium whilst 7000 series is used on the upper wing skins and the requirement for large resistance to crack growth, GLARE was considered as a lighter alternative to these materials. However, the significantly larger thicknesses required in the wing structures created complexities in production using current GLARE manufacturing processes. These factors led to the development of CentrAL. CentrAL initially consisted of two thick Aluminium layers centrally reinforced by GLARE as shown in Figure 4. The total thicknesses of the outer layers are made up of a number of multiply thin aluminium sheet layers joined together. The multiple layers improve the fatigue properties compared to the original concept of one thick piece of aluminium either side of the GLARE reinforcement. The initial problem in CentrAL was the requirement to optimise the balance between crack bridging and delamination resistance between the thick metal sheets and the outer layers of GLARE. The development of Bondpreg™, a combination of S2-glass prepreg and standard adhesive, provided the required balance to overcome this initial setback. This resulted in an easy to manufacture, thicker material which possesses higher fatigue and strength properties than current grades of GLARE (Roebroeks, Hooijmeijer, Kroon & Heinimann 2007).

D. Hybrid Titanium Composite Laminate

One of the more recent FRMLs which is receiving growing interest and which is under current development for aerospace applications is the range of composite laminates HTCLs. HTCLs are a combination of composite plies and thin titanium plies as shown in Figure 5. NASA Langley Research Centre started work in developing titanium/high temperature graphite polymer composite hybrids, which showed considerable promise, towards the end of the 1980s (Johnson & Hammond 2008). The main cause of failure during the fatigue testing of HTCLs is delamination between the layers of plies. For this reason, development of HTCLs over time has focused on improving the surface treatments and adhesives of the plies. HTCLs are still seen as a potential material for future applications in aerospace structures. The main advantages of HTCLs over traditional laminate composites are their ability to be readily inspected for impact damage. In addition, they have improved toughness, beneficial material properties, and lower crack growth rates resulting in an improvement in their damage tolerance properties. (Bernhardt et al. 2007).
IV. Methods and Theories

A. Micromechanics of Composites

The micromechanics of a composite material look at the relationship between the composite materials and the interaction of the individual constituents’ properties which make-up the composite. The composite material’s strength and stiffness is related to the percentages of the constituents within that composite. Micromechanics allow us to mathematically estimate the properties of the composite. The micromechanics theory of composite materials from the book “Mechanics of Composite Materials” (Jones 1999) is employed in this study. The basic assumptions for this approach assume that the bond between the matrix and the fibre is perfect. The fibres are continuous, uniformly spaced, and are aligned parallel with each ply. The materials for the matrix and fibre are linear elastic, each of their elastic modulus is constant and they approximately follow Hooke’s Law. Finally the composite has no voids or defects present (Altenbach, Altenbach & Kissing 2004).

The mechanics of materials approach was used for determining the various engineering constants with varying volumetric fibre content \( v_f \). The variations in \( v_f \) not only determine the engineering constants of the composite but they also affect the mass of the laminate. The mass will increase as the amount of S-2 fibres within the epoxy increases. The increase in the mass is related to the density of the fibres \( \rho_f \) which is more than twice the \( \rho_m \) (density of the matrix). Therefore as shown in Eq. (1) using the rule of mixture, the \( \rho_c \) (density of the composite) will increase as the volumetric fibre content increases, producing a laminate with a higher mass for the same physical size.

\[
\rho_c = \rho_f v_f + \rho_m \left(1 - v_f\right)
\]

(1)

The variation of the \( v_f \) parameters affects other engineering constants, such as the effective longitudinal modulus of elasticity \( E_1 \), the effective transverse modulus of elasticity \( E_2 \), the effective major Poisson’s ratio \( \nu_{12} \), the transverse Poisson’s ratio \( \nu_{23} \), the effective in-plane shear modulus \( G_{12} \), and the transverse shear modulus \( G_{23} \). Due to the large number of slight variations for the parameter \( v_f \) a MATLAB code was used to calculate the engineering constant for each individual \( v_f \) of S-2 fibres within epoxy. Equation (2) is the rule of mixture (often referred to as the Voigt estimate). It is used to calculate the effective longitudinal modulus of the lamina if the Young’s modulus of the fibre \( E_f \) and the matrix \( E_m \), and the \( v_f \) parameter value are known.

\[
E_1 = E_f v_f + E_m \left(1 - v_f\right)
\]

(2)

To calculate the \( v_{12} \) we need to have the \( v_f \) parameter and the Poisson’s ratio for the fibre \( \nu_f \) and matrix \( \nu_m \) values. If the longitudinal strains in the fibres, matrix, and the composite are assumed to be equal, we are able to assume the Voigt model of parallel connection to combine them as shown in Eq. (3). The major Poisson’s ratio also follows the rule of mixture.

\[
\nu_{12} = \nu_f v_f + \left(1 - v_f\right) \nu_m
\]

(3)

Equation (4) with the use of Hooke’s Law can be utilised to calculate \( G_{12} \), assuming that the shear stresses applied are equal for both the fibres and matrix of the lamina, but the shear strains experienced by the matrix and fibres are different. As with the early calculations the value of \( v_f \) is also required.

\[
G_{12} = \frac{G_m G_f}{\left(1 - v_f\right) G_f + v_f G_f}
\]

(4)

The equations to calculate the variables \( G_f \) and \( G_m \) are in Appendix E.
The three engineering constants above utilise the rule of mixture to calculate the combined values when the fibres are placed within a matrix (Altenbach, Altenbach & Kissing 2004).

The calculations for the transverse engineering components, $E_2$, $\nu_{23}$, and $G_{23}$, using the assumption that the resulting composite properties are transversely isotropic are given in the following equations (Kaw 2006).

$$E_2 = 2(1 + \nu_{23})G_{23}$$  \hspace{1cm} (5)

Were engineering constant $\nu_{23}$ is calculated by Eq. (6).

$$\nu_{23} = \frac{K^* - mG_{23}}{K^* + G_{23}}$$  \hspace{1cm} (6)

The equations to calculate the variables $m$ and $K^*$ are in Appendix E.

Engineering constant, $G_{23}$ is calculated by solving a pre-determined acceptable quadratic equation as shown below Eq. (7).

$$A \left( \frac{G_{23}}{G_m} \right)^2 + 2B \left( \frac{G_{23}}{G_m} \right) + C = 0$$  \hspace{1cm} (7)

The evaluation of the constants $A$, $B$ and $C$ in Eq. (7) are enclosed in Appendix E.

B. **Finite Element Analysis**

Finite Element Analysis (FEA) also referred to as Finite Element Method (FEM) is one of the most powerful numerical methods, which is used to solve engineering problems. It is an efficient way to predict structures’ performance especially for the complicated geometric components which are difficult to be solved analytically. It can be used to define the displacements, stresses, vibration and buckling characteristics under a designated set of boundary conditions and loads for structures compiled of metal or composite materials (Hutton 2004).

FEA is an effective tool in engineering as it offers the ability to consider an array of options for a problem using computer simulation. The computer simulation allows these options to be considered at a reduced cost, both financial and time, compared to analyses involving processes where materials are developed and physically tested (Barker et al. 2004). FEA leads to shorter time on developing a product that is fit for service and in theory produces a higher quality material. FEA was used in this research to compare large variety of combinations/variations of the parameters to determine their influences of the chosen FRML structural behaviour in a cost-efficient way.

ANSYS was used to evaluate the parameter variations as it is a recognised and reliable engineering FEA software tool used widely throughout the engineering fields, such as biomedical, automotive, civil and aerospace engineering. The procedures of FEA in ANSYS include pre-processing, solution, and post processing. Pre-processing is considered as the model definition. Defining the model involves defining the geometric shape of the model; the element type to be used and the material properties and dimensions of the elements. The model is then meshed to a mesh size with the size of the mesh determining the accuracy of the model and the time taken to calculate the solution. In the solution process, boundary conditions are then placed on the model, and the load is placed onto the model. The solution phase involves computing the primary field variables from algebraic equations assembled in a matrix form. These primary field values are then used to calculate other values such as element stresses, and reaction forces. The postprocessing is the review and analysis of the FEA results. These results are used to create plots of the deflection produced, stress distribution and even animate the dynamic model behaviour.

V. **Finite Element Analysis of Fibre-Reinforced Metal Laminates**

The methodology of this research is to develop a FEA model for the various FRMLs and model the structural behaviour under ANSYS environment. The ideas are to determine the type of ANSYS shell element to use to determine the type of material of the individual constituents of the composite. This is followed by a validation of the FEA model against analytical methods and experimental data in order to decide on the parameters which may influence the structural behaviour when varied, and finally analyses of the structural behaviour of the FRMLs are assessed as the parameters are varied.
A. Geometric Model

A diagram of the plate used for the modelling is shown in Figure 6. The plate has dimensions of 0.5m by 0.5m. The dimensions were constructed on ANSYS in two-dimensional drawing. The plate size remains constant throughout the parameter variations. All four sides of the plate were clamped; this is indicated by the anchor symbols in Figure 6. The load applied to all materials and parameter variations were evenly distributed over the top surface of the plate.

B. Elements

Linear layered shell analysis on ANSYS uses SHELL 99. This element consists of six degrees of freedom for each node. Translations in the x, y, and z directions were combined with rotations about the x, y, and z axes. It is a quadratic element with midside nodes. The element is defined by eight nodes, average thickness, and material properties. The restrictions for this element assume no slippage between the layers with shear deflections included in the element. If multiple load steps are used, the number of layers must remain constant between load steps. The stress varies linearly through the thickness of each layer. The interlaminar transverse shear stresses assume no shear is carried at the top and bottom surfaces of an element. All inertial effects are assumed to be in the nodal plane. The large deflection option is not as convergent as other elements. Therefore if large deflections are expected, it is necessary to use a more appropriate element such as SHELL 91.

The shell element used for this research of nonlinear geometric layered element analysis on ANSYS was SHELL 91. The element is a quadratic element with midside nodes. The element is defined by eight nodes, layer thickness, layer material, direction angle, and material properties. The element’s degrees of freedom are translations in the x, y, and z directions and rotations around the x, y, and z-axes, a total of six degrees of freedom. The use of SHELL 91 has assumptions and restrictions for its implementation, similar to SHELL 99. An extra restriction is for a nonlinear material is that no layer can be thicker than a 1/3 of the average element thickness (ANSYS 2007).

C. Validation of Finite Element Model

The finite element model needs to be validated to show it is an accurate representation of composite plate behaviour under loading. The model was validated against a composite plate which was clamped (bolted down) along all four sides and exposed to a uniformly distributed load across one surface. The square plate consisted of four layers of cross ply laminate with a lay-up configuration of 0°/90°/90°/0°. The dimensions of the plate on all sides were \( L = 12\text{ in.} \), and the thickness of each of the layers were \( t = 0.096\text{ in.} \). The engineering constants for the plate were the longitudinal Young’s Modulus was \( E_1 = 1.8282 \times 10^6 \text{ psi} \), whilst the transverse Young’s Modulus was \( E_2 = 1.83015 \times 10^6 \text{ psi} \), in-plane shear moduli and transverse shear modulus were equal at \( G_{12} = G_{13} = G_{23} = 3.125 \times 10^6 \text{ psi} \), and the major Poisson’s ratio \( \mu_{12} = 0.23949 \) whilst \( \mu_{13} = 0 \) and the transverse Poisson’s ratio of \( \mu_{23} = 0 \) (Zhang & Kim 2005). The clamped side constraints were simulated by restricting the four sides of the model plate in all six degrees of freedom. This condition was achieved by setting the x-direction, x-rotation, y-direction, y-rotation, z-direction, and z-rotation all to the value of zero. The uniform distributed force was simulated by apply a pressure to the top surface area.

The validation of the ANSYS model was conducted with the use of experimental data (Zaghloul & Kennedy 1975), and numerous analytical methods of FEA of thin to moderately thick laminated composite plates. The numerical methods used were the mixed element method by Putcha and Reddy (Putcha & Reddy 1986), the four node quadrilateral displacement based laminated element RDKQ-L24 (Zhang & Kim 2004) utilising nodes with six degrees of freedom, and element LDT18 (Zhang & Kim 2005) a simple based three node, eighteen degree of freedom flat triangular shell/plate element.
1. Linear Validation

Initially, the finite element model is validated against a linear problem to ensure that the boundary conditions and engineering constants were correct. The ANSYS shell element that was utilised for linear simulation was SHELL 99. The ANSYS results are compared with the accepted numerical methods, Putcha and Reddy mixed element method, RDKQ-L24, and LDT18 are displayed in Table 4 and graphically represented in Figure 7. The graphical representation of the linear results shown in Figure 7 demonstrates the correlation of ANSYS finite element model for linear analysis when compared to accepted numerical modelling techniques. These results confirm that the methods used to simulate the clamping of the sides of the plate and the application of an evenly distributed load on the ANSYS model were an acceptable representation of the reaction of the composite plate. Therefore these simulations of the model were acceptable for analysis of composite plate behaviour.

Table 4. Central Deflection Linear Solution (Zhang & Kim 2005)

<table>
<thead>
<tr>
<th>Central Deflection (in.)</th>
<th>Applied Load (psi)</th>
<th>Putcha and Reddy</th>
<th>LDT18</th>
<th>RDKQ-L24</th>
<th>ANSYS (Shell 99)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4</td>
<td>0.0869</td>
<td>0.0851</td>
<td>0.0842</td>
<td>0.0821</td>
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<tr>
<td></td>
<td>0.8</td>
<td>0.1650</td>
<td>0.1703</td>
<td>0.1684</td>
<td>0.1642</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
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<td>0.2463</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>0.3304</td>
<td>0.3406</td>
<td>0.3367</td>
<td>0.3284</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>0.4087</td>
<td>0.4257</td>
<td>0.4209</td>
<td>0.4105</td>
</tr>
</tbody>
</table>

2. Nonlinear Validation

The accuracy of a linear numerical method is only valid for small deflections of the composite plates. After a load of approximately 0.5 psi was applied, the linear calculations over-estimated and continued in a linear function where as the experimental results show the deflection of the composite plate were nonlinear. For this reason, a more accurate method of modelling was required to be able to predict the behaviour of composite plates. To achieve an acceptable level of accuracy for the composite plate behaviour geometric nonlinearity numerical modelling methods were used. The shell element used for simulating geometrically nonlinear analysis in the presence of large deflections on ANSYS was Shell Element 91. The results from the ANSYS model once again were compared to the results of the accepted numerical modelling methods Putcha and Reddy mixed element method, RDKQ-NL24, and LDT18 geometrically nonlinear analysis. Furthermore, the geometrically nonlinear analyses methods had also been compared to experimental results obtained by Zaghloul and Kennedy in 1975 as shown in Table 5 and are represented graphically in Figure 8.

Initially when compared to the experimental results of Zaghloul and Kennedy of 1975 the calculated results of the ANSYS model in Figure 8 followed the same trend pattern at a lower value. Even though the ANSYS modelling under-estimates the deflection of composite plates when compared to the actual experiment results, the values calculated by ANSYS were located between the accepted nonlinear numerical methods of Putcha and Reddy, RDKQ-NL24, and LDT 18 and the actual recorded deflection by Zaghloul and Kennedy. For this reason the ANSYS model was considered an acceptable representation of the behaviour of composite plates under loading. Therefore ANSYS models were used to model the FRML and analysis their structural behaviour for parameter variations in this research.
Table 5 Central Deflection Nonlinear Solution (Zhang & Kim 2005)

<table>
<thead>
<tr>
<th>Applied Load (psi)</th>
<th>Putcha and Reddy</th>
<th>Experiment</th>
<th>LDT18</th>
<th>RDKQ-NL24</th>
<th>ANSYS (Shell 91)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.062</td>
<td>0.078</td>
<td>0.0614</td>
<td>0.0612</td>
<td>0.0651</td>
</tr>
<tr>
<td>0.8</td>
<td>0.096</td>
<td>0.122</td>
<td>0.0962</td>
<td>0.0960</td>
<td>0.1006</td>
</tr>
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<td>1.2</td>
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<td>0.174</td>
<td>0.1394</td>
<td>0.1393</td>
<td>0.1423</td>
</tr>
<tr>
<td>2.0</td>
<td>0.150</td>
<td>0.187</td>
<td>0.1550</td>
<td>0.1549</td>
<td>0.1572</td>
</tr>
</tbody>
</table>

D. Materials

The three materials that were chosen for the research were GLARE, CentrAL, and HTCL. GLARE was chosen as it was a FRML that has been extensively utilised by the aerospace industry. CentrAL as a material that gives the ability to manufacture thicker FRML components and possesses higher strength and fatigue properties was selected as it showed promise for future use in aerospace. HTCL was a FRML that had improved mechanical properties over traditional laminates. Due to these improved properties there is an interest from the aerospace industry.

The metal alloy material used in the metallic layers of GLARE and CentrAL is aluminium type 2024-T3. HTCL metallic layers are titanium alloy type 15-3-3. The composite layers within all three types of FRML consist of an epoxy matrix reinforced with S-2 glass fibres. The materials remain constant throughout the investigations as the layout parameters are changed.

E. Parameters

The four parameters investigated in this research were the volumetric fibre content, the matrix thickness, the lay-up configuration and the orientations of the fibre within the matrix.

1. Volumetric Fibre Content

A type of fibre which is commonly used in manufacturing of epoxy is S-2, or “structural” glass fibres. Glass fibres are the most commonly used reinforcement due to their good balance of mechanical properties and low costs to produce. The S-2 type of fibre was used in all the modelling on ANSYS. The volumetric fibre content \( f_{\nu} \) used in epoxy is approximately 59% (Campbell 2006). The general practice of epoxy manufacturing does vary the \( f_{\nu} \) between a range of values of 50% to 60%. The maximum \( f_{\nu} \) is limited by the way in which the fibres are packed in the epoxy. If the fibres are packed in the layer wise or square fibre packing method the maximum \( f_{\nu} \) value is limited to 78.5%, whilst if the fibres are packed utilising the hexagonal method it limits the maximum value of \( f_{\nu} \) to 90.7% (Altenbach, Altenbach & Kissing 2004). Therefore a good representation of the \( f_{\nu} \) parameter was considered to be between the values of 40% through to 75% for this research.

The variation of \( f_{\nu} \) affected the engineering constants of the materials. The calculations that were used for the variation of engineering constants are shown in Micromechanics of Composites section in chapter IV.

2. Matrix Thickness

The second parameter within a FRML which may be easily varied is the thickness of the matrix. The common thickness of an epoxy matrix used in the manufacture of GLARE is approximately 0.127 mm (0.005 in) (Campbell 2006). This research has numerically modelled varying thicknesses ranging in values between 0.1 mm to 0.5 mm at intervals of 0.025 mm. All the other materials properties and parameters were kept constant throughout the modelling.

3. Lay-Up Configuration

Lay-up configuration was investigated by varying the number of metal alloy sheets and epoxy layers present for each composite plate. An example of GLARE in a 3/2 lay-up as represented by ANSYS is shown in Figure 9. Material one is the Aluminium alloy plates whilst material two is the epoxy layers. The configurations were varied.
around the standard configurations used in the other parameter modelling as shown in Table 6 below. The rest of parameters and material properties were kept constant.

### Table 6  Lay-Up Configuration for GLARE, CentrAL, and HTCL

<table>
<thead>
<tr>
<th>Material – GLARE Configuration</th>
<th>Material – CentrAL Configuration*</th>
<th>Material – HTCL Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Lay-up Configuration</td>
<td>Metal Alloy</td>
<td>Metal Alloy</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
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<td>7</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>14</td>
</tr>
</tbody>
</table>

*Note the CentrAL configuration is of the internal GLARE reinforcement and does not include the top and bottom 4 mm thick layers of aluminium alloy.

4. **Fibre orientation**

The final parameter considered was the fibre orientation. Fibre orientation is the angle of the fibres within the matrix with respect to the designated x direction. The angles that were investigated ranged from 0° to ±90°. An ANSYS representation of GLARE with ±45° fibre orientation is shown in Figure 9. The aluminium alloy layers (material one) are in the x-direction whilst the epoxy layers are varied. The lines represent the angle of orientation. The angles were individually modelled. The variation of the fibre orientation had no effect on the overall mass of the plate.

### VI. Results

The structural behaviour due to the variations of the parameters’ volumetric fibre content, the thickness of the matrix layer, the configuration of matrix and metal layers, and the fibre orientation were modelled on ANSYS and recorded. The deflection and stress behaviour was then plotted individually against the chosen key parameters and then the masses of the plate which varied as a result of the parameter variations. The deflection recorded was the maximum deflection of the plate recorded when exposed to a uniformly distributed load. The stress plotted was the maximum stress experienced under the uniformly distributed load by the plate. The comparison of the structural behaviour and the mass of the plate was important given that major advantages of using composite laminates over traditional metal alloys are that composite laminates are considered to possess higher strength-to-weight and stiffness-to-weight ratios.

The materials used in GLARE, CentrAL and HTCL are mentioned in the Materials section of chapter V Finite Element Analysis of Fibre-Reinforced Metal Laminates. The parameters of the composite unless otherwise stated are as follows:

1) **GLARE** - the volumetric fibre content of 59%, matrix thickness of 0.127 mm, metal alloy thickness of 0.2 mm, lay-up configuration of 3/2 (three layers of metal alloy and two layers of epoxy), and the fibre orientations were ±45°

2) **CentrAL** - the volumetric fibre content of 59%, matrix thickness of 0.127 mm, lay-up configuration of a 4 mm top and bottom layer of aluminium with GLARE inserted in between consisting of a 3/2 (three layers of metal alloy and two layers of epoxy), the metal layers within the GLARE component were 0.2 mm, and the fibre orientations were ±45°

3) **HTCL** - the volumetric fibre content of 59%, matrix thickness of 0.127 mm, metal alloy thickness of 0.2 mm, lay-up configuration of 1/4 (one layer of metal alloy and four layers of epoxy), and the fibre orientations were 0°, ±45°

Due to the effects that parameters have on the structural behaviour a plot of the parameters against the deflection/maximum deflection ratio, and the stress/maximum stress ratio were included. The ratio values of deflection and stress was chosen due to the large variations in magnitude difference in the absolute values between the materials. The ratio plots demonstrate the trends of the different composites in relation to the maximum result of that parameter. The ratio is calculated by dividing the individual value recorded by the maximum recorded value for that range of parameters.

The results due to varying the volumetric fibre content, the thickness of the matrix layer, the configuration of matrix and metal layers, and the fibre orientation parameters are discussed in the following sections.
A. Volumetric Fibre Content

The general variation in the parameter $\nu_f$ used in the manufacturing of fibre reinforced epoxy is between the values of 50% to 60% (Altenbach, Altenbach & Kissing 2004). The values of $\nu_f$ which have been numerically modelled during this research are between values of 40% to 75%.

The graphs in Figure 10 to Figure 17, demonstrate the structural behaviours of the maximum deflection and stress as the $\nu_f$ parameter was varied for the materials modelled: GLARE, CentrAL, and HTCL. The variation of this parameter also created a variation in the mass of the plate. The magnitudes of the deflection and stress behaviours are graphically represented as a plot against both the varying $\nu_f$ and mass of the plate.

1. Deflection due to variations of the Volumetric Fraction Content and Mass for GLARE

Figure 10 demonstrates the maximum deflection of GLARE in respect to both the $\nu_f$ of the S-2 fibres in the epoxy and the mass of the plate. The two graphs in Figure 10 represents the relationship between the deflection that occurred as both the mass of the plate and the $\nu_f$ were increased. The trends that were seen was the deflection value decreased as both the $\nu_f$ of the epoxy and the mass of the plate were increased.

2. Stress due to variations of the Volumetric Fraction Content and Mass for GLARE

Figure 11 represents the relationship between the GLARE material and the stress produced under a constant load compared to the varying $\nu_f$ and the plate’s mass respectively.

Figure 11 supports the trends of decreased stress experienced as the mass of the plate and the $\nu_f$ are increased. The trends of the stress and deflection behaviour were quite similar throughout the $\nu_f$ parameter variations.
3. Deflection due to variations of the Volumetric Fraction Content and Mass for CentrAL

The deflection behaviour recorded by the variation of both the \( \nu_f \) and the mass of the plate for CentrAL FRML is shown in Figure 12.

The internal GLARE’s epoxy layers were the location in which the parameter \( \nu_f \) is varied. The deflection behaviour with respect to both \( \nu_f \) and the mass of the plate are shown in Figure 12.

The trends of the deflection behaviour graphs in Figure 12 were similar to the deflection behaviour relationships of the GLARE material in Figure 10. This type of behaviour was expected as the internal components of the CentrAL plate were the same type of GLARE. The deflection for CentrAL was of lower magnitude. The trends for CentrAL were that as both the plate mass and \( \nu_f \) parameters were increased the deflection of the plate decreased.

4. Stress due to variations of the Volumetric Fraction Content and Mass for CentrAL

The stress behaviour of CentrAL laminate is shown below in Figure 13. The stress is compared to the \( \nu_f \) parameter and plate mass variations. The type of CentrAL utilised for the stress analysis was of the same configuration as the material used for the deflection modelling.

The stress value of the plate decreased as the plate’s mass and the \( \nu_f \) of the epoxy were increased, refer to Figure 13. The trends of decreasing stress values were similar to the GLARE results. This behaviour was expected as the internal components of CentrAL were constructed from the same GLARE configuration. The stress and deflection behaviour produced similar trends as both the mass of the plate and the \( \nu_f \) parameters were increased.

Figure 12 Deflection behaviour of CentrAL with respect to the Volumetric Fibre content and the Mass of the plate respectively

Figure 13 Stress behaviour of CentrAL with respect to the Volumetric Fibre content and the Mass of the plate respectively
5. **Deflection due to variations of the Volumetric Fraction Content and Mass for HTCL**

The final FRML plate that was modelled on ANSYS with the varying parameter of $\nu_f$ was HTCL. The layers of epoxy is where the parameter of $\nu_f$ is varied. Figure 14 highlights the relationship between the deflection behaviour of HTCL and the variations of the plate’s mass and the $\nu_f$ of the epoxy layers.

![Figure 14 Deflection behaviour of HTCL with respect to the Volumetric Fibre content and the Mass of the plate respectively](image)

The deflection behaviour of the HTCL, similar to both the GLARE and CentrAL deflection behaviour, decreased as the $\nu_f$ parameter was increased. The deflection of the plate decreased as the overall mass of the plate increased. The trends of the deflection of the HTCL plate in respect to both the increased $\nu_f$ and plate mass were demonstrated in Figure 14.

6. **Stress due to variations of the Volumetric Fraction Content and Mass for HTCL**

The stress behaviour in relation to the $\nu_f$ and mass of the plate variations is shown in Figure 15. The HTCL plate modelled for the stress behaviour was of the same configuration of the plate employed in the deflection analysis.

![Figure 15 Stress behaviour of HTCL with respect to the Volumetric Fibre content and the Mass of the plate respectively](image)

The trends of the stress behaviour decreased with both the increased $\nu_f$ and mass of the plate refer to Figure 15, were initially increasing between the $\nu_f$ values of approximately 40% to 45% before decreasing. This stress behaviour is quite different to what was experienced by the GLARE, and CentrAL. Although it has a slight increase between a limited range of the parameters it proceeded to decrease the stress as the parameter was increased.

7. **Compare Materials**

Figure 16 and Figure 17 demonstrate that volumetric fibre content variations were affecting the deflection and stress behaviour. Table 7 is the recorded values of stress and deflection experienced by varying volumetric fibre content.
The magnitude of deflection and stress by the three materials were quite varied, making the comparison of the absolute deflection and stress quite difficult. For this reason, the deflection and stress ratios of the three materials were compared.

Figure 16 represent all three materials deflection ratio against the \( \nu_f \) parameter. The effect that \( \nu_f \) had on CentrAL was quite limited. GLARE’s reaction to the \( \nu_f \) variations was a slight variation over the range examined. The plates of HTCL deflection ratio were more susceptible to the variations of \( \nu_f \) parameter. HTCL showed the largest variation the deflection ratio. This suggests that for GLARE and CentrAL the parameter \( \nu_f \) had little effect on their deflection behaviour. However, for HTCL, a material with a greater number of epoxy to metal alloy layers, the effect of \( \nu_f \) on the deflection behaviour was more influential.

Figure 17 graphically represent the stress ratio of GLARE, CentrAL, and HTCL against the variations of the parameter \( \nu_f \). The stress ratio CentrAL possessed the lowest effect of the stress ratio over the \( \nu_f \). GLARE and HTCL demonstrated a greater effect of the stress ratio over the parameters range of values. HTCL plate had again displayed the highest deviation in the stress ratio. However when the amount of stress ratio experienced by the HTCL was compared to the deflection ratio the effect \( \nu_f \) had on the stress ratio was quite minimal. Therefore the deflection behaviour of composite containing a higher ratio of epoxy layers to metal alloy layers are affected by the \( \nu_f \), the stress behaviours of the three composite materials were minimally affected by the variation of the \( \nu_f \) parameter.
B. Matrix Thickness

The variation of the thickness of matrix layers was between the ranges of 0.1 mm through to 0.5 mm values. The range of values used was based on information on current practice in GLARE manufacturing utilises a matrix thickness of 0.127 mm (Campbell 2006). The value of each matrix thickness was applied to all matrix layers within the FRML’s lay-up configuration at the one time. Therefore all the matrices had the same thickness. The variation of the matrices thickness parameter not only influenced the structural behaviour of the composite but it interfered with the overall mass of the plate.

The stress and deflection trends of varying the matrix thickness of GLARE, CentrAL, and HTCL were individually plotted in respect to the matrix thickness and the mass of the various plates. These plots are from Figure 18 to Figure 25.

1. Deflection due to variations of the Matrix Thickness and Mass for GLARE

The plots in Figure 18 represent the maximum deflection in relation to the thickness of the matrices and to the total mass of the plates for GLARE.

The trends of the graphs in Figure 18 demonstrate that as the matrix thickness was increased the maximum deflection experienced decreased. The deflection of the GLARE plate decreased with the increased of the plate mass.

![Figure 18 Deflection behaviour of GLARE with respect to the Matrix Thickness and the Mass of the plate respectively](image)

2. Stress due to variations of the Matrix Thickness and Mass for GLARE

Figure 19 graphically represents the maximum stress of GLARE with respect to both the matrix thickness and overall plate mass. The configuration used for GLARE was the same of that utilised for the deflection modelling.

![Figure 19 Stress behaviour of GLARE with respect to the Matrix Thickness and the Mass of the plate respectively](image)

The increase of the matrix thickness produced a decrease of the stress experienced within the plate. These trends are demonstrated from the results represented in Figure 19. The trends of the stress within the GLARE over the varying thickness of the matrix were similar to the deflection behaviour for the same parameter variations.
3. **Deflection due to variations of the Matrix Thickness and Mass for CentrAL**

The parameter variation of matrix thickness for CentrAL was the variation of the thicknesses of the matrix of the internal GLARE component of the composite. The deflection behaviour with respect to matrix thickness and the mass of the plate are demonstrated in Figure 20.

The maximum deflection behaviour was plotted against both the varying plate mass and varying matrix thickness as shown in Figure 20. The trends recorded a decrease of the plate’s deflection value as both the matrix thickness and plate mass were increased. This deflection behaviour was once again similar to the GLARE behaviour.

4. **Stress due to variations of the Matrix Thickness and Mass for CentrAL**

Figure 21 displays the relationship between the maximum stress behaviour of the CentrAL plate in respect to both the matrix thickness and the mass of the plate. The CentrAL configuration utilised was the same as the configuration as the deflection model.

The trends of the stress within CentrAL, refer to Figure 21, were similar to the deflection behaviour. The stress recorded decreased where both the matrix thickness and overall mass values increased. This structural behaviour was expected as CentrAL is a configuration of two aluminium sheets reinforced by a GLARE composite.

5. **Deflection due to variations of the Matrix Thickness and Mass for HTCL**

The third FRML plate that was modelled with the varying parameter of matrix thickness was HTCL. The graphs in Figure 22 represent the structural behaviour of deflection experienced by the HTCL composite plate when exposed to varying matrix thicknesses. The deflection of the HTCL plate was also compared to the plate mass variations.

The overall trend for the HTCL is that the increase of both the matrix thickness and the mass of the plate decreased the magnitude of deflection which occurred within the plate. The decreased deflections were demonstrated by results plotted in Figure 22.
6. **Stress due to variations of the Matrix Thickness and Mass for HTCL**

The effects of varying the matrix thickness with the stress within the HTCL plate were represented in Figure 23. The HTCL configuration for the stress modelling was the same as the composite plate utilised for the deflection investigation.

The trends shown in Figure 23 of the maximum stress of HTCL are similar to what was seen in that materials deflection property when exposed to the same parameter variations. When both of the thickness of the matrix and the overall plate mass increased the value of the stress experienced by the HTCL was decreased.

7. **Compare Materials**

The three materials; GLARE, CentrAL and HTCL, were all influenced by the variation of the matrix thickness parameter. The parameter variations are shown in the graphical results of Figure 24 and Figure 25. The magnitude of maximum deflection and stress for the three materials are shown in Table 8.

---

**Table 8** **Deflection and Stress Values for Varying Matrix Thickness**

<table>
<thead>
<tr>
<th>Matrix Thickness (mm)</th>
<th>GLARE Maximum Deflection (m)</th>
<th>GLARE Maximum Stress (Pa)</th>
<th>CentrAL Maximum Deflection (m)</th>
<th>CentrAL Maximum Stress (Pa)</th>
<th>HTCL Maximum Deflection (m)</th>
<th>HTCL Maximum Stress (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.17907E-03</td>
<td>8210032</td>
<td>1.70880E-06</td>
<td>86029</td>
<td>1.37471E-03</td>
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<td>7575522</td>
<td>1.65228E-06</td>
<td>84113</td>
<td>9.78313E-04</td>
<td>3821157</td>
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<tr>
<td>0.2</td>
<td>9.58481E-04</td>
<td>6942398</td>
<td>1.59828E-06</td>
<td>82262</td>
<td>5.90309E-04</td>
<td>2596193</td>
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<tr>
<td>0.25</td>
<td>8.42215E-04</td>
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<tr>
<td>0.3</td>
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<td>5727385</td>
<td>1.49731E-06</td>
<td>78747</td>
<td>2.11181E-04</td>
<td>1270596</td>
</tr>
<tr>
<td>0.35</td>
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<td>5177578</td>
<td>1.45009E-06</td>
<td>77077</td>
<td>1.38133E-04</td>
<td>953548</td>
</tr>
<tr>
<td>0.4</td>
<td>5.38251E-04</td>
<td>4682615</td>
<td>1.40491E-06</td>
<td>75462</td>
<td>9.51144E-05</td>
<td>741864</td>
</tr>
<tr>
<td>0.45</td>
<td>4.61774E-04</td>
<td>4245882</td>
<td>1.36164E-06</td>
<td>73901</td>
<td>6.82374E-05</td>
<td>593640</td>
</tr>
<tr>
<td>0.5</td>
<td>3.97633E-04</td>
<td>3864752</td>
<td>1.32020E-06</td>
<td>72391</td>
<td>5.06044E-05</td>
<td>485807</td>
</tr>
</tbody>
</table>
Due to the large variations in values the deflection and stress quantities were normalised to compare the effects of the matrix thickness on the three FRMLs.

The deflection ratio was plotted against the matrix thickness; refer to Figure 24, to determine how much each material was affected by this parameter. The plate constructed of the CentrAL configuration was the least affected by the various values of matrix thickness. Both plates which consisted of GLARE and HTCL were affected by the parameter variations. The HTCL configuration deflection values were affected at a faster rate than GLARE. Therefore HTCL deflection behaviour is the most affected by the variation of matrix thickness. The increased thickness of the matrix produced a plate with increased stiffness for all three materials. The increased stiffness of the FRMLs reduced the amount of deflection which occurred.

Figure 25 shows the effects the matrix thickness had on the stress ratio of all three materials. The results show that all three materials stress ratio decreased as the matrix thickness increased. The results suggest that Central was again the least effected by the variation of the matrix thickness. GLARE and HTCL plates stress ratio were more affected. This behaviour shows that the HTCL was affected the most out of the three materials by the matrix thickness parameter. The increased thickness of a matrix with constant volumetric fibre content produced a matrix with a greater number of fibres present. The stress within a matrix was distributed evenly over the fibres present. Therefore as the thickness was increased, the fibre content increased, reducing the overall stress experienced by the plate.

Figure 24 and Figure 25 suggest that the deflection and stress behaviour are effected similarly for the variation of the matrix thickness parameter.

C. Lay-Up Configuration

The variation of the lay-up configuration effects of the maximum deflection and stresses experienced within the composite plates of the three materials are represented graphically in Figure 26 to Figure 33. The variation of the lay-up configuration involves looking at a different number of layers of both the metal alloy sheets and the epoxy matrices. The configurations that were modelled for each of the materials are in Table 6. As the number of layers increased the overall mass of the plate increased. The maximum deflection and stress behaviour of the plate was plotted against both the various lay-up configurations and mass of the plate.

1. Deflection due to variations of the Lay-Up Configuration and Mass for GLARE

The GLARE used for Figure 26 was varied in its lay-up configurations as shown in Table 6. The trends shown in Figure 26 for the maximum deflection behaviour of GLARE in relation to the lay-up configuration and the overall plate thickness demonstrate that as the number of layers present and the mass of the plate increases the amount of deflection experienced decreases.
2. Stress due to variations of the Lay-Up Configuration and Mass for GLARE

The graphical representation displayed in Figure 27 is the maximum stress present within the plate when exposed to both various lay-up configurations of GLARE, and the variations of overall mass of the plate. The GLARE material used for the stress modelling was the same as the deflection investigations.

3. Deflection due to variations of the Lay-Up Configuration and Mass for CentrAL

The CentrAL used for Figure 28 was varied in its lay-up configurations as shown in Table 6.

Figure 26 Deflection behaviour of GLARE with respect to the Lay-Up Configuration and the Mass of the plate respectively

Figure 27 Stress behaviour of GLARE with respect to the Lay-Up Configuration and the Mass of the plate respectively

The trends of the maximum stress behaviour of GLARE with respect to both the lay-up configuration and the overall plate mass are shown in Figure 27. Similar to the deflection behaviour of GLARE the magnitude of the stress experienced within the plate decreased as there is an increase in both the layers in the lay-up and the plate mass.

Figure 28 Deflection behaviour of CentrAL with respect to the Lay-Up Configuration and the Mass of the plate respectively
The effects of the change in both the lay-up configuration and overall plate mass of CentrAL with the maximum deflection are shown below in Figure 28.

The trends of the CentrAL’s maximum deflection is similar, but at a different magnitude, to that of GLARE. The deflection decreases with an increase of both the number of layers of the composite reinforcement and the mass of the plate.

4. Stress due to variations of the Lay-Up Configuration and Mass for CentrAL

The type of CentrAL lay-up configurations used in the modelling of the maximum stress experienced was the same as the material used for the deflection modelling. The results of the maximum stress experienced by the plate are plotted against both the lay-up configuration and the overall mass of the plate are demonstrated in Figure 29.

The trends in the stress result, as with the deflection, of the CentrAL plates show a decrease in the stress experienced. This decrease is present for both the increase of the number of layers in the configuration and the greater the overall mass of the plate.

5. Deflection due to variations of the Lay-Up Configuration and Mass for HTCL

The final composite plate modelled with the varying parameter of the lay-up configurations was HTCL. The effects of increasing the number of layers in the lay-up configuration of HTCL, which in turn created a plate with greater mass, are shown in Figure 30. The lay-up configuration was varied as shown in Table 6.

The graphs in Figure 30 represent the trends of the maximum deflection in respect to the number of layers and mass of the plate. As with GLARE and CentrAL the magnitude of deflection is decreased as both the number of layers in the configuration and the overall mass of the plate are increased.
6. **Stress due to variations of the Lay-Up Configuration and Mass for HTCL**

The type of HTCL plate used in the stress analysis was the same as in the deflection analysis. The results reflect similar trends to the deflection of HTCL in reference to lay-up configuration. As the number of layers increase, which forces the mass of the plate to increase, the maximum stress experienced by the plate decreases. These trends are shown below in Figure 31.

![Stress behaviour of HTCL with respect to the Lay-Up Configuration and the Mass of the plate respectively](image)

7. **Compare Materials**

The investigation of the three materials; GLARE, CentrAL and HTCL, demonstrates that they are affected in a similar way when the lay-up configuration is varied. The values of deflection for all three materials are reduced as the numbers of layers are increased in the lay-up configuration variations. The deflection and stress values between the three FRML are displayed in Table 9.

**Table 9  Deflection and Stress Values for the Lay-UP Configuration**

<table>
<thead>
<tr>
<th>Type of Lay-Up Configuration</th>
<th>GLARE</th>
<th>CentrAL</th>
<th>HTCL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Deflection (m)</td>
<td>8.42215E-04</td>
<td>3.96078E-04</td>
<td>1.97097E-04</td>
</tr>
<tr>
<td>Maximum Stress (Pa)</td>
<td>6321084</td>
<td>3761961</td>
<td>2333691</td>
</tr>
<tr>
<td>Maximum Deflection (m)</td>
<td>1.54667E-06</td>
<td>1.34018E-06</td>
<td>1.16962E-06</td>
</tr>
<tr>
<td>Maximum Stress (Pa)</td>
<td>80474</td>
<td>73179</td>
<td>66774</td>
</tr>
<tr>
<td>Maximum Deflection (m)</td>
<td>1.69895E-03</td>
<td>1.23484E-03</td>
<td>6.91733E-04</td>
</tr>
<tr>
<td>Maximum Stress (Pa)</td>
<td>5151170</td>
<td>4474278</td>
<td>2905346</td>
</tr>
</tbody>
</table>

The comparisons of the variation of the lay-up configuration effects on the three materials are shown in Figure 32 and Figure 33. As the results had large differences in the magnitude of value we have used normalised values to compare the effects.

The results for the deflection ratio against the lay-up configuration are represented in Figure 32. The deflection ratio of CentrAL shows that this FRML is the least affected over the range of configuration variations. The deflection ratio for GLARE and HTCL varies the same over the parameters studied. GLARE had a rate of the reduction in deflection greater than that for HTCL. These results confirm the increase in the number of layers within a FRML plate reduces the maximum deflection experienced. The increase in the number of layers, of both the matrix and metal alloy, increases the stiffness of the plate. The increase in stiffness produces a greater resistance to the deflection of the plate.

![Deflection/ Maximum Deflection Ratio Versus Lay-Up Configuration](image)
The stress ratio was used to compare the effect the lay-up configuration had on the stress experienced by the different material plates. The effects of the variation of the Lay-up configuration parameter on the stress ratio are graphically represented in Figure 33. The results show that the stress in CentrAL is the least affected by the configuration variations. Once again GLARE and HTCL show the same amount of variation in their stress ratios. GLARE reduction in stress ratio occurs at a faster rate than HTCL. The stress ratio decreases for all three materials analysed when the numbers of layers of epoxy and metal alloys are increased. The increased number of epoxy layers provides a larger number of fibres within the plate; allowing the stress to be distributed over a larger number of fibres, reducing the magnitude of stress experienced by the plate.

D. Fibre Orientation

The last parameter examined in this research was the orientation of the fibre direction within the epoxy. The variations of the angles of the fibre directions were 0°, ±15°, ±30°, ±45°, ±60°, ±75°, and ±90°. The fibre direction had no effect on the overall mass of the composite plate. Therefore the results of the maximum deflection and stress were plotted against the fibre orientation variations only. The graphical representations of the results are Figure 34 to Figure 41.

1. Deflection due to variations of the Fibre Orientation for GLARE

The effects that variation of the fibre orientation parameter had on the deflection behaviour of GLARE are shown in Figure 34. This shows that the maximum deflection increases from 0° to ±45°, and then decreases from ±45° to ±90°. From the results the fibres at 0° produced the same deflection results as the fibres orientated at ±90°. The deflection values did vary across the fibre orientation range. However, the magnitude of the deflection is quite small compared to the other parameter variations.

2. Stress due to variations of the Fibre Orientation for GLARE

The GLARE material used in modelling for the maximum stress within the plate consisted of the same configuration and properties as the material utilised in the investigation of deflection for GLARE. Figure 35 demonstrates how the variation of the orientation fibre angle affects the maximum stress in the composite plate. The trend demonstrates an interesting behaviour of the stress within the plate. It is similar to deflection behaviour as the minimum stress was at 0° and ±90° fibre orientation. The variation is where the maximum stress occurred. The maximum stress was recorded at ±30° and ±60° with a decrease (saddle trend) between them. As with the deflection trend the variation of fibre orientation affected the stress at a lower level than that of the other parameters.
3. **Deflections due to variations of the Fibre Orientation for CentrAL**

The deflection behaviour of CentrAL in respect to the varying fibre orientations within the epoxy are demonstrated in Figure 36. The maximum deflection recorded for CentrAL was again at the ±45°. The minimum deflection was experienced at the 0° and ±90°. These trends were expected as they were similar to the GLARE variations at a lower magnitude. The difference in the absolute deflection values across the parameter range is very low. These quite small variations in deflection supports that CentrAL was similar to GLARE as their deflection behaviour was not susceptible to the variations within the fibre orientation of the epoxy layers.

4. **Stress due to variations of the Fibre Orientation for CentrAL**

The modelling for the stress behaviour in relation to the fibre orientation was constructed with the same properties as the CentrAL plate utilised in the deflection investigation. Figure 37 graphically represent the effects of the angle in which the fibres were orientated within the epoxy with the stress experienced by the plate. The behaviour of CentrAL replicates the trends of GLARE. The maximum stress of the composite plate was recorded at ±30° and ±60°. The minimum value of deflection was recorded at both 0° and ±90°. The saddle behaviour between ±30° and ±60° was noted. The major difference between the GLARE and CentrAL results was their magnitude of absolute stress and deflection experienced.

5. **Deflection due to variations of the Fibre Orientation for HTCL**

The third composite plate modelled for the affects of the angle of fibre orientation was HTCL. The orientations of the fibres within the epoxy varied through designated angles. The effects on the maximum deflection from varying the fibre orientations within the epoxy are shown in Figure 38.

The trends of the maximum deflection which the HTCL plate had when an evenly distributed load was applied against the angle of fibre orientation are shown in Figure 38. The behaviour displayed an increase in the deflection between 0° and ±45°. The deflection decreased between the fibre orientations angles ranging from ±45° to ±90°. This trend did demonstrated basic similarities as GLARE and CentrAL behaviour. However, HTCL did not show a relationship of equal values for 0° and ±90° fibre orientation as did GLARE and CentrAL materials. The minimum deflection was experienced at the angle value of 0°. The overall magnitude of deflection from the affect of the varied fibre orientations is quite small.
6. Stress due to variations of the Fibre Orientation for HTCL

The effects of the fibre orientation with respect to the stress recorded utilises the same type of HTCL plate which was used for the deflection analysis. Figure 39 represents the relationship between the maximum stress value and the angle of fibre orientation. The trend of the stress recorded for HTCL was dissimilar to GLARE and CentrAL. At a fibre angle of ±45° the stress experienced was at minimum value. The maximum stress present was recorded at ±90°. The behaviour of the stress was from 0° to ±45° the value decreased, whilst form ±45° to ±90° the stress increased up to its maximum value. The trend of stress was of a saddle shape with the difference in absolute maximum and minimum stress values experienced greater than experienced by the GLARE and CentrAL plates.

7. Comparison between the materials

The trend of the three materials; GLARE, CentrAL, and HTCL, with respect to the variations of the fibre orientation within the epoxy produced different results than the other parameters investigated. The GLARE and CentrAL materials demonstrated similar trends at different magnitudes for stress and deflection behaviour. The deflection behaviour with respect to fibre orientation of HTCL had similar trends as GLARE and Central. However, the stress of the HTCL plate produced a result of greater variation than GLARE and CentrAL. The results are displayed as fibre orientation variation and the deflection ratio refer to Figure 40, and the effects on the stress ratio as the fibre orientation were changed in Figure 41.

The absolute values of the maximum deflection behaviour results for all three materials were quite different in magnitude therefore deflection and stress ratios were plotted against fibre orientation. Figure 40 show the comparison of all three materials’ deflection ratios with respect to the various fibre orientations. HTCL plate demonstrated the greatest variation in its deflection ratio, and the CentrAL was seemingly unaffected by the changes in the fibre directions. Although HTCL produced the greatest deflection ratio, the results show that the greatest difference of deflection ratio was low. These results support that the variation of the orientation of the fibres within the epoxy layers do not significantly affect the overall deflection experienced by a FRML.

The results in Figure 41 from the stress ratio against the fibre orientation produced results dissimilar to other parameters investigated. However, the HTCL plate results were the reversed of the deflection trends for CentrAL and GLARE. This behaviour didn’t follow the trends produced by the variation of the other three parameters. The values of the stress ratios versus the fibre orientation are a lot smaller than the other parameters. These results support that the effect of the varying the fibre orientation parameter did not affect the stress behaviour of the three materials. This did show that even though the stress ratio behaviour was not similar to that of its deflection ratio, overall the effects of the fibre orientation didn’t influence either the deflection or stress behaviour significantly.

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Figure 39 Stress behaviour of HTCL with respect to the Fibre Orientation

Figure 40 Deflection/ Maximum Deflection Ratio Fibre Orientation

Figure 41 Stress / Maximum Stress Ratio Fibre Orientation
VII. Conclusion

All three materials GLARE, CentrAL and HTCL were affected by variations of the key parameters volumetric fibre content, the matrix thickness, the lay-up configuration, and the fibre orientation within the epoxy layers.

Volumetric fibre content affected the deflection of all three materials. In general, as the fibre content increased, the deflection and stress ratio decreased. These results demonstrated that the least affected by the increased volumetric fibre content on their deflection ratio was CentrAL. The material which had the greatest effect on their deflection ratio was HTCL. For the stress ratio, CentrAL demonstrated the lowest effects due to volumetric fibre content variations. HTCL had the maximum variation of stress ratio over the parameter variation. Although volumetric fibre did affect stress and deflection, the amount of variation is dependent on the type of laminate. Stress was affected at a lower magnitude. These reductions support that the volumetric fibre content affects on deflection and stress in FRML.

The parameter variation of matrix thickness produced an effect on the structural behaviour of the three FRMLs. The increase in the thickness of the matrix within the FRML resulted in lower maximum deflection and stress experienced by the plate. Comparing the deflection ratios over various matrix thicknesses supported that CentrAL deflection was the least affected by the parameter. GLARE and HTCL deflection were affected more with thickness variation. HTCL deflection ratio was affected the greatest by the varying matrix thickness. The stress behaviour was affected in a similar trend as the deflection. Generally as the matrix thickness was increased the maximum stress experienced in all three FRML decreased. The variation of the matrix thickness effect on the CentrAL stress ratio was the lowest. HTCL was again the material that was the most effected. This supports the trends of the stress and deflection behaviour over the matrix thickness variations are the same. The magnitude of reduction in stress and deflection is related to the epoxy to metal alloy layers ratio.

Lay-up configurations were varied by adding extra metal alloy and/or epoxy layers on the FRML plates. GLARE, CentrAL, and HTCL were all affected as the number of layers was increased. The maximum deflection and stress results were reduced for all three materials as the layers were increased. The deflection of the CentrAL plate was the least affected by the variation of the lay-up configuration. However the amount of variation created by the additional layers was greater than experienced for other parameters. GLARE and HTCL plates experienced overall the same amount of change in the deflection ratio over the parameter ranges. The stress ratios of the CentrAL plate decreased as the number of layers in the composite increased. GLARE and HTCL stress ratios were affected overall by similar values. The lay-up configuration variations support that increasing the metal alloy layers affects the structural behaviour greater than varying the number of epoxy layers.

The effect of the fibre orientation directions on the maximum deflection and stress experienced by the three materials in general were not significant. The deflection ratio variations over the fibre orientations angle parameters demonstrated minimal difference. CentrAL deflection ratio remained almost constant. GLARE varied acutely over the angle range. The HTCL, which experienced the greatest difference in deflection, deflection ratio was quite small. This supports the observation that the deflection within the plate is not dependant on the fibre orientation within the epoxy layers. The stress ratio demonstrated limited effects in respect to the parameter of the epoxy fibre orientations. CentrAL stress ratio, as with the deflection ratio, remains almost constant. GLARE stress ratio was only slightly affected. HTCL demonstrated a small stress ratio variation over the parameter values. The low deflection and stress ratios which were a result from the variation of fibre orientation support that fibre orientation variation does not affect the structural behaviour of FRML significantly.

The results analysed in this research show that the lay-up configuration had a major influence on the structural behaviour on all three materials. The volumetric fibre content effects FRML structural behaviour depending on its configuration. The matrix thickness has an effect on the composites with a significant amount of epoxy within its configuration. However the greater the number of metal alloy layers with respect to epoxy layers present limits the effect of the matrix thickness. Furthermore, the variation of fibre orientation has an insignificant effect on the deflection and stress behaviour FRMLs.
VIII. Recommendations

Based on my research area I recommend that further development for composite material use in aerospace structures to be of CentrAL with the following key parameter values for the internal GALRE reinforcement:

1) Volumetric fibre content of 60%
2) Matrix thickness of 0.3 mm
3) Lay-up of 5/4 configuration (5 aluminium alloy sheets and 4 epoxy layers)
4) Fibre orientation of ±45°

Although the mass of this composite is greater, for a given size, its structural behaviour was less affected by the parameters variations. CentrAL would be suitable for further research to determine its suitability to the aerospace industry.

The next level of research recommended would be to investigate the effect temperature has on the FRML behaviour. This could involve the investigation on how temperature will affect the results from variation of the key parameters. This would require an Investigation what range of temperatures that FRML are exposed to in aerospace industry. It would be necessary to determine if the variations in key parameters variations produced similar trends throughout the predicted operating temperature range.

Further investigation could be developed into the effects these key parameters have on common failures such as buckling and delamination of FRMLs. Research would need to be conducted to determine if the combinations which reduce deflection and stress have greater resistance to delamination and buckling. Further research is required to investigate which key parameters influence the delamination and buckling.

The research on the structural behaviour of FRML can be utilised to assist with further development towards an optimal design of FRML for use in the aerospace industry.

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