The influence of the inter-ply hybridisation on the mechanical performance of composite laminates: Experimental and numerical analysis

Hussein Dalfi, Anwer J Al-Obaidi and Hussein Razaq
Department of Mechanical Engineering, University of Wasit, Wasit, Iraq

Abstract
Recently, high tensile fibres composite laminates (i.e. glass composite laminates) have been widely used in the civil and military applications due to their superior properties such as lightweight, fatigue and corrosion resistance compared to metals. Nevertheless, their brittle fracture behaviour is a real downside for many sectors. In the present study, the impact of the hybridisation of Kevlar woven layers with glass woven layers on the reducing the strain failure problem in pure glass woven laminates is investigated. In this work, multi-layers Kevlar-glass with different stacking sequences have been used to prepare the hybrid composite laminates using vacuum–assisted resin moulding method. The influence of the layers hybridisation on the mechanical performance of composites laminates was investigated using tensile strength tests. Furthermore, finite element analysis is performed to analyse the mechanical response of the hybrid composite laminates using Abaqus software. The elastic constants of woven fabric layers in the numerical study were predicted through geometric model based on the textile geometry and analytical method in order to assert accuracy of the predicted elastic constants. The experimental results showed that the hybrid composite laminates tend to fail more slowly than glass woven laminates, which illustrates low strain to failure. In the theoretical part of the study, it was found that the proposal model can be useful to capture the mechanical behaviour and the damage failure modes of hybrid laminates. Thus, the catastrophic failure can be avoided in these laminates.

Keywords
Inter-ply hybridisation, glass fabric, Kevlar fabric, tensile strength, FEA

Corresponding author:
Hussein Dalfi, Department of Mechanical Engineering, University of Wasit, Kut, Wasit 52001, Iraq. Email: hqumar@uowasit.edu.iq

Creative Commons Non Commercial CC BY-NC: This article is distributed under the terms of the Creative Commons Attribution-NonCommercial 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/) which permits non-commercial use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
Introduction

Despite the popularity of the glass fibre reinforced polymer composites (GFRP) use in aircraft and aerospace engineering industries, for a long time due to their high specific strength-to-weight ratio, non-corrosive properties and have a very low strain-to-failure.\textsuperscript{1–4} Accordingly, this is considered as a disadvantage for using these laminates under a tensile or flexural loading conditions.\textsuperscript{5} Additionally, in civil infrastructures, structural stability is a key factor that maintains a structure to be safe in usage under static or dynamic loading conditions.\textsuperscript{6} Kevlar has excellent mechanical properties such as high strength with lightweight, thermal stability and good resistances to abrasion resulting in wide use in aerospace, military applications, protective apparel and marine industry.\textsuperscript{3,7,8} However, the major limitation for using them in the different sectors are their weaknesses in tensile, compression and bending loading.\textsuperscript{9} One possible way to achieve better performance is by adopting a hybrid composite that is made up of two or more different fibres or resins. Hybridisation of fibres can be combined the high modulus fibres, which has capability for carrying load with the low modulus fibres.\textsuperscript{10,11} Thus, hybridisation will provide advanced performance (i.e. improves damage tolerance, impact resistance and reduces the material cost than that obtained from an individual reinforcement).\textsuperscript{4,12,13} Based on the numbers and distribution of fibres in a hybrid composite, they can be categorised into, interlaminated hybrids where different layers are stacked together, intra-ply or intra-yarn hybrids, where many yarns or bundles are mixed together in one layer and intermingled hybrids, where the consistent fibres are mixed as randomly as possible in the composite laminates.\textsuperscript{14–16} Many researchers have successfully used intra-ply hybridisation technique to enhance the mechanical properties of composite laminates.\textsuperscript{17–20} This can be attributed to enhancement of the first failure strain of the low-elongation fibres by incorporating more ductile fibres and that can improve the specific ultimate properties of composites.\textsuperscript{21} Besides that, hybrid layers (inter-ply layers) of composite laminates can strongly influence on their mechanical properties,\textsuperscript{22} and impact loading resistance and damage tolerance.\textsuperscript{23–25} Recently, researchers have paid attention for using numerical analysis and simulation of mechanical behaviour of composite laminates.\textsuperscript{26} The main target is to show the advantage of the additional woven layers such as basalt,\textsuperscript{27–29} carbon,\textsuperscript{5,30–32} and kevlar woven layers\textsuperscript{20,33} with glass woven layers in case of hybrid composite laminates comparatively with composite laminates reinforced only with glass woven layers. The complex geometry of woven fabrics imposed many challenges in the numerical analysis of woven fabrics composites.\textsuperscript{34} Thus, development of effcient methods for prediction elastic constants of woven fabrics composite is essential.\textsuperscript{35–41} The prediction models for elastic constants of woven composites classified into two types; numerical model based on the finite element method\textsuperscript{39,42–44} and analytical models.\textsuperscript{45} The numerical model based on the finite element offered higher accuracy because of less simplifying assumptions and consideration of more details, however the implementation of these models is expensive and consumed more time compared to the analytical models.\textsuperscript{40,46} In the other hand, the analytical
models for prediction of woven fabric composites are usually depend on the multi-scale modelling, which known as the top-down-bottom-up methods.47

The main novelty of this study is the investigation of tensile response of glass/Kevlar layers composite laminates considering the hybridisation effect. These laminates were manufactured using vacuum bagging process and tensile strength characteristics of hybrid laminates were experimentally measured. In addition, the simulation of tensile performance of hybrid laminate was done using FEA with aiding of Abaqus software and compared with experimental results. The elastic constants of composite lamina, which were used in the numerical model, have been predicted through the geometrical model based on the fibre architecture and analytical methods.

Materials and experimental tests

Materials

Glass and Kevlar fabrics are used in this study and they are illustrated in Figure 1. The specifications of these fabrics are showed in the Table 1. The fabric count (i.e. the number of warp and weft in 1 cm), areal density and thickness are measured according to ASTM standards, which are D3775-02, D3776-09 and D1777-09, respectively.

Composite laminate manufacturing

The low viscosity resin (Sikadur-52) and its hardener with mixing ratio (1:2) were used to create the matrix in the composite laminate. The composite laminates were
made by infusing epoxy resin with aiding a vacuum bagging technique in which four layers of fabrics with a stacking of [0, 90] degrees were laid over one another to manufacture glass fabric and Kevlar fabric composite laminates as seen in Figure 2(a) and (d). While two types of the hybrid composite laminates were produced; the former was done by laid Kevlar fabrics on the top and bottom and glass fabrics on core of composite laminates (Figure 2(b)), the later made by laid glass fabrics on the top and the bottom and Kevlar fabrics on the core (Figure 2(c)).

**Preparation of resin and infusion**

Sikadur-52 resin and its hardener were used to create the matrix in the composite laminate preparation. After mixing with a ratio of 1:2 and stirring for 10 min, the mixture was put in a degassing machine for a period of 1 h to ensure the complete removal of gas bubbles to make a void free panel. The resin was introduced into the bag through the PVC feed pipe by connecting a vacuum pump to the exit pipe. The ingress of resin was kept slow enough to ensure adequate wetting of the preform. After the resin reached the end of the panel, the vacuum pump was turned off and the PVC pipes were sealed using clamps. The last stage of manufacture of the composite included the curing of the panel in room temperature for 24 h. When the curing cycle was complete, the panel was taken out and de-moulded, then machined with handsaw to obtain samples with the required dimensions.

**Table 1.** Specifications of glass and Kevlar fabrics.

| Type of fabric               | Ends (cm) | Picks (cm) | Density (g/m²) | Areal density (kg/m²) | Thickness (mm) |
|------------------------------|-----------|------------|----------------|-----------------------|----------------|
| Glass fabric (3H satin)      | 12        | 12         | 2.54           | 436.60 (±1.80)        | 0.321 (±0.014) |
| Kevlar fabric (plain)        | 7         | 7          | 1.44           | 415.80 (±1.30)        | 0.544 (±0.010) |

**Figure 2.** Composite laminates configurations.
Table 2. Average properties of composite laminates.

| Composite name | Vf of glass fibre (%) | Vf of Kevlar fibre (%) | Density (g/cm³) | Thickness (mm) |
|----------------|------------------------|------------------------|-----------------|----------------|
| GG            | 32.00 (±3.50)          | 0                      | 1.58 (±0.05)    | 2.13 (±0.21)   |
| KG            | 15.80 (±1.52)          | 26.80 (±2.65)          | 1.44 (±0.04)    | 2.18 (±0.23)   |
| GK            | 16.00 (±1.50)          | 27.00 (±2.50)          | 1.45 (±0.03)    | 2.15 (±0.18)   |
| KK            | 0                      | 43.00 (±1.80)          | 1.26 (±0.02)    | 2.66 (±0.11)   |

**Experimental methods**

**Density and fibre volume fraction tests**

The density of composite laminates are measured according to the ASTM D792-08 standard. The volume fraction of these composite laminates are measured in both experimental and theoretical methods, respectively. For example, the volume fraction of the glass only and Kevlar only composites are measured experimentally according to the BS EN ISO 1172:1999 standards, meanwhile the volume fraction of hybrids layers composites are calculated theoretically as shown in equation (1) because of the difficulty of burning method with hybrid layers.

\[
V_f = \frac{\text{Volume of fibre}}{\text{Volume of Composite}} = \frac{n_{layer} \times g_r}{h \times \rho_f} \quad (1)
\]

Where, \(n_{layer}\), \(g_r\), \(\rho_f\) and \(h\) are the numbers of fabrics layers, linear density of fabric (g/km), density of fibres (kg/m³) and thickness of composite laminates respectively. Table 2 illustrates the specification of composite laminates used in this study. The GG and KK are referred to the composite laminates made of glass woven layers and Kevlar woven layers respectively, while the KG and GK are referred to the composite laminates made of Kevlar layers outside and glass layers in the core, and glass layers outside and Kevlar layers in the core respectively.

**Tensile properties tests**

The tensile properties of all composite samples were also evaluated using a tensile strength test. The specimens were cut from the laminates with a diamond cutter; samples measured 250 mm x 25 mm (length x width) and had a gauge length of 50mm, in accordance with the ASTM D3039M 2008 standard.\(^{48}\) Five specimens were created for each case. End tabs were affixed to the specimens in order to reduce the gripping effects. Tensile tests were conducted using an Instron 5982 universal testing machine at a crosshead rate of 2mm/min, corresponding to a strain rate of 0.2%/s. Tensile test machine and sample of test have been illustrated in Figure 3.
Numerical analysis

Finite element model description

The mechanical performance of hybrid composite laminates, which are experimentally investigated, can be represented and assessed by using numerical analysis since it is relatively accurate, less cost and less time-consuming. For this aim, a finite element method using commercial software package Abaqus/Explicit has been adopted to simulate the response of hybrid composite laminates under tensile strength test.

The hybrid composites being investigated in this study are manufactured from two types of fabrics, Satin E-glass and Kevlar plain into a common matrix epoxy. The elastic constants of lamina of these hybrid composites, which are including the longitudinal modulus $E_{11}$; the transverse modulus $E_{22}$ and $E_{33}$; and the shear moduli $G_{12}$, $G_{13}$ and $G_{23}$; and Poisson ratio $\nu_{12}$, $\nu_{13}$ and $\nu_{23}$ are predicted through two methods: the geometric model and analytical process. In this study, the geometric model based on the local fabric geometry, weave type and material properties is described in the following steps:

Formulation of geometric model. The simulation of mechanical properties of composite laminates are mainly focused on the stiffness of each lamina and these properties must be calculated either numerically or analytically. Additionally, the stiffness of the lamina and laminates depended significantly upon various factors (i.e. basic mechanical properties of the matrix and fibre, amount or volume fraction of matrix and fibre and type and orientation of reinforcement).

In this regard, an analytical strategy has been proposed to predict elastic properties of lamina of woven composite. Emphasis is on elastic model and on the parametric study of the effects of fibre volume fraction, local fabric geometry, weave type and material properties. In the geometry model, overlap between neighbouring yarns is accounted; orientation and crimp angle of sub-volume of yarns is predicted based on experimental measured fabric local geometries.
In this model, elastic properties of the yarn are predicted based on a linear rule of mixture. Then a two level homogenisation approach is applied to predict engineering constants of woven composite based on constituent material properties: at micro-level or yarn level, transformation matrix is applied to calculate the stiffness matrix of warp and fill yarn in global system. At macro-level or unit cell level, homogenisation based on iso-strain and iso-stress assumptions is carried out to predict the elastic properties of unit cell.

Formulation of geometric model for woven composite lamina starts with defining the yarn shape in the fabric and neighbouring yarn configuration. The parameters determined in yarn shape and neighbouring yarn. The cross-section of a yarn in the woven lamina composite is assumed lenticular shape. This assumption is realistic as a fill yarn is interlocked and compressed by over-and under-laid warp yarns as depicted in Figure 4.49 where a cross-section factor \( a_f \), is defined as fill yarn width divided by filled yarn thickness \( d_f \). Then the radius \( r_f \) is the inner angle. The cross-section factor \( a_f \) and the section area, \( A_f \) of the fill yarn can be expressed in equations (2) to (4):

\[
\begin{align*}
    r_f &= \frac{d_f}{4}(1 + \alpha_f^2) \\
    \alpha_f &= 2\sin^{-1}\left(\frac{2a_f}{1 + a_f^2}\right) \\
    A_f &= r_f^2(\alpha_f - \sin\alpha_f)
\end{align*}
\]

For the case of warp yarn, the subscript \( f \) is changed with \( w \) in above equations. Conventionally, it is assumed that there is a gap between neighbouring yarns and yarn-to-yarn distance can be calculated based on this assumption. When the gap is
large, a straight portion of yarns can exist. This configuration is shown in Figure 5.\textsuperscript{49} The gap between neighbouring yarns is shown as $L_{wg}$ in Figure 5.

In this configuration, the yarn to yarn distance, $L_w$, is expressed in terms of yarn width and gap length and $L_{wg}$:

$$L_w = a_f d_f + L_{wg}$$  \hspace{1cm} (5)

Where $L_{wg}$ is a measured parameter from composite samples. The warp crimp angle $\theta_{wc}$, the slope angle $\theta_{wo}$ of line AB and the length of the straight portion of the warp yarn $L_{ws}$, can be calculated from equations (6) to (8):

$$\theta_{wo} = \tan^{-1}\left(\frac{2r_f + d_w - d_f}{L_f}\right)$$  \hspace{1cm} (6)

$$\theta_{wc} = \sin^{-1}\left(\frac{2r_f + d_w}{\sqrt{L^2_f + 2(2r_f + d_w - d_f)^2}}\right) - \theta_{wo}$$  \hspace{1cm} (7)

$$L_{ws} = \sqrt{L^2_f - 2d_f (2r_f + d_w) + d^2_f}$$  \hspace{1cm} (8)

For warp yarn sections, the similar forms of equation are written by exchanging subscript $f$ with $w$ and $w$ with $f$. The above-determined parameters are conventionally used in later homogenisation procedure: volume fractions of yarns and unit

---

**Figure 5.** Geometric model of woven fabric when there is a straight portion of yarn.\textsuperscript{49}
cells are calculated based on above parameters and used in volume average approaches.

However, in case of woven composite with yarn, it is found when the fibre volume fraction is relatively high (≥ 40%), the gap length $L_{wg}$ disappear and neighbouring yarns overlap with each other. This situation is shown in Figure 6(a). In this case, previously mentioned equations cannot be applied. To calculate the yarn-to-yarn distance, a schematic drawing of overlaped yarn in fabric is given in Figure 6(b). Based on a simple geometry analysis, the yarn-to-yarn distance $L_f$ and crimp angle $\theta_{wc}$ are expressed in equations (9) and (10):

$$L_f = a_f d_f - L_{fOLP}$$  \hspace{1cm} (9)

$$\theta_{wc} = \arcsin \left( \frac{a_f d_f - L_{fOLP}}{2r_f + d_w} \right)$$  \hspace{1cm} (10)

Where $L_{fOLP}$ represent the overlap length between neighbouring yarns as shown in Figure 5.

**Calculate fibre volume fractions for different fabric structures.** In this section, volume of warp yarns $V_w$, volume for fill yarns $V_f$ and volume for unit cell $V_u$ are calculated for plain weave and satin weave, which are used as weave fabrics in this study. For every weave structure, the volumes for a general configuration and a high value of volume fraction of each configuration are calculated.

**Plain weave.** The unit cell definition of a plain weave fabric is presented in Figure 7. The configuration of this unit cell is already given in Figure 5.
The volumes of warp yarns, $V_{yw}$, and fill yarns, $V_{yf}$, are obtained via multiplying the yarn cross-section area by the respective length of the yarn and they represented in equations (11) and (12):

$$V_{yw} = 4A_w[(2r_f + d_w)\theta_{wc} + L_{ws}]$$  \hspace{1cm} (11) \\
$$V_{yf} = 4A_f[(2r_w + d_f)\theta_{wc} + L_{fs}]$$  \hspace{1cm} (12)

The volume of unit cell, $V_u$, and fibre volume fraction of plain woven composites, $V_f$, can be expressed in equations (13) and (14):

$$V_u = 4(d_w + d_f)L_fL_w$$  \hspace{1cm} (13) \\
$$V_f = \frac{V_{yw} + V_{yf}}{V_{yf}}k$$  \hspace{1cm} (14)

where $k$ is the fibre packing fraction, which normally range between 0.6 and 0.8.

For the high fibre volume fraction configuration shown in 5, $L_{fOLD}(L_{wOLD})$, the overlap length between neighbouring yarns, is used in the mathematical expressions of $V_{yw}$, $V_{yf}$ and $V_u$ which are given in equations (15) to (17):

$$V_w = 4A_w[(2r_f + d_w)\theta_{wc}]$$  \hspace{1cm} (15) \\
$$V_f = 4A_f[(2r_w + d_f)\theta_{fc}]$$  \hspace{1cm} (16) \\
$$V_u = 4(a_f d_f - L_{fOLD})(a_w d_w - L_{wOLD})(d_w + d_f)$$  \hspace{1cm} (17)

Satin weave. The unit cell definition and fibre undulation of a satin weave fabric given in Figure 8. \hspace{1cm} (50) For a general configuration, the volumes of warp yarns, $V_{yw}$, and fill yarns, $V_{yf}$, and the volume of unit cell, $V_u$ are obtained from equations (18) to (20):

$$V_w = 8A_w[(2r_f + d_w)\theta_{wc} + L_{ws} + L_f]$$  \hspace{1cm} (18)
\[ V_f = 8A_f \left[ (2r_w + d_f)\theta_{fc} + L_{fs} + L_w \right] \]  
\[ V_u = 16(d_w + d_f)L_f L_w \]  

For a high value of volume fraction of configuration, above expressions change into:

\[ V_w = 5A_w \left[ 2(2r_w + d_w)\theta_{wc} + 3(a_f d_f - L_{wOLP}) \right] \]  
\[ V_f = 5A_f \left[ 2(2r_w + d_f)\theta_{fc} + 3(a_w d_w - L_{fOLP}) \right] \]  
\[ V_u = 25(d_w + d_f)(L_f - L_{wOLP})(L_w - L_{fOLP}) \]  

**Elastic property of woven lamina composite.** The materials researched here are two types of fabrics known as plain glass and satin Kevlar fabrics. In this regard, the following section describes the process of determining the elastic properties of lamina composite based on constituent material properties, fabric geometry parameters, and weave type. Compliance matrix of different partitions in weft/fill yarn, including the straight part outside the crimp, the straight part in warp and crimp part in warp, are calculated separately and then assembled to obtain the final compliance of weft/fill yarn. The compliance of woven composite lamina consists of contribution from the matrix and yarns (i.e. weft yarn and fill yarn).

**Compliance matrix of matrix.** The matrix used is epoxy with isotropic properties. The compliance of matrix epoxy is given below:
Where $E, G, \nu$ are the elastic modulus, shear modulus and Poisson’s ratio, respectively.

**Compliance matrix of yarn.** The coordinate system of a crimp yarn sub-volume in a woven composite showed in Figure 9. The local coordinate system is shown as 1–2–3 where 1 is at the yarn direction. The global coordinate system is shown as $x$–$y$–$z$, where $x$, $y$ and $z$-axes are in the warp, fill and thickness direction of composite panel.

Due to the crimp nature of woven fabric, the global coordinate system is not coinciding to the local coordinate system. Then, the compliance matrix of yarn in the local coordinate system is transformed to a compliance matrix in global system by:

$$[S^m] = \left( \begin{array}{cccc} \frac{1}{E} & -\frac{1}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{1}{E} & \frac{1}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & -\frac{\nu}{E} & \frac{1}{E} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G \end{array} \right), \quad (24)$$

Figure 9. Coordinate systems of a crimp yarn in woven fabric reinforced composites.49

Where $[S^m]_w$ is the compliance of yarn in local coordinate system, $[T]$ is the transformation matrix and $[T]^T$ is a transposed matrix of $[T]$. $[S]_{ws}$ is also the compliance of straight partition in warp.

The mathematical equation of $[S]_w$ is given below:
where the elastic modulus, shear moduli and Poisson’s ratios are obtained from the fibre (Glass/PP) and matrix (epoxy) material properties. The hybrid yarn can be regarded as a transverse isotropic material. Previous studies\textsuperscript{51–53} on longitudinal elastic properties of interlayer hybrid composite demonstrated that elastic modulus obey a linear rule of mixtures. Same rule is used here to calculate the elastic properties of the yarn based on experimentally measured fibre volume fraction. $[S]$ is also the compliance of the straight part outside the warp. The transformation matrix is given below:

$$[S]_{\text{w}} = \begin{pmatrix} 1/E_{11} & -v_{12}/E_{11} & -v_{12}/E_{11} & 0 & 0 & 0 \\ -v_{12}/E_{11} & 1/E_{22} & -v_{23}/E_{12} & 0 & 0 & 0 \\ -v_{12}/E_{11} & -v_{23}/E_{12} & 1/E_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{12} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{pmatrix},$$

(26)

Averaging method to determine elastic properties. If external load is applied in the warp or fill yarn direction, iso-strain assumption is typically applied in calculating elastic properties. Thus, the stiffness matrix is applied in the volume averaging. If $\theta$ is the crimp angle, the crimp compliance for a fill yarn can be obtained by changing subscript $w$ to $f$ in above equations. Compliance of weft/fill yarn

The compliance matrix of woven fabric is obtained by assembling contribution from three parts:

$$[S]_{\text{wxyz}} = (1 - \lambda_{ws} - \lambda_{wc})[S]_{w} + \lambda_{ws}[S]_{ws} + \lambda_{wc}[S]_{wc},$$

(29)

The two indexes $\lambda_{ws}$ and $\lambda_{wc}$ can be calculated based on fibre volume fraction, yarn shape parameters and weave type of fabric type as presented in Table 3.

The compliance for the crimp part in the warp of a fill yarn can be obtained by changing subscript $w$ to $f$ in above equations. Compliance of weft/fill yarn

\begin{equation}
(S_{ij})_{\text{wc}} = \frac{1}{\theta} \int_{0}^{\theta} (S_{ij})_{w} d\theta (i, j = 1, \ldots, 6)
\end{equation}

(28)
external load is applied in the thickness direction of the plate, iso-stress state is assumed and compliance matrix is used in volume averaging. The compliance matrix and stiffness matrix for iso-strain and iso-stress condition can be described as:

$$[C] = [C_m]c_m + [C_w]c_w + [C_f]c_f$$

$$[S] = [S_m]c_m + [S_w]c_w + [S_f]c_f$$

Where $c_m$, $c_w$ and $c_f$ are volume fraction of matrix, weft yarn and fill yarn. They can be determined by

$$c_w = k \frac{V_w}{V_u}, c_f = k \frac{V_f}{V_u}, c_m = 1 - c_w - c_f$$

The elastic properties of composite lamina for each type of fabric are calculated using Matlab code.

**Model validation and parametric studies**

The geometry factor and material properties for both a glass woven lamina composite with satin fabric and Kevlar woven lamina composite with plain fabric types are given in Table 4. Calculated elastic properties are compared with experimentally measured data.

**Validation with analytical model.** The elastic properties of woven fabric lamina for both satin glass and Kevlar plain fabrics, which extracted from the geometric parameters model, are also compared with the properties that adopted from Chamis model and the micro-mechanical relationships to calculate the elastic constants of yarns, given by equations (33) to (37):

$$E_{11} = V_f E_f + (1 - V_f)E_m$$

$$E_{22} = E_{33} = \frac{E_m}{1 - \sqrt{V_f} \left(1 - \frac{E_m}{E_f}\right)}$$

---

**Table 3. Geometric parameters of woven fabrics reinforced epoxy.**

| Weave type | General configuration | High fibre volume fraction |
|------------|-----------------------|---------------------------|
|            | $\lambda_{ws}$ | $\lambda_{wc}$ | $\lambda_{ws}$ | $\lambda_{wc}$ |
| Plain      | $1 - \lambda_{wc}$ | $(2r_f + d_w) \sin \theta_{wc}$ | 0 | 1 |
| Satin      | $0.4 - \lambda_{wc}$ | $(2r_f + d_w) \sin \theta_{wc}$ | 0 | 0.4 |

$V_w$, $V_u$, $L_w$, $r_f$, $d_w$, $\theta_{wc}$

$E_f$, $E_m$, $E_{11}$, $E_{22}$, $E_{33}$
\[ G_{12} = G_{13} = G_{23} = \frac{G_m}{1 - \sqrt{V_f \left( 1 - \frac{E_m}{E_f} \right)}} \]  
\[ \nu_{12} = V_f \nu_f + (1 - V_f)\nu_m \]  
\[ \nu_{23} = \frac{E_{22}}{2G_{23}} - 1 \]

Where \( V_f, \nu_f, E_f \) and \( G_f \) represented the fibre volume fraction, Poisson’s ratio, modulus of elasticity and modulus of rigidity of the fibres. The constants \( \nu_m, E_m, G_m \) represented the Poisson’s ratio, modulus of elasticity and modulus of rigidity of the matrix. The constants \( E_{11}, E_{22}, E_{33}, G_{12}, G_{13}, G_{23}, \nu_{12} \) and \( \nu_{23} \) represented the effective modulus of elasticity, modulus of rigidity and Poisson ratio of the woven laminat composite in the local coordinate systems(1,2,3).

**Simulation tensile strength of hybrid composite laminates**

In this work, it decided to adopt the Abaqus/Explicit analysis method because the steps of this analysis handle large deformations, nonlinear material model and multiple contacts and the time spent for running the analysis has significantly reduced.

In this simulation, Abaqus /CAE input file generates the laminates for modelling and rectangular part is modelled as a 3D deformable solid with continuum shell elements (SC8R) in a CAE Part Module. One lamina is modelled with 0° direction and assigned with density, damage failure of this lamina and elastic properties, which supplied from the above analytical process. In addition, the longitudinal tensile strength \( (X_t) \) values of composite samples were taken from the experimental work, while tensile strength of epoxy \( (Z_t) \) is obtained from the supplier. In-plane shear strengths \( (S_{12}, S_{23} \text{ and } S_{13}) \) of the composite laminates were calculated from equations (38) and (39).
\[ S_{12} = F_{ms} C_v \left[ 1 + \left( V_f - \sqrt{V_f} \right) \left( 1 - \frac{G_m}{G_f} \right) \right] \]  

(38)

Where \( G_m \) and \( G_f \) are the shear modulus of the matrix and fibre respectively; \( F_{ms} \), shear strength of matrix; \( C_v \), coefficient of voids, which measured from the equation (39):

\[ C_v = 1 - \sqrt{\frac{4V_v}{\pi(1 - V_f)}} \]  

(39)

Where \( V_v \), is the void volume fraction in composite laminates.

The mechanical properties such as longitudinal compressive strength \((X_c)\), transverse tensile strength \((Y_t)\) and transverse compressive strength \((Y_c)\) of composite laminas were obtained by using equations (40) to (45):56

\[ X_c = \frac{E_{11}(\varepsilon^T_2)}{\nu_{12}} \]  

(40)

\[ \varepsilon^T_2 = (\varepsilon^T_m)(1 - V_f^{1/3}) \]  

(41)

\[ Y_t = E_{22}(\varepsilon^T_2) \]  

(42)

\[ Y_c = E_{22}(\varepsilon^c_2) \]  

(43)

\[ \left( \varepsilon^c_2 \right) = \left[ \frac{d}{s} \times \frac{E_m}{E_f} + \left( 1 - \frac{d}{s} \right) (\varepsilon^c_m) \right] \]  

(44)

\[ \frac{d}{s} = \left[ \frac{4(V_f)}{\pi} \right]^{1/2} \] (For circular fibres with square array packing)  

(45)

Where \( \varepsilon^T_2 \), ultimate transverse tensile strain of lamina; \( \varepsilon^T_m \), ultimate tensile strain of epoxy; \( V_f \), fibre volume fraction; \( \varepsilon^c_2 \), ultimate compressive failure strain of lamina; \( \varepsilon^c_m \), ultimate compressive failure strain of matrix; \( d \), diameter of the fibres; \( s \), center-to-center spacing between the fibre; \( E_m \), modulus of epoxy; \( E_f \), modulus of fibres. \( \varepsilon^c_m \) is 0.03 for epoxy matrix.56

The two-dimensional Hashin failure criteria,57 which is available in Abaqus software, used to predict the progressive failure damage of composite laminates with including the sub-option of the damage evolution and damage stabilisation option respectively. In this criterion, four different damage initiation mechanisms, which considered interact independently at the ply level, occurred at the degradation of the composite laminate. These damage failures are tensile fibre failure \( F_{t1} \), compressive fibre failure \( F_{c1} \), tensile matrix failure \( F_{2t} \), and compressive matrix failure \( F_{2c} \).

The Hashin criteria for the two-dimensional case are presents in equations (46) to (49):
Tensile fibre failure \( F_{1t} = \left( \frac{\sigma_{11}}{X_t} \right)^2 \) if \( \sigma_{11} \geq 0 \) \( (46) \)

Compressive fibre failure \( F_{1c} = \left( \frac{\sigma_{11}}{X_c} \right)^2 \) if \( \sigma_{11} < 0 \) \( (47) \)

Tensile matrix failure \( F_{2t} = \left( \frac{\sigma_{22}}{Y_t} \right)^2 + \left( \frac{\tau_{12}}{Z_t} \right)^2 \) if \( \sigma_{22} > 0 \) \( (48) \)

Compressive matrix failure \( F_{2c} = \left( \frac{\sigma_{22}}{Y_c} \right)^2 + \left( \frac{\tau_{12}}{Z_c} \right)^2 \) if \( \sigma_{22} < 0 \) \( (49) \)

Where, the quantities \( X_t \) and \( X_c \) are represented the values of tensile and compressive strengths in the longitudinal direction, respectively, while, the quantities \( Y_t \) and \( Y_c \) are denoted the values of transverse tensile and compressive strengths in the transverse direction, respectively. The \( Z_t \) denoted the value of longitudinal shear strength, \( \sigma \) is the stress, which was applied on the element along various directions of composite and \( \tau \) stands for shear strength of the element.

The growth of intralaminar damages can strongly influence on the composite laminate stiffness. Therefore, this degradation of the stiffness represented as the plane stress constitutive stiffness matrix in the numerical analysis. This matrix, which has three independent damage indices \( d_1, d_2 \) and \( d_6 \), defined in the domain [0,1] as follow:

\[
C = \frac{1}{D} \begin{bmatrix}
E_1^0(1-d_1) & E_{21}^0(1-d_1) & 0 \\
E_1^0\nu_{21}(1-d_1)(1-d_2) & E_2^0(1-d_2) & 0 \\
0 & 0 & G_{12}^0(1-d_6)
\end{bmatrix}
\]

(50)

\[
D = 1 - \nu_{12}\nu_{21}(1-d_1)(1-d_2)
\]

(51)

The damage indices \( d_1, d_2 \) and \( d_6 \) are derived from the damage parameters \( d_{1t}, d_{1c}, d_{2t} \) and \( d_{2c} \), which are associated to the four independent intralaminar damage modes.

The initiation of delamination in the composite laminates characterised by using a quadratic nominal stress criterion, which was also available in the Abaqus software. This criterion assumed that the damage initiate when a quadratic interaction function, which included the nominal stress ratio, reached a value of one as presented in the following expression

\[
\left[ \frac{\sigma_n}{\sigma_{nc}} \right]^2 + \left[ \frac{\sigma_t}{\sigma_{tc}} \right]^2 + \left[ \frac{\sigma_s}{\sigma_{sc}} \right]^2 \geq 1
\]

(52)

Where \( \sigma_n, \sigma_t \) and \( \sigma_s \) denote the normal stress and two shear stress, and \( \sigma_{nc}, \sigma_{tc} \) and \( \sigma_{sc} \) are the peak values of the nominal stress when the deformation is either purely normal to the interface or in the first or the second shear direction
respectively. Furthermore, with increasing load, the damage can progress inside the composite laminate. Therefore, the propagation of damage at the cohesive zone can be represented by power law fracture criteria based on the mixed mode inter-laminar damage

\[
\left[ \frac{G_I}{G_{cI}} \right]^\alpha + \left[ \frac{G_{II}}{G_{cII}} \right]^\beta + \left[ \frac{G_{III}}{G_{cIII}} \right]^\gamma \geq 1
\]

(53)

Where \( G_I, G_{II} \) and \( G_{III} \) represent the mode I, II and III energy release rate, respectively. \( G_{cI}^c, G_{cII}^c \) and \( G_{cIII}^c \) refer to the mode I, II and III critical energy release rate, respectively, and the parameters \( \alpha, \beta \) and \( \gamma \) are determined experimentally. Thus, the value of the damage evolution is calculated experimentally from the area under the stress-strain curve of tensile and compression in both longitudinal and transverse directions. Moreover, to stabilise the simulation process and overcome convergence difficulties, the stabilisation coefficient was also used. Then, a copy of the same lamina was made but with 90 directions. The elastic constants and the orientation angle assigned to each lamina of the laminate in the CAE Property Module. Four laminas with sequence stacking [0/90] selected to model the all-composite laminates as shown in Figure 9. In order to model inter-laminar damage failures (i.e. delamination) in the composite laminates, the cohesive zone method is also adopted as shown in Figure 10. In Abaqus/Explicit, there are two types of approaches to define cohesive zone known as the cohesive element and the cohesive contact (or surface-to-surface cohesive contact) formulations. There is similarity between these formulations. In this simulation, the cohesive contact formulation has been used between layers of composite laminates. This method behaved as surface interaction properties and assumed one layer of composite behaved as master and connects with the slave nodes of another layer. Additionally, it assumed that there was no separation between the surfaces of layers of composite laminates. The quadratic traction stress and the power law criteria were used to define the initiation and evaluation of delamination respectively. The rectangular model was loaded in X-direction and velocity of the point of load was set at 0.034 mm/s to
mimic the experimental loading condition of 2 mm/min loading. Encastre boundary condition applied to one side of the rectangular model as shown in Figure 11. This is to ensure no movement and no rotation in any direction in this end of the model. Further, each lamina of the composite laminates meshed with global size 0.0008 with linear continuum shell element in the Mesh Module as illustrated in Figure 12.

**Results and discussions**

**Tensile strength tests results**

The tensile strength tests were conducted experimentaly to investigate the influence of hybridisation based on the hybrid layers on the ultimate tensile strength, which equals to the maximum load divided by the cross-sectional area of tested specimen, Young modulus, strain to failure and toughness of the all composite laminates. The tensile properties results are also listed in Table 5.

Representative stress-strain plots of the hybrid composite specimens have also been illustrated in Figure 13. It can be clearly seen from Figure 12 that the glass
composite laminates (i.e. GG samples) exhibit the highest strength and highest slope with linear response until breakage compared to all composites laminates. This is because of the high volume fraction of glass fibres in the loading direction. On the other hand, the stress-strain curve of Kevlar composite laminates (i.e. KK samples), which showed pronounced non-linearity, had more features that are distinct. The first linear part of the curve was considerably appeared up to stress level around 50 MPa and it is called the elastic region. Then, at the end of this portion, the stress-strain curve again became linear until fracture. This second region is called the yielding phase. Thus, the ultimate failure strain is relatively high with around 22 % more than strain to failure of the GG laminates. This is because of higher ductility of Kevlar fibres in the KK composite laminates. These findings are agreed with investigation of Jones and DiBenedetto.\textsuperscript{58}

Typical stress-strain graphs of hybrid layers composite laminates, that is KG and GK laminates can be also observed in Figure 13. There is a combination of high stiffness and strength properties from the glass fabric and the higher strain to failure properties from Kevlar fabric layers. Thus, the tensile strength of hybrid layers composite (i.e. KG and GK laminates) were slightly lower than the glass composite laminates, but their tensile strength are approximately 1.21, and 1.20 times higher than KK laminates. At the same time, compared to strain–to-failure of glass laminates, an improvement is observed.

Additionally, Figure 14 presented the average values of tensile strength, a modulus of elasticity, strain to failure and toughness for all composite laminates. It can be noticed that the strength and stiffness of composite laminates are strongly depended on the glass volume fraction as seen in Figure 14(a) and (b). Meanwhile,
the strength and stiffness of Kevlar composite laminates appeared lowest values due to the lower strength and stiffness of Kevlar fibre.

Elongation and strain to failure of composite laminates are presented in Figure 14(c). It is observed that the elongation of the glass woven laminates is lower than the other laminates; meanwhile, the elongation is appeared higher in the Kevlar woven laminates. The strain of the woven fabric strongly depends on the strain of the individual fibres, which can sustain while they are subjected to tensile loading. So that, the Kevlar fibres have extra length between jaws and are stretched more compared to glass fibres during tensile test. The hybrid layers laminates showed values of elongation are moderate between glass and Kevlar fibres. The relation of toughness with layers hybridisation is also presented in Figure 14(d). The toughness value are measured from integrated area under stress-strain curves. It can be seen from Figure 14(d) that the high value of toughness has been achieved at Kevlar woven laminates, followed by medium value at hybrid layers composites (KG and GK laminates) and lastly the lowest values have been obtained at glass woven laminates. The improved toughness of Kevlar woven laminates is strongly attributed to the high strain to failure of Kevlar fibres.
Comparing the numerical analysis with experimental results

The summary of elastic constants of composite lamina, which are predicted through the analytical and geometric model, and employed for the FEA model are listed in Table 6. It can be seen that the longitudinal moduli \( E_{11} \), \( E_{22} \), and \( E_{33} \) and Poisson ratio \( \nu_{12} \) and \( \nu_{13} \) are predicted by both methods were in close to other. However, the transverse Poisson's ratio \( \nu_{23} \) and shear moduli \( G_{12}, G_{13} \) and \( G_{23} \) showed slightly difference in prediction. The effect of local fibre aggregation, distribution of fibres in yarns and variation of fibres diameters are the main factors, which might affect the predicted elastic constants from geometric model.

Further, the experimental curves of stress-strain were graphically compared with curves that obtained from FEA model for all composite laminates and presented in Figure 15. Generally, it can be observed that the model curves have a good matching with the experimental plots in the elastic domain. However, the model results exhibited higher stiff composite laminates, where the curves close to y-axis compared to the experimental results. This is due to the crimp effect, which can play role for enhancement the ductile behaviour of woven laminates under tensile loading and the influence of this crimp are not include in the model calculation.

Figure 16 illustrated the displacement of all composite laminates on the direction of applying load. Clearly, it can be seen that the glass woven composite showed lowest displacement (Figure 16(a)) compared to all composite laminates and this was because of higher volume fraction of higher stiffness of glass fibres, meanwhile,
Kevlar woven composite laminates presented highest displacement at same load compared to all composite laminates (Figure 16(d)). The tensile load displacement response of hybrid composites as shown Figure 16(b) and (c) having different values and theses values are better than glass woven response. Hence, it is established that the hybrid layers composite laminates would be the convenient design.

Conclusion

Experiments conducted in this study for investigation the mechanical properties of composite laminates by selective hybridisation at lamina levels. Hybrid layers composite are produced via combining high-strength layer (i.e. glass woven layer) and high-toughness layer (i.e. Kevlar woven layer). Regarding their influence on the mechanical properties, two types of hybrid layers composite laminates were developed via vacuum assisted resin infusion method and compared with glass composite laminate and Kevlar composite laminates only. The mechanical
properties of the hybrid laminates are investigated by using tensile strength tests. Furthermore, the finite element analysis with aiding Abaqus software has been used to simulate the mechanical performance (i.e. tensile strength properties) of hybrid composite laminates. Hashin failure criteria and cohesive elements have been utilised (or proposed or adopted) in this model for prediction the intra-lamina and inter-lamina damage failures respectively in the laminates. In addition, the elastic constants of woven fabric layers, which are used in this numerical study were predicted through geometric model based on the textile geometry and analytical methods in order to assertion accuracy the predicted elastic constants. From the mechanical experimental test and simulation results, the conclusions can be drawn as follows:

- Tensile strength results showed that the hybridisation of layers could significantly affect the mechanical properties of hybrid composites. The ultimate tensile strength of glass woven laminates are highest compared to the

Figure 16. Distribution of displacement in the direction of applying load in case of: (a) GG, (b) KG, (c) GK and (d) KK composite laminates.
laminates made of Kevlar layers. This is because of higher volume fraction of glass fibres. However, the strength of Kevlar laminates was significantly improved by sandwiching with glass layers (i.e. KG and GK laminates). It was found that the ultimate strength of the hybrid layers (i.e. KG and GK laminates) are higher (~ 17% and 15%) than Kevlar laminates. However, rupture strain of hybrid layers composites was reduced compared to that of Kevlar laminates.

- According to comparison between the simulation and experimental results based on the global impact parameters, the simulation illustrated more efficient in term of CPU time (lower computational cost) and its predication for tensile strength are more promising compared with experimental results.
- The elastic constants predicted through geometric model and analytical methods were compared and show a good matching between them.
- The proposed simulation predicted well different failures mechanisms in the composite laminates during the tensile strength tests, that is shear damages, matrix cracks and fibre fractures. Although, the current simulation are reliable for prediction damage failure which are available in composite laminates have glass fibre only, it seems that the level of accuracy decreases with increasing number of interfaces of constituents inside the composite laminates for instance, hybrid composite laminates. This way, further improvements in computational efficiency of mode can be achieved by using VUMAT subroutine to predict the failures occurred in hybrid yarns composite laminates.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Hussein Dalfi https://orcid.org/0000-0002-6162-797X

References

1. Kelly J, Cyr E and Mohammadi M. Finite element analysis and experimental characterisation of SMC composite car hood specimens under complex loadings. J Compos Sc 2018; 2: 53.
2. Finegan IC and Gibson RF. Recent research on enhancement of damping in polymer composites. Compos Struct 1999; 44: 89–98.
3. Shaari N, Jumahat A, Abdullah SA, et al. Effect of hybridization on open-hole tension properties of woven Kevlar/glass fiber hybrid composite laminates. *Jurnal Teknologi* 2015; 76: 91–96.

4. Fu S-Y, Lauke B, Mäder E, et al. Hybrid effects on tensile properties of hybrid short-glass-fiber-and short-carbon-fiber-reinforced polypropylene composites. *J Mater Sci* 2001; 36: 1243–1251.

5. Ikbal MH, Wang Q and Li W. Effect of glass/carbon ratios and laminate geometry on flexural properties of glass/carbon fiber hybrid composites. In: *International conference on materials chemistry and environmental protection* 2015, 2016. China: Donghua University.

6. Hung P-y, Lau K-t, Cheng L-k, et al. Impact response of hybrid carbon/glass fibre reinforced polymer composites designed for engineering applications. *Compos Part B Eng* 2018; 133: 86–90.

7. Muhi RJ, Najim F and de Moura MF. The effect of hybridization on the GFRP behavior under high velocity impact. *Compos Part B Eng* 2009; 40: 798–803.

8. Bulut M, Erkliğ A and Yeter E. Hybridization effects on quasi-static penetration resistance in fiber reinforced hybrid composite laminates. *Compos Part B Eng* 2016; 98: 9–22.

9. Mayer RM and Hancox N. *Design data for reinforced plastics: a guide for engineers and designers*. Hong Kong: Springer Science & Business Media, 2012.

10. Swolfs Y, Gorbatiikh L and Verpoest I. Fibre hybridisation in polymer composites: a review. *Compos Part A Appl Sci Manuf* 2014; 67: 181–200.

11. Haery HA, Zahari R, Kuntjoro W, et al. Tensile strength of notched woven fabric hybrid glass, carbon/epoxy composite laminates. *J Ind Text* 2014; 43: 383–395.

12. Stefaniak D, Kappel E, Kolesnikov B, et al. Improving the mechanical performance of unidirectional CFRP by metal-hybridization. In: *ECCM15-15th European conference on composite materials*, Venice, Italy, 2012.

13. Sarasini F, Tirillò J, Valente M, et al. Hybrid composites based on aramid and basalt woven fabrics: impact damage modes and residual flexural properties. *Mater Des* 2013; 49: 290–302.

14. Pegoretti A, Fabbri E, Migliaresi C, et al. Intraply and interply hybrid composites based on E-glass and poly (vinyl alcohol) woven fabrics: tensile and impact properties. *Polym Int* 2004; 53: 1290–1297.

15. Yu H, Longana ML, Jalalvand M, et al. Pseudo-ductility in intermingled carbon/glass hybrid composites with highly aligned discontinuous fibres. *Compos Part A Appl Sci Manuf* 2015; 73: 35–44.

16. Mallick P. *Fiber-reinforced composites materials, manufacturing, and design*. New York, NY: Marcel Decker ed Inc., 1993.

17. Tomašić D, Ilinčić P and Pilićović A. Influence of layers lay-up on the mechanical properties of hybrid composites in field of aeronautics. *Polimeri časopis za plastiku i gumen* 2015; 36: 5–10.

18. Jayabal S, Natarajan U and Sathiyamurthy S. Effect of glass hybridization and staking sequence on mechanical behaviour of interply coir–glass hybrid laminate. *Bull Mater Sci* 2011; 34: 293–298.

19. Noorunnisa Khanam P, Ramachandra Reddy G, Raghu K, et al. Tensile, flexural, and compressive properties of coir/silk fiber-reinforced hybrid composites. *J Reinf Plast Compos* 2010; 29: 2124–2127.
20. Bulut M, Erkli̇γ A and Yeter E. Experimental investigation on influence of Kevlar fiber hybridization on tensile and damping response of Kevlar/glass/epoxy resin composite laminates. *J Compos Mater* 2016; 50: 1875–1886.
21. Peijs A and De Kok J. Hybrid composites based on polyethylene and carbon fibres. Part 6: tensile and fatigue behaviour. *Composites* 1993; 24: 19–32.
22. Mariatti M, Nasir M and Ismail H. Effect of stacking sequence on the properties of plain-satin hybrid laminate composites. *Polym Plast Technol Eng* 2003; 42: 65–79.
23. Naik N, Ramasimha R, Arya H, et al. Impact response and damage tolerance characteristics of glass–carbon/epoxy hybrid composite plates. *Compos Part B Eng* 2001; 32: 565–574.
24. Dalfi H, Katnam KB and Potluri P. Intra-laminar toughening mechanisms to enhance impact damage tolerance of 2D woven composite laminates via yarn-level fiber hybridization and fiber architecture. *Polym Compos* 2019; 40: 4573–4587.
25. Katnam K, Dalfi H and Potluri P. Towards balancing in-plane mechanical properties and impact damage tolerance of composite laminates using quasi-UD woven fabrics with hybrid warp yarns. *Compos Struct* 2019; 225: 111083.
26. Cerbu C and Botă M. Numerical modeling of the flax/glass/epoxy hybrid composite materials in bending. *Proc Eng* 2017; 181: 308–315.
27. Czigány T. Special manufacturing and characteristics of basalt fiber reinforced hybrid polypropylene composites: mechanical properties and acoustic emission study. *Compos Sci Technol* 2006; 66: 3210–3220.
28. Fiore V, Di Bella G and Valenza A. Glass–basalt/epoxy hybrid composites for marine applications. *Mater Des* 2011; 32: 2091–2099.
29. Carmisciano S, De Rosa IM, Sarasini F, et al. Basalt woven fiber reinforced vinyl ester composites: flexural and electrical properties. *Mater Des* 2011; 32: 337–342.
30. Mahdi E, Hamouda A, Sahari B, et al. Effect of hybridisation on crushing behaviour of carbon/glass fibre/epoxy circular–cylindrical shells. *J Mater Process Technol* 2003; 132: 49–57.
31. Dong C, Ranaweera-Jayawardena HA and Davies IJ. Flexural properties of hybrid composites reinforced by S-2 glass and T700S carbon fibres. *Compos Part B Eng* 2012; 43: 573–581.
32. Giancaspro JW, Papakonstantinou CG and Balaguru P. Flexural response of inorganic hybrid composites with E-glass and carbon fibres. *J Eng Mater Technol* 2010; 132: 021005.
33. Amuthakkannan P, Manikandan V, Jappes JTW, et al. Hybridization effect on mechanical properties of short basalt/jute fiber-reinforced polyester composites. *Sci Eng Compos Mater* 2013; 20: 343–350.
34. Tanov R and Tabiei A. Computationally efficient micromechanical models for woven fabric composite elastic moduli. *J Appl Mech* 2001; 68: 553–560.
35. Naik N and Shembekar P. Elastic behavior of woven fabric composites: I—lamina analysis. *J Compos Mater* 1992; 26: 2196–2225.
36. Crookston J, Long A and Jones I. A summary review of mechanical properties prediction methods for textile reinforced polymer composites. *Proc Inst Mech Eng L* 2005; 219: 91–109.
37. Angioni SL, Meo M and Foreman A. A comparison of homogenization methods for 2-D woven composites. *Compos Part B Eng* 2011; 42: 181–189.
38. Adumitroaie A and Barbero EJ. Stiffness and strength prediction for plain weave textile reinforced composites. *Mech Adv Mater Struct* 2012; 19: 169–183.
39. Komeili M and Milani A. The effect of meso-level uncertainties on the mechanical response of woven fabric composites under axial loading. *Comput Struct* 2012; 90: 163–171.
40. Kowalczyk P. Parametric constitutive model of plain-weave fabric reinforced composite ply. *Adv Compos Mater* 2016; 25: 287–303.
41. Ming Huang Z. The mechanical properties of composites reinforced with woven and braided fabrics. *Compos Sci Technol* 2000; 60: 479–498.
42. Kowalczyk P. Enhanced geometric model for numerical microstructure analysis of plain-weave fabric-reinforced composite. *Adv Compos Mater* 2015; 24: 411–429.
43. Tan P, Tong L and Steven GP. Micromechanics models for the elastic constants and failure strengths of plain weave composites. *Compos Struct* 1999; 47: 797–804.
44. Ishikawa T and Chou T-W. Nonlinear behavior of woven fabric composites. *J Compos Mater* 1983; 17: 399–413.
45. Naik N and Ganesh V. An analytical method for plain weave fabric composites. *Composites* 1995; 26: 281–289.
46. Rao M, Pantiuk M and Charalambides P. Modeling the geometry of satin weave fabric composites. *J Compos Mater* 2009; 43: 19–56.
47. Angioni SL, Meo M and Foreman A. A critical review of homogenization methods for 2D woven composites. *J Reinf Plast Compos* 2011; 30: 1895–1906.
48. Materials ACDoC. *Standard test method for tensile properties of polymer matrix composite materials*. West Conshohocken, PA: ASTM International, 2008.
49. Lee S-K, Byun J-H and Hong SH. Effect of fiber geometry on the elastic constants of the plain woven fabric reinforced aluminum matrix composites. *Mater Sci Eng A* 2003; 347: 346–358.
50. Scida D, Aboura Z, Benzeggagh M, et al. Prediction of the elastic behaviour of hybrid and non-hybrid woven composites. *Compos Sci Technol* 1998; 57: 1727–1740.
51. Zhang Y, Li Y, Ma H, et al. Tensile and interfacial properties of unidirectional flax/glass fiber reinforced hybrid composites. *Compos Sci Technol* 2013; 88: 172–177.
52. Bunsell A and Harris B. Hybrid carbon and glass fibre composites. *Composites* 1974; 5: 157–164.
53. Marom G, Fischer S, Tuler F, et al. Hybrid effects in composites: conditions for positive or negative effects versus rule-of-mixtures behaviour. *J Mater Sci* 1978; 13: 1419–1426.
54. Liu Y, Straumit I, Vasiukov D, et al. Prediction of linear and non-linear behavior of 3D woven composite using mesoscopic voxel models reconstructed from X-ray microtomography. *Compos Struct* 2017; 179: 568–579.
55. Lupasteanu V, Tararu N and Popoaei S. Theoretical strength properties of unidirectional reinforced fiber reinforced polymer composites. *Buletinul Institutului Politehnic din Iasi. Sectia Constructii, Arhitectura* 2013; 59: 83.
56. Kaw Ak. *Mechanics of composite materials*. New York, NY: CRC Press, 2005.
57. Nali P and Carrera E. A numerical assessment on two-dimensional failure criteria for composite layered structures. *Compos Part B Eng* 2012; 43: 280–289.
58. Jones KD and DiBenedetto AT. Fiber fracture in hybrid composite systems. *Compos Sci Technol* 1994; 51: 53–62.
Author biographies

Hussein Dalfi is a lecturer of material engineering at Mechanical Department/College of Engineering/Wasit’s University/Iraq. He obtained his PhD from School of Material, University of Manchester in 2018. Prior to joining Wasit University in 2006, he finished his BSc and MSc studying in Material Engineering from Babylon University in 1998 and 2002 respectively from Iraq.

Anwer J Al-Obaidi is a lecturer in the engineering college - mechanical engineering department at the Wasit University – Iraq, where he has been a college member since 2010. Al-Obaidi completed his PhD in mechanical engineering at the University of Sheffield (UK) – 2018. He obtained his BSc and MSc studies from the Al-Nahrain University – Iraq in 2005, and 2009, respectively. Al-Obaidi is an Associate Fellow of The Higher Education Academy (HEA) in the UK.

Hussein Razaq is a lecturer in the mechanical engineering department, College of Engineering, Wasit University. He obtained his BSc and MSc in Applied mechanics from the University of Baghdad in 2002 and 2006, respectively. In the 2016, he obtained his PhD in the mechanical and aerospace engineering from Strathclyde University in the UK. His research involves the stress analysis, vibration analysis and fault diagnosis.