Numerical study of hybrid composites containing basalt fibres under flexural loading

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Abstract

In this study, a modelling approach based on finite element analysis (FEA) for predicting the flexural properties of fibre reinforced hybrid composites containing basalt fibres is presented. The FEA model was validated against the experimental data of various hybrid composites including carbon/basalt, E glass/basalt, aramid/basalt, flax/basalt and carbon/basalt/flax hybrid composites. With the developed FEA model, the carbon/basalt and glass/basalt hybrid composites of various degrees of hybridisation were investigated. It is shown that for the carbon/epoxy hybrid composite, the flexural strength can be improved via hybridisation with basalt fibres. For the other hybrid composites, no significant positive hybrid effects in the flexural strength exists.

Keywords Composites · Hybrid · Basalt · Flexural**Mathematics Subject Classification** 74E30

1 Introduction

Basalt fibres have mechanical properties similar to those of glass fibres, high operating temperature and good chemical resistance. These advantages make basalt fibres a good alternative to glass fibres as reinforcing material in composites used in several fields such as marine, automotive, sporting equipment, civil, etc. [1]. Basalt fibres have been used to reinforce vinylester and epoxy to make composites [2, 3]. A review on basalt fibre composites is given by Fiore et al. [1].

The hybrid composite consisting of multiple reinforcement types in one common matrix is developed for retaining the advantages of its constituents [4]. Hybrid composites may be produced in various configurations, e.g. intra-ply, inter-ply, sandwich or intimately mixed [4]. One commonly utilised example is the carbon and glass fibre reinforced hybrid polymer composite [5–8].

A general rule of mixtures (RoM) approach is often utilised to evaluate their mechanical properties, e.g. modulus and strength, of a hybrid composite. A material property is calculated from the constituent properties and their volume concentrations. However, it is often noticed that the RoM prediction differs from the experimental result. This difference is defined to be hybrid effect. A positive or negative hybrid effect is defined as a positive or negative deviation of a certain mechanical property from the RoM behaviour, respectively [9].

Previous studies [5–8] suggested that the flexural strength could be improved by replacing carbon fibres by glass fibres from the compressive face of carbon fibre reinforced composites, i.e. positive hybrid effects existed. This is because incorporating high elongation (glass) fibres into low elongation (carbon) fibres can enhance the strain-to-failure [10]. High elongation fibres enhance the strain levels required to propagate cracks through

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the composites and hence behave like crack arrestors on a micromechanical level [11].

Since basalt fibres are a good alternative to glass fibres, it is of great interest to develop hybrid composites containing basalt fibres. Hybrid composites containing basalt fibres including glass/basalt [12–14], carbon/basalt [15, 16], and aramid/basalt [17–20] hybrid composites have been studied. Similar to the carbon/glass fibre reinforced hybrid composites, Ary Subagia et al. [15] found the existence of positive hybrid effects on the flexural properties of the carbon and basalt woven fabric hybrid composites. Fiore et al. [13] showed that highest improvement in the mechanical properties was achieved when two external glass mats were replaced by uniaxial basalt fabrics. Bozkurt [19] showed that higher improvements on the flexural properties of aramid composites were found with the introduction of basalt layers to the compressive side, compared to the introduction of basalt layers to the tensile side. For the glass/basalt and aramid/basalt hybrid composites, it was also shown that the sandwich-like structures offered the best flexural behaviour [12, 17]. Hybridisation with basalt fibres could also improve the impact performance. Sarasini et al. [12] showed that the impact energy absorption and damage tolerance capacities of the glass fibre composites could be improved by hybridisation with basalt fibres. Similar improvements were found by hybridising aramid fibres with basalt fibres [17]. Wang et al. [18] studied the low velocity impact properties of interply and intraply 3D woven basalt/aramid hybrid composites, and found that the interply hybrid composites had much larger energy absorption compared to the intraply hybrid composites. This was because the interply hybrid composites failed in a layer-by-layer mode while the intraply hybrid composites showed a brittle mode.

Hybrid composites containing basalt and natural fibres were also studied [14, 21–23]. Petrucci et al. [14] studied the mechanical properties of hybrid epoxy composites reinforced by basalt, glass, flax and hemp fibres. It was found that the mechanical performance of the hybrid composites was higher than the hemp and flax fibre composites but lower than that of the basalt fibre composites. Fragassa et al. [21] studied the bidirectional composites reinforced by flax and/or basalt fibre fabrics. Nisini et al. [22] studied hybrid epoxy composites reinforced by basalt, carbon and flax fibres in two different stacking sequences. It was found that intercalation with basalt layers improved the stiffness while the impact performance was not substantially improved. Czigány [23] studied hybrid polypropylene composites reinforced by basalt, hemp, glass and carbon fibres, and found a slight increase in the mechanical properties when the hemp fibre composites were hybridised with basalt fibres. For the carbon and glass

fibre composites, however, a significant improvement was found by hybridisation with basalt fibres.

This study aimed at finding if hybridisation could improve the flexural properties of hybrid composites containing basalt fibres. A modelling approach based on finite element analysis (FEA) was developed, and the model was validated against the experimental data of various hybrid composites including carbon/basalt, E glass/basalt, aramid/basalt, flax/basalt and carbon/basalt/flax hybrid composites. With the developed FEA model, the carbon/basalt and glass/basalt hybrid composites of various degrees of hybridisation were investigated, and the effect of hybridisation on the flexural properties were found.

2 Finite element modelling

2.1 Lamina properties

An interply hybrid composite consists of a number of laminas. Each lamina is reinforced by a type of fibre. The elastic properties of the lamina are dependent on the constituent properties and fibre volume fraction. In this study, the elastic properties including the longitudinal modulus E_{11} and the shear moduli G_{12} , G_{13} and G_{23} , were derived by Hashin's model [24]. The transverse moduli E_{22} and E_{33} were derived from the stress–strain relationship [25].

2.2 Modelling

In this study, a commercial FEA software package ANSYS APDL was used to model the flexural properties of hybrid composites, and the details can be found in our previous studies [26, 6]. SOLID185 element was used to construct the FEA model. The lamina properties were defined as material models and applied to the elements according to the stacking sequence. As an example, the close-up shot of the FEA model for $[C_6B_4]$ is shown in Fig. 1. Carbon/epoxy and basalt/epoxy laminas are on the compressive and tensile faces, respectively.

According to procedure A of ASTM D7264/D7264M-15, the standard specimen width is 13 mm (0.5 in.) with the

Fig. 1 FEA model for $[C_6B_4]$ hybrid composite

specimen length being about 20% longer than the support span. For a specimen in three point bend test, the flexural strength (S_F), strain to failure (ϵ_F) and modulus (E_F) are given by [27]:

$$S_F = \frac{3P_{\max}L}{2bh^2} \quad (1)$$

$$\epsilon_F = \frac{6Dh}{L^2} \quad (2)$$

$$E_F = \frac{\Delta\sigma_F}{\Delta\epsilon_F} \quad (3)$$

where L , b and h are the span, width and depth of the specimen, D is the maximum deflection before failure, $P_{\max}$ is the maximum load encountered before failure, and σ_F is the flexural stress.

The schematic drawing of a test specimen under three point bend is shown in Fig. 2 including the coordinate system, boundary conditions and loads. The boundary conditions were applied in such way to simulate simple

supported supports. A bending load, P , was applied at the mid-span.

The bending load being applied at the mid-span was increased until failure occurred. At a given bending load, the corresponding displacement and stress were obtained. As an example, the displacement δ_z and stress σ_{xx} for [C₆B₄] in [15] when the bending load is 1 N are shown in Fig. 3. The maximum compressive and tensile stresses are 57.01 MPa and 37.87 MPa, respectively. The compressive stress is higher because carbon fibre laminas are placed on the compressive face. The flexural modulus was obtained using Eq. (3).

2.3 Failure criterion

It was found that failure occurred at the compressive face first, as reported in other studies [15], and kinking (highly localised fibre buckling [28]) or microbuckling occurred due to compression. Thus, a suitable model for predicting the compressive strength is needed. For the microbuckling or kinking mode, the compressive strength can be predicted by Lo-Chim model [29] or Budiansky and Fleck [30] model. Lo-Chim model is given by.

$$S_C = \frac{G_{12}}{1.5 + 12(6/\pi)^2(G_{12}/E_{11})} \quad (4)$$

where S_C is the compressive strength, and G_{12} and E_{11} are the shear and tensile moduli, respectively.

Budiansky and Fleck model is given by

$$S_C = \frac{G_m}{(1 - V_f)(1 + \phi/\gamma_Y)} \quad (5)$$

Fig. 2 Boundary conditions and loads

Fig. 3 Displacement δ_z (mm) and stress σ_{xx} (MPa) of [C₆B₄] hybrid composite

where V_f is the fibre volume fraction, γ_y is the longitudinal shear yield strain of composite, and ϕ is the initial misalignment angle.

For a lamina of arbitrary ply angle, a proper failure criterion is needed to predict the failure initiation. A Separate Failure Mode criterion [31] was chosen in this study for this purpose, which reads.

For fibre failure

$$\begin{aligned} \frac{\sigma_{11}}{S_T} &= 1 \quad \sigma_{11} > 0 \\ \frac{\sigma_{11}}{S_C} &= 1 \quad \sigma_{11} < 0 \end{aligned} \quad (6a)$$

For matrix failure

$$\begin{aligned} \left(\frac{\sigma_{22}}{S_{TT}}\right)^2 + \left(\frac{\tau_{12}}{S_S}\right)^2 &= 1 \quad \sigma_{22} > 0 \\ \left(\frac{\sigma_{22}}{S_{CT}}\right)^2 + \left(\frac{\tau_{12}}{S_S - 0.6\sigma_{22}}\right)^2 &= 1 \quad \sigma_{22} < 0 \end{aligned} \quad (6b)$$

where σ_{11} is the longitudinal stress; σ_{22} is the transverse stress; τ_{12} is the shear stress; S_T is the longitudinal tensile strength; S_{TT} is the transverse tensile strength; S_{CT} is the transverse compressive strength; S_S is the shear strength.

Because the stress distribution is uniform in compression but non-uniform in bending, from Weibull statistical theory [32], the maximum bending load was increased by about 30% and the flexural strength was calculated by Eq. (1).

2.4 Comparison of FEA and experimental results

2.4.1 Carbon/basalt hybrid composites

The carbon/basalt hybrid composites from [15] were studied with the developed model. The hybrid composites were made by reinforcing an epoxy resin (HTC-667C) with woven carbon fibre fabrics (C120-3K) and woven basalt

fibre fabrics (EcoB4-F210). The longitudinal modulus and strength of carbon fibre were taken to be 230 GPa and 4900 MPa, respectively [6]. The modulus and strength of basalt fibre were taken to be 89 GPa and 2800 MPa, respectively [1]. The stacking sequences being experimentally investigated are shown in Table 1, together with the flexural moduli and strengths from experiments and FEA. It is shown that the FEA predictions for the flexural modulus are mostly in good agreement with the experimental results, with the relative differences less than 15%, except for $[B_2C_3]_2$, for which the FEA prediction is 16% higher than the experimental result.

For the flexural strength, the FEA and experimental results are in good agreement except for $[C_3B_2]_5$ and $[B_4C_6]$. All hybrid specimens exhibited microbuckling, and some debonding and delamination were also present. This suggests that the compressive strength model based on microbuckling can well explain the flexural failure. The experimental flexural strength of $[C_3B_2]_5$ is 14% lower than the FEA prediction. It was found the specimens of this stacking sequence ($[C_3B_2]_5$) exhibited crack initiation at the carbon/epoxy section, fabric buckling and delamination. Basalt fibre pull-out, which could be due to inefficient basalt-epoxy bonding was also present. This inefficient basalt-epoxy bonding probably led to the lower flexural strength.

The flexural strength of a hybrid composite according to the RoM is given by $S_{F_{RoM}} = S_{Fc}(1 - r_h) + S_{Fb}r_h$, and the hybrid effect is given by $e_h = S_F/S_{F_{RoM}} - 1$, where S_{Fc} and S_{Fb} are the flexural strengths of the composites only containing carbon and basalt fibres, respectively. The hybrid effects for the hybrid stacking sequences are shown in Fig. 4. It is shown that positive hybrid effects occur when the carbon/epoxy laminas are placed on the compressive face. If the basalt/epoxy laminas are placed on the compressive face, negative hybrid effects occur. The maximum positive hybrid effect is 21.5% with $[C_3B_2]_5$. However, this

Table 1 Flexural moduli and strengths of carbon/basalt hybrid composites of various stacking sequences

Stacking sequence	Hybrid ratio	Flexural modulus (GPa)			Flexural strength (MPa)		
		Experiment	FEA	Relative difference (%)	Experiment	FEA	Relative difference (%)
$[C]_{10}$	0	54.172	53.791	0.71	861	885	- 2.72
$[C_3B_2]_5$	0.4	45.438	52.058	- 12.72	740	860	- 13.93
$[C_6B_4]$	0.4	41.104	36.345	13.09	738	725	1.83
$[C_3B_2]_2$	0.4	40.331	40.911	- 1.42	737	740	- 0.37
$[C_2B_2C]_5$	0.4	46.408	47.938	- 3.19	717	793	- 9.57
$[B_4C_6]$	0.4	39.026	36.350	7.36	712	638	11.62
$[B_2C_3]_2$	0.4	34.512	40.914	- 15.65	679	657	3.39
$[B_2C_3]_5$	0.4	35.006	31.434	11.36	656	639	2.62
$[B]_{10}$	1	25.374	25.327	0.19	428	442	- 3.15

Fig. 4 Hybrid effects of carbon/basalt hybrid composites of various stacking sequences

was based on the FEA prediction, and the actual flexural strength was much lower as aforementioned.

2.4.2 E Glass/basalt hybrid composites

The E glass/basalt hybrid composite from [13] was studied with the developed model. The hybrid composites were made by reinforcing an epoxy resin (SP 106) with randomly oriented E glass fibre mats and uniaxial non-woven basalt fabrics. The modulus and strength of E glass fibre were taken to be 72 GPa and 3450 MPa, respectively [8]. The stacking sequences being experimentally investigated and the corresponding flexural moduli and strengths are shown in Table 2. Laminas 1 and 6 are compressive and tensile faces, respectively. It is shown that the FEA predictions for the flexural modulus are in good agreement with the experimental results. The FEA predictions for the flexural strength of the hybrid composites were significantly higher than the experimental results because all hybrid composite specimens failed in delamination mode.

Table 2 Flexural moduli and strengths of E glass/basalt hybrid composites of various stacking sequences

Configuration	Position of basalt fibres	Flexural modulus (GPa)		Flexural strength (MPa)	
		Experiment	FEA	Experiment	FEA
GFRP	—	9.00	9.00	204	205
B1	Lamina 1	11.72	12.99	148	252
B2	Lamina 2	10.84	10.70	141	272
B3	Lamina 3	10.69	9.56	138	224
B4	Lamina 4	10.79	9.56	137	207
B5	Lamina 5	10.56	10.70	141	214
B6	Lamina 6	12.41	12.99	158	241
B1–6	Laminas 1 & 6	19.51	19.45	295	295

2.4.3 Aramid/basalt hybrid composites

The aramid/basalt hybrid composite from [19] was studied with the developed model. The hybrid composites were made by reinforcing an epoxy resin with woven aramid fibre fabrics and unidirectional basalt fabrics. The flexural moduli and strength of asymmetric stacking sequences are shown in Fig. 5, and those of symmetric stacking sequences are shown in Fig. 6.

It is shown from Figs. 5 and 6 and good agreement is found except the flexural strengths of two asymmetric stacking sequences.

2.4.4 Flax/basalt hybrid composites

The hybrid composites reinforced by bidirectional flax and basalt fibre fabrics were simulated with the developed model. The material properties and experimental procedure can be found in [21]. The flexural moduli and strengths from the experiments and simulation are shown in Fig. 7. It is shown that both the flexural modulus and strength of the flax/basalt hybrid composite from the experiments is lower than the FEA prediction. This may be due to the problems in the consolidation of composites and the non-negligible presence of voids [22].

2.4.5 Carbon/basalt/flax hybrid composites

Besides hybrid composites reinforced by two fibre types, the carbon/basalt/flax hybrid composite in [22] was studied using the developed model. The hybrid composites were made by reinforcing epoxy resin with basalt woven fabrics (Basaltex 350.1270.A), unidirectional flax fabrics (FIDFLAX UNIDIR 430 HS43) and plain weave carbon fabrics (Toray). The composite specimens contained 24.7% flax, 6.9% basalt and 9.2% carbon fibres. Two stacking sequences $[(0/90)_C/(\pm 45)_C/(0/90)_B/(0_F/90_F)_2/(0/90)_B/(\pm 45)_C/(0/90)_C]$ and $[(0/90)_C/(\pm 45)_C/90_F/(0/90)_B/0_F/90_F/$

Fig. 5 Flexural moduli (left) and strengths (right) of asymmetric aramid/basalt hybrid composites

Fig. 6 Flexural moduli (left) and strengths (right) of symmetric aramid/basalt hybrid composites

Fig. 7 Flexural moduli (left) and strengths (right) of hybrid composites reinforced by flax and basalt fibres

$(0/90)_B/0_F/(\pm 45)_C/(0/90)_C]$ were studied. The FEA predictions and experimental results are shown in Table 3.

It is seen that the FEA predictions are higher than the experimental results. This can be ascribed to the problems in the consolidation of composites and the non-negligible

presence of voids [22]. However, both the FEA predictions and experimental results show these two stacking sequences have similar flexural moduli, and $[(0/90)_C/(\pm 45)_C/90_F/(0/90)_B/0_F/90_F/(0/90)_B/0_F/(\pm 45)_C/(0/90)_C]$ has higher flexural strength.

Table 3 Flexural moduli and strengths of carbon/basalt/flax hybrid composites

Stacking sequence	Flexural modulus (GPa)		Flexural strength (MPa)	
	Experiment	FEA	Experiment	FEA
[(0/90) _C /((±45) _C /((0/90) _B /(0 _F /90 _F) ₂ /(0/90) _B /((±45) _C /(0/90) _C]	16.42 ± 0.55	22.22	256 ± 10	284
[(0/90) _C /((±45) _C /90 _F /(0/90) _B /0 _F /90 _F /(0/90) _B /0 _F /((±45) _C /(0/90) _C]	17.08 ± 1.00	22.28	287 ± 15	313

Table 4 Typical properties of fibres and epoxy resin

Material	Tensile modulus (GPa)	Tensile strength (MPa)	Density (g/cm ³)
High strength carbon fibre	230	4900	1.8
E glass fibre	72	3450	2.58
Aramid fibre	131	3620	1.45
Flax fibre	59	345	1.5
Basalt	89	2800	2.8
Epoxy	3.1	69.6	1.09

3 Model application

The hybrid composites containing carbon or glass and basalt fibres under flexural loading were investigated with the aid of the developed FEA model. Both unidirectional and bidirectional laminates were studied. The typical properties of high strength carbon, E glass, aramid, flax and basalt fibres and epoxy resin are shown in Table 4 [6, 8, 1, 33].

All composite laminates consist of 10 laminas of 0.2 mm thickness. Carbon, glass, aramid or flax is the primary fibre type and basalt is the secondary fibre type. In a previous study on the carbon and glass fibre reinforced hybrid composites, it was concluded that the fibre volume fraction of the glass/epoxy laminas needed to be higher than or equal to that of the carbon/epoxy laminas in order to achieve positive hybrid effects [26, 34]. In this study, the fibre volume fractions of the laminas containing the primary fibre type and the basalt/epoxy laminas were chosen to be both 50%.

First, the laminas of the primary fibre type were replaced by basalt/epoxy laminas layer-by-layer from the compressive to the tensile faces, as shown in Fig. 8. With reference to Fig. 9, in order to quantify the degree

Fig. 8 Variation of number of basalt/epoxy laminas **Fig. 9** Definition of hybrid ratio

of hybridisation, a hybrid ratio is defined to be the relative volume fraction of basalt in all fibres, i.e.

$$r_h = \frac{h_b V_{fb}}{h_p V_{fp} + h_b V_{fb}} \quad (7)$$

where h_p and h_b are the thicknesses of the laminas containing the primary fibre type and basalt fibres, respectively, and V_{fp} and V_{fb} are the fibre volume fractions of the laminas containing the primary fibre type and basalt fibres, respectively.

For the unidirectional composites, the normalised flexural strengths and the normalised strain energy densities are shown in Figs. 10 and 11, respectively.

It is seen from Fig. 10 that for the E glass/basalt and flax/basalt hybrid composite, the flexural strength increases with the introduction of basalt fibres, since basalt fibres have better properties than the E glass or flax fibres. For

Fig. 10 Normalised flexural strengths of unidirectional hybrid composites containing basalt fibres

Fig. 11 Normalised strain energy densities of unidirectional hybrid composites containing basalt fibres

the carbon/basalt hybrid composite, it is shown $[B_2C_8]$ has the highest flexural strength and hybrid effect. The flexural strength can be improved via hybridisation, similar to that of the carbon/glass fibre hybrid composites [26, 34]. For the aramid/basalt hybrid composite, only slight improvement is seen by replacing one aramid/epoxy lamina by basalt/epoxy lamina.

It is shown from Fig. 11 that the energy absorption capability can be significantly improved by hybridising basalt fibres with carbon fibres. $[B_2C_8]$ shows the highest strain energy density, with 72% improvement compared to the full carbon composite. Slight improvement can be seen in the other hybrid composites.

Compressive face

Tensile face

Fig. 12 Variation of location of basalt/epoxy lamina

Fig. 13 Normalised flexural strengths of unidirectional hybrid composites containing basalt fibres (Laminas 1 and 10 are compressive and tensile faces, respectively.)

Secondly, the influence of the stacking sequence was investigated. All composite laminates contained 1 basalt/epoxy lamina and 9 laminas of the primary fibre type, and the location of the basalt/epoxy lamina was altered from the compressive to the tensile faces, as shown in Fig. 12.

The normalised flexural strength of the unidirectional hybrid composites containing basalt fibres are shown in Fig. 13. For the E glass/epoxy and flax/epoxy composites, the flexural strength can be improved with the introduction of one basalt/epoxy lamina. The flexural strength reaches the minimum when the basalt/epoxy lamina is lamina 5 or lamina 6. For the carbon/epoxy composite, when the basalt/epoxy lamina is on the compressive face (lamina 1), significant improvement in the flexural strength

Table 5 Flexural moduli and strengths of unidirectional and bidirectional carbon/basalt hybrid composites of various stacking sequences

Stacking sequence	Flexural modulus (GPa)	Flexural strength (MPa)
<i>Unidirectional</i>		
[B ₂ C ₈]	83.887	1458
[B ₂ C ₃ BC ₄]	83.889	1459
[B ₂ C ₃] ₂	83.091	1468
[B ₂ C ₃ B ₃ C ₂]	79.401	1454
<i>Bidirectional</i>		
[B ₂ C ₈]	46.11	816
[B ₂ C ₃ BC ₄]	46.101	816
[B ₂ C ₃] ₂	45.657	826
[B ₂ C ₃ B ₃ C ₂]	43.778	830
[B ₂ C ₃ B ₄ C]	39.192	787

is seen. When the basalt/epoxy lamina is lamina 6 or lamina 7, the flexural strength is slightly higher than that of the full carbon/epoxy composite. A similar trend is seen for the aramid/epoxy composite.

It is shown from Fig. 10 that [B₂C₈] has the highest flexural strength. It is shown from Fig. 13 that when the basalt/epoxy lamina is lamina 6 or lamina 7 (i.e. below the mid-plane), the flexural strength is slightly higher than that of the full carbon/epoxy composite. When both factors were considered, the flexural moduli and strengths of selected stacking sequences are shown in Table 5. It is shown that [B₂C₃]₂ has the maximum flexural strength for the unidirectional composites and [B₂C₃B₃C₂] has the maximum flexural strength for the bidirectional composites.

4 Conclusions

In this study, a modelling approach based on FEA for predicting the flexural properties of fibre reinforced hybrid composites containing basalt fibres is presented. It is shown the experimental results and FEA predictions are in good agreement. It is shown the stacking sequence plays an important role in the flexural strength. For the carbon/epoxy hybrid composite, the flexural strength can be improved via hybridisation with basalt fibres. The maximum flexural strength occurs when the basalt/epoxy laminas are both on the compressive face and below the mid-plane. For the other hybrid composites, no significant positive hybrid effects in the flexural strength exists.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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