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Numerical analysis of low-velocity impact of carbon-basalt/epoxy hybrid laminates

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In this paper, an attempt has been made to numerically investigate the transient dynamic response of carbon-basalt/epoxy laminated composites subjected to low velocity impact. Carbon laminates are expensive hence, inclusion of cheaper basalt to obtain an improved, yet economical laminate is necessary. Finite element analysis (FEA) technique has been employed to simulate the laminated models. Loading profiles and test conditions from drop-weight tests have been obtained from literatures and necessary validation of FEA has also been performed. A correlation between impactor mass and velocity on the maximum laminate centre deflection has been established. In addition, the influence of hybrid stacking sequence and carbon position in the hybrid on laminate damage response has been studied. It has been observed from the study that hybrid 3 (H3) with stacking sequence CCBC-2 (best combination) showed the least deflection of all the stacking sequence sets and has the lowest deflection in all the low velocity impact testing conditions.

Keywords: Low-velocity impact, Hybrid laminate, Basalt fibre, Carbon fibre, Finite element analysis

1 Introduction

Laminated composite materials are widely used in industries such as aerospace, transport, and defence because they possess better mechanical properties compared to standalone materials[1,2]. Nonetheless, their behaviour under impact is a major concern, as impact damage has the potential to reduce the overall strength of the structure. Throughout their service life, composites are subjected to numerous loading conditions, including low-velocity impact which is particularly critical to the failure of aerospace composite structures[3].

In the aerospace industry, carbon fibre reinforced polymer composite is a favourable material of choice due to its high specific stiffness and strength. However, carbon's damage resistance to impact is poor. In order to rectify this, many methods have been successfully employed. The first approach comprises of enhancing matrix properties as proposed by Reis *et al*.[4] They investigated impact behaviour and damage tolerance of kevlar/filled epoxy matrix with two different fillers; *viz.* cork powder and nano-clays. They reported that, with the addition of fillers, the maximum impact load increased, which in turn depended on the type of filler, especially for high energy impact. The addition of nano-clays increased the damaged area by approximately 29% with improvement in residual strength of laminates. The other approach is hybridization, mostly with a high strain-to-failure fibre in order to enhance composites' damage resistance to low velocity and instrumented impact. In light of that, glass fibres have been in use for many years and have always been considered as the best option in terms of cost, ease of processing, environment friendliness, in addition to its availability. Hybrid carbon-glass fibres have continuously demonstrated better damage tolerance under impact compared with other carbon fibre composites. Numerous data are available on low velocity impact analysis of carbon epoxy laminates[5-7], similarly on glass fibre reinforced laminates[8-11] and on metal fibre reinforced epoxy laminates[12].

In recent years, basalt fibres have attracted a considerable amount of attention as a possible replacement for the conventional glass fibres. Newly introduced basalt fibres are made from natural rock and are employed as part of the innovation in composite reinforcement engineering technology. Basalt fibres have distinct mechanical as well as chemical properties[13-17]. They are capable of withstanding conditions such as high temperatures, acid and other solvents, and also have good insulation properties[18-21].

Numerous studies investigating low-velocity impact on laminated composites were conducted

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previously. Sarasini *et al.*[3], examined the effects of basalt fibre hybridization on quasi-static mechanical properties as well as low-velocity impact behaviour of carbon/epoxy laminates. In their experiments, the researchers used inter-ply hybrid specimens with two different stacking sequences (sandwich-like and intercalated) and tested them with three different impact energies (5 J, 12.5 J and 25 J). Their results showed that hybrid laminates with intercalated configuration have superior impact energy absorption capacity and improved damage tolerance compared with the all-carbon laminates. Meanwhile, sandwich-like configuration exhibits the most suitable flexural behaviour. Furthermore, other examinations on normal impact, high-velocity impact and post impact analysis of basalt-carbon/epoxy laminates have been conducted by researchers like Tirillo *et al.*[22], Petrucci *et al.*[23], Ferrante *et al.*[24], Sarasini *et al.*[25] and Subagai *et al.*[26-27]. Their work also covered basalt fibre inclusion in carbon fibre reinforced composite for low velocity impact. The effect of stacking sequence on the flexural properties of hybrid composite was also studied.

Choi *et al.*[28,29], carried out one of the earliest experimental and numerical studies on laminated composites. They investigated failure mechanisms and mechanics of fibre reinforced composites resulting from impact and determined the underlying parameters that govern impact damage. Using a *line-nosed* impactor that could produce an evenly dispersed transient dynamic load across the specimen's width, they concluded that matrix cracking is linked with the initial impact damage and that stacking sequence greatly affects composites' impact resistance.

Wang, Wu and Ma[30] conducted experimental along with numerical research on low-velocity impact characteristics and residual tensile strength of carbon fibre composite laminates. They performed low-velocity impact and residual tensile strength tests using an instrumented drop-weight machine and static test machine respectively, while the finite element simulation was carried out using *ABAQUS/Explicit*. They observed two damage modes due to different impact energies. They also found that degradation of residual tensile strength could be divided into three stages under different impact energies and that amplitudes of degradation are affected by stacking sequence.

Subagia and Kim *et al.*[26-27], studied the flexural properties of basalt-carbon/epoxy laminate composites. They formulated an expression for predicting variation in flexural strength and modulus of the hybrid composites based on the quantity of basalt fibre. The authors also reported that basalt fibre position in the stacking affects the flexural properties of the composite.

Aslan and Karakuzu[5], investigated experimentally and numerically the transient response of E-glass/epoxy composite laminates subjected to low-velocity impact. The laminate samples were prepared with ASTM test standards[31]. They utilized a drop-weight tower and a piezoelectric force transducer to measure contact force. In the numerical analysis, E-glass/epoxy cross-ply laminates were investigated under three different impact velocities (1 m/sec, 2 m/sec and 3 m/sec) and two impactor masses (0.135 kg and 2.6 kg) using 3DIMPACT computer code. The researchers established that impact forces and centre deflections were proportional to projectile velocity. Also, magnitudes of deflections and impact forces were found to be directly proportional to the impactor mass and both increase with the increase in mass.

In this paper, low-velocity impact of carbon-basalt/epoxy hybrid laminated composites were investigated using finite element analysis software – ANSYS Mechanical APDL, Transient Dynamic Analysis. Lack of sufficient research data on carbon-basalt/epoxy laminated composites has prompted this attempt.

1.1 Modelling of low-velocity impact

1.1.1 Virtual test set-up

Finite element models were developed in ANSYS Mechanical APDL, Transient Dynamic Analysis, to replicate some of the physical processes which occur during low-velocity impacts on composites. Emphasis was put on the correct geometrical representation of the physical system, boundary conditions, material behaviour and loads. Figure 1 shows an example of meshed FE model along with its boundary conditions and loading. The laminate depicted in Fig. 1 is of H3 composite code and two sides of the laminate were constrained in all degrees of freedom (DOF). The impactor load was applied at the centre of the laminate.

Shell 181, a four-noded element with six degrees of freedom at each node was used for modelling. The composite models were meshed using a total of 2400 mesh elements. A total of nine eight-ply laminated

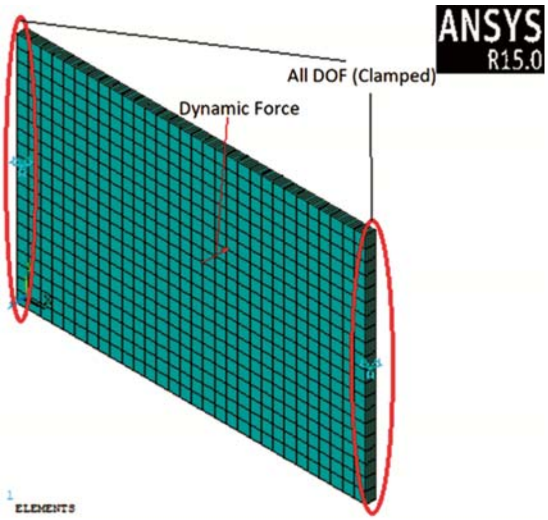

Fig. 1 — Sample of FE meshed laminate (H3 composite) along with its boundary conditions.

composite plates were simulated. The composite plates were designed in accordance to ASTM test standard D7136/D7136M-05[31], with the dimensions of 150 mm x 100 mm x 4 mm (Length x Width x Thickness). The loading profile obtained from drop-weight tests carried out in Aslan and Karakuzu[5] using piezoelectric force transducer was adapted and extended in this transient dynamic analysis.

2 Materials Used

The carbon and basalt fibres' mechanical properties are listed in Table 1[32]. Basalt fibre (300 g/m^2 uni-directional, 450 g/m^{2}woven) and carbon fibre (300 g/m^2 unidirectional) were obtained from Suretex Composite International, China. These properties formed the major input in the FEA formulation.

2.1 Configuration of the composites

Composite laminates were categorized into two types:

(i) Pure Laminates - comprised of all basalt and all carbon fibres i.e. laminate B and C, respectively. They were modelled to serve as reference data. (ii) Hybrids- Hybrid 1 (H1) to Hybrid 7 (H7) were composed of both basalt and carbon fibres having different lay-ups. The complete arrangement of the hybrids along with their reference code and stacking sequence are given in Table 2[32].

2.2 Methodology and validation

The methodology of this paper is primarily an extension of the work carried out by Aslan and Karakuzu[5]. Validation was carried out using transient dynamic analysis model. The model was discretised

Table 1 — Properties of carbon and basalt fibres[32].

Material Property	Basalt	Carbon
Elastic Modulus, E_x (GPa)	30.2	74.7
Elastic Modulus, E_y (GPa)	5.2	4.7
Elastic Modulus, E_z (GPa)	5.2	4.7
Poisson's Ratio, v_{xy}	0.2	0.48
Poisson's Ratio, v_{yz}	0.21	0.47
Poisson's Ratio,v_{xz}	0.21	0.47
Rigidity Modulus,G_{xy}(GPa)	2.05	21.5
Rigidity Modulus,G_{yz}(GPa)	3.6	1.45
Rigidity Modulus,G_{xz}(GPa)	3.6	21.5

Table 2 — Arrangement of the hybrids[32].

Composite	Code	Stacking Sequence
CCBB-4	H1	$[0_C/0_C/0_B/\pm45_B]_s°$
CCBB-4	H2	$[0_C/0_C/\pm45_B/0_B]_s°$
CCBC-2	H3	$[0_C/0_C/\pm45_B/0_C]_s°$
BBCC-4	H4	$[0_B/\pm45_B/0_C/0_C]_s°$
BBCC-4	H5	$[\pm45_B/0_B/0_C/0_C]_s°$
BCCB-4	H6	$[0_B/0_C/0_C/\pm45_B]_s°$
BCCB-4	H7	$[\pm45_B/0_C/0_C/\pm45_B]_s°$
BFRP	B	$[0_B/0_B/0_B/0_B]_s°$
CFRP	C	$[0_C/0_C/0_C/0_C]_s°$

B = basalt fibre& C = carbon fibre

using SOLID 185 element type as it helped to replicate the drop-weight tests carried out in ref[5]. SOLID 185 was chosen because of its plasticity, stress stiffening, large deflection, and large strain capabilities.

The FEA required a few assumptions; one of them was utilizing the rule of mixtures to approximate the composite as an isotropic material. The Young's modulus and Poisson's ratio were extracted using the same method. The model design as well as the impact loads obtained by Aslan and Karakuzu[5]were strictly followed. Comparison of finite element model centre deflection values and that obtained from the literature is provided in Table 3 and Table 4. Two test conditions as provided in the reference 5 were implemented in this study and subsequent model analysis was carried out;

1) A constant impactor mass of 2.6 kg and increasing velocity of 1, 2 and 3 m/sec.
2) A constant impact velocity of 3 m/sec and two different impactor masses of 0.135 and 2.6 kg, respectively.

The work basically compares the centre deflection of the laminates for two different types of loading at different velocities, as shown in Fig. 2(a) and Fig. 2(b). Later, ANSYS analysis was carried out on the laminates for the same loading conditions for

Table 3 — Comparison of centre deflection values due to a constant impactor mass of 2.6 kg and increasing velocities

Velocity	FE	Experiment	% Diff
1 m/sec	2.00 mm	2.05 mm	2.4
2 m/sec	3.76 mm	4.10 mm	8.3
3 m/sec	6.24 mm	6.25 mm	0.2

Table 4 — Comparison of centre deflection values due to a constant impactor velocity of 3 m/sec and two different masses

Mass	FE	Experiment	% Diff
0.135 kg	2.12 mm	1.40 mm	51.4
2.6 kg	6.24 mm	6.25 mm	0.2

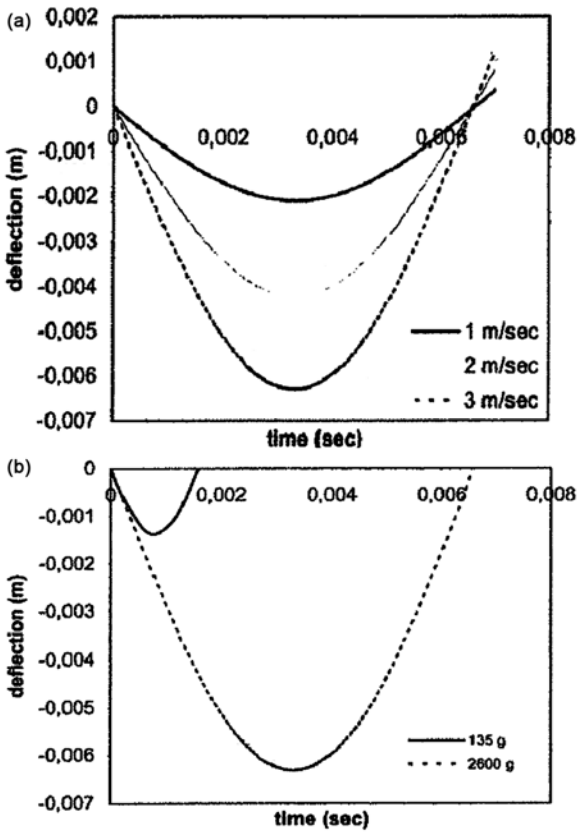

Fig. 2 — Laminates centre deflection (a) constant impactor mass of 2.6 kg and increasing velocity and (b) constant projectile velocity of 3 m/sec for two different masses[5].

validation purposes. The result of ANSYS analysis, for an example case, is shown in Fig. 3. It can be observed that the centre deflections were in agreement with the previous literature[5]. The maximum percentage difference for the case of impactor mass of 2.6 kg is 8.3%. However, for the impactor mass of 0.135 kg, a large difference was noticed. This could have been the experimental issues due to the light weight of the impactor. Perhaps, the measurement of deflection due to impact was not stable for light weight impactors.

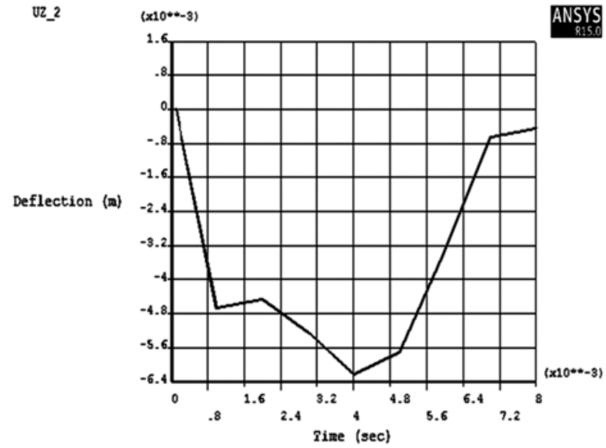

Fig. 3 — Validation model centre deflection for a constant impactor mass of 2.6 kg at a velocity of 3 m/sec.

Therefore, in this study, the impactor mass of 2.6 kg was employed for the impact resistance assessment of carbon-basalt/epoxy hybrid composites.

3 Results and Discussion

3.1 Constant mass and increasing velocity

In the first test condition, the impactor mass was held constant at 2.6 kg while its velocity was varied for three instances; (i) 1 m/sec, (ii) 2 m/sec and (iii) 3 m/sec. From the laminates' deflections comparison bar graph (Fig. 4), centre deflections of the laminates were observed to increase with the increase in impact velocity. Pure basalt composite laminate registered the highest overall centre deflection while pure carbon was the least deflected, as expected for low impact energies. It is because carbon possesses higher elastic modulus compared to basalt.

Among the seven hybrid laminates, Hybrid 7 and Hybrid 6 recorded highest deflections, followed by Hybrid 1, Hybrid 5, Hybrid 2 and Hybrid 4. The least deflected hybrid laminate was Hybrid 3. This variation in hybrid centre deflections is attributed to the number of carbon to basalt layers present in the hybrid as well as its lay-up. For instance, Hybrid 3 had a carbon to basalt ratio of 3:1 compared to its counterparts which had an equal number of the two fibre layers. Alternating basalt and carbon in the first 2 layers, with basalt at the exterior, leads to higher deflection (H7 and H6 compared to other hybrids). Unidirectional fibre orientation provides better resistance to deflection compared to 45-degree fibre orientation, H6 compared to H7, for low energy impact. The position of carbon in the laminate does not have great influence to the overall strength of the hybrid in terms of low energy impact as the results do

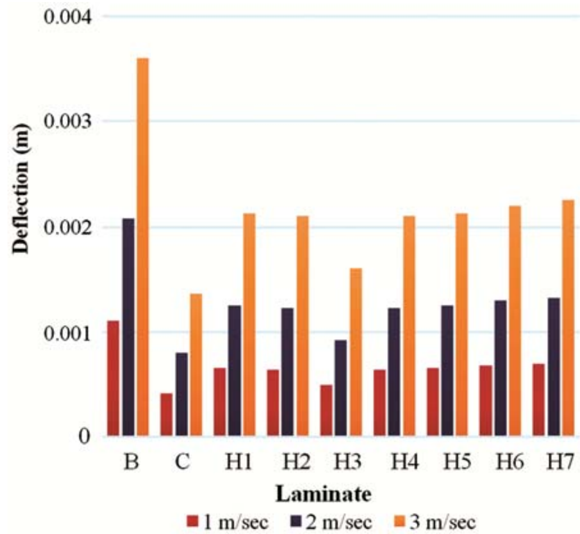

Fig. 4 — Effect of constant impactor mass and increasing velocity on laminates' centre deflections.

not defer much, H1 and H2 compared to H4 and H5. It is interesting to note that the addition of carbon to basalt improved the performance of pure basalt in terms of resistance to deflection due to low energy impact.

Figure 5 shows the case of impactor mass of 2.6 kg and velocity of 3 m/sec imposed on pure carbon and Hybrid 3 laminates, where it can be observed that Hybrid 3 follows the pure carbon laminate in least deflection, 0.0016 m as compared to 0.0014 m. This shows that Hybrid 3 has the best strength after pure carbon laminate with around 12% more deflection. Thus it forms the best combination of basalt/carbon epoxy laminate for low-velocity impact loading. Hybrid 3 is much better compared to other hybrid combinations whose deflections are higher than 0.002 m.

3.2 Constant velocity and varying mass

With the impactor velocity held constant at 3 m/sec, two impactor masses were tested; a) 0.135 kg and b) 2.6 kg. The larger impactor mass resulted in higher laminates centre deflections as it can be seen in the laminates' deflection comparison bar graph (Fig. 6). These results indicate that laminated composite plate centre deflection is directly related to impactor mass. Pure basalt composite laminate recorded the highest overall deflection, while pure carbon composite laminate steadily registered lowest overall deflection. This observation is quite obvious for low energy impact due to higher elastic modulus of carbon. Hybrid 7 and Hybrid 6 were the most deflected hybrids, followed by Hybrid 1, Hybrid 5,

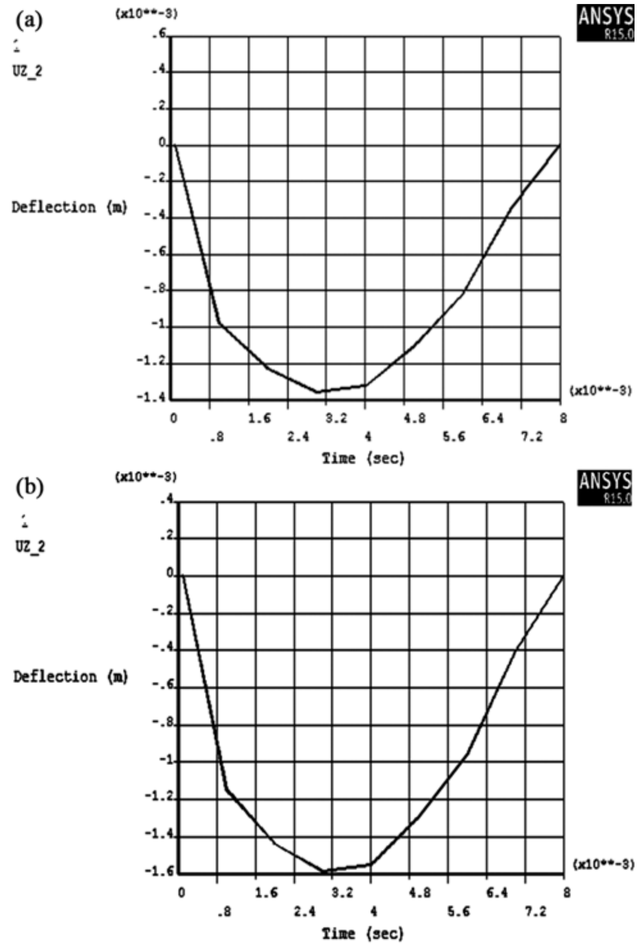

Fig. 5 — Laminated composites' centre deflections under a constant impactor mass of 2.6 kg and a velocity of 3 m/sec (a) pure carbon laminate and (b) Hybrid 3laminate.

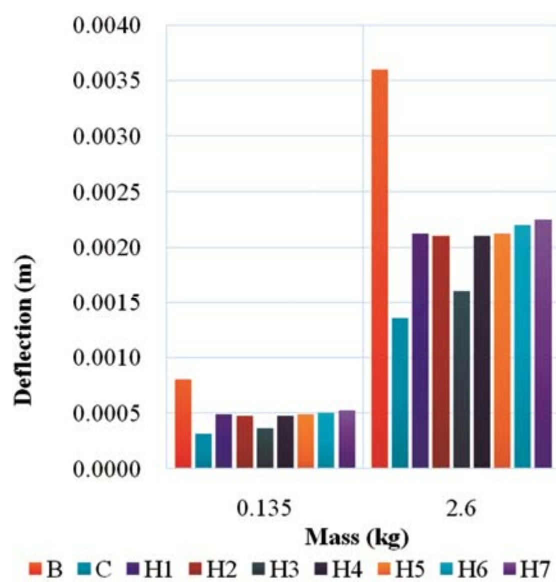

Fig. 6 — Laminates centre deflections under constant projectile velocity for two different masses.

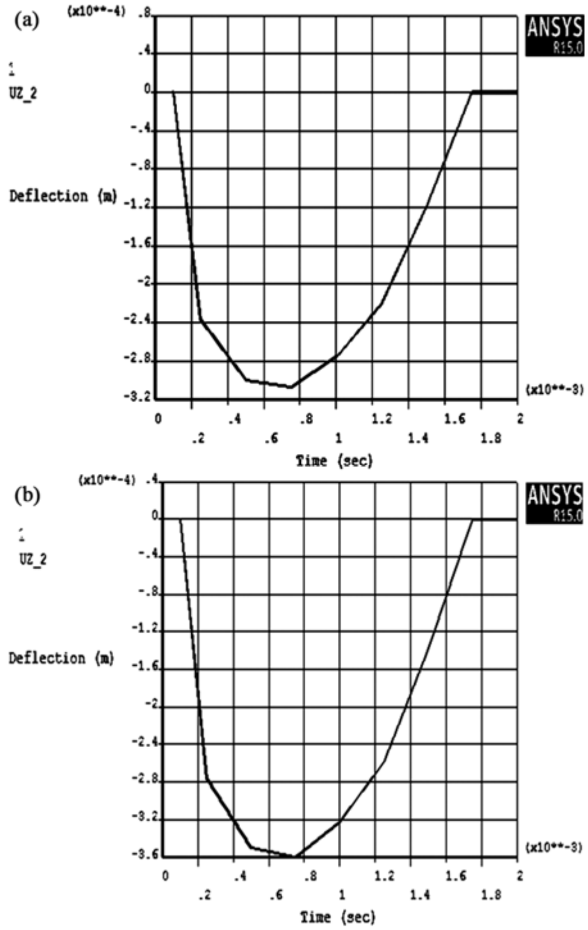

Fig. 7 — Laminated composites centre deflection under a constant impactor velocity of 3 m/sec and a mass of 0.135 kg (a) pure carbon laminate and (b) Hybrid 3composite laminate.

Hybrid 2 and Hybrid 4. Hybrid 3 was consistently the least deflected composite among the seven hybrids. Thus, again implying that the larger proportion of carbon fibres improved the performance of hybrid epoxy composite.

Similar to earlier loading case, constant velocity and varying mass also showed that Hybrid 3 has the best strength after pure carbon laminate. Figure 7 shows the centre deflections of pure carbon (0.0003 m) and Hybrid 3 laminates (0.00036 m) for a sample case of constant impactor velocity of 3 m/sec and impactor mass of 0.135 kg. Thus, the study showed that Hybrid 3 combination is the optimum combination when compared with other hybrid combinations which gave higher deflections for the said loadings.

4 Conclusions

Numerical analysis of low-velocity impact of carbon-basalt/epoxy laminated composites was carried out. From the results obtained, a correlation between impactor velocity and mass on laminate centre deflection was established. Furthermore, the influence of carbon-basalt hybrid stacking sequence together with carbon position in hybrid lay-up was demonstrated. It was observed from the study that pure carbon stacked laminate gave the least deflection and pure basalt stacked laminate gave the most deflection for the low energy loading conditions. These results are quite obvious when correlated with the properties of the composites. Even though the laminates with pure carbon returns good behaviour for low energy impact, employing laminates made of pure carbon fibre is expensive. As a cheaper alternative, basalt fibre can be incorporated along with carbon fibres to form hybrid laminate structures giving comparable resistance to low energy impact loadings.

It was observed that Hybrid 3 with stacking sequence CCBC-2 showed the least deflection compared to other hybrid stacking sequence combinations due to greater amount of carbon fibre content. In addition, positioning unidirectional fibre orientation at the exterior assists in improving the low energy impact resistance, H6 compared to H7. Finally, the arrangement of alternating basalt and carbon for the initial 2 layers returns higher deflection (H7 and H6 compared to other hybrids).

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