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Ballistic damage in hybrid composite laminates

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Abstract. Ballistic damage of hybrid woven-fabric composites made of plain-weave E-glass-fabric/epoxy and 8H satin-weave T300 carbon-fabric/epoxy is studied using a combination of experimental tests, microstructural studies and finite-element (FE) analysis. Ballistic tests were conducted with a single-stage gas gun. Fibre damage and delamination were observed to be dominating failure modes. A ply-level FE model was developed, with a fabric-reinforced ply modelled as a homogeneous orthotropic material with capacity to sustain progressive stiffness degradation due to fibre/matrix cracking, fibre breaking and plastic deformation under shear loading. Simulated damage patterns on the front and back faces of fabric-reinforced composite plates provided an insight into their damage mechanisms under ballistic loading.

1. Background

Woven fabric-based polymer-matrix composites (PMCs) are finding an increased use in defence-related applications thanks to their high strength and stiffness and ability to produce structures with tailored shapes and mechanical properties. Additionally, such PMCs lead to better energy absorption in ballistic impact events, especially thanks to their balanced in-plane properties. Recent studies [1, 2] showed that a hybrid composite structure - a combination of glass- and carbon-based epoxy composites may further improve the energy absorbing capacity of such composites. Thus, it is of great interest to a scientific community to understand their mechanical behaviour in high-velocity impact events.

In ballistic impact events, PMCs absorb projectile's kinetic energy by undergoing either elastic or permanent deformation. In the latter case, PMCs often exhibit different damage modes such as delamination, punching and fibre breakage. The condition for perforation, known as the *ballistic limit velocity* (V_{50}), is one of the most important factors for design of a suitable protective structure in this regard [1-4]. It represents an average of equal numbers of highest partial-penetration velocities and lowest complete-penetration velocities of a projectile for a specific velocity range, resulting in 50% probability of partial penetration and perforation of a target. Recently, Naik and Doshi [2] reported on ballistic-impact behaviour of typical woven-fabric E-glass/epoxy thick composites employing an analytical approach and found that shear plugging was the major energy-absorbing mechanism in these laminates. The level of V_{50} was also calculated and found to vary non-linearly with a linear



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increase in the laminate's thickness. Zhu [3] investigated a response of woven Kevlar/polyester laminates of varying thickness to quasi-static and dynamic penetration by cylindro-conical projectiles. Damage patterns in these composites were found to differ significantly under dynamic loading from those for quasi-static penetration conditions. There are some shortcomings of experimental ballistic schemes: typical experiments involve a plethora of safety protocols and often their output is difficult to quantify in a reliable manner given a short duration of such events. Thus, computer simulations are often employed as a virtual tool to analyse performance of structures in ballistic events and support their optimisation and design.

Simulating the mechanical behaviour of a fabric-reinforced composite structure under ballistic impact is a challenging task. Unlike metallic components that can yield and dissipate energy by undergoing plastic deformation, composites can mostly dissipate energy through various damage processes that usually degrade stiffness of structural components. Hence, an advanced modelling tool that can adequately simulate such events is essential in the design process. However, due to the complexity of involved processes and mechanisms, most models attempt to provide acceptable trade-off in performance analysis [4-8]. To model a woven-fabric down to a level of crossovers of individual yarn would certainly be preferred in order to study the underlying frictional and crimping effects, but such studies are computationally impracticable for dynamic problems. In this regards, this work focuses on the development of a FE model of a ballistic-impact response of woven-fabric-reinforced composites. The experimental studies, reproduced in numerical simulations, are discussed first, followed by a brief description of the developed FE model. Its results and discussion are presented next.

2. Ballistic experiments

A ballistic-impact test apparatus operated by a single-stage gas-gun (Fig. 1) was used to carry out experimental studies. It consisted of a projectile-propelling mechanism, a chronograph for velocity measurement, a support stand for holding the specimen, a containment chamber, safety devices and a strain-measuring facility. Compressed air was used as a propellant in the system. The main components of this propelling mechanism were a cylindrical barrel to guide the projectile, a quick release valve to relieve the trapped air and a nitrogen gas-driven solenoid valve to operate this valve. The cylindrical barrel (through which a projectile was propelled) was 1.5 m long. Its inner diameter was chosen to suit a projectile used in these experiments.

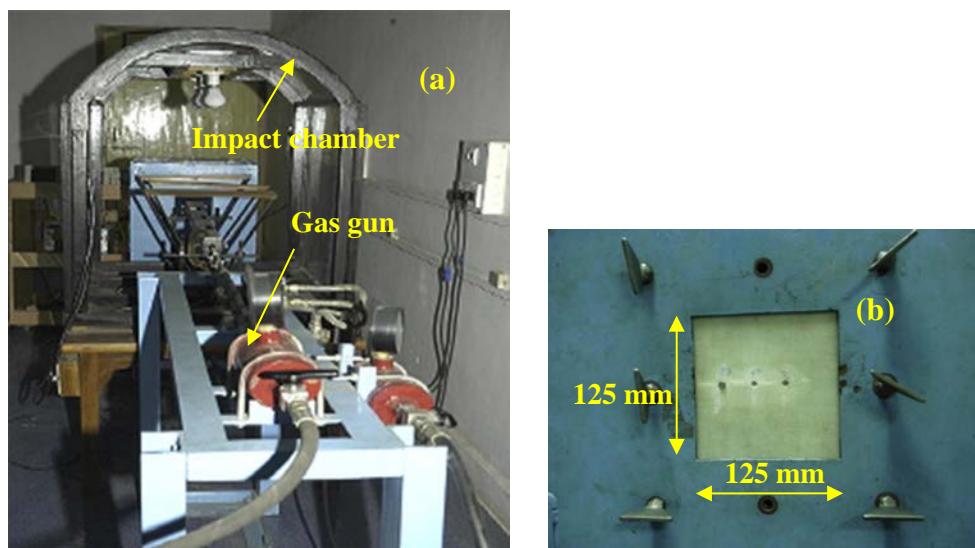


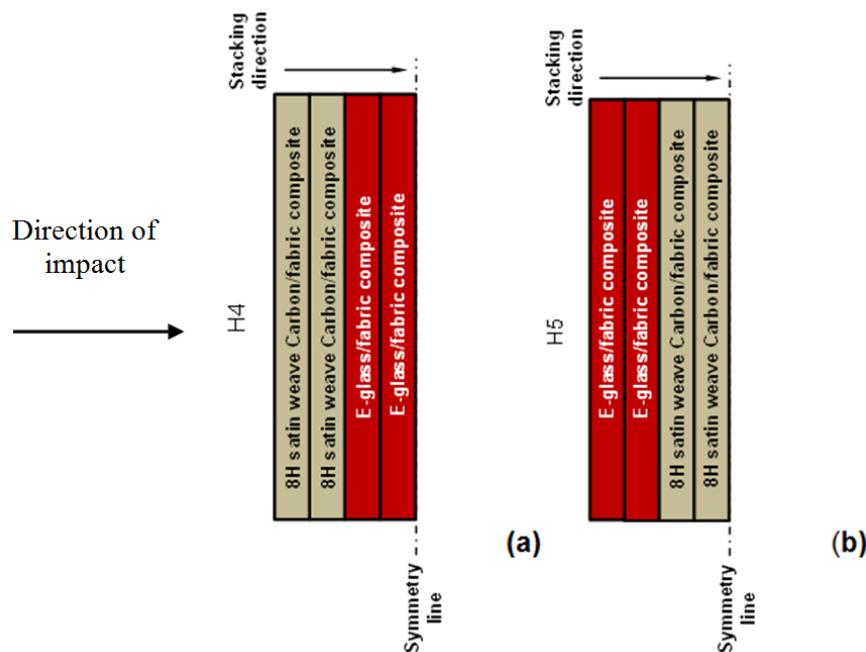
Figure 1. Ballistic test setup: (a) single-stage gas gun; (b) typical test specimen

A velocity of projectiles was varied up to 200 m/s by changing the air pressure in the cylinder. The experimental studies were carried out on flat specimens with dimensions 125 mm × 125 mm with different thicknesses (refer to Table 1). The specimen's dimensions were chosen in such a way that they can be accommodated into a fixture designed as an integral part of the ballistic-impact test apparatus. The mass of flat-end cylindrical projectiles made of hardened steel and their diameter was kept constant for all the tests. The experiments were carried out on at least four specimens for each impact condition to ensure repeatability.

Table 1. Parameters of ballistic tests

(target dimensions: 125 mm × 125 mm; projectile diameter: 6.36 mm)

Sr. No.	Projectile mass (g)	Projectile length (mm)	Target thickness (mm)
(A) Plain-weave E-glass epoxy			
1	6.42	25.3	2.5
2	6.42	25.3	3.0
3	6.42	25.3	4.5
4	6.42	25.3	5.0
(B) 8H satin-weave T300 carbon/epoxy			
1	6.42	25.3	3.0
(C) Hybrid (H4 and H5)			
1	6.42	25.3	3.0
2	6.42	25.3	3.0

**Figure 2.** Architecture of hybrid composite laminates: (a) H4; (b) H5

Four symmetric cross-ply woven fabric composites were studied: plain-weave E-glass fabric/epoxy, 8H satin-weave T300 carbon fabric/epoxy and their hybrids. Specifications of tows/stands, fabrics, resin and composites for plain weave E-glass/epoxy and 8H satin-weave T300 carbon/epoxy composites can be found in [1]. For simplicity, these composite laminates are designated below as *E*, *C*, *H4* and *H5*, respectively. The ply architecture of hybrids *H4* and *H5* is shown in Figs. 2a and b, respectively.

3. Finite-element model

A ply-level constitutive model was developed to analyse the mechanical response of the fabric/epoxy composites. This model was implemented as a material subroutine VUMAT in ABAQUS [9]. Each ply was modelled as a homogeneous orthotropic material with potential to sustain progressive stiffness degradation due to fibre/matrix cracking and plastic deformation under shear loading. Delamination between the neighbouring plies was modelled using a cohesive-zone-element (CZE) technique. The setup of FE model is shown in Fig 3. Details of a constitutive model for fabric-reinforced composites and damage modelling framework used in this FE model are not explained here for the purpose of brevity; they can be found in [10].

A schematic of the developed FE model is shown in Fig. 3. Both the woven-fabric-reinforced plate and the bullet were modelled as 3D deformable solids. A dynamic explicit solver was used in simulations to account for the time-dependent loading and complex interaction between the target and the projectile.

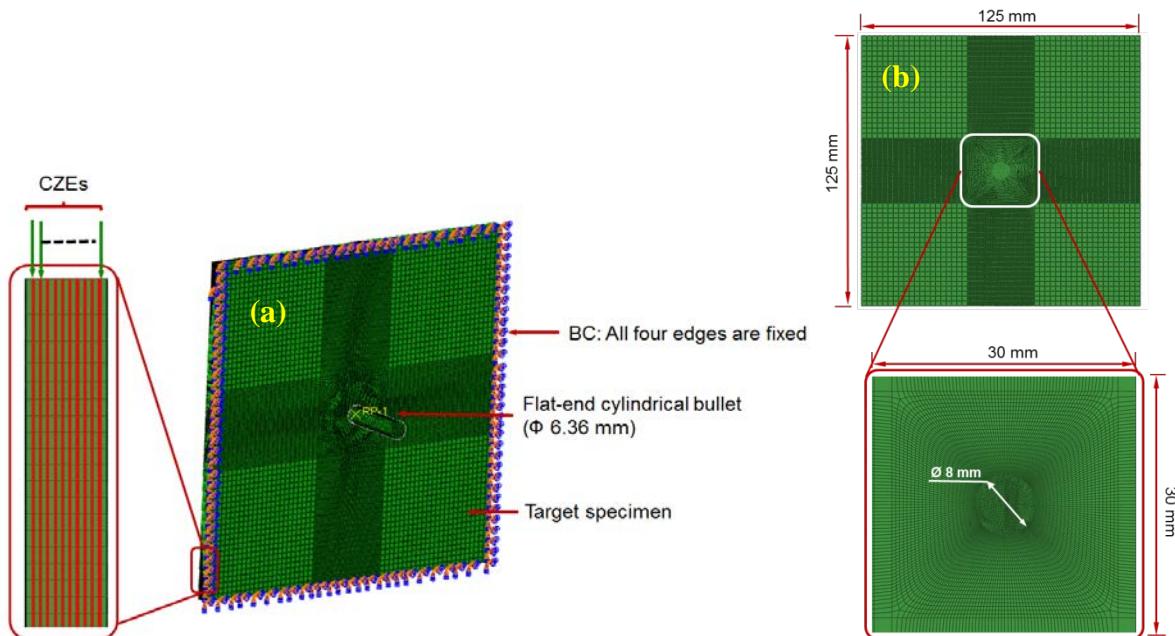


Figure 3. FE model of ballistic impact: (a) setup; (b) typical meshed specimen, $t = 3$ mm

3 mm-thick symmetric cross-ply hybrid laminates were modelled. The laminate consisted of 5 plies each of *C* and *E* composites with a thickness of 0.32 mm and 0.28 mm, respectively. The local coordinate systems were defined to account for orientations of individual plies. In experimental trials, a cylindrical projectile with mass of 6.42 g and length of 25.3 mm impacted the centre of the workpiece in the axial direction (see Fig. 3a). In simulations, this was achieved using a pre-defined velocity boundary condition. Contacts between the projectile, on the one hand, and the composite plate and all contacted plies of the laminate, on the other, were defined by a general contact algorithm available in ABAQUS/Explicit. This algorithm generated the contact forces based on a penalty-enforced contact

method. The friction coefficient μ was used to account for shear stress of the surface traction with contact pressure p and can be represented as $\tau = \mu p$. In this case, the frictional contact between a bullet and composite laminate was modelled with a constant coefficient of friction of 0.3 [7]. The models require on average 11 hours on 24 Intel quad-core processors with 48 GB RAM each to finish the analysis using the High Performance Computing (HPC) facility available at Loughborough University, UK.

4. Results and discussions

The finite-element models of ballistic-impact on studied composite laminates were validated using experimental measured ballistic limit velocity (V_{50}) and analytically calculated energy absorbed by a laminate. The ballistic limit velocity (V_{50}) was assessed for the same thickness of laminates, impactor geometry and mass to provide an assessment of their relative performance. It should be noted that, though, thickness of all the studied laminates was the same, the areal weight of two underlying fabric materials (E-glass plain-weave and carbon satin-weave) was different. Thus, a more viable comparison of their ballistic performance was provided in terms of a normalised parameter – V_{50} per unit areal weight of the target. The fracture mechanisms in these laminates were also studied, and their contribution to absorption of incident impact energy is discussed below.

(a) V_{50} for same target thickness and per unit areal density

In FE simulations, V_{50} was calculated at the reference point R_f tied to a bullet using an equation constraint to reduce the computational efforts. Figures 4a-b present the ballistic limit velocity V_{50} for *G*, *C*, *H4* and *H5* composites for the same thickness and per unit areal density, respectively.

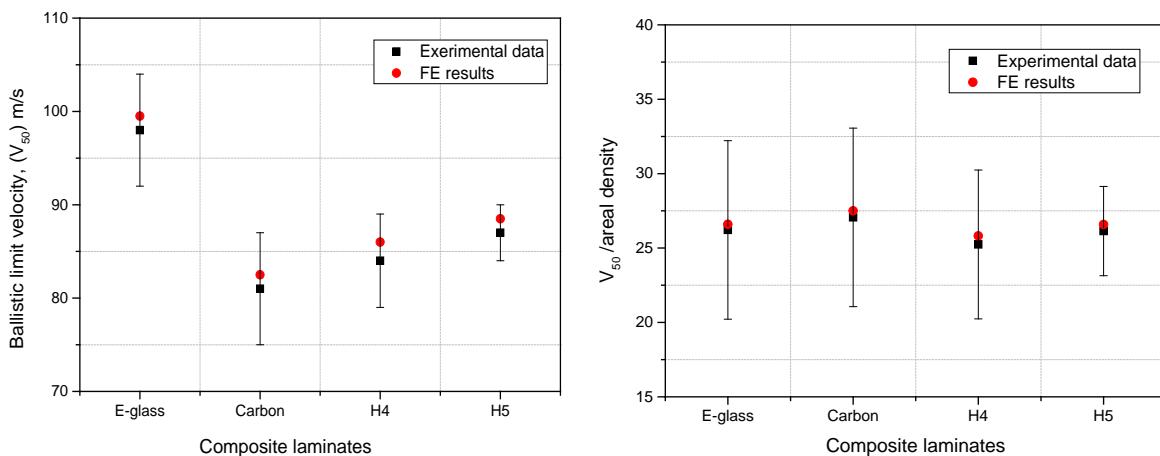


Figure 4. Ballistic-impact velocities for same thickness (a) and per unit areal density (b) for studied composite laminate (projectile mass 6.42 g, projectile length 25.3 mm)

It can be observed that the ballistic limit velocity V_{50} had considerably different hierarchies for the assessed criteria and laminates; thus, selection of appropriate composite mostly depends on the type application, in other words, it should consider the importance of higher stiffness or better specific energy absorption capacity for the working structure. In the former case, E-glass-based composite provided a better performance but at a price of a higher weight.

(b) Damage in composite panels

Damage assessment in the studied composite laminates was carried out using numerical simulations with the developed FE model. Damage patterns obtained at the front and the back face of studied composite laminates are shown in Fig 5. Impact-generated damage was visible on the both faces of the

composite panels and was measured along both warp and fill directions from the centres of specimens (where they were impacted) and compared with respective magnitudes obtained with the FE analysis (Fig. 6). The damage mechanisms in *G* and *C* laminates were observed to be similar, though overall damage at the front and back faces was more pronounced for *G* plates than for *C* ones due to lower stiffness of the glass-fibre plies (see cases A and B in Fig. 5).

Hybridisation of *G* and *C* laminates could potentially give a rise to either improved or reduced material properties. In case of *H4* (hybrid laminate with exterior *G* plies), the dominant damage processes were the same as found in *C* and *G*, namely, tensile fracture of the back plies and crushing of the front plies under the impactor. The intraply cracks in the front and back plies grew upwards and downwards, respectively, leading to development of delamination cracks, and final fracture took place by formation of a crack through the laminate thickness. However, the amount of damage at the back face of *H4* laminate was far lower than in *G* and moderately less than in *C* under equivalent impact conditions (cases A and C in Fig. 5). On the other hand, in case of *H5* (the hybrid laminate with *C* plies at the exterior), apart from ply fracture at the back and crushing at the front, large deformation in the stiff carbon plies led to extensive delamination and intraply fracture that grew rapidly towards the back. Ply fracture due to crushing at the front also accelerated this process resulting in greater damage on the back face of *H5* (case D in Fig. 5).

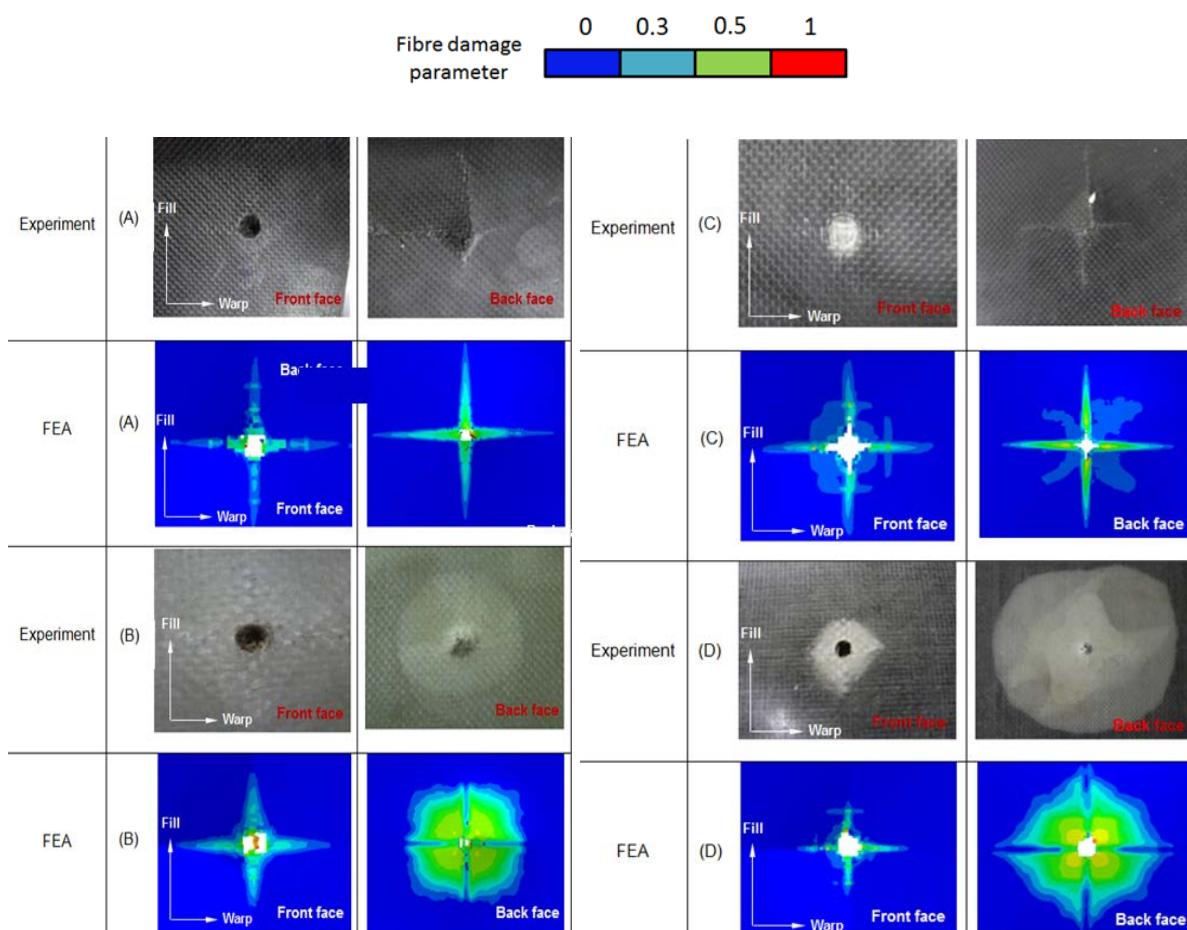


Figure 5 Damage patterns on front and back faces of composite panels: (A) 8H satin-weave T300 carbon/epoxy composite ($V_{50} = 99.5$ m/s); (B) plain-weave E-glass/epoxy composite ($V_{50} = 82$ m/s); (C) hybrid H4 ($V_{50} = 86$ m/s); (D) hybrid H5 ($V_{50} = 88$ m/s) (laminate thickness 3 mm)

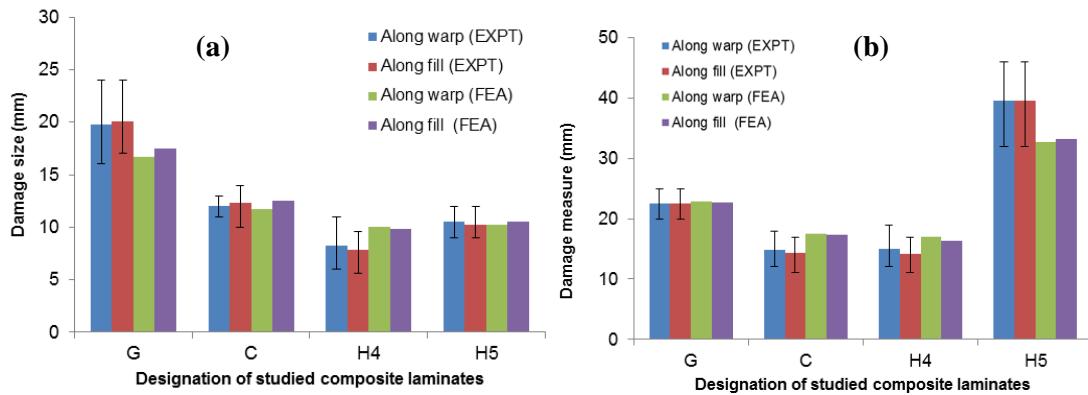


Figure 6. Measured and calculated damage size for studied composite laminates: (a) front face; (b) back face (laminate thickness 3 mm) Used notation: G - plain-weave E-glass/epoxy composites impacted at $V_{50} = 99.5$ m/s; C - 8H satin-weave T300 carbon/epoxy composites at $V_{50} = 82$ m/s; H4 - hybrid composite H4 at $V_{50} = 86$ m/s; H5 - hybrid composite H5 at $V_{50} = 88$ m/s.

(c) Contribution of damage modes to energy absorption

The trends of energy absorption mechanisms in the studied laminates were quite similar (Fig. 7), with most of incident kinetic energy absorbed due to deformation of secondary yarns, while energy absorption related to failure of primary yarn/fibre was relatively low and that due to matrix cracking and delamination was marginal.

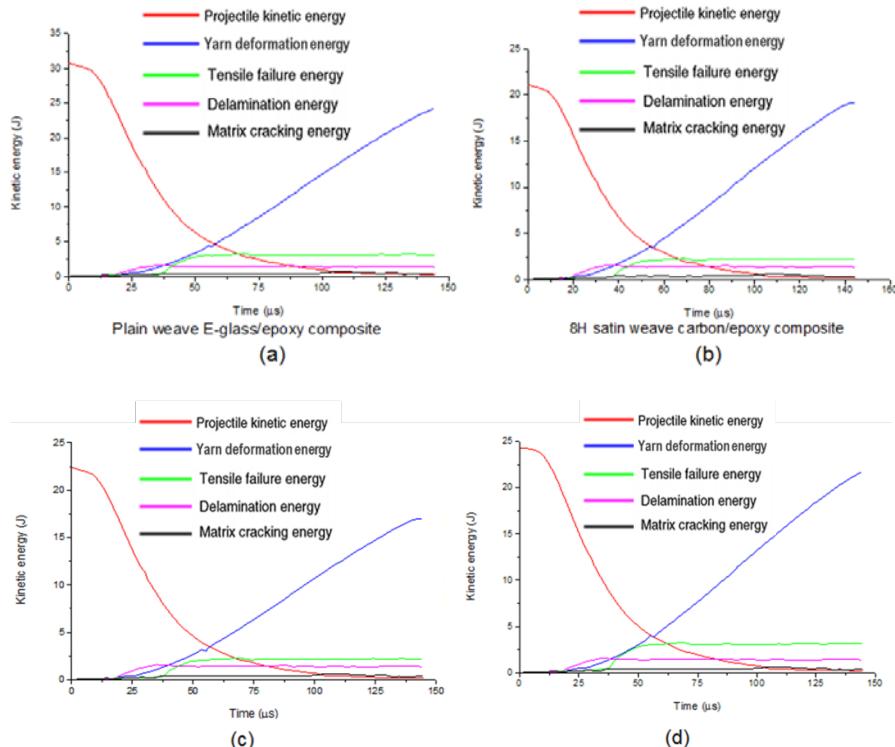


Figure 7. Contribution of damage modes to kinetic energy absorption: (a) plain-weave E-glass/epoxy composite at $V_{50} = 99.5$ m/s; (b) 8H satin-weave carbon/epoxy composite at $V_{50} = 82$ m/s; (c) hybrid composite H4 at $V_{50} = 86$ m/s; (d) hybrid composite H5 at $V_{50} = 88$ m/s (laminate thickness 3 mm)

This may be explained by a highly transient nature of impact events, with a time of contact between projectile and target of some 150 microseconds and highly localised deformation of the target, where damage initiated in the form of fibre failure directly below the projectile and had hardly any time to diffuse through the laminate before the projectile penetrates it. The contribution of damage modes to total energy absorbed for the studied composite laminates is shown in Fig. 7.

5. Conclusions

A ballistic-impact response of four woven fabric composite laminates *E*, *G*, *H4* and *H5* was studied experimentally and using the developed finite-element model. The ballistic damage on the front and back faces of the studied laminates was observed. The effect of hybridisation on damage modes and their contribution to energy-absorption capacity of the laminates was also discussed. The FE model predicted the pattern and extent of damage in the studied laminates reasonably and provided an insight into their probable damage mechanisms. Some fundamental observations based on this study are listed:

- Improvements due to hybridization in the behaviour of the laminates under impact were due to the higher strain-to-fracture ratio of the E-glass-fibre plies located near the front and back laminate surfaces. These plies were able to sustain higher deformations before fracture and hindered propagation of damage to the inner plies from the broken plies on the front and back surfaces, increasing the maximum load-bearing capability of the composite.
- The hybridisation provided a reasonable trade-off between in-plain strength and failure strain that resulted in better ballistic-impact resistance properties compared to high-modulus fibre-reinforced composites. In addition, the presence of E-glass fibres helped to sustain higher deformations before fracture of the laminate by the percolation of a through-thickness crack, significantly increasing the energy dissipated under impact. Most of the benefits of the E-glass fibre could be attributed to the plies located near the laminate surfaces. The presence of inner plies provided more limited improvements, particularly in terms of specific properties.

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