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Compressive failure of hybrid multidirectional fibre-reinforced composites

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ABSTRACT

In this paper, the hybridisation of multidirectional carbon fibre-reinforced composites as a means of improving the compressive performance is studied. The aim is to thoroughly investigate how hybridisation influences the laminate behaviour under different compression conditions and thus provide an explanation of the "hybrid effect". The chosen approach was to compare the compressive performance of two monolithic carbon fibre/epoxy systems, CYTEC HTS/MTM44-1 and IMS/MTM44-1, with that of their respective hybrids. This was done by keeping the same layup throughout ($(0/90/45/-45)_{2S}$) while replacing the angle plies in one case or the orthogonal plies in the other case with the second material, thus producing two hybrid systems. To investigate the compressive performance of these configurations, compact and plain compression test methods were employed which also allowed studying the sensitivity of compressive failure to specimen geometry and loading conditions. The experimental results and the subsequent fractographic analysis revealed that the hybridisation of selective ply interfaces influenced the location and severity of the failure mechanisms. Finally, in light of this knowledge, an update of the generic sequence of events, previously suggested by the authors, which lead to global fracture in multidirectional fibre-reinforced composites under compression is presented.

1. Introduction

The term hybrid applies to composites which contain more than one type of reinforcement and/or more than one type of matrix [1,2]. The main purpose of composite hybridization is often to improve specific properties or lower the overall manufacturing cost. In the case of fibre-reinforced composites, various fibres can be used in different plies or even within the same ply as co-woven, twisted or bound with a binder. In the case where the second filler is in the form of particles, these are usually mixed with the fibres within the lamina or even located between adjacent laminae. The incorporation of mainly carbon fibres with other types such as glass [3,4], aramid [5] and other polymeric fibres [6,7], has mainly served to enhance the toughness or impact resistance. In particular, hybridization enhances the failure strain [8,9] but on the other hand it leads to a decrease in stiffness, as has been reported by Chung [10]. Moreover, it has been observed that the failure strain of the carbon fibres in a hybrid composite is greater than that in a monolithic material, referred to throughout the literature as the hybrid effect [10]. However, so far no study has adequately explained the mechanism behind the "hybrid effect" and how failure processes are affected by hybridisation. With regards to compressive failure of hybrid fibre-reinforced composites, the literature is sparse [11–14], focussing on compressive failure of unidirectional and woven fabric laminates made by hybridising carbon fibres with glass and silicon carbide fibres (or woven fabrics). The novelty of the present work is not limited to the mere study of the compressive failure of the hybrid multidirectional composite laminates and a comparison with the monolithic laminates. On the contrary, this study aims to provide detailed fractographic observations on how the compression damage processes had ensued and the effect of the fibre hybridisation on these processes under two different loading conditions. The use of two different types of compression testing not only allowed to shed light on the difference in the failure sequence of progressive compression damage development (compact compression) and unstable failure process (plain compression) in monolithic multidirectional composite laminates, but also to highlight how fibre hybridisation influenced the dominant compression failure modes in light of experimental observations made previously by the authors [15]. In particular, the findings from the extensive fractographic analysis (X-ray radiography, optical and

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scanning electron microscopy) on multidirectional laminates (made of UD HTS/MTM44-1 and IMS/MTM44-1 pre-preg tapes) are presented for the various configurations in both compact and plain compression and used to deduce the sequence of events that led to global fracture. It is beyond the scope of this paper to provide a predictive approach which has been the topic of a wealth of studies; on the contrary the high fidelity results and detailed fractographic observations on the key mechanisms can be used by other workers on the field to validate their numerical models. The study presented in this paper has been part of the CRASHCOMPS Project [16].

2. Experimental details

2.1. Laminate fabrication and specimen configurations

The materials used were 12 K HTS/MTM44-1 and 24 K IMS/MTM44-1 unidirectional pre-pregs supplied by CYTEC [17]. The experimentally determined values for lamina thickness were 0.246 ± 0.011 mm and 0.249 ± 0.012 mm whilst the fibre volume fraction values were 60.2 ± 0.7% and 59.5 ± 1.1% for HTS/MTM44-1 and IMS/MTM44-1 respectively [15]. With respect to the mechanical properties (Table 1), IMS/MTM44-1 is stronger and stiffer both in tension and compression but weaker and more compliant in shear [17].

Four panels (430 mm × 300 mm) were manufactured according to the supplier's recommendations [15], each having a $(0/90/45/-45)_{2S}$ layup. This particular layup was used due to the superior failure strength it exhibits compared to other multidirectional layups as has been reported by the authors [15,18]. Each panel had a different material configuration namely monolithic HTS (*HTS*); hybrid HTS/IMS with 0° and 90° HTS plies and ±45° IMS plies (*HTS_IMS_A*); hybrid HTS/IMS with 0° and 90° IMS plies and ±45° HTS plies (*HTS_IMS_O*) and finally monolithic IMS (*IMS*). For simplicity, the notation which will be used henceforth for these four configurations is *HTS*, *HTS_IMS_A*, *HTS_IMS_O* and *IMS* respectively. Note that the *HTS* configuration was deemed as the baseline against which the remaining configurations were compared. To obtain the compact and plain compression specimens, rectangular sections were cut using a wet saw to dimensions 60 mm × 65 mm and 132 mm × 50 mm respectively. For the compact compression specimens [19], holes for loading pins were drilled and a notch was introduced using a 4 mm wide diamond-coated circular saw, whilst for the plain compression specimens [20], a 6 mm cutter was utilised for producing the notch (Fig. 1). The surfaces were painted white and a fine black speckle pattern was then introduced on top using an airbrush to facilitate Digital Image Correlation (DIC) [15,18].

2.2. Experimental setup and characterisation

For the compact compression testing a 10-ton servo-hydraulic Instron machine with a 10 kN loadcell was employed to apply compression load via the loading pins. Plain compression testing was carried out in a 50-ton Zwick 1488 machine with hydraulic grips with a 200 kN loadcell. An antibuckling guide was utilised to ensure uniform compressive load distribution and stability [15,20]. DIC was performed (Fig. 1) on both compact and plain compression tests using a GOM Aramis (v6.2) and a pair of Schneider Kreuznach Componon S-1.4/100 mm DIC cameras illuminated by two Schneider Kreuznach LED lights (40 W). Five specimens were tested per configuration, each of which was loaded in displacement control at a rate of 1 mm/min for compact compression and 2 mm/min for plain compression; load–displacement data were recorded every second and DIC pictures were taken every three seconds – to provide more accurate displacement data LVDTs were used instead of the those recorded by the Instron machine, while DIC was also used for verification. Finally, whilst compact compression tests were halted prior to catastrophic failure, this was not possible for plain compression due to the unstable nature of the test [15]. Instead these tests were stopped once a significant load drop, i.e. catastrophic failure, had occurred. It should be noted that other more traditional compression tests such as the ASTM D3410 and D6484 (mainly developed for unidirectional laminates) were also considered for this study. However, such tests employ highly supported specimens which do not allow for progressive damage growth and thus more realistic conditions; a key requirement for this study. In the process of selecting the most appropriate test the authors have considered and appreciated issues pertain to notch sensitivity as these have been reported in numerous studies in the literature [15]. Nevertheless, the investigation of progressive damage growth from more realistic conditions as well as the interaction between key failure mechanisms such as delamination and fibre microbuckling could not be conducted using unnotched specimens where free edge effects such as shear fracture have been observed [15].

To investigate the compressive failures, X-ray radiography as well as optical and scanning electron microscopy were employed. Microscopy provided information about the dominant delaminations, in-plane shear fractures and their interactions at and 15.5 mm away from the notch. X-ray radiography was best suited for characterising localised translaminar damage, longitudinal and off-axis intralaminar damage, especially at the notch as well as the extent of the interlaminar damage across the specimens.

After conducting a parametric study and considering recommendations from the literature [21], for the X-ray radiography it was found that soaking the failed specimens in dibromoethane for five minutes was adequate for the penetrant to reach the full extent of the damaged area. The specimens were then left to dry for twenty minutes so that a satisfactory contrast between the pristine composite and the damage could be achieved. To facilitate microscopy, rectangular sections of 45 mm × 20 mm and 50 mm × 35 mm were cut for the compact and plain compression specimens respectively, which enclosed the damage, were carefully cut using a dry saw [15,18] at and 15.5 mm away from the notch (i.e. at the midpoint between the notch and the free edge). Regarding Optical Microscopy, the rectangular sections were mounted in potting resin, ground and polished to achieve a smooth surface. For Scanning Electron Microscopy the rectangular sections were carefully dissected, bonded on stubs using a two-part epoxy, sputter-coated with gold and marked with silver dag to ensure electrical conductivity. Optical microscopy was carried out on an Olympus BHM incident optical microscope and a Q-Imaging Micro-Publisher 5.0RTV camera; Scanning Electron Microscopy was used a Hitachi S-3400 N microscope at an acceleration voltage of 15 kV.

Table 1
Lamina mechanical properties of HTS/MTM44-1 and IMS/MTM44-1 [17].

Property	HTS/MTM44-1	IMS/MTM44-1	Percentage difference (%)
X_C	−1330	−1459	10
X_T	2159	2738	27
S_L	113	76	33
$E_{x\text{-}tension}$	123.2	147.2	19
$E_{x\text{-}compression}$	128.9	174.6	35
G_{12}	4.1	3.6	12
Tow size	12 K	24 K	–

3. Results

The compact compression results of the $(0/90/45/-45)_{2S}$ monolithic and hybrid laminates are summarized in Table 2 and typical force–displacement curves are shown in Fig. 2, while in Fig. 3 and Fig. 4 force-displacement curves for all *HTS* and *HTS_IMS_A* respectively are presented. Both monolithic and hybrid