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Hybrid effect and pseudo-ductile behaviour of unidirectional interlayer hybrid FRP composites for civil engineering applications

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HIGHLIGHTS

- Influence of several factors on hybrid effect was investigated.
- Significant hybrid effects on both ST carbon and HM carbon materials were registered.
- Combining HM carbon with E-glass or basalt or ST carbon lead to pseudo-ductile tensile behaviour.
- Existing analytical model satisfactorily predicted the response of these hybrid composites.

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ABSTRACT

An experimental study on the tensile stress-strain curves of interlayer (layer-by-layer) unidirectional hybrid FRP composites was conducted aiming at evaluating the corresponding hybrid effect and pseudo-ductility of this innovative solution. Different combinations of the following dry unidirectional fabric materials, also varying the number of layers, were adopted in tests: high-modulus carbon, standard carbon, E-glass, and basalt. The composites were produced layer-by-layer by hand lay-up method, using an epoxy-based resin as matrix.

The results have shown a strain increase at failure of both standard carbon and high-modulus carbon fibres with the volume decrease of these materials in hybrid combinations. It was also concluded that combining high-modulus carbon with E-glass, high-modulus carbon with basalt, or high-modulus carbon with standard carbon can lead to very good pseudo-ductile tensile behaviour. Finally, it should be highlighted that an existing analytical model in the literature was satisfactorily adopted to predict the tensile response of these hybrid composites.

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1. Introduction

Unidirectional (UD) Fibre Reinforced Polymers (FRP) composites are brittle materials, exhibiting a linear elastic behaviour up to failure. Therefore, structures made of these materials, although apparently without any problem, may fail abruptly [1]. This characteristic does not allow to take full advantage of FRP properties, namely the high tensile strength due to conservative design limits [2]. For this reason, to obtain composites with progressive failure behaviour ensuring safe, strain hardening, and meaningful ultimate tension strain are seen as priority goal by different industries [2], including civil engineering.

Hybridisation, i.e., the incorporation of two or more types of fibres within the same polymeric matrix [3], is an established approach to deal with the problem above mentioned, since this strategy promotes synergies between the adopted reinforcing materials, lessening their intrinsic disadvantages [4]. For instance, when submitted to uniaxial tension, Low Strain (LS) fibres fail earlier than High Strain (HS) fibres and this fracture behaviour can be used as a warning sign before the ultimate failure of the hybrid FRP composite [1,4]. Furthermore, it has been observed that hybridisation increases the apparent strain at LS fibres failure [5]. This phenomenon has been described as "hybrid effect" [6]. In the case of carbon/glass hybrid composites, the values for this effect are typically in the range of 10–50% [4]. Nowadays, however, there is some controversy about the hybrid effect definition because, in

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traditional uniaxial tensile testing configuration, stress concentration at the grips may cause premature composite failure, leading to an underestimation of the strain at the failure of the baseline LS material [7]. For this reason, these results should be critically interpreted.

Nevertheless, the most relevant advantage of hybrid composites is their gradual, and thus non-catastrophic, failure mode that has been registered in UD layer-by-layer configurations [2,8], when both the configuration and materials combination are appropriately selected. This is due to the load transfer between LS and HS layers, fragmentation (a damage process where multiple fractures take place) of the formers, followed by the stable delamination of the LS layers from the HS layers, close to the LS layer fractures, ending with the failure of the latter [1]. This behaviour is known as pseudo-ductility [1,4]. It should be stressed that the term 'pseudo-ductility' is used because it is possible to achieve a flat-topped stress-strain curve of monotonic tensile tests up to the failure of some unidirectional hybrid FRP composites.

The topic of hybrid composites has become a highly active research area in the 1970's and 1980's [3,5,9–16]. Over the time, several literature reviews on this subject were published [3,4,16]. The study of hybrid composites was essentially motivated in the scope of the aerospace and automotive industries [3,4,17]. It has been demonstrated that hybrid composites have greater advantages over traditional composites. The vast majority of the works published generally reported mechanical tension test results of hybrid composites indicating: (i) a linear increase of elastic modulus in respect to HS material (generally glass fibres) with the addition of LS material (in most part of cases, carbon fibres) [3], (ii) a load drop at the LS material fracture (in non-catastrophic cases), and (iii) a significant hybrid effect [2].

Swolfs et al. [18] explained that, in non-hybrid UD composites, when a fibre fails, it locally loses its load transfer capability. The surrounding matrix is loaded in shear and transfers the load carried out by the broken fibre to the surrounding ones, increasing their probability of break. When enough neighbouring fibres are broken, a critical cluster size is reached and catastrophic failure occurs. The restriction caused by HS fibres adjacent to a LS fibre broken, has been reported as the main factor contributing for the hybrid effect, since HS fibres inhibit the formation of critical clusters [4,7]. However, other reasons for the hybrid effect have been pointed out, namely: (i) thermal residual stresses, i.e., residual shrinkage stresses due to differences in the thermal contraction of the two fibre types, and (ii) the modification, relatively to non-hybrid composites, of the temporary dynamic stress concentrations, due to stress wave travelling along each fibre when it fails [4]. The latter has received no attention at all in the past two decades and remains poorly investigated today [4].

Recently, Swolfs and his co-authors have carried out extensive work aiming at understanding the hybrid effect [18–25]. In [21], the effect of fibres dispersion on the initial strain at the failure and cluster development in UD carbon/glass hybrid composites was numerically studied. It was concluded that the strain at the failure of carbon fibre composites can be dramatically increased with a large fraction of well-dispersed glass fibres. However, random dispersion configurations are not the best option to achieve maximum hybrid effect. Layer-by-layer hybrids are more efficient in delaying the failure development. Furthermore, it was indicated that the hybrid effect gradually increases with the increase in volume fraction of HS fibres. In [24] and [25], it was demonstrated that the higher the scatter of LS fibres strength, the higher the hybrid effect.

Simultaneously, an exhaustive work to achieve pseudo-ductile tensile response with UD hybrid composites has been carried out at both the University of Bristol and the Budapest University of Technology and Economics [1,7,8,26–29]. It has been demonstrated that for achieving pseudo-ductility in hybrid composites two damage mechanisms should to take place simultaneously, namely: (i) the fragmentation of the LS material and (ii) the stable delamination of the LS material from the HS material layers close to the LS fractures. In carbon/glass hybrid composites made with prepreg plies, it was shown that, if the carbon layer is thin enough, catastrophic delamination propagation around the first carbon fracture is suppressed and, therefore, further fractures in the carbon layer may occur, introducing pseudo-ductility into the stress-strain curve [1,27]. According to Jalalvand et al. [8], the fragmentation in the low strain material becomes saturated and stops when there is no longer any part of the low strain material with constant stress. The different failure mechanisms in carbon/glass hybrid composites were found to be dependent on the ratio of carbon to glass thickness and also the absolute thickness of the carbon [26]. As explained in detail by Jalalvand et al. [27], the control of the two mentioned factors can lead to four possible tensile damage modes of UD hybrid composites, as described in Section 2.5.3.

An important milestone achieved by Jalalvand et al. [8] was the development of an analytical model to predict all possible damage modes of thin-layer UD hybrids. Predictions of this model proved to be in good agreement with nonlinear tensile response of different UD layer-by-layer hybrid configurations. Damage mode maps were generated to study the effects of absolute and relative thicknesses of the carbon layers; these maps have proven to be a very efficient design tool for hybrid composites [27,28].

In civil engineering context there are already several examples of applying the hybrid composite concept, mainly in the research and development of three main systems: (i) reinforcing bars for reinforced concrete (RC) structures [30–37]; (ii) externally bonded strengthening for RC structures [17,38–52], and (iii) pultruded profiles for new structures [53–55]. In a general way, experimental results have shown that a significant ductile response, similar or even better, than that of a steel-reinforced concrete member can be achieved with hybrid composites [31,36]. In addition to gradual failure mode, hybrid composites have the benefit of eliminating the corrosion problems of steel materials [35,37].

Cui and Tao [35] and Cheung and Tsang [36] conducted works on the development of hybrid composite reinforcing bars. In the design of these solutions four different reinforcing materials, namely carbon, aramid, glass, and steel, were simultaneously used. The resulting hybrid bars demonstrated pseudo-ductile behaviour, with a tensile strength of 644 MPa, a modulus of 140 GPa and an ultimate strain of circa 3%. A series of concrete beams reinforced with the proposed solution were tested and it was demonstrated that the beams had the ability to undergo large inelastic deformations. Pseudo-ductility was found to be similar to that of conventional steel-reinforced beams.

Grace et al. [38] develop a UD fabric composed of two types of carbon fibres and one type of glass fibres. In this case, the pseudo-ductility of the composite was achieved through the combination of the different ultimate strain of each of the adopted types of fibres. In [39], the same authors further developed the initial concept by introducing fibres in the diagonal direction, thus enabling the use of the hybrid fabric for simultaneous flexural and shear strengthening of concrete beams. The last work resulted in one US patent [56].

Wu et al. [17] developed hybrid composites made of high-strength and high-modulus carbon sheets. The resulting solution was applied in the upgrading of pre-cracked RC beams. It was concluded that the hybrid composites allowed achieving the desired flexural stiffness, 'yielding' strength, and pseudo-ductility.

Several of these attempts (in the field of civil engineering) have been developed/applied without a complete understanding about the behaviour of hybrid composites at material level. In most works, the concept of pseudo-ductility was defined as the

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