DUCTILITY OF PLATELET COMPOSITES INSPIRED BY NACRE DESIGN

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ABSTRACT

Platelet composite design inspired by nacre microstructure has attracted wide interest as a means to improve toughness of materials. A systematic comparative numerical and experimental study is described in this paper to identify the relationship between ply-overlap length and strain ductility. Larger ply overlap length is found to retain 45% and 93%, respectively, of the tensile strength and failure strain of the continuous fibre composite counterpart. A relatively small pseudo-ductility strain of 1.07% was observed. Analytical modelling studies towards these were conducted on platelet or discontinuous fibre reinforced epoxy composites with varying aspect ratio and tiling configurations. Results suggest that the staggering of the neighbouring ply terminations resulted in an increased tensile strength whereas aligning the ply-termination for each second consecutive ply leads to the increase in strain-to-failure. The incorporation of z-pin reinforcements (stainless steel, copper and carbon fibre/BMI) through-the-thickness of the platelet composite was investigated. The shear-induced work hardening of the metal pins further enhances the pseudo-ductile strain and strength simultaneously; supplementing the shear lag process between the ply overlaps.

1 INTRODUCTION

Discontinuous fibre reinforced polymer composite such as chopped strand mats [1], unidirectionally arrayed chopped strands (UACS) [2] or platelet composite structures [3] offer better processability and drapability when manufacturing advanced lightweight structures than continuous fibre composites. However, a major drawback of discontinuous fibre reinforced epoxy composites are the low mechanical properties (such as static strength) compared to their continuous counterparts [1-3]. Similar to continuous fibre composites, platelet composites have been found to exhibit quasi-linear-elastic stress-strain behaviour with an inherent lack of ductility under tensile loading conditions [1-3]. Hence, there is a desire for developing new techniques to engender graceful failure modes to platelet composites.

High strain ductility is a major requirement in civil applications of fibre reinforced polymer composites. Recently significant research has focused on ways to impart ductility or pseudo-ductility to laminated carbon fibre reinforced epoxy composites. Current methods include the incorporation of cross-ply or angled-ply layup configurations whereby the shear-induced rotation of the angled fibres induces a large strain prior to rupture [4]. Another popular technique is hybridization or intermingling of a ductile reinforcement phase such as a metal, glass fibre or polymer reinforcements [5 & 6]; resulting in a non-linear stress-strain response. On the other hand, natural composite structures such as nacre contain an alternating, staggered and overlapping network of brittle constituents (i.e. platelets) [7]. Nacre, when subjected to a tensile load, tend to exhibit a progressive failure mode whilst simultaneously exhibiting a greater strength with increasing strain [7]. These are often dominated by the extrinsic and intrinsic toughening process that occur between the interfaces of the platelet overlaps [7]. Czel et al. [8] demonstrated that a pseudo-ductile strain response could be achieved in unidirectional discontinuous carbon fibre/epoxy prepreg composite containing a half-tile offset joint configuration; where the ply gaps were aligned for every second ply, consecutively. However, it is not clear how the staggering of the ply terminations and changes in the mode II interlaminar fracture toughness affect the ductility of platelet composites.

The present paper describes a study on the effect of ply overlap length and z-pins on the quasi-static tensile stress-strain response of platelet composites. Firstly a systematic experimental and finite element analysis was conducted. Secondly a numerical investigation on the effect of tilting configuration and the mode II interlaminar fracture of the representative unidirectional platelet composite containing sixteen plies. Finally an experimental investigation is conducted by inserting micron diameter scale metal and composite rods, or z-pins to through-the-thickness of platelet composite, mimicking the mineral bridging and in-elastic shearing between the platelets of nacreous structures.

2 METHODOLOGY

2.1 Experimental details

Unidirectional T700 carbon fibre-epoxy prepreg tape (VTM 264 supplied by Lavender composites) was selected to manufacture continue fibre composite and platelet composite. The specimen design and test fixture are shown in **Fig. 1a**. The specimens, similar to a finger joint, consisted of four–ply $[0]_4$ laminate with ply overlap lengths ranging in between 10 mm to 80 mm. The width, thickness, and length of the specimens are 20 mm, 0.9 mm, and 220 mm. Glass fibre composite tabs (50 mm in length) were attached on the ends. In assessing the effects of z-pins on the mechanical properties of the platelet composite carbon fibre/BMI, stainless steel (316L) and copper (99.9% purity) z-pins were used. Pin dimater is 0.5mm and the areal density of z-pins is 2.0%. The z-pinned composite contained a ply stacking sequence of $[0/90]_{7s}$ that were cut into 25 mm wide, 610 mm thick and 145 mm long samples containing a 50 mm long glass fibre tabs on the ends. The carbon fibre/ BMI z-pins (Albany Engineered Composite Pty Ltd.) were inserted through-the-thickness of the ply overlapped region of the joint using the ultrasonically-assisted pinning (UAZ) process [9]. As described in [9], the copper and stainless steel z-pins were inserted using a template assisted approach. For the first and third study, quasi-static tensile tests were conducted using a 100 kN MTS and a 50 kN Instron universal testing machine for the first and third study, respectively, at a loading rate of 1.0 mm/min. The gauge region of the samples was coated white paint along with a black speckle pattern for *in-situ* strain measurement via digital image correlation (DIC) when testing.

2.2 Computational modelling

The continuous fibre and platelet composite laminates were modelled using ABAQUS CAE 6.14 to predict the in-plane tensile stress-strain versus behaviour of four-ply half-tile offset joints and sixteen-ply, $[0]_{16}$, platelet composite containing a unidirectional layup. As indicated by the schematics depicted on **Fig. 1a** and **Fig. 2**, the individual plies were modelled using continuum shell elements (SC8R), where the interfaces between the carbon-carbon ply overlaps were modelled using cohesive elements (COH3D8). Fibre and matrix damage were modelled using the continuum damage mechanical (CDM) approach with the Hashin criterion [10]. Cohesive zone modelling (CZM) was used to model the delamination between the ply-overlaps. The parameters used for the modelling studies are listed in Table 1. Through mesh refinement study, the optimal element length and width was 0.2 mm.

For the platelet composites, two configurations were considered: (a) ordered discontinuous and (b) staggered discontinuous tiling configuration, as shown in **Fig. 2a** and **Fig. 2b,** respectively. Ordered discontinuous tiling configuration contains a ply overlap length that is half of the platelet length. The staggered discontinuous tiling configuration containing a ply overlap length that is 40% of the platelet length. Numerical analysis was carried out using ABAQUS/Implicit solver using a displacement control.

	T700/VTM264	
Parameters (Units)	**Value**	**Source**
Longitudinal tensile strength, $X_{11,t}$ (MPa)	2500	[10]
Input Longitudinal compressive strength, $X_{11,c}$ (MPa)	1235	[10]
Transverse tensile strength, $Y_{22,t}$ (MPa)	40	[10]
Transverse compressive strength, $Y_{22,t}$ (MPa)	182	[10]
Longitudinal shear strength, $S_{12,t}$ (MPa)	85.7	[10]
Longitudinal tensile fracture toughness, G_{ft} (kJ/m^2)	70	[10]
Longitudinal compressive fracture toughness, G_{fc} (kJ/m^2)	78	[10]
Transverse tensile fracture toughness, G_{mt} (kJ/m^2)	0.3	[10]
Transverse compressive fracture toughness, G_{mc} (kJ/m^2)	0.76	[10]
Interlaminar peel strength, S_{33} (MPa)	40	[10]
Interlaminar shear strength, S_{13} (MPa)	77	[10]
Interlaminar shear strength, S_{33} (MPa)	77	[10]
Mode I fracture toughness, G_{Ic} (kJ/m^2)	0.3	[10]
Mode II fracture toughness, G_{IIc} (kJ/m^2)	1.1	[11]
Mode III fracture toughness, G_{IIIc} (kJ/m^2)	1.1	Assume $G_{IIc} = G_{IIIc}$
Cohesive stiffness, K_1, K_{II} and K_{III} (N/mm^3)	1 x 10^6	[10]

Table 1: Parameters used for the numerical modelling study.

3 RESULTS AND DISCUSSION

3.1 Experimental vs. numerical modelling results of four-ply half-tile offset joints

Fig. 1b, **1c** and **1d** present a comparison of the experimental and numerical modelling results of the four ply half-tile offset joint depicting the in-plane stress-strain behaviour, ultimate tensile strength and peak tensile strain, respectively, as a function of the ply overlap length. Numerical modelling results are in good agreement with the experimental results within ~95%, indicating that the combined CDM and CZM approach captures the damage mechanisms of ply rupture and delamination along the interfaces between the ply overlaps. As shown in **Fig. 1b**, the stress-strain curve rises linearly to a peak in-plane tensile stress of ~1100 MPa. For the joint containing the 30 mm overlap length, this was followed by a non-linear pseudo-ductile strain of 0.15%, where the joint failed along the co-cured interface. As depicted in **Fig. 1c** and **1d**, a strength retention of 1100 MPa and a pseudo-ductile strain of 1.07% were achieved when the ply overlap length exceeded 80 mm.

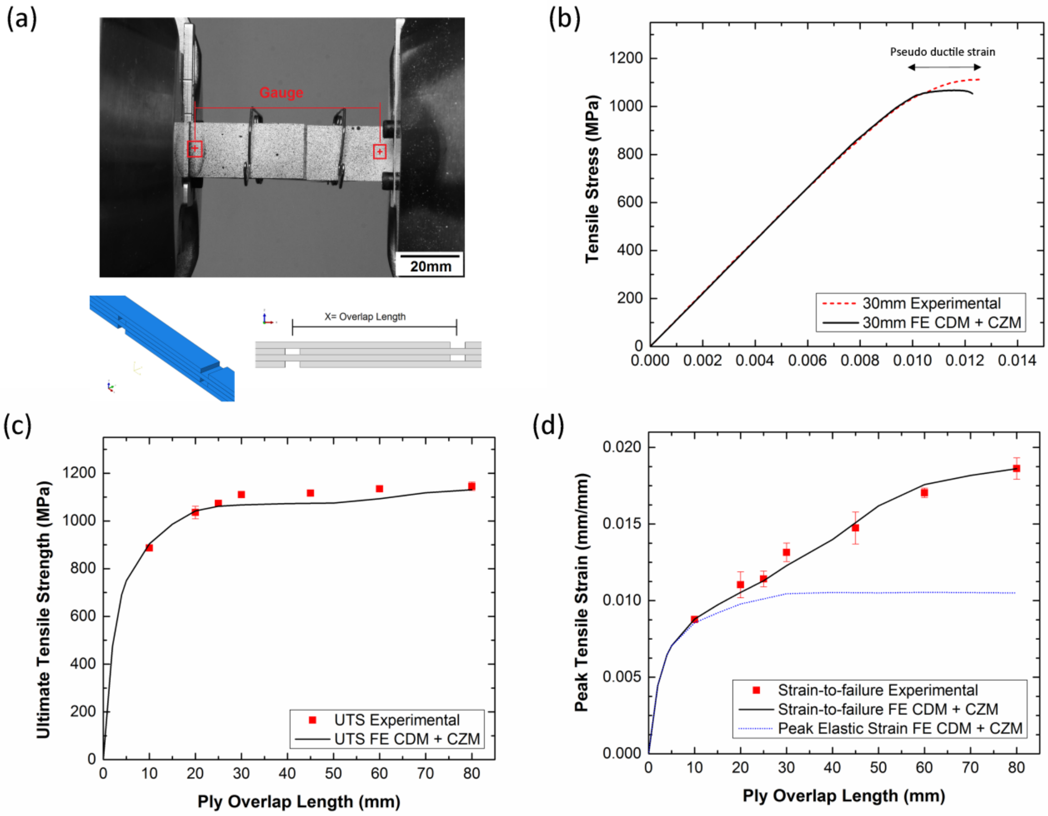

Figure 1: (a) image of the failure mode of the unidirectional four-ply half-tile offset joint. Comparison of experimental and numerical modelling results of 4 ply half-tile offset unidirectional joint depicting (b) stress versus strain curve of joint containing a 30 mm ply overlap length, (c) ultimate tensile strength and (d) peak tensile strain as a function of the ply overlap length.

During loading, the pseudo-ductile strain observed was a result of the shear-lag between the ply-overlap s as crack growth occurred along the bond-line. Previously it has been shown, that a longer ply-overlap length with similar joint configuration reported within this study does promote a pseudo-ductile strain response due to the transitioning of the bond-line crack from an unstable to stable mode. The progressive crack growth along the ply interface slightly increases the in-plane shear load transfer between the adherends. The in-plane tensile strength of the joint for short ply overlap lengths is influenced by the interlaminar shear strength [5 & 10], whereas at large overlap length the in-plane tensile strength is dominated by the interlaminar mode II fracture toughness [5 & 10].

3.2 Effect of tiling configuration on quasi-static tensile properties of unidirectional platelet composites

Fig.3a, 3b and 3c present the in-plane stress-strain behaviour, ultimate tensile strength and peak tensile strain of the unidirectional ordered and staggered discontinuous platelet composite as a function of the ply overlap length. As shown in **Fig. 3a** where the ply overlap length is approximately 80mm, the sixteen ply configuration with a staggered discontinuous platelet architecture exhibited a much greater retention of the ultimate tensile strength than the model of the ordered discontinuous platelet architecture. The increase in the ultimate tensile strength is further illustrated in **Fig. 2b,** with the increase in ply overlap length. Baucom et al. [3] and Ahamed et al. [10] demonstrated that offsetting the ply gap along the thickness of a fibre reinforced polymer composite laminate does lead a greater retention in the ultimate tensile strength and often considered when designing bonded composite structures. During tensile loading, the stress concentration level near ply gaps in the staggered discontinuous platelet configuration is far less those pertaining to the ordered discontinuous composite, due to the non-alignment of the ply terminations. Nacreous structures such as abalone shell do indeed exhibit this type of platelet architecture; leading to a greater exhibition of strength and, most importantly, ductility [7 & 12].

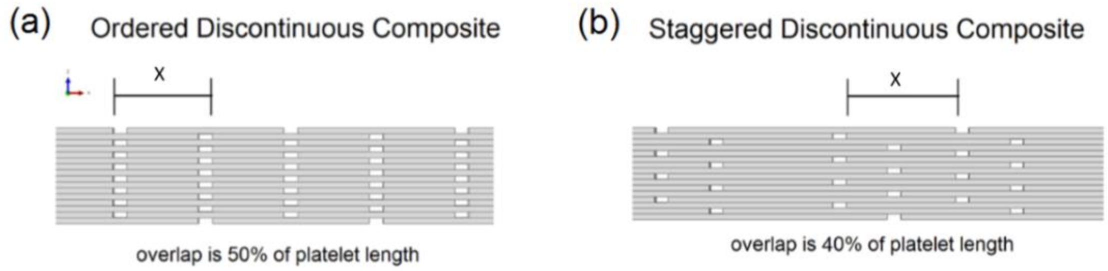

Figure 2: Representative volume of unidirectional platelet composite architecture containing (a) ordered discontinuous and (b) staggered discontinuous ply terminations. Note: the length of the representative volume of the platelet composites is the sum of three platelet length plus a 20mm excess gauge region on each end.

It is interesting to note, however, that the strain-to-failure of the ordered discontinuous platelet composite is greater than that of the staggered discontinuous platelet composite with increasing length, as shown in **Fig. 3c**. The stress-strain response of the ordered platelet composite is more linear than that of the staggered counterpart.

Numerical modelling of the influence of the interlaminar mode II fracture toughness (G_{IIc}) on the strength and ductility of staggered discontinuous platelet composite showed that residual ultimate tensile strength increased with an increasing G_{IIc} till 2.0kJ/m^2 as shown in **Fig. 3d**. The dominant failure mode of the discontinuous composites described within the *Section 3.1 and* 3.2 of this paper is the progressive interlaminar delamination between the plies. Increasing the G_{IIc} results in higher load to propagate the delamination. Nacre uses multiple toughening mechanisms at multiple length scales to enhance progressive failure and to increase the tensile strength. Established techniques for improving the G_{IIc} range from 3D fibre reinforce binder [13] to discrete through-the-thickness reinforcement such as z-pins [9, 11 & 13].

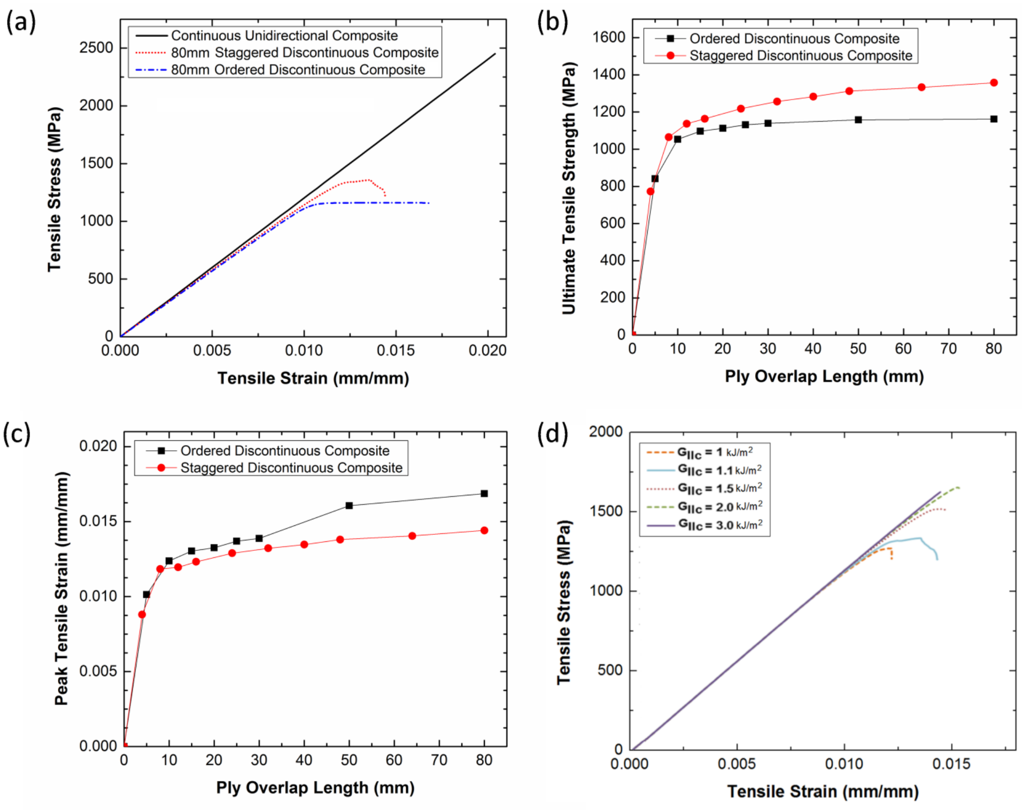

Figure 3: Comparison of numerical modelling results of 16 ply platelet composite depicting (a) stress versus strain curve of joint containing an 80mm ply overlap length, (b) ultimate tensile strength and (c) peak tensile strain as a function of the ply overlap length. Effect of mode II interlaminar fracture toughness on the stress versus strain behaviour of the discontinuous composite with a ply overlap length of 80mm.

3.3 Effect of z-pin type on quasi-static tensile properties of butted double lap joints

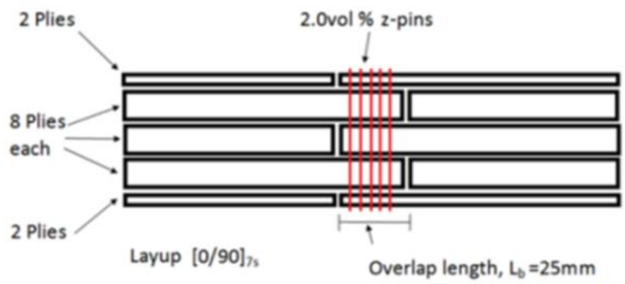

Figure 4: Double lap butted joint configuration containing z-pin reinforcements

Fig.5a presents the influence of z-pin reinforcement type towards the tensile stress-strain behaviour of the butted double lap joints. For the unpinned joint, the stress-strain curve rises linearly to a peak in-plane tensile stress of 287 MPa with a minimal ductility before final fracture. The double lap joint failed along the co-cured bond-line interface; as shown in **Fig.5b**. A 5% and 18% improvement in the ultimate tensile strength and strain-to-failure, respectively was observed for composite joints containing the copper and stainless steel pins; exhibiting various failure modes. As observed in **Fig. 5c**, the copper pins failed under shear. The stainless steel pins underwent pull-out demonstrated in **Fig. 5b and 5d**. Evidence of shear-induced necking was observed along the cross-sections of the two metal pin types.

The pseudo-ductile failure strain for the copper and steel z-pin reinforced joints was measured to be 0.112% (±0.012%) and 0.104% (±0.011%), respectively. The double lap joint containing the carbon fibre/BMI z-pins did exhibit a higher strength by 12% in comparison to the unpinned joint. However, no statistically significant improvement in the failure strain was observed. The carbon fibre/BMI z-pins failed under shear, consistent with that reported in [11 &13]. Previous studies on the Mode II traction load have demonstrated that a grid of carbon z-pins exhibit higher shear strength yet lower strain to failure compared to stainless steel and copper z-pin under in-plane shear loading [11]. In comparison to the metal pins the carbon z-pins are effective in sustaining load after bond-line crack, further inhibiting delamination crack growth resulting in a higher strength. The metals pins are capable of carrying a greater load over a high shear strain [11, 13-15]. The metal z-pins bridged the crack faces behind the crack front and underwent plastic deformation over a large strain before shear induced rupture [11]. The toughening mechanisms induced by the z-pins are analogous to the mineralized bridging that occurs in nacreous natural structures [7, 12, 16 &17]. These mechanisms, along with additional intrinsic and extrinsic toughening mechanism that operate at multiple length scale promote an enhanced strength and strain to failure simultaneously [7 & 17].

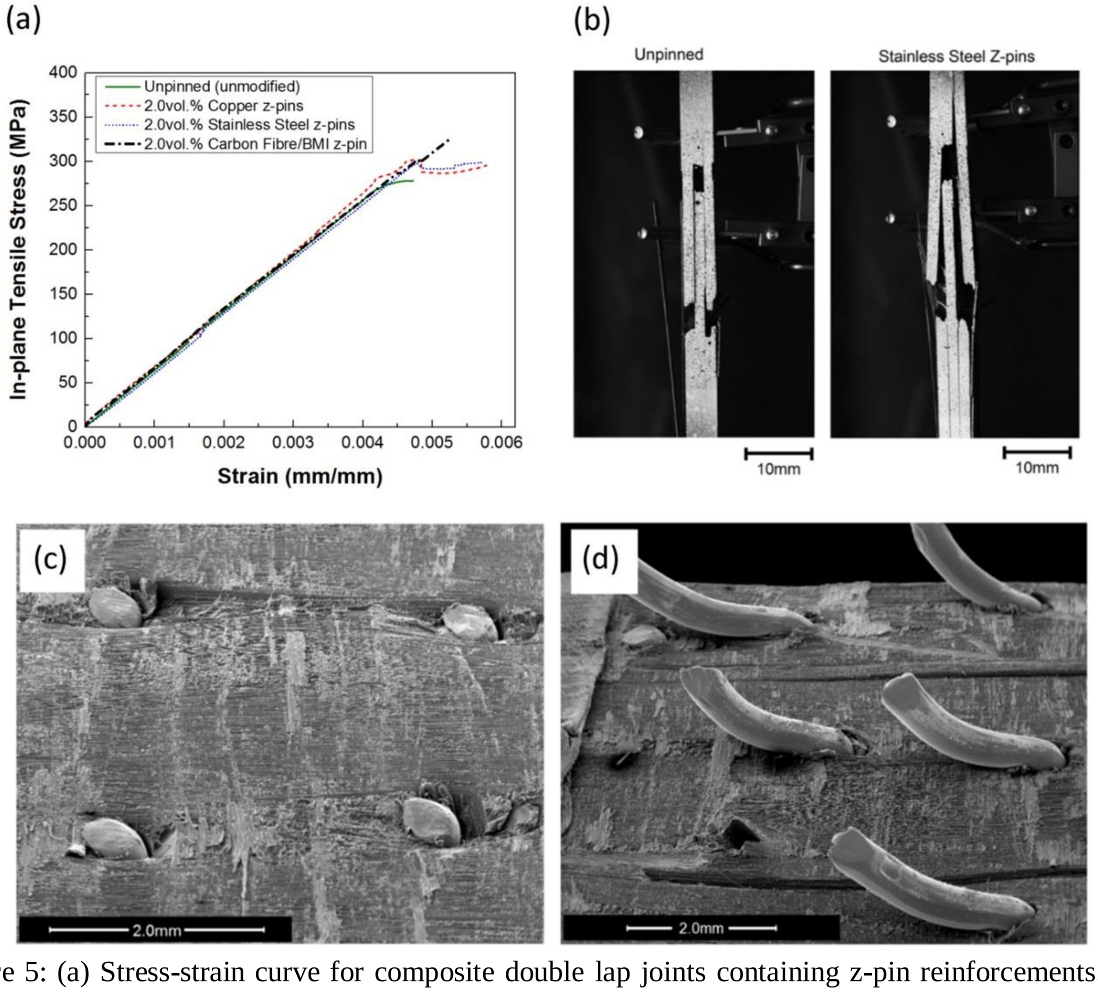

Figure 5: (a) Stress-strain curve for composite double lap joints containing z-pin reinforcements. (b) Representative optical microscope images of the failure modes observed for unpinned and stainless steel z-pinned co-cured double lap joints. SEM fractography of double lap joints containing (c) copper z-pins and (d) stainless steel z-pins.

4 SUMMARY

Two different designs of platelet composites based on nacre-inspired design motifs, with the joints being fully aligned or staggered, have been investigated to characterise the effect of overlap length on strain ductility. The results show that both strength and ductility increase asymptotically with ply-overlap length. Computational models have been developed to capture the damage and delamination mechanisms. Staggering the ply gaps throughout the thickness of the discontinuous composites further enhances the ultimate tensile strength retention. Mimicking the extrinsic toughening mechanisms observed in nacre microstructures, through-the-thickness reinforcements, or z-pins, have been found to provide additional ductility enhancement. These new results suggest that through-thickness reinforcement using ductile z-pins offers a promising technique to engender platelet composites with a pusedo-ductility characteristic.

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