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Residual properties of square FRP composite tubes subjected to repeated axial impact

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ABSTRACT

In this paper, the residual properties of square composite tubes under axial impact were experimentally investigated. The effects of damage factors such as the mass of the impactor, incident energy, and number of impacts on their post-impact behaviour were emphasised. Low-velocity impact tests were performed by repeatedly impacting a 100 mm square FRP pultruded tube with energy levels up to 742 J using a drop-weight apparatus. Coupons were then taken from the impacted tubes and tested statically to determine the residual compressive, tensile, and flexural properties. Results show that the levels of impact energy, number of impacts, and the mass of the impactor significantly influenced the residual strength degradation of the impacted tubes. Their effects, however, are almost negligible in the residual modulus property. It was found that the maximum reductions of residual compressive, tensile, and flexural strengths of the impacted tubes are 6.8%, 0.3%, and 10%; respectively. It was also found that effect of impact damage on the reduction of residual compressive strength of the tube is concentrated only in region closer to the impact point.

1. Introduction

Fibre reinforced polymer (FRP) materials exhibit distinct properties such as light weight, high specific strength, high durability, corrosion resistance, chemical and environmental resistance, and low maintenance cost [1]. These characteristics made FRP composites tubes suitable alternative for piling application in harsh marine environment. Fig. 1 shows the FRP square pultruded tubes recently applied in Australia as hollow composite piles installed into the ground using impact driving [2]. Driving these piles, however, requires more careful consideration due to their relatively low stiffness and thin walls. The possibility of damaging the fibre composite materials during the process of impact driving is imminent (Fig. 1b). As a result, the structural performance of the FRP composite tubes after installation is in question. Therefore, there is a need to have a clear understanding on the effect of impact damage to the post-impact performance of the fibre composite materials to ensure their structural integrity.

Impact damage has adverse effect on the load bearing capability of the materials, referred to as "residual strength" or "strength-after-impact" [3]. For fibre composite materials, the study on the effect of impact events to their residual properties has been very extensive. Most of these studies, however, are limited on composite laminates for aerospace and automobile applications. Wyrick and Adams [4] investigated the compressive and tensile degradation behaviours of the 16-ply quasi-isotropic composite plates impacted by energy levels up to 30 J and 100 impact repetitions. The results showed that impact energy level and number of impacts were found to be major factors influencing the loss of strength. The degradation, however, was concentrated only on the region near the impact point. Sanchez-Saez et al. [5] characterised the compressive residual strengths of thin carbon/epoxy laminates made of different lay-ups (quasi-isotropic, cross-ply, and woven) to determine their impact damage tolerance. They found that woven laminate offered the highest residual strength under all impact energies. The highest value, according to them, was attributed to the architecture of the reinforcement which controls the spread of damage. On the other hand, the quasi-isotropic laminate provided the least loss of normalised strength at increasing impact energy. Davies et al. [6] investigated the residual compressive-after-impact (CAI) strength of a woven fabric glass/polyester laminate impacted by an increasing energy level. The emphasis of their study is on the effect of laminate geometries on the post-impact performance of composite laminate. The outcome showed that the impact response and energy absorption behaviours are dependent on laminate geometries. They reported that the residual compressive strength is reduced very rapidly with the increase of impact damage due to extensive delamination. Short et al. [7] examined the residual compressive strength of a curved glass FRP laminate impacted by an energy level up to 9 J. Their purpose

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(a) Installation using impact driving. (b) Condition of the tube at the end of driving.

Fig. 1. Pultruded composite tubes used in shoring up boardwalks, Tweed Heads, New South Wales. (Courtesy from Wagners CFT, Queensland, Australia).

is to characterise the variation of residual strengths between flat and curved laminates. Their result indicates that the post-impact compressive strength of a curved laminate was found to be similar to that of a flat laminate. This result, however, is in contrary to what Ambur and Starnes [8] had found that the residual compressive strength reduces with increasing laminate curvature.

Wang et al. [9] experimentally and numerically investigated the post-impact tensile strength of a 4-ply carbon fibre composite laminate subjected by energy levels between 9.4 and 31.2 J. Results revealed that the degradation of residual strengths can be divided into three stages: stage one is lower impact degradation stage, stage two is plateau stage, and stage three is higher impact energy degradation stage. They reported that the residual tensile strength with angle-ply stacking sequence can keep a higher level compared to cross-ply stacking sequence. A test was conducted by Found and Howard [10] on a composite laminate to characterise the effect of impact energy on their residual tensile strength. This was achieved by subjecting a 0.8 mm Carbon FRP laminate under single and multiple impacts with an energy level between 0.54 and 1.71 J. The results of the test indicated threshold energy for no effect on residual strength of a value close to 0.5 J. However, the laminate lost its strength by approximately 60% when singly impacted by 1.71 J.

Zhang and Richardson [3] evaluated the effect of impact-induced damage on the residual flexural properties of a pultruded glass FRP composite laminate. They revealed that impact-induced damage reduced significantly the residual flexural properties of the laminate. They also stated that the residual flexural strength is more susceptible to damage than its corresponding modulus. The work conducted by Santiuste et al. [11] focused on an experimental study of flexural-after-impact behaviour of a 3 mm thick glass/polyester laminate. This study evaluated the influence of impact energy, laminate width, and impactor-nose geometry on its flexural strength. It was found that the residual strength of the specimen is lower when the damage reached the edges of the beam. Similarly, the residual strength was lower in specimens impacted with Charpy-nose impactor than in the specimens impacted with hemispherical-nose impactor. This study also revealed that narrower specimens presented a lower residual flexural strength than did the wider ones. Belingardi et al. [12] conducted a flexural test on a 100 mm square composite laminates repeatedly impacted by various energy levels. Their purpose is to correlate the damage index (DI) to the residual flexural properties of the composite laminate. The result demonstrated that a single power function can fit well the relationship between DI and flexural properties. The fitted curve suggested a significant drop of residual properties when perforation is approached. The flexural strength and inter-laminar shear strengths of stitched glass-reinforced laminate under conditions of increasing impact energy and number of impacts were studied by Mouritz et al. [13]. The results show that under single impact loading, the composites suffer a slight reduction in flexural strength but a large reduction in inter-laminar shear strength. The severe reduction in shear strength was emphasised by Mouritz et al. as a result of damage due to shear failure such as shear-induced matrix cracking, debonding, and delamination. Unlike single impact, the laminates experienced large flexural strength degradation when subjected by repeated impacts due to fracture of glass fibres.

Few studies characterising the effects of impact events on the post-impact performance of composite tubes have been reported. All of these studies, however, focused on the residual properties of the tube under transverse impact. Abdallah et al. [14] studied the effect of impact damage development on the residual compressive strength of a composite tube. They stated that the cause of failure of the sample which happens instantly is due to the stress concentration around the damage area of the tube. This damage, according to them, decreased the residual compressive strength by 5–20%. Chotard et al. [15] presented an experimental investigation on the residual behaviour of patch-repaired composite pultruded shapes with initial impact damage. The results indicate that the residual performances of both undamaged and repaired specimens are influenced by the profile geometry. Gning et al. [16] developed a finite element model to predict the effect of impact damage on the post-impact performance of a composite tube. They revealed that the impact damage reduced significantly the residual strength of the tube. They also reported that a 12 J level of impact reduces the strength by 40%. The residual torsional strength-after-impact of Carbon FRP tube was studied by Minak et al. [17]. A total of 24 specimens were subjected to a 7 J transverse impact under various torsional pre-loads. Results show that impact induced localised delamination, with a subsequent reduction of the critical buckling load of the plies. This damage, according to Minak et al. reduced the residual tensile strength by a factor of two with respect to the strength of the undamaged tubes. Deniz et al. [18] investigated experimentally the effects of the tube diameter and the impact energy level in the CAI behaviour of a filament-wound glass/epoxy composite tube. The 1.75 mm thick composite tube was subjected to various impact energy levels between 1 and 25 J. Results indicated that both specimen diameter and impact energy affect the CAI strength of the composite tube.

Literature review shows that parameters such as impact load (or mass), incident energy, and impact repetitions affect the post-impact performance of composite laminates or tubes under transverse impact. It is also equally important to know on how these parameters affect the residual properties of composite tubes when they are axially impacted. Currently, information on the post-impact behaviour of FRP composite tubes under repeated axial impact is very limited. There is a need, therefore, to conduct a study that will systematically characterise the effects of these parameters on their residual properties.

This paper presents an experimental investigation on the post-impact behaviour of square FRP pultruded tubes under repeated axial impact. The effects of parameters such as impactor mass, incident energy and number of impacts on the residual compressive,