Composite Structures 97 (2013) 211–221

Contents lists available at SciVerse ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Experimental investigation on the behaviour of square FRP composite tubes under repeated axial impact

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ARTICLE INFO

Article history:
Available online 8 November 2012

Keywords:
Impact behaviour
Damage tolerance
Impact fatigue
Pultruded tubes

ABSTRACT

Series of impact tests were conducted to investigate the behaviour of fibre reinforced polymer (FRP) composite tubes under axial impact. The effects of damage parameters such as the mass of the impactor, incident energy and number of impacts on their behaviour were studied. The tests were performed by axially impacting 100 mm square FRP pultruded tubes to 130 repeated impacts or up to collapse using a drop-weight type impact apparatus. Impact masses and drop heights were varied to produce incident energies ranging from 158 to 635 J. The results showed that the peak load degradation of collapsed tubes is more rapid when it is impacted by higher incident energy. Heavier impactors caused more damage to the tubes at lower incident energies as reflected by their lower number of impacts to collapse, however, its effect gradually decreases at relatively higher energies. The incident energy is a major damage factor in the collapse of the tubes for lower number of impacts. However, the number of impacts becomes the key factor when the value of the incident energy decreases.

1. Introduction

The emergence of fibre reinforced polymer (FRP) composite tubes as a structural component made these materials potential for composite pile. The high corrosion-resistant characteristic of FRP materials made them as suitable alternatives 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. 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 always a concern. One of the main factors that affect the driving performance of these piles and needs special attention is the impact strength of the fibre composite materials [1]. Therefore, there is a need to understand the impact behaviour of these materials in order for them to be safely and effectively driven into the ground.

Studies on FRP composite tubes under axial impacts focused mostly on single impact that usually evaluate their energy absorption capacity and collapse behaviour for automobile application [2–7]. Common findings obtained from these studies showed that the load response of the impacted composite tubes initially behaves elastically and rises at a steady rate until the crushing point. Their post-crushing performance is described by a characteristic oscillation about the mean post-crushing load accompanied by severe fluctuation amplitudes. This highly serrated response is due to the dynamic nature of loading and the inertial response of the hammer [7] or attributed by the different micro-fracturing mechanism of the tubes [8].

In general, the responses of square and circular composite tubes collapsed under single impact developed almost similar load and deformation behaviour. However, few distinctions between them are worth noting. The mean crushing load of the square tubes is lower than their circular counterpart as a consequence of stress concentration along their corners [8]. For circular tubes, the continuous formation of a central crack length along their wall is developed during the impact regime; while for square tubes, this length diminishes from the centre of the sides towards their corners where the typical crush zone disappears [7].

Research on impact fatigue behaviour of FRP materials has been extensive; however, they are limited on composite laminates or tubes which are transversely impacted. Belingardi et al. [9] investigated the response of glass reinforced laminates under repeated impacts using different energy levels. The result showed that the maximum peak force sustained by the laminate is usually not reached in the first impact. This phenomenon has been reported by other researchers as well [10] and can be explained as a result of compaction process [11] or change of dominant damage mode [12]. Sugun and Rao [13] characterised the impact fatigue behaviour of glass, carbon and Kevlar composites using a range of impact energies. They reported a numerical relationship between the impact energy and the number of impacts to perforation. As the incident energy was varied in arithmetic

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http://dx.doi.org/10.1016/j.compstruct.2012.10.033

(a) Boardwalk project under construction, Tweed Heads, New South Wales.

(b) Finished boardwalk project, Mackay, Queensland.

Fig. 1. Pultruded composite tubes used in shoring-up boardwalks. (Courtesy from Wagners CFT, Queensland, Australia.)

progression, the number of impacts to perforation varied in harmonic series. They also emphasised that the peak load decreases while the total energy increases until the perforation of the composite laminates. In another study, Found and Howard [14] performed repeated impact tests on carbon FRP laminates using drop-weight impact rig. Impact tests were conducted from a height of 0.5 m whilst the mass was varied to produce a wide range of impact energies between 0.54 and 0.93 J. The outcome of their study revealed that the damage caused by repeated impacts at energies of 0.54 and 0.73 J did not produce changes in the peak impact force. However, a second impact at 0.93 J produced a significant reduction in the peak force and an increase in impact duration.

The behaviour of high and medium strength carbon fibre-vinyl ester composite tubes under repeated transverse impacts was studied by Roy et al. [15]. This study was conducted by impacting the tubes up to 10,000 cycles with an energy level between 0.06 and 0.16 J using pendulum-type impact apparatus. The result indicated an existence of a plateau region in the impact fatigue behaviour curve between 10 and 100 cycles immediately below the single cycle impact strength. This was followed by a progressive endurance with decreasing impact loads terminating at an endurance limit at about 71% and 85% of the single impact strength for high and medium strength composite tubes, respectively. Their analysis on the fractured surface of the tube revealed debonding, fibre breakage and pull-out at the tensile zone of the impacted samples.

Literature review shows that parameters such as impact load (or mass), incident energy, and the number of impacts affect the behaviour of composite laminates or tubes which are transversely impacted. It would be equally important to know on how these parameters affect the behaviour of composite tubes when they are axially impacted. Currently, information on the behaviour of FRP composite tubes under repeated axial impacts is very limited. There is a need therefore to conduct a study that will systematically define their impact behaviour and will characterise the effects of these parameters on their behaviour.

This paper presents an experimental investigation on the behaviour of square FRP pultruded tubes under repeated axial impacts. The effect of parameters such as impactor mass, incident energy and number of impacts on their damage tolerance limit are also presented. It is expected that the information provided in this paper contributes for the development of efficient techniques and guidelines in driving hollow FRP piles.

2. Material and methods

2.1. Material

The 100 mm square pultruded tubes, manufactured by Wagners Composite Fibre Technology (WCFT), Australia, are made from E-glass fibres and vinyl ester resin. The tube wall is consisted of nine plies with a total thickness of 5.25 mm. Starting from the exterior of the wall, the stacking sequence of the plies is in the form of [0°/+45°/0°/−45°/0°/−45°/0°/+45°/0°], where the 0^0 direction coincides with the longitudinal axis of the tube. Table 1 shows the effective mechanical properties of the coupons taken from the composite tubes. It should be noted that the mechanical properties listed are values along the longitudinal direction.

2.2. Repeated impact testing and data processing

Impact test was performed using an un-instrumented drop weight impact testing machine defined in AS 4132.3 [16] with some modifications on the steel clamping frame to suit for the testing condition of the specimen (Fig. 2). The maximum drop mass (mass of the impactor and added weights) that can be attained from the set-up is 25 kg. The impactor is a 135 mm diameter steel cylinder with a flatted-nose contact surface. The nominal mass of the impactor is 16 kg, with additional 5 kg steel weights can be attached to the impactor as desired. The maximum available drop height is 3 m, in which the applied energy can be varied up to 736 J. A 10 mm thick steel plate was used in capping the top of the tested tube to help in evenly distributing the impact load and to simulate actual pile driving condition. The steel cap was held by a spring connected to the steel frame to avoid overthrowing during the rebound. During test, the impactor is raised manually to the desired drop height through an attached rope. It is then temporarily held and later released by an improvised clamping devise positioned a distance from the impact apparatus. The rope is caught manually after each impact to avoid bouncing and extraneous impacts on the specimen. Steel cap is removed at least every three impacts to check the position of the impactor relative to the contact section of the tube and to ensure that the tup strikes the specimen each time at approximately same location. This process is repeated until the required number of impacts on the tube is achieved or damage is observed on the specimen.

Two replicates with a length of 375 mm for any given incident energies were subjected to a maximum of 130 impacts or up to

Table 1
Coupon test results.

Property	Value	Unit
Specific mass	1970	kg/m^3
Fibre fraction	77	%
Tensile strength	610	MPa
Comp. strength	510	MPa
Flexural strength	980	MPa
Modulus of elasticity	36,400	MPa