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Composite Structures 70 (2005) 413–429
COMPOSITE STRUCTURES
www.elsevier.com/locate/compstruct

On the experimental investigation of crash energy absorption in laminate splaying collapse mode of FRP tubular components

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Available online 5 November 2004

Abstract

In this experimental work the crash energy absorption of fibre reinforced plastic (FRP) tubular components that collapse in laminate splaying mode is investigated by means of a new testing method, the "curling test". This test method was used trying rectangular carbon, aramid and glass FRP strips—in which the reinforcing fibres were in the form of reinforcing woven fabric (carbon and aramid FRP specimens) and multi-axial fibre reinforcements (glass FRP specimens). Apart from the analysis of the system of bending and friction forces acting on the specimens during the curling tests in comparison with the forces acting in the case the laminate splaying collapse mode and the observations related to the deformation and crushing induced on the FRP specimens by this force combination, the analysis of the test results focused on the influence of the most important geometric and laminate material properties—such as thickness, flexural rigidity, number of reinforcing fibre layers, laminate stacking sequence and constituent material mechanical properties—on the specific energy absorption and the peak load.

Keywords: FRP; Tubular components; Laminate splaying; Curling test; Regression analysis

1. Introduction

FRP tubular components of various cross-sections ranging from simple cylinders to tubes of complex profile have been found to be excellent collapsible energy absorbers in a broad range of crashworthiness applications in the transportation sectors [1,2]. Their use in automotive and aerospace engineering is currently getting wider since apart from significant functional and economic benefits gained by their use—like enhanced strength and durability at reduced weight and lower fuel consumption, FRP tubular components provide improved level of vehicle crashworthiness, being capable of absorbing large amounts of crash energy in the case of a sudden collision [3–5]. This feature of FRP tubular components is achieved mainly when they collapse progressively in a stable manner despite the fact that the constituent materials of a FRP structure are in most of the cases extremely brittle such as carbon and glass fibres and epoxy resin. Stable progressive crushing of a FRP tube takes place when the collapse mode is the one classified by D. Hull as laminate splaying [6]—or "lamina bending" according to Farley and Jones classification [7]. See Fig. 1 for a representative picture of a square CFRP tube that collapsed in this mode subjected to axial compressive loading and a typical micrograph of a tube-wall section [8].

As laminate splaying is the collapse mode of FRP tubular components featured by the higher crash energy absorption in static and dynamic axial compression [1,6,7,9–11], it is worthy insisting on the investigation of material and construction parameters that influence most significantly the crushing characteristics of the FRP structures and especially the crash energy absorption. Aiming

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doi:10.1016/j.compstruct.2004.09.002

Nomenclature

E	modulus of elasticity	P	load applied by the press crosshead
E_{abs}	absorbed energy	P_i	reaction forces
E_s	specific energy absorption	$\overline{P}$	average load
I	moment of inertia	P_{max}	peak load
k	number of reinforcing layers in a group of plies	$P_{max,1}$	critical damage load
L	length of the specimen	s	displacement of the press crosshead
LU	load uniformity index	s_{max}	total displacement
m	specimen mass	T_i	friction forces
m_c	crushed laminate mass	t	specimen thickness
n	total number of reinforcing fibre layers	V_f	fibre volume content
		w	specimen width

to contribute to this investigation, a new testing method was developed in order to simulate the laminate splaying collapse mode without actually testing a whole FRP tubular component but just a rectangular strip of the tested material. This test method—briefly call the "curling test" because of the characteristic permanent deformation induced on the tested laminate—was developed based on a suggestion made by Yuan and Viegelahn for the modelling of the crushing behaviour of fibreglass/vinylester tubes [12]. It employs the use of a curved test fixture that enforces the tested FRP strip to be deformed and crushed along a specific path which is the same as the deformation path of a strip of a FRP tube-wall that collapses in laminate splaying mode. The curling test method was utilised in a series of tests performed using carbon, [1] aramid and glass FRP specimens. In the following pages the particulars of the curling test method are presented in detail, focusing on the influence of the most important geometric and laminate material properties—such as thickness, flexural rigidity, fibre volume content, number and orientation of reinforcing plies in the laminate stacking sequence and the mechanical properties of the constituent materials—on the specific crash energy absorption, the overall peak load and the critical damage load that initiates the collapse of the specimen.

2. Experimental

2.1. Equipment and procedure

The curling tests for the experimental investigation of crash energy absorption in laminate splaying mode of FRP tubular components were performed on a standard INSTRON 4482 testing machine using the characteristic curved test fixture depicted in Fig. 2(a) and (b). Each test was conducted by pushing the rectangular test specimen through the curling test fixture, bending and crushing in this way the FRP strip just as each bundle of plies is deformed in the case of the tube wall splaying in the static and dynamic compression of FRP tubes collapsing in lamina splaying mode. In all cases the testing of the FRP strips started with the specimen inserted between the two steel plates of the curling test fixture just as much as required to place the edge of the specimen at the upper end of the curved segment of the fixture—marked as point A in Fig. 2(a)—and it was interrupted when the total displacement of the press head, s_{max} was equal to 40 mm.

Curling tests were performed at quasi-static conditions i.e. at constant crosshead speed equal to 5 mm/min and from the load, P/displacement, s curves that were recorded directly during the testing works the following testing characteristics of the FRP specimens were calculated and recorded:

- peak load, P_{max};
- critical damage load, $P_{max,1}$, i.e. the first peak load of the P/s curve marking the damage initiation;
- absorbed crash energy E_{abs}, i.e. the area under the P/s curve;
- average load, $\overline{P}$ ($\overline{P} = E_{abs}/s_{max}$, is the ratio of absorbed energy to max. displacement, s_{max});
- specific energy E_s ($E_s = E_{abs}/m_c$ is the absorbed energy per unit of the crushed mass m_c);
- load uniformity index, LU ($LU = P_{max}/\overline{P}$).

Testing works were performed at ambient temperature equal to 20 °C and relative humidity equal to 55%, i.e. conditions within the range of the recommended control conditions for testing of composites.

[1] The materials tested in the series of curling tests described herein include the construction materials of the CFRP tubes subjected to static axial compressive testing in the referenced experimental work [8], in which laminate splaying collapse mode was observed in the 45% of the tests.