EFFECT OF COLLAPSE TRIGGER MECHANISM ON THE ENERGY ABSORPTION CAPABILITY OF FRP TUBES

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Keywords: *Energy absorbing mechanism, Collapse trigger mechanism, Progressive crushing*

Abstract

A study on the crushing performance of fiber reinforced plastics (FRP) tubes was carried out in this paper. The target of this paper is to examine the effect of the device as a new collapse trigger for the practical application of composite. The specimens were tested in the both axial quasi-static compression and impact test. And the photomicrographs of the cross section of the crushed zone were examined to clarify the micro-fracture mechanisms under the effect of device.

It is found that the device could trigger progressive crushing as well as taper. However be different with taper, device can change the energy absorption capabilities of crushed materials significantly. The crushed tube wall was forced to be bent towards inside only with a small radius of bending curvature which was imposed by the R of the device. As a result, high bending stresses was occurred and then led to multi-micro factures generated which contributed to high energy absorption.

1 Introduction

In the automobile field, the safety of the driver and passengers in a vehicle during accidents was always being under research and developed. Additionally, recently the fuel economy is being another focus because of the lack of natural source and the will to protect the earth. The reduced the weight of body car is considered as an effective way to increase the fuel economy. Therefore, modern fiber reinforced plastics (FRPs) are attractive as a good candidate instead of traditional metal materials. Because FRPs tubes are be of light weight and found to be absorbed impact energy through a stable crushing behaviour known as progressive crushing which is suitable for energy absorption member. Therefore, they are gradually adopted in range structural applications particularly in automotive field.

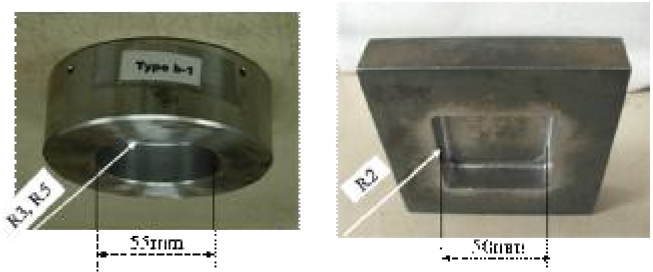
However, FRP tubes, as energy absorption members, generally need a collapse trigger mechanism to generate progressive crushing rather than a sudden catastrophic type of failure, for example chamfering one end of the tube into a taper, which has been proved to work well to initiate progressive crushing [1-4]. However, such triggers bring difficulty in assembling processes and labor cost during manufacturing.

Thus, in the experiments of this paper, devices which restrict the crushed tube wall to be spread towards only inner side are designed and employed. Their effect on the energy absorption capability of FRP tube as a new way for triggering stable crushing were identified through both quasi-static and impact tests. The specific energy absorption (Es) is used to value those devices compared with the most popular collapse trigger mechanism for FRP tubes i.e. taper. It is found that the device could trigger progressive crushing as well as taper. However unlike taper, the energy absorption capabilities of the tested composite tubes increased significantly in the usage of the device.

2 Materials and experiments

2.1 Device

The designed devices for circular and square FRP tubes are shown in Fig.1 (a) and (b) respectively. Specially, an R with a radius was modified on the place, where the end of FRP tube contacts with the device. They are 3mm and 5mm in the device for circular FRP tube and 2mm in the device for square FRP tube. In order to put the FRP tubes into the devices comfortably and stably, the sizes of the devices are made just same as the outer diameters or outside lengths of the FRP tubes.



(a) for circular FRP tubes (b) for square FRP tubes

Fig.1. Designed devices.

2.2 Materials

Several kinds of specimens given in Table 1 were used in the present study to assess the viability of those devices. They are the tubes with different cross section geometries: circular and square, with different reinforcements: glass fibers and carbon fibers, or with different reinforced forms: unidirectional, woven, braided, and multi-axial warp knitted fabric. In detailed, circular tubes contain glass woven/polyester FRP tube and carbon braided /epoxy FRP tube. On the other hand, Square tubes have unidirectional carbon (UD carbon) /polyester FRP tube and carbon multi-axial warp knitted fabric (Carbon MWK fabric) hybrid FRP tube. The circular tubes have an outer diameter of 55mm and a thickness of 2.5mm. And the square tubes have an outside length of 50mm and a thickness in the flat wall of 4.2mm. In particular, for the square tubes, the inner and outer radii of the corners are 6 and 2mm, respectively. The fiber volume fraction of all above of the FRP tubes is about 50%.

2.3 Experiments

2.3.1 Quasi-static compression test

The tubes were machined into individual specimens with of 100 mm height. Quasi-static tests were employed on an AUTOGRAPH testing machine (SHIMADZU) with the maximum load cell of 250kN. Specimens were axially crushed between parallel steel flat platens at a constant cross-head speed of 5.0mm/min. The frequency of data recording 200ms (5Hz) was chosen i.e. 5 data points were recorded every second to follow the track of the load during the crushing process. Three repeat experiments were carried out for each kind of tube to verify the stability of energy absorption capability.

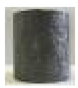
2.3.2 Impact compression test

Impact test was carried out with the help from Tokai Techno-research Company, Japan. The impactor was 120kg which could fall freely from 12m height place to create the impact velocity of 55km/H. The sampling rate of load during impact test is 50μs (20 kHz). The experiment tested two duplicate specimens with a height of 300mm.

2.3.3 Experimental methods

As the compression modes illustrated in Fig.2, in order to assess the practicability of the device, the effect of device on the energy absorption capability of FRP tubes was compared to that on the effect of taper i.e. before the experiments, one end of the specimens was chamfered into a sharp edge with a degree of 45 in order to initiate progressive crushing.

Table 1 Specimens

	Geometry	Reinforcement	Reinforcement form	Thickness (mm)	Outer diameter/ Outside length (mm)	Cross section (mm^2)	Photo	Compression tests
Glass woven /polyester FRP tube	Circular	Glass fibers	Woven	2.5	55	412		Quasi-static
Carbon braided /epoxy FRP tube	Circular	Carbon fibers	Braided	2.5	55	412		Quasi-static
UD carbon/ polyester FRP tube	Square	Carbon fibers	Unidirectional	4.2	50	769		Quasi-static Impact
Carbon MWK fabric hybrid FRP tube	Square	Carbon/glass fibers	MWK and Unidirectional	4.2	50	769		Quasi-static Impact

After compression, the tested specimens were cast in polyester resin to preserve the morphology of the crushed zone. Subsequently, some appropriate cross-sections were selected, polished and observed microscopically.

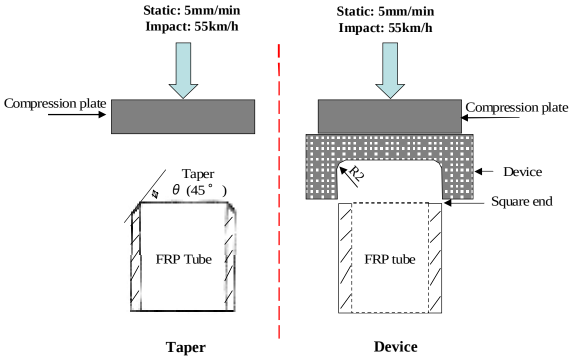


Fig.2. Illustration of the compression modes.

3 Results and discussion

3.1 Crushing performance and Es

All the tubes were crushed in a stable crushing mode i.e. progressive crushing. However the crushing performances and the energy absorption capacities of FRP tubes were quite different between these two cases i.e. taper and device. Photographs of the tested specimens and the typical load displacement curves from UD carbon/polyester FRP tubes are shown in Fig.3 as an example.

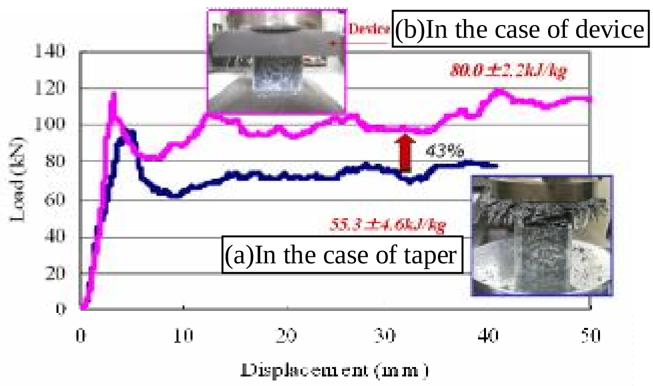


Fig.3. Test results of UD carbon/Polyester FRP tubes
from the both compression modes
i.e. (a) taper and (b) device.

In the case of taper, as compression progresses, crushing was initiated from the taper part, and then the tube wall was split into several pieces and bent imposed by the compression plate as shown in Fig.3 (a). A slight noise, that seemed to emanate from cracks, was heard during the crushing process. After the test, the compressive plate was removed. The bent tube walls sprang back because of the relaxation of the forces. This is especially so for the one crushed in the impact compressive test, in which case the fronds snapped back. Unlike the spreading fronds in the case of taper, the crushed tube walls were bent towards the inner side only in the case of usage of device (Fig.3.(b)). After compression tests, the tested specimens could not be taken out of the devices easily, so the compacted pieces had to be dug out with a sharp stamp and hammer in some cases. It also should be noted that a higher temperature hand feeling could be felt in the usage of device, especially in the impact tests.

Es was used to evaluate the energy absorption capacity of FRP tubes. It is defined as the absorbed energy per unit mass of the crushing materials with a unit of kJ/kg. It is calculated from dividing the area under the load-displacement curve i.e. the total absorbed energy by the mass of the crushed part. The Es values of all FRP tubes tested in both compression cases are summarized in Table 2.

Table 2 Es of all of the specimens from different compression modes and compression tests.

	Geome-try	Tests	Compressi-on mode	Es (kJ/kg)
Glass woven /polyester FRP tube	Circular	Quasi-static	Taper	**67.0**
		Quasi-static	R3 device	**75.0**
		Quasi-static	R5 device	**49.0**
Carbon braided /epoxy FRP tube	Circular	Quasi-static	Taper	**94.3**
		Quasi-static	R3 device	**110.8**
		Quasi-static	R5 device	**43.9**
UD carbon/ polyester FRP tube	Square	Quasi-static	Taper	**55.3**
		Quasi-static	R2 device	**80.0**
		Impact	Taper	**52.1**
		Impact	R2 device	**59.6**
Carbon MWK fabric hybrid polyester FRP tube	Square	Quasi-static	Taper	**47.7**
		Quasi-static	R2 device	**68.0**
		Impact	Taper	**32.2**
		Impact	R2 device	**67.4**

For all the tested FRP tubes which even have different reinforcements, reinforce forms, or cross section geometries, because of the higher Es, it could be concluded that their energy absorption capabilities could be enhanced significantly with the usage of reasonable devise. In the case of quasi-static compression tests with the usage of R3 devices, glass woven/polyester FRP tube and carbon braided /epoxy FRP tube obtained 12% and 17% higher Es value respectively. Specially, for UD carbon/polyester FRP tube and Carbon MWK fabric hybrid FRP tube, about 44% higher Es could be get with the usage of R2 device in quasi-static test. While in the impact test, the crushed tube walls of UD carbon/polyester FRP tube could not be bent entirely into the inside of the device, and the Es values are lower than that from the quasi-static tests, the device still shows its advantage and application potential as compared to the taper.

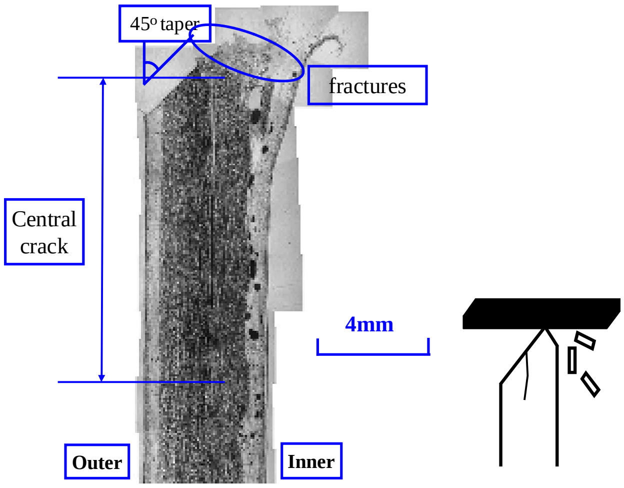
3.2 Collapse trigger mechanism

As shown in Fig.3 from the test results of UD carbon/polyester FRP tubes, the small fluctuating of loads show specimens could create progressive crushing by both collapse trigger mechanisms. The step by step compression tests were carried out in order to clarify the crushing mechanisms during the initial load increasing stage, i.e. the quasi-static compression test was stopped when the FRP tubes were compressed about 5mm displacement, cut the appreciate cross section and then observe.

If the tube with a taper was crushed directly by flat compression plate, during the initial load increasing period, a long central crack propagated and the taper part was bent to inside of the tube. Owning to creating the fracture in the taper part, the load was decreased before the load reached the critical load of the structure (Fig.4). On the other hand, for that specimen which crushed directly by the device, during the load rapid increasing stage, a big fracture was generated from where the square end touched the R of the device (Fig.5.). It is thought that the load decreased and prevented catastrophic failure by creating this initial fracture with the usage of device.

3.3 Effect of R of device on energy absorption mechanism

R3 and R5 device were employed for circular FRP tubes. From results of Glass woven /polyester FRP tubes and Carbon braided/epoxy tubes, it is Obvious that with usage of R3 device, higher energy absorption capability could be obtained i.e. a smaller radius can lead to better energy absorption capability.



(a) Photograph (b) Illustration

Fig.4. Cross section through the crush zone of UD carbon/polyester FRP tube with a taper during the initial load increasing stage.

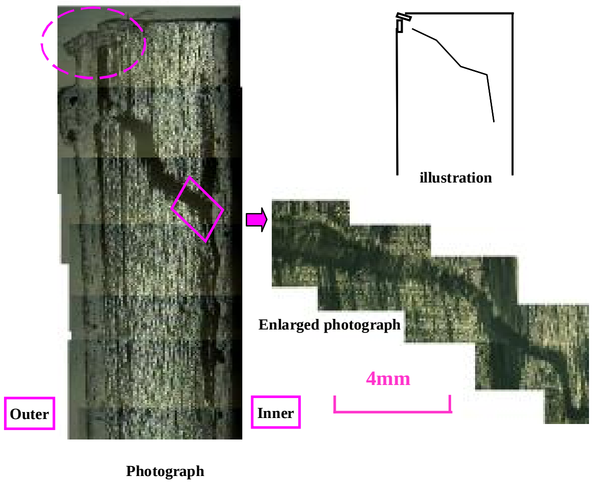


Fig.5. Cross section through the crush zone of UD carbon/polyester FRP tube crushed under R2 device during the initial load increasing stage.

The observation results from Carbon braided /epoxy FRP tube crushed directly under the R3 device are given in Fig.6. At the beginning of the crushing process, with the limitation imposed by device, the tube wall was forced to bend inwards only. Shearing stresses were induced to split the integrated tube wall into pieces. Besides of the smaller bending curvature, many shearing and fiber fractures are found in the crush zone of the specimens crushed by R3 device as shown in the

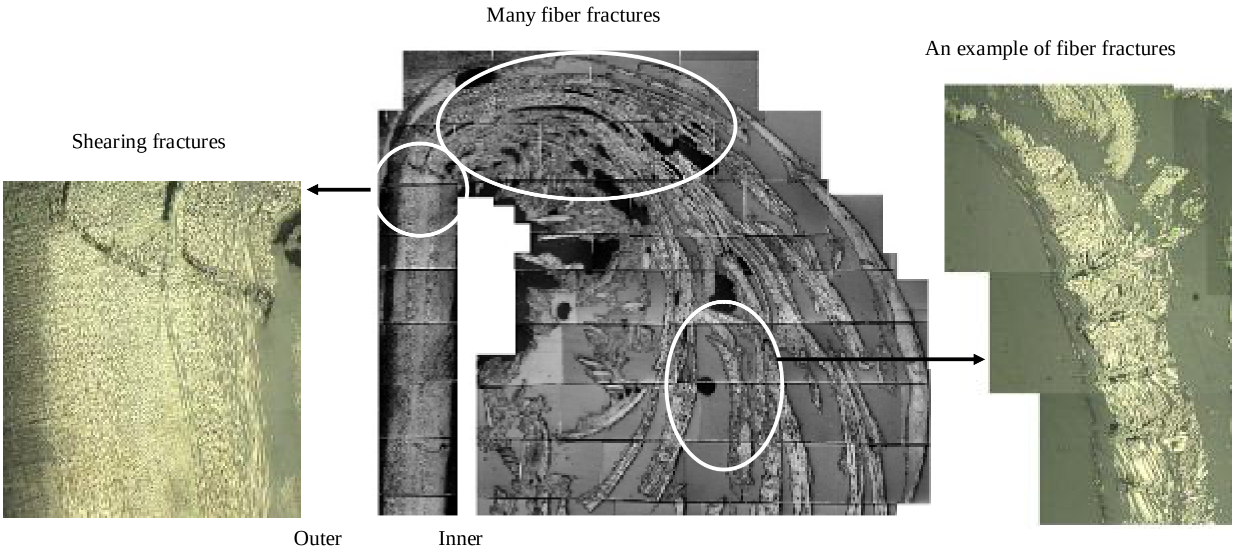


Fig.6. Observation results on the cross section through the crush zone of Carbon braided/epoxy FRP tube which crushed directly under the R3 device in the quasi-static compression test.

enlarged photographs in Fig.6 which could not be found in the FRP tubes with the usage of R5 device.

During the process of bending the fronds over a radius of curvature, the magnitude of these stresses (σ) depends on the radius of curvature and the thickness of the beam as the relationship expressed by Eq. 1.

$$s = \frac{E}{2r}t \qquad (1)$$

Where, E is the elastic modulus of the beam parallel to the fibers. And ρ and t are the minimum radius of curvature and the thickness of the beam, respectively. The bending stress is in direct proportion to the thickness of the beam but in inverse proportion to the bending radius of curvature. In the case of usage of device, the bending radius of curvature is 3 or 5mm because of the limitation imposed by device. So higher bending stresses generated on the tensile and compressive sides of the fronds by the usage of R3 device than R5 device. As result, more fiber fractures were occurred and contributed to higher energy absorption. That is why R3 device could get higher Es value than R5 device. The reasonable design of the R of device can be helpful to improve the energy absorption capability of FRP tubes.

3.4 Energy absorption mechanism between taper and device

In the case of taper, after fractures of the taper, the tube was split into two parts and bend to both sides of the tube (Fig.7(a)). Owing to the multiple micro-fractures involved fiber fractures, progressive crushing generated. On the other hand, in the case of device, after the initial fracture (Fig.5), the fronds bent towards inside of the device and many shearing and fiber fractures generate which led to progressive crushing (Fig.7 (b)). When the thickness of the bending fronds increased in the case of device as compare to those in the case of taper, the bending moment and shearing force were increased significantly. As a result, more fractures were generated to obtain higher energy absorption.

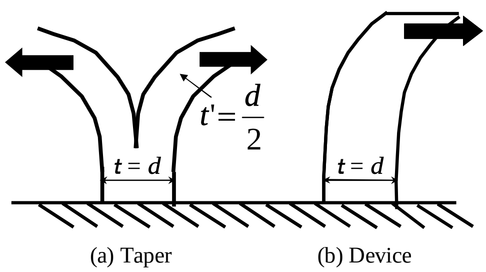


Fig.7. Crushing behavior (taper vs. device)

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