FAILURE ANALYSIS OF ULTRA-THIN CHOPPED CARBON FIBER TAPE REINFORCED THERMOPLASTIC IN MECHANICAL JOINTS

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Abstract

Ultra-thin chopped carbon fiber tape reinforced thermoplastic (UT-CTT) shows appealing potential for commercial applications as it bridges the gap between the lack of formability of continuous fiber composites and the lack of mechanical properties of short fiber composites. Promising prospect of UT-CTT could make great contribution to mitigate the fossil consumption and global warming. In this paper, an experimental study was carried out to investigate the failure characteristics of mechanical fastened UT-CTT. A parametric study considering the effects of width to diameter ratio and edge distance to diameter ratio was conducted to identify the failure of pin-laded UT-CTT. Special failure modes that different with conventional composites materials were observed, in addition, it was found that the bearing failure process is extremely stable, the stable failure offers very positive signal to the realistic application in the mass production of automobile. Finally, bearing strength was calculated and compared with each other for different geometric parameters.

1. Introduction

Carbon fiber reinforced thermoplastics (CFRTP) attracts much attention from all over the world in recent years owing to their outstanding weight-saving potential and in-plant recycling properties. Seldom dangerous chemical emissions in manufacture process of CFRTP make the application of CFRTP becomes environmentally friendly in mass-production vehicles [1]. Additionally, recent CFRTP research and development have concentrated on cost reduction and automatic processing, which can markedly increase production efficiencies to promote the development of mass production. Discontinuous carbon fiber reinforced thermoplastic (DCFRTP) has already been used in many engineering fields due to their excellent productivity and formability, but the poor mechanical property impeded the development and the application of DCFRTP.

Ultra-thin chopped carbon fiber tape reinforced thermoplastic (UT-CTT), which is a kind of randomly oriented strands (ROS) made by water dispersed thin tape, is a type of new material produced by compression molding with excellent performance in formability and mechanical properties. Moreover, UT-CTT can fill the gap between continuous fiber composite with poor formability and discontinuous fiber composite with poor performance of mechanics [2]. Attractive mechanical performance and relatively low price leave UT-CTT promising prospects for mass production in automobile industry.

Mechanical joints are the weakest link due to the stress concentration around the hole, however, the demand for mechanical fastening remains inescapable in automobile industry. Hence, a large amount of attention has been paid to the study of mechanical joints [3]. Scores of parameters can affect the mechanical properties of joint structures, such as joining method, clearance, pin-elasticity, clamping torque and washers etc. On account of the significance of this problem, pin-loaded laminated composites have been studied experimentally and numerically [4-7]. However, little research about

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mechanical joint in chopped fiber tape material was conducted until now since it's an emerging material, but which is developing rapidly these years.

In this paper, to investigate the effects of geometric parameters on the failure strength for double bearing pin-loaded UT-CTT tests, different width/diameter (*w/D*) and edge distance/diameter (*e/D*) ratios were considered. Bearing strength and coefficient of variation (*CoV*) were calculated to evaluate the performance of UT-CTT in the pin-loaded tests. In addition, special failure modes different from laminates composite were observed in the failure process of UT-CTT, which shows smooth failure and excellent energy absorption.

2. Procedure

2.1. Material

Ultra-thin chopped carbon fiber tape reinforced thermoplastic (UT-CTT) shows great utilization potentiality in automobile mass-production because of its outstanding mechanical property and affordable cost. UT-CTT is produced by compression molding with randomly oriented ultra-thin prepreg tapes, which are composed of carbon fiber (TR 50S, Mitsubishi Rayon Co., LTD.) and Polyamide-6 (PA6), and the thickness of this tape is extremely thin (about 44 µm) compared with the conventional tape (150 µm). It was observed that thin-ply laminated composites can suppress the microcracking, delamination and splitting damage for static, fatigue and impact loadings, which draws a lot of attention these days [8]. Tapes are cut with 18 mm length and 5 mm width by automated cutter and Tomson cutter, and then through random dispersion and compression molding process, UT-CTT is shaped into the plate. In addition, the finished specimens have an average thickness of 3.3 mm with a fiber volume fraction (V_f) of 55%.

Tensile tests and compressive tests have been performed on UT-CTT rectangular specimens according to the ASTM D3039/D3039M-00 [9] and ASTM D3410/D3410M-03 [10] standards, parameters such as tensile modulus (E_t), compressive modulus (E_c) and Poisson's ratio (v_{12}) etc. are determined as shown in Table 1.

Table 1. Properties of UT-CTT with 18 mm tape length.

	Symbol (Units)	Average	*CoV* (%)
Density	ρ (g/cm^3)	1.51	-
Tensile modulus	E_t (GPa)	40.8	3.43
Compressive modulus	E_c (GPa)	41.1	9.47
Poisson's ratio	v_{12} (-)	0.28	10.3
Tensile strength	σ_t (MPa)	528	7.24
Compressive strength	σ_c (MPa)	370	3.39

2.2. Test configuration

The configuration of UT-CTT specimen is shown in Fig. 1(a), following the ASTM D5961/D5961M-13 standard [11], the length of all specimens are 100 mm. Moreover, in the tensile test, the specimens were 6 mm drilled to give 20 kinds of specimens with *e/D*=1 to 5 and *w/D*=2 to 5. The specimens were tested in Shimadzu testing machine of 250 kN load capacity. A double-lap fixture shown in Fig. 1(b)

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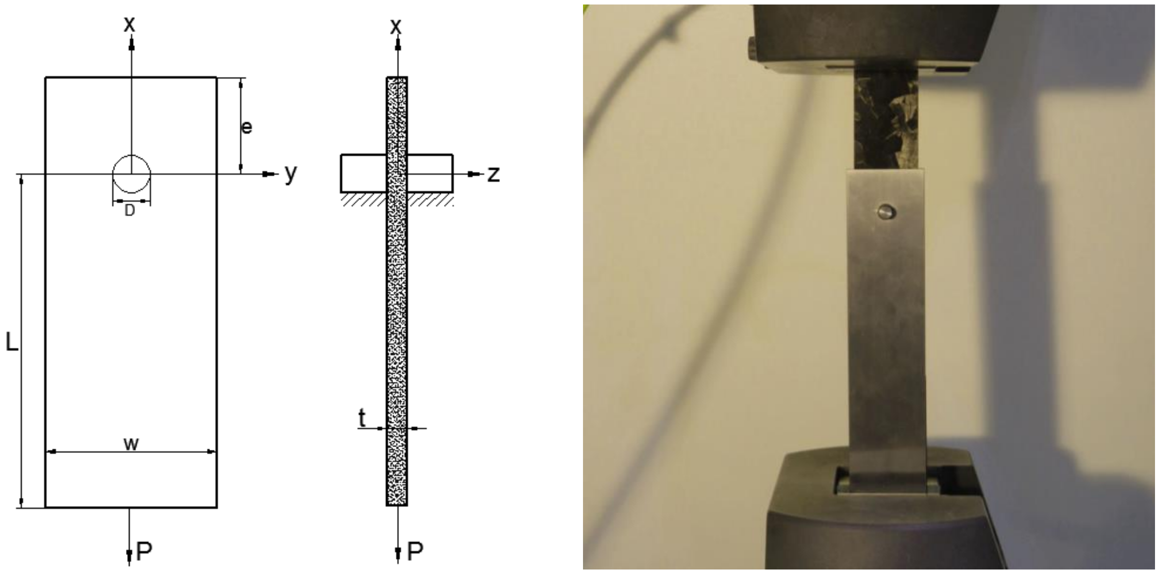
was used to perform the tests. 6 specimens were used when *e/D* and *w/D* ratios equal to 5, and 2 specimens were tested in other each ratio.



(a) (b)

Figure 1. Geometry of specimen with pin-loaded hole (a) and fixture assembly for double-lap, single pin joint (b).

Load is applied slowly with a speed of 0.4 mm/min when *w/D*=2 and 2 mm/min for other ratios, during the loading, the specimen is allowed to deform until it reaches ultimate failure, at which point the specimen cannot sustain any additional load. Following factors were observed during this process:

- Failure progression before ultimate failure.
- Failure modes.
- The load-displacement response for each specimen.
- The ultimate failure load.

Bearing strength is calculated with Eq. 1 [11] as following:

$$F^{bru} = P^{\max} /(k \times D \times t) \tag{1}$$

where F^{bru} is ultimate bearing strength, k equals to 1 for single-fastener test, D is the diameter of the hole and t is the thickness of specimen.

3. Results

3.1. Failure modes and failure process

Three types of failure modes were observed in the pin-loaded double bearing tests as Table 2 shows. End fracture occurs when *e/D* ratio decrease to 1, fracture surface is shown as Fig. 2(a). In addition, abrupt failure of net section happens when *w/D* ratio is 2, shown as Fig. 2(b). When *w/D* and *e/D* ratio is big enough, which means *w/D* ratio is from 3 to 5 and *e/D* ratio is from 2 to 5, bearing failure occurs, shown as Fig. 2(c) and Fig. 2(d).

Table. 2 Failure modes under different *w/D* ratio and *e/D* ratio.

	e/D=1	e/D=2	e/D=3	e/D=4	e/D=5
w/D=2	E	N	N	N	N
w/D=3	E	B	B	B	B
w/D=4	E	B	B	B	B
w/D=5	E	B	B	B	B

E: end fracture; N: net section; B: bearing

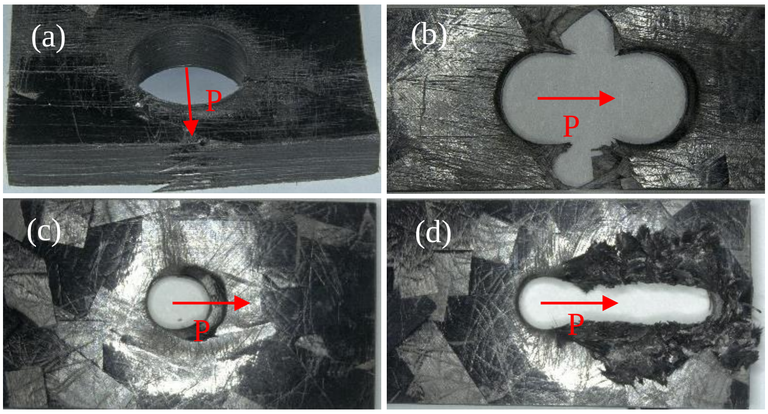


Figure 2. Appearance of failure modes. (a) End Fracture (b) Net section (c) Bearing failure (d) Progressive failure after bearing failure. (P: Pin loading direction.)

The general failure process of UT-CTT material was obtained from load/displacement curve from the testing machine as shown in Fig. 3. As the pin displacement increased, the load increased in an almost linear manner and reached the peak (first peak) loads between 7 and 10 kN. Then, failure started with different modes for different geometries. After the first peak, the load directly reduced to zero because net section failure happened when *w/D*=2, as shown in Fig. 3. In addition, when *e/D* ratio is 1, end fracture occurred and the load decreased dramatically, shown as an almost perpendicular line in load/displacement curve. What's more, the load decreased slowly and the pin pulled out steadily for specimens of *e/D*=2 to 5 and *w/D*=3 to 5, the loads fluctuated between 5.8 and 8 kN during the slowly pull out process, which is named as progressive failure period, then, final failure will occur in the way of end fracture, shown as Fig. 4, which repeats the failure mode of specimens with *e/D*=1.

As shown in Fig. 3, the pin displacements at which failure occurred vary from 2.27 mm for short edge distance specimens to 3.19 mm for the specimens with long edge distance when *w/D*=2. When *w/D*=3 to 5, the pin displacements of first failure occurred vary from 1.95 mm to 3.08 mm. In addition, final failure occurred as end fracture could be seen for bearing failure specimens, about 1 mm to 2 mm length was left from pin edge to specimen end when the final end fracture started to occur.

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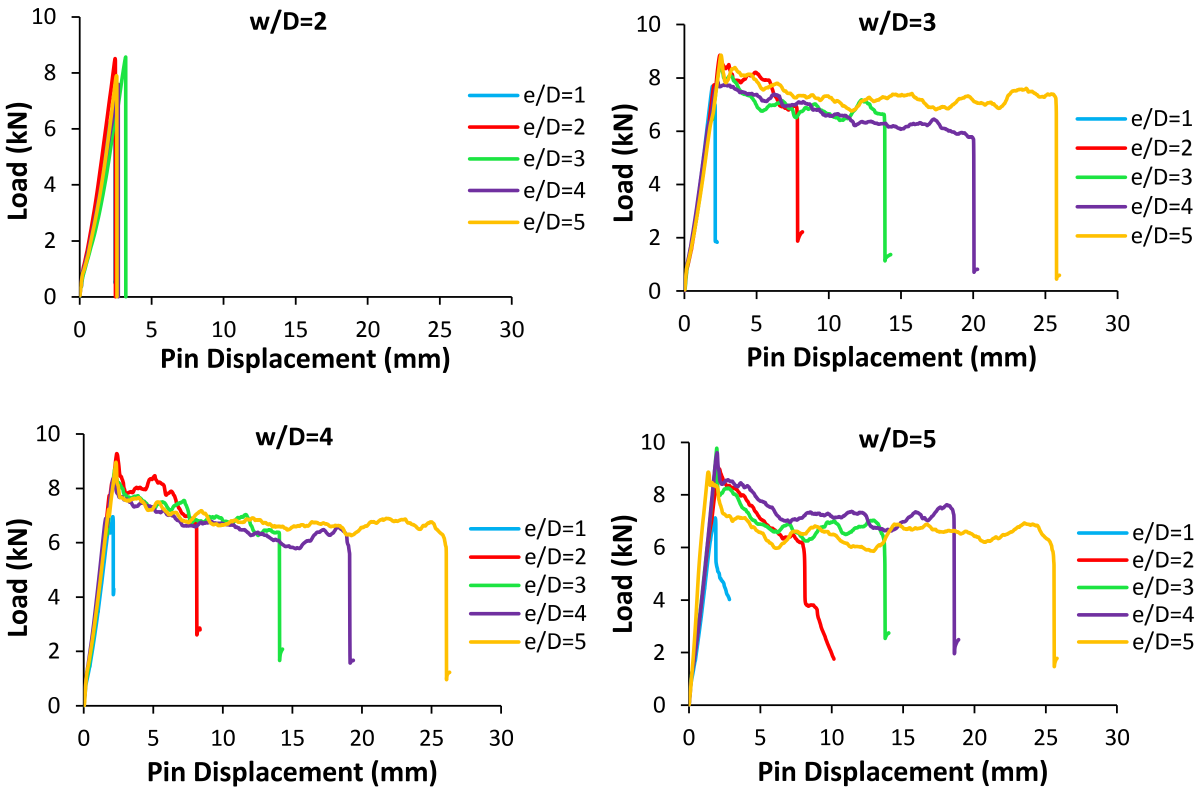

Figure 3. Load/displacement curves for UT-CTT.

3.2. Bearing strength

Six specimens with *e/D* and *w/D* ratios equal to 5 were tested to investigate whether the coefficient of variation (*CoV*) is big. Maximum load sustained by the specimen was used as a measure of joint strength, and bearing strength was calculated according to Eq. 1. The results showed average bearing strength is approximate 473 MPa and *CoV* is only 2.18%, which means the failure strength is extremely stable.

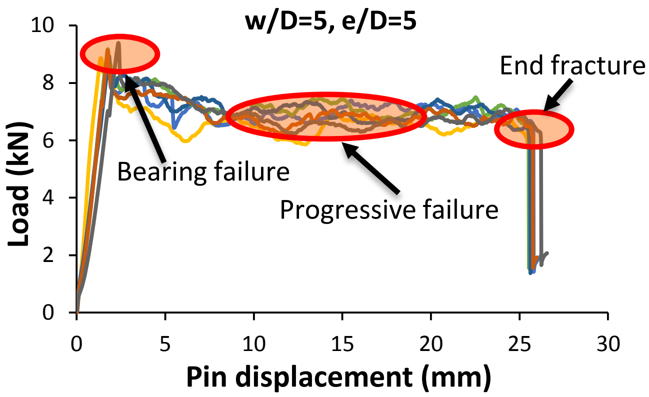

Figure 4. Failure process when *w/D*=5, *e/D*=5.

The effects of *e/D* ratio and *w/D* ratio on the bearing strength of UT-CTT are shown in Fig. 5. The bearing strength is defined as the ultimate bearing load divided by the area that is the product of pin

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diameter and specimen thickness. Bearing strength increases when *e/D* ratio increases from 1 to 2, at this time, the failure modes changed from end fracture failure to net section and bearing failure. After that, the bearing strength becomes almost stable with the increase of *e/D* ratio, which means an increase in edge distance does not seem to affect bearing strength under same failure mode. Similarly, bearing strength increases when *w/D* ratio increases from 2 to 3, and failure mode changed from net section to end fracture and bearing failure at this time. The right figure of Fig. 5 also shows the bearing strength is not affected by the increase of width under bearing failure mode when *w/D* ratio is from 3 to 5. The abnormal variation when *e/D* equals to 1 may be mainly caused by big scatter, because the tape length is 18 mm, but the distance from pin edge to specimen end is only 3 mm.

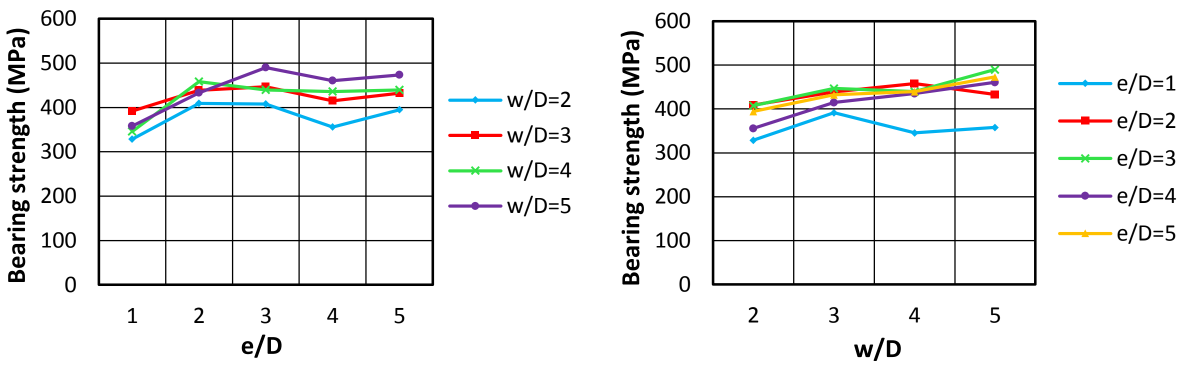

Figure 5. The effects of *w/D* ratio and *e/D* ratio on the bearing strength for UT-CTT.

4. Conclusions

In present research, the study has explained the effect of geometric factors on failure modes and bearing strength in pin-loaded UT-CTT with 18 mm tape length. The width of the specimen and the distance from edge of specimen to the hole center were taken as geometric factors.

- It was found the critical *e/D* ratio is 2 and the critical *w/D* ratio is 3 for the failure modes convert from end fracture and net section to bearing failure.
- The displacements at which first failure occurred vary from approximate 2 mm to 3 mm for all specimens. Progressive failure occurred after bearing failure and final failure occurred as end fracture for bearing failure specimens, as shown in Fig. 2 and Fig. 4, distances about 1 mm to 2 mm from pin edge to specimen end were left when the final end fracture occurred.
- The average bearing strength is approximate 473 MPa and *CoV* is only 2.18% when *w/D* ratio and *e/D* ratio are both 5, thus, the variation of failure strength is extremely stable, which shows excellent potential in the application of mass production of the automobile.
- It was shown that, the bearing strength increases as *e/D* ratio and *w/D* ratio increases when the failure mode changes, and bearing strength almost does not be influenced by *e/D* and *w/D* ratio under same failure modes.

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