Effect of geometric factor, winding angle and pre-crack angle on quasi-static crushing behavior of filament wound CFRP cylinder

Xiaolong Jia\(^a\), Gang Chen\(^a\), Yinhua Yu\(^a\), Gang Li\(^b\), Jinming Zhu\(^a\), Xiangpeng Luo\(^b\), Chenghong Duan\(^b\), Xiaoping Yang\(^a,*, \textit{David Huic}\)

\(^a\) State Key Laboratory of Organic–Inorganic Composites, College of Materials Science and Engineering, Beijing University of Chemical Technology, Beijing 100029, PR China
\(^b\) College of Mechanical and Electrical Engineering, Beijing University of Chemical Technology, Beijing 100029, PR China

\(^*\) Corresponding authors. Fax: +86 10 64412084.

\textit{E-mail addresses: yangxp@mail.buct.edu.cn (X. Yang), DHui@uno.edu (D. Hui).}

\section{1. Introduction}

With potential advantages over cylinders made of conventional materials, such as high strength, light weight and resistance to corrosion, carbon fiber reinforced plastics (CFRPs) cylinders have been increasingly used for a variety of applications, including chemical plants and high pressure containers [1–3]. The filament winding process was an efficient technique, commonly used in the mass production of high performance CFRP cylinders. The properties and performance of the filament wound products like cylinders were mainly affected by geometric and winding factors such as end reinforcing layer and winding angle [3–5]. The practical applications of CFRP cylinders required adequate assessment of their response under severe conditions like high compression loading. Specifically, crushing failure was of much interest, which often limited engineering applications of CFRP cylinders due to the lower compressive strength relative to tensile strength. However, crushing failure of filament wound CFRP cylinders was inherently complex. At present, there was a large uncertainty of understanding about effect of end reinforcing layer and winding angle on crushing failure behavior of these cylinders.

On the other hand, many fundamental researches reported that the crushing failure for cylinders occurred initially from the cracks existing in their structures [6–10]. These cracks have been viewed in different forms, orientations, locations, size and types, for instance, through thickness cracks, from single or double edge cracks and surface cracks [6,7]. For glass/epoxy filament wound pipes, the effect of a surface cracks on the tensile strength and fatigue behaviors under internal pressure has been investigated by Tarakcioglu and Samanci et al. [7–10], as well as the effect of surface crack angle on the tensile strength has been studied by Arikian [6]. Among these cracks, through thickness crack problems resulted in more serious failures of the cylinders than other crack problems. Moreover, practically applying CFRP cylinders required a complete understanding of through thickness cracks, especially with respect to the effect of their angle on crushing failure behavior of the cylinders.

Noticeably, finite element model was an efficient and economic method for simulating the crushing failure mode of the cylinders. With those numeral simulations, the complicated crushing behavior of the cylinders was better understood by analyzing the discrepancy between the experimental and predicted results. However, only a few literatures reported the numerical studies on the axial crushing response of CFRP cylinders up to now. For instance, Mamalis et al. [11] used a three-layer finite element model to predict the axial crushing response of carbon woven fabric reinforced epoxy square cylinders without cracks. McGregor et al. [12] reported a continuum damage mechanics based model to simulate failure propagation of braided composite cylinders without cracks.
under axial compression. However, practical test results revealed that the crushing mechanism was far more complex for the cylinders with through thickness cracks than for conventional materials, including matrix cracking, fiber-matrix debonding, delamination and fiber breakage. These reported numerical models in the literatures could hardly simulate crushing failure mode of the cylinders with through thickness cracks. Therefore, the vital issue of simulating crushing failure mode of such cylinders was to establish an effective numerical model.

To bridge this gap, the effect of geometric factor, winding angle and through thickness crack (which were pre-made in the cylinder and named pre-crack in this work) angle on crushing behavior of filament wound CFRP cylinder under quasi-static compression condition were investigated in details. To this end, (i) the effect of geometric factor such as end reinforcing layer on compressive properties of CFRP cylinders was discussed; (ii) the variation of compressive strengths of CFRP cylinders with various winding angles was evaluated, and the related crushing mechanism and crushing efficiency were analyzed on the basis of optical and SEM observations on fractured CFRP cylinders with various winding angles; (iii) and the effect of pre-crack angle on compressive properties of CFRP cylinders were also studied, as well as the numerical simulation based on Chang–Chang failure criteria was performed and compared with the experimental results to elucidate the effect of pre-crack angle on the crushing behavior of the cylinders.

2. Experimental section

2.1. Materials

The resin matrix, diglycidyl ester of aliphatic cyclo (DGEAC) type epoxy resin (epoxy value, 0.85) was supplied by Tianjin Jindong Chem, China. The diluter, diglycidyl ether of butanediol (epoxy value, 0.65–0.75) was synthesized by authors to reduce the viscosity of DGEAC resin. The harders, DDM and DETDA (74–80% 3,5-diethyltoluene-2,4-diamine and 20–26% 3,5-diethyltoluene-2,6-diamine) were obtained from Tianjin Synthetic Material Research Institute, China and from Lonza, Switzerland, respectively. The reinforcement, T700 carbon fibers (CFs) were purchased from Toray Co., Japan. T700 CFs possess a diameter of 7 μm, a tensile strength of 4.9 GPa, a modulus of 240 GPa and an elongation of 2.1%.

2.2. Sample preparation

The epoxy resin system was obtained by uniformly mixing DGEAC resin, DGB, DDM, DETDA and 2,4-EMI with a weight ratio of 100:20:24:19:1 at 40 °C, as following our previous works [13]. Filament wound CFRP cylinders with the winding angles of 20°, 40°, 60° and 90° were prepared with four CF layers by the filament winding machine (MAW 20-LS1-6, MIKROSAM Co.) after a bundle of CFs were coated with the epoxy resin systems. These cylinders were cured at 80 °C(1 h + 120 °C/2 h + 150 °C/3 h) on a mandrel in a slow motion rotary oven. After pulling out the mandrel, the obtained cylinders with dimensions of 65 mm inside diameter and 1 mm average thickness were cut into 130 mm length, respectively.

The end reinforcing layers with dimensions of 72 mm width and 2.25 mm average thickness were also prepared on the obtained cylinders with the winding machine. Then, the final cylinders with the end reinforcing layers were obtained by re-curing the resulted cylinders at the aforementioned conditions. In addition, the 15 mm pre-cracks with angles of 0°, 20°, 40°, 60°, 80° and 90° relative to the cylinder axis were carved on the final cylinders.

2.3. Characterizations

2.3.1. Compression properties

The axial compression tests of specimen cylinders were performed between two flat platens on a testing machine (Instron 1121) at a crosshead speed of 0.5 mm/min. Load platens were set parallel to each other before testing and all cylinders were compressed until limited crush. The final values were averages of five measurements.

The compressive strengths of the cylinders were calculated by the following equation:

$$\sigma_c = \frac{4P}{\pi(D^2 - d^2)}$$

where $P$ is the crush load, $D$ and $d$ are the outside and inside diameters of the cylinders, respectively.

The compressive modulus of the cylinders were obtained from the following equation:

$$E = F/Ae$$

where $F$ is the load along the longitudinal axis of the cylinders, $A$ is the transverse cross-section area of the cylinders and $e$ is the maximum strain along the longitudinal axis of the cylinders.

Stroke efficiency of the compression on the cylinders was calculated from the following equation [14]:

$$SE = U' / L$$

where $U'$ is the stroke length that is the distance the cylinder is crushed before the cylinder “bottoms out” and the load sharply increases. $L$ is the length of the cylinders.

2.3.2. Morphology observation

Morphologies of fractured surfaces of CFRP cylinders were observed by scanning electron microscopy (S4700, HITACHI Co., Tokyo, Japan). The debris of the composite specimens were placed on the glass slide during optical observation.

Morphologies of the debris of fractured CFRP cylinders were observed by optical microscopy (CK × 41, OLYMPUS Co., Tokyo, Japan). The debris of the composite specimens were placed on the glass slide during optical observation.

2.3.3. Modeling of crushing behavior

Failure criteria were only intended as a useful tool for material characterization and estimating the load carrying capacity of a structure. The failure mode of CFRP cylinder was predicted with Material type 54 in LS-DYNA, using the Chang–Chang failure criterion. This criterion was given as follows [15–17]: For the tensile longitudinal direction,

$$\sigma_{xx} > 0 \quad \text{then} \quad \varepsilon^e_{xx} = \frac{\sigma_{xx}}{X_{c}} - 1 \quad \{ \geq 0 \quad \text{failed} \quad \varepsilon^e_{xx} < 0 \quad \text{elastic} \}$$

If failed, then $E_x = E_y = E_z = v_{xy} = v_{yx} = 0$.

For the compressive longitudinal direction,

$$\sigma_{xx} < 0 \quad \text{then} \quad \varepsilon^e_{xx} = \frac{\sigma_{xx}}{X_{c}} - 1 \quad \{ \geq 0 \quad \text{failed} \quad \varepsilon^e_{xx} < 0 \quad \text{elastic} \}$$

If failed, then $E_x = v_{yx} = v_{xy} = 0$; for the tensile transverse direction,
3. Results and discussion

3.1. Effect of geometric factors

Fig. 1 shows the effect of end reinforcing layer on compressive strength and modulus of CFRP cylinders with winding angle of 60° (without cracks). The compressive strength and modulus were much higher for CFRP cylinders with end reinforcing layer than those without end reinforcing layer, which was strongly related with their failure mode. Fig. 2 shows optical images of the final failure of CFRP cylinders with and without end reinforcing layers (without cracks). As shown in Fig. 2, the failure of CFRP cylinders with end reinforcing layer took place with the crack propagation in the central circumference as a result of load transfer along the longitudinal axis, while the failure of those without end reinforcing layers occurred at both ends in the form of fiber and matrix breakage due to large transverse stress and strain at both ends of the cylinders. Actually, it was found that adding end reinforcing layers were beneficial to enhancing the strength efficiency of the fibers and corresponding mechanical properties of the cylinders. Therefore, CFRP cylinders with end reinforcing layers were used in the following parts of this study.

3.2. Effect of winding angle

3.2.1. Compressive properties

Fig. 3 shows the effect of winding angle on compressive strength and modulus of CFRP cylinders (without cracks). With winding angle increasing, the compressive strength generally exhibited the decreasing trend as shown in Fig. 3, while the strength value was minimum at the winding angle of 40°, which agreed with similar studies on glass fiber reinforced pipes by other researchers [18–20]. The decreasing trend was obviously attributed to the reduction of load bearing by the fiber and the resultant enhancement of longitudinal deformation because of the decreasing of fiber alignment along the longitudinal axis with winding angle increasing. However, the minimum value of compressive strength was related with the local buckling crushing mode of the cylinder with the winding angle of 40°, which would be discussed in details in the following parts of this study. Furthermore, the compressive modulus of the cylinders linearly decreased with the winding angles as shown in Fig. 3, which was consistent with variation trend of compressive strength and also resulted from the decreasing of the fiber alignment along the longitudinal axis.

3.2.2. Crushing mechanism

Fig. 4 shows optical images of fractured CFRP cylinders with various winding angles (without cracks). It could be seen that the macro-cracks propagated just along the direction of winding angles for 20°, 60° and 80°, implying that the cracks perpendicular to the fiber direction were inhibited effectively by the fibers. However, for the cylinder with winding angle of 40°, the failure occurred along with the plastic deformation in the central circumference and no fractured fibers were observed. Thus, the morphologies of fracturing cracks of these cylinders were quite different, which was strongly related with the crushing mechanisms at different winding angles. According to the literatures [21,22], the crushing behaviors of the continuous fiber reinforced composites

\[ \sigma_{ij} > 0 \text{ then } e_m^2 = \left( \frac{\sigma_{ij}}{Y_i} \right)^2 + \left( \frac{\sigma_{ij}}{Y_j} \right)^2 - 1 \begin{cases} \geq 0 & \text{ failed} \\ < 0 & \text{ elastic} \end{cases} \]

If failed, then \( E_x = \nu_{xy} = G_{xy} = 0 \); and for the compressive transverse direction,

\[ \sigma_{xy} < 0 \text{ then } e_m^2 = \left( \frac{\sigma_{xy}}{2\tau_x} \right)^2 + \left( \frac{\sigma_{xy}}{2\tau_y} \right)^2 - 1 \begin{cases} \geq 0 & \text{ failed} \\ < 0 & \text{ elastic} \end{cases} \]

If failed, then \( E_x = E_y = G_{xy} = \nu_{xy} = 0 \); where \( \sigma_{ij} \) is stress in the \((ij)\) direction, \( E_x \) is Young’s modulus in the \((i)\) direction, \( G_{xy} \) is in plane shear modulus in the \((j)\) direction, \( \nu_{ij} \) is Poisson’s ratio in the \((ij)\) direction, \( S \) is shear strength and \( X, Y \) is strength, respectively.

![Fig. 1. Effect of end reinforcing layer on compressive strength and modulus of CFRP cylinders with winding angle of 60°: (a) without end reinforcing layers and (b) with end reinforcing layers.](image1)

![Fig. 2. Optical images of fractured CFRP cylinders (a) without and (b) with end reinforcing layers.](image2)

![Fig. 3. Effect of winding angle on compressive strength and modulus of CFRP cylinders.](image3)
were dominated by four main mechanisms: (1) transverse shearing, (2) lamina bending, (3) local buckling and (4) brittle fracturing. Actually, the brittle fracturing was normally considered as a mixed mode of the transverse shearing and lamina bending modes.

Fig. 5 shows SEM images of fractured surfaces of CFRP cylinders with various winding angles (without cracks). At the winding angle of 20°, the fractured surfaces were scalloped and a large number of interlaminar and longitudinal cracks were found as shown in Figs. 4a and 5a, which were the characteristics of brittle fracturing mode [21]. At the higher angles of 60° and 80°, the wedge-shaped cross-section of the laminate with interlaminar and longitudinal cracks were clearly observed from Fig. 5c and d, which manifested the typical feature of transverse shearing crushing mode [22]. The lamina bundles which consisted of a single lamina or multiple laminae were resulted from interlaminar and longitudinal cracks. It was found that these bundles behaved as integrated element to bear the load and the interlaminar crack propagation ended after the edges of these bundles were fractured, finally producing a wedge-shaped cross-section. According to the literatures [21], the number, location, and length of the cracks were dependent of
the structure of the specimen and the basic properties of material constituents.

However, the crushing behavior was much different at the winding angle of 40° compared to other angles. As shown in Fig. 4b, the plastic deformation of the cylinder occurred in the region of a buckle. The deformation of the material between adjacent buckle nodes showed elastic characteristics, while the plastic deformation of the material at a buckle node was not uniformly distributed through the thickness of the cylinder. On the convex and concave sides of the buckle node, the material was in a state of tension and compression, respectively. It was worth noting that the obvious failure associated with fiber breakage was not observed from Figs. 4b and 5b. All these features implied that the crushing behavior of the cylinder with winding angle of 40° was predominated by the local buckling crushing mode. This mode was attributed to the smaller interlaminar stresses relative to the strength of the matrix when the winding angle was close to 45° [18,19]. At this condition, the epoxy matrix with the higher failure strain than the carbon fiber exhibited plastic deformation under the load [23]. The interlaminar cracks were reduced or prohibited by the matrix with higher failure strain during the compression. Thus, the interlaminar cracks were just generated at the buckles where the local interlaminar cracks did not propagated to adjacent buckles. Therefore, it concluded that the crushing behavior of the cylinder was dominated by brittle fracturing mode at low winding angle of 20° and by transverse shearing crushing mode at high winding angles from 60° to 80°, while it was controlled by local buckling mode at moderate winding angle of 40°.

3.2.3. Crushing efficiency

The crushing efficiency of composite cylinders was a measure of the effectiveness of energy absorption during crushing, which also could provide some information about the crushing mode of the cylinders. Practically, stroke efficiency along with the debris size and crack length were often used to measure crushing efficiency [24,25]. Stroke efficiency was obtained by dividing the stroke length with the original length of the cylinder. Usually, the higher stroke efficiency along with the smaller the debris size and crack length indicated the more efficient crushing process. Fig. 6 shows the effect of winding angle on the stroke efficiency and crack length of CFRP cylinders and Fig. 7 shows optical microscope images of the debris of fractured CFRP cylinders with various winding angles after the test of stroke efficiency. With winding angle increasing, the stroke efficiency increased distinctively as shown in Fig. 6, while the debris size and crack length showed the opposite trend as shown in Figs. 6 and 7, which indicated that the energy absorption was effectively enhanced at the higher winding angles. In addition, as observed from Fig. 7, the crushing debris existed in form of pieces with large dimension at the low winding angle for the brittle fracturing mode, whereas the debris size ranged from lengths equal to lamina bundle thickness to near powders at the high winding angles for the transverse shearing mode, which meant that more materials were destroyed in the crushing process. At the moderate winding angle for the local buckling mode, the
debris was the mixture of small powders and large pieces. Coupled with the aforementioned crushing mechanism, it concluded that the transverse shearing mode showed highest crushing efficiency, sequentially followed by the local buckling mode and brittle fracturing mode, respectively.

3.3. Effect of pre-crack angle

3.3.1. Compressive properties

With the aims of better understanding crushing behavior of the cylinder under compression loads, the pre-cracks (through thickness cracks) were caved in the cylinder and used as the crushing initiator. Meanwhile, the performance of cylinders with winding angle close to 60° was much of interest to many researchers [6,8,9]. Thus, the effect of pre-crack angle on crushing behavior of the cylinders with winding angle of 60° were investigated in this part of our study in order to expose the relationship of crushing mechanism with the structural defects of the cylinders. Fig. 8 shows the effect of pre-crack angle on compressive strength and modulus of CFRP cylinders. As expected, the strength and modulus values of the cylinders with pre-cracks were lower than those of the cylinders without pre-cracks. With the pre-crack angle increasing, the compressive strength and modulus initially decreased to the minimum values when the pre-crack angle equaled or close to the winding angle, and subsequently increased. This variation trend was attributed to the decrease and increase of depression effect of the fibers on the crack propagation in the cylinder with the included angle variation between pre-crack angle and winding angle. Specifically, the cracks initiated from the pre-crack propagated more easily in the condition of the pre-crack angle parallel to the winding angle.

3.3.2. Modeling of crushing behavior

Fig. 9 shows experimental and simulated loads–displacement curves and crushing loads of CFRP cylinders. It was clearly seen from Fig. 9a that the simulated loads–displacement curve correlated well with the experimental result for CFRP cylinders with pre-crack angle of 60°. The loads reached initial peak values along with the failure of the cylinders and abruptly dropped to level-off values due to the formation of the crush zone in the cylinders. Actually, for CFRP cylinders with various pre-crack angles, experimental and simulated loads–displacement curves also correlated well and showed the similar trend. Additionally, conforming to the variation trend of compressive strength and modulus shown in Fig. 8, the crushing loads decreased distinctively with the pre-crack angle increasing up to the angle of 60°, and subsequently increased as shown in Fig. 9b.

Fig. 10 shows experimental failure images and simulated compression strain distribution of CFRP cylinders with various pre-crack angles. The materials failed when the maximum principal compression strain in a material element exceeded the uniaxial compression strength of materials. As shown in simulated compression strain distribution in Fig. 10, the cylinders would be damaged from the location with maximum compression strain. Noticeably, the simulated failure model generally conformed to experimental crushing behaviors for CFRP cylinders with various pre-crack angles, which proved that the Chang–Chang failure criteria could accurately represent the quasi-static crushing failure of laminates in the cylinder. However, the crushing behavior of the cylinders with various pre-crack angles was quite different, judging from the experimental failure images and simulated compression strain distribution.

At the pre-crack angle of 60°, the interfacial adhesion surrounding the pre-crack was poor since the pre-crack angle was parallel to the winding angle and the region formed at the interface between the fiber and the matrix at the location of the pre-crack was maximum. As shown in Fig. 10d, it was noted that the significant stress concentration clearly occurred in the circumferential area close to the pre-crack in the simulated model due to the circumferential tension during crush, resulting in the crack propagation of the cylinder, which was quite consistent with the observed experimental failure mode. At this case, the pre-crack acted as the crack initiator.
and resulted in the final fracture of the cylinder under lower loads. When the cracks in the matrix grew and reached the interface, the crack deflection occurred along the interface and led to the delamination of the interface. According to the literatures [26,27], the crack propagation at the interface of composites was characterized by two competing effects of crack evolution: deflection and penetration. Thus, the crack propagation was predominated by deflection effect for the cylinder with pre-crack angle of 60°, and the failure band was formed by increasing delamination. Following the band separation, the failure ended with sudden seepage in the crack zone.

At the lower pre-crack angle such as 0°, the failure of the cylinder was not initiated by the pre-crack as shown in Fig. 10a. This was because the fracture region formed at the interface at the location of the pre-crack was small when the pre-crack angle was much different from winding angle. At this case, the fracture of the cylinder occurred randomly at the site of the biggest defects in the matrix under the higher loads. With the loads further increasing, the cracks grew in the matrix and penetrated the fibers at the interface, showing the brittle fracture perpendicular to the load direction. As the pre-crack angle increased to 90°, the fracture region formed at the interface around the pre-crack was reduced and the interfacial adhesion surrounding the pre-crack was strong due to the relatively smaller deviation between pre-crack angle and winding angle. The cracks were initiated by the pre-crack and the fracture of the cylinder started from the matrix at the end of the pre-crack under lower loads. When the cracks in the matrix grew and reached the interface, the deflection effect competed with the penetration effect, thus making that the fracture synchronously occurred in the directions parallel to the fiber alignment and perpendicular to load direction as shown in Fig. 10f.

4. Conclusions

The CFRP cylinder with end reinforcing layer showed higher compressive properties along with failure mode of crack propagating in its central circumference. With winding angle increasing, the compressive strength, compressive modulus and crack length of the cylinder generally exhibited the decreasing trend, whereas the crushing efficiency showed the opposite trend. At the lower winding angle of 20°, the cylinder showed the brittle fracturing mode, whereas the cylinder showed transverse shearing crushing mode at the higher winding angles of 60° and 80°. Particularly, the crushing behavior of the cylinder was predominated by the local buckling crushing mode at the moderate angle of 40°. Besides, with pre-crack angle increasing, the compressive strength and modulus of the cylinder initially decreased to the minimum values when the pre-crack angle equaled or close to the winding angle, and subsequently increased. Moreover, the crack propagation initiated by pre-crack and the fracture region formed at the interface in the cylinder were strongly dependent of pre-crack angle as a result of the competition between deflection effect and penetration effect of crack evolution. The simulated loads–displacement curve, crushing load and failure mode correlated well with the experimental results, indicating that the Chang–Chang failure criteria used in this study was effective in representing the quasi-static crushing behavior of CFRP cylinder.

Acknowledgement

The authors are very pleased to acknowledge financial support from the National High Technology Research and Development Program of China (Grant No. 2012AA03A203).
References