CRUSHING PERFORMANCE OF BRAIDED COMPOSITE RODS

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SUMMARY: The crushing energy absorption properties of braided composite rods were studied. Braided composite rods showed the characteristic fracture mode generally called as progressive crushing. For an actual application, we used rods fabricated by braided pultrusion process (BPP) which could fabricate products with constant cross-sectional shape continuously. We introduced crushing effects of braided rods with triggered jigs for a curtailment of the processing costs.

KEYWORD: braided pultrusion process (BPP), energy absorption properties, progressive crushing, Es value, triggered jig, restraint of cost, load shift stability, fracture mechanism

INTRODUCTION

FRP shows not only the excellent strength with lighter weight than metal, but also energy absorption properties when a conical chamfer is made at the one end. Therefore FRP has been applied to structural components for various vehicles recently. Particularly, braided composites are expected to use for safety components, because they show the fracture mode called progressive crushing, which proceeds under constant load. Figure 1 shows the representative crushing mechanism of the progressive crushing. Energy absorption caused by the progressive crushing occurred by combination of fiber fracture, delamination or cracking et al. Therefore crushing energy absorption value is considered to equal the total sum of the energies of these fractures.

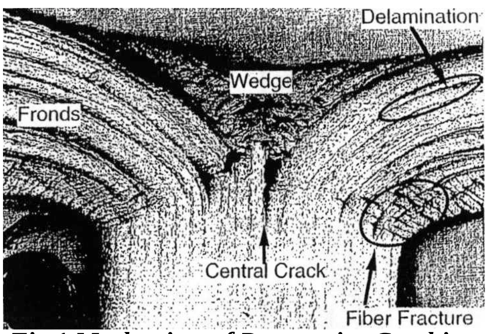

Fig.1 Mechanism of Progressive Crushing.

Cost of fiber reinforced plastics might be determined by several factors such as cost of constitute materials, manufacturing equipments, fabrication cost such as labor time and so on. Therefore, high volume fabrication process has to be developed for a low cost performed FRP. SMC compression method is a kind of high volume fabrication process for exterior panel and BMC injection molding is also good example [1]. Short fiber reinforced thermoplastics and injection molding can fabricate large volume at low cost. However, these processes need specific material systems and the weakest point is that their reinforcements are discontinuous, because material flow in mold is required. Basic and simple concept of FRP is effective usage of high modulus and strength of reinforcement fibers along longitudinal direction. Unidirectional fiber reinforced plastics are the simplest solution of the concept. However in actual applications unidirectional composites are hardly used due to extreme low strength in transverse direction. Multiaxial laminated composites are fabricated with prepreg materials by using autoclave manufacturing method. Clearly, this method needs high cost. Therefore there would be large gap between the basic concept and the cost, fabrication system.

Pultrusion process is one of high volume fabrication system for unidirectional composites. A limitation of application, however, is involved in pultruded composites. That is weak transverse strength. Mat materials are often wound around the unidirectional aligned fibers [2,3], so that strength reduction in transverse direction is suppressed and moreover impregnation state can be improved by the surface mat material.

In this study, as way to satisfy both cost and strength requirements, we use braided pultrusion process (BPP), which can fabricate constant quality products continuously. Therefore this fabrication process can restrain fabrication cost comparatively. In this paper the crushing performance of braided rods which consist of uni-directional fibers surrounded by braided fabrics produced by BPP. Usually a chamfer trigger is made at the one end of tube or rod to produce progressing fracture for high energy absorption. However, machining of FRP for the chamfer also one of the source of high cost, so that the triggered jig was used for non-machined BPP braided rods. This method was based on mechanism of progressive crushing. It is thought that wedge extends fronds to circular direction as shown in Fig.1. Therefore by using triggered jig instead of wedge, it is thought that specimen would show progressive crushing. This method would be a new approach to usage of real applications, and new concept of energy absorber.

1. BRAIDED PULTRUSION PROCESS (BPP)

The construction of braided pultrusion process is shown in Fig.2. From the left, in order, that consists of resin impregnator, braider, heated die, puller and cutter.

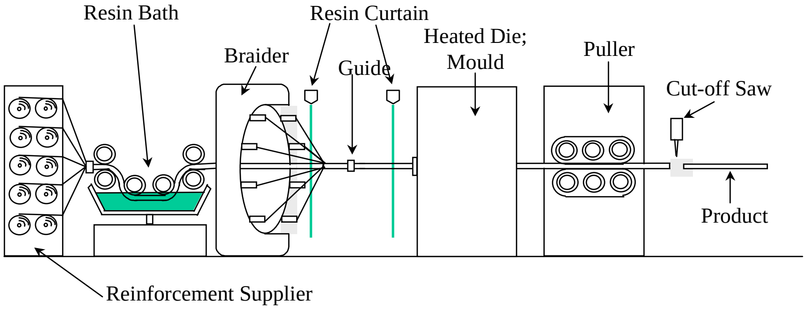

Fig.2 Scheme of Braided Pultrusion Process (BPP) System.

With this system, high-performance composites can be fabricated at low-cost. In addition, it is possible to not only manufacture pultruded products of various cross-sectional shapes, but also obtain the products with various mechanical characteristics by changing the braiding angle, the number of middle-end-fibers and axial fibers.

2. MATERIAL AND SPECIMEN

Construction of fabricated rod in this paper is shown in Fig.3. Braided rod is constructed by uni-directional axial fiber and braiding fiber. In this study, materials were used epoxy resin as matrix, and glass or carbon fiber as reinforcement fibers. Five types of braided rod were fabricated and the fabrication conditions are shown in Table 1. As shown in this table, G/G was fabricated by glass braiding fiber and glass axial fiber. GUD, that was uni-directional rod, was fabricated by uni-directional glass fiber. C/C was fabricated carbon braiding fiber and carbon axial fiber. CUD, that was uni-directional rod, by carbon fiber, and G/C was fabricated by glass braiding fiber and carbon axial fiber. Other type rods, S and UD, were fabricated by batch method due to compare energy absorption properties with above-mentioned BPP rods. S was fabricated by glass braiding fiber and glass axial fiber, and uni-directional rod, UD, was fabricated by uni-directional glass fiber.

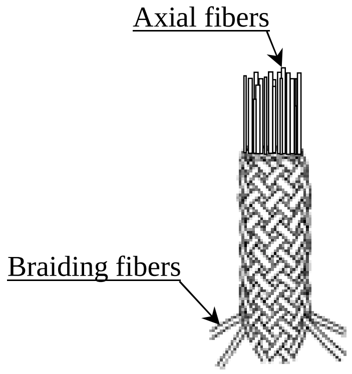

Fig.3 Construction of Braided Perform.

Rod Type	Braiding Fiber	Axial Fiber (Uni-direction)
G/G	Glass	Glass
GUD	——	Glass
C/C	Carbon	Carbon
CUD	——	Carbon
G/C	Glass	Carbon

All rods were cut off in 50mm length for use as specimen. For crushing test, a 30 degree conical trigger was made at the one end of the specimen rod. Compression load was applied to longitudinal direction at constant speed of 5mm/min. For crushing test by jig, specimen did not have a chamfer, and was compressed by triggered jig shown in Fig.4. Triggered jigs were separated in two types, one was sensitive type which had sharp head and another was insensitive type which had un-sharp head. In sensitive type, there were two types of jigs, which maximum trigger diameter were ϕ3 and ϕ5. And insensitive type jigs had four types; ϕ3, ϕ5, ϕ10 and ϕ30. Because sharpness of trigger head thought not to influence, insensitive type of ϕ10 and ϕ30 jig were not prepared.

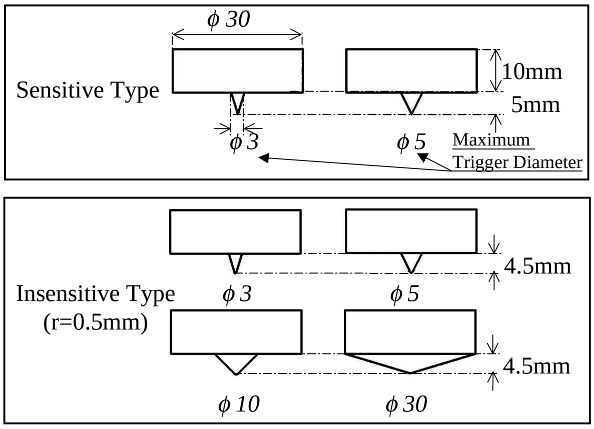

Fig.4 Scheme of Triggered Jigs.

3. ENERGY ABSORPTION PROPERTIES

3.1. Rod Reinforced by Glass Fiber

Photographs of after testing specimens; S, UD, G/G and GUD, were shown in Fig.5. These specimens were made chamfer at the one end. S and G/G fractured with expanding axial fibers in radial pattern like petals, therefore they showed progressive crushing. UD and GUD cracked longitudinal direction and showed brittle failure.

Figure 6 is load-displacement curves measured by compression testing. Load value increased with increase of displacement, and indicated approximately constant value after achieved maximum value.

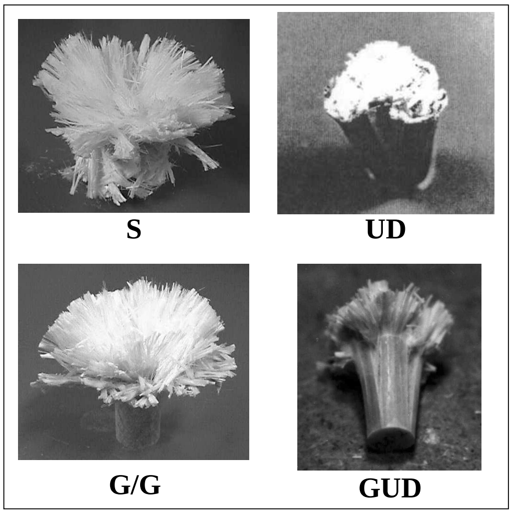

Fig.5 Photographs of After Testing Specimens.

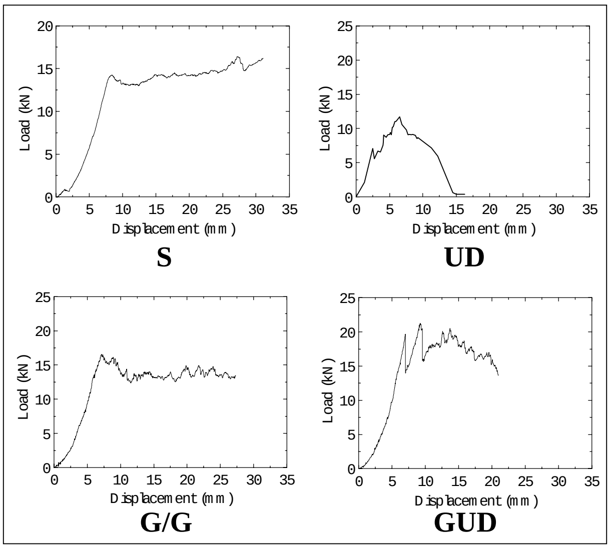

Fig.6 Load-Displacement Curves of Tapered Specimens.

Next, energy absorption properties of S and G/G were compared. When we compare energy absorption properties among various materials, specific energy absorption value (Es value) is used as appraising way generally. Es value is calculated by mean crushing load (P), area of cross section (A) and density of material (ρ) as follows:

$$Es = P / A\rho \qquad (1)$$

The unit of Es is kJ/kg which express the crushing performance.

Table 2 showed Es value of S and G/G calculated by Eqn 1. Es values of the other composite and metal tubes were listed for comparison. From this table, G/G indicated lower Es value than S, however G/G showed equivalent or higher value than Glass/Epoxy, Kevlar/Epoxy or steel tube. Therefore G/G rod had good energy absorption property.

Table 2 Es Values of Tapered Specimens and Other Materials.

Specimen Type	Es value (kJ/kg)
S	64.7
G/G	55.3
C/C	62.8
G/C	53.6
G/C type rod fabricated by batch method	84.8
Glass/Epoxy Tube	53.7
Kevlar/Epoxy Tube	57.9
Steel Tube	33.7
Aluminum Tube	66.9

3.2. Rod Reinforced by Carbon Fiber

C/C, CUD and G/C showed fracture mode as shown in Fig.7. C/C and G/C showed progressive crushing, and CUD also showed brittle failure. Figure 8 is load-displacement curves measured by compression testing. As shown in Fig.8, after sudden increment, both C/C and G/C fractured with load value increasing and decreasing in range about 5kN. CUD showed sharp increment of load, and later load value gradually decrease with cracking in longitudinal direction.

Es values of C/C and G/C showed in Table 2. From this table, Es value of C/C indicated 14% higher than G/G and nearly equal with G/G fabricated by batch method. The Es value of G/C indicated 37% lower than G/C fabricated by batch method. Nevertheless carbon fiber is stronger than glass fiber, C/C did not showed so high Es value, and also G/C showed lower Es value. For this reason, it is thought that carbon fiber was not impregnated well with using same processing conditions as glass fiber in BPP.

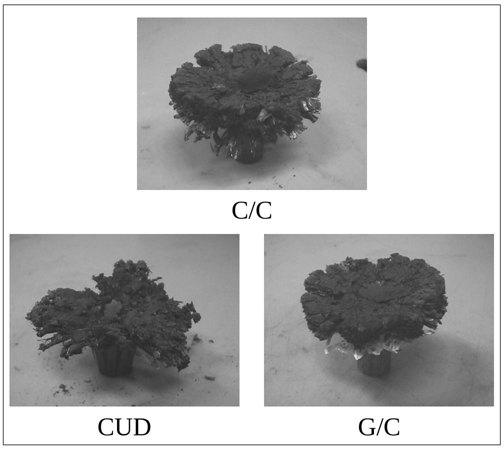

Fig.7 Photographs of After Testing Carbon Specimens.

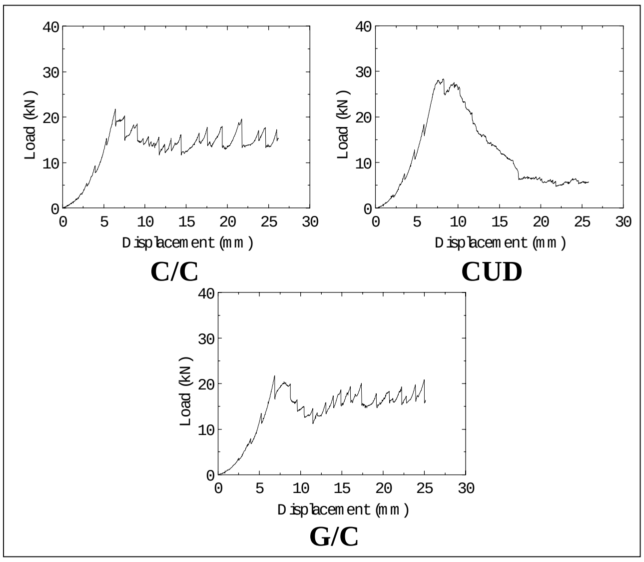

Fig.8 Load-Displacement Curves of Tapered Carbon Specimens.

4. CRUSHING WITH TRIGGERED JIG

In crushing test by triggered jig, the results were dramatically different by size of maximum trigger diameter. Photographs and load-displacement curves of crushed specimens are shown in Fig.9. Specimen crushed by both sensitive and insensitive ϕ3 jig showed brittle failure with cracking in longitudinal direction. In the case of ϕ5 jig, load increased slowly before 5mm that was height of trigger, but increased very sharply at just after 5mm. After that, specimens crushed at constant load. From these results, it was thought that sharpness of trigger head did not influence fracture mode. Although specimen crushed by ϕ10 jig also showed sharply increment of load value at 5mm, maximum load value was lower than using ϕ5 jig. Specimen crushed by ϕ30 jig showed stable load value through testing. All specimens without ϕ3 jig had stable load area, so we judged these specimens showed progressive crushing.

From above results, Es values were calculated as shown in Table 3. Specimen crushed by jig showed approximately 50% lower Es values of tapered specimen totally. It is thought that these low Es values were caused by following reasons. First fracture mode not to occur smoothly than tapered specimen, and this brittle fracture mode continued through compression testing. Therefore it is able to say that stable fracture mode in progressive crushing depended on first fracture mode. Here, we propose a new parameter of load shift stability as stability indicator of fracture progress. This parameter, we named ratio of fracture stability; R_{fs}, is defined percentage of maximum load value to mean crushing load value. In table 3, R_{fs} increased with increasing maximum trigger diameter. In future research, relationship of R_{fs} and maximum trigger diameter was investigated, and optimal jig configuration for higher energy absorption properties should be obtained.

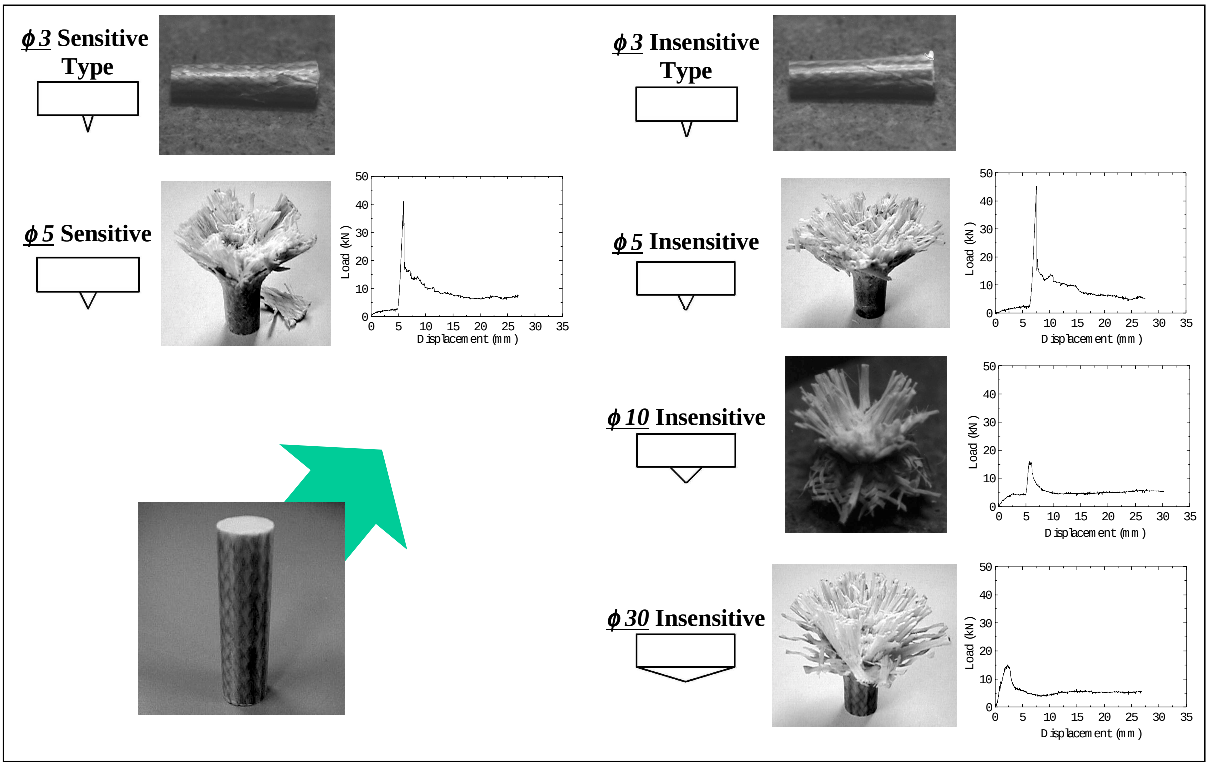

Fig.9 Photographs of Specimens Crushed by Triggered Jigs.

Table 3 Es Values of Specimens Crushed by Triggered Jigs.

Specimen Types	Maximum Trigger Diameter (mm)	Mean Load *P* (kN)	*Es* (kJ/kg)	R_{fs}
Sensitive Type	φ5	6.97	27.9	17.4
Insensitive Type	φ5	7.12	28.6	15.4
	φ10	4.99	20.0	34.3
	φ30	5.18	20.8	31.6
Tapered G/G	——	13.8	55.3	79.4

CONCLUSIONS

In this study, we investigated energy absorption properties of braided pultrusion process (BPP) rods with considering with fabrication cost and process cost. First, glass fiber reinforced braided rod showed progressive crushing, and indicated lower Es value than S, however it showed equivalent or higher value than Glass/Epoxy, Kevlar/Epoxy or steel tube. Therefore it is able to say that BPP rod has good energy absorption property. Second, carbon fiber reinforced braided rod also showed progressive crushing, however this type rod did not indicate so high Es value. It is thought that carbon fiber was not impregnated well with using same system to glass fiber. At last, to restrain machining cost, we used triggered jig instead of wedge. In this testing, specimen crushed by jig showed approximately 50% lower Es values of tapered specimen totally. For this reason, first fracture mode not to occur smoothly than tapered specimen, and this brittle fracture mode continued through compression testing. Hence we need to investigate optimal jig configuration for higher energy absorption properties.

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