Study of the impact energy absorption characteristics of GFRTP and JFRTP deep-drawn products

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Abstract

This paper studies impact energy absorption characteristics of FRTP deep drawn structures having three representative shapes, i.e., hemi-shere, truncated cone and cylinder. Two kinds of woven fibers, i.e., glass fiber and jute fiber, are used as reinforcement. Three distinct P-u characteristics are obtained corresponding to the structural shapes, for both the cases. Deformation and fracture modes under impact compression are compared in terms of load-displacement (P-u) curve, total absorbed energy and its efficiency, and their interrelationships are extensively discussed.

1 Introduction

Fiber reinforced plastics (FRP) have many excellent properties, such as low weight, high strength, and high resistance to the corrosion, and have been used in
various areas including industries and daily lives those for the sport articles. Especially for the safety design in the automobile industries, not only the structural design but also the design of the materials themselves which can efficiently and effectively absorb impact energy has become significantly important in recent years. It is necessary for the impact absorption material to have not only high energy absorption ability but also light weight to efficiently reduce consumed energy. Such well-balanced combination will be easily made realize by using FRP and its structures. So far, to the authors' knowledge, only several simple FRP structures like hollow cylinder have been widely studied in terms of impact energy characteristics. Kawada investigated energy absorption of CF/PEEK cylinder, where fracture mode and its impact speed dependency are systematically examined. Hull's study is on effects of configuration of laminates on the energy absorption mechanism for various FRP circular pipes, where several parameters such as test speed are changed. But these studies did not fully discuss the effect of structural aspect of FRPs on the impact energy characteristics, although structural shapes, especially cup shapes, are expected to significantly affects such characteristics even for the same FRP. The objective of this study is to investigate the effect of the structural shapes of FRP products on the impact energy characteristics, i.e., load-displacement curve and total absorbed energy. When such characteristics can be changed with the structural shape for a single FRP, we will be able to design or control them freely by arbitrarily combining certain fundamental structures. In this study, three representative shapes of products of fiber reinforced thermoplastics (FRTP) are chosen, i.e., hemi-sphere, truncated cone and cylinder, and are formed by using deep drawing technique. Two types of reinforcement fibers are used, i.e., glass fiber and degradable jute fiber. Impact compression tests are conducted under several test speed conditions and the effect of the structural shape on the impact energy characteristics are extensively discussed. Comparison is also made between the GFRT and the JFRT.

2 Specimen and experimental procedure

2.1 Specimen

2.1.1 Production of the laminates
Two thermoplastic resin sheets between which a fiber cloth is sandwiched were heated beyond the melting temperature and compressed in order for the resin to be impregnated into the fibers. The glass fiber cloth used as for the reinforced is Nitto Boseki #7628 (fabric density: warp 44 lines/25mm, weft 32 lines/25mm, weight: 215g/m²), while the jute fiber cloth is provided by Koizumi Jute Mills Ltd. Fine Hessian (fabric density: warp 16 lines/25mm, weft 14 lines/25mm, weight: 273g/m²). The thermoplastic resin used as the matrix is nylon sheet (NIHON MATAI, Elfan NT120 (polyamide (nylon) system resin,
64.47% for GFRTP and 47.04wt% for JFRTP. Mass content of the fiber in the laminates are 0.1mm, melting point: 120-130 degrees). Thickness of the laminates is 0.4mm for GFRTP and 1.2mm for JFRTP. Mass content of the fiber in the laminates are 64.47wt% for GFRTP and 47.04wt% for JFRTP.

2.1.2 Forming method
The specimen used in this study is formed into their cup shapes by using corresponding die sets. Shape and dimensions of the deep drawn specimen together with the pictures are shown in Fig.1. Here, hemi-spherical, truncated conical and cylindrical cups are chosen as the representative shapes.

![Fig. 1 Shapes and dimensions of GFRTP and JFRTP deep drawn products.](image)

2.2 Impact compression test

2.2.1 Experimental device for the test
Impact compression test is carried out and load-displacement curve is obtained from the measured load and velocity history of the deforming specimen. Schematics of the experimental apparatus for the impact compression tests used in the present study is shown in Fig.2. The dynamic load is measured by a quarts

![Fig. 2 Schematic diagram of experimental arrangement for impact test.](image)
piezoelectric type load washer and displacement of the deforming specimen is measured by the optical sensor together with a bar code film attached on the flyer, which makes possible a non-contact measurement. The flyer is accelerated by the air gun through the push-rod made of high dense wood. The mass of the flyer and the push-rod are 1.7kg and 1.3kg, respectively. The inertia of the flyer is efficiently absorbed by a stopper set in the end of the stroke guide so that the over-load is not converted to the load measurement system, even when specimen was completely fractured. The load washer is mounted in the rear of the base and fixed on the block by a preloading bolt. The test speed is ranged from 3.0m/s to 7.5m/s for JFRTP, while from 5.0m/s to 10.0m/s for GFRTP. The each test is repeated seven times to minimize the scatter of the data. The amount of energy absorption is calculated from the load-displacement curve.

2.2.2 Load measurement
The load washer(KISTLER company type 9021, allowable load 35kN) used in this study. Sensitivity of the load washer is (4.3pC/N), and the rigidity is (0.29mm /kN).

2.2.3 Measuring displacement
The measurement system is composed of the optical sensor (KEYENCE, FS-M1H), optical fiber (KEYENCE, type FU-75F), receiver and the transparent bar cord film attached and fixed on the flyer. Maximum response time of the sensor is 20μs. The bar cord space photocopied on a transparent film is 0.5mm. The bar cord film intercuts the laser beam penetrating between the optical fiber and the receiver. By analyzing the time history of the output voltage change, displacement of the deforming specimen is evaluated.

2.3 Static compression test
We also conducted static compression test for comparison by using the tension-compression Instron machine (Instron, type 4206) with the test speed of 60mm /min. Details of the deformation behavior together with the buckling mode and fracture mode are examined in comparison with the corresponding load-displacement curves for the three types of cup shapes.

3 Experimental results

3.1 GFRTP products

3.1.1 Observation of fractured specimen for GFRTP
Fractured specimen for the three representative shapes are shown in Fig.3, where a test speed of 10.0m/s is chosen as an example for the impact condition. For comparison those obtained under static compression is also shown. Here, the
fiber directions of the specimen in each picture are aligned so as to coincide with
the longitudinal and the transverse directions of the paper. We can observe
basically the same fracture modes as those under static loading condition for all
the specimen shapes. This implies that we can expect similar load-displacement
characteristics for the two cases, which will be discussed later. However we find
slight difference in the damage condition between the two. There observed many
whitened areas especially for the impact cases for all the shapes. Since the
whitening generally corresponds to the damage mainly due to microscopic
separation between fiber and matrix caused by relatively small plastic
deformation of the matrix, we can say that the response under impact loading
becomes rather brittle compared with the static case.

3.1.2 Load-displacement characteristics
Figure 4 shows load-displacement curves for the three representative shapes
comparing test speed effect. For the impact test the test speed of 10.0m/s is
shown an example. Distinct load-displacement curves corresponding to the three
different shapes are clearly observed. We also find the load-displacement curves
under impact loading condition is similar to the static case. This implies the
similar deformation and buckling modes for the two cases. Figure 5 shows
photographs of the deformation and buckling process for the cylindrical
specimen under static compression.

3.1.2.1 Hemi-spherical product The top part of the hemi-spherical specimen is
initially dented inward, yielding small and constant increase rate of load on the
load-displacement curve up to \( u = 17 \text{mm} \). When the top part touches the base at around \( u = 17 \text{mm} \), the load increase rate becomes large.

3.1.2.2 Truncated-conical product In the initial deformation stage for the truncated-cone type specimen, deflection occurs in the side wall of the specimen (\( u = 0-6 \text{mm} \)) followed by buckling which produces the first load peak. The load decreases rapidly after the buckling and keeps low value until the buckled part touches the base (\( u = 23 \text{mm} \)) where the load rises again. Therefore the load-displacement curve in this case can be characterized by the existence of the load plateau-like region following the first load peak.

3.1.2.3 Cylindrical product The cylinder shape exhibits the similar load-displacement curve to the truncated-cone shown above but has two peaks of load. Although the second peak is not so pronounced as the first one, it
characterizes different features of the load-displacement curve from the truncated-cone. The first peak corresponds to buckling of the side wall as in the other case. The second peak, on the other hand, is caused by buckling of columnar-like parts as clearly observed in Fig.5.(III).

3.2 JFRTP products

3.2.1 Observation of fractured specimen

Fractured specimen for the three representative shapes are shown in Fig.6, where

(a) Hemi-spherical
(b) Truncated-conical
(c) Cylindrical

(a-1) static  (b-1) static  (c-1) static

(a-2) impact [7.5m/s]  (b-2) impact [7.5m/s]  (c-2) impact [7.5m/s]

Fig. 6 Deformation of JFRTP deep drawn product.

a test speed of 7.5m/s is chosen as an example for the impact condition. On the contrary to the GFRTP discussed previously, different fracture modes are clearly observed between the two conditions. Particularly, the impact case exhibits brittle fracture modes causing fragmentations. The static case, on the other hand, roughly yields the same fracture mode as those in the GFRTP case. As pointed out above, impact loading condition tends to make FRP structures relatively brittle. This tendency is much more pronounced in the case of JFRTP.

3.2.2 Load-displacement characteristics of the fundamental shapes

Load-displacement curves of the three representative shapes for the JFRTP are shown in Fig.7 comparing static and impact loading conditions. As examples, results obtained under the test speed of 7.5m/s are chosen for the impact loading condition. As a whole, similar trend to the case of GFRTP discussed above can be observed except the cylindrical shape under impact loading. We will discuss the details in the following.

3.2.2.1 Hemi-spherical product Let us first observe the deformation process under static compression for the hemi-spherical specimen (the picture is not shown here). Similar to the GFRT case, the top part of the specimen is dented
Fig. 7 Load-displacement curves for JFRTCP deep drawn products obtained in impact loading test.

3.2.2.2 Truncated conical product In this case similar trend of the load-displacement characteristics as the glass cloth case can be observed, i.e., it has a single load peak followed by a load plateau-like region. We can observe basically the same deformation mode of the specimen under static compression, i.e., buckling of the side wall results in the first load peak. The impact condition, on the other hand, demonstrates quite different trend caused by completely different fracture mode, although shapes of the load-displacement curves together with the load levels for the both conditions coincide. There are two fracture modes for the impact condition. One is rather similar to the case of the cylinder cup shape shown below, where the top part is punched out right after the upper part of the side wall is bent inward without buckling. The side wall is successively bent and is collapsed in the final stage. Since no buckling occurs in this process relatively large load can be maintained even during the collapse, resulting in the same load level as the static case. The other case yields inward first. This first buckling, however, causes much larger increase rate of load in comparison with that for the GFRTP. This continues up to about $u=17\text{mm}$ where the dented top part touches the base causing larger load increase rate. The load reaches a peak at around $u=22\text{mm}$ and then it drops due to buckling of the side wall. Folded side wall causes further load increase after $u=25\text{mm}$. The impact compression test exhibits somewhat different load-displacement behavior from the static case mainly due to the different fracture mode as shown in the last section. The top part is also dented inside and touches the base resulting in the load increase in the first stage of the deformation with the same load level. During this process, however, cracks are initiated and rapidly propagated in the 45-degree directions from the fiber orientation on the top part giving rise to slight drop of the load at around $u=10\text{mm}$, which is not observed in the static case. The side part of the specimen supports the load after the cracking for a while, but it reaches final stage of fracture where the side part is buckled and then fractured circumferentially. The top part is broken into four pieces. As a whole, the impact case yields smaller load level than the static case.
3.2.2.3 Cylindrical product Similar to the truncated-cone shape shown above, the static case exhibits almost the same load-displacement characteristics to the corresponding GFRTP product, while the impact case shows distinct tendency, which is rather close to that of the truncated cone. The similar trend for the static case is because of the same deformation mode, i.e., buckling of the side wall causes the first load peak and is followed by small second load peak given rise to another buckling of the columnar-like parts. The different trend observed in the impact condition, on the other hand, is mainly due to the different fracture mode as pointed out in the previous section. The fracture occurs mainly in the side wall, whereas almost no damage can be observed in the top part. Buckling occurs firstly as in the static case, but it is rapidly followed by circumferential cracking at the edge part of the cylinder because of high load concentration. This punches out the top part, while the side wall breaks perpendicularly into several pieces, which results in very low load level.

4 Comparison of absorbed impact energy

Figure 8 compares amount of impact energy absorption as a function of test speed between the JFRT and the GFRTP products for each specimen shape. For all the cases and the range of test speed, the GFRTP exhibits larger energy absorption as can be easily predicted from the load-displacement characteristics discussed above. The JFRT tends to become brittle under impact loading conditions, resulting in the smaller amount of energy absorption. For both the
GFRT and the JFRTP, the cylinder exhibits the largest absorbed energy. The minimum absorbed energy, on the other hand, goes to the truncated cone for the GFRT and to the hemi-sphere for the JFRTP. The truncated conical, the order of the hemi-spherical with JFRTP.

5 Conclusion

Impact energy absorption characteristics of FRTP deep drawn structures having three representative shapes, i.e., hemi-sphere, truncated cone and cylinder, is studied in this paper. Three distinct load-displacement characteristics are obtained corresponding to the three structural shapes, for both the FRPs. Deformation and fracture modes under impact compression are compared in terms of load-displacement curve, total absorbed energy and its efficiency, and their interrelationships are examined. Major results obtained in this study are summarized as follows.

(1) Three distinct load-displacement curves are demonstrated to be obtained when the three representative cup shapes are chosen, which is controlled mainly by the deformation mode and partially by the fracture mode. Load peaks which characterize the load-displacement characteristics are closely related to buckling of the structure.

(2) Difference in the reinforcing fiber material, glass and jute fibers, mainly affects the fracture mode. The difference in the fracture mode causes rather different trends of load-displacement behavior and total energy absorption.

(3) The GFRT structures show relatively small effect of impact speed on the load-displacement characteristics, i.e., the shape of the curve, in comparison with the JFRTP structures, where increasing impact speed causes brittle fracture modes like separation of fibers from the matrix. The load level, on the other hand, is sensitive to the test speed for the GFRT, while it is insensitive for the JFRTP.

References

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