INVESTIGATION ABOUT DYNAMIC FLEXURAL FRACTURE PROPERTIES OF CARBON FIBER REINFORCED THERMOPLASTICS

T. Matsuo[1]*, J. Takahashi[1], K. Uzawa[1], T. Asakawa[1] and K. Kiriyama[2]
[1] Department of Systems Innovation, School of Engineering, The University of Tokyo, Tokyo, Japan
[2] TOYOBO CO., LTD., Research Center, Otsu, Japan
* Corresponding author (matsuo@giso.t.u-tokyo.ac.jp)

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1 Introduction

With the development of processing technology of high performance thermoplastic polymers, light-weight structural applications for fiber reinforced thermoplastic composites are expanding rapidly in a number of sectors because thermoplastic composites have potential to achieve high-cycle and low-cost manufacturing and high recyclability in contrast to thermosetting composites [1][2]. Above all, polypropylene (PP), by itself or with other polymers, has been widely applied to automotive structural members such as bumper faces and interior parts because of high toughness and simple fabrication techniques [3][4]. The wide practical use of such polymer components has been supported by the advanced vehicle body design with use of various computer simulation techniques.

Complying with this trend, Japanese METI-NEDO project has been developing a new type of advanced thermoplastic composite materials, carbon fiber reinforced thermoplastic composites (CFRTP), which are composed of surface treated carbon fiber (Mitsubishi Rayon) and maleic-acid modified polypropylene (TOYOBO), aiming to apply to the automobile main frame structures for the purpose of significant reduction of vehicle weight [2][5].

In particular, the main frame structural members of automobiles are required high energy absorption for collision safety. With increasing expectation of wide applications for the developed CFRTP, it is getting more important to predict the impact energy absorption by crash simulation. For this, it is essential to evaluate the mechanical properties and obtain the fracture behavior of the materials applied to the vehicle structure.

This study focused on the fracture behavior of the thermoplastic composites, observing the fracture phenomenon and investigating the yield stress dependent on the strain-rate.

2 Observation of Impact flexural behavior in high-speed three-point bending test

2.1 Experimental setup

In tensile test for carbon fiber reinforced plastics (CFRP), a high-speed photography has great effect in explanation of the fracture behavior of high-strength CFRP [6]. At first in this study, a high-speed camera (Hyper Vision HPV-1 by SHIMADZU) observed the dynamic flexural behaviors of the CFRP in high velocity three point bending test by using the impact tower (Dynatup by Instron), which has a recording system of load and deflection. A specimen with rectangular cross section rests on two supports and is impacted by means of dropping a crosshead with a loading nose right above the center of the specimen as shown in Fig.1. Some frames at the instant that the specimens are fractured by the impact load are took by the high-speed camera.

2.2 Test results - in comparison to carbon fiber reinforced thermosetting composites (CFRTS)

The experiments are conducted for two types of quasi-isotropic laminates. One is constructed from the developed CFRTP and the other is from commonly-used CFRTS. From test results, it was found that the flexural fracture behavior of the CFRTP is clearly different from that of the CFRTS.

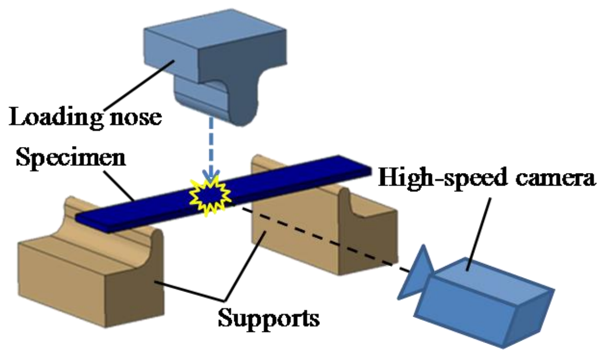

Fig.1. Observation of impact flexural behavior

Fig.2. Photographic images at the instant of flexural fracture of CFRTS by high-speed camera

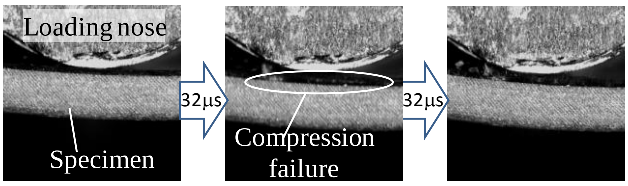

Fig.3. Photographic images at the instant of flexural fracture of CFRTP by high-speed camera

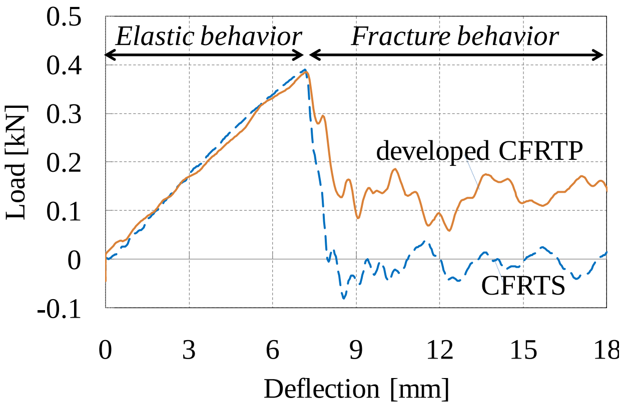

Fig.4. Adjusted load-deflection curves in impact flexural test

In the case of CFRTS, as illustrated in Fig.2, at just a 32 micro second intervals of the impact instant, a wide range of delamination occurs on the other side of the impacted surface. So after the first failure, the flexural stiffness of the specimen decreases rapidly and the load measured by the load cell attached to the loading nose falls down close to zero immediately following the maximum in the load-deflection curve, which is represented as a dashed line in Fig.4.

On the other hand, Fig.3 shows that the CFRTP specimen causes a compression failure of only a few surface layers at the beginning of the fracture during the same intervals instead of a large delamination. And, the load expressed as a solid line in Fig.4 is in a relatively gradual decline after the maximum load. In other words, the developed CFRTP has its potential to have higher impact absorption than the CFRTS. Where, both lines are adjusted so that their stiffness and strength are equal to each other and high frequent noises by oscillating at impact are reduced.

In addition to an assumption that what causes this mechanical behavior is largely dependent on the interfacial adhesive strength between the carbon fiber and the matrix resin, it is also necessary to investigate the mechanism how the interfacial property affects the dynamic behavior with relation to the strain rate dependency of the composites.

3 Relationship between yield stress and strain-rate of thermoplastic composites

3.1 Effect of strain rate on viscoelastic behavior of the polymer

In general, the yield stress is assumed by the Eyring theory for the yielding of polymers [4][7], which leads equation (1) and (2).

$$\sigma_y = \frac{RT}{V^*} \sinh^{-1}\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0^{\ *}}\right) \qquad (1)$$

$$\dot{\varepsilon}_0^{\ *} = \dot{\varepsilon}_0 \exp\left(-\frac{\Delta H}{RT}\right) \qquad (2)$$

where, σ_y is the yield stress, V^* is the activation volume, ΔH is the activation enthalpy, $\dot{\varepsilon}$ is the imposed strain rate at yield, $\dot{\varepsilon}_0^{\ *}$ is the constant reference strain rate, R is Boltzmann's constant and T is temperature.

For examination about the strain-rate dependency of the materials, the high-velocity three point bending tests with higher strain rate than 5 s^{-1} are performed by the impact tower mentioned above, and the low-velocity three point bending tests with strain rate ranging from 0.0001 s^{-1} to 0.1 s^{-1} are performed by the universal testing machine (Autograph AGS-X by SHIMADZU).

The load-deflection curves are recorded by the testing machines, and the stress-strain curves are obtained by assuming linear elastic relationship, where the stress and the strain are calculated from the load and the deflection taking into account the thickness and the width of the specimen and the support span. In a similar way, the strain rate is calculated with respect to the crosshead velocity of the testing machine.

3.2 Verification for the developed PP

In the process of developing a new type of CFRTP, TOYOBO has developed two types of polypropylene whose properties such as modulus, strength and adhesive strength between carbon fiber have been improved as shown in Table.1.

For obtaining the strain rate dependency of the developed PP, the experiments were performed about low modified PP by maleic acid. The resulting stress-strain curves are shown on Fig.5. Each curve has a yield point at which 0.2 % plastic strain remains after removing load. So, the yield stress is given at the yield point.

These curves demonstrate that the yield stress and the modulus of PP increase as the strain-rate gets higher. Fig. 6 indicates the relationship between the strain rate and the yield stress of low modified PP. It is clear that the yield stress σ_y increases linearly with the logarithm of the strain rate $\dot{\varepsilon}$, following the Eyring theory as represented in equation (1) and (2).

Table.1. Main properties of the developed PPs

	Low modified PP by maleic acid	High modified PP by maleic acid
Tensile modulus [GPa]	2.4	1.6
Tensile strength [MPa]	33	38
Interfacial shear strength between carbon fiber [MPa]	10	39

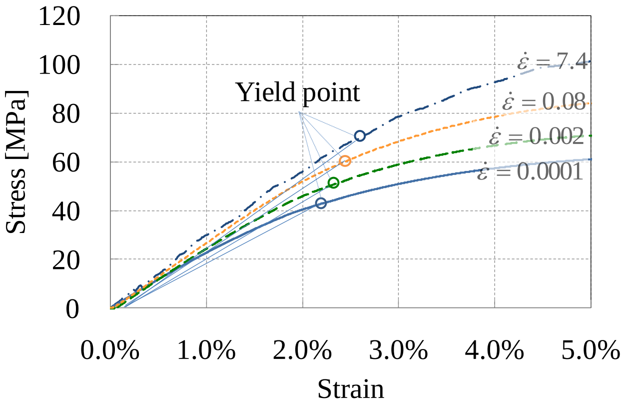

Fig. 5. Stress-Strain curves of low modified PP at several strain rates

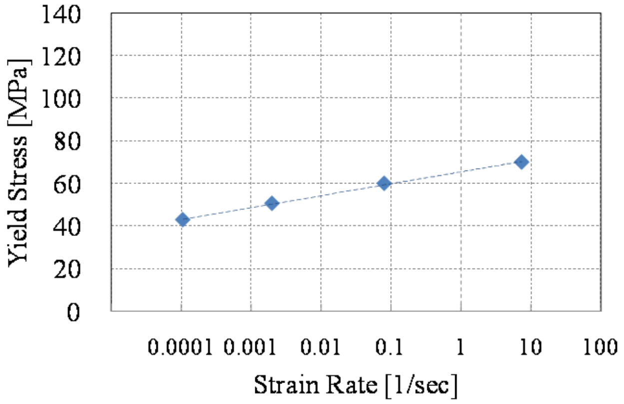

Fig. 6. Yield stress vs. strain rate of low modified PP

3.3 Verification for the developed carbon fiber reinforced thermoplastic composites (CF/PP)

In order to investigate how the interfacial behavior of CF/PP makes an effect on the strain rate dependency, two types of carbon fiber reinforced thermoplastic composite laminates are examined. Each of them is manufactured from a prepreg. A molding process from the prepreg to the uni-directional composite laminate is shown in Fig.7 [8]. The prepreg tape is a bundle of unidirectional carbon fibers impregnated with modified PP. Two types of composite laminates are greatly different from each other in terms of interfacial shear strength between CF and PP measured by the drop-let test as written in Table.1 [9].

The three-point bending tests controlling the crosshead velocity resulted in the stress-strain curves as shown on Fig.8. Clearly seen from these curves, the yield stress is considerably higher than that of the matrix PP itself at every strain rate by the reinforced effect of the carbon fiber, comparing to the stress-strain curves of PP in Fig.5. And, the yield stress increases with the strain rate, but the elastic modulus is the same at every strain rate.

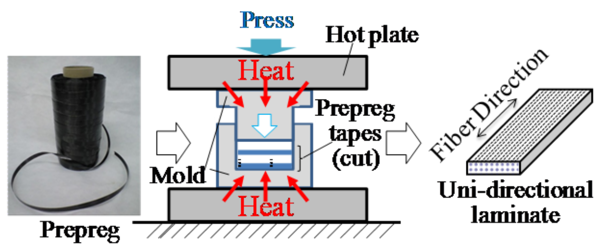

Fig. 7. Molding process for uni-directional laminate from thermoplastic prepreg

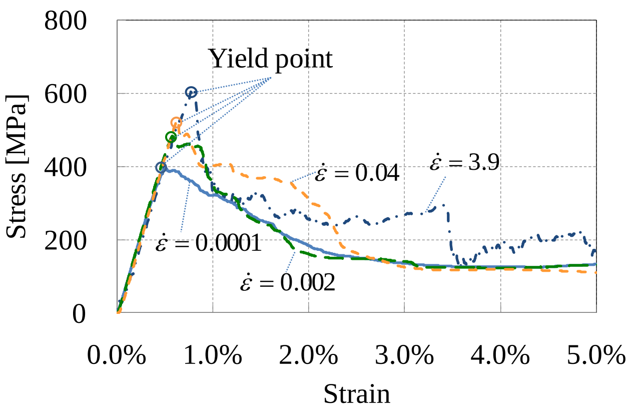

Fig. 8. Stress-Strain curves at several strain rates of the developed composite material (carbon fiber and low modified PP)

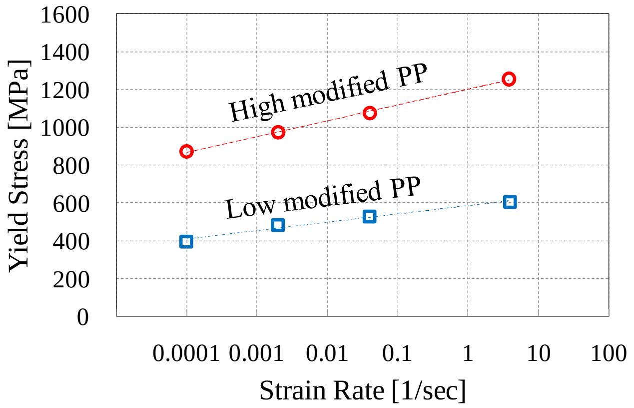

Fig. 9. Yield stress vs. strain rate of the developed CFRTP (impregnated with low modified PP and high modified PP)

It appears that not so much the elastic modulus as the yield stress is mainly affected by the strain rate in case of the composite materials.

In Fig.9, every yield stress obtained by low or high velocity bending test is plotted as a function of strain rate. The lower plots and line (from 400 *MPa* to 600 *MPa*) indicate test results with relation to low modified PP, and the upper ones (from 800MPa to 1300MPa) indicate test results with relation to high modified PP. In both cases, the yield stress increases linearly with the logarithm of the strain rate. Moreover, the yield stress in case of high modified PP is approximately proportional to that in case of low modified PP at every strain rate through the influence of the interfacial shear strength between carbon fiber.

4 Conclusion

The dynamic flexural behaviors of the developed thermoplastic composites were examined by low and high velocity three-point bending tests. Observation test using the high-speed camera and verification experiments for the strain rate showed the following.

1. The developed CFRTP exhibits high toughness, and its impact absorption is superior to the CFRTS. The high-speed photography made clear the influence of the fracture mode at impact.
2. The composites also followed the yielding theory for polymers that the yield stress is linearly with the logarithm of the strain rate.
3. The improvement of the interfacial adhesive strength between CF and PP results in the increase of the yield stress of the developed thermoplastic composites, not only in static behavior but also in dynamic behavior.
4. These results make it possible to estimate the yield stress at the compression failure in dynamic flexural behavior particularly from the strain rate and the interfacial property of fiber reinforced thermoplastic composites.

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