Flexural Properties of Multi-Tow Structures Constructed from Glass/Polypropylene Tape under Various Manufacturing Conditions

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Abstract: In this study, a multi-tow structure that can provide load-bearing functionality was fabricated through a proposed consolidation process proposed using polypropylene-impregnated continuous-glass-fiber composite tape (glass/PP tape). The flexural properties of the multi-tow structure were analyzed to evaluate the influence of the processing temperature, processing speed, number of glass/PP tapes, and glass fiber content of the glass/PP tapes. The proposed process for constructing the multi-tow structure can generate straight, curved, and looped three-dimensional structures by using a multi-joint robot and instantaneous consolidation of glass/PP tapes. As the number of glass/PP tapes increased, the resin-rich area increased and the void volume fraction in the multi-tow structure increased from 2 to 5 vol%, while the flexural strength decreased. However, when the number of glass/PP tapes and processing temperature were adjusted appropriately, the flexural strength of the multi-tow structure that can be constructed at speeds 30 times faster than those of conventional pultrusion process was relatively superior. The results of a finite element analysis, confirmed that the inclusion of the proposed multi-tow structure in a bumper beam was effective in reducing deformation and absorbing the impact energy due to external loads.

Keywords: Multi-tow structure, Continuous-glass-fiber-reinforced composites, Glass/PP tape, Insert injection molding, Bumper beam

Introduction

Fiber reinforced composites, which have seen widespread applications in aircraft manufacturing, have also been used in a variety of industries, including military defense, construction, sports, leisure, and automotive industries. In particular, for automotive parts, plastic materials have traditionally been used for both the interior and exterior components of vehicles. Such materials are typically used for components with low load-bearing requirements and are fabricated using simple injection molding processes.

In terms of environmental protection, there is a constant need to reduce the weight of vehicles to improve the fuel efficiency of internal combustion engines. Recently, for electric vehicles that have been developed to reduced global emissions, automotive companies have strived to increase the driving range by reducing the weight of parts other than batteries. To reduce the weight of vehicles, a wide range of studies have been conducted on the application of various fiber-reinforced composites to components requiring structural strength and the development of processes capable of applying such composites [1-6]. Fiber-reinforced thermoset composites applied to aircraft structures have been adopted in small quantities in high-performance and expensive automobiles. In recent years, the application of such composites to passenger cars was first introduced in the “i series” vehicles of BMW, however, they are currently difficult to recycle economically. In 2020, despite the decline in car production due to the COVID 19 crisis, approximately 78 million vehicles were produced worldwide [7]. If it is assumed that at least one kg of thermoset composites are applied to every vehicle, then approximately 78,000 tons of composite waste will be generated by the end of those vehicle’s life cycle, which is difficult or impossible to recycle. Additionally, if the reinforcing fiber is carbon, which is approximately 10 times more expensive than glass fibers, it can be a huge burden on consumers because of the increase in the price of automobile components. Therefore, various studies have being conducted on fiber reinforced composites in which natural fibers are the reinforcement in thermoplastic polymer matrices, making them recyclable, cost competitive, and applicable to automobile parts [1-3]. However, the mechanical properties of natural fiber reinforced composites are still inferior compared to glass fiber-reinforced composites. When applying glass fiber reinforced composites to automobile parts, short fiber reinforced thermoplastic composites can be applied to various mass-produced parts while satisfying the high design freedom of parts through injection molding. However, short fiber thermoplastics have limited applications in high-performance parts owing to their low strength and stiffness [8-11]. In contrast, continuous fiber reinforced thermoplastic composites have sufficient strength and stiffness [12], but it is difficult to form complex shapes from such materials [13]. For the commercialization of such continuous fiber reinforced composites, the pultrusion process has been used traditionally, but this process is difficult to apply to curved parts. Additionally, the production speed of the pultrusion process is slow, leading to high production costs for the pultrusion of curved parts [14,15]. Many researchers have studied the
development of integrated processes to increase the degree of freedom of parts design and the productivity of continuous glass fiber reinforced thermoplastic composites. A combined process considering glass mat thermoplastics (GMTs), which are a type of continuous fiber reinforced composite, and short glass fiber reinforced composites [16], as well as an over-molding process for multiple strands of commingled glass, polypropylene, and GMT based on compression molding [17] were studied. However, such studies have been limited to plate shapes based on the use of compression molding processes for GMT molding.

In order to overcome the aforementioned limitations, in this study, a multi-tow structure made of continuous glass fiber thermoplastic composite is inserted and a production method for injecting short fiber reinforced thermoplastics on the exterior of the multi-tow is proposed. This method can implement various part shapes, and where load support is required, the multi-tow structure can serve as sufficient load support. Since the multi-tow structure can fabricate various curvatures, it can be applied to various parts, allowing greater degrees of design freedom in the manufacturing of parts. In addition, higher productivity than that of the pultrusion process is expected to lower the manufacturing cost. The multi-tow structure with load-bearing functionality was fabricated through a consolidation process using polypropylene-impregnated continuous glass fiber tape (glass/PP tape). Additionally the flexural properties of the multi-tow structure were analyzed to evaluate the influence of the processing temperature, processing speed, number of glass/PP tapes, and glass fiber content in the glass/PP tapes. Through this, an attempt was made to suggest effective manufacturing conditions for load bearing of the multi-tow structure. Finite element analysis (FEA), a common method for evaluating structural behavior [18], was carried out to apply the multi-tow structure to the rear bumper beam of automobiles, which was fabricated through the injection molding of only short glass fiber thermoplastics, and assess whether the application of the multi-tow structure improves the structural performance compared to the case with only short glass fiber thermoplastics. It was confirmed that deformation was reduced and the absorption of impact energy was improved under external loads for the rear bumper beam by inserting a multi-tow structure in the core and injecting short glass fiber reinforced thermoplastics into the shell parts.

### Experimental

#### Material Composition

The glass/PP tapes used in this study were manufactured by LOTTE Chemical and impregnated with LOTTE Chemical polypropylene and Owens Corning glass fibers (SE4121). Table 1 lists the properties of the glass fibers and the polypropylene resin used. The glass fiber content and mechanical properties of the glass/PP tape manufactured by LOTTE Chemical are listed in Table 2, and the shape is presented in Figure 1. The glass fiber content in the glass fiber tape used was confirmed by measuring the density of the tape in accordance with ASTM D 792.

#### Multi-tow Structure Manufacturing Process

The proposed multi-tow structure for load-bearing parts was fabricated through a three-step process, as shown in Figure 2. First, multiple strands of glass/PP tape were fed into an oven at uniform speed through an unwinder, then heated to an appropriate temperature in an oven, passed through nozzles of uniform diameter, and fabricated into a multi-tow structure. The multi-tow structure was bent into the final structure of the reinforcing shape by a multi-axis

### Table 1. Properties of the glass fibers and polypropylene

| Glass fibers          | Manufacturer data | Test data (Mean±Standard Deviation) |
|-----------------------|-------------------|------------------------------------|
| Linear density (tex)  | 2,400             | (2,398±2.4)                        |
| No. of filaments      | 4,000             | -                                  |
| Specific gravity (mg/m³) | 2.62-2.66        | -                                  |
| Tensile strength (MPa)| 3,750             | 2,525±304                          |
| Young’s modulus (GPa) | 81                | 80.7±3.6                           |
| Average fiber diameter (µm) | 17            | (16.95±0.16)                       |

| Polypropylene          | Manufacturer data | Test data                          |
|------------------------|-------------------|------------------------------------|
| Glass fiber weight content (%) | 39.5              | (18.3 vol %)                       |
| Theoretical density (mg/m³) | 1.22              | 1.33                               |
| Measured density (mg/m³)  | 1.20              | 1.29                               |
| Void volume content (%)  | 1.32              | 3.23                               |
| Tensile strength (MPa)   | 408±26            | 448±13                             |
| Young’s modulus (GPa)    | 15.8±0.47         | 18.2±0.50                          |
Before the structure was cooled, the multi-axis robotic system was manufactured by Kistar Ltd., Korea, as shown in Figure 3. In this study, the experimental results were mainly obtained using 4 or 6 strands of glass/PP tapes while the 3 to 6 strands were used to obtain the results according to the number of glass/PP tapes used. The glass/PP tape contains 40, 50 wt% of glass fiber each. Since this is consolidated, the glass fiber content of the multi-tow structure is also maintained at 40, 50 wt%, respectively.

As shown in Table 3, multi-tow structures were fabricated with various processing temperatures, processing speeds, numbers of glass/PP tapes, and glass fiber content in the
Measurements of the flexural properties of the multi-tow structures were carried out as shown in Figure 5 using the ASTM D 4476/D4476M-14, which is a measurement standard for the flexural properties of drawn fiberglass-reinforced plastic rods. Based on ASTM D 2734-16, the void volume fraction in the multi-tow structures was calculated using the following equation.

\[
\text{Void volume fraction (\%)} = \left(1 - \frac{\rho_{\text{m-tow, m}}}{\rho_{\text{m-tow, t}}}\right) \times 100
\]

where \(\rho_{\text{m-tow, m}}\) and \(\rho_{\text{m-tow, t}}\) are the measured density and theoretical density, respectively, based on the mixture rule for multi-tow structures assuming there is no void present.

**Results and Discussion**

**Effects of Consolidation Temperature on Flexural Strength**

To investigate the effects of temperature on the consolidation process of the glass/PP tapes, the flexural strength was measured for multi-tow structures consisting of six strands of glass/PP tape with glass fiber contents of 40 and 50 wt% while increasing the processing temperature from 170 to 220 °C. As shown in Figure 6, when six strands of glass/PP tape with a glass fiber content of 50 wt% were used, the change in the flexural strength was negligible based on the temperature of the oven. The average flexural strength was approximately 305±6.8 MPa.

However, for the multi-tow structure of six glass/PP tapes with a glass fiber content of 40 wt%, the trend was different from that of the above case with a glass fiber content of 50 wt%. As shown in Figure 7, the average flexural strength increased with increasing processing temperature. In particular, the flexural strength increased by approximately 10-20 % compared to the multi-tow of glass fiber content of 50 wt% in the temperature range of 200-220 °C. In the case of the 50 wt% multi-tow structure, the content of
polypropylene, which acts as a binder in the glass/PP tape, was relatively small, so it melted even at a low temperature above *Tm* (melting temperature), and the variation in flexural strength according to the processing temperature was small. In the case of the 40 wt% multi-tow structure containing a relatively large amount of polypropylene, if the retention time in the oven for tape consolidation was long, the deviation of the increase in flexural strength according to the increase in processing temperature is expected to decrease. In this case, there was the problem that productivity was lowered owing to the increase in retention time. Therefore, to fabricate a multi-tow structure with high flexural strength without compromising productivity, it was necessary to maintain the processing temperature above 200 °C to facilitate the consolidation of the glass/PP tape by sufficiently melting the polypropylene matrix.

**Effects of the Number of Glass/PP Tapes on Flexural Strength**

In order to investigate the flexural strength according to the number of glass/PP tape strands, the flexural strength of the multi-tow structure made using 3 strands of glass/PP tape with 50 wt% glass fiber content was compared with that using 6 strands fabricated at the processing temperature of 200 °C, which is the reference condition, and the consolidation speed of 0.5 m/sec. Experimentation was carried out in order to find a way to improve the flexural strength of the multi-tow structure made of glass/PP tape with glass fiber content of 50 wt%. The experiment result showed that the flexural strength decreased for the multi-tow structure made using 5 or more strands of glass/PP tape of 50 wt% glass fiber content as shown in Figure 8. Observation of the cross section using an optical microscope as shown in Figure 9 revealed that voids were present in not only within the glass/PP tape but also in the interface between tapes, which was judged to be the most significant cause of the flexural strength degradation as presented in literature where the presence of voids led to material property degradation [19, 20]. To confirm the effect of voids on the flexural strength, the flexural strength was measured for the multi-tow structure made by using 4 strands of glass/PP tape with a glass fiber content of 50 wt% and varying the processing temperature from 170 to 220 °C. As shown in Figure 10, the flexural strength increased in comparison to that of the multi-tow made using 6 strands of glass/PP tape with a glass fiber content of 50 wt% at the processing temperature of 190 °C or higher, which was greater than the flexural

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**Figure 8.** Flexural strengths of multi-tow structures with different numbers of glass/PP tapes (glass fiber content of 50 wt%).

**Figure 9.** Optical microscope images of cross sections of multi-tow structures with different numbers of glass/PP tape (glass fiber content of 50 wt%); (a) three tows, (b) four tows, (c) five tows, and (d) six tows.

**Figure 10.** Flexural strengths of multi-tow structures with different numbers of glass/PP tapes (four and six strands with a glass fiber content of 50 wt%).
strength of the multi-tow structure made using 6 strands of 40 wt% glass/PP tape.

Effects of Glass Fiber Content on Flexural Strength
To investigate the effect of the glass fiber content in the glass/PP tapes on the flexural strength of the multi-tow structures, multi-tow structure specimens were fabricated from six strands of glass/PP tape with glass fiber contents of 40 and 50 wt%, and their flexural strengths were measured. As shown in Figure 11, the average flexural strength of the multi-tow structure over the entire processing temperature range was 327±17 MPa for the glass fiber content of 40 wt% and 305±6.8 MPa for the glass fiber content of 50 wt%. The average flexural strength of the six-stranded multi-tow structure with a glass fiber content of 40 wt% was approximately 7% greater than that with a glass fiber content of 50 wt%. Figure 12 reveals that the six-stranded multi-tow structure with a glass fiber content of 40 wt% had a lower void content based on the optical microscope images of the cross sections of the consolidated structure. For multi-tow structures with a glass fiber content of 40 wt%, the flexural strength tended to improve as the processing temperature increased. Therefore, the processing temperature had a greater impact on the flexural strength of the multi-tow structures compared with the influence of the glass fiber content.

Effects of Production Speed on Flexural Strength
The process of fabricating the multi-tow structure was similar to that of the conventional pultrusion process, but it was at least 30 times faster than the pultrusion process at a speed of 1.0 m/min [10,11]. To analyze the effects of the production speed on the consolidation states of the multi-tow structures, four strands of glass/PP tape with a glass fiber content of 50 wt% were used and the process temperature was fixed at 180 °C while the production speed was varied from 0.5 to 1.0 m/sec. As shown in Figure 13, when the production speed was 0.5 m/sec, the average flexural strength was 323±46 MPa and the average flexural strength was 337±49 MPa for 1.0 m/sec. The flexural strength of the multi-tow structure produced at a higher production speed was approximately 7% greater than that of the structure produced with the lower production speed. As the production speed of the multi-tow structure increases, greater tension was applied to the glass/PP tape, resulting in a more compact consolidation state. The multi-tow structure manufacturing process proposed in this study did not deteriorate the flexural strength of the produced structure even when the production speed was higher than that of the conventional pultrusion process.

FEA of Tow Inserted Bumper Beam

Finite Element Analysis
To verify the effectiveness of the multi-tow structures, a
A central impact test model for an automotive rear bumper beam with and without a multi-tow structure was constructed based on the low speed impact regulation requirements of ECE 42, as shown in Figure 14. The analysis are carried out using the LS-DYNA software. As shown in Figure 15, the multi-tow structures and short glass fiber reinforced thermoplastics were composed of hexahedral and tetrahedral solid elements, respectively, whilst the other parts consisted of triangular and rectangular shell elements. The interfacial adhesions of the hexahedral elements of the multi-tow structure and tetrahedral elements of the short glass fiber reinforced thermoplastics were configured as tied contacts. The MAT 24 (MAT PIECEWISE LINEAR PLASTICITY) and MAT 54 (MAT ENHANCED COMPOSITE DAMAGE) material profiles provided by LS-DYNA were applied to the bumper beam and multi-tow structure, respectively. MAT 24 and MAT 54 used in FEA are material cards that have been verified in previous study [21] and their mechanical properties are listed in Table 4. Among the mechanical properties of the multi-tow structure, the transverse directional properties and

**Table 4.** Mechanical properties of the multi-tow structure and short glass fiber thermoplastics

| Property                         | Multi-tow structure | Short glass fiber |
|----------------------------------|---------------------|-------------------|
| Matrix                           | Polypropylene       |                   |
| wt% of glass fibers              | 40                  | 30                |
| Density (mg/m³)                  | 1.20                | 1.14              |
| Tensile strength (MPa)           | 312                 | 98                |
| 1 dir                            |                     |                   |
| 2 dir                            | 31                  |                   |
| Tensile modulus (GPa)            | E₁                   | 14.9              |
| 1)                               | E₂                   | 7.0               |
| 2)                               | (Isotropic)         |                   |
| Flexural strength (MPa)          | 330                 | 110               |
| Flexural modulus (GPa)           | 17                  | 5.4               |
| Shear modulus (G_{12}, GPa)      | 1.0                 | 2.7               |
| Poisson’s ratio                  | v12                 | 0.36              |
| 1)                               | v23                 | 0.40              |
| 2)                               | (Isotropic)         |                   |

Notations 1, 2, and 3 indicate the longitudinal, transverse, and thickness directions of each fiber, respectively and the multi-tow was assumed to be a transversely isotropic material in 2 and 3 directions.

**Figure 14.** Bumper beam analysis model; (a) bumper cover and trunk panel cross-section and (b) center pendulum impact test layout.

**Figure 15.** Finite element configuration for structural analysis; (a) hexahedral elements of the multi-tow structure and tetrahedral elements of the over-molding and (b) tetrahedral elements of the short fiber reinforced thermoplastics without the multi-tow structure.
shear modulus could not be measured by the multi-tow itself, so the glass/PP tape was made into a laminate specimen for measurement. The notations 1, 2, and 3 indicate the longitudinal, transverse, and thickness directions of each fiber, respectively. In addition, the multi-tow was assumed to be a transversely isotropic material in 2 and 3 directions. For the 30 wt% short glass fiber material, injection specimens in accordance with ASTM were prepared, their mechanical properties were measured, which was assumed to be an isotropic material. The total weight of the inserted multi-tow structure was 75.4 g. The weight of the bumper beam was increased by only 14 g from 2,020 g to 2,034 g because the multi-tow structure was inserted in the place of the original 30 wt% short fiber material so that only the weight with respect to the difference in density increase by 0.6 wt%. To investigate the bumper beam performance, an FEA was performed based on a center pendulum impact of 4.0 km/h (2.5 mph) on a 1,250 kg compact vehicle.

The deflection, intrusion, deformation shapes, and energy absorption of the bumper beam were analyzed and the results for the bumper beams are shown in Figure 16. The impacted pendulum was rebounded at 0.039-0.040 s and the bumper beam was impacted by an external load until it rebounded. After the rebound, no additional external load was applied to the bumper beam, and no additional damage was applied to the vehicle. Therefore, the bumper beam needed to be designed to absorb as much impact energy as possible and rebound in a short period of time.

At the impact of the pendulum, the intrusion and deflection of the bumper beam with the multi-tow structure were smaller than those of the bumper beam without the multi-tow structure by approximately 1.1 and 1.6 mm, respectively. The energy absorption of the bumper beam with the multi-tow structure and the bumper beam with only the short glass fiber thermoplastics up to the rebound time was 554 and 536 J. Thus the energy absorption of the bumper beam increased by 19 J (3.4 %) through the insertion of the multi-tow structure. Additionally, crack initiation was delayed approximately 0.003 s at the impact zone of the bumper beam with a multi-tow structure, however, the location of crack initiation was similar in both cases. The cracked part was considered to be fundamentally vulnerable.

Figure 16. Comparisons of bumper beams with and without the multi-tow structure; (a) deflection and intrusion plots of the bumper beam, (b) deformed cross-sectional shapes of the bumper beams, (c) crack occurrences at 0.021 and 0.024 s, and (d) force-displacement curve.
Therefore, the FEA revealed that the multi-tow structure fabricated from glass/PP tape was effective at alleviating bumper beam deformation and increasing impact energy absorption under external impact.

**Conclusion**

The rear bumper beam of automobiles prevents the penetration of objects (obstructions or other vehicles) that
impact at low velocities and protect passengers by absorbing the impact energy through flexural loading. Therefore, the flexural strengths of multi-tow structures fabricated from glass/PP tapes were investigated. To analyze the effects of different processing conditions, this study compared the flexural strengths of the multi-tow structures by varying the processing temperature, processing speed, number of glass/PP tapes, and glass fiber content in the glass/PP tapes. The main cause of the poor flexural strength was attributed to the voids introduced into the multi-tow structures during the consolidation of the glass/PP tapes in the manufacturing process. Analysis of the effects of the processing conditions on the multi-tow structures provided the following results.

1. The processing temperature must be maintained above 190 °C to ensure proper consolidation. When six strands of glass/PP tape with a glass fiber content of 40 wt% were processed at 200 °C and four strands of glass/PP tape with a glass fiber content of 50 wt% were processed at 190 °C, the flexural strength increased for both cases.

2. By varying the number of glass/PP tape strands from three to six strands, it was confirmed that the flexural strengths of the multi-tow structures fabricated using less glass/PP strands were greater than those of the multi-tow structures fabricated using more glass/PP tape strands.

3. The higher glass fiber content of the glass/PP tape resulted in a lower flexural strength of the multi-tow structure. This phenomenon was a result of the insufficient amount of PP in the matrix due to the higher glass fiber content, which leads to poor bonding of the glass/PP tape during the heating process and higher void content.

4. The proposed fabrication process provided high production speeds compared to the conventional pultrusion process (approximately 30 times faster). When comparing the flexural strengths of the multi-tow structures fabricated at speeds of 0.5 m/sec and 1.0 m/sec, the flexural strength was greater at higher processing speeds. In the multi-tow structure fabrication, greater tension was applied to the glass/PP tapes as the production speed increased, which had a positive effect on the consolidation. This feature is advantageous in that high-performance multi-tow structures with improved productivity can be developed.

5. Numerical analysis of the structural performance of bumper beams with and without inserted multi-tow structures showed that the energy absorption rose by about 3.4 % whereas the design weight of the bumper beam increased by 0.6 wt% due to the multi-tow structure insertion, revealing that the insertion of the multi-tow structure was an effective reinforcement. Additionally, it was observed that the insertion of the multi-tow structure fabricated from glass/PP tapes was effective at reducing the bumper beam deformation and crack occurrence under external loads. It is expected that optimization of the multi-tow structure insertion can be useful when designing highly efficient bumper beams against external impact loads.

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Conflicts of Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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