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Collapse characteristics of a circular-cross-section CFRP pipe structure member using finite element analysis

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Abstract: Carbon fiber reinforced plastics (CFRPs) are advanced composite materials that have been used as lightweight structural materials for vehicles. Unlike general isotropic materials, the structural characteristics of composite materials are strongly influenced by the stacking directions and sequences of the composite laminates. In this study, finite element analysis was used to predict the material properties of the carbon fibers and the resin composing a CFRP in cases of laminated carbon fibers and modified external angles. The results verify the approach's reliability by comparing the simulation results and the real test results related to the material properties of the carbon fibers and the resin. The results of the finite element analysis and the experimental results were compared with the load-displacement curves and the maximum load. The $[0_2/90_2]_S$, $[90_2/0_2]_2$, and $[0/90]_{2S}$ specimens showed a maximum error rate of 8.6%, whereas the $[90_2/0_2]_S$, $[0_2/90_2]_2$, and $[90/0]_{2S}$ specimens showed a maximum error rate of approximately 12.93%. By applying CFRP static collapse analysis of fiber properties and resin properties through basic experiments and basic theory, we predicted the properties of CFRPs through finite element analysis; an error rate of approximately 10% indicated that our approach is effective.

Keywords: CFRP; FEA; GENOA; pipe structure member; static-collapse.

1 Introduction

The recent development of the techniques used in high-tech industries can be categorized into two types: technical advances for safety and convenience and advances in mechanical technology toward achieving eco-friendly and lightweight materials. In this regard, automotive and aerospace industries have inspired the development of advanced materials (1). In the automotive industry, the critical objectives include ensuring pedestrian safety, protecting the environment and developing new materials and energy sources. Accordingly, the greening of automobiles relates to not only the use of green fuels but also a reduction in fuel consumption. Thus, automotive weight has become an important issue that remains to be solved by the automotive industry for achieving high fuel efficiency. The most important goals in terms of the design of automobiles are safety and environmental-friendliness. A vehicle's structure must be lightweight to improve the fuel-efficiency and reduce exhaust emissions (2, 3). Therefore, in addition to considering approaches to reduce the weight of a vehicle structure, vehicle designers should be the most concerned about ensuring a good safety performance. Carbon fiber reinforced plastics (CFRPs) are advanced composite materials that have been used as structural materials for vehicles. They offer numerous, advantages, including high specific strength, high specific rigidity, low thermal deformation, good corrosion resistance and good vibration-attenuation properties (4, 5). Unlike general isotropic materials, the structural characteristics of composite materials are strongly influenced by the stacking directions and sequences of composite laminates. CFRPs comprise carbon fibers and a matrix. Composite laminas with different characteristics, such as different material properties, thicknesses and azimuths, can be stacked together to produce a very effective structure. This approach enables composite laminates to be adapted to exhibit a specific response under specific load conditions (6). In some cases, the structure of laminates provides unique advantages for reducing weight and manufacturing costs. The mechanical properties of CFRPs comprising a matrix of nonlinear fiber materials are particularly difficult to precisely measure because the techniques for measuring their mechanical and physical properties are expensive and require extensive

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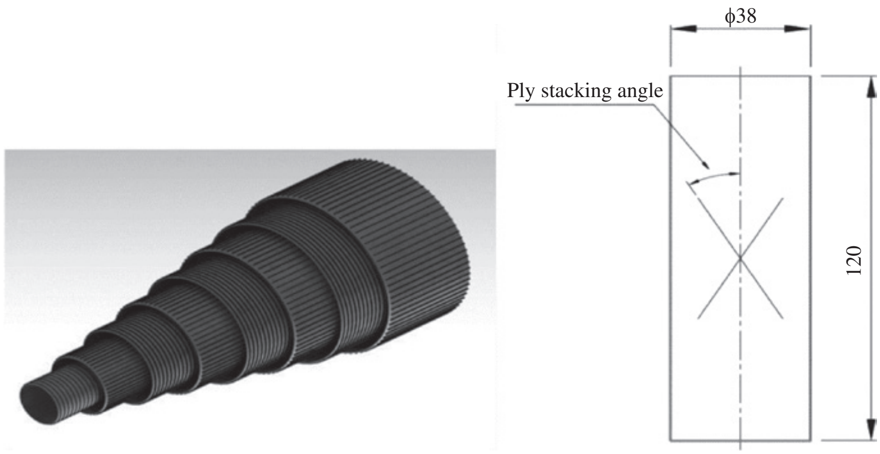

Figure 1: Static collapse specimen circular member geometry and drafting.

experimental time. Numerous investigations have been conducted to analyze the mechanical properties of composite materials via various experiments (7, 8). In the present study, finite element analysis was used to predict and obtain the material properties of a carbon fiber and a resin even when the interface of the carbon fiber laminates changed and the external stacking angle was modified. Through a comparison of the simulation results and actual test results, we verify the reliability of our measurement method for predicting the material properties of the carbon fiber and the resin.

Table 1: CFRP prepreg sheet material properties and definition of CFRP specimen.

	Fiber (carbon)	Resin (epoxy)	Prepreg sheet
Density (kg/m^3)	1.83×10^3	1.24×10^3	–
Tensile strength (GPa)	–	–	2.53
Elastic modulus (GPa)	240	3.6	132.7
Breaking elongation (%)	21	3	1.3
Poisson's ratio	–	–	0.3
Resin content (% wt)	–	–	33

Table 2: Definition of CFRP specimen.

Interface number	External angle [90]	External angle [0]
2	$[90_2/0_2]_s$	$[0_2/90_2]_s$
4	$[0_2/90_2]_2$	$[90_2/0_2]_2$
6	$[90/0]_{2s}$	$[0/90]_{2s}$

2 Materials and methods

2.1 Static-collapse specimen

Static-collapse specimens are the basic shapes of the front-end side members used in vehicles. As shown in Figure 1, a CFRP prepreg sheet was used to form a circular composite material with eight layers. In addition, to evaluate the collapse characteristics according to the change in stacking composition of the CFRP, which is an anisotropic material, the stacking angle was altered by laminating the eight prepreg sheets in the axial direction. The geometry of the test specimen was a circular pipe: diameter, 38 mm; length, 120 mm. The specimen materials were unidirectional prepreg sheets (Hankuk Carbon Co., Ltd, Korea, CU125NS carbon/epoxy composite, unidirectional 125 g/m^2). The specimen specifications and prepreg-sheet properties are shown in Tables 1 and 2, respectively. To ensure the reproducibility of the measurements, five static-collapse tests were conducted for each specimen (9, 10).

2.2 Static-collapse experiment methods

We conducted static-collapse tests to investigate the collapse characteristics according to the change in the external angle of the circular CFRP structure members. This method delivers a compressive force to the specimen using a universal testing machine (UTM) (Universal Testing Machine, AG-IS 100 kN). Two compression jigs were positioned between the load cell and the actuator to enable an equal compressive load to be applied at 10 mm/min through displacement control (11). To increase the reproducibility, five static-collapse tests were performed. However, as evident from the measurements conducted under different environmental conditions, the properties of a CFRP can be influenced by the environment. The static-collapse tests in this study were performed at

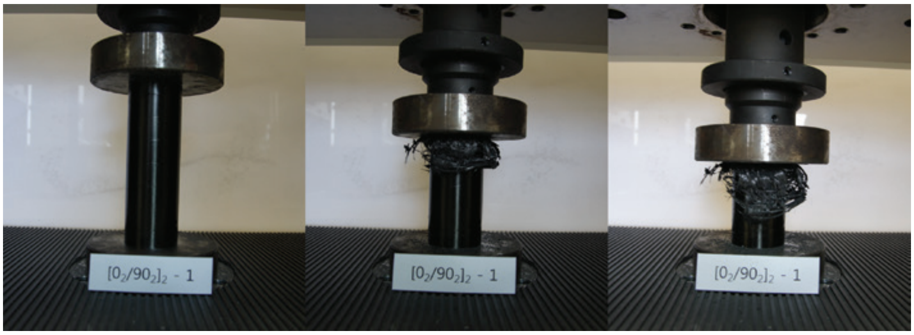

Figure 2: Collapse processing of a circular CFRP composite structure member, $[90_2/0_2]_s$.

23±3°C and at a relative humidity of 50±10% to prevent experimental failures due to environmental factors (12). The collapse process for the $[90_2/0_2]_s$ circular CFRP composite structure members is shown in Figure 2.

2.3 Finite element analysis

The finite element method (FEM) is a numerical technique used for continuous functions in a discrete model, where in the body to be examined is divided into several smaller parts, called elements. This element model is composed of several continuous element functions. The elements are interconnected through nodes. The accuracy of the FEM improves with increasing number of nodes (13). In this study, a finite element model of the composite-specimen static-collapse

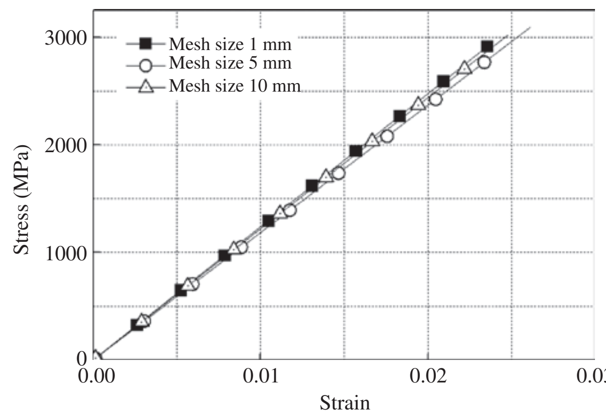

Figure 3: Grid independence test on $[\pm0]_{10}$ tensile testing.

load was constructed and finite element analysis was conducted. Finite element simulation was performed for a CFRP

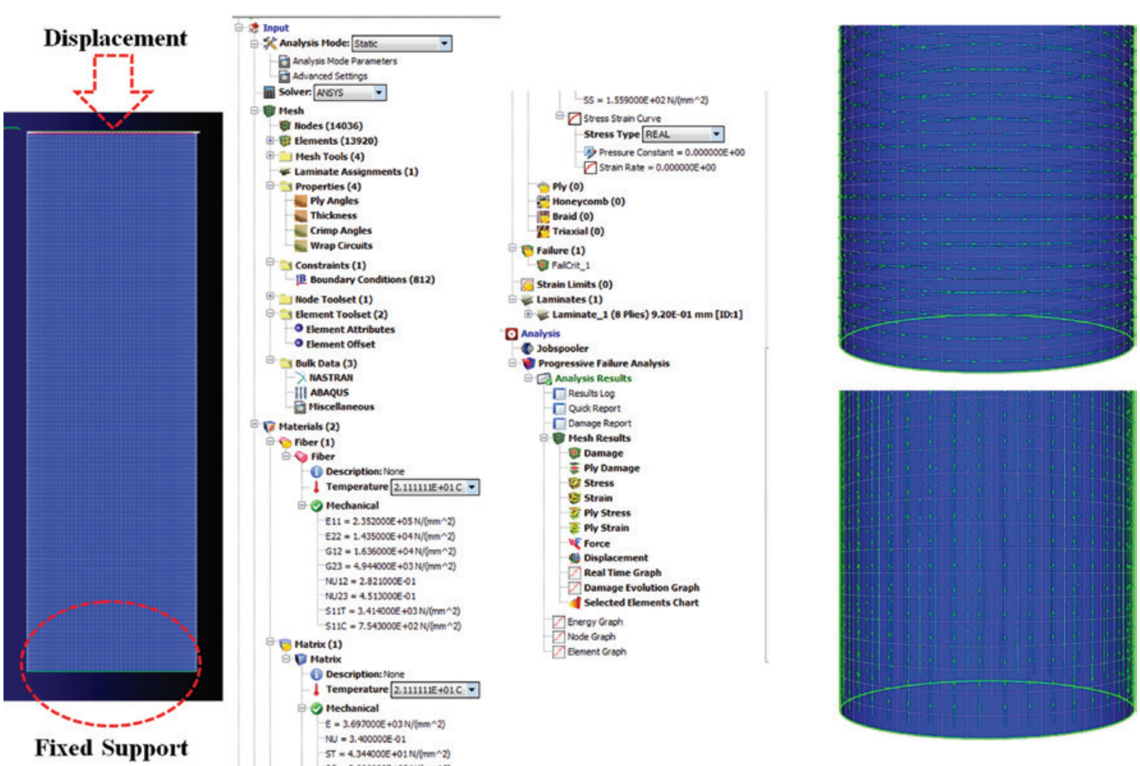

Figure 4: Boundary condition setting and GENOA analysis process and fiber direction according to the external stacking angle changed.

collapse specimen using ABAQUS, Dassault System, France, general-purpose analysis software and GENOA-MCQ, ALPHA STAR Co., USA (14), a dedicated analysis tool for composites that solves complex engineering problems ranging from linear to non-linear behavior. The geometry of the specimen was modeled as 120 mm in length and 38 mm in outer diameter. As shown in Figure 3, the size of element is determined 1 mm by the grid independence test. The material properties applied to the FEM are orthogonal anisotropic material properties because the CFRP prepreg is an orthotropic material. As shown in Figure 4, the fiber direction was set to 0 degrees, and the coordinate system for each layer was changed to input the angle for each prepreg. To replicate the actual test, the boundary condition and displacement condition were kept similar to those in the actual test experiments. Figure 4 shows that the bottom of the specimen was fixed in all directions and that the top of the specimen was fixed but unconstrained in the longitudinal direction, and the angle of the fiber according to the external stacking angle changed. The top of the specimen was tested to control the displacement with a speed of 10 mm/min.

3 Results and discussion

3.1 Collapse-test results

We plotted graphs to determine the collapse properties of the specimens according to the interface number and external angle. To construct the load displacement curves, the displacement and collapse loads measured through collapse testing were used. The average collapse stress can be calculated as where

$$\sigma_{av} = \frac{P_{av}}{A} = \frac{P_{av}}{2\pi Rt}, \quad [1]$$

where σ_{av}, P_{av} and A are the collapse stress, average collapse force measured by the UTM during the experiments, and the cross-sectional area of the specimen, respectively. Using this equation, we obtained the load displacement curves.

As shown in Figure 5, the specimens with a 0° CFRP prepreg external angle collapse in the fragmentation and splaying mode, where the fibers expand and fracture outside the member and collapse. In the fragmentation and splaying mode, the fibers in the 0° direction expand outside and attempt to escape. However, despite showing the highest load value, they are broken by the 90° fibers while interfering with the laminas bending because of the effect of the 90° fibers. Also, when the external angle is 0°, the external fibers induce laminar fracture of the inner fibers by bending the lamina. Thus, the maximum load at an external stacking angle of 0° is lower than that at an external angle of 90°. When the external stacking angle is 0° and 90°, the load increases as the number of interfaces was increased to two, three and six. The reason for this behavior is that the CFRP collapse energy factor corresponds to fiber breakage and crack propagation, and

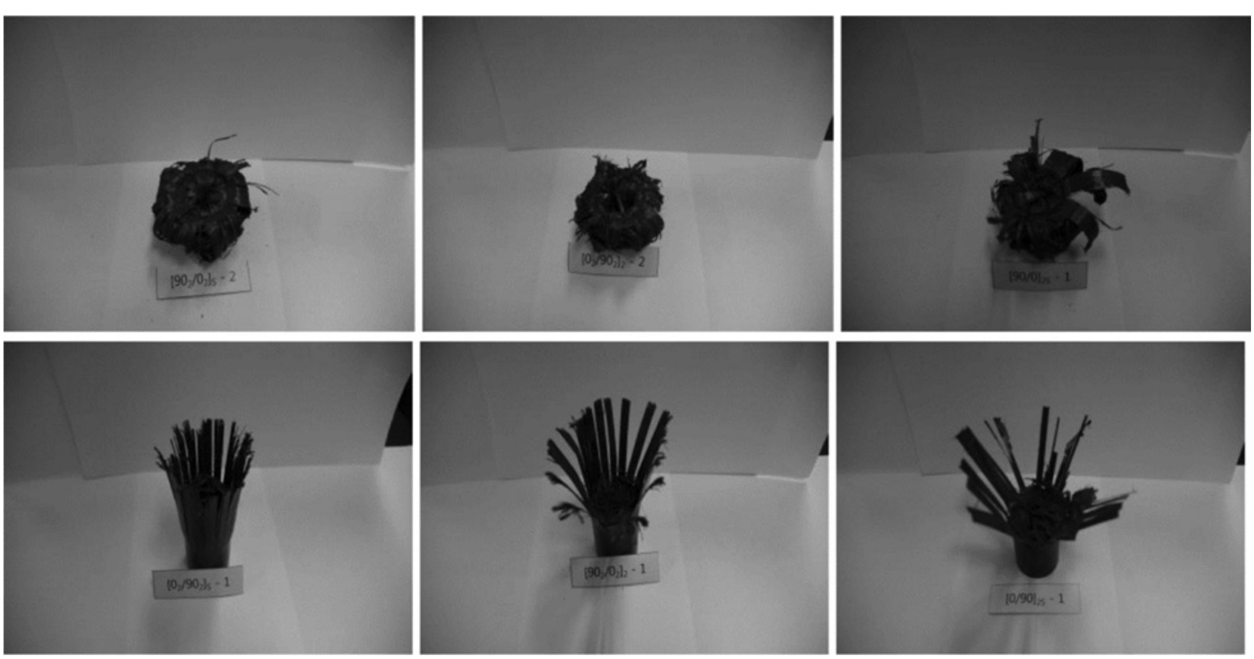

Figure 5: Typical collapse modes of the 90° external sheet CFRP specimen and typical collapse modes of the 0° external sheet CFRP specimens.

cracks are categorized as inter-laminar cracks, intra-laminar cracks and central cracks (15). We consider that the load value increased because of an increase in the number of inter-laminar cracks and an increase in the total number of cracks in the layer. Figure 5 shows the collapsed shape of the specimens after the collapse-test.

As the aforementioned results show, when the external angle is 0°, the internal fiber is almost broken because of the fragmentation and splaying mode. However, when the external angle is 90°, lamina bending of the external fibers causes most of the internal fibers to undergo laminar fracture.

3.2 Results of the finite element analysis

In this study, a finite element model of the composite-specimen static-collapse load was constructed and finite element analysis was performed. The finite element simulation was performed on a CFRP collapse specimen using

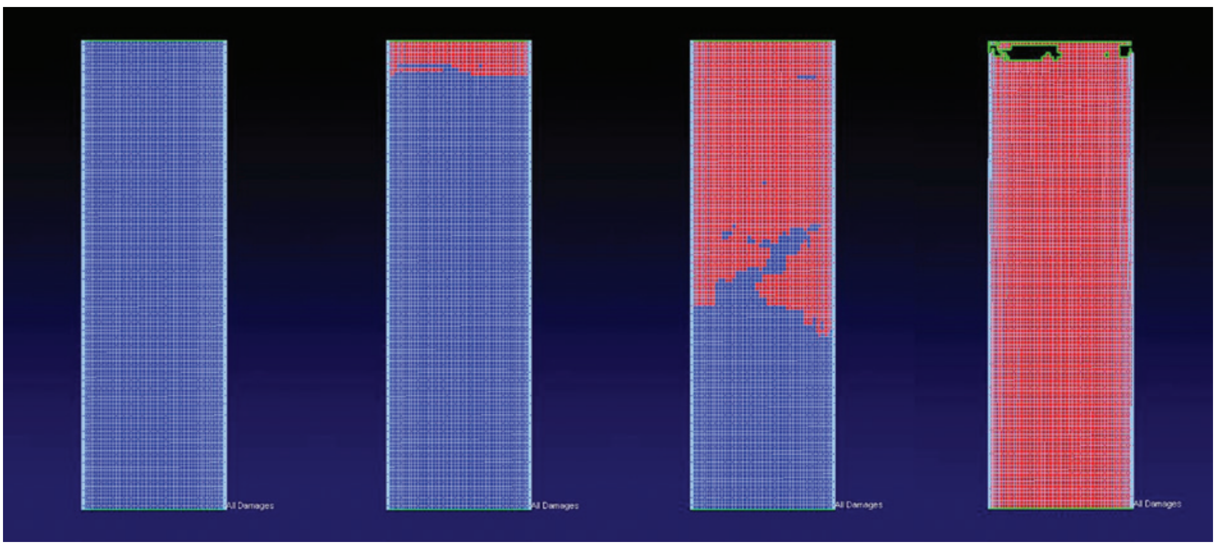

Figure 6: Collapse-test FEM model.

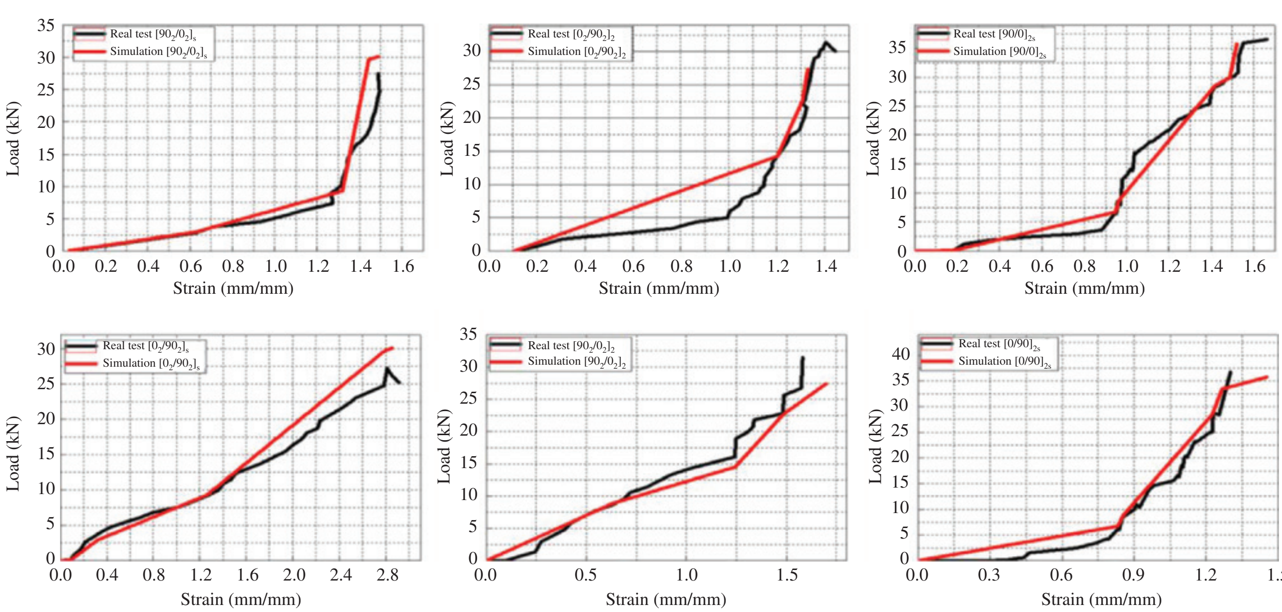

Figure 7: Comparisons between the experimental and simulation load-displacement curves collapse-test results for specimens $[90_2/0_2]_s$, $[0_2/90_2]_2$, $[90/0]_{2s}$, $[0_2/90_2]_s$, $[90_2/0_2]_2$ and $[0/90]_{2s}$.

ABAQUS and GENOA-MCQ. The analysis results and load displacement graphs are shown in Figures 6 and 7.

As shown in Figure 6, when a constant load is applied to the top of the test specimen, cracks occur when the specimen limit load is reached. As shown in Figure 7, each specimen initially showed a linear load displacement curve; however, the load suddenly increased after a constant load and it tended to rapidly decrease at the maximum load.

3.3 Comparison of the actual test results and finite element analysis simulations

In this section, to ensure the reliability of the predicted data, the experiments conducted in finite element analysis were applied to an actual model and the results were compared with the experimental results. Figure 7 and Table 3 show the results of the collapse test and finite element analysis.

Among the three specimens with an external angle of 90°, the $[90_2/0_2]_S$ specimen showed a difference of approximately 8.6% between the finite element analysis prediction and the experimental result. The error rate of the $[0_2/90_2]_2$, specimen was approximately 14% and that of the $[90/0]_{2S}$ specimen was approximately 1.04%. The test specimens with an external angle of 90° showed an error rate of approximately 7.8%. In addition, among the three specimens with an external angle of 0°, the $[0_2/90_2]_S$ specimen showed a difference of approximately 10.48% between the finite element analysis prediction and the experimental result. Further, the error rate of the $[90_2/0_2]_2$ specimen was approximately 12.93%, whereas that of the $[0/90]_{2S}$ specimen was approximately 2.72%. The test specimens with an external angle of 0° showed an error rate of approximately 8%. In the case where the finite element analysis was applied to the CFRP static-collapse specimen, the error rate was approximately 8%. We found that the finite element analysis can predict the properties of CFRP composites to a certain degree.

Table 3: Comparison between real tests and the FEM predictions.

	Real test (kN)	FEM (kN)	Deviation (%)
$[90_2/0_2]_s$	27.4855	30.09945	−8.6
$[0_2/90_2]_2$	31.3784	27.38737	14
$[90/0]_{2s}$	36.5169	36.13652	1.04
$[0_2/90_2]_s$	27.2512	30.10749	−10.48
$[90_2/0_2]_2$	31.4572	27.38757	12.93
$[0/90]_{2s}$	36.7385	35.73693	2.72

4 Conclusion

In this study, finite element analysis was used to predict and obtain the material properties of carbon fibers and resins even in the case of a carbon-fiber laminate and a modified external angle. The results verify this approach's reliability through a comparison of the simulation results and actual test results to predict the material properties of a carbon fiber and resin. The conclusions obtained from this study are summarized as follows.

1. The CFRP circular structural member collapsed at different orientation angles due to compounding of four different modes: transverse shearing, laminar bending, brittle fracture and local bucking.
2. When the external angle was 0°, the external fiber induced laminar bending in the inner fibers such that it had a lower load value than in the case where the external angle was 90°. However, when the external angle was 90°, the 0° fiber was fractured while interfering with the laminar bending to expand the inner 0° fiber, which exhibited the highest load value because of greater fiber breakage.
3. As the number of interfaces was increased to two, three and six, the load applied to the specimens with two, three, six interfaces increased linearly.
4. The collapse characteristics of the CFRP structural member increased the average collapse load by absorbing energy via inter laminar and intra laminar cracks in the layer. However, when the number of interfaces was greater than seven, we considered that the average load decreased because crack initiation in the layer did not appear as a result of reduced interlayer cracking due to a reduction in the interlayer thickness.
5. By analyzing the fiber and resin properties through basic experiments basic theory using the CFRP static-collapse, we demonstrated that predictions through finite element analysis were effective because the error rate was approximately 10%.
6. The results of the finite element analysis and the experimental results obtained according to the external changes were compared with the load displacement curve and the maximum load. The $[0_2/90_2]_S$, $[90_2/0_2]_2$ and $[0/90]_{2S}$ specimens showed a maximum error rate of 8.6%, and the $[90_2/0_2]_S$, $[0_2/90_2]_2$ and $[90/0]_{2S}$ specimens showed maximum error rates of approximately 12.93%.

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