Evaluation of Carbon Fiber Grid Reinforced Concrete Panel for Disaster Response and Improved Seismic Performance

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Abstract: The purpose of this study is to enable emergency recovery of damage caused by earthquakes in structures and prevent secondary damage by controlling progressive collapse. Although there have been many previous studies using reinforcing bars and meshes, there have been few studies using carbon grid fibers as a substitute for tension members. This study aims to quantitatively present disaster response seismic performance by manufacturing concrete panels with no layers, one layer, or two layers of carbon fiber grids inserted and to compare the flexural strength and energy dissipation capacity. Flexural strength increased by 7% with one layer and 15% with two layers compared with no layer. Energy dissipation capacity increased by 30 times with one layer and by 56 times with two layers compared with no layers, and showed great improvement in terms of seismic performance. Especially because of the large increase in the energy dissipation capacity, the carbon fiber grid reinforcement method is considered to be an effective method for improving seismic performance.

Keywords: evaluation; carbon fiber grid; reinforced concrete panel; disaster response; seismic performance

1. Introduction

Korean legislation has stipulations on risk evaluation of earthquake-damaged buildings. The intention is to minimize casualties from secondary disasters and economic losses from delayed recovery by enabling emergency measures to be taken on buildings damaged by earthquakes, but there are no specific standards yet for risk evaluation of damaged buildings [1]. Risk evaluation standards for damaged buildings are urgently needed to reduce secondary damage to the level equivalent to that in developed countries. In consideration of the architectural structures in Korea, it is necessary to develop and evaluate a reinforced concrete structure with reinforced seismic resistance and a pre-casting concrete panel applied with carbon fiber hybrid. Additionally, there is a need to implement a technology for evaluating residual seismic performance.

Carbon fiber sheets suppress cracking activities by reinforcing cracks formed on the surface of reinforced concrete structures due to impact, excessive load, and fatigue load [2–4]. They can also recover the strength of concrete structures, provide excellent wear resistance by reinforcing the surface of existing concrete structures, and increase the flexural strength by reinforcing concrete structures on the tensile side [5–7].

The quantity of reinforcement work has increased in Korea, with an emphasis on the importance of maintenance. From 1 December 2017, owners of a new building construction are required to receive from the designer and submit documents confirming structural safety and seismic design. Korean construction companies should increase investment in seismic technologies and strengthen their capacity in advanced seismic technologies to secure technological competitiveness and enter the global construction market. The Ministry of Public Safety and Security established the 2017 Seismic Reinforcement Measure for Public Facilities, which covers various public facilities such as structures, roads, and schools. According to phase 2 of the Master Plan for Seismic Reinforcement...
of Public Facilities, 28 government ministries and 17 local governments will spend KRW 839.3 billion to conduct seismic reinforcement of 2542 places out of 105,448 places subject to seismic reinforcement from 2016 to 2020. The demand will increase with the application of seismic response standards to asphalt works.

Institutional standards for seismic design in Korea were prepared based on the design standards of the United States. The Seismic Design Regulation was enacted in 1988 and has been reinforced consistently ever since with the expansion of application areas. Seismic engineering technologies were mainly developed by countries experiencing frequent earthquakes, such as the United States and Japan. Other countries engaging in active research on seismic design include France, New Zealand, and Canada. The Korean government is constantly strengthening seismic design regulations, and national interest in earthquakes increased after the Gyeongju Earthquake in September 2016.

Japanese construction companies have developed independent reinforcement methods such as the AF method, the SR-CF method, the CRS-CL method, and the WARS method, which are centered on the composite fiber attachment method. Such methods are being actively applied at construction sites. Accordingly, Japan engages in vigorous R&D and the history of reinforcement methods can be seen as well as the history of composite fiber reinforcement methods. In particular, the Japanese Ministry of Construction started a five-year research project called the “Development of New Technologies to Improve Seismic Performance of Existing Structures” in 1996. During this project, the Building Research Institute and CF Construction Association created a nationwide research system and set up a continuous fiber sheet method review committee to develop technologies for improving the seismic performance of existing buildings using continuous fibers such as carbon fiber and aramid fiber. After numerous studies, the Japanese Guideline for Design and Construction of Building Structures was prepared in 1990, and the Guideline for Design and Construction of Reinforced Concrete Bridge Reinforcement Method Using Carbon Fiber Sheet was published in 1995. In particular, the performance of many bridges was improved after the Kobe Earthquake in 1995. Japan is making tremendous efforts to systematize and develop sustainable performance improvement technologies using composite materials.

The technological trend of composite fiber reinforcement methods in Europe has lagged behind that of Japan, but Europe engages in the development of technologies that are independent of those being developed in Japan. Germany has implemented the “integrated material/construction certification system” for the maintenance of bridges and national facilities. This system stipulates bridge maintenance standards and repair regulations so that facilities are only constructed using a method that has obtained “integrated material/construction certification” according to the technical regulations of the Federal Highway Research Institute (BASf). This system can minimize the subjective judgment of engineers and obtain uniform quality because it includes definite regulations for material characteristics, minimum requirements, and the construction environment. In the CONMAT Program, in which USD 2 billion was invested from 1995 to 2005, the United States allocated the largest budget in the field of composite fiber construction towards the development of various reinforcement technologies using composite fibers. Canada formed ISIS Canada in 1995 to develop various FRP reinforcement technologies and make efforts to improve performance and extend the life of aged structures.

The seismic construction market is forecast to continue growing. Although the level of technology in Korea is inferior to that in developed countries, the attention of the construction industry to seismic technologies is gradually increasing because of greater awareness of earthquake risks. Sales of seismic materials and related construction areas are expected to show continued growth, and the market will expand to KRW 1–1.5 trillion and account for 1% of the entire construction market in 2020.

Fiber reinforcement methods have been studied by universities and companies since the early 1990s. Since the carbon fiber sheet reinforcement method was applied to Mukjeong Underground Parking Lot in Jung-gu, Seoul in 1994, the quantity of reinforcement
works has increased because of the increased importance of maintenance in Korea. Additionally, research in Korea is advancing from the identification of basic dynamic behavior of reinforcement methods to detailed development to increase ductility. In terms of load type, research has progressed to flexural strength from dead load and verification of shear reinforcement performance. Korea was generally perceived as an earthquake safety zone, which led to a lack of awareness about the seriousness of earthquake damage. As a consequence, there is a shortage of studies on earthquake activities to secure the seismic performance of structures. However, the seriousness of earthquake damage was recently realized with the nuclear plant explosion caused by an earthquake in Japan and a strong earthquake of magnitude 5.38 with about 450 aftershocks. Seismic reinforcement was deemed especially important after the magnitude 6 earthquake that occurred in Gyeongju on 12 September 2015. The Korean government compiled the “Master Plan for Seismic Reinforcement of Public Facilities (2011–2015)”, and consults with various ministries such as the Ministry of Strategy and Finance, Ministry of Land, Infrastructure, and Transport, and Ministry of Public Administration and Security in order to implement seismic reinforcement of existing structures.

The purpose of this study is to enable emergency recovery of damage caused by earthquakes in structures and to prevent secondary damage by controlling progressive collapse. Another purpose is to secure the short and long-term stability of mid- to low-rise buildings by obtaining convenient construction, stiffness against deformation, and ductility for efficient energy absorption [8,9].

In relation to this, an objective of this study is to investigate the seismic performance of double-row reinforced ceramsite concrete sandwich wall panels. The feasibility of upgrading a new wall panel from a non-load-bearing partition wall to a load-bearing seismic wall has been examined by conducting cyclic load tests on five wall panel specimens [10]. Other researchers have presented experimental and mechanical studies on the flexural behaviors of fiber-reinforced polymer (FRP) fabric-reinforced ultra-high-performance concrete (UHPC) panels. Glass FRP (GFRP) and carbon FRP (CFRP) fabrics were investigated [11]. In addition, researchers have investigated the behavior of reinforced concrete beams strengthened in flexure using externally bonded CFRP rod panels (CRPs) fabricated using 4-mm rods spaced at 9.5 mm. The experimental program consisted of a control beam and three beams strengthened with either a continuous CRP, a spliced CRP with two half-length CRPs spliced through a 150 mm finger joint, or a spliced and end anchored CRP [12]. In other research, a method of connecting precast concrete walls with GFRP composite sheets was investigated. The method can be used either as a seismic retrofit of existing welded steel plate connections or in new construction [13]. Additionally, an experimental study of the improvement of the tensile and flexural strength of CC panels through the employment of external reinforcement by an FRP sheet was presented in which the tensile and flexural behaviors of CC and FRP-reinforced CC panels were investigated through uniaxial tensile and four-point bending tests in both warp and weft directions [14]. Another study investigated the impact and post-impact behavior of steel–concrete composite (SC) panels. Impact tests were carried out on eight specimens in an instrumented drop hammer rig [15]. In addition, three kinds of GFRP connector, including a flat plate, a corrugated plate, and a hexagonal tube connector, were investigated for potential use in precast concrete sandwich panels (PCSPs) [16]. Other experiments investigated the blast-resistant characteristics of hybrid fiber-reinforced concrete (HFRC) panels by contact detonation tests. Control specimens of plain concrete, polypropylene (PP), polyvinyl alcohol (PVA), and steel fiber-reinforced concrete were prepared and tested for characterization in contrast with PP-Steel HFRC and PVA-Steel HFRC. The fiber-hybrid effect index was introduced to evaluate the hybrid effect on the explosion-resistance performance of HFRC panels. It revealed that neither PP-fiber nor PVA-fiber provide a positive hybrid effect on blast-resistant improvement of HFRC panels [17].

A disadvantage of previous research is that increasing the strength of the damaged structure requires reinforcement of the structural members and a lengthening of the con-
struction period. However, based on this study, it is possible to recover the damaged part of the structure by making a concrete panel and prevent secondary cascading collapse. Although there have been many studies on concrete reinforcement using reinforcing bars and mesh, there have been few studies using carbon grid fibers instead of tension members. In addition, this study shows that it is possible to increase the flexural strength by using the carbon fiber grid, which is effective in suppressing cracking activity. Ultimately, this study aims to develop concrete composite panels with carbon fiber grids for emergency earthquake damage recovery and reinforcement.

2. Experiments

This study aims to quantitatively present the disaster response seismic performance by manufacturing 1200 × 600 × 75 mm concrete panels with no layers, one layer, or two layers of carbon fiber grids inserted as shown in Figure 1 and compare the flexural strength and energy dissipation capacity. The experimental plan is presented in Table 1. The number of carbon fiber grid layers, the experimental factor, was configured as zero (unreinforced), one, or two. The carbon fiber grid was arranged in the middle at 37.5 mm of the 75 mm panel thickness in the case of one layer. Two layers were arranged at 25 mm and 50 mm by dividing the 75 mm panel thickness into three parts.

![Figure 1. Specimen of carbon fiber grid reinforcement panel (Unit: mm). (a) Concrete panel. (b) Carbon fiber grid. (c) One layer. (d) Two layers.](image)

| Specimen Size (mm) | Carbon Grid | Concrete Compressive Strength (MPa) | Experiments |
|--------------------|-------------|------------------------------------|-------------|
| 1200 × 600 × 75    | -No layer   | 50.0                               | Flexural strength |
|                    | -1 layer    |                                    | Energy dissipation capacity |
|                    | -2 layers   |                                    |              |
| Design strength (MPa) | W/B (%) | S/A (%) | Binding material (kg/m³) | Unit quantity (kg/m³) | Cement | Fly ash | Silica fume | Fine aggregate | Coarse aggregate |
| 50                 | 29.6        | 49        | 550 | 163 | 418 | 110 | 22 | 815 | 875 |
| Type of binder     | Specific surface area (cm²/g) | Density (g/cm³) | Lg. loss | Chemical composition (%) |  |
| OPC                | 3.14        | 3.15 | 1.32 | 21.7 | 5.7 | 3.2 | 63.1 | 2.8 | 2.2 |
|                    | Specific surface area (cm²/g) | Density (g/cm³) | Lg. loss | Chemical composition (%) |  |
| 160,000            | 2.21        | 1.38 | 96.65 | 1.87 | 0.03 | 0.38 | 0.19 | 0.32 |
| Admixture type     | Specific gravity | Fineness (cm²/g) | Ignition loss (%) | Moisture content (%) | Unit quantity ratio (%) | SiO₂ | Activity factor (%) |
| Boryeong fly ash   | 2.22        | 2976 | 4.0 | 0.1 | 101 | 53.2 | 93.1 |
Table 1. Cont.

| Admixture type | Phase | Color | Main component | Toxicity | Specific gravity |
|----------------|-------|-------|----------------|----------|-----------------|
| Superplasticizer | Liquid | Yellow | Polycarboxylic acid-based | None | 1.04 |

| Type | Size (mm) | Fineness modulus (F.M.) | Specific gravity | Absorption rate (%) | Performance rate (%) | Unit weight (kg/l) | Remarks |
|------|-----------|-------------------------|------------------|---------------------|----------------------|--------------------|---------|
| Fine aggregate | 5         | 3.04                    | 2.56             | 0.64                | 67.45                | 1.73               | Sea sand |
| Coarse aggregate | 20        | 6.02                    | 2.65             | 1.39                | 62.52                | 1.66               | Crushed coarse aggregate |

| Type | Tensile strength (kN/m) | Secant modulus of elasticity (kN/m) | Tensile strain rate (%) | Nominal strength tensile strain rate (%) |
|------|-------------------------|------------------------------------|-------------------------|----------------------------------------|
| Machine | Width | Machine | Width | Machine | Width | Machine | Width |
| Carbon fiber grids | 182.7 | 108.44 | 12,019 | 4180 | 2.2 | 3.6 | 3.5 | 3.8 |

The concrete mix comprised 29.6% W/B, 49.0% S/A, 550 kg/m$^3$ of binding material, and 163 kg/m$^3$ of unit quantity to satisfy the design strength of 50.0 MPa. In addition, ordinary Portland cement (OPC), fly ash, and silica fume were used to replace 20% and 4% of the binding material. The concrete mix is presented in Table 1, and OPC was used with a specific surface area of 3.14 cm$^2$/g and a density of 3.15 g/cm$^3$, sold by Company S in South Korea; Norwegian silica fume with a density of 2.21 g/m$^3$ and a specific surface area of 160,000 cm$^2$/g; Korean fly ash from Boryeong with a density of 2.22 g/cm$^3$, a specific surface area of 2976 cm$^2$/g, and an ignition loss of 4.0%; polycarboxylic acid-based superplasticizer from Company E S in South Korea for superplasticizer; crushed coarse aggregate with a maximum size of 20 mm for coarse aggregate; and sea sand with a maximum size of 5 mm for fine aggregate.

Carbon fiber grids are normally manufactured as geo-grids using a warp-knitting machine. Unlike the conventional polyester high-strength thread of carbon fiber produced as 1500 d × 3 Ply or 1500 d × 8 Ply, a stiff hybrid thread with the ductility of single or para-aramid was manufactured as the woven type using an exclusive weaving machine for rapier grids. Fabrics made using the hybrid thread of carbon fiber and para-aramid can have an almost identical tensile strength in the machine direction (MD) and cross-machine direction (CD). The physical properties of carbon fiber grids are presented in Table 1 and Figure 2 [18]. The construction was made using Carbon fiber 12K T700 50C 2 threads in the longitudinal (MD) direction, and was weaved using a “Leno” weaving system. The transverse (CD) direction was made using Carbon fiber 12K T700 50C 2 threads in a flat rapier system, mostly using Carbon fiber 12K, 24K “Leno” weaving system with a rapier loom machine. The grid mesh distance was (MD) 21 mm × (CD) 21 mm.

In this study, the flexural performance of the carbon fiber grid reinforcement panels was evaluated by the four-point method according to KS F 2566 at the age of 28 days as shown in Figure 3. Span length was 1000 mm, and the loading rate was 0.2 mm/min using the displacement control method. Two linear variable displacement transducers (LVDT) were attached in the middle of the specimen to measure the deflection under load. The following equation for calculating concrete flexural strength presented in KS F 2566 was used to calculate flexural strength.
The concrete mix comprised 29.6% W/B, 49.0% S/A, 550 kg/m³ of binding material, 4% of the binding material. The concrete mix is presented in Table 1, and OPC was used as 1500 d × 3 Ply or 1500 d × 8 Ply, a stiff hybrid thread with the ductility of single or para-aramid was manufactured as the woven type using an exclusive weaving machine for rapier grids. Fabrics made using the hybrid thread of carbon fiber and para-aramid can as 1500 d × 3 Ply or 1500 d × 8 Ply, a stiff hybrid thread with the ductility of single or para-aramid was manufactured as the woven type using an exclusive weaving machine for rapier grids. Fabrics made using the hybrid thread of carbon fiber and para-aramid can

\[ f_r = \frac{P}{bh^2} \]  

where \( P \) is maximum load, \( \ell \) is span length, \( b \) is width of fracture surface, and \( h \) is height of fracture surface.

In the case of reinforced concrete buildings that take a cyclic load such as seismic load, the energy dissipation capacity is an extremely important factor for evaluating seismic performance. Buildings must be designed to have a high energy dissipation capacity. Therefore, the energy dissipation capacity is generally computed by the area surrounded by the hysteretic behavior curve, as shown in Figure 4.

**Figure 2.** Carbon fiber grid. (a) Specimen. (b) Detail of carbon fiber grid. (c) MD direction. (d) CD direction.

**Figure 3.** Flexural strength test. (a) Details of flexural strength test. (b) Setup for flexural test.
Figure 4. Energy dissipation capacity.

3. Results and Discussion

The flexural strength of the concrete panels was 8.08 MPa for the no-layer specimen (Figure 5), 8.65 MPa for the one-layer specimen (Figure 5), and 9.27 MPa for the two-layer specimen (Figure 5), and increased with the increasing number of carbon fiber grids. Flexural strength increased by 7% with one layer and 15% with two layers compared with no layer (Table 2, Figure 6). The maximum displacement in the middle of the concrete panels was 2.66 mm with no layers, 14.86 mm with one layer, and 16.29 mm with two layers, and increased with increasing number of carbon fiber grids. Concrete reinforced with carbon fiber grid had excellent ductility compared with unreinforced concrete. With more carbon grid fiber reinforcement layers, the maximum load was greater, and the deformation capacity increased as the displacement increased. Sufficient ductility was secured through tensile deformation curing behavior from initial cracking until fracture because of the carbon fiber grid reinforcement. A similar study confirmed that stress increased with increased numbers of carbon grid fiber layers when a carbon fiber grid was applied to Engineered Cementitious Composites (ECC) [1]. This phenomenon was found to grow with increasing number of reinforcement layers.

![Energy dissipation capacity](image)

Figure 5. Results of flexural strength experiment. (a) Flexural strength. (b) Flexural strength ratio.

Table 2. Experimental results.

| Results                  | No Layer | One Layer | Two Layers |
|--------------------------|----------|-----------|------------|
| Flexural strength (MPa)  | 8.08     | 8.65      | 9.27       |
| Max. load (kN)           | 27.3     | 29.2      | 31.3       |
| Max. displacement (mm)   | 2.66     | 14.86     | 16.29      |
applied to Engineered Cementitious Composites (ECC) [1]. This phenomenon was found to grow with increasing number of reinforcement layers.

Table 2. Experimental results.

| No Layer  | One Layer  | Two Layers |
|-----------|------------|------------|
| Max. load (kN) | 27.3       | 29.2       | 31.3       |
| Max. displacement (mm) | 2.66    | 14.86      | 16.29      |
| Flexural strength (MPa) | 8.08    | 8.65       | 9.27       |

Figure 6. Results for specimens. (a) Fracture pattern (0 layer). (b) Load–displacement curve (0 layer). (c) Fracture pattern (1 layer). (d) Load–displacement curve (1 layer). (e) Fracture pattern (2 layer). (f) Load–displacement curve (2 layer).

The energy dissipation capacity of the concrete panels was 0.06 kN·m with no layers, 1.89 kN·m with one layer, and 3.52 kN·m with two layers, and increased with the increasing number of carbon fiber grids (Figure 7). The energy dissipation capacity increased by 30 times with one layer and by 56 times with two layers compared with no layers, showing great improvement in terms of seismic performance. The cumulative energy dissipation capacity of the concrete panels was 23.0 kN·m with no layers, 219.2 kN·m with one layer, and 371.6 kN·m with two layers, and increased with the increasing number of carbon fiber grids. The cumulative energy dissipation capacity increased by 9.5 times with one layer and 16 times with two layers compared with no layers, and showed great improvement in terms of seismic performance.
Figure 6. Results for specimens. (a) Fracture pattern (0 layer). (b) Load–displacement curve (0 layer). (c) Fracture pattern (1 layer). (d) Load–displacement curve (1 layer). (e) Fracture pattern (2 layer). (f) Load–displacement curve (2 layer).

The energy dissipation capacity of the concrete panels was 0.06 kN \cdot m with no layers, 1.89 kN \cdot m with one layer, and 3.52 kN \cdot m with two layers, and increased with the increasing number of carbon fiber grids (Figure 7). The energy dissipation capacity increased by 30 times with one layer and by 56 times with two layers compared with no layers, showing great improvement in terms of seismic performance. The cumulative energy dissipation capacity of the concrete panels was 23.0 kN \cdot m with no layers, 219.2 kN \cdot m with one layer, and 371.6 kN \cdot m with two layers, and increased with the increasing number of carbon fiber grids. The cumulative energy dissipation capacity increased by 9.5 times with one layer and 16 times with two layers compared with no layers, and showed great improvement in terms of seismic performance.

Figure 7. Displacement ductility and energy dissipation capacity. (a) Energy dissipation capacity (0 layer). (b) Cumulative energy dissipation capacity (0 layer). (c) Energy dissipation capacity (1 layer). (d) Cumulative energy dissipation capacity (1 layer). (e) Energy dissipation capacity (2 layer). (f) Cumulative energy dissipation capacity (2 layer). (g) Energy dissipation capacity (Total). (h) Cumulative energy dissipation capacity (Total).
4. Conclusions

This study aimed to quantitatively present the disaster response seismic performance by comparing the energy dissipation capacity of concrete panels inserted with carbon fiber grids, and the conclusions are as follows:

(1) The flexural strength of concrete panels was 8.08 MPa with no layers, 8.65 MPa with one layer, and 9.27 MPa with two layers, and increased with the increasing number of carbon fiber grids. Flexural strength increased by 7% with one layer and 15% with two layers compared with no layer.

(2) The energy dissipation capacity of concrete panels was 0.06 kN·m with no layers, 1.89 kN·m with one layer, and 3.52 kN·m with two layers, and increased with the increasing number of carbon fiber grids. Energy dissipation capacity increased by 30 times with one layer and 56 times with two layers compared with no layer and showed improvement in terms of seismic performance.

(3) Concrete panels with carbon fiber grids showed 7–15% higher flexural strength and 30–56 times higher energy dissipation capacity compared with no carbon fiber grid. Especially because of the large increase in the energy dissipation capacity, the carbon fiber grid reinforcement method can be considered an effective method for improving seismic performance.

(4) This study compared the flexural strength characteristics of panels using carbon grids to those of unreinforced concrete, and a comparison with panels using existing reinforcing bars and meshes will be carried out in the future.

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