Investigation of flexural behaviors of hybrid beams formed with GFRP box section and concrete

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HIGHLIGHTS

► We developed five different hybrid GFRP-Concrete beams groups.
► We applied physical and mechanical experiments on the beams.
► Flexural strength and fracture toughness of developed hybrid beams increased about 3 and 10 times.
► It becomes possible to produce elements with smaller sections with the same strength.

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ABSTRACT

This study investigated the use of concrete, which is known to have high compressive strength, as a hybrid beam with GFRP box sections which have a high tensile stress. Hybrid construction elements were formed by placing concrete in plastic form inside GFRP box profiles and experimental tests were performed on the materials. Firstly, the properties of the GFRP profiles were determined and the flexural behaviors of the hybrid beams produced with different profiles were analyzed. The developments of the hybrid material to its components, which are concrete and GFRP profiles, were examined. To increase the adherence of concrete to GFRP profile, sand particles were pasted in the interior surface of the profile using epoxy and the hybrid beams were improved by increasing the profile felt. Study results showed that in addition to many advantages due to its formation, the hybrid design showed superior physical and mechanical properties. It was found that the flexural strength and fracture toughness values of hybrid beams significantly increased when compared to reference values.

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1. Introduction

Like in all technical fields, the needs and demands of humans in the field of material technologies increase each day in parallel to the problems experienced in materials. Researchers investigate new material types and applications and try to produce new designs to decrease these problems and to satisfy these demands. In recent years, many researchers have concentrated on composite materials and hybrid designs, which can be considered as a derivative of these materials. Composite materials have required properties and are preferred in a wide variety of fields including the construction sector. Fiber Reinforced Plastic (FRP) composites are one of these composite types [1]. In addition to their high resistance and good performance towards environmental factors, these materials are preferred since they have all the properties desired by the researchers and they can be produced in different combina-

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which are not considered as bearing elements in the construction sector, are today also used as bearing elements, as main construction elements. Particularly after the increase of the serial production of FRP composites, they began to be used more effectively in buildings for different purposes. The use of fiber reinforced composites, which are lightweight and have a high resistance, in reinforcement, repair and improvement works has increased [7]. Reinforcement and improvement works involving the wrapping of FRP laminates on the bottom surfaces of beams and FRP fabrics on all surfaces of columns are the most widely known applications of these types of composites with concrete [8–12].

Studies reveal that research which uses carbon or glass fiber FRP fabric or laminates with different fiber contents will further develop in the future and concentration on hybrid systems, which combine profile FRP elements with bearing properties and conventional construction materials such as concrete or steel, will increase [13]. Like in various study units, the most recent research and development studies have concentrated on hybrid systems where conventional construction materials particularly such as concrete and composite materials are used in combination [6]. Recently much of the research has focused on hybrid FRP columns formed by concrete-filled or hollow FRP pipes [14–17]. The tendency in scientific studies clearly shows that in the near future, the use of FRP composites in new buildings will mainly concentrate on the use of hybrid structure [18]. Many studies have shown that the use of FRP composites with conventional materials like concrete was one of the solutions to eliminate certain deficiencies and disadvantages in construction elements fully made of FRP [19].

The first studies on hybrid designs, where FRP profiles and concrete were used in combination, began in 1981 [20]. In the first studies, positive results were obtained by using concrete to increase rigidity and compressive strength inside FRP profile. The idea of using FRP-Concrete hybrid system as a flexural element was first introduced in 1990 [21]; it was reported that the FRP profile used in the formed system offered advantages in formwork, lightweight structure and resistance and could yield more than 50% lightweight structure when compared to conventional plate systems. In addition, some researchers [22] investigated hybrid floor covering systems. They formed permanent formwork by using concrete in a T-section GFRP profile and increased material resistance. In previous studies on hybrid systems which were formed by filling concrete inside the FRP profile; the behavior of a hybrid system under uniaxial load [23,24] flexural behavior in 1997 were again analyzed by the same researchers in 1999 [24–26]. Various studies were conducted on the long term creep and shrinkage effects of hybrid beams in 2002 [27], on behaviors under repetitive loads in 2005 [28,29], on the effects on impact loads in 2007 [30], on shear behavior and material fatigue in 2008 [31–34] and on frost-thaw effects in 2008 [30,35].

2. Aim of the study

This study was carried out in parallel to the increasing attention on fiber reinforced composites. The study analyzed hybrid use of highly preferred Glass Fiber Reinforced Plastic (GFRP) composite box sections among FRP composites and concrete, which is the principle construction material and has long been used in construction. GFRP profiles, which have many positive properties, were combined with concrete which is the most widely preferred construction material. New hybrid beams, which are produced by benefitting from positive aspects of both components, were analyzed; improvements were conducted and solutions were offered for identified problems.

In this study, the aim was for two materials to contribute to each other by making use of the superior properties of concrete and GFRP profiles. The aim was to obtain the advantages presented in Fig. 2.

Formwork advantages: forming small parts to prepare the necessary formwork to give the concrete the desired shape requires a long time and extra cost. Since GFRP box sections serve as a formwork, there is no need for a secondary element to shape the concrete, which fills inside the box section (Fig. 3). This is considerably time saving and cost efficient. This property, which is termed as permanent formwork in literature, is considered to be one of the principle advantages of hybrid materials [36–42].

Cross-section advantages: with the combination of these two materials, GFRP profiles with high tensile stress are expected to meet tensile stresses, and concrete, whose most important mechanical property is compressive strength, is expected to meet compressive stresses. Thus, thanks to two-component hybrid material, it will be possible to produce elements which have the same strength as box profile and plain concrete with smaller cross-sections.

Preventing local damage in GFRP profile: these materials, which have many superior properties, are exposed to regional and local fractures in profile form particularly under flexural effect [43,44]. In GFRP profiles formed by filling concrete, since the concrete will be in a hardened form, local fractures will be reduced or eliminated.
Curing advantage in concrete: GFRP prevents the concrete in plastic thickness which is placed in box section from losing its water and moisture and makes this vital procedure highly advantageous [45]. In standards [46,47], concrete is required to be cured for 28 days in 100% relative humidity. However, in this procedure the concrete will not lose its water and the hydration process will be achieved without any problems.

Strength and rigidity increases: hybrid material is formed by placing concrete inside a GFRP box section. With the collective behavior of these two components, local fractures in the profile are expected to decrease or be eliminated and similarly, increases of varying ratios are expected in material resistance since the GFRP profile meets tensile stresses.

Impermeability and insulation advantages: the epoxy materials that are one of the components of GFRPSs and which wrap the fibers are impermeable due to their plastic based structure. Thus, the GFRP profile which wraps the concrete protects the concrete by preventing permeation of exterior water or moisture and prevents the minerals inside the water from damaging the concrete.

3. Experimental studies

Although many properties of concrete which has a long history are well-known by researchers, the fact is that GFRPs are new generation materials and have limited production in Turkey. Therefore, firstly some physical and mechanical properties of profiles were determined. Thus, experimental studies are presented in two sections which are determining properties of GFRP profiles and beam tests.

3.1. Determining properties of GFRP profiles

The unit weight, specific weight, fiber ratios and tensile properties of the GFRP box sections used in beam tests were determined using related test methods.

Firstly, 10 samples cut from box sections were used to determine the unit weight and specific weight values. The unit weight values and specific weight values of GFRP materials were found to be 1.738 g/cm$^3$ and 1.822 respectively.

To determine the fiber ratios, the resin burn-off method was applied to the samples obtained from the profiles to determine the fiber and matrix ratios affecting the mechanical behaviors of GFRP box sections [48]. Samples were prepared by cutting 2 cm wide parts from the GFRP box sections. The samples were kept in an oven for 2 h at a temperature of 600 °C and the felt and longitudinal fiber weights were determined. The lateral fiber ratios of the profiles were increased by wrapping extra felt fiber around the exterior surface of the profile. The fiber ratio test results of standard GFRP profiles and the ones to which extra fiber was added are presented in Table 1.

Evaluation was made by calculating the current felt amount of the profiles with additional felt. It was found that the felt amount increased by 50% in profiles with additional felt according to the felt weight in the unit section. The effects of lateral fiber amount used in the profiles in varying ratios on the flexural resistance of the hybrid samples were determined and analyzed in detail.

Tensile tests were performed to determine the tensile properties and modulus of elasticity of GFRP materials. Samples were prepared and tested in line with related standards for GFRP [49–51] and test conditions. The necessary data were recorded, and the modulus of elasticity, tensile and unit deformations of GFRP material were calculated in Table 2.

GFRP material was found to have a modulus of elasticity ($E$) of 29,333 N/mm$^2$ and a tensile strength of 561 N/mm$^2$. Stress-unit deformation graphs were drawn for each sample. The sample obtained from the tests is presented in Fig. 4.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tensile strength (N/mm$^2$)</th>
<th>Modulus of elasticity ($E$) (N/mm$^2$)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>620.45</td>
<td>28981.3</td>
<td>0.99</td>
</tr>
<tr>
<td>2</td>
<td>505.78</td>
<td>29751.5</td>
<td>0.99</td>
</tr>
<tr>
<td>3</td>
<td>521.77</td>
<td>29645.9</td>
<td>0.99</td>
</tr>
<tr>
<td>4</td>
<td>576.71</td>
<td>30676.3</td>
<td>0.99</td>
</tr>
<tr>
<td>5</td>
<td>547.83</td>
<td>27968.1</td>
<td>0.99</td>
</tr>
<tr>
<td>6</td>
<td>567.22</td>
<td>30827.3</td>
<td>0.99</td>
</tr>
<tr>
<td>7</td>
<td>574.25</td>
<td>31209.2</td>
<td>0.99</td>
</tr>
<tr>
<td>8</td>
<td>542.29</td>
<td>26846.2</td>
<td>0.99</td>
</tr>
<tr>
<td>9</td>
<td>609.42</td>
<td>31092.9</td>
<td>0.99</td>
</tr>
<tr>
<td>10</td>
<td>543.38</td>
<td>26636.4</td>
<td>0.99</td>
</tr>
<tr>
<td>Average</td>
<td>560.91</td>
<td>29333.5</td>
<td>0.99</td>
</tr>
</tbody>
</table>

$y = 28981x + 27.25$

$R^2 = 0.99$

Fig. 4. GFRP tensile chart.
3.2. Beam tests

In beam tests, the results of the flexural test performed on GFRP box profiles with cross-section dimensions of 4–100–100 mm, length of 1500 mm and effective span of 1350 mm and different hybrid beams were presented (Fig. 5). A total of five different beam types were produced. Of these beams, three were hybrid beams. The felt amount was increased in some samples and the internal surfaces were sand blasted in some samples. Hybrid beams were obtained by filling concrete inside the profile starting from GFRP box profiles. Hybrid beams with increased adherence by plastering 2 mm diameter sand particles on the interior surfaces of profiles (Fig. 6) and hybrid beams with increased lateral felt amount by wrapping extra felt (Fig. 7) were produced. As the final sample type, hybrid beams were produced from sand-blasted profiles in the interior and wrapped with extra felt were produced. Four-point flexural tests were performed on these hybrid beams (Fig. 8).

Load–deflection graphs were drawn for the five beams in each test group; the flexural load, flexural strength and fracture toughness values were calculated and compared. The mean fracture loads, flexural strength and fracture toughness obtained from flexural tests are presented in Table 3.

Analysis of the beam tests showed that the GFRP box profiles had a mean flexural load of 11,991 N, flexural strength of 16.19 N/mm² and fracture toughness of 80,981 N mm. After the improvements, hybrid samples with additional felt and sand had a mean flexural load of 35,482 N, flexural strength of 47.90 N/mm² and fracture toughness of 815,142 N mm. Load–deflection graphs drawn for hybrid beams which were formed by filling the GFRP box profiles with concrete and sample graphs representing the GFRP box profiles and hybrid beams to analyze the effect of hybrid formation on flexural behavior are compared in Fig. 9. It is understood from the graphs that there were significant increases in the flexural strength, deflection amount and rigidity of hybrid beams.

Hybrid sandy samples were prepared to prevent formation of interface between GFRP box sections and concrete and to increase adherence by sand-blasting the interior surfaces of the profiles. Load–deflection graphs of the hybrid and sandy hybrid

<table>
<thead>
<tr>
<th>Table 3</th>
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<tbody>
<tr>
<td>Flexural test results.</td>
</tr>
<tr>
<td>Max load (N)</td>
</tr>
<tr>
<td>GFRP box profiles</td>
</tr>
<tr>
<td>Hybrid</td>
</tr>
<tr>
<td>Sandy hybrid</td>
</tr>
<tr>
<td>Additional felt hybrid</td>
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<tr>
<td>Additional felt and sandy hybrid</td>
</tr>
</tbody>
</table>

Fig. 6. Sandy samples.

Fig. 7. Extra felt sample.

Fig. 8. Four-point flexural test system.

Fig. 9. Load–deflection curves for box profile and hybrid.

Fig. 10. Load–deflection curves for hybrid and sandy hybrid.
beams with sand were compared to analyze the effect of adherence of concrete and profile on the flexural behavior of the material (Fig. 10). It was found that the flexural strength, deflection amount and thus, the fracture toughness of hybrid beams with sand increased.

A flexural graph comparing hybrid samples with additional felt produced from the profiles with 50% increase of the felt amount in the unit section and hybrid samples with sand is presented in Fig. 11. Analysis of the graph shows that rigidity increased when compared to hybrid samples with additional felt. On the other hand, in the hybrid samples with additional felt, additional felt fibers increased the deflection amount and thus, fracture toughness without losing load value.

It was found that in hybrid felts, an increase in felt amount or sand-blasting of interior surfaces increased flexural performance and thus, both samples both with sand and additional felt were prepared. Load–deflection graphs of hybrid samples with additional felt and hybrid samples with additional felt + sand beams were compared (Fig. 12).

Analysis of the flexural test graphs of hybrid beams with additional felt and sand shows that all samples showed a linear behavior up to a 35,000 N load value and sudden fractures were observed. Analysis of the comparison graph shows that the flexural strength of hybrid beams with additional felt + sand increased by approximately 90% when compared to hybrid samples with additional felt, and rigidity increased by sand-blasting the interior surfaces of the profile and increasing the adherence with the concrete. As a result, it was found that improvement of shear behavior of GFRP profiles by increasing the felt amount and simultaneously increasing adherence with concrete significantly contributed to material behavior. In addition, the fracture situation of hybrid beam is presented in Fig. 13.

After the tests were performed on the beams, the graphs representing each sample group were shown and compared on a single graph (Fig. 14). It is understood from the graph that after each improvement work performed on the material, flexural strength increased particularly in the box profiles, and hybrid beams with additional felt + sand showed a great performance.

Comparisons of the flexural strengths of the specified sample species are presented in Fig. 15. Thus, it was found that the flexural strength of hybrid samples with additional felt + sand increased approximately 2.8 times when compared to the hollow profiles of the same size and approximately 2 times when compared to standard hybrid samples.
The fracture toughness values of the different sample types were calculated and compared in Fig. 16. Similarly, it was found that the fracture toughness values of hybrid samples with additional felt + sand increased approximately 10 times when compared to the GFRP profiles and approximately 4 times when compared to the standard hybrid samples.

4. Conclusions

The results of improvement works on hybrid design and hybrid beams are summarized below:

- In addition to their numerous superior properties, GFRP profiles are more advantageous than other construction materials due to their lightweight structure, corrosion resistance and high tensile stress. Thus, the use of these materials as an alternative material in the construction industry can solve many construction material problems.

- A hybrid construction system which involves the combination of traditional construction materials and new generation composites improves the inadequate aspects of the existing construction materials and new generation materials become more feasible. It was found that hybrid construction materials produced with the combination of concrete-GFRP box section had superior properties than other components.

- Since GFRP box sections serve as formwork in a hybrid system, there is no need for a second formwork element to shape the concrete in plastic form. Thus, the system significantly saves time and formwork costs.

- As both materials function collectively in a hybrid construction element, it shows a higher strength than both hollow GFRP profile and plain concrete. Thus, it becomes possible to produce elements with smaller sections with the same strength. Local fractures in GFRP profiles under flexural load decrease in a hybrid system which is formed with concrete filling and thus, flexural strength increases.

- In a hybrid system, the GFRP profile will protect the concrete from the minerals in water by preventing exterior water and moisture. Since GFRPs are good insulators, the problems caused by energy consumption due to heat transfers and problems related to thermal stresses will decrease. In addition, it will prevent the concrete in plastic form placed inside GFRP box section from losing its water and moisture and will significantly contribute to the curing procedure.

- It was found that in hybrid samples with additional felt, flexural strength increased approximately 3 times when compared to hollow GFRP profiles of the same size and approximately 2 times when compared to hybrid samples. It was found that the fracture toughness of hybrid samples with additional felt increased approximately 10 times when compared to hybrid samples and approximately 4 times when compared to standard hybrid samples.

- It is believed that performing the procedures of developing profile properties by wrapping felt fiber to the exterior surface of GFRP box sections in a laboratory with special set ups will further improve and increase ratios in material strength. On the other hand, the fact that as a result of all the tests performed on the available profiles, GFRP box sections were not deformed from longitudinal fibers, but, that the latitudinal fibers ruptured indicates that decreasing longitudinal fiber ratios and increasing latitudinal fiber ratios will provide positive results in terms of economy and strength.

- Hybrid systems which are formed by a combination of GFRP box sections and concrete have the potential to address durability and corrosion problems as a separate column or beam appearing in coastal buildings or the ones which are exposed to sea water. In addition, GFRP-Concrete hybrid construction elements can be used in buildings such as chemical production facilities, bridge beams and docks.

References


