Effect of Reinforcement Ratio on Time-Dependent Deflection of Hybrid GFRP/Steel Reinforced Concrete Beams

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**Abstract**. The paper experimentally investigated the influence of steel reinforcement ratio on time-dependent deflections in hybrid GFRP/steel RC beams. A total of three hybrid RC beams and one reference GFRP RC beam were cast and tested under sustained load for a period of 180 days in varying environmental conditions. The tested beams differed in longitudinal steel reinforcement, resulting in a range of steel reinforcement ratios from 0% to 1.08%. The results revealed the impact of the steel reinforcement ratio on long-term deflections of hybrid GFRP/steel RC beams.

The experimental time-dependent deflections of hybrid GFRP/steel RC beams were compared to theoretical values derived from design equations for FRP RC structures found in ACI 440.1R-15. The outcome showed that these design standards overestimated the long-term deflection of hybrid RC beams. Also, a design method based on ACI 440.1R-15 with experimentally based adjusted time-dependent factors was presented for hybrid GFRP/steel RC beams. The predicted values were in good agreement with the experimental values.

**Keywords:** GFRP; Concrete beam; Time-dependent; Sustained load; Deflection, Reinforcement ratio.

1. Introduction

Fiber Reinforced Polymers (FRP) can be a good alternative to steel reinforcement in certain situations, particularly in concrete structures that are exposed to harsh environmental conditions, such as corrosion or electromagnetic fields. FRP has several advantages over steel, such as high strength, corrosion resistance, lightweight, and ease of installation. However, FRP also have many disadvantages, and one of the most disadvantages of FRP reinforcement is its low elastic modulus. This disadvantage causes low stiffness of FRP reinforced structures, leading to an increase in the total cost of a building due to the requirement of over reinforcement according to design standards and restricts the application of FRP for reinforced concrete structures despite their many advantages [1-10]. To improve the stiffness and other characteristics, additional steel bars were suggested to add to FRP reinforced concrete (RC) structures, in the results, hybrid FRP/steel RC. In hybrid FRP/steel RC beams, steel bars mainly confer ductility and FRP bars provide strength [11-15].

In the last decades, a significant amount of work, including experimental, analytical and simulation, has been performed to investigate the flexural performance of hybrid FRP/steel RC beams under instant static load. Most of the research focused on the investigation of flexural behavior, crack resistance, crack width, deflection, stiffness, ductility, optimal reinforcement ratio and proposed the corresponding analytical equations for the design of these characteristics of the beam [11, 15-26].

Despite a lot of research of short-term behavior of hybrid RC beams was carried out under static load, there was no available data on the time-dependent behavior of hybrid FRP/steel RC structures. Recently, Duy Nguyen, Hiep Dang [27] conducted long-term test of three hybrid glass fiber reinforced polymer (GFRP)/steel RC beams under static load during a period of 330 days. The outcomes showed that initial deflections and environmental conditions significantly influenced the long-term deflections of hybrid beams. Based on the experimental results, the authors classified three stages of the development of deflections. Also, the authors proposed a method considering the influence of hybrid GFRP/steel reinforcement on the creep coefficient for calculating the time-dependent deflections of GFRP/steel RC beams.

To contribute to the experimental database of hybrid GFRP/steel RC beams, this work mainly focuses on the experimental study of the influence of steel reinforcement ratio on the long-term deflections of hybrid GFRP/steel RC beams. The compatibility of some design standards for hybrid RC beams was also verified and a recommendation for calculating the time-dependent deflections of hybrid RC beams based on ACI 440.1R was also adopted.

1. Experimental program
   1. Details of beam specimens and properties of materials

In this experiment, four beams were tested under a four-point bending scheme. Three of them were simply supported hybrid GFRP/steel beams (namely: B2-0.54%; B3-0.79% and B4-1.08%), while the fourth was a GFRP control RC beam (namely: B1-0%). All beams had the same dimensions of 100 mm ×200 mm × 2000 mm (width × height × length). In hybrid RC beams, the GFRP bars took the primary reinforcement role and were arranged in the outermost layer, whereas the steel bars were located deeper in the second layer to ensure sufficient concrete cover protection. All beams were reinforced with a 6-mm diameter plain round steel bar in the compression zone, and in the tension zone, they were reinforced with one 14-mm diameter GFRP bar with a clear concrete cover *Cg* = 20 mm and one deformed steel bar having a diameter either of 10 mm, 12 mm, or 14 mm with clear concrete cover *Cs* = 50 mm. One-legged stirrups made of a 6-mm plain round steel bar were used to reinforce the beam specimens to avoid shear failure. Reinforcement details of beam specimens were shown in Fig. 1 and Table 1. In the hybrid RC beams, the GFRP reinforcement ratio was constant, while the steel reinforcement ratios varied from 0% to 1.08% to investigate its influence on the long-term deflection of tested beams.



Note: S refers to steel bar; G denotes GFRP bar

**Fig. 1.** Reinforcement details of beam specimens.

**Table 1.** Beams designation.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Specimen | *b×h*, mm | GFRP reinforcement | | | | |  | Steel reinforcement | | | | |
| *Bars* | *Ag*, mm2 | *Cg,* mm | *dg*, mm | *μg,*% |  | *Bars* | *As*, mm2 | *Cs,* mm | *ds* | *μs,*% |
| B1-0% | 100×200 | 1Ø14 | 127.6 | 20 | 173 | 0.74 |  | - | - | - | - | 0 |
| B2-0.54% | 100×200 | 1Ø14 | 127.6 | 20 | 173 | 0.74 |  | 1Ø10 | 78.5 | 50 | 145 | 0.54 |
| B3-0.79% | 100×200 | 1Ø14 | 127.6 | 20 | 173 | 0.74 |  | 1Ø12 | 113.1 | 50 | 144 | 0.79 |
| B4-1.08% | 100×200 | 1Ø14 | 127.6 | 20 | 173 | 0.74 |  | 1Ø14 | 153.9 | 50 | 143 | 1.08 |

Note for table 1: Beam specimen designations are *Bi-x%* where *Bi* is the sequence number of the beams, *x*% is the steel reinforcement ratio; *Ag* and *As* are the areas of GFRP and steel reinforcement bars, respectively; *Cg*, *Cs*, *dg* and *ds* are as shown in Fig. 1; *μg=Ag/*(*b×dg*) and *μs=As/*(*b×ds*) are the GFRP and steel reinforcement ratios.

The beam specimens were all made using concrete that had a targeted cubic strength of 30 MPa. The concrete mix proportion for 1 m3 was shown in Table 2. The average cubic strength was determined experimentally to be 32.3 MPa from five cubes measuring 150 mm ×150 mm ×150 mm, which were tested after 28 days. The mechanical properties of GFRP and steel bars based on the experimental test and provided by the manufacturer were summarized in Table 3.

**Table 2.** Concrete mix for 1 m3.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Cement PCB400, kg | Sand, m3 (kg) | Gravel, m3 (kg) | Water, lit | W/C | *R, MPa* |
| 349 | 0.45 (648) | 0.71 (1134) | 195 | 0.56 | 32.3 |

**Table 3.** Characteristics of reinforcements.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Reinforcement type | Diameter, mm | Yield strength, MPa | Ultimate strength, MPa | Elastic modulus, GPa |
| GFRP bar | 14 | - | 970 | 44.3 |
| Deformed steel bar | 12 | 396 | 463 | 200 |
| Plain round steel bar | 6 | 376 | 481 | 200 |

* 1. Experimental setup for short-term and long-term tests

All beam specimens were cast and cured according to current standards. Following a 28-day curing period, the specimens were placed at the testing site and exposed to environmental conditions for an additional 30 days to minimize the impact of dry shrinkage on the results prior to loading. Afterward, all beam specimens underwent preliminary treatment.

The beam specimens were subjected to four-point bending with an 1800 mm span, and a 600 mm shear span as depicted in Fig. 1 and Fig. 2. To prepare for the long-term test, the theoretical cracking loads, yielding loads and ultimate loads of beam specimens were calculated using the formulas proposed by Kartal and Kalkan [28] and Nguyen, Dang [14] and summarized in Table 4. The theoretical characteristic loading points from Table 4 were used to select a sustained load value of *P* = 7.5 kN for the long-term test. This load value was about 1.79 to 1.97 times of the cracking loads and about 0.43 to 0.67 of the yielding loads.

**Table 4.** Sustained loading levels for long-term tests.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Beam’s ID | *Pcrc,t, kN* | *Py,t, kN* | *Pu,t, kN* | Sustained load *P*, kN | *P/Pcrc,t* | *P/Py,t* | *P/Pu,t* |
| B1-0% | 3.8 | - | 23.3 | 7.5 | 1.97 | - | 0.32 |
| B2-0.54% | 4.0 | 11.2 | 25.5 | 7.5 | 1.88 | 0.67 | 0.29 |
| B3-0.79% | 4.0 | 14.0 | 26.8 | 7.5 | 1.88 | 0.54 | 0.28 |
| B4-1.08% | 4.2 | 17.3 | 28.3 | 7.5 | 1.79 | 0.43 | 0.27 |

Notes for Table 4: *Pcrc,t*, *Py,t* and *Pu,t* are the theoretical cracking load, yielding load and ultimate load, respectively.

The long-term deflection of specimens under sustained load was monitored by a dial indicator with a reading accuracy of 0.001 mm, which was installed at the mid-span through a steel bar that was attached to supports at the ends of the beams (Fig. 2). The long-term tests were conducted outdoors, but the experimental area was protected by a roof and wall to prevent rain and wind from affecting the testing system. Throughout the tests, a humidity meter (PCE-HT 110) was used to measure the temperature and relative humidity in the testing area.

|  |  |
| --- | --- |
|  |  |

**Fig. 2.** Long-term test setup.

The loading procedure was performed as follows: First, the static loading was performed up to the load of *P* = 7.5 kN on each beam with the loading rate being controlled by midspan deflection at approximately 0.2 mm/min. During the static test, the instantaneous deflections were recorded. After this, the loads were maintained on the beam specimens for long-term tests.

1. Experimental results and discussions

The measured instantaneous deflections of beam specimens are illustrated in Fig. 3 and Table 5. As evident from previous studies and Table 5, the presence of steel reinforcement raises the stiffness of hybrid FRP/steel RC beams. Under the same load, the instantaneous deflections of hybrid RC beams are inversely proportional to the steel reinforcement ratio.

Figure 4 illustrates the evolution of the total deflections over time since loading, which includes immediate deflection and long-term deflection due to creep and shrinkage. The curves of hybrid and GFRP RC beams have the same trend, as seen in Fig. 4. The long-term deflection of RC beams is influenced by many factors, such as creep and shrinkage of concrete; reinforcement properties; relaxation of steel; beam geometry; loading conditions; the age of concrete; curing conditions, etc. Among these factors, the creep and shrinkage of concrete have the most significant effect. Concrete creep and shrinkage are higher during the initial period of loading and decrease over time. Thus, the deflections of tested beams under sustained load exhibited rapid development initially, followed by a gradual decrease with the extension of the experimental time, as shown in Fig. 4. At three days since loading, the long-term deflections increased between 27.1% and 37.6% of the total increase in all tested beams, and at 60 days, these values ranged from 88.3% to 95.2%.



**Fig. 3.** Load versus instantaneous midspan deflection of testing beams.



**Fig. 4.** Time-dependent deflections of tested beams.

**Table 5.** Immediate deflection and total-to-immediate deflection ratio for tested beams.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Beam’s ID | *finst mm* | *f3/finst* | *f10/finst* | *f30/finst* | *f60/finst* | *f90/finst* | *f120/finst* | *f150/finst* | *f180/finst* |
| B1-0% | 2.73 | 1.32 | 1.47 | 1.65 | 1.81 | 1.79 | 1.84 | 1.85 | 1.86 |
| B2-0.54% | 1.41 | 1.34 | 1.43 | 1.6 | 1.91 | 1.9 | 1.99 | 1.98 | 2.03 |
| B3-0.79% | 1.28 | 1.23 | 1.34 | 1.52 | 1.75 | 1.72 | 1.8 | 1.76 | 1.84 |
| B4-1.08% | 1.24 | 1.23 | 1.31 | 1.5 | 1.65 | 1.59 | 1.64 | 1.62 | 1.68 |

Note: *finst* is the immediate deflection; *fi* is the total deflection at *i* days.

To evaluate the influence of steel reinforcement on the long-term deflection of hybrid GFRP/steel RC beams, the total-to-immediate deflection ratios of tested beams were established at several periods since the loading, as shown in Table 5. At 3 days since loading, these ratios for tested beams B1-0%, B2-0.54%, B3-0.79% and B4-1.08% were 1.32, 1.34, 1.23 and 1.23, respectively. At 180 days, these ratios increased to 1.86, 2.03, 1.84 and 1.68 for the same beams. The ratios for other periods can be found in Table 5.

As can be seen in Fig. 4 and Table 5, the beams with a lower steel reinforcement ratio experienced greater immediate and long-term deflections, resulting in more total deflections than that of beams with a higher steel reinforcement ratio (and higher total reinforcement ratio), when subjected to the same initial sustained load. Obviously, with the same sustained load (same bending moment), the stress levels of materials are inversely proportional to the total reinforcement ratio. Furthermore, a higher reinforcement ratio typically results in a stiffer and stronger beam, which can resist deflection more effectively. Both lower stress levels and higher stiffness of a beam with a higher reinforcement ratio reduce the immediate and long-term deflections in comparison with the beam with a lower reinforcement ratio.

Figure 5 illustrates the correlation between initial instantaneous and total deflections. Typically, the ratio of instantaneous deflection to the total deflection ratio of tested beams was directly proportional to the steel reinforcement ratio (total reinforcement ratio).



**Fig. 5.** Variation of instantaneous deflection/deflection.

The long-term test was carried out under natural conditions. The chart depicting the changes in temperature and relative humidity during the experimental period is shown in Fig. 4. During the test period, the temperature fluctuated between 15.90°C and 32.30°C, while the relative humidity ranged from 63% to 98%. Although the influence of temperature and humidity on the long-term deflection of the beam was not specifically monitored in this experiment, their impact can be observed from the variations in the long-term deflection change chart depicted in Fig. 4.

1. Theoretical estimation of long-term deflection of hybrid GFRP/steel RC beams

Even though significant research has been conducted on hybrid FRP/steel reinforced concrete structures, there is currently a lack of established design guidelines for this particular type of structure. For FRP-reinforced structures, The ACI 440.1R design guide [29] provides a formula to determine the total deflection of a beam under long-term loading, as follows:

 ()

where λ is the long-term multiplier and is defined as follows:

 ()

where *ξ* is the time-dependent factor for sustained loads, which includes the effects ofcreep and shrinkage and equal 1.0, 1.2 and 1.4 for 3, 6 and 12 months, respectively. For 5 years or more *ξ* = 2.0*.* Other values of *ξ* for a time period of fewer than 5 years may be obtained from Fig. 6.



**Fig. 6.** Multipliers for long-term deflections [30].

The comparison between experimental and theoretical total deflections of tested beams obtained according to the recommendations of ACI 440.1R in Fig. 7 shows that ACI 440.1R overestimates the long-term deflections of GFRP and hybrid GFRP/steel RC beams.

One of the advantages of the ACI 440.1R’s formula for estimating the long-term deflections of RC beams is its simplicity in comparison with other existing methods. In an effort to use this method for hybrid GFRP/steel RC beams, we suggest redefining the time-dependent factor *ξ* in eq. (2) based on the experimental data of tested beams. The average time-dependent factor obtained from the tests is displayed in Fig. 6.

The theoretical long-term deflections of tested beams obtained from the eq. (1) with the proposed time-dependent factor are shown in Fig. 7. It can be seen in Fig. 7 that the theoretical curves of long-term deflections well fit with the experimental curves.

The deflections of tested beams were theoretically determined using eq. (1) with the adjusted time-dependent factor, and the results are presented in Fig. 7. The figure shows that the theoretical curves obtained from the proposed method more closely match the experimental curves compared to ACI 440.1R's recommendations. Specifically, at 180 days since loading, the theoretical deflection values for tested beams B1, B2, B3, and B4 were 0.98, 0.89, 0.99, and 1.08 times the corresponding experimental deflection values (with an average ratio of 0.99). In contrast, the ratios obtained from ACI 440.1R's recommendations were 1.18, 1.08, 1.20, and 1.31 (average ratio of 1.19).



**Fig. 7.** Comparison between the theoretical and experimental total deflections.

Conclusions

An experimental study was conducted by testing one GFRP RC beams and three hybrid GFRP/steel with different steel reinforcement ratios under the same sustained load to study the long-term deflection behavior for 180 days. The results of this study are summarized below:

- The higher the steel reinforcement ratio (and a higher total reinforcement ratio), the lower the immediate deflections in the beams.

- Higher total-to-immediate deflection ratios are observed in the hybrid beams with lower steel reinforcement ratio (lower total reinforcement ratio).

- The existing methods for estimating the long-term deflections of reinforced concrete beams are not suitable for hybrid GFRP/steel RC beams. The ACI 440.1R’s model for estimating the long-term deflections of FRP RC beams were adopted for hybrid GFRP/steel RC beams by adjusting the time-dependent factor for sustained loads based on the experimental results.

It should be mentioned that the above conclusions are based on experimental and theoretical studies on a limited number of specimens and conditioning environments. Thus, it may not directly extend to other beam configurations or environmental conditions. Further investigation into the effect of wider ranges of beam configurations and weather conditions and for a longer duration should be done.

Conflict of interest

None declared

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