



# Strength of compression lap-spliced GFRP bars in concrete columns with different splice lengths

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## HIGHLIGHTS

- Columns reinforced with GFRP and steel splices were tested under compression.
- Behavior of lap-spliced GFRP bars were evaluated under compression.
- Contribution of strength components of GFRP compression splices were determined.
- Compression splices of GFRP bars were compared with those of steel bars.

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## ABSTRACT

Recent years have seen valuable research work on using glass-fiber-reinforced-polymer (GFRP) bars in reinforced-concrete (RC) members under compression. Nonetheless, lap splicing of GFRP bars under compression has not yet been explored with due consideration of its components. To address this knowledge gap, this paper comparatively demonstrates the results of an experimental investigation pertaining to the effect of splice length on the compression lap splicing of GFRP bars in concrete columns. The experiment comprised 11 large-scale circular columns measuring 300 mm in diameter and 1600 mm in height: seven specimens reinforced with GFRP bars, three specimens with steel bars for comparison purposes, and one specimen without reinforcement (plain concrete). All columns were tested under a monotonically increasing concentric load. The test variables included the reinforcement type (GFRP versus steel) and splice length. The results were compared in terms of the stress–strain curves, ultimate loading, displacement capacity, and splice strength. The test results indicate that the required compression splice length for GFRP bars is less than that required for steel. As the strength of a compression splice consists of end-bearing and bond components, the contribution of each part was scrutinized in detail using measured strain values. The required splice length for GFRP bars was considerably based on the end-bearing component. Based on the experimental results, a length of  $8d_b$  can reliably be considered as the required splice length for No. 5 GFRP bars in compression.

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## 1. Introduction

Corrosion of steel reinforcing bars stands out as a significant factor limiting the life expectancy of reinforced-concrete infrastructure exposed to harsh environmental conditions. In the last decade, the use of fiber-reinforced polymer (FRP) as an alternative reinforcing material in reinforced-concrete (RC) structures has emerged as an innovative solution to the corrosion problem [1].

Extensive research programs have been conducted to investigate the flexural and shear behavior of concrete members reinforced with FRP bars [2–11]. FRP design provisions for shear and flexure are now well established and included in codes and design standards.

Glass-FRP (GFRP) bars are becoming more attractive to the construction industry because they cost less than other types of FRP materials. GFRP bars have been used successfully as the main shear and flexural reinforcement in concrete bridges, parking garages, tunnels, and water tanks [1,12,13]. Nevertheless, current guidelines do not cover the subject of FRP-reinforced concrete members subjected to axial compression loads. Using GFRP bars as the main reinforcement in compression members is still under consideration. This can be partly attributed to the insufficient recognition

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of certain parameters that influence the analysis and design of such members. These parameters may include, but are not limited to, reinforcement type, ratio of longitudinal FRP reinforcement, and volumetric ratio and configuration of transverse reinforcement. While the first two parameters influence the loading capacity of an FRP-reinforced concrete column, the displacement capacity and ductility are mainly affected by the confinement action provided by the transverse reinforcement. Lateral confinement can also prevent local and global buckling of longitudinal reinforcement. Recently, valuable research work has been conducted to investigate the effect of different parameters on the behavior of concrete members reinforced with GFRP bars subjected to compression axial loads or simultaneous flexural loads [14–21]. The outcomes of these experimental studies may ultimately provide a convincing case to allow the limited use of FRP bars in columns. Aside from the current study, almost no experimental work on concrete members reinforced with lap-spliced GFRP bars subjected to compression loads has been conducted.

The results of axially loaded concrete columns reinforced with GFRP bars could hardly be different than that of their steel-reinforced counterparts. De Luca et al. [14] tested rectangular concrete columns reinforced with GFRP and conventional steel bars. The reinforcement ratio of the longitudinal bars in all the columns was equal to 1% of the total cross-sectional area. Within this range of longitudinal reinforcement, the loading capacity of the columns reinforced with GFRP bars were similar to those reinforced with steel. In addition, the contribution of GFRP bars to the column capacity at peak load was about 5%, compared to approximately 12% for the steel reinforcement. Assuming a reduction factor of 0.35 for the contribution of GFRP reinforcement, Afifi et al. [16] reported an equal ultimate strength for circular columns reinforced with GFRP and steel longitudinal reinforcement at ratios of 2.2% and 1.7%, respectively. Based on their results, the load carried by the GFRP-reinforced columns was 7%, on average, less than those reinforced with steel. The average load carried by the longitudinal GFRP bars, however, ranged between 5% and 10% of the peak load, compared to about 16% for the steel bars. In another study, Tobbi et al. [15] tested rectangular GFRP-reinforced concrete columns with two longitudinal reinforcement ratios of 0.8% to 1.9%. Their results indicated a relatively close contribution of the GFRP and steel reinforcement to the column capacity (10% and 12% of the peak load for the GFRP and steel bars, respectively).

Research works conducted on eccentrically loaded GFRP-reinforced concrete columns have also demonstrated the efficiency of using GFRP bars in the tension and compression sides [18–21]. The experimental results showed that the axial load and bending-moment capacity of the GFRP-reinforced concrete columns were comparable to those of the conventional steel-reinforced concrete columns with similar reinforcement ratio, concrete strength, and cross section [18]. Hadhood et al. [19] experimentally constructed the failure envelope for 10 large-scale circular GFRP-reinforced concrete columns. They concluded that compression failure due to concrete crushing controlled the ultimate capacity of the specimens tested under concentric and low eccentric loading. The experimentally predicted axial and flexural capacities of the GFRP-reinforced high-strength-concrete columns using ACI 440.1R-15 [1] and CSA/CAN S806-12 [22] assumptions and ignoring the compression contribution of the GFRP bars were reasonable but rather conservative relative to the experimental results [20].

In addition to the experimental studies, valuable theoretical approaches have been developed by many researchers to better estimate the nominal axial force and bending moment of GFRP-reinforced concrete columns under static eccentric loading. Zadeh and Nanni [12] developed axial load-bending moment interaction diagrams theoretically, assuming that longitudinal GFRP bars are

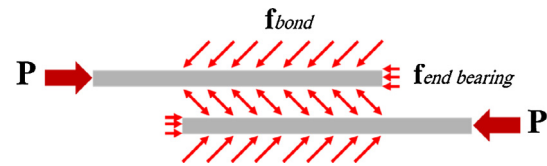


Fig. 1. Components of compression lap spliced bars.

only effective in tension. When subject to compression, they can be replaced with the equivalent area of concrete as if they were not present in the cross section. Recently, Zadeh and Nanni [2] proposed design equations to estimate the flexural stiffness of GFRP-reinforced concrete columns whether for structural analysis or for slenderness effects.

While numerous research endeavors have elaborated on the use of FRP bars as the main reinforcement in compression elements, lap splicing of FRP bars in compression has not been explored in detail. It should be noted that, due to considerations such as ease of storage and transportation, FRP bars are manufactured in certain lengths. Thus, splicing is inevitable in reinforced-concrete structures, although it should be minimized in field applications. In such cases, the resistance of a bar spliced along its length is mainly governed by the splice strength. Inadequate splicing can lead to undesirable failure of the member. The pioneering scrutiny of compression splicing dates back to over 40 years ago in which Pfister and Mattock [23] examined the requisite length for spliced steel bars in compression. Based on their experimental findings, the strength of a spliced steel bar comprises two components—end bearing and bond—as depicted in Fig. 1. The provisions for splicing under compression in ACI 318-14 [24] were mainly derived from this study. Chun et al. [25] later evaluated the relation in ACI 318-14 [24] to determine the splice length of bars in compression. Comparing the experimental and predicted values underlined the necessity to modify the ACI relation. Due to the inherent differences between GFRP and steel reinforcement, the provisions recommended in design codes and guidelines for steel bars [24,26] cannot be used for GFRP reinforcement. This knowledge gap was the main motivation behind the current experimental campaign aimed at describing the performance of compression lap-spliced GFRP bars in concrete columns with different splice lengths.

## 2. Research significance

Despite the recent investigations confirming the possibility of using FRP bars as longitudinal reinforcement in columns, no research has been conducted to investigate the lap splicing of FRP reinforcement bars in compression. The primary aim of this research was to yield a better understanding of the strength of lap-spliced FRP bars under compression. This was achieved by describing the strength components in compression splices and their contributions. In addition, the experimental results can be used to assess the load-carrying capacity and behavior of circular concrete columns reinforced with spliced GFRP bars under concentric axial compression.

## 3. Experimental programme

### 3.1. Material properties

All of the specimens were cast on the same day with normal-weight, ready-mix concrete. The 28-day compressive strength of the concrete, determined by the average test results of five cylinder samples (100 × 200 mm), was about 40.5 MPa. On the testing date,

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