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# Effect of Axial Load and Steel Fibers on the Seismic Behavior of Lap-Spliced Glass Fiber Reinforced Polymer-Reinforced Concrete Rectangular Columns

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A B S T R A C T

In this study, the behavior of six full-scale lap-spliced glass fiber-reinforced polymer reinforced concrete rectangular columns is presented. The columns were tested under simultaneous axial and quasi-static cyclic reversed loads. The experimental program was designed to determine the adequate splice length in such columns as well as the effect of different axial load levels on their performance. In addition, the effect of using steel fiber reinforced concrete (SFRC) on the behavior of columns with inadequate splice length is investigated. Test results showed that a splice length of 60 times the diameter of the longitudinal bar is adequate to transfer the full bond forces along the splice length and were able to maintain the lateral load carrying capacity when subjected to higher levels of axial loads and drift ratios. Furthermore, the use of SFRC in columns with inadequate splice increased the peak lateral strength and the energy dissipation of the specimens.



## 1. Introduction

The use of glass fiber-reinforced polymer (GFRP) reinforcement, as a replacement of the corrodible steel reinforcement in concrete structures, has become a viable solution. Nevertheless, the different mechanical characteristics of GFRP bars must be considered. The GFRP bars behave in a linear-elastic manner (no yielding) up to failure and have a relatively low modulus of elasticity compared to steel bars. Moreover, they have different bond characteristics which are very critical in transferring forces between lap spliced bars. Therefore, the current codes for steel-reinforced concrete (RC) members cannot be directly used for the GFRP-RC members.

A considerable amount of research has been conducted on the cyclic behavior of lap-spliced steel-RC columns. A splice length of 40 $d_b$ was found to be adequate where $d_b$ is the largest diameter of column reinforcing bars; however, good confinement should be provided by transverse reinforcement [1,2]. The lateral load-deflection response, strength and stiffness degradation and the ability of lap-spliced steel-RC columns to resist the axial load after loss of lateral load resistance are also well investigated. Results revealed that columns subjected to low levels of axial loads were able to maintain the axial load carrying capacity at high drift ratios [3]. Also, the axial load level affected the ability of the column to dissipate energy where the energy dissipation capacity decreases as the level of axial load increases.

Recent studies on the behavior of GFRP-RC columns subjected to cyclic-reversed loads showed that the use of GFRP bars as reinforcement is feasible in RC columns in seismic regions [4–6]; however, with less energy dissipation compared to that of their steel-RC counterparts. The hysteresis response of steel-RC columns exhibited significant pinching of the hysteresis loops, due to yielding of steel reinforcement. Conversely, for the GFRP-RC columns, hysteresis loops were aimed approximately at the origin of the load-drift ratio relationship, however, in a more stable manner than their steel counterparts. The seismic stability refers to the ability of an RC structure to carry loads and to exhibit high levels of deformability, following the peak response. The major source of instability of steel-RC columns is the developed inelastic tensile strains, within the plastic hinge region, imposed by pre-peak cycles. During the unloading phase, wide cracks still exist, as a result of plastic tensile strains that were developed in the bars during the loading phase. In contrast, due to the linear-elastic behavior of the GFRP bars, the GFRP column longitudinal bars can sustain large elastic deformations while tensile stresses and strains reduce to approximately zero (closing the flexure cracks) during the unloading phase. Furthermore, the ultimate tensile strength of the GFRP bars is approximately three times the yield strength of

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**Nomenclature**

| | |
|---|---|
| $A_c$ | cross-sectional area of the core of a compression member measured to the centerline of the perimeter hoop or spiral, $mm^2$ |
| $A_g$ | gross area of section, $mm^2$ |
| $A_{fv}$ | total cross-sectional area of FRP shear reinforcement, $mm^2$ |
| $A_{sh}$ | total area of FRP shear reinforcement in each cross-sectional direction, $mm^2$ |
| $b_c$ | column width, mm |
| COV | coefficient of variation |
| $d_b$ | diameter of longitudinal GFRP bar, mm |
| $d_f$ | diameter of steel fiber, mm |
| $f'_c$ | concrete compressive strength at the day of testing, MPa |
| $f_{Fh}$ | design stress level in FRP transverse confinement reinforcement, MPa |
| $f^{D}_{600}$ | Residual flexural strength at net deflection of $L/600$ |
| $f^{D}_{150}$ | Residual flexural strength at net deflection of $L/150$ |
| $f_P$ | Peak flexural strength, MPa |
| $f_r$ | tensile strength of concrete at the day of testing, MPa |
| $h_c$ | cross-sectional dimension of column core, mm |
| $k_c$ | confinement efficiency constant |
| $L$ | Span length, mm |
| $L_f$ | length of steel fiber, mm |
| $s$ | spacing of transverse reinforcement, mm |
| $sl$ | spacing of tie legs or the spacing of grid openings in the cross-sectional plane of the column, mm |
| $P$ | applied axial load on the GFRP-RC columns, kN |
| $P_o$ | nominal unconfined axial load capacity of the column, kN |
| $P^{D}_{600}$ | residual load at net deflection of $L/600$ |
| $P^{D}_{150}$ | residual load at net deflection of $L/150$ |
| $P_P$ | peak load, kN |
| $T^{D}_{150}$ | area under the load vs. net deflection curve from 0 to L/150 |
| $\delta$ | design lateral drift ratio |
| $\delta_P$ | net deflection at peak load, mm |
| $v_f$ | fibers % by volume |
| $\rho_{FRP}$ | FRP longitudinal reinforcement ratio |
| $\rho_b$ | FRP longitudinal balanced reinforcement ratio |
| $\rho_v$ | transverse FRP reinforcement ratio. |

the steel reinforcement. Therefore, the GFRP-RC columns behave in a more stable manner than their steel-RC counterparts [5,6].

In addition, the use of steel fiber-reinforced concrete (SFRC) is common in many structural applications. Osorio et al. [7] reported that using SFRC in columns subjected to simultaneous axial and lateral loads enhanced the ductility and energy dissipation. Transverse reinforcement provides resistance against the propagation of the splitting cracks, which controls the lateral expansion of concrete and enhances the bond strength of lap-spliced bars [8,9]. Also, it was found that, similar to transverse reinforcement, the presence of steel fibers in the plain concrete improves the behavior of lap-spliced steel-RC members. The presence of steel fibers delays the formation and propagation of cracks in RC members and, therefore, high bond strength is expected [10]. Similarly, it was reported that the use of SFRC enhances the bond performance of GFRP bars [11].

The current study, up to the authors' knowledge, is the first to investigate the seismic behavior of lap-spliced GFRP-RC columns under different axial load levels and with varied steel fiber volumetric ratio.

## 2. Experimental program

A total of six full-scale lap-spliced GFRP-RC columns were constructed and tested to failure under combined axial and reversed cyclic lateral loads, simulating a seismic event. The test matrix is shown in Table 1. For comparison purposes, one GFRP-RC column (control specimen without lap splice) tested by Ali and El-Salakawy [6] is also included in Table 1. The column specimen represented the portion between the point of contra-flexure and maximum moment section at the column footing interface. The rectangular column had a 350-mm square cross-section and was 1,850-mm long with a shear span of 1,650 mm (distance between the column-footing interface and point of load application). Each column had a 350 × 550 × 400 mm top head which was provided to transfer the axial and lateral loads to the column. A 1,400 × 1,400 × 600 mm steel-RC footing was designed to provide adequate fixity to the column.

All specimens had a longitudinal reinforcement ratio of 1.3% (8 No. 16 GFRP bars with a nominal diameter of 15.9 mm), which is higher than the minimum longitudinal reinforcement ratio of 1.0% specified in Clause 8.4.3.8 of the CSA/S806-12 code [12], for GFRP-RC columns. For all columns, size No.10 bent GFRP bars (perimeter hoops and cross ties) with a diameter of 9.5 mm were used as transverse reinforcement. According to CSA/S806-12 [12], a stirrup spacing of 75 mm (one quarter of the column depth) was used in all specimens. Straight GFRP dowel bars were embedded in the steel-RC footing with an embedment length of 575-mm. A week later, the column was cast to simulate field conditions. It is worth mentioning that this 575-mm embedment length of the dowels exceeds the development length required by relevant codes [13,14]. Moreover, the reported strain profiles by Ali and El-Salakawy [6] showed that the embedment length of 575 mm was adequate, and assured no slippage. The footing was adequately

**Table 1**
Characteristics of test specimens.

| Specimen | Concrete Strength, $f'_c$ (MPa) | Splice Length (mm) | Axial Load, $P/f'_cA_c$ (%) | Fibers content by volume, $v_f$ (%) |
|---|---|---|---|---|
| NO-10-0.0[a] | 38 | None | 10 | 0 |
| 60-10-0.0 | 40 | 960 | 10 | 0 |
| 40-10-0.0 | 41 | 640 | 10 | 0 |
| 60-15-0.0 | 39 | 960 | 15 | 0 |
| 60-20-0.0 | 41 | 960 | 20 | 0 |
| 40-10-1.0 | 49 | 640 | 10 | 1 |
| 40-10-2.0 | 47 | 640 | 10 | 2 |

Note: For all specimens, the longitudinal and transverse reinforcement ratio is 1.30 and 0.27%, respectively.
[a] NO-10-0.0 is an identical column without lap splice tested by Ali and El-Salakawy [6].