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1 **Experimental and Analytical Behavior of Short Concrete Columns**

2 **Reinforced with GFRP Bars under Eccentric Loading**

3 Koosha Khorramian¹ and Pedram Sadeghian²

4 **ABSTRACT:** This paper presents experimental and analytical studies on short concrete columns
5 reinforced with glass fiber-reinforced polymer (GFRP) towards characterizing compressive
6 behavior GFRP bars. The experimental program consisted of fourteen 500 mm-long specimens
7 with a square cross-section (150x150 mm) including nine GFRP reinforced (6#5) and five plain
8 concrete specimens. The specimens were tested under concentric and eccentric compressive load
9 up to failure. Three eccentricity to width ratios of 0.1, 0.2, and 0.3 were considered, where the
10 eccentricities applied symmetrically at both ends of simply supported columns. The experimental
11 program showed no crushing of GFRP bars at peak load and the corresponding strain did not reach
12 50% of their crushing capacity obtained from material test. In addition, an analytical model was
13 developed and verified against the experimental test data. The model considered both material
14 nonlinearity and geometrical nonlinearity. Using the model, a parametric study was performed on
15 the effect of eccentricity, reinforcement ratio, and concrete strength, which confirmed the
16 capability of GFRP bars to sustain high strains without reaching the compressive strain capacity
17 of the bars. The study showed that GFRP bars can be considered as load bearing longitudinal
18 reinforcement of concrete columns and ignoring their effect is not necessary.

19 **KEYWORDS:** GFRP, Column, Concrete, Crushing, Test, Model.

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20 1. INTRODUCTION

21 Fiber-reinforced polymer (FRP) composite bars have been used in construction industry as an
22 alternative to steel reinforcing bars (rebars) in concrete structures where high corrosion resistance
23 is needed [1]. Moreover, glass FRP (GFRP) have a unique electromagnetic transparency which
24 makes them suitable for applications where electromagnetic fields are recognized as critical design
25 criterion [2]. There have been many investigations on the behavior of GFRP bars in concrete beams
26 [3, 4, 5], slabs [6, 7, 8], bridge decks [9, 10], and walls [11, 12]. As a result, the use of GFRP bars
27 have become widespread in structural applications where bending capacity is needed. However,
28 the application of GFRP bars in concrete columns has been limited, although multiple researchers
29 performed different studies on GFRP bars in columns [13, 14, 15, 16, 17, 18, 19].

30 It is commonly believed that GFRP bars are not as effective as steel bars in load bearing
31 capacity of concrete columns. For example, the ACI 440.1 [20] design guide for GFRP bars
32 neglects the contribution of the GFRP bars in compression and allows the replacement of them
33 with concrete in calculations. Another example is CAN/CSA S806 [21], Canadian standard for
34 design and construction of building structures with GFRP, which allows the use of GFRP bars in
35 concentrically loaded columns only if the designer neglects their contribution in strength.
36 Furthermore, *fib* Bulletin 40 [22] mentioned that since the contribution of the compressive GFRP
37 rebars to the load carrying capacity of concrete column is less than the steel rebars, their
38 contribution is ignored.

39 Choo et al. [23] performed an analytical study on FRP reinforced concrete columns and
40 mentioned that ignoring FRP rebars in the compression zone may be conservative, however, they
41 have not checked the compressive strain of FRPs in compression to see whether compressive
42 failure of FRPs occur or not. Also, De Luca et al. [2] tested large-scale concrete columns reinforced

43 with GFRP bars under concentric compression and concluded that GFRP bars are more susceptible
44 to instability since their compressive strength and stiffness in compression are less than in tension.
45 On the other hand, Tobi et al. [24] showed the compressive strength of GFRP bars at peak load of
46 concrete columns is 35% of their capacity in tension. They also reported that the contribution of
47 GFRP bars were 10% of column capacity, which is close to steel bars' contribution (12%) which
48 proves that GFRP bars could be used in columns where adequate confinement is provided. Hales
49 et al. [16] conducted an experimental evaluation of slender high strength concrete columns
50 reinforced with GFRP bars and found that GFRP spirals and longitudinal bars are a viable system
51 of reinforcement for short and slender columns. Mohamed et al. [25] studied the performance of
52 concrete columns reinforced with longitudinal FRP bars and determined that carbon FRP (CFRP)
53 and GFRP bars experienced the compressive strain of 0.004 and 0.007 mm/mm which confirm
54 that the compressive FRP bars are effective in load-carrying capacity of columns. Also,
55 Khorramian and Sadeghian [26] and Fillmore and Sadeghian [27] experienced similar results in
56 experimental investigation of concrete columns and observed that GFRP bars can sustain a
57 significant level of compressive strains in columns.

58 As shown, the literature indicates that there are unknowns and controversial opinions
59 regarding the behavior of GFRP bars in concrete columns. There are doubts about modulus and
60 strength of GFRP bars in compression and the possibility of their premature crushing and/or
61 buckling in concrete columns. Lack of standard method for testing GFRP bars in compression has
62 also caused a gap of data regarding the corresponding mechanical properties. Thus, more research
63 is needed to evaluate if there is a safety issue regarding compressive behavior of GFRP bars in
64 concrete. Moreover, as considering an accidental load eccentricity is mandatory in column design,
65 the compressive behavior of GFRP bars in concrete columns under combined axial load and

66 bending moment needs to be investigated more in-depth to address their effectiveness for more
67 realistic cases.

68 Since the contribution of FRP bars as longitudinal reinforcements of concrete columns has
69 not been recognized by current design guidelines and their effects have been neglected, the
70 industry and design engineers are skeptical of using FRP bars in compression, even ignoring their
71 contribution. In addition, there is no standard test method for testing FRP bars in compression to
72 establish a reliable data platform clarifying all unknown regarding compressive behavior of FRP
73 bars. Manufacturers are also suffering from lack of a standard test method for evaluating the
74 compressive behavior of their FRP products. Therefore, the motivation of this paper was to
75 investigate the characteristics of FRP bars in compression where surrounded by concrete as well
76 as proposing a simple coupon test method for testing FRP bars in compression. The results will
77 help researchers, engineers, and manufacturers to understand better the behavior of FRP bars in
78 compression.

79 This study focuses on the compressive behavior of GFRP bars in concrete columns under
80 eccentric loading using both experimental and analytical methods for a selected square cross-
81 section and GFRP rebar type which are explained in the following sections. In the experimental
82 part, fourteen medium-scale GFRP reinforced concrete columns were tested under eccentric and
83 concentric loads. In the analytical part, a model was developed and verified to mimic the behavior
84 of the test columns and to perform a parametric study providing more information about the
85 compressive behavior of GFRP reinforced concrete columns.

86

87 **2. EXPERIMENTAL PROGRAM**

88 The experimental program consisted of testing of GFRP reinforced concrete columns as well as
89 plain ones under concentric and eccentric loads. The major test parameter was load eccentricity.
90 This section starts with details of test matrix and material properties, followed by explanation of
91 fabrication and test set up, and concluded by results and discussion.

92 **2.1. Test Matrix**

93 A total of fourteen 500 mm long concrete columns with a square cross section (150×150 mm) were
94 prepared and tested under concentric and eccentric compressive loadings. Nine of these specimens
95 were reinforced with six GFRP bars #5 (16 mm diameter). Four specimens consisting two plain
96 concrete and two specimens reinforced with GFRP bars were tested under concentric axial load
97 and other specimens were tested under eccentric loads at 15, 30, and 45 mm, i.e. 10, 20, and 30
98 percent of width of the cross-section, respectively. The test matrix is provided in Table 1. To name
99 the specimens, a label like “A-ex-y” was used where A, x, and y indicate the column type (P or
100 R), the eccentricity (e0, e10, e20, or e30), and the specimen number (1, 2, or 3), respectively. The
101 column type is identified by “P” for plain (i.e. no reinforcement), or “R” for GFRP reinforced
102 concrete columns. For example, “R-e10-1” means that it is the first specimen reinforced with
103 GFRP rebar and tested under 10 percent eccentricity.

104 **2.2. Material Properties**

105 A ready-mix concrete with maximum aggregate size of 12.5 mm was used for making the concrete
106 specimens. The concrete strength at the time of testing was 37.0 ± 0.8 MPa by testing three concrete
107 cylinders (100×200 mm). To reinforce the concrete specimens, six #5 sand coated GFRP bars with
108 a diameter of 16 mm and nominal cross-sectional area of 197.9 mm^2 were used. To determine
109 tensile characteristics of rebars, five tensile specimens were prepared and tested per ASTM

110 D7205M [28]. The mean and standard deviation of the tensile strength, tensile modulus, and
111 ultimate tensile strain of rebars were evaluated as 629 ± 30 MPa, 38.7 ± 1.5 GPa, and 0.0162 ± 0.0011
112 mm/mm, respectively. Figure 1(a) shows the stress-strain curves.

113 The compression properties of rebars were also examined by applying pure compression
114 load on five short rebar specimens with a free length twice the diameter of rebars as shown in
115 Figure 1(b). In order to eliminate the stress concentration and premature failure at the ends of rebar
116 specimens, two steel caps including a steel hollow cylindrical section with inner diameter of 32
117 mm and depth of 12.7 mm were used. The caps were filled with a high strength epoxy-based grout
118 to fix the rebar specimens. For the compression test, a spherical platen was used at the bottom of
119 the specimens to align them with the axis of loading minimizing accidental eccentricities. Mode
120 of failure of rebars in compression test was crushing and no buckling observed during the test. The
121 compression strength, compression modulus, and crushing strain of bars at peak were evaluated as
122 783 ± 74 MPa, 41.2 ± 1.2 GPa, and 0.0190 ± 0.0017 mm/mm, respectively. It should be highlighted
123 that there is no ASTM standard for the compression test.

124 Figure 1(a) also shows the stress-strain curve obtained from the compression and tension
125 tests. Two strain gauges used at the center of the compression rebar specimens which were
126 malfunctioned/broken before reaching the ultimate load. Therefore, in order to complete the stress-
127 strain curves for compression specimens, the values of stroke divided by a proper gauge length,
128 which gives the tangent slope of the point at which strain gauge broke, were used as shown in
129 Figure 1. The average of compression strains at which the strain gauges were broken was 0.0133
130 mm/mm called “proportional limit” for compression strains, before which the stress-strain curves
131 are linear. The average proportional limit is 70% of the average crushing strain of 0.0190 mm/mm.

132 Moreover, the corresponding stress to the proportional limit was 534 MPa which was 68% of the
133 average crushing stress (783 MPa).

134 It was observed that the modulus of elasticity of GFRP rebar tested in compression and
135 tension are close to each other. Thus, the assumption of having the same modulus of elasticity in
136 tension and compression is rational and it can be used to model the behavior of GFRP bars. The
137 other observation is the comparatively higher crushing strength of GFRP in compression than its
138 rupture strength in tension. Thus, ignoring compressive strength of GFRP bars and considering
139 their strength and modulus like concrete in compression per ACI 440.1R [20] is too conservative.
140 Since there is no standard method for testing FRP bars in compression, different values for the
141 compressive strength have been reported. De Luca et al. [2] reported reductions in the compressive
142 strength and elastic modulus of GFRP bars by up to 45 and 20% with respect to the values in
143 tension, respectively. On the other hand Khan et al. [29] tested FRP bars both in compression and
144 tension and the results showed considerably higher modulus and strength of tensile tests in
145 comparison to compression tests while Mallick [1] referred to the typical mechanical properties of
146 different laminas which shows lower, equal, or higher compressive strength than tensile ones
147 depend on their type. Overall, the performance of GFRP bars in concrete could be different than
148 coupon test. That is another reason for designing the experimental program.

149 **2.3. Fabrication**

150 Fresh concrete was casted in wooden molds which was prepared to hold the bars, and the
151 movement of rebar was restricted by two wooden plates with holes, as shown in Figure 2(a), that
152 were attached to the end of the mold as presented in Figure 2(b). The cover of GFRP rebar was
153 selected as 25.4 mm in each direction which is consistent with available specifications for FRP
154 rebar [20]. The center to center distance between two bars was 41.6 mm, and the distance from the

155 edge of concrete to the center of rebar was 33.4 mm. There were two rows of rebar that each of
156 them consisted of three rebar as is shown in Figure 2(a). The specimens were casted in one batch
157 as shown in Figure 2(c), and were cured at room temperature by covering with plastic sheets to
158 prevent losing the moisture as presented in Figure 2(d). In this experimental program, no tie was
159 applied to the column specimens because of the scale of tests. Since the shear loads are very small
160 because of the size of specimens and symmetric load eccentricities, and the confinement effect
161 was not target of this study, the only possible function of ties could be providing GFRP bars with
162 less unbraced length and prevent premature buckling before the specimens reach their ultimate
163 capacity. In fact, the specimens were designed to allow any possible buckling of GFRP bars
164 especially after the peak load to observe the post peak behavior of the specimens. Since the load
165 concentration at bottom and top of the specimens, where the load applied, was expected to cause
166 a premature failure, both ends of concrete columns were strengthened with two layers of 50 mm
167 wide unidirectional basalt fabric and epoxy resin. The surface of concrete was grinded at the
168 location of basalt wraps before applying epoxy resin to provide roughness, and wet basalt fabrics
169 stretched on the surface of concrete using hand to be fit to the edges and corners of specimens for
170 end wrappings. The corners were not rounded. Then, the top and bottom surfaces were flattened
171 using a grinder to provide a smooth surface at top and bottom of each specimen.

172 **2.4. Test Set Up**

173 In this study, the boundary condition was pin-pin, which allows rotation at end of column, and
174 load applied with the same eccentricity at both ends of column. Thus, two symmetric steel caps
175 were used at the end of columns to satisfy the boundary condition and loading condition, as shown
176 in Figure 3. The steel cap consists of a notched, 30 mm thick steel plate welded on a rigid steel
177 plate (250×250×10 mm). A steel cylinder with the same length of notch, lubricated with grease

178 was put in contact with steel cap through notch which permits the rotation of the specimen during
179 testing. In addition, the location of steel caps on steel plate was adjusted based on different
180 eccentricity demands using weld. Moreover, four adjustable angle profiles were attached to the
181 steel cap to restrict the column's sway and cause consistent end rotation of steel cap and specimen.
182 To make the steel cap more integrated with the testing specimens, two plastic bags were filled with
183 fresh quick set cement based grout and placed between the interface of steel caps, including the
184 interior surface of adjustable angles and the top steel plate, and the end of concrete specimens,
185 both at top and bottom of column.

186 To analyze the behavior of the specimens, the horizontal and vertical displacement of
187 column as well as the strains at outer surface of bars were measured using a data acquisition system
188 reading the data from strain gauges and linear variable differential transformers (LVDTs) at 0.1
189 sec. time steps, as shown in Figure 3. Vertical LVDTs (i.e. LVDT 1 and 2), with a gauge length of
190 100 mm, were applied to secure enough data in case of malfunctioned strain gauges. Furthermore,
191 two horizontal LVDTs (i.e. LVDT 3 and 4) were aligned with the center of concrete columns to
192 measure the deflection of the mid-height of columns. The tests were performed by a 2 MN
193 universal testing machine using a displacement control approach with a rate of 0.625 mm/min.

194

195 **3. RESULTS AND DISCUSSION**

196 A summary of the test results is shown in Table 2, in terms of the peak load (P_u), the strain of
197 extreme compressive rebar at P_u and its ratio to proportional strain (i.e. 0.0133 mm/mm) and
198 crushing strain (i.e. 0.0190 mm/mm) of GFRP coupons in compression. The table also shows the
199 strain of extreme compressive rebar at $0.85P_u$ (post peak) and its ratio to proportional strain and

200 crushing strain plus failure modes. In this section, the failure modes of test specimens and the
201 effect of eccentricity on the load- displacement and the strain of GFRP bars are discussed.

202 **3.1. Failure Mode**

203 In this study, three modes of failure were detected including concrete crushing in compression
204 (CC), concrete spalling in compression (CS), and concrete destruction (CD) as presented in Table
205 2. However, no buckling or crushing of GFRP bars were observed before the peak load. After peak
206 load, some bars were locally buckled when the compressive concrete crushed and is not
207 contributed to load bearing system. However, no crushing of GFRP bars were observed even after
208 spalling of concrete and buckling of bars. The concrete crushing (CC) is defined as the state at
209 which the strain at the extreme layer of compressive concrete reaches the strain of 0.003 mm/mm
210 as is considered as the ultimate strain of concrete in compression by ACI 318 [30]. Most of time,
211 crushing of concrete followed by the separation of concrete segments from the column which is
212 defined as concrete spalling (CS). For nearly all eccentrically loaded specimens, the crushing and
213 spalling of compressive concrete happened without crushing or buckling of bars as shown in
214 Figure 4. For 10 percent eccentricity ratio, the plain concrete specimens (P-e10 group) immediately
215 destructed after the spalling and split in half, which is called concrete destruction (CD) in this
216 paper. Overall, for GFRP reinforced specimens, no crushing of GFRP bars were observed after
217 significant lateral deformations and tests were terminated for safety reason.

218 **3.2. Effect of GFRP Bars on Load and Displacement Behavior**

219 Table 2 shows the average peak load of each group of specimens. It shows that the average load
220 capacity of plain specimens under pure axial load was 719.2 kN and it increased to 774.9 kN for
221 GFRP reinforced specimens (i.e. 7.74% increase). At the eccentricity ratio of 0.1, the load capacity
222 of plain specimens was 596.3 kN and it increased to 692.8 kN for GFRP reinforced specimens (i.e.

223 16% increase). This indicates that GFRP bars contributed to the load bearing capacity of the
224 specimens. Figure 5(a) shows the axial load vs. lateral displacement of the GFRP reinforced
225 specimens under 0.1, 0.2, and 0.3 eccentricities. The curves of two identical specimens for each
226 eccentricity are presented. It is observed that as the eccentricity increases, the peak load decreases
227 and the lateral displacement at peak load increases. Overall, the post peak behavior of the GFRP
228 reinforced specimens shows a gradual descending branch without sudden drops which is
229 compatible with the test observations indicated no crushing of GFRP bars.

230 **3.3. Effect of Eccentricity on Strain of GFRP Rebars**

231 Figure 5(b) shows the axial load vs. strain of GFRP bars under 0.1, 0.2, and 0.3 eccentricity ratios.
232 The figure indicates, as the eccentricity ratio increased, the strain of GFRP bars at peak load
233 increased. It also shows that GFRP bars sustained considerable level of strain at the compression
234 side and the level of strains in GFRP bars were much less than their crushing strain obtained in
235 coupon test, which means GFRP bars were stressed much less than their capacities in tension and
236 compression. This is due to low modulus of GFRP bars. It should be noted that for one of
237 specimens in group R-e20 shown in Figure 5(b), the strain in compressive rebar was not continued
238 to the peak load while the strain in tensile side was continued to the peak load, which could be due
239 malfunction of the strain gauge in the compression side. In addition, it is observed that for
240 specimens tested under eccentricity to width ratio, both strain gauges attached to GFRP bars
241 experience compressive strain up to failure due to the comparatively low eccentricity. However,
242 after the peak load the tests continued since the displacement control approach used for these
243 experiments and as a result as the stroke displacement increases, the strain at compressive side
244 increases and to satisfy the equilibrium of the section, the depth of neutral axis and compressive
245 area contracted which leads to recording tensile strains after peak load on the tensile side. Table

246 2 shows that when the eccentricity ratio increased from 0 to 0.3, the strain of GFRP bars at peak
247 load increased from 0.00275 to 0.00361 mm/mm. The ratio of recorded strains to proportional
248 limit (i.e. 0.0133 mm/mm) and crushing strain (i.e. 0.0190 mm/mm) from coupon tests were
249 calculated and presented in table 2. As shown, at peak load, the average ratios to proportional limit
250 and crushing strain were 0.23 and 0.16, respectively. It means GFRP bars at peak load of specimens
251 had a significant distance to their ultimate strain.

252 In order to have a better idea about post peak behavior of the specimens, an ultimate
253 condition was defined for the specimen at which the axial load was dropped 15 percent according
254 to a study on combined axial and flexural loads performed by Hognestad [31]. The importance of
255 studying the post peak behavior reveals once the failure of GFRP bars did not observed at the peak
256 load. Therefore, expectation of failure phenomenon such as crushing and buckling tracked up to a
257 certain load after crushing which is 85% after peak load, ($0.85P_u$) in this study. Table 2 provides
258 the average ratios of GFRP bar strains at 0.85 of peak load to the proportional limit and crushing
259 strain of the GFRP bars. The results reveal that, in average, the strain of GFRP bars in compression
260 at 0.85 of peak load were 0.0048 mm/mm, about 0.36 and 0.25 of proportional limit and crushing
261 strain of GFRP rebar, respectively. It means compressive GFRP bars did not reach their capacity
262 in crushing. It is noted that no buckling at peak load were observed which leads to the conclusion
263 that GFRP bars are reliable reinforcing bars in load carrying system at peak load. In addition, even
264 after 15% drop of peak load, the average strain of compressive GFRP bars were just quarter of
265 their crushing strain. It should be highlighted that the values of strain at 0.85 of peak load would
266 be even less than 0.0048 mm/mm if lateral ties limited their susceptibility to local buckling. This
267 also indicates that GFRP rebars should be considered different than steel rebars in design of
268 concrete columns. The contribution of GFRP rebars is a function of their modulus and level of

269 strain at the ultimate condition, rather than tensile/compressive strength of bar materials. In the
270 next section, an analytical model is presented to consider the effect parameters such as
271 reinforcement ratio and concrete strength which were not considered in the experimental program.
272

273 **4. ANALYTICAL STUDIES**

274 This section presents an analytical study to model the behavior of FRP reinforced concrete
275 columns under eccentric loading. The model generates load-strain, moment-curvature, and load-
276 displacement curves considering both material and geometrical nonlinearities using an iterative
277 cross-sectional analysis in MATLAB software.

278 **4.1. Model Description**

279 The analytical model consists of a combination of cross-sectional analysis and second-order
280 analysis which depends on column cross-section, rebar layout, material properties, length, load
281 eccentricity, and boundary condition. The cross-section of a rectangular column consisting of n
282 layers of GFRP rebar is presented in Figure 6(a). The cross-sectional area, the distance from the
283 furthest compressive fiber, and the location of each rebar layer from the neutral axis are presented
284 by “A”, “d”, and “y” in the figure, respectively. Moreover, the depth of neutral axis is shown by
285 “C” and the plastic centroid is presented by “C_P”. The sign convention is positive for compression
286 zone and negative in tension zone. It is assumed that the perfect bond exists between the concrete
287 and GFRP bars so that the strains profile is considered as a linear, continuous function through the
288 section for both compressive and tensile sides as shown in Figure 6(b). In order to find lateral
289 displacement of column, a moment-curvature relationship at each particular load is needed which
290 is derived by assuming the strain at the furthest compressive fiber in the section, ϵ_c , and the depth
291 of neutral axis, C, as shown in Figure 6, discretizing the section to concrete fibers, finding strains,

292 stresses, and controlling the satisfaction of equilibrium, which is explained in the following. The
 293 strain at the location of each rebar layer or at the center of every concrete fiber is calculated by:

$$\varepsilon_i = \left(\frac{\varepsilon_c}{c} \right) y_i \quad (1)$$

294 where ε_i is strain of concrete or GFRP bar, and y_i is the location of GFRP layer, or concrete fiber
 295 as shown in Figure 6(a). Once the strains are determined, a proper stress-strain relationship for
 296 concrete and GFRP bars gives the stresses at each rebar layer or concrete fiber. This model
 297 considers the stress-strain relationship of concrete in compression proposed by Popovics [32] as
 298 follows:

$$f_c = \frac{f'_c \left(\frac{\varepsilon_c}{\varepsilon'_c} \right)^r}{r - 1 + \left(\frac{\varepsilon_c}{\varepsilon'_c} \right)^r} \quad (2)$$

299 where ε_c is the strain of compressive concrete, and f_c is the corresponding stress of concrete, f'_c
 300 is the concrete compressive strength, and E_c is the compressive modulus of elasticity of concrete.

301 In Equation 2, other parameters are considered as $\varepsilon'_c = 1.7 \frac{f'_c}{E_c}$, $E_c = 4700 \sqrt{f'_c}$, $r = \frac{E_c}{E_c - E_s}$, and

302 $E_s = \frac{f'_c}{\varepsilon'_c}$, where the values of concrete strength and modulus of elasticity of concrete are in MPa.

303 Since the purpose of this model is to determine the behavior of concrete columns around the peak
 304 load, the tensile strength of concrete and tension stiffening effect are neglected to simplify the
 305 model. The stress-strain relationship of GFRP bars were considered as a linear, elastic curve up to
 306 the crushing in compression or rupture in tension with the same modulus of elasticity for both
 307 tension and compression sides as follows:

$$f_f = E_f \varepsilon_f \quad (3)$$

308 where f_f is the stress of GFRP bar, E_f is the modulus of elasticity of bars, and ε_f the strain
 309 corresponding to the stress. Although the modulus of elasticity assumed the same, the strength in

310 tension and compression are different. For each GFRP bar layer, the stress is evaluated using
 311 Equation 2, and the internal force corresponding to each GFRP layer is derived by multiplication
 312 of the cross-sectional area of all bars in that layer and the stress at the center of the layer. The
 313 concrete section is discretized to a number of fibers whose stress is evaluated at the center of each
 314 layer using Equation 1 and Equation 2. Then, the internal force of concrete derived by summation
 315 of forces in all fibers, which are obtained by multiplying the area of each fiber and its
 316 corresponding stress and considering the effects of bars in compression part, as follows:

$$F_c = \sum_a \sum_{\bar{y}_{c_i} \geq 0} \frac{1}{2} (f_{c_i} + f_{c_{i+1}}) b \delta_y - \sum_a \sum_{y_f \geq 0} \frac{1}{2} (f_{c_i} + f_{c_{i+1}}) A_f \quad (4)$$

317 where F_c is the concrete internal force, f_{c_i} and $f_{c_{i+1}}$ are concrete stresses at top and bottom of each
 318 concrete fiber, b is the width of section, δ_y is the height of each concrete fiber, \bar{y}_{c_i} is the location
 319 of center of each concrete fiber from neutral axis, y_{f_i} is the location of compressive GFRP layer
 320 from neutral axis, and A_f is the cross-sectional area of each GFRP layer. The number of layers in
 321 compressive zone was changed by changing the neutral axis location. In this study, the
 322 compressive zone always was divided into layers with 0.25 mm height. Afterwards, the sum of all
 323 internal loads gives the total internal force, P_n , which is calculated as follows:

$$P_n = F_c + \sum F_f \quad (5)$$

324 where P_n is the sum of all internal forces, F_c is the internal force of concrete, and F_{f_i} is the internal
 325 force of i^{th} layer of GFRP rebar. If the sum of internal forces is equal to the applied load, the
 326 equilibrium is satisfied, otherwise, the whole process must be repeated by changing the depth of
 327 neutral axis until the satisfaction of equilibrium.

328 Once the equilibrium of forces is satisfied, the sum of all internal moments about the neutral
 329 axis is calculated for concrete and GFRP layers. For each GFRP layer the internal moment is

330 calculated as the internal force times the corresponding distance from neutral axis while the
 331 internal moment of concrete fibers from neutral axis is calculated by:

$$M_c = \sum_a \sum_{\bar{y}_{c_i} \geq 0} \frac{1}{2} (f_{c_i} + f_{c_{i+1}}) b \delta_y \bar{y}_{c_i} - \sum_a \sum_{y_f \geq 0} \frac{1}{2} (f_{c_i} + f_{c_{i+1}}) A_f y_{f_i} \quad (6)$$

332 where, M_c is the concrete internal moment and other parameters are the same as Equation 4. Since
 333 the moment of internal forces is calculated about the neutral axis while the load eccentricity is
 334 measured from the center of plastic, the eccentricity is derived using Equation 7. The
 335 corresponding bending moment, M_n , for a determined curvature, which is defined as the furthest
 336 compressive concrete fiber divided by the depth of neutral axis, is then derived by Equation 8.

$$e^* = \frac{M_c + \sum F_s y_s}{P_n} \quad , \quad e = e^* - c + c_p \quad (7)$$

$$M_n = P_n e \quad (8)$$

337 In the equations, M_n is the total internal moment, P_n is the total internal force, e is the
 338 eccentricity of internal force from the center of plastic, e^* is the load eccentricity from the neutral
 339 axis, C is the depth of neutral axis, C_p is the depth of center of plastic, as shown in Figure 6(c),
 340 and other parameters are defined earlier. The mentioned process is repeated for a certain load and
 341 different values of furthest compressive concrete strain to find different curvatures and
 342 corresponding moments which leads to building the moment-curvature diagram of a given load.
 343 In this study, the loading path is derived by assuming the curvature and, in turn, the deflected shape
 344 of the column as a sine function as follows:

$$\phi(x) = (\phi_m - \phi_0) \sin \frac{\pi}{L} x + \phi_0 \quad (9)$$

345 where $\phi(x)$ is the curvature function of the column at the distance x from the bottom of the column,
 346 ϕ_m and ϕ_0 are the curvatures at the middle and the bottom of the column, respectively, and L is

347 the length of the column. White and Macgregor [33] implemented a sine shape function for the
 348 deflected shape of slender steel-reinforced concrete columns and derivation of moment
 349 magnification factor. In addition, the assumption of deflected shape as a sine function was adopted
 350 from Broms and Viest [34], Lloyd and Regan [35], Claeson and Gylltoft [36] for steel reinforced
 351 concrete columns which was later verified by Sadeghian et al. [37] for FRP-wrapped concrete
 352 columns. Recently, the sine function was implemented for externally bonded concrete columns
 353 with longitudinal FRP laminates [38]. Although Mirmiran et al. [39] used a half cosine function
 354 as the deflected shape of GFRP reinforced concrete columns, their model used only to predict the
 355 capacity of columns. The model presented in the current study predicts the load displacement, the
 356 loading path, strain of concrete and FRP rebars up to the peak load (ascending branch), and after
 357 peak load (descending branch) behavior of GFRP reinforced concrete columns, which includes
 358 post-buckling behavior of slender columns and the behavior of the columns after concrete crushing
 359 for short columns.

360 By applying the moment-area theorem and having the curvature function, the maximum
 361 deflection, δ_m , is derived in the form of Equation 10. By integration, Equation 10 is rewritten as
 362 Equation 11.

$$\delta_m = \int_0^{L/2} \phi(x) dx = (\phi_m - \phi_0) \int_0^{L/2} \sin \frac{\pi}{L} x dx + \int_0^{L/2} \phi_0 dx \quad (10)$$

$$\delta_m = \frac{L^2}{\pi^2} \phi_m + \phi_0 \left(\frac{L^2}{8} - \frac{L^2}{\pi^2} \right) \quad (11)$$

363 At a certain load, by building the moment-curvature and assuming the deflected shape of
 364 the column as a sine shape, an iterative process is used to find the deflection of column at its mid-
 365 height which is illustrated in Figure 7. In this process, three nodes are considered, one at the mid-
 366 height of column and two at the ends of column. An initial value of deflection at mid-height of

367 column is assumed and based on that value and the initial eccentricity, the total load eccentricity
368 and in turn, the corresponding moments are computed. Afterward, by using the moment-curvature
369 diagram of that specific load, and reading the points corresponding to the initial and mid-height
370 eccentricities, the values of curvature at the end of column, ϕ_0 , and at the middle of column, ϕ_m ,
371 are determined. It is worth mentioning that for each step, by changing the axial load, the
372 corresponding moment-curvature diagram was recalculated according to the mentioned process.
373 By substituting these values into Equation 11, the deflection of mid-height of column is computed.
374 If the latter and the assumed deflection are the same, the answer is valid, otherwise, other values
375 for deflection should be tried until a valid answer is found as shown in Figure 7. This process
376 begins with an initial deflection at mid-height of column, followed by an increased increment in
377 this deflection, which defines as the displacement step. The difference between the initial
378 deflection and the deflection calculated based on the sine function assumption, which is defined
379 as the control value, is tracked as the initial deflection increases. There is a certain deflection at
380 which the sign of the control value changes, which means in the current step the answer is passed.
381 Therefore, the process of finding a valid answer is started with a smaller displacement step
382 repeatedly until the control value is less than 10^{-10} or approaches zero. In the latter case, if the
383 control value decreased by changing the deflection at mid height of the column, the convergence
384 would happen and a valid answer exists, otherwise, the code cannot find a valid answer. The
385 explained process is the second-order analysis of the column which considers the effect of initial
386 eccentricity and the deflection caused by axial force in finding the final deflected shape of the
387 column. The latter is applied by considering $P(e+)$ as the bending moment used to find the
388 curvatures for the iterative process, as illustrated in Figure 7.

389 The applied load increases in some steps, and after finding a satisfaction of convergence
390 achieved, the values of deflection at mid-height of column, strain of GFRP rebar in compression
391 and tension, the bending moment, and curvature are captured for each load step. This process
392 continues up to the point that the deflections are huge enough to demand moments higher than
393 peak moment in the moment curvature diagram. After this point, instead of increasing the load,
394 the load will be decreased in each load step to build the descending branch using the same
395 procedure. The critical control in this process is the record of curvature in each step; which means
396 the curvature is not allowed to be less than the curvature in the past step. This condition helps to
397 find the proper answer when there are two possible answers for a certain bending moment demand
398 in moment curvature diagram for the descending branch as illustrated in Figure 7.

399 **4.2. Verification**

400 Using the experimental results which was presented in Section 3 of this paper, the proposed
401 analytical model was verified. The analysis performed for three different GFRP reinforced
402 concrete columns. The column used for verification is explained in the experimental section,
403 however, the modulus of elasticity of GFRP bars were considered equal to 38.74 GPa for both
404 tension and compressive bars. For the calculation of axial load-bending moment interaction
405 diagram, the same process as finding the moment-curvature applied using Equation 1 through
406 Equation 8, however, the strain at the furthest compressive fiber in concrete was taken 0.003
407 mm/mm as the point of crushing of concrete per ACI 318 [30]. Three eccentricity to width ratios
408 of 0.1, 0.2, and 0.3 were used to analysis, and the results are shown in Figure 8. There were two
409 sets of experimental data for each case which is reduced to one in Figure 8 by taking average of
410 them.

411 In Figure 8(a), the strain of GFRP bars from strain gauges at the mid height of column in
412 both tension and compression side are shown. The results show a good agreement between the
413 strains predicted by the proposed model the average experimental strains. Figure 8(b) shows the
414 moment- curvature of the column at mid-height derived from the model which is in a good
415 agreement with average experimental values calculated using the values of strain gauges. In Fig
416 8(c), the load versus the displacement of the column at its mid-height is shown, where the model
417 predicts the slope and the peak load of the experimental curves very well, and predicts the
418 descending branch up to the point that is numerically achievable. The loading path calculated by
419 model, as shown in Figure 8(d), are exactly the same as the ones calculated from average
420 experimental data.

421 The values of peak loads as well as the values of displacement, compressive and tensile
422 strains, moment, and curvature at the peak load derived by analytical model as well as the average
423 of test data are presented in Table 3. It is noticed that these average values are different from
424 average curves presented in Figure 8, since only the average of mentioned parameters were shown
425 in Table 3. This means, if the peak loads of two specimens with the same eccentricity happens at
426 different displacements, they are not summed in Figure 5 while the summation is presented in
427 Table 3. Table 3 shows that model can predict the peak load and its corresponding bending
428 moment with roughly 7% error. It is seen that as load eccentricity increases, the prediction of the
429 values of compressive strain of GFRP bars and deflection at the mid-height of the column
430 specimens are less accurate. Moreover, another verification considered in which load displacement
431 behavior and rebar strains of a circular column with a diameter of 305 mm and a length of 1500
432 mm (slenderness ratio of 20) reinforced with eight #5 GFRP rebars of 16 mm diameter in a study
433 performed experimentally by Hadhood et al. [14] is verified versus the model as shown in Figure

434 9. The cross-sectional area of each rebar was 199 mm^2 and the cover was 25 mm. The modulus of
435 elasticity and strength of GFRP were 54.9 GPa and 1289 MPa, respectively, while the concrete
436 strength was 35 MPa. Four pin-pin columns called C2-P2, C3-P2, C4-P2, and C5-P2 with the load
437 eccentricity of 25,50,100,200 mm, respectively, were verified against the analytical-numerical
438 model. Overall, the results show a good agreement between the results of the proposed model and
439 experimental data. In the next section, using the verified model, a parametric study on important
440 parameters is presented.

441 **4.3. Parametric Studies**

442 In this section, the analytical model developed in this study used to perform a parametric study.
443 As one of goals of this study was to find out the effectiveness of GFRP bars in compression, the
444 first subsection is assigned to compressive GFRP bars. In addition, parameters such as the
445 reinforcement ratio, and concrete strength are considered in the following sections.

446 ***4.3.1. Effect of ignoring compressive bars***

447 In this subsection, the analytical model was used to investigate the effects of ignoring compressive
448 GFRP bars in the behavior of short concrete columns as suggested by major design guides/codes.
449 The parametric study considered the cross-section and material properties introduced in
450 verification section, but using different eccentricities. As it is presented in Figure 10, there is no
451 significant difference in the load deflection behavior and loading path between considering GFRP
452 bars in compression or neglecting them. However, the interaction diagram shows higher axial
453 capacities using the compressive layer of GFRP bars. Table 4 provides the results of the analysis,
454 including the axial and the corresponding bending moment capacities of columns determined by
455 the analytical model, once with considering GFRP bars in compression, and once by neglecting
456 them. For all cases, the axial and bending moment capacities at peak load are higher when GFRP

457 rebar is considered in the calculation which proves the effectiveness of compressive GFRP bars.
458 In addition, the axial and bending moment capacities of the columns at strain of 0.003 mm/mm,
459 which is used for design purpose suggested by ACI [30], approaches to the same values when
460 compression rebar exists or not as the load eccentricity reaches higher values. As presented in
461 Table 4. This means that the calculation of column capacity is not different by considering
462 compressive GFRP bars in higher eccentricities.

463 ***4.3.2. Effect of reinforcement ratio***

464 To investigate the effect of reinforcement ratio in the compressive strain of GFRP bars, a
465 parametric study consisting of eight reinforcement ratios of 1.27, 1.90, 2.25, 3.38, 3.52, 5.07, 5.28,
466 and 7.60% (4#3, 6#3, 4#4, 6#4, 4#5, 4#6, 6#5, and 6#6) were considered. In addition, the columns
467 in three eccentricity to width ratios of 0.1, 0.2, and 0.3 were examined, and all other parameters
468 were the same as the ones used for the model verification. The corresponding compressive strain
469 at peak load are presented in Figure 11. The results show that as the reinforcement ratio increases,
470 the strain in compressive rebar increases for all eccentricities, however, their values at peak load
471 does not reach even half of the proportional limit which was introduced in Section 2.2 of this study.
472 The results confirm the compressive strains sustained by the GFRP bars cannot lead to crushing
473 of bars in compression.

474 ***4.3.3. Effect of concrete strength***

475 In this subsection, a parametric study was performed to reveal the effect of concrete strength on
476 the behavior of compressive GFRP bars. Thirteen concrete strength of 20, 25, 30, 35, 40, 45, 50,
477 55, 60, 65, 70, 75, and 80 MPa were examined with three eccentricity to width ratios of 0.1, 0.2,
478 and 0.3 while all other parameters were kept unchanged and the same as verification section. The
479 results including the compressive strain at peak load, and where available, the ones at 85 percent

480 drop after peak load are presented in Figure 12. The results show that by increasing the concrete
481 strength the compressive strain of GFRP increases in all eccentricities. Again, the results at peak
482 load and 0.85 of peak load show that the compressive strains do not reach their critical value, and
483 in turn, do not cause catastrophic damage in GFRP bars.

484 ***4.3.4. Effect of modulus of elasticity of GFRP bars***

485 The effect of modulus of elasticity of GFRP bars on the behavior of compressive GFRP bars were
486 also evaluated using eleven different values ranging from 30 to 80 GPa by analyzing the same
487 model used in verification part and with three eccentricity to width ratios of 0.1, 0.2, and 0.3. The
488 strain of GFRP bars in compression at peak load and 0.85 of peak load, which is recorded at mid-
489 height of specimens, for various modulus of elasticities of GFRP bars and diverse load
490 eccentricities are presented in Figure 13. For all eccentricity to width ratios, as modulus of
491 elasticity of GFRP bars increases, the compressive strain of bars at peak load slightly decreases
492 while this value at 85% of peak load is approximately constant, as shown in Figure 13. It is
493 observed that the values of compressive strain of GFRP at peak load and 0.85 of peak load are
494 getting closer as eccentricity increases. Similar to other subsections, no damage due to compressive
495 failure of GFRP is expected at peak load and 0.85 of peak load since the strain values are far below
496 the crushing strength of GFRP bars.

497

498 **5. CONCLUSION**

499 In this study, the performance of short concrete columns reinforced with GFRP bars were
500 investigated experimentally and analytically. A total of fourteen column specimens including nine
501 reinforced and five plain specimens were tested under four load eccentricity to width ratios of 0,

502 0.1, 0.2, and 0.3. Moreover, an analytical model was developed and verified with test results, and
503 a parametric study was performed using the model. The following conclusions can be drawn:

504) Based on coupon tests, the modulus of elasticity of GFRP bars used in this study were close
505 in tension and compression, and the strength in compression was even higher than in
506 tension.

507) No buckling or crushing of GFRP bars in compression were observed during the test before
508 the failure of specimens.

509) The average of experimental compressive strain of GFRP bars, read from strain gauges
510 after failure of specimens, were 22% and 16% of the ultimate capacity of bars in
511 compression, derived from coupon test, and were 36% and 25% of the proportional limit
512 of 0.0133 mm/mm. In other words, even the 50% of capacity of compressive GFRP bars
513 were not reached in the tests.

514) The proposed analytical model showed very good agreement with the experimental results.
515 The model predicted the peak load of the test specimens with an average error of less than
516 7%.

517) The parametric study revealed that the capacity of column by considering GFRP bars in
518 compression or neglecting them is similar up to the defined crushing strain of concrete
519 0.003 mm/mm, however there is a gain in capacity at the peak load which requires higher
520 strains; even experimental results did not reach their peak load at 0.003 mm/mm which is
521 compatible with the numerical model.

522) Based on the results of the parametric study, it was observed that the values of compressive
523 strain of GFRP bars in compression at peak load and even the compressive strain at 85%
524 of peak load (after peak) did not reach 50% of crushing strain of GFRP bar. From design

525 point of view, for the limited parameters considered in this study, this paper suggests to
526 consider GFRP bars in compression as linear elastic materials until concrete reached to its
527 compressive strain limit of 0.003 mm/mm. However, more studies are required to give a
528 design suggestion such as risk assessment study and more comprehensive experimental
529 program considering more variability in parameters.

530) Overall, for the selected set of tests and parametric study which has performed in this study,
531 the contribution of GFRP bars in compression can be considered in the design of GFRP
532 reinforced short concrete columns and its ignorance in design guidelines is conservatively
533 recommended.

534

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Table 1. Test matrix

No.	Specimen ID	Eccentricity (mm)	Eccentricity ratio	Reinforcement
1	R-e0-1	0	0	GFRP
2	R-e0-2	0	0	GFRP
3	R-e10-1	15	0.1	GFRP
4	R-e10-2	15	0.1	GFRP
5	R-e10-3	15	0.1	GFRP
6	R-e20-1	30	0.2	GFRP
7	R-e20-2	30	0.2	GFRP
8	R-e30-1	45	0.3	GFRP
9	R-e30-2	45	0.3	GFRP
10	P-e0-1	0	0	Plain
11	P-e0-2	0	0	Plain
12	P-e10-1	15	0.1	Plain
13	P-e10-2	15	0.1	Plain
14	P-e10-3	15	0.1	Plain

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Table 2. Summary of test results

Specimen group	Peak Load, P_u (kN)	Rebar strain at P_u (mm/mm)	Rebar strain at P_u to prop. limit	Rebar strain at P_u to crush. strain	Rebar strain at $0.85P_u$ (mm/mm)	Rebar strain at $0.85P_u$ to prop. limit	Rebar strain at $0.85P_u$ to crush. strain	Failure mode	
P-e0	719.2	-	-	-	-	-	-	CS	CD
R-e0	774.9	0.00275	0.21	0.14	0.00459	0.35	0.24	CC	CS
P-e10	596.3	-	-	-	-	-	-	CS	CD
R-e10	692.8	0.00279	0.21	0.15	0.00416	0.31	0.22	CC	CS
R-e20	578.2	0.00289	0.22	0.15	0.00472	0.36	0.25	CC	CS
R-e30	354.1	0.00361	0.27	0.19	0.00588	0.45	0.31	CC	CS
Average	-	-	0.23	0.16	-	0.36	0.25	-	-

551 Note: The results are average of identical specimens. Rebar strain recorded by SG2 (see Figure 3) installed on the
552 middle rebar at the extreme compressive layer; $0.85P_u$ is related to post peak; NA: not available; CC: concrete
553 crushing; CS: concrete spalling; CD: concrete destruction; prop. limit = 0.0133 mm/mm; crush. strain = 0.0190
554 mm/mm.
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Table 3. Comparison of model and experimental results

Characteristic	e/h (%)	Test	Model	Error (%)	Absolute Error (%)
Peak Load (kN)	10	692.8	667.7	3.62	6.73±6.20
	20	578.2	498.0	13.87	
	30	354.1	363.7	-2.7	
Lateral mid-height displacement at peak load (mm)	10	0.92	0.67	27.18	26.82±8.77
	20	1.11	0.91	17.87	
	30	2.03	1.31	35.4	
Compressive bar strain at peak load (mm/mm)	10	-0.00279	-0.00256	8.28	20.80±14.14
	20	-0.00289	-0.00237	17.98	
	30	-0.00360	-0.00230	36.14	
Tensile bar strain at peak load (mm/mm)	10	-0.00072	-0.00069	3.49	52.19±70.87
	20	0.00008	0.00019	-133.5	
	30	0.00117	0.00140	-19.58	
Moment at peak load (kN-m)	10	11.00	10.46	4.88	6.74±7.00
	20	18.00	15.39	14.48	
	30	16.70	16.84	-0.85	
Curvature at peak load (1/km)	10	20.85	22.19	-6.43	5.58±3.44
	20	29.91	30.44	-1.79	
	30	48.12	44.03	8.51	

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Note: e/h is the load eccentricity to width ratio.

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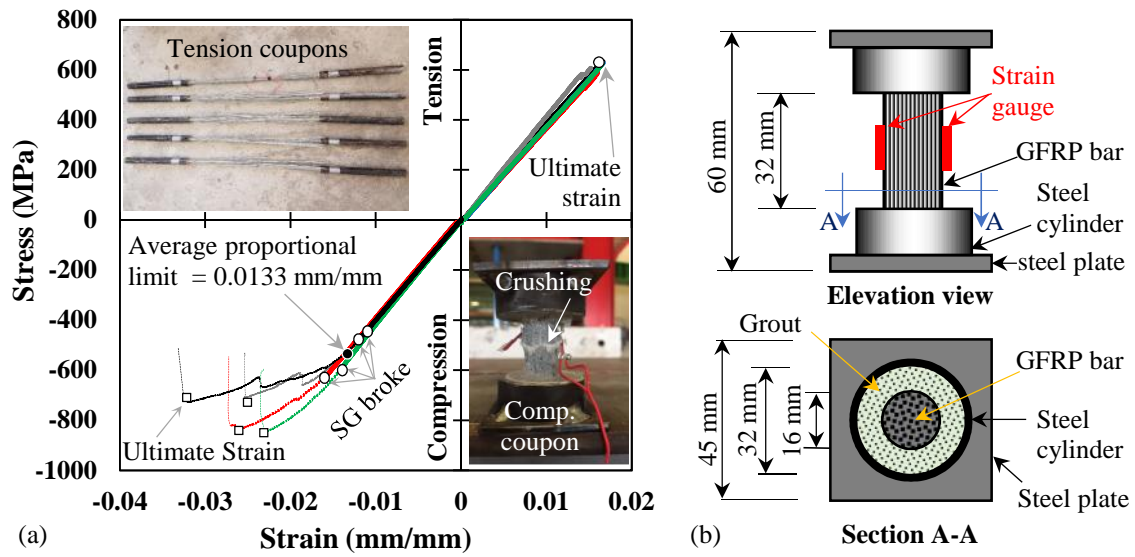
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Table 4. Comparison of axial load and corresponding bending moment capacities with and without compressive bars based on parametric study

e/h (%)	@ compressive strain of 0.003						@ Peak load					
	Axial load (kN)			Bending moment (kN-m)			Axial load (kN)			Bending moment (kN-m)		
	with comp. rebar	W/O comp. rebar	Diff. (%)	with comp. rebar	W/O comp. rebar	Diff. (%)	with comp. rebar	W/O comp. rebar	Diff. (%)	with comp. rebar	W/O comp. rebar	Diff. (%)
0	898.9	856.9	4.67	-	-	-	908.7	870.6	4.19	-	-	-
5	762.4	744.4	2.35	6.09	5.87	3.70	762.5	744.4	2.37	6.10	5.87	3.84
10	664.8	645.9	2.85	10.37	10.04	3.23	667.7	645.9	3.27	10.46	10.04	4.07
15	579.4	565.2	2.46	13.44	13.07	2.71	581.8	565.2	2.87	13.54	13.07	3.41
20	495.1	486.3	1.76	15.25	14.95	2.00	498.0	486.3	2.34	15.39	14.95	2.92
25	420.4	415.7	1.11	16.15	15.95	1.22	424.5	415.7	2.07	16.37	15.95	2.56
30	357.0	355.1	0.51	16.44	16.34	0.62	363.7	355.8	2.17	16.84	16.39	2.71
35	306.1	305.5	0.19	16.43	16.38	0.30	315.9	307.6	2.64	17.08	16.53	3.23
40	266.1	266.1	-0.01	16.31	16.30	0.08	279.1	270.0	3.29	17.26	16.58	3.94
45	234.7	234.9	-0.10	16.17	16.17	-0.02	250.5	240.4	4.03	17.44	16.61	4.76
50	209.7	209.9	-0.07	16.04	16.04	0.00	227.8	216.9	4.78	17.64	16.65	5.63
60	172.8	173.0	-0.13	15.83	15.85	-0.08	195.3	181.8	6.90	18.24	16.73	8.27
80	128.3	128.3	0.03	15.63	15.62	0.06	151.9	138.1	9.06	18.79	16.90	10.09
100	102.2	102.1	0.07	15.53	15.52	0.09	124.2	111.8	9.96	19.12	17.07	10.75

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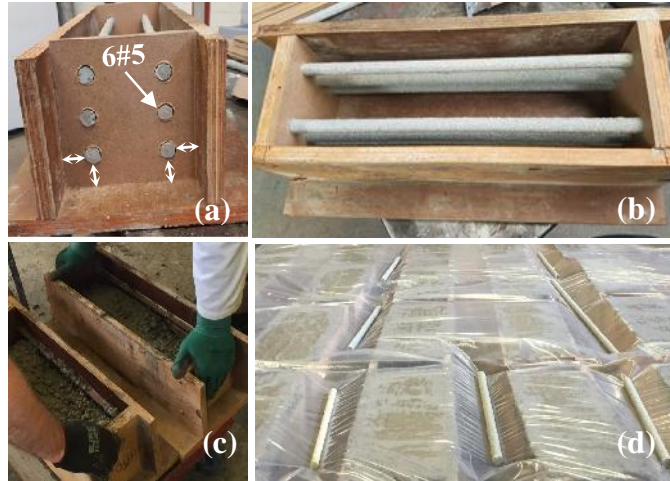
Note: e/h is the load eccentricity to width ratio; “comp.”, “Diff.”, and “W/O” are used in the table instead of “compressive”, “Difference”, and “without”, respectively.



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570 **Figure 1. Material test: (a) Stress-strain curves of GFRP bars in tension and compression;**
571 **and (b) schematic drawing of GFRP bar coupon for compression test.**

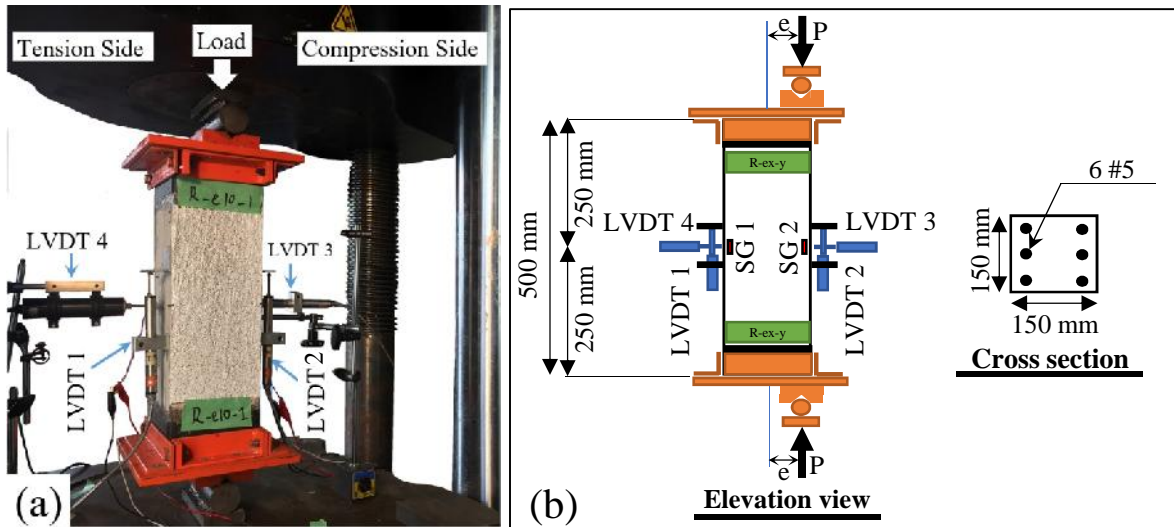
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574 **Figure 2. Specimen fabrication: (a) cross section; (b) top view; (c) casting; and (d) curing.**

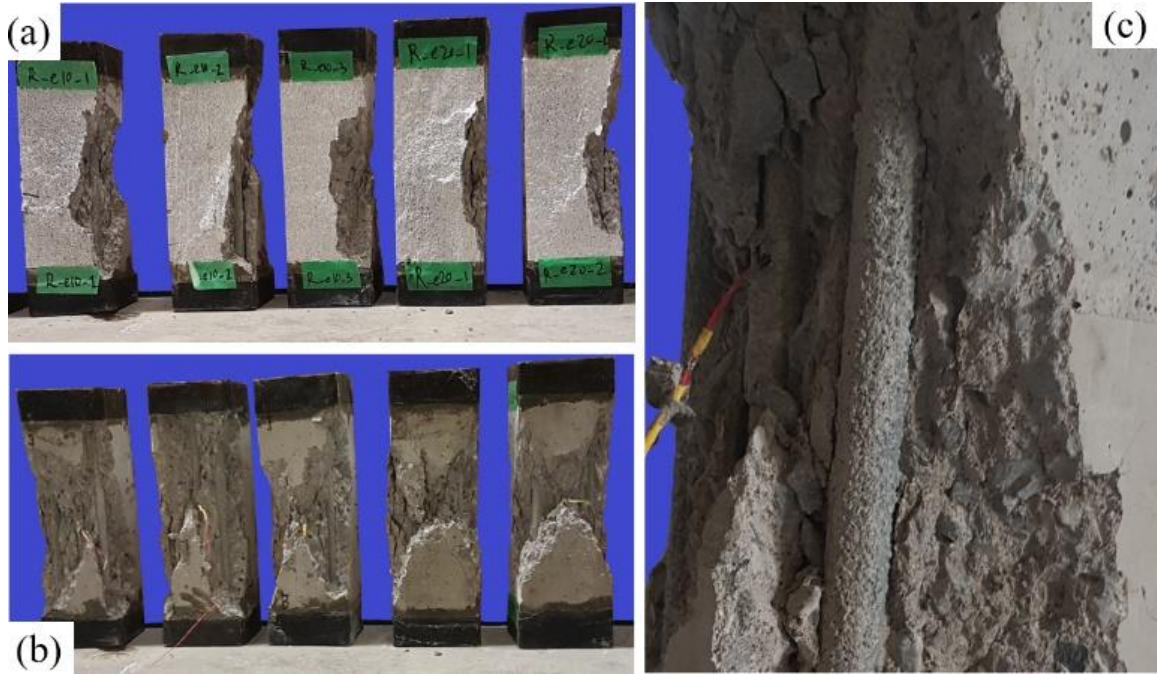
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577 **Figure 3. Test set up and instrumentation: (a) testing machine and instrumentation, and (b)**
 578 **schematic testing specimen and reinforcement layout**

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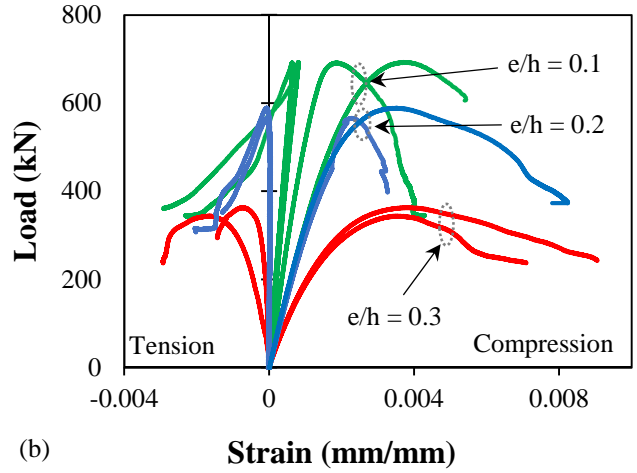
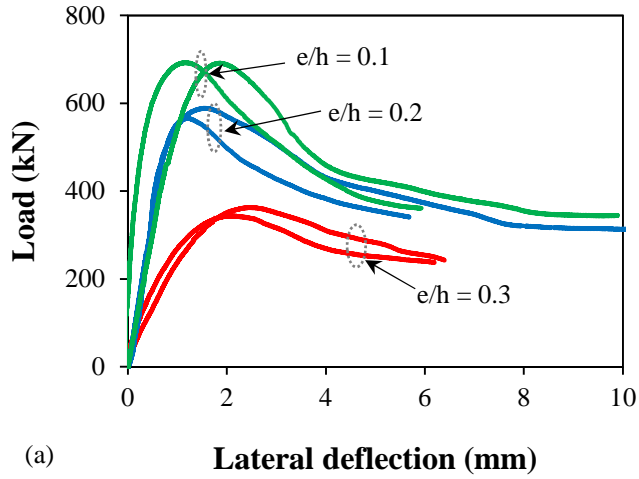


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Figure 4. Mode of failures: (a) side view; (b) compression side; and (c) crushed concrete and visually intact compressive rebar.



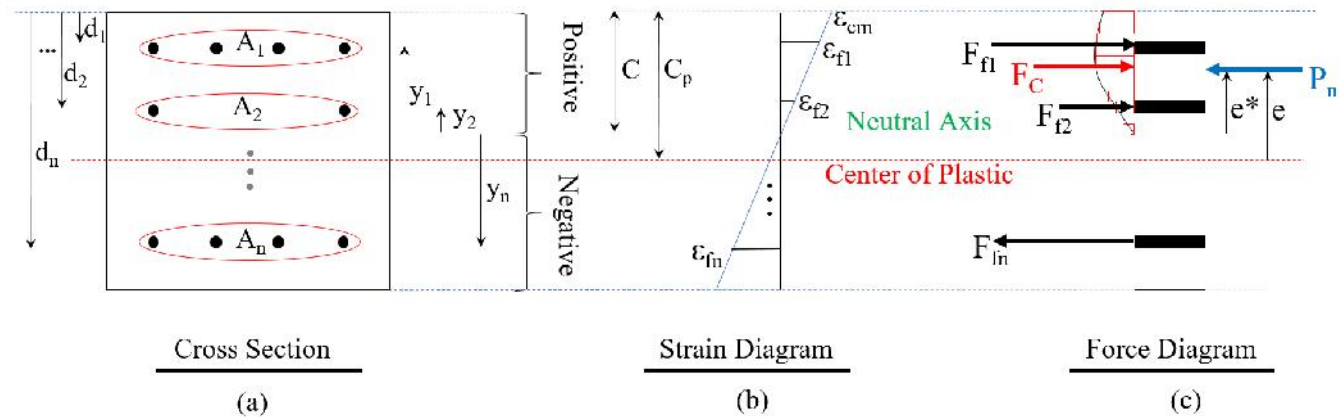
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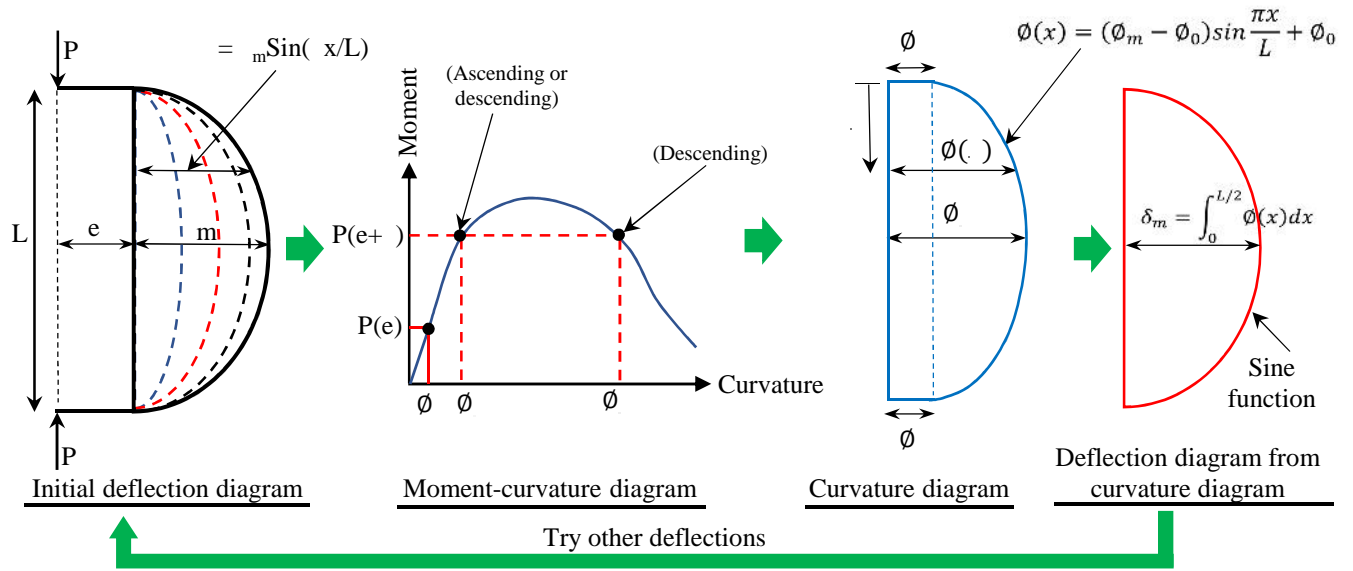
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Figure 5. Test results: (a) axial load vs. lateral displacement of specimens at mid-height; and (b) axial load vs. strain of compressive and tensile GFRP bars.



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590 **Figure 6. Mechanism of cross-sectional analytical model: (a) section definitions; (b) strain**
 591 **diagram; and (c) force diagram.**
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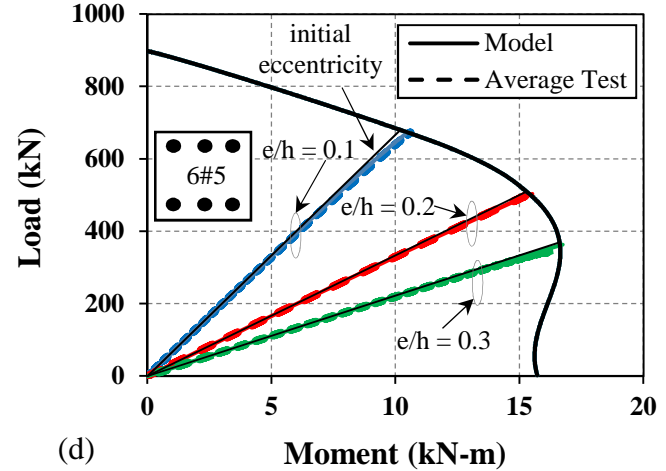
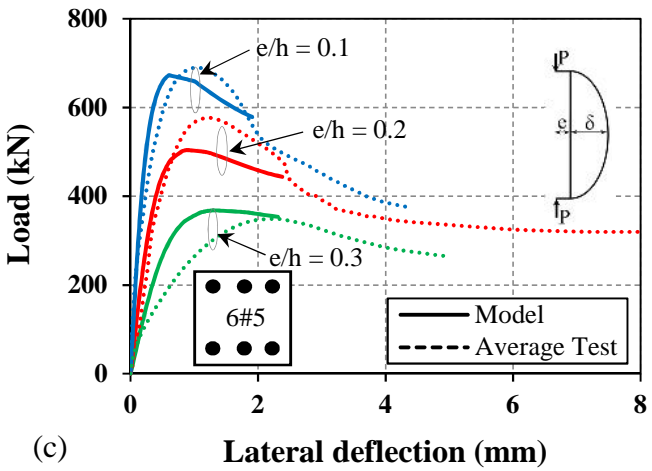
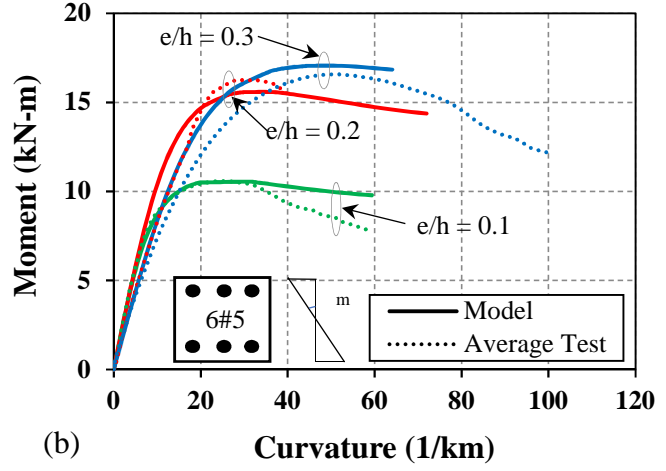
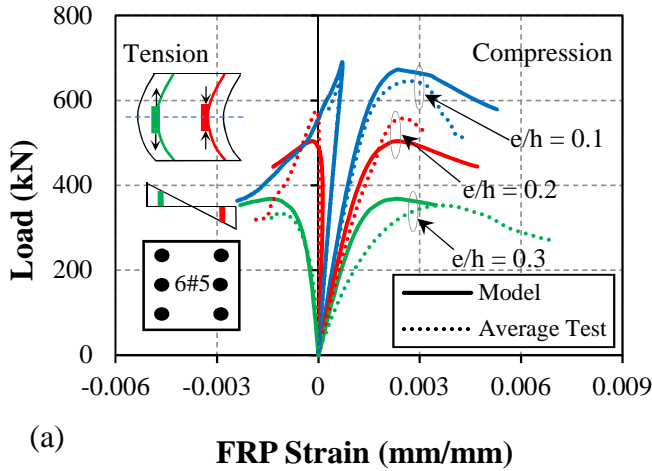


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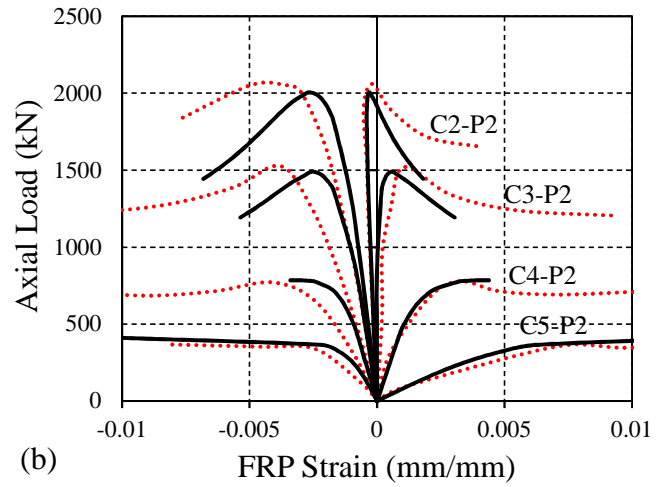
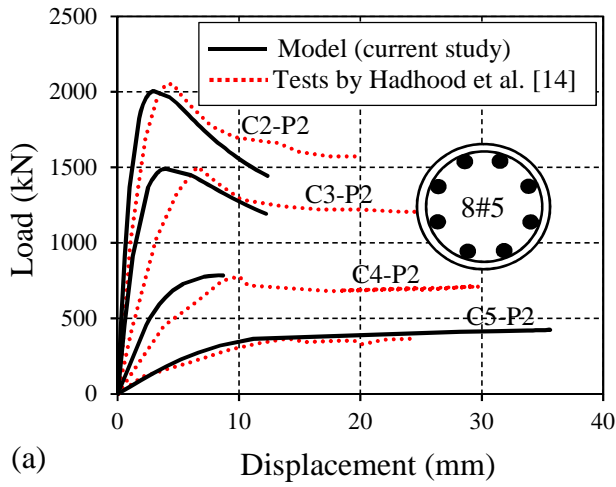
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Figure 7. Schematic iteration process for finding deflection at mid height of column.



598 **Figure 8. Model verification: (a) axial load vs. strain of compressive and tensile GFRP bars**
 599 **at the mid height; (b) moment vs. curvature diagram at the mid-height; (c) axial load vs.**
 600 **lateral displacement of specimens at the mid-height; and (d) axial load vs. bending moment**
 601 **interaction diagram and loading path curves.**
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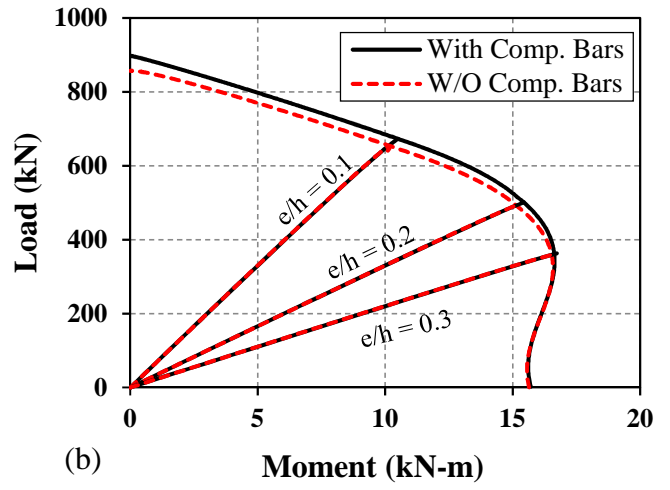
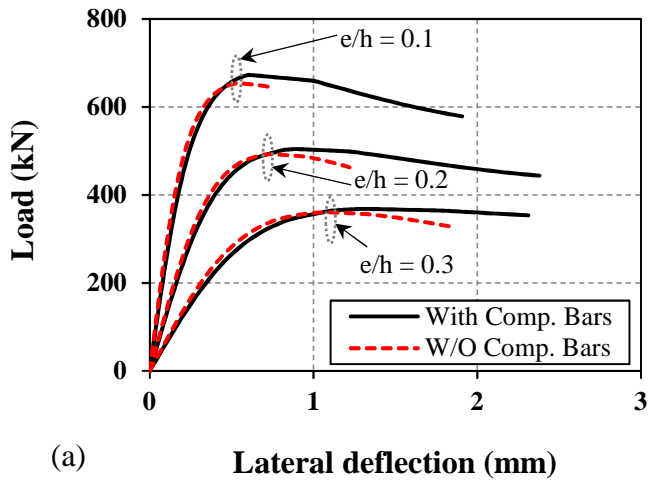
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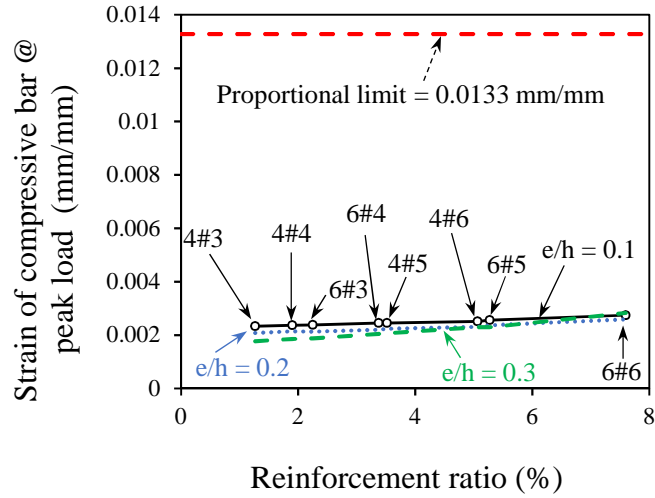
Figure 9. Model verification with circular GFRP reinforced concrete column tested by Hadhood et al. [14]: (a) axial load vs. lateral displacement of specimens at mid-height; and (b) axial load vs. strain of compressive and tensile GFRP bars at the mid-height.

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610 **Figure 10. Compressive rebar effect: (a) axial load vs. lateral displacement of specimens at**
611 **mid-height; and (b) axial load vs. bending moment interaction diagram and loading path.**
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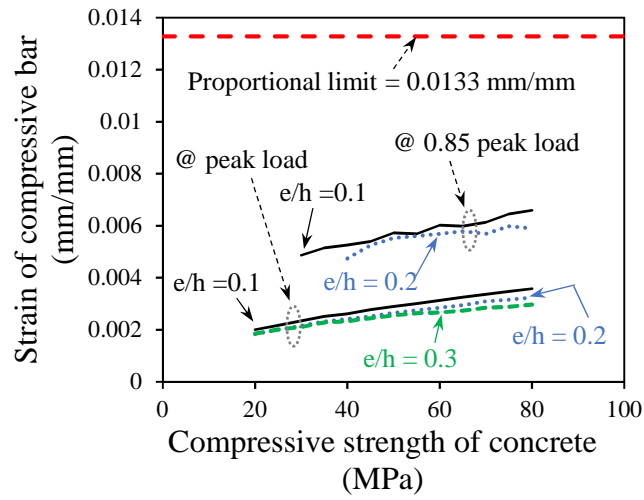


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Figure 11. Effect of reinforcement ratio on strain of compressive GFRP bars.

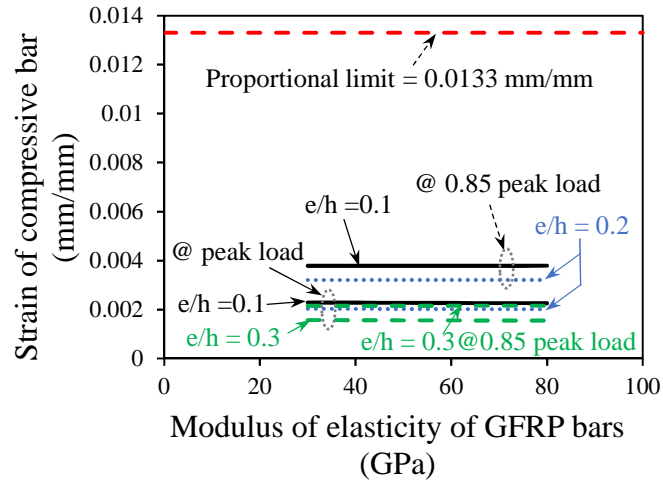
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617 **Figure 12. Effect of compressive strength of concrete on strain of compressive GFRP bars.**

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Figure 13. Effect of modulus of elasticity of GFRP bars on strain of compressive bars.

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