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# Modelling glass fibre-reinforced polymer reinforced geopolymer concrete columns

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## ABSTRACT

Glass fibre-reinforced polymer (GFRP) bar and stirrup reinforced geopolymer concrete (GPC) is increasingly recognised as a potential replacement to the conventional steel-reinforced ordinary Portland cement (OPC) concrete due to its superior durability. This paper proposed an analytical model to predict the load-displacement relationship of the concentrically and eccentrically loaded GFRP-GPC columns. The cross-section was divided into a number of strips and a strain gradient was assigned to determine the stresses in the cover, core and reinforcement. The theoretical predictions were then validated using experimental results from previous studies on the behaviour of GFRP-GPC, GFRP-OPC concrete and steel-GFRP concrete systems. It was found that the predicted peaks load, displacements at peak load and ductility indices were generally in close agreement with the experimental results of the GFRP-GPC columns. However, the model had a tendency to over-predict the stiffness of GFRP-OPC concrete and steel-OPC concrete columns in the elastic range. Overall, the proposed analytical model is suitable for GFRP-GPC systems and could facilitate the widespread use of this composite material.

## 1. Introduction

Corrosion causes millions of dollars of damage in steel reinforced concrete structures every year. The service life of such structure is critically affected without adequate corrosion protection, especially in harsh environments such as the coastal zones in Australia. Therefore, alternative construction materials were investigated to reduce the cost and maintenance of the structure. Geopolymer concrete (GPC) was considered to have better chloride and sulphate resistance than the Ordinary Portland Cement (OPC) concrete [1,2]. The GPC relies on the formation of an amorphous polymeric Si-O-Al framework instead of the calcium-silicate-hydrates (C-S-H) and calcium hydroxides (C-H) found in OPC matrix. The lack of C-H is advantageous as it actively reacts with the chlorides and sulphates, which in turn reduces the alkalinity in the matrix. The improved chemical stability means that the GPC will continuously provide protection to the embedded reinforcement, extending the service life of the structure. Due to the difference in microstructure, GPC has a lower elastic modulus than OPC concrete [3].

Glass Fibre-Reinforced Polymer (GFRP) is also gaining popularity due to its excellent corrosion resistance and high tensile strength. Unlike steel, the GFRP bars do not yield and could be assumed to possess a linear elastic behaviour until failure [4]. GFRP bars have a

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much lower elastic modulus than steel, therefore they are more susceptible to buckling in compression [5]. Therefore, the unrestrained distance should be reduced by decreasing the spacing of the transverse reinforcement, such as spirals, hoops or stirrups. The short spacing also increased the overall stiffness of the transverse reinforcement, delaying rupturing failures. It was found that by increasing the transverse reinforcement ratio, the load capacity of the members significantly increased [6,7], which demonstrated the contribution of longitudinal GFRP bars in compression. However, international GFRP-reinforced concrete design standards such as ACI 440.1-R15 [8] and CAN/CSA S806-12 [9] do not recommend the inclusion of GFRP bars in the load capacity of the members in compression. Therefore, a better understanding is required for more efficient designs using GFRP.

As the concrete continues to rise in compressive strength and reduce in ductility, the ability to predict the load-displacement curves becomes increasingly important. Analytical models were developed for steel-reinforced OPC systems to predict the behaviour under load and determine its ductility. This requirement becomes more apparent for GFRP-reinforced members due to GFRP's inability to yield. For steelreinforced OPC systems, a handful of analytical models were available. Various confinement models were proposed for axially loaded reinforcement concrete columns. Mander et al. [10] proposed a set of







formulations for square, rectangular and circular reinforcement arrangements, which was widely accepted by the research community. However, the opinions on the stress-strain relationship of the eccentrically loaded columns were divided into a few main categories [11]. The first group considered the same stress-strain relationship could be used for both concentrically and eccentrically loaded columns [12,13]. Alternatively, it was believed that a separate stress-strain model must be proposed for eccentrically loaded columns due to the flexural loading [14,15]. The strain-gradient had an influence on the stress distribution in the concrete section, thus affecting the load capacity and ductility of the member. The confinement level varied in each strip of concrete in the cross-section, resulting in a distinct stress-strain relationship. This could be simplified by establishing a model that incorporates the strain gradient effect. Ho and Peng [16] proposed a set of empirical equations for the inverted T-shaped specimens and found good agreements between experimental and predicted results. Feng and Ding [17] introduced the concept of equivalent confinement volume to Mander's model and found that the analytical results matched experimental results closely.

A number of research works reported on the behaviour of concentrically or eccentrically loaded GPC or OPC concrete columns fully reinforced with GFRP bars and stirrups. The contribution of longitudinal GFRP bars to the column load carrying capacity varied from 3% to 11% [5,18-21]. The variability was mainly attributed to the amount of transverse reinforcement. For example, the axially loaded column with 75 mm stirrup spacing had a 13.7% and 30.4% higher load carrying capacity than that with a 150 mm and 250 mm stirrup spacing, respectively [5]. Additionally, a high transverse reinforcement ratio improved the ductility of the columns and prevented catastrophic brittle failures [5,7]. Overall, GFRP-reinforced columns were more susceptible to slenderness effects than steel due to the lower modulus of GFRP [22]. It was recommended to adopt a slenderness limit of 17 instead of 22 for steel [22]. The main difference between GPC and OPC concrete was that GPC columns had reduced moment capacities, especially when loaded at high eccentricities [7], due to its smaller rectangular stress block [23]. Despite of the distinct behaviour of GFRP-GPC systems from steel-OPC concrete systems, no analytical analysis was carried out for GFRP-reinforced GPC or OPC concrete columns.

The literature review highlighted the lack of analytical models for GFRP-reinforced GPC systems. In this study, an analytical model based on flexural analysis was proposed for GFRP-reinforced GPC columns under concentric or eccentric loading. The model was established on the existing principles for modelling the behaviour of steel-reinforced OPC concrete members. It integrated the effect of strain gradient of the confining pressure produced by the transverse GFRP stirrups. Justifications were made to reflect the differences in concrete and reinforcement types, and the loss of load capacity of the concrete cover after spalling. The coefficient of effectiveness was also adjusted accordingly to suit the particular sections studied in this work. The theoretical results were compared against the experimental results for both GFRP-reinforced GPC and OPC concrete columns reported in the literature [5,24].

## 2. Experimental setup

An experimental investigation of 9 GFRP-reinforced GPC columns was carried out by Elchalakani et al. [5]. The GPC mix had by mass: 15% binder, 6.5% alkali activator mixed with 6.1% water and 0.1% superplasticiser, 29.4% fine aggregates, and 47.3% coarse aggregates. The equal parts fly ash and ground granulated blast-furnace slag (GGBS) binder allowed the specimens to be cured in ambient conditions. The 28-day compressive strength ( $f'_c$ ) of the GPC was 26.0 MPa. Three specimens with a stirrup spacing of 75 mm, 150 mm and 250 mm were tested under concentric loading and the other six specimens with a 75 mm or 150 mm stirrup spacing were tested at 25 mm, 50 mm and 75 mm eccentricities (e). The low, medium and high eccentricities were



Fig. 1. The schematics of the columns.

selected to examine the effect of bending moment on load capacities. All the specimens have the same rectangular cross-section of  $b \times d = 260 \text{ mm} \times 160 \text{ mm}$  and height of h = 1200 mm. The specimens were fully reinforced by GFRP bars and stirrups. The longitudinal bars were 14 mm in diameter and the 8 mm stirrups were used as transverse reinforcement. A 20 mm concrete cover was selected due to the stronger corrosion resistance of the GFRP [5]. The reinforcement layout in the columns is shown in Fig. 1.

The GFRP-reinforced OPC concrete columns constructed by Elchalakani and Ma [24] had a similar cross-section and reinforcement arrangement. A total of 7 GFRP-reinforced columns were tested under concentric and eccentric loading. Another 6 columns were constructed with steel rebars and steel ties. The effect of high load eccentricity was not studied. The  $f'_c$  of OPC concrete was 32.8 MPa, corresponding to 26.2% higher compressive strength than GPC. The OPC concrete columns were reinforced with 12 mm longitudinal GFRP bars and 6 mm GFRP stirrups. The same 20 mm cover was used in GFRP-reinforced specimens where a 40 mm cover was adopted for steel-reinforced specimens.

The specimens in both studies were tested to failure using a universal testing machine with a capacity of 2000 kN. A load-controlled regime was used as the displacement-controlled regime was not

#### Table 1

The properties of the specimens.

Parameters	GFRP-reinforced GPC columns	GFRP-reinforced OPC concrete columns	Steel-reinforced OPC concrete columns		
	(Elchalakani et al. [5])	(Elchalakani et al. [18])	(Elchalakani et al. [18])		
Section width (mm)	260	260	260		
Section height (mm)	160	160	160		
Cover (mm)	20	20	40		
$d_b^{a}$ (mm)	14	13	12		
$d_t^{a}$ (mm)	8	6	6		
a <sup>a</sup> (mm)	212	214	174		
b <sup>a</sup> (mm)	112	107	68		
Ultimate tensile strength of longitudinal bars (MPa)	930	708	540		
Ultimate tensile strength of stirrups (MPa)	650	784	270		
Tensile elastic modulus of longitudinal bars (GPa)	59	46.3	200		
Tensile elastic modulus of stirrups (GPa)	55	46.1	200		
Ultimate strain in tension of longitudinal bars	0.017	0.017	0.05		
Ultimate strain in tension of stirrups	0.012	0.019	0.05		

<sup>a</sup> As shown in Fig. 1.

available on the machine. A loading rate of 20 kN/min was applied to the column specimens. The eccentricity was provided through a pair of steel rollers welded to the top and bottom end plates of the columns. The rotation about the weaker axis was allowed to ensure that the capacity of the testing machine was sufficient to load the specimens to failure. The specimens were designated in terms of the concrete type ("G" for GPC, "O" for OPC concrete, "S" for steel reinforced OPC concrete), the stirrup spacing in millimetre and the loading condition ("C" for concentric loading, "F" for flexural loading or a number corresponding to the eccentricity in millimetre). For example, "G75-150" represents the GFRP-reinforced GPC column with a 75 mm stirrup spacing loaded at a 150 mm eccentricity. The key design parameters of the specimens tested in the two studies were summarised in Table 1.

## 3. Analytical model

The constitutive models used for confined geopolymer concrete, steel and the procedure used in obtaining the load-deformation curves are described in the following sub sections.

## 3.1. Proposed stress-strain model for confined geopolymer concrete

The model proposed in this paper was initially developed by the authors for normal and high strength concrete. Further details of the model can be found elsewhere [25]. Two different exponential curves form the complete stress-strain relationships for confined normal strength concrete and geopolymer concrete. The terms described in this constitutive model are shown in Fig. 2.

The uniqueness of this model is that it can predict the lateral deformation as well which can be used to find the confinement exerted by



Fig. 2. Terms used in the stress-strain relationship for geopolymer concrete.

the confining steel or FRP. The confined region was determined based on the recommendations by Mander et al. [10], as illustrated in Fig. 3. The constitutive model is briefly described here for the convenience of the reader.

Axial strain ( $\varepsilon_1$ ) is related to lateral strain ( $\varepsilon_2$ ) as follows:

$$\frac{\varepsilon_{2}}{\varepsilon_{cc}^{\prime}} = \begin{cases} \nu_{l}^{a} \left(\frac{\varepsilon_{1}}{\varepsilon_{cc}}\right)^{i} f \varepsilon_{1} \leq \varepsilon^{\prime} \\ \left(\frac{\varepsilon_{1}}{\varepsilon_{cc}}\right)^{2} i f \varepsilon_{1} > \varepsilon^{\prime} \end{cases}$$
(1)

 $\varepsilon_{cc}$  and  $\varepsilon'_{cc}$  are axial and lateral strains corresponding to peak axial stress. Parameter *a* is a function of the uniaxial concrete strength ( $f_c$ ) and it is a property of the material. It is given as in Eq. (2).

$$a = 0.0177 f_c + 1.2818 \tag{2}$$

Eq. (1) can be used to find  $\varepsilon'$  as follows:

$$\varepsilon' = \varepsilon_{cc} (v_i^a)^{\frac{1}{a-1}} \tag{3}$$

The initial Poisson's ratio  $(\nu_i^a)$  is given as below:

$$\nu_i^a = 8 \times 10^{-6} (f_c)^2 + 0.0002 f_c + 0.138 \tag{4}$$

Eq. (1) completely defines the relationship between axial strain and lateral strain if axial strain ( $\varepsilon_{cc}$ ) and lateral strain ( $\varepsilon'_{cc}$ ) corresponding to peak axial stress are known. Axial strain corresponding to peak axial stress  $\varepsilon_{cc}$  can be expressed as follows.

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + (17 - 0.06f_c) \left(\frac{f_l}{f_c}\right)$$
(5)

 $f_l$  is the confining pressure and  $\varepsilon_{co}$  is the axial strain corresponding to the peak uniaxial compressive strength. Peak axial stress for confined concrete  $f_{cc}$  is defined as:

$$\frac{f_{cc}}{f_c} = \left(\frac{f_l}{f_t} + 1\right)^k \tag{6}$$

where k is a constant given by:

$$k = 1.25 \left( 1 + 0.062 \frac{f_l}{f_c} \right) (f_c)^{-0.21}$$
<sup>(7)</sup>

 $f_t$  is the tensile strength which is given by:

$$f_t = 0.9 \times 0.32 (f_c)^{0.67} \tag{8}$$

For a given axial strain, Eqs. (1)–(8) can predict the lateral strain if the peak stress and corresponding lateral strain are known for unconfined concrete strength. The following section describes how to find



(Z-Z) Fig. 3. The effectively confined regions.

the lateral strain corresponding to peak axial stress.

Similar to the observations for normal and high strength concrete [25] and for geopolymer paste [26] it is assumed that geopolymer concrete samples will return to the original volume when the axial strain is corresponding to the peak axial stress. Therefore, at peak stress:

$$\overline{\varepsilon_{\nu}} = \frac{\varepsilon_1 + 2\varepsilon_2}{\varepsilon_{\nu,max}} = 0 \tag{9}$$

$$\varepsilon_{cc} = 2\varepsilon_{cc}' \tag{10}$$

Using the secant value of Poisson's ratio at peak stress ( $\nu_f^a$ ), Eq. (10) can be re-written as follows:

$$v_f^a = 0.5$$
 (11)

Using shear stress and shear strain factors, axial stress ( $\sigma_1$ ), axial strain ( $\varepsilon_1$ ) and lateral strain ( $\varepsilon_2$ ) relationships for normal/geopolymer concrete can be expressed as:

$$\sigma_{1} = \left\{ 2\tau_{mp} \left( 1 - e^{-c \left(\frac{\varepsilon_{1} + \varepsilon_{2}}{2\gamma_{mp}}\right)} \right) + f_{l} \text{ before peak}, 2\tau_{mp} \left( 1 - e^{d \left(\frac{\varepsilon_{1} + \varepsilon_{2}}{2\gamma_{mp}}\right)} - d \right) + f_{l} \text{ after peak}$$
(12)

*c* and *d* are material parameters defined as follows:

$$c = -0.1f_c + m \text{ and } d = -0.0003f_c - 0.0057$$
 (13)

c is the only material parameter that was modified for normal concrete and geopolymer concrete. m for OPC concrete was used as 5 and that for geopolymer concrete was used as 7.

 $\tau_{mp}$  is the maximum shear stress at peak and  $\gamma_{mp}$  is the corresponding shear strain and are defined in Eq. (14).

$$\tau_{mp} = \frac{f_{cc} - f_l}{2}; \, \gamma_{mp} = \frac{\varepsilon_{cc} + \varepsilon'_{cc}}{2} \tag{14}$$

Therefore, Eqs. (1)-(14) completely define the deformational behaviour of geopolymer concrete.

## 3.2. Stress-strain model for longitudinal bars

A simple idealised elasto-plastic stress-strain model was used for

steel in this investigation.

$$f_{s} = \begin{cases} E_{st} \varepsilon_{s} \text{ if } 0 \le \varepsilon_{s} \le \varepsilon_{y} \\ f_{sy} \text{ if } \varepsilon_{s} > \varepsilon_{y} \end{cases}$$
(15)

where  $f_s$  and  $\varepsilon_s$  are steel stress and strain respectively,  $E_{st}$  is the modulus of elasticity and  $f_{sy}$  and  $\varepsilon_y$  are the yield strength and corresponding yield strain of steel.

FRP bars are modelled using the below equation.

$$f_{frp} = \begin{cases} E_{frp} \varepsilon_{frp} \text{ if } 0 \le \varepsilon_{frp} \le \varepsilon_u \\ 0 \text{ if } \varepsilon_{frp} > \varepsilon_u \end{cases}$$
(16)

where  $f_{frp}$  and  $e_{frp}$  are steel stress and strain respectively,  $E_{frp}$  is the modulus of elasticity and  $e_u$  is the ultimate strength of FRP bars.

## 3.3. Load-deformation relationships

In the analysis process, the section is divided into a number of strips (*N*). As opposed to concentrically loaded columns, eccentrically loaded columns are subjected to a strain gradient as shown in Fig. 4. In order to draw the load deformation curves, a range for the curvature is defined ( $\varphi_{\text{initial}} = 0$  to  $\varphi_{\text{final}}$  in steps of  $\varphi_{\text{step}}$ ). For an assumed strain distribution (using the given curvature,  $\varphi$  and the assumed strain at extreme compression side,  $\varepsilon_i$ ), strains for each strip as well as for each reinforcement are first determined. Stresses in the core, cover and reinforcement are calculated using the corresponding stress-strain relationships in the previous section. Cover concrete stresses are considered as unconfined concrete stresses while the stresses in reinforcements are obtained using either Eqs. (15) or (16) for the corresponding stress are used to find the stresses in core concrete:

- Use Eq. (1) to find the lateral strain for each of the *N* number of strips. This is used to final the final lengths for each strip.
- Deduct the total original lengths of all the N strips (*R*) from the total final lengths of all the N strips (*Q*). Use this to find the strain and finally the stress in the stirrup which is used to find the confining pressure provided to the core.
- Use Eqs. (1)-(14) to find the confined concrete stress for each strip



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Fig. 4. The strain gradient in the cross-section.

in the core.

Using all the stresses, forces in core, cover and reinforcement are calculated which are used to find the applied load, the moment and the resulting eccentricity for the assumed strain at extreme compression side,  $e_t$ . For a given curvature,  $\varphi$  and eccentricity,  $e^*$ ,  $e_t$  is iterated until the calculated eccentricity is equal to the actual eccentricity within a given tolerance level. At this point calculated load is stored for the corresponding curvature which was used to calculate the deformation. This process is repeated until the curvature reaches  $\varphi_{\text{final}}$ . The procedure used in getting the load-deflection curve is shown in Fig. 5. The analysis process was carried out using a computer program coded in MATLAB.

#### 4. Comparisons and discussions

## 4.1. Predicted load and displacement

The experimental and theoretical results are summarised in Table 2. Overall, the theoretical predictions matched well with the experimental results. The predicted loads for GFRP-GPC, GFPR-OPC concrete and steel-OPC concrete all had an average variation of 6% from the experimental data. The variations of the predicted displacements at peak load ranged between 7%-8%. The main discrepancy in the load predictions came from specimens loaded at higher eccentricities. For example, the load capacities of specimen G75-75 and G150-75 loaded at a very high eccentricity of 75 mm were over-predicted by 17% and 10%, respectively, whereas their corresponding concentrically loaded columns had a 1% and 2% variation, respectively. The over-prediction was less severe in GFRP-OPC concrete and steel-OPC concrete systems. The predicted loads were on average 2% and 5%, respectively, lower than the experimental results, as compared to an average 2% over-prediction for GFRP-GPC systems. It was pointed out that reinforced GPC columns tended to have a reduced rectangular stress block [23]. Therefore, as the moment increased in the cross-section, the load capacity was significantly affected. However, the proposed analytical solution was still valid for GFRP-GPC systems. A 97% accuracy was achieved for GFRP-GPC columns loaded at no eccentricity to medium eccentricities. The

predicted deflections did not have a clear trend, however a high accuracy of 92% was achieved for all the specimens.

## 4.2. Predicted ductility

As a load-controlled loading regime was adopted for both studies, a special method (Eq. (17)) proposed in Elchalakani and Ma [24] was used to measure the ductility of the columns.

$$DI = \frac{ADE}{ABC} \tag{17}$$

The ductility index (DI) was a ratio of the work done post peak to the work done in the elastic range. The former was represented by the area ADE under the load-displacement curve, up to the point on the post-peak segment where the load equalled 85% peak load, and the latter was represented by the area ABC up to 75% peak load in the elastic range. The method was illustrated in Fig. 6. The DI values of all the experimental curves and theoretical predictions are reported in Table 2. The ductility of the GFRP-GPC columns was on average the highest (2.9) among the three groups, followed by GFRP-OPC concrete columns (2.4) and finally the steel-OPC concrete columns (2.3). It could be seen that a combination of GFRP bars and GFRP stirrups could improve the ductility over their steel counterpart, despite that GFRP reinforcement did not yield and have lower stiffness. The columns reinforced with steel rebars and stirrups were able to reach a higher peak load, however with a reduced ductility. The steel-reinforced columns had the lowest ductility indices among the three groups, which was likely attributed to the stiffer response of the steel stirrups. It was reported that the GFRP stirrups gradually opened up post peak, causing a more steadier loss of capacity observed in specimens such as G75-C [5]. The reason that GPC columns outperformed OPC concrete columns was that the transverse reinforcement use in the GPC columns was larger in size, which provided better restraint to the longitudinal bars and better confinement to the concrete.

The analytical results of GFRP-GPC columns were on average the same (2.9) as the experimental results, showing that the model was appropriate for GPC columns. The model tended to slightly over-predict the ductility of GFRP-GPC columns loaded at no or low eccentricities and under-estimate those loaded at higher eccentricities. In



Fig. 5. Flow chart used to draw load-deflection curves.

comparison, the ductility of all the OPC concrete columns reinforced with steel or GFRP was over-estimated. The average predicted ductility was 3.5 and 2.8 for steel and GFRP reinforced OPC concrete columns, respectively. The reason was likely that a stiffer elastic range was assumed in the analytical model, resulting in a lower ADE value and a greater ductility than tested. The steel-reinforced columns had the lowest ductility indices, similar to the experimental results.

## 4.3. Steel-reinforced OPC concrete columns

For steel-reinforced columns as shown in Fig. 7, the analytical model was able to produce accurate peak loads and deflections at peak load. For S75-C, the discrepancy was relatively small and the predicted curve successfully captured the rising and descending segments. However, the predicted elastic range of S75-25 and S75-35 were stiffer than the experimental curves, which resulted in a large predicted ductility.

#### Table 2

The comparison between experimental and theoretical results.

Specimen Volumetric ratio of		Volumetric ratio of	Experimental		Analytical		Differences (%)						
transverse reinforcement, ρs	reinforcement, ρs	transverse reinforcement, ρc	Peak load (kN)	Axial deflection at peak load (mm)	Ductility	Peak load (kN)	Axial deflection at peak load (mm)	Ductility	Peak load (kN)	Axial deflection at peak load (mm)	Ductility		
GFRP-GPC columns from Elchalakani et al. [5]													
G75-C	2.1%	2.2%	1357	6.3	3.0	1370	6.4	4.2	1%	2%	43%		
G75-25	2.1%	2.2%	804	6.7	2.2	772	6.7	2.4	-4%	-1%	10%		
G75-50	2.1%	2.2%	454	5.2	3.4	433	5.7	3.7	-5%	11%	8%		
G75-75	2.1%	2.2%	244	10.8	3.8	285	12.0	3.3	17%	12%	-13%		
G150-C	1.1%	2.2%	1194	7.0	2.4	1215	7.7	2.1	2%	10%	-10%		
G150-25	1.1%	2.2%	657	6.2	2.2	618	5.9	2.3	-6%	-4%	2%		
G150-50	1.1%	2.2%	353	4.0	3.3	363	3.9	2.7	3%	-3%	-18%		
G150-75	1.1%	2.2%	234	10.3	3.4	257	11.7	2.6	10%	13%	-24%		
G250-C	0.6%	2.2%	1041	5.7	2.2	1001	6.0	2.8	-4%	5%	32%		
GFRP-OPC	concrete columns from	Elchalakani et al. [18]											
075-C	1.2%	1.6%	1449	4.4	2.2	1447	4.1	3.7	0%	-8%	68%		
075-25	1.2%	1.6%	917	4.0	2.8	825	4.4	3.4	-10%	11%	25%		
075-35	1.2%	1.6%	788	4.3	2.3	655	4.0	3.6	-17%	-8%	56%		
O150-C	0.6%	1.6%	1367	3.9	1.4	1364	4.1	3.8	0%	5%	170%		
O150-25	0.6%	1.6%	880	4.3	2.8	861	4.3	3.4	-2%	1%	19%		
0150-45	0.6%	1.6%	584	3.4	2.3	657	3.9	3.4	12%	14%	46%		
O250-C	0.7%	1.6%	1402	3.8	2.8	1404	4.1	3.3	0%	8%	18%		
Steel-OPC concrete columns from Elchalakani et al. [18]													
S75-C	1.2%	1.6%	1533	4.0	2.0	1591	4.4	2.5	4%	11%	21%		
S75-25	1.2%	1.6%	908	3.8	2.3	884	4.0	2.9	- 3%	4%	28%		
S75-35	1.2%	1.6%	815	4.3	2.3	655	4.0	3.6	-20%	-8%	56%		
S150-C	0.6%	1.6%	1622	4.3	2.4	1445	4.4	2.5	-11%	3%	3%		
S150-25	0.6%	1.6%	959	3.7	2.5	890	4.0	2.9	-7%	8%	17%		
S150-45	0.6%	1.6%	567	3.5	2.4	541	3.9	2.8	-5%	12%	15%		



The peak loads of the two columns were slightly under-estimated by the analytical model. A similar trend was observed for those with 150 mm stirrup spacing. The behaviour of the concentrically loaded S150-75 was accurately modelled, however the peak loads of those loaded at an eccentricity were over-estimated. Due to the reduced transverse reinforcement ratio, S150-25 and S150-45 loaded at an eccentricity failed in a more brittle manner. Expectedly, lower residual strengths were seen in the analytical results than the columns with 75 mm stirrup spacing. However, they were still higher than test results, which caused the over-estimation of ductility.

## 4.4. GFRP-reinforced OPC concrete columns

The behaviour of the GFRP-reinforced OPC concrete columns was generally well captured by the analytical model. A 6% and 8% variation in peak loads and their corresponding displacements from the





Fig. 7. Experimental and predicted axial load-axial displacement curves for steel-reinforced OPC concrete columns.



Fig. 8. The axial load-axial displacement curves of GFRP-reinforced OPC concrete columns.



Fig. 9. The load-displacement curves of O250-C and G250-C.

experimental results is observed in Fig. 8, respectively. The rising and descending curves of the concentrically loaded columns from the analytical model were moderately accurate. However, similar to the OPC concrete reinforced with steel rebars and stirrups, the elastic ranges of the eccentrically loaded columns were stiffer than the test results, resulting in larger ductility indices. The post peak responses of the columns with 75 mm stirrup spacing were well modelled by the theoretical predictions. Similar trends were observed for columns with 150 mm stirrup spacing. However, the O150-45 failed in a brittle manner and was not shown in the predicted curve. In terms of columns with large stirrup spacings as shown in Fig. 9, the predicted behaviour of O250-C also agreed well with the experimental results, similar to O75-C and O150-C.



Fig. 10. Comparison between analytical and experimental load-deflection curves of the GFRP-reinforced GPC columns.



Fig. 11. The axial load-axial displacement curves of G75-75 and G150-75.

## 4.5. GFRP-reinforced geopolymer concrete columns

Figs. 10 and 11 show the predicted axial load-axial displacement curves of the GFRP-GPC columns loaded at zero to medium eccentricity (50 mm), and high eccentricity (75 mm), respectively. The GFRP-GPC columns were most accurately modelled in the elastic ranges and post peak collapse curves. Therefore, the variations in peak loads, displacements at peak load and ductility indices were satisfactory at 6%, 7% and 18%, respectively. The predicted post peak responses also agreed well with the experimental behaviour. The elastic range of the G75-C was better captured by the analytical model than the OPC concrete specimens. As the load eccentricity increased, the inaccuracy of the results increased. This was attributed to the susceptibility of GPC to bending moment [23]. The height of the rectangular stress block was

smaller than OPC concrete. Despite that, the model was successful in accurately predicted the behaviour of GFRP-GPC columns loaded at no to medium eccentricity. The columns with 150 mm stirrup spacing had more brittle responses than those with 75 mm stirrup spacing as a result of the less effective transverse reinforcement. This was reflected by the lower *DI* values as shown in Table 2. The predicted curve of G250-C was amended to Fig. 9. From this figure, it could be seen that with a similar geometry and reinforcement arrangement, the GPC columns had a softer elastic range. The post peak response of the GPC column was also more brittle, similar to G150-C. Therefore, sufficient transverse reinforcement must be provided for GPC columns, due to its lower elastic modulus than OPC concrete [3].

## 5. Conclusions

A model was proposed to predict the load-displacement behaviour of the GPC columns fully reinforced with GFRP bars and stirrups. The model was validated by experimental results, including GFRP-GPC, GFRP-OPC concrete and steel-OPC concrete columns.

It was concluded that model was suitable for modelling the behaviour of the concentrically or eccentrically loaded GFRP-reinforced GPC columns. On average, the analytical predictions were only 6% and 7% away from the experimental results. The elastic and post peak behaviour could be accurately predicted up to medium eccentricity (e/d = 0.31). As the eccentricity continued to increase, the accuracy of the model reduced. The proposed model could be applied to the GFRP-reinforced GPC columns.

The model was able to produce accurate predictions of GFRP and steel-reinforced OPC concrete columns. A larger variation of the predicted ductility of GFRP or steel-reinforced OPC concrete columns was observed. The model tended to over-estimate the stiffness of the OPC concrete columns in the elastic range, resulting in an over-estimation of the ductility. In comparison, the stiffness of most GPC columns was accurately modelled in the elastic range.

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