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Experimental study of short concrete columns reinforced with GFRP bars under monotonic loading

Vu Hiep Dang [a], *Phan Duy Nguyen* [b], *Vinh An Le* [c,*]

[a] *Hanoi Architectural University / HAU, Hanoi, Vietnam*

[b] *Mientrung University of Civil Engineering / MUCE, Phuyen, Vietnam*

[c] *University of Transport and Communications / UTC, Hanoi, Vietnam*

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ABSTRACT

The glass fiber reinforced polymer (GFRP) bars are considered as an alternative reinforcement to steel in concrete structures subjected to chloride environment because of their non- corrosive and non-magnetic properties. To examine the applicability of GFRP bars to performance of concrete columns, this work was conducted. The effect of the compressive reinforcement ratio and stirrup spacing on the load carrying capacity of concrete columns reinforced with GFRP bars is experimentally investigated. Nine short concrete columns with dimensions of 150 × 150 × 600 *mm* were cast and tested until failure under displacement-controlled concentric loading. The experimental results demonstrated that by increasing the reinforcement ratio from 0.37% to 3.24%, the load-bearing capacity of GFRP RC columns was found to increase by an average of 28%. Moreover, the tested results confirmed that the GFRP stirrup spacing had a significant influence on the load-carrying capacity of the columns.

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1 Introduction

In recent years, fiber reinforced polymer (FRP) has been widely used in concrete members as it possess excellent material properties, such as corrosion resistance, high tensile strength and light weight over the conventional steel reinforcements. Besides the obvious advantages, FRPs have the low compressive strength, low compressive modulus and brittle behavior compared with traditional steel rebars. Experimental tests have shown that concrete columns reinforced with GFRP under concentrically axial load exhibit a decrease in the axial load-carrying capacity in comparison with concrete columns reinforced with the same steel bar ratios [1]. Ehab's research [2] revealed that the relationship between load-carrying capacity and GFRP reinforcement ratio is almost linear up to a reinforcement ratio of 1.628%. Tu et al. [3] tested eight GFRP-

* *Corresponding author. Tel.: +84888681018.*
E-mail address: levinhan@utc.edu.vn

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reinforced concrete columns with ratios of longitudinal bars in range of between 0.5% and 1.5% indicated that the contribution of GFRP bars to the ultimate compressive strength of a GFRP-RC column is 3%–7%. Moreover, the compression properties of GFRP bars are difficult to predict due to the lack of stability of individual fibers in a bar. Therefore, the contribution of the GFRP bars to the column capacity could be limited or may be ignored as recommendation of ACI440.1R [4]. In another study, Choo et al. [5] suggested that to prevent brittle tension failure of rectangular concrete columns reinforced with FRP bars, the minimum required reinforcement ratio, $\rho_{f,min} = 0.59\%$. This means that it is possible to use FRP reinforcements for concrete columns as long as a minimum reinforcement ratio must satisfy the condition as said above.

It can see that the experimental researches on GFRP-RC columns are still needed to clarify the contribution of GFRP bars to axial strength of columns. Therefore, the aims of this article are firstly, to investigate the general behavior of short GFRP-RC columns with longitudinal reinforcement ratios ranging widely from $\rho_f = 0.37\%$ to $\rho_f = 3.24\%$ under concentric monotonic loading. Secondly, the compression contribution of GFRP bars to ultimate strength of GFRP RC columns is estimated through analysis of tested results and proposed equation.

2 Experimental programme

2.1 Materials and specimen production

The average ultimate longitudinal tensile properties of the GFRP materials were provided by the manufacture (FRP VIETNAM., JSC [6]) and reported in Table 1. All GFRP-RC columns were transversally reinforced with 6mm diameter GFRP stirrups. Meanwhile, the longitudinal reinforcement of columns used the bars of 6, 8, 9, 12, 14 *mm* diameter.

Table 1 – Mechanical and physical properties of GFRP bars [6]

Bar size *(mm)*	Diameter *(mm)*	Nominal area *(mm²)*	Modulus of elasticity *(MPa)*	Tensile strain *(%)*	Tensile strength *(MPa)*
6	6±0.5	19.62			
8	8±0.5	33.16			
10	9±0.5	56.71	44300	1÷3	900
12	12±0.5	86.54			
14	14±0.5	122.65			

A single batch of normal strength with a maximum coarse aggregate size of 20 *mm* was employed to cast all columns. All used aggregates were in compliance with current Vietnamese Standards.

Table 2 - GFRP reinforcement and experimental results

Specimen ID	Longitudinal reinforcement		Stirrups		$P_{u,\exp.}$ *(kN)*
	Number of bars	ρ_f, %	Bar size*(mm)*	Spacing *(mm)*	
#1	4G6	0.37		100	450
#2	4G8	0.62		100	485
#3	4G10	1.06		100	490
#4	4G12	1.62		100	515
#5	8G10	2.12	6	100	530
#6	4G14	2.29		100	528
#7	8G12	3.24		100	576
#8	4G12	1.62		50	579
#9	4G12	1.62		200	468

The average concrete compressive strength was determined based on testing three 150 × 150 × 150 *mm* concrete cubes cured under the same conditions as the column specimens. The measured average concrete compressive strength (R_m) was 31.6 *MPa* at the start of testing day.

A total of nine GFRP-reinforced concrete square specimens were cast horizontally in steel prism mould. All columns were the dimensions of 150 *mm* ×150 *mm* × 600 *mm*. The longitudinal GFRP bars were set in the four sides of the column cross section with a cover thickness of 20 *mm*. The two end faces of the specimens were strengthened by steel nets to protect them from crushing. The reinforcement arrangement of the specimens is presented in Fig. 1. The nine column specimens were identified as indicated in Table 2.

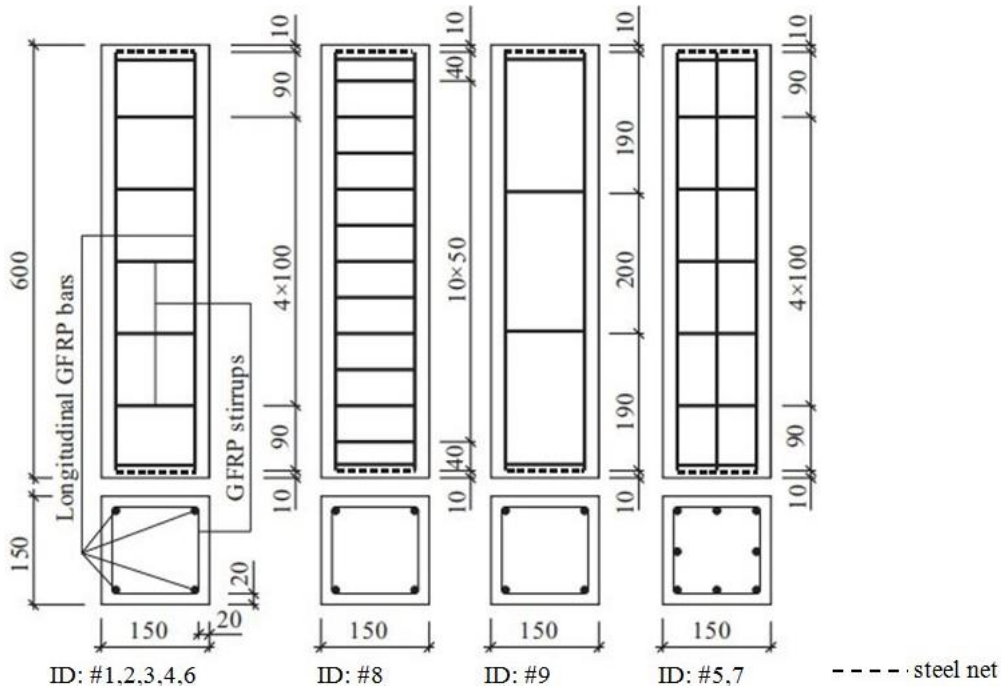

Fig. 1 – Layout of GFRP-RC columns

2.2 Instrumentation and loading test

Both end faces of the specimens were supported with a couple of 8mm thick steel plate. Prior to testing, to obtain uniform distribution of the applied loads, both ends of each column were capped with a rubber plank. The column was then placed in the compression machine with a maximum scale of 100 tons.

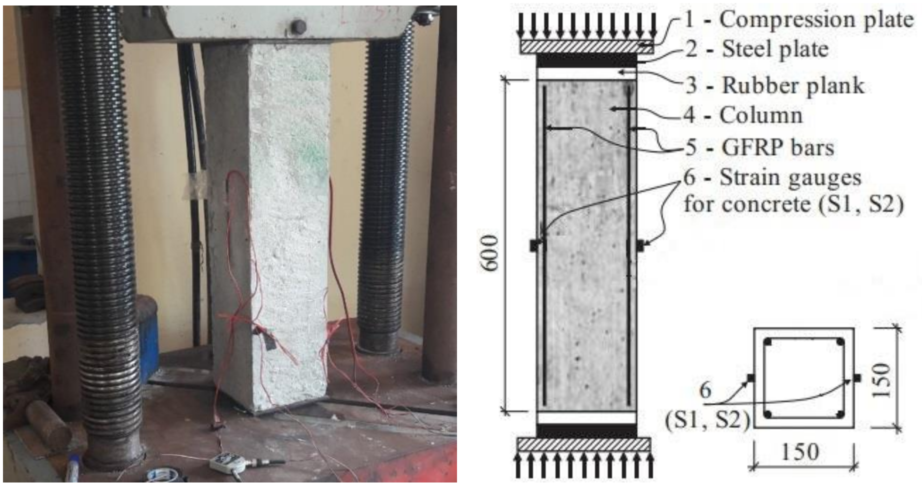

Fig. 2 – Test setup

The axial strains were measured at the middle of the concrete columns by strain gauges (Fig. 2). All column specimens were initially loaded up to level of 10% of the estimated loading capacity to check and eliminate eccentricity. Testing continued under displacement control until the column is destroyed by either crushing concrete or rupturing longitudinal GFRP bars.

3 Analysis of results and discussion

3.1 Effect of GFRP ratio on load-carrying capacity

Table 1 shows the experimental ultimate axial strength of all tested GFRP-RC specimens. The almost linear relationship between the bearing capacity and the GFRP reinforcement ratio can be seen at 100 *mm* stirrup distance, as displayed on Fig. 3. The increase in amount of GFRP reinforcement from 0.37% to 3.24% leads to an increase of bearing capacity by an average of 28%. With this observation, it is clear that a significant increase in the longitudinal GFRP ratio does not plenty enhance the ultimate loading capacity of the specimens.

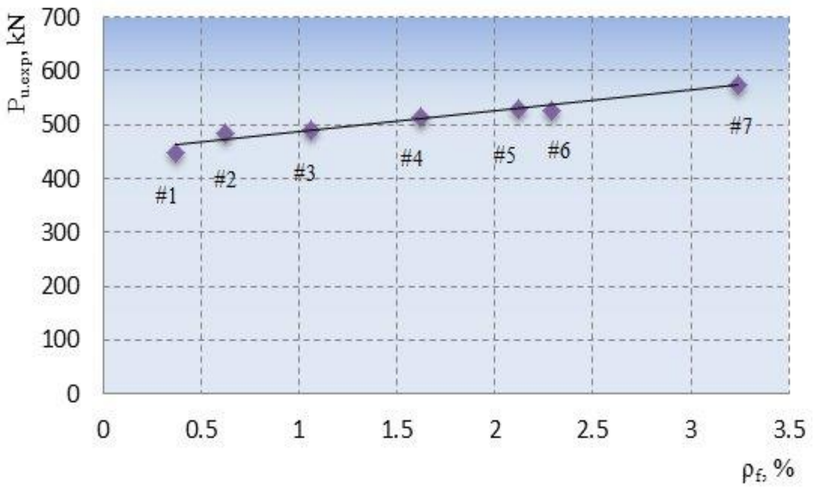

Fig. 3 – Ultimate axial load capacity-GFRP ratios

The load-axial strain relationship of all specimens is shown in Fig. 4. The axial strain of compressive concrete is computed as the measured average of the two strain gauges S1, S2. Figure 4 indicates that axial strain is gradually enhanced as the increase in axial load up to approximately 90% of the ultimate load.

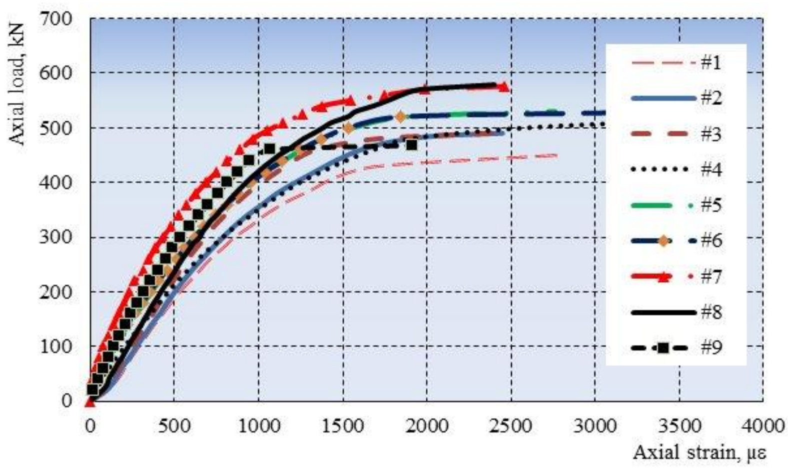

Fig. 4 – Load-axial strain curves of different columns

The recorded maximum concrete strains of specimens range from 1921 to 3300εμ. These collected values are in agreement with the experimental results reported by Tu et al. [3] and El-Gamal et al. [7]. The comparisons of the load-axial strain curves of columns depicts the under the same load, the axial strain of concrete of columns with high reinforcement ratio is higher than that of low reinforcement ratio. On the other hand, the results of #4, #8, and #9 specimens demonstrate that the effect of stirrup distance on the strain of concrete at ultimate load is observed.

3.2 Effect of stirrup spacing on load-carrying capacity

Works of Luca et al. [1] indicated that the 305mm spacing of the GFRP stirrups does not contribute to increasing the ultimate axial load. In fact, the smaller spacing of the GFRP stirrups provides a higher confinement for strengths and ductility [8]. Recently, El-Gamal et al. [7] tested the circular concrete short columns reinforced with GFRP bars and spirals also reported that the columns with the larger spirals spacing had the lower ultimate load. This is totally similar to measured results of #4, #8 and #9 columns as shown in Fig.5 and Table 1. #8 column with the smallest stirrup spacing exhibits the highest axial load-carrying capacity compared with the same longitudinal reinforcement as #4 and #9 columns. Figure 5 shows that using 50mm stirrup spacing in the #8 column enhances the ultimate load by more than 23% compared to the #9 column with 200mm stirrup spacing.

4 Prediction of load-carrying capacity

Vietnamese Standard 5574:2012 [9] provided the following equation to predict the load-carrying capacity of conventional RC short columns under concentric loading:

$$P_{ou} = R_b(A - A_{st}) + R_s A_{st} \tag{1}$$

where A - the cross-sectional area of the column; A_{st} – total cross-sectional area of longitudinal steel bars; R_b – factored compression strength of concrete; R_s – factored yielding strength of steel bars.

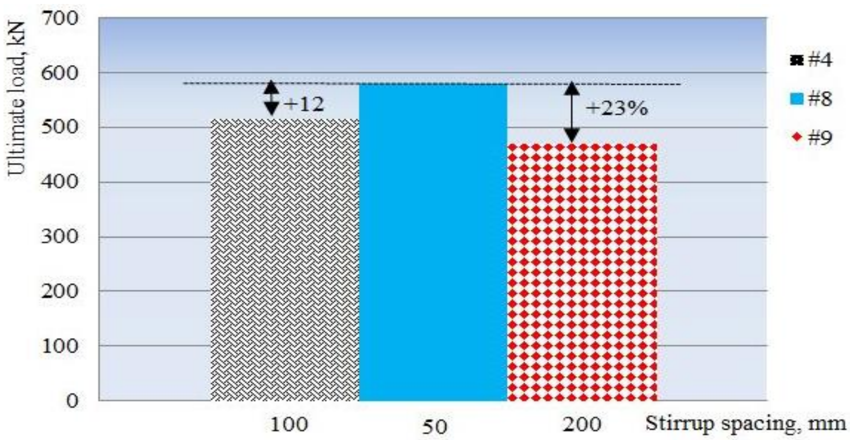

Fig. 5- Effect of stirrup spacing on ultimate carrying capacity

Based on equation (1) and Tu et al.'s research [3], in this work, equation (2) is introduced to take into consideration the GFRP compressive strength contribution to ultimate strength.

$$P_{ou} = 0.65 R_m (A - A_f) + 0.1 f_{fu} A_f \tag{2}$$

where A_f – total cross-sectional area of longitudinal GFRP bars; f_{fu} – tensile strength of GFRP bars.

Fig. 6 reveals the ratio between the experimental maximum load and the theoretical ultimate capacity predicted by equations (2). These ratios vary from 0.96 to 1.19 that depend significantly on both GFRP reinforcement ratio and stirrup spacings. Indeed, the #1 specimen has a lower GFRP ratio than recommended by Choo et al. [4] resulting in premature failure mechanism in compression concrete. This leads to the degradation of the ultimate load of #1 specimen. Meanwhile, the #9 specimen with 200mm stirrup spacing could be the cause of compressive buckling of the GFRP bars under axial load, resulting in a decrease in ultimate load. Furthermore, predicting the load capacity for #8 specimen with the closest stirrup spacing is underestimated by 19% due to the lack of consideration of concrete core confinement effect of equation (2). More researches on the effect of closer stirrup spacing on ultimate load of GFRP-RC columns are needed.

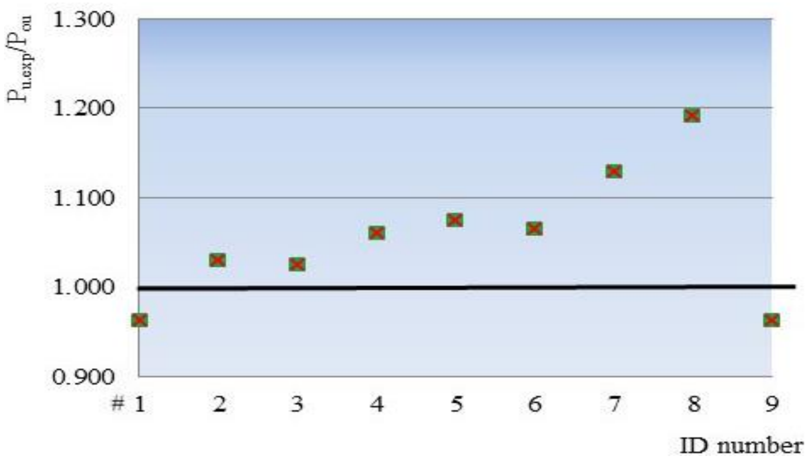

Fig. 6 – Experimental load capacity versus predicted load capacity

5 Conclusion

The effect of the longitudinal reinforcement ratio and spacing of stirrup on strength of GFRP-RC short columns is investigated through test of nine concrete columns reinforced with reinforcement ratio ranging from 0.37% to 3.24%, stirrup spacing of 50,100 and 200 *mm*. It could be concluded from the experimental results of this study that:

- The relationship between the load-carrying capacity of GFRP RC columns and the reinforcement ratio is nearly linear at the same spacing of stirrup.
- Similar to steel stirrups, GFRP stirrups, providing concrete confinement effect, affect greatly load-carrying capacity of the GFRP-RC columns. The increase in load-carrying capacity is up to 23%.
- The ultimate load predicted by equation (2) gives the conservative results except for column with lower GFRP ratio than 0.59% and column with large spacing of stirrup. Further researches are necessary to investigate the limit stirrup spacing for GFRP-RC columns.

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