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Analytical calculation on shear capacity of RC columns internally confined with CFRP strips

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Analytical calculation on shear capacity of RC columns internally confined with CFRP strips

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Abstract. In the present work, behaviour of reinforced concrete columns transversely confined with carbon fibre reinforced polymer (CFRP) strips has been investigated. Focus was given on shear capacity provided by CFRP strips in the RC columns using analytical approach. The analytical calculation showed good correlation with results obtained from numerical analyses. Results from analytical calculations indicate increases in shear capacity when distance between the FRP strips reduced from 200mm to 150mm and 100mm by 33.4% and 83.4%. Furthermore, when the number of plies increased from single to two and three plies of FRP strips, shear capacity in RC column increases by 99.6% and 149.7%, respectively.

1. Introduction

Behaviour of reinforced concrete (RC) columns is directly related to the confinement condition provided for concrete. As can be seen from figure 1, the higher the confinement rate in the concrete, the higher will be its compressive strength. Therefore, columns with better confinement condition have higher axial load capacity. In addition, good confinement also can enhance its ductility under horizontal loads as well as increase the shear force capacity of the columns.

For many years, steel bar has been widely used for making the reinforcement bars, ties and hoops. However, in harsh environments, RC structures have experienced severe loss in serviceability or safety much earlier than expected, due to the corrosion of reinforcing steel in the concrete. Corrosion creates two significant problems in RC structures, which includes loss in cross-section of steel bars and corrosion products take place a large volume than the original steel [1]. These may reduce the strength of reinforcing steel and cause high tensile forces in the concrete which led to crack and spall off [2]. Figure 2 shows an example of corroded RC structures.

Another main issue with confinement in RC elements is the improper design of transverse reinforcement, which lead to structural failure when subjected to horizontal loads such as earthquake. This problem among the main concern for both academicians and industry practitioners [3]. The current design of transverse reinforcement for low-ductile columns with 90° hooks and widely space between the stirrups were not able to withstand severe displacement caused by the horizontal loads [4, 5]. As mentioned, proper confinement can enhance shear capacity and deformability of the columns. Hence, stringent requirements were outlined in design codes regarding the specification of stirrups for high ductile columns including 135° hooks, additional crossties and closely space between the stirrups

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in order to maintain structural integrity under earthquake [6]. However, the requirements are not adhered.

Nowadays, when it comes to corrosion problems of carbon steel reinforcements, two options are available; usage of stainless steel reinforcements and application Fibre Reinforced Polymers (FRP) [7]. The main issue with stainless steel reinforcements is related to their expensive cost compared with carbon steel and FRP's. However, unlike carbon reinforcements, FRP bars is hard to be bent and to be used as hoops or ties. On the other hand, FRP sheets can easily be bent and shaped. So far, many studies have conducted using externally bonded FRP sheets to enhance shear and flexural strength on the existing structural members including columns, beams and slabs [8]. In this study, however, investigates the behaviour of concrete columns transversely reinforced using carbon fibre reinforced polymers, CFRP.

This paper presents structural failure of RC buildings caused by inadequate or improper design of confinement and how CFRP strips can enhance the performance of RC columns. The results for both RC columns transversely reinforced with steel stirrups and CFRP were compared based on analytical calculation.

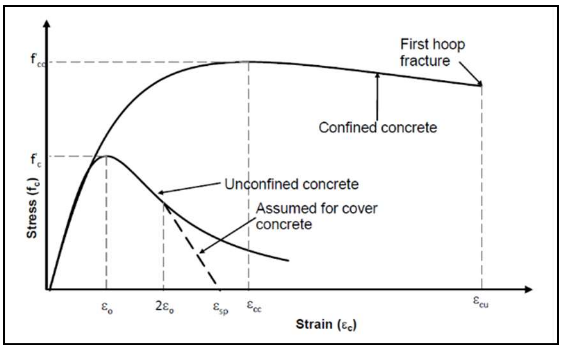

Figure 1. Stress-strain relation of confined and unconfined concrete. [9]

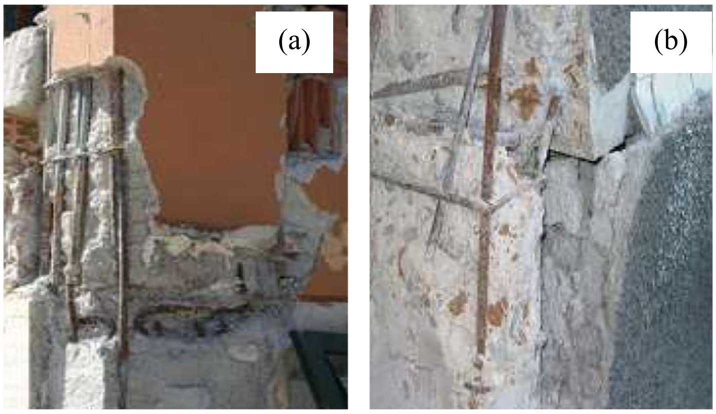

Figure 2. Corroded reinforcement bars reduces tensile strength in structural elements during earthquakes; (a) L'Aquila Earthquake, Italy and (b) Karliova earthquake, Turkey [10].

2. Failures due to improper transverse reinforcement

Low-ductile RC columns are vulnerable to horizontal loads such as earthquake. Figure 3 shows the failures of RC column during earthquakes. Severe ground motion, improper design and detailing, and poor construction practices of conventional steel stirrups caused the excessive cracking and spalling of concrete, followed by buckling of longitudinal steel bars between the widely spaced transverse ties [11]. Shear failure occurs, when the concrete element lost its ability to support lateral loads and failed before steel yielding. Furthermore, the 90° hooks of steel stirrups tend to open up which lead to little or no confinement of concrete especially at critical zone like plastic hinge region in beam-column joints [12].

Table 1 presents the summary of insufficient transverse reinforcement of columns that induced the structural failure during earthquake event. Most of the failures indicate inadequate confinement and improper design and detailing of columns with no seismic design consideration [5, 13]. This shows that although stringent guidelines have been provided, however, it does not been adhered.

Moreover, earthquake affects buildings differently based on the type of ground motions and the design of buildings. Generally, shorter columns receive high-frequency energy of nearby earthquake compared with long-period energy exhibit in taller structures of long distance earthquake [14]. Most of the buildings were designed with soft story conditions [15].

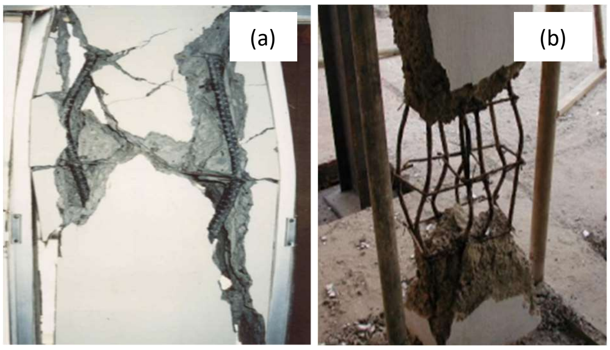

Figure 3. Failure of RC columns; (a) buckling of longitudinal bars [11] and (b) 90° hooks transverse ties opened up [16].

3. Properties of FRP composites

Fibre Reinforced Polymers (FRP) are well known as an alternative material to replace the corrosive steel bar in concrete structures, as well as an effective seismic retrofit material for existing concrete buildings due to its durability under harsh environment and loads [17]. The advantages of FRP composites including high strength-to-weight ratio, lightweight, and low lifecycle costs will be briefly explained in this section.

3.1 High strength-to-weight ratio

FRP composites consists of fibers and matrix. The main function of fibers is to carry load and provide stiffness, strength, thermal stability and other structural properties to FRP. Figure 4 shows the stress-strain curves of FRP and mild steel rebar typical used as transverse reinforced. The elastic-linearly characteristic of FRP without yielding in tension allow FRP to exhibit 2 to 10 times higher tensile strength than mild steel. This will give huge advantages for RC columns. The high tensile strength of FRP strips transversely reinforced columns may improve the axial load capacity and ductility of columns to fully utilized the flexural capacity provided by longitudinal steel bars [21]. Thus, the failure mode of columns can also be improved from brittle failure to ductile failure.

3.2 Lightweight

In seismic impact study, lightweight structures can reduce the inertial force in the building and help in protecting its integrity. The weight of a building is a major reason influencing its withstand towards the ground motion than the impact of the earthquake itself. FRP composites only weight 10 kg/m^2 which is beneficial for seismic construction [22].

Table 1. Summary of structure failure during earthquake due to improper transverse reinforcement.

Earthquake	Magnitude of earthquake	Failure observed	Reasons of failure
2015 Gorkha Earthquake, Nepal [5]	M7.8	Shear failure with 45° shear cracks, plastic hinging at beam-column joints and subsequent buildings collapse.	i. Inadequate reinforcement ii. Poor detailing
2014 Chiangmai Earthquake, Thailand [13]	M6.3	Sudden failure of buildings.	i. Most of buildings not design with seismic consideration ii. No building regulation to resist earthquake for buildings below 15 m
2010 Chile Earthquake and Tsunami [18]	M8.8	Shear failures of short columns. Concrete spalling, cracking and buildings collapse.	i. Confining ties with 90° hooks ii. Inadequate transverse reinforcement with large spacing between stirrups iii. Smooth longitudinal bars and transverse bars without ribbed iv. Corrosion of transverse steel before the earthquake
2009 L'Aquila Earthquake, Italy [19]	M6.3	Failures of columns at the ground floor	i. Soft/weak story conditions ii. The used of no ribbed longitudinal bars iii. Inadequate shear reinforcement using 6 mm diameter of confining steel with 200 mm spacing
2004 Sumatra Earthquake and Indian Ocean Tsunami [20]	M9.0	Severe cracking infill walls and brittle failure of ground story RC columns.	i. Not all buildings were properly designed with ductile detailing ii. Inadequate lateral reinforcing steel

3.3 Low lifecycle cost

Lightweight construction material is indirectly reducing the transportation, handling and installation cost [22]. In addition, since the biggest problem in RC structures is corrosion of reinforcing steel bars, the maintenance itself is much higher due to retrofitting and rehabilitation of old buildings. Thus, the utilization of robust material such as FRP composites may reduce the cost of maintenance.

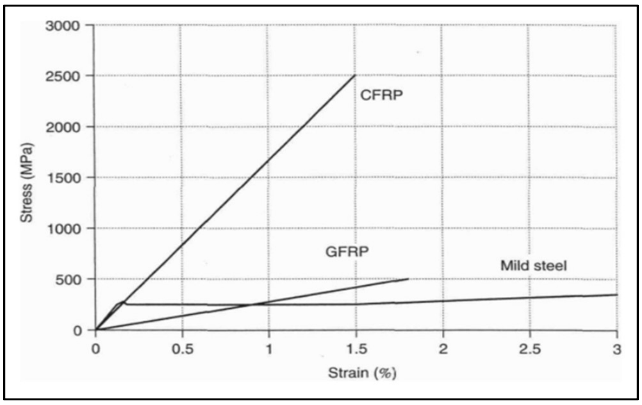

Figure 4. Stress-strain curves of FRP and mild steel [23].

4. Behaviour of column transversely reinforced with FRP strips

In this section, analytical calculation of RC columns transversely reinforced with FRP strips were analysed using similar dimension or size of RC column from FE modelling by authors in the previous studies [24] and will be referred herein for validation purpose.

The equivalent geometrical properties between FRP strips and the conventional stirrups, as well as shear capacity of FRP strips were calculated according to Eurocode 2 and ACI 440.2R-08 [25]. This document provides guidance for the selection, design, and installation of FRP strips in RC columns. The aim was to compare the existing analytical calculations for FRP strips and results from FE models, in terms of deflection curves, load carrying capacity and failure modes of the columns.

4.1 Equivalent geometrical design

Eurocode 2 has specified the standard design of transverse reinforcement using mild steel grade with 6 mm, 8 mm and 10 mm diameter of steel links. In order to get the equivalent design using FRP strips, the design force, V for steel bars can be defined as follows:

$$V = f_y A \tag{1}$$

where f_y is the tensile strength of steel and A is the area of steel bars. The design force, V then can be used to determine the equivalent width of FRP strips by using the same equation (6) with the area of rectangular instead of bars for conventional stirrups. Table 2 shows the equivalent geometry of FRP strips to the respective size of carbon steel stirrups.

Table 2. Equivalent geometrical design of FRP strips

Types of materials	Strength (MPa)	Diameter or width (mm)		
Carbon steel stirrups	361	6	8	10
FRP strips	933	28.7	51	79.7

4.2 Ultimate strength

The shear strength provided by FRP depends on the orienting of fibres in a direction of transverse to the axis or perpendicular to the shear cracks [26] as shown in Figure 5 according to ACI 440.2R-08 [25].

(a) (b)

Figure 5. FRP wraps as (a) straight or (b) inclined strips

The nominal shear strength, V_n of concrete shear strength, V_c and FRP system, V_f should be greater than required shear strength, V_u calculated using equation in ACI 440.2R-02:

$$\phi V_n \geq V_u \tag{2}$$

where the strength reduction factor, ϕ for shear is 0.85 as recommended by ACI 440.2R. the shear strength of FRP wrap can be evaluated from forces resulting from the tensile stress in the FRP wraps, which depends on the fiber and crack orientation (α) angle with reference to the longitudinal axis of concrete. To simplify the analysis, the inclination of the crack (α) is assumed to be 45°. The fibers are oriented at 45° (vertical strip) to the crack or at 90° (inclined strip) as shown in Figure 8. Calculations can be carried out using equation 7a. The ultimate tensile strength, f_{fe} of FRP strips can be calculated using equation 7c. Meanwhile, the nominal shear strength of FRP strips confined concrete member can be determined as equation 7a. The contribution of FRP system to shear strength, V_f with additional reduction factor, ψ_f=0.95 for fully wrapped members.

$$\phi V_n = \phi(V_c + \psi_f V_f \tag{3}$$

V_c can be calculated using equation ACI 318-02:

$$V_c = \lambda \times 2.0\sqrt{f'_c} b_w d \tag{4}$$

where, λ = 1 for normal weight concrete.
while, V_s is conventional stirrups (straight) computed by,

$$V_s = \frac{A_s f_y d}{s} \tag{5}$$

From equation for rectangular spirals, Vs in ACI 318-02,

$$V_s = \frac{A_s f_s d(\sin\alpha + \cos\alpha)}{s} \tag{6}$$

Therefore, the shear strength contribution of the FRP wrap in the form of discrete strips along the length of longitudinal reinforcements can be calculated by using:

$$V_f = \frac{A_{fv} f_{fe}(\sin\alpha + \cos\ ) d_f}{s_f} \tag{7a}$$

where,

$$A_{fv} = n(2t_f w_f) \tag{7b}$$

$$f_{fe} = \varepsilon_{fe} E_f \tag{7c}$$

where n is number of plies used for each FRP strips.

4.3 Validation of analytical calculations

In order to validate the analytical calculation using equation 7a, comparison in the ultimate load capacity between analytical and numerical analyses were performed.

Figure 6 shows the comparison between analytical calculation and numerical analysis based on earlier study conducted by the authors [24]. The ultimate load capacity obtained from analytical calculation is 17.9kN, which is correlates well with the one obtained from Finite Element (FE) analysis (18kN) with 0.56% differences in the values. Thus, the analytical approached able to estimate structural capacity of RC column transversely reinforced with FRP strips.

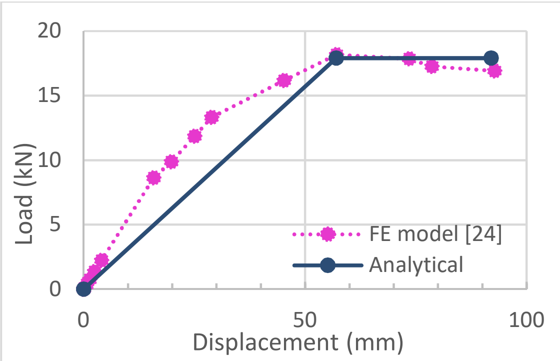

Figure 6. Comparison of backbone curves of numerical model and analytical calculation for RC column transversely reinforced with FRP strips [24].

4.4 Effects of different configuration of FRP strips

As shown in section 4.3, a good correlation was observed between the results of analytical and numerical analyses. Shear strength provided by FRP strips with different spacing and number of layers were analysed and presented in Table 3.

Based on Table 3, the shear load capacity of FRP strips with closely spaced between the spirals at 150mm and 100mm increases the shear strength by 33.4% and 83.4%, respectively compared with 200 mm spacing. This is because closely spaced between the spirals increase shear strength contribution in confining core concrete and the longitudinal reinforcement dowel action. Also, reduction in the spacing between the spirals minimized the shear cracks and distribute the pressure uniformly along the shear span [27]. Increase in the number of plies to two and three layers increases the shear strength by 99.6% and 149.7%, respectively compared with single FRP strips layer. Results indicate that increase in the number of plies gives significant improvement in shear capacity compared with closely spaced between the spirals.

Table 3. Shear strength provided by FRP strips with different spacing and number of plies.

Spacing between spirals, S_f (mm)	Shear strength, V_f (kN)		
	n = 1	n = 2	n =3
200	17.9	35.8	53.7
150	23.9	47.7	71.6
100	35.8	71.6	107.4

5. Conclusion

This study shows the potential application of FRP strips to be used as transverse reinforcements in RC columns. The FRP strips are able to increase shear capacity of RC columns compared to the conventional steel stirrups.

Analytical approach applied in this study is able to estimate the equivalent properties when FRP strips is used instead of steel stirrups. It also provides good correlation with results obtained from FE analysis. Reducing the distance between FRP strips to 150mm and 100mm increases the shear strength by 33.4% and 83.4%, respectively compared with 200mm spacing. Meanwhile, using 2 and 3 layers of FRP strips increases the shear strength by 99.6% and 149.7%, respectively compared with single FRP strips. From the results, we can see that increase in the number of plies significantly improve the shear strength of columns compared with reduction in the distance between the FRP strips.

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