UDC 624.012.45.046

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PARAMETRIC EVALUATION OF THE PLASTIC DEFORMATION CAPACITY OF FIBER REINFORCED POLYMERS CONFINED SQUARE AND RECTANGULAR COLUMNS

ABSTRACT. Confinement with fiber reinforced polymers of reinforced concrete columns is promising retrofit solution for improving ductility of existing structure. In the study, plastic deformation capacity of fiber reinforced polymers confined square and rectangular reinforced concrete columns were parametrically evaluated. Recently released seismic strengthening recommendations of American Concrete Institute were considered for calculating plastic rotation of specified columns. Fiber reinforced polymers confined concrete model provided by the design guideline was utilized for calculating moment curvature relationship of fiber reinforced polymers confined reinforced concrete columns. Numerous sectional analysis was performed with combination of various parameters (concrete strength, axial load ratio and number of fiber reinforced polymers plies). Plastic rotations of columns were determined with plastic part of the curvature and plastic hinge length for evaluating the effects of parameters on plastic deformation capacity.

KEY WORDS: fiber reinforced polymers confinement, plastic deformation, seismic strengthening

ПАРАМЕТРИЧНЕ ОЦІНЮВАННЯ ЗДАТНОСТІ ДО ПЛАСТИЧНОЇ ДЕФОРМАЦІЇ ЗАЛІЗОБЕТОННИХ КОЛОН КВАДРАТНОГО І ПРЯМОКУТНОГО ПОПЕРЕЧНОГО ПЕРЕРІЗУ, ПІДСИЛЕНИХ ПОЛІМЕРНОЮ ФІБРОЮ

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АНОТАЦІЯ. Розглянуто виготовлення залізобетонних колон із використанням підсилення бетону полімерною фіброю для забезпечення його підвищеної деформативності. В дослідженнях параметрично оцінено збільшення граничних деформацій бетону і їх вплив на несучу здатність залізобетонних колон квадратного і прямокутного перерізу, підсилених полімерною фіброю. Виконано аналіз останньої рекомендації Американського інституту бетону щодо впливу сейсмічного навантаження на несучу здатність зазначених колон.
Модель бетону, підсиленого полімерною фіброю, була використана при розрахунку діаграми «момент - кривизна» зазначених залізобетонних колон. Чисельний аналіз було виконано при варіації різних параметрів (міцність бетону, ступінь осьового навантаження і кількість шарів полімерної фібри). Було визначено вплив підсиленого бетону на несучу здатність колон із урахуванням їх кривизни і довжини.

КЛЮЧОВІ СЛОВА: полімерна фібра, пластична деформація, підсилення бетону

INTRODUCTION

Existing reinforced concrete (RC) buildings that have inadequate ductility due to lack of confinement on RC members vulnerable to heavy damage or collapse under severe seismic action. External confinement of columns with fiber reinforced polymers (FRPs) is an effective retrofitting method for improving seismic performance in terms of ductility. Effectiveness of retrofitting has been extensively investigated with several experimental studies (Balsamo et al. [1], Di Ludovico et al. [2], Tore et al. [3]) in the last two decade. Beside the effectiveness on seismic performance, ease application and completion time are other advantages of FRP confinement of columns. Many design guidelines [4-7] and codes [8] have been published for design calculation and application of FRP wrapping. ACI440.2R is one of the most preferred guideline for design FRP strengthening techniques. FRP confinement of columns was not directly addressed for seismic strengthening in previous version of ACI440.2R [4, 5]. Design of the FRP confinement for seismic application was proposed to ensure required confined concrete strain that associated with seismic displacement demand for RC columns. Recently released version of ACI440.2R [6] contains a unique chapter for seismic strengthening which includes a detailed information about improving seismic performance of existing structure compatible with seismic evaluation and retrofit codes.

In the study, sectional analysis of specified FRP confined square and rectangular RC columns were performed according to recommendations of new version of ACI440.2R [6] for ductility enhancement in seismic strengthening. Moment curvature relationships of FRP confined concrete columns obtained from sectional analysis for various parameters: axial load ratio, unconfined concrete strength and number of wrapped FRP layers. Effect of the parameters on deformation capacity of FRP confined columns was parametrically evaluated in terms of the plastic rotation which is common measure for seismic performance.

ACI440.2R (2017) RECOMMENDATIONS FOR FRP CONFINEMENT

ACI440.2R [6] contains various seismic strengthening application for RC structural members (i.e. frame elements, beam-column joints and shear walls) under seismic flexural and shear actions. Confinement with FRP is proposed for preventing buckling of longitudinal reinforcing bars, improving deformation capacity of plastic hinge and increasing clamping action of poorly detailed lap-splices. Improvement of deformation capacity is ensured by enhancement of axial concrete strain relies on FRP confinement. Only the effect of FRP confinement on deformation capacity of plastic hinge were evaluated in the scope of this study.

FRP confinement provides passive confining pressure to confined cross section of RC member with similar principle of steel stirrups and hoops. Axial strength and strain capacity of confined concrete are significantly improved due to triaxial stress state caused by confinement action. Because of high mechanical properties of FRP composites, adequate increment on strength and strain capacity can be ensured with small thickness FRP jacket. Improved axial behavior of FRP confined concrete are generally represented by stress strain relationship model obtained from experimental database. Lam and Teng [9,10] model is given in ACI440.2R [7] for stress strain relationship among several FRP confined concrete models in the literature. Model consists of parabolic and linear branches calculated from following expressions.

$$f_c = \begin{cases} E_c - \dfrac{(E_c - E_2)^2}{4 f_c^{'}} \varepsilon_c^{\,2} & 0 \le \varepsilon_c \le \varepsilon_t^{'} \\ f_c^{'} + E_2 \varepsilon_c & \varepsilon_t^{'} \le \varepsilon_c \le \varepsilon_{ccu} \end{cases} \quad (1.a)$$

$$E_2 = \frac{f_{cc}^{'} - f_c^{'}}{\varepsilon_{ccu}} \quad (2.b)$$

$$\varepsilon_t^{'} = \frac{2 f_c^{'}}{(E_c - E_2)} \quad (3.c)$$

In these expressions, $f_{cc}{'}$ is a peak confined concrete compression strength;

ε_{ccu} is a ultimate confined concrete strain corresponding to confined concrete peak strength;

$f_c^{'}$ is a unconfined concrete strength;

E_c is a elasticity modulus of concrete.

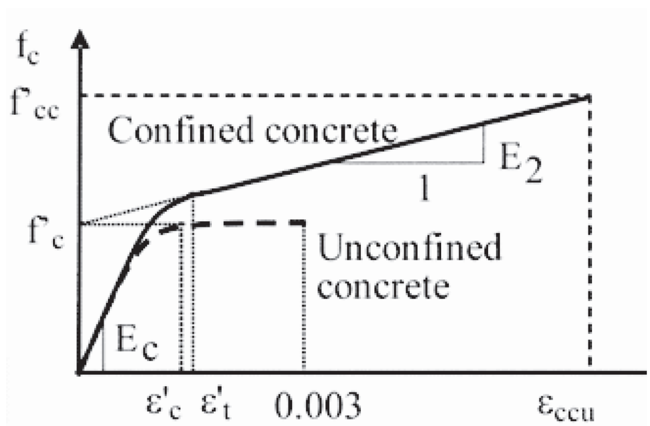

Fig. 1. Graphic representation of the solution of the loss equation.

Fig. 1. Confined concrete compression peak strength and corresponding ultimate strain are calculated from empirical Eqs. (2) and (3). Confinement efficiency is reduced with Ψ=0.95 factor for calculating FRP confined concrete strength. Maximum confining pressure is calculated from

Eq. (4). Unconfined concrete strain corresponding to peak strength can be considered 0.002. FRP strain efficiency factor at Eq. (5) can be considered approximately 0.55, however FRP effective strain should be limited with 0.004 to ensure the shear integrity of confined concrete. Further details about model can be found at ACI440.2R [6].

$$f_{cc}'=f_c'+\Psi 3.3\kappa_a f_l \quad (2)$$

$$\varepsilon_{ccu}=\varepsilon_c'\left(1.50+12\kappa_b\frac{f_l}{f_c'}\left(\frac{\varepsilon_{fe}}{\varepsilon_c'}\right)^{0.45}\right) \quad (3)$$

$$f_l=\frac{2E_f n t_f \varepsilon_{fe}}{D} \quad (4)$$

$$\varepsilon_{fe}=\kappa_e\,\varepsilon_{fu} \quad (5)$$

цhere f_l is a maximum lateral confining pressure;

ε_c' is a unconfined concrete strain;

κ_a and к_b shape efficiency factors;

ε_{fe} is a FRP effective strain;

κ_e is FRP strain efficiency factor;

E_f is a tensile modulus of FRP;

ε_{fu} is a ultimate (rupture) strain of FRP;

D is a equivalent diameter of confined cross section;

n and t_f are number of FRP plies and thickness of one ply FRP sheet respectively.

According to ACI440.2R [6], FRP confinement is not recommended for rectangular sections with aspect ratio (h/b) more than 1.5 and largest side length is greater than 900 mm. To ensure effective confinement, confining pressure to concrete strength ratio (f_l/f_c') should be minimal 0.08. In addition to these, allowable ultimate confined concrete strain is limited to 0.01 for avoiding loss of concrete integrity with severe cracking.

SECTIONAL ANALYSIS OF FRP CONFINED COLUMNS

Sectional analysis calculations to obtain moment curvature relationship of FRP confined columns were performed with code based CUMBİA program (Montejo and Kowalsky [11]). RC column sections are divided into finite number of concrete and steel fiber elements and specific material stress strain relationship can be assigned to each fiber element. Originally program uses Mander et al. [13] concrete model and King et al. [12] reinforcing steel model. Iterative procedure is performed for estimating neutral axis corresponding to each extreme concrete fiber compression strain to satisfy force equilibrium equations considering plane section remains plane assumption. Moment and curvature values are obtained from calculation for each extreme concrete strain increments up to the strain reach ultimate point of material stress strain relationship. In addition to moment curvature calculation, CUMBİA program analyses force displacement relationship and critical points (i.e. buckling point of longitudinal reinforcement, shear failure displacement) of single or double bending RC columns with rectangular and circular cross section. Detailed information can be obtained from Montejo and Kowalsky [11]. FRP confined concrete model provided from ACI440.2R [6] was added to program for sectional analysis of FRP confined RC columns.

Properties of the considered columns for parametric evaluation are presented in Fig.2. Cross section dimensions were selected for square columns 300x300 mm and rectangular columns are 300x450 due to the aspect ratio limitation (h/b<1.5) of ACI440.2R [3]. Longitudinal reinforcement ratios of square and rectangular columns were 0.014 and 0.011 respectively. Yield strength of reinforcements were considered as 420 MPa. Confinement effects of stirrups were neglected because of poor details (large spacing and 90 degree hooked end) as the same as substandard RC building. Sharp corners of the cross sections were assumed to rounded 30 mm for preventing stress concentration on corners to improve effectiveness of FRP confinement. Commercially available carbon fiber reinforced polymer (CFRP) sheet was taken into account with properties of 230 GPa elastic modulus, %2.1 ultimate strain and 0.166 mm thickness of one CFRP sheet.

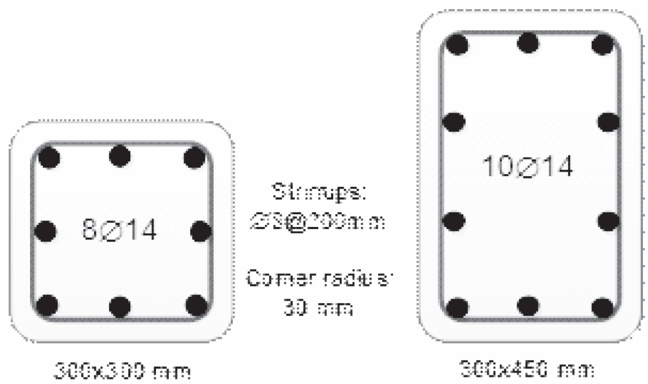

Fig. 2. Details of square and rectangular columns.

Numerous sectional analysis was conducted for stated range of the parameters; number of CFPR plies 1 to 10, axial load ratio (ALR) %10 to %70 and concrete strength (f_c') of 10, 20 and 30 MPa. ALR is the ratio of axial load to axial capacity of columns without contribution of reinforcing bars. Samples of the moment curvature relationships of columns with concrete strength 10 MPa and %20 axial load ratio for different number of CFRP plies is given at Fig.3. Reference curves in Fig.3 represents the unconfined column behavior up to extreme compression concrete strain 0.0035.

PARAMETRIC EVALUATION OF PLASTIC ROTATIONS FOR FRP CONFINED CONCRETE COLUMNS

Plastic rotation is one of the most preferred deformation measure for evaluating seismic performance of RC member which is used by modern seismic assessment and retrofit codes. Plastic rotation capacity is calculated by multiplying plastic part of ultimate curvature with plastic hinge length (Eq.6). Among various parametric expression of plastic hinge length, ACI440.2R [3] provides Eq.7 for calculating plastic hinge length of FRP confined concrete Plastic rotation capacity of columns was calculated considering combination of parameters. Variation of plastic rotation depends on parameters is presented in Fig.4 and Fig.5.

$$\theta_p=(\varphi_u-\varphi_y)\times L_p \quad (6)$$

$$L_p=g+0.044d_b\, f_y \quad (7)$$

where

θ_p is a plastic rotation capacity;

φ_u is a ultimate curvature;

φ_y is yield curvature;

L_p is a plastic hinge length;

g is a gap between FRP jacket and adjacent RC member;

d_b and f_y are diameter and yield strength of longitudinal reinforcement, respectively.

As seen in Fig 4.a and 4.b, FRP confinement is more effective for square columns than rectangular ones with the same section width. Even though shape efficiency factor for rectangular section (κ_b in the Eq.3) is approximately 1.58 times greater than square section's, confining pressure f_l is lower for rectangular section due to the greater equivalent diameter. Dotted parts of the lines in Fig4. represent low confinement cases (f_l/f_c') ratio is less than 0.08) which is not recommended from ACI440.2R [3]. FRP confinement is more effective for lower concrete strength, however number of FRP plies is limited with 6 plies for concrete strength of 10 MPa owing to 0.01 strain limit of confined concrete in ACI440.2R [3]. Plastic deformation capacity improvement for 10 MPa unconfined concrete strength case with maximum number of CFRP plies (6 plies) are 5.76 and 3.90 times by comparison unconfined reference for square and rectangular sections, respectively. Plastic rotation increment is considerably low for concrete strength of 20 and 30 MPa cases with the same amount of FRP plies. Addition to these results, adverse effect of axial load ratio on plastic rotation capacity can be seen from Fig.5 which is quite identical with effect on regular reinforced concrete columns. Effectiveness of FRP confinement is dramatically reduced with an increase on axial loading especially for square column sections. Therefore, retrofitting design with FRP confinement

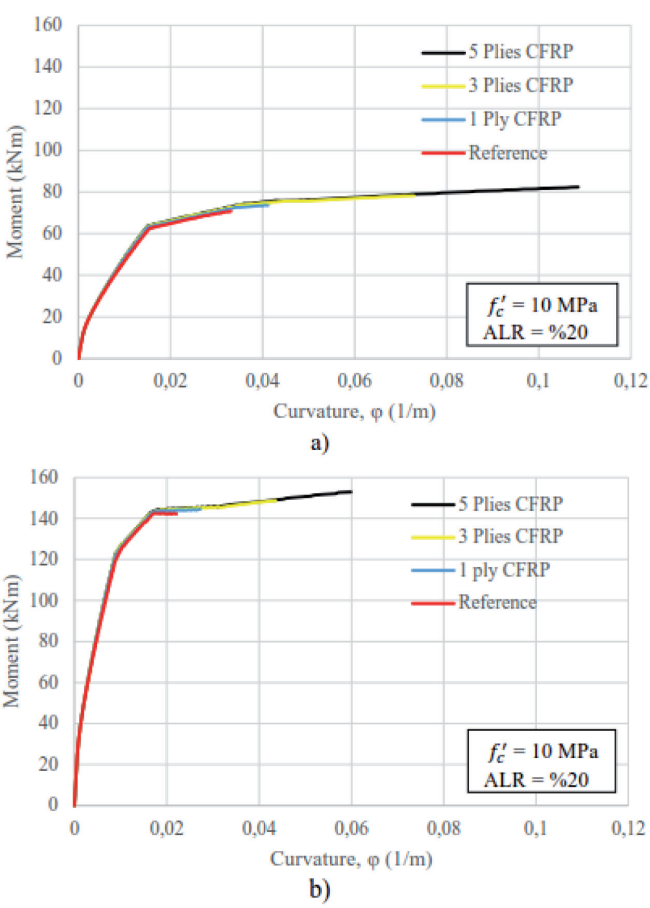

Fig. 3. Moment curvature relationship of a) square b) rectangular columns.

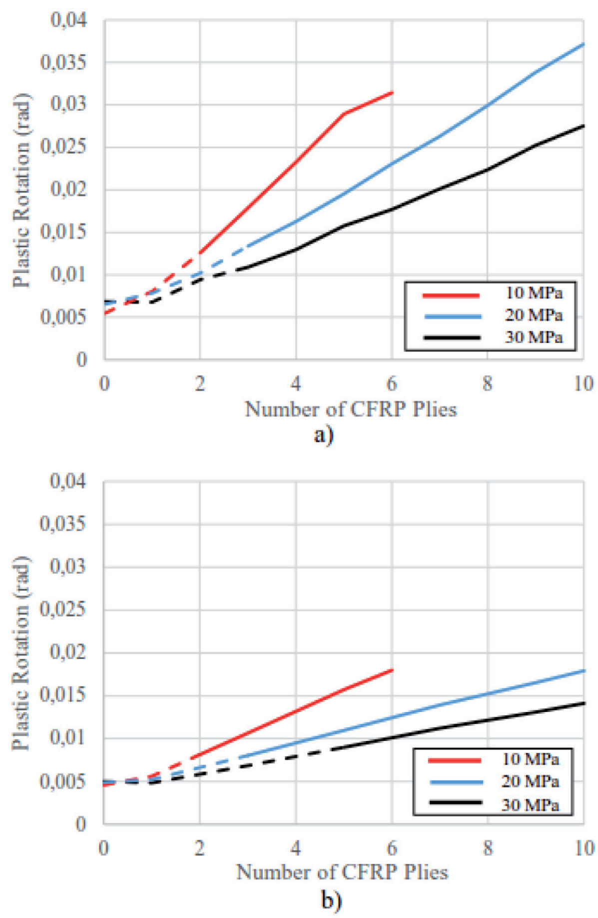

Fig. 4. Effect of concrete strength and number of fiber reinforced polymers plies a) square b) rectangular columns.

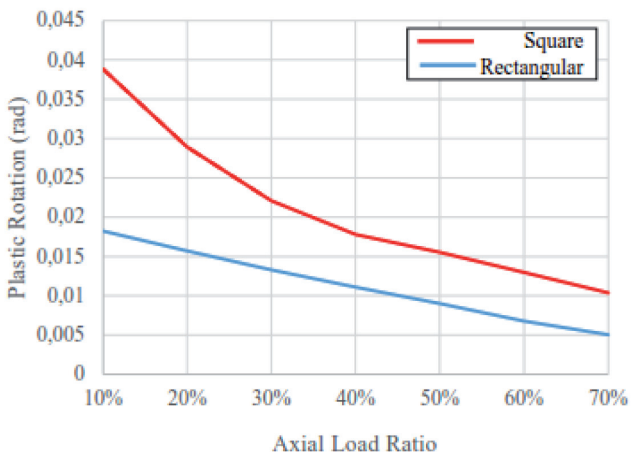

Fig. 5. Effect of axial load ratio on plastic rotation capacity.

to meet seismic demand of columns under high axial load can be lead uneconomic consequences.

CONCLUSION

In this study, last version of ACI 440.2R recommendations for deformation capacity enhancement of RC columns with FRP confinement is introduced. The FRP confined concrete model provided by ACI 440.2R [3] was added to code based sectional analysis program to obtain moment curvature relationship of FRP confined RC member with square or rectangular sections. A parametric evaluation was carried out for investigation effects of concrete strength, axial load ratio and number of wrapped FRP plies on plastic rotation capacity of specified square and rectangular RC columns. Plastic rotation capacities were obtained from multiplication of plastic part of the curvature and plastic hinge length calculated from expression of ACI 440.2R [3]. Results of the parametric study demonstrate that concrete strength and cross section aspect ratio critically affect confinement efficiency. Additionally, columns that are subjected to very high axial loading (axial load ratio 0.6 and 0.7) are not suitable for seismic strengthening with FRP confinement due to the non-economic design requirement. Numerical results of this study are only valid for specified columns, considered FRP material and confined concrete model provided by ACI 440.2R [3].

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