Numerical analysis study on seismic behavior of resilient high
strength concrete columns reinforced by ultra-high-strength
bars

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Abstract. To make concrete columns with drift-hardening behavior and small residual
deformation, a simple method is proposed. The method is the use of ultra-high-strength (UHS)
PC wire strands as longitudinal reinforcements of concrete columns. The effectiveness of the
method has been verified by experiments. The purpose of this paper is to present an analytical
method for simulating seismic behavior of resilient high-strength concrete columns reinforced
by PC strands, based on reliable constitutive laws of the PC strands and the concrete. Five
square concrete columns with the cross-section of 250mm × 250mm, the height of 1000 mm,
the shear span ratio of 2.0, the axial load ratio of 0.25 and compressive cubic strength of 95
MPa were fabricated and tested. The experimental results were compared with the results
predicted by the analytical method. Comparisons indicate that the proposed method can predict
the development trend and feature points of the envelop curve of the columns until large
deformation. Comparisons also indicate that the calculated flexural capacities by the proposed
method show very good agreement with the test results. Utilizing the proposed method and the
current design code, which are used to evaluate the ultimate flexure and shear capacities,
respectively, can give a reasonable evaluation of the failure mode of concrete columns.

1. Introduction

The investigation of concrete structures damaged by the 2008 Sichuan Earthquake and the 2011 East
Japan Earthquake [1-2] indicates that the ductile concrete structures designed according to current
seismic design codes can achieve the goal of preventing buildings from collapsing. But some are left
serious damages and large residual drifts, making the structures difficult to be repaired or reused after
earthquakes. Therefore, from the perspective of post-earthquake rapid recovery and reconstruction,
ductile concrete structures are no longer considered as the only solution in earthquake-prone areas. It
is desirable to provide new alternatives for a higher seismic performance than simple life safety.

The main methods for how to achieve resilience of concrete structures are: the utilization of high-
strength prestressed rebars in the longitudinal direction of beam-column joints and columns of
reinforced concrete structures [3-4]. Studies have shown that the application of high-strength post-
tensioned prestressed rebars is very effective in reducing structural damage and residual deformation.
The researchers of this paper have proposed another method, which only uses ultra-high-strength (UHS) PC wire strands instead of deformed rebars of the column. Test results indicate that the concrete columns utilizing PC strands have a stable increase in lateral resistance until the drift ratio reaches 4%, which is two times of safety limit of drift ratio, and have reduced residual deformation, which can significantly enhance reparability of concrete columns.

The use of high-strength rebars as the longitudinal reinforcement of the column can significantly improve the flexural capacity, but does not improve the shear capacity, and that may result in unexpected shear failure of the column before large deformation. Therefore, it is necessary to reasonably and reliably evaluate the ultimate flexural and shear capacities of the columns, and the failure mode of the columns. However, the flexural capacity calculated based on the code equation of plane cross-section assumption clearly overestimates the measured flexural capacity. It is necessary to establish a calculation method to solve the theoretical analysis problem of the practical application of resilient concrete structures with UHS PC strands.

In recent years, researchers have conducted extensive research on numerical simulation and model establishment of hysteretic behavior of high-strength reinforced concrete structures. Some of the studies rely on the plane cross-section assumption [5-6]. Some other studies need to consider the effect of bond slip of longitudinal rebars. The beam-column joints of the rebars with a yield strength of 600 MPa located in the longitudinal direction of beam-column joints and columns of reinforced concrete structures were tested under pseudo-static test, and the finite element model considering the effect of bond slip of the beam end was established, and the prediction results were in good agreement with the test results [7-8].

This paper is to present an analytical method for evaluating the seismic behavior of resilient concrete square columns with UHS PC strands and deformed rebars. The method can consider the steel amount of UHS PC strand and the confinement configuration of transverse reinforcement. To verify validity and accuracy of the proposed method, the predicted results by the method are compared with the measured results by the test. Attention is primarily paid to envelop curves and the feature points of envelope curves. In addition, the proposed method and the current design code are used to evaluate the ultimate flexure and shear capacities and the failure mode of the columns, and to verify the applicability of the proposed method for concrete columns reinforced by UHS PC strands.

2. Analysis method and material models

2.1. Analysis method

Fig. 1 shows strain and stress distribution in the cross section of the column end. The procedures of the proposed analysis method can be described as follows: 1) For a given drift ratio $R_k$, according to the equivalent plastic hinge theory, calculate the curvature $\Phi_k$ in the plastic hinge zone. 2) Due to plane cross-section assumption, give an initial value to the strain at the edge of the compression zone $\varepsilon_k$, and obtain the column section strain distribution. 3) According to the stress-strain relationship of concrete [9], the coefficients $\alpha$ and $\beta$ are calculated to determine the equivalent rectangular stress block, and total concrete compression force at the column end section $\alpha f_c \beta cb$ is calculated. 4) According to the stress-strain relationships of rebars [10], determine total force of rebars in the plastic hinge zone $\Sigma \sigma_{si} A_{si}$. 5) Calculate the internal axial load $N (= \alpha f_c \beta cb + \Sigma \sigma_{si} A_{si})$, If the axial load $N$ balances the applied axial force.
load \( P \) within a tolerable error, the moment \( M_k \) and the lateral force \( V_k \) corresponding to the given \( R_k \) are obtained. 6) Give a new \( R_k \) and repeat the above steps till the target drift ratio.

2.2. Stress-Strain Relationships for Confined High-Strength Concrete
The stress-strain constitutive model is applied to define the envelop curve, unloading curve and reloading curve for confined HSC under compression. This analytical method uses the concrete stress-strain constitutive model based on reference 9, because of the wide applicability in aspects of the concrete strength and the configuration type of transverse reinforcement. Figure 2 shows the envelope curve, unloading curve and reloading curve of concrete. The envelope curve of this model is defined by equation (1), and the unloading and reloading curves are defined by equations (2) and (3), respectively.

\[
f_c = K f_p^{aX^2(b-1)X^2} \\
\text{for } X = \frac{e_c}{e_{co}} \text{ and } e_c \text{ is peak strain, } e_{co} \text{ is }\]

\[
f_c = f_{un} (\frac{e_{un}}{e_{un0}})^2 \] (2)

\[
f_c = f_{re} + (\frac{b}{2}) (\frac{e_{un}}{e_{un0}}) (e_c - e_{re}) \] (3)

Where \( f_c \) is the axial compressive stress of the confined concrete, \( K \) is the strength enhancement ratio of the confined concrete, \( f_p \) is the unconfined concrete strength, \( X = \frac{e_c}{e_{co}} \), \( e_c \) is peak strain, \( e_{co} \) is peak strain, \( a = (E_s e_{co})(Kf_p) \), \( E_s \) is the Young’s modulus of the concrete, \( b = 1.5 - 0.017f_p + \sqrt{(K - 1)f_p/23} \), \( \gamma = 1.6 \) (hoop confinement), \( e_{un} \) and \( f_{un} \) is unload point strain and stress, respectively, \( e_{re} \) and \( f_{re} \) is reload point strain and stress, respectively, \( e_{un0} \) is unloading strain to the coordinate axis.

2.3. Stress-Strain Relationships for High-Strength Rebar
The UHS strand does not have a clear yield plateau in the stress-strain curve, and the equation (4) and equation (5) proposed in the reference 10 are used to define the envelope curve and the unloading and reloading curves of the strand. Figure 3 shows the envelope curve, unloading curve and reloading curve of the stress-strain relationship of the model.

\[
f_s = E_s \varepsilon_s \left[ Q + \frac{1 - Q}{(1 + |\varepsilon_s/\varepsilon_{ch}|)^{1/2}} \right] \] (4)

\[
f_s/\varepsilon_{un0} = E_s \left[ Q_1 + \frac{1 - Q_1}{(1 + |\varepsilon_{un}/\varepsilon_{ch1}|)^{1/2}} \right] \] (5)

Where \( f_s \) and \( \varepsilon_s \) are the stress and strain of the steel strand, respectively, \( f_0 \) and \( \varepsilon_0 \) are the stress and strain of the starting point of the reloading curve, respectively, \( \varepsilon_{ch} \) and \( \varepsilon_{ch1} \) are the characteristic strains of the envelop curve and the reloading curve, respectively; \( Q \) is the ratio of the tangential stiffness at the peak to the initial stiffness, \( Q_1 \) is the ratio of the tangential stiffness at the start point, which is equal to the modulus of elasticity, to that at the end point. \( E_s \) is the modulus of elasticity, \( N \) and \( N_1 \) are the curvature coefficients of the envelop curve and the reloading curve, respectively.

Figure 2. Confined concrete stress-strain curve  Figure 3. High-strength rebars stress-strain curve
3. Outlines of the experiment compared with the proposed method

Five square concrete columns were fabricated and tested under combined constant axial load and reserved cyclic lateral loading. The main experimental variables included the amount of UHS PC strand and the confinement configuration of transverse reinforcement, i.e., two legged stirrups, four legged stirrups, Carbon Fiber Reinforced Polymer (CFRP). As longitudinal reinforcements of the test columns, two kinds of high strength reinforcements were used. They are UHS PC strands and deformed bars. The former whose nominal diameter is 12.7mm and tensile strength is 1860MPa is twisted by seven cold drawing and plain wire strands with low bond strength, and is noted as 1×7-12.7-1860 in Chinese code [11], and is referred to as ø12.7 hereafter. The latter is high-strength deformed bar with normal bond strength, and is called as Hot-rolled Ribbed Bar (HRB) in Chinese code [12], and is referred to as HRB400 hereafter, which has yield strength of 400MPa. The transverse stirrups used in the test are HRB335. Table 1 shows outlines of the test columns.

Table 1. Outlines of the test columns.

| Notation | $f_{c'}^{a}$ (MPa) | $\lambda^{b}$ | $n^{c}$ | The type of longitudinal rebars (the amount) | The type of transverse stirrups and the confinement configuration |
|----------|-------------------|--------------|---------|---------------------------------------------|------------------------------------------------------------------|
| No.1     | 80.3              | 2            | 0.25    | ø12.7(0), HRB400(12) Square and two legged stirrups, ø6@30, HRB335 |
| No.2     | ø12.7(4), HRB400(8) |              |         | Square and two legged stirrups, ø6@30, HRB335 |
| No.3     | ø12.7(8), HRB400(4) |              |         | Square and two legged stirrups, ø6@30, HRB335 |
| No.4     | ø12.7(8), HRB400(4) |              |         | Square and four legged stirrups, ø6@45, HRB335 |
| No.5     | ø12.7(8), HRB400(4) |              |         | Square and two legged stirrups, CFRP, ø6@30, HRB335 |

\(^{a}\) Compressive strength of concrete prism (300mm height by 150mm length and 150 width of the cross-section).

\(^{b}\) Shear span ratio.

\(^{c}\) Axial load ratio.

Reinforcement details and dimensions of the specimens are shown in figure 4. The physical and mechanical properties of the used rebars are shown in table 2. All the specimens were the square section of 250 × 250mm. The column No.4 was confined by four legged stirrups, and the other four
Table 2. The physical and mechanical properties of the rebars used.

| Notation | Nominal diameter | Yield strength $f_{yk}$ (MPa) | Yield strain $\varepsilon_s$ (%) | Ultimate strength $f_{tk}$ (MPa) |
|----------|------------------|-----------------|-----------------|-----------------|
| øs12.7   | 12.8             | 1760            | 0.96            | 1910            |
| HRB400   | 11.8             | 440             | 0.21            | 590             |
| HRB335   | 6.3              | 320             | 0.16            | 500             |

Specimens were confined by two legged stirrups. The spacing of four legged stirrups was 45mm, and the spacing of two legged stirrups was 30mm. In addition to two legged stirrups, one layer of CFRP whose type was CFS-I-300 was wrapped around the entire surface of the column No.5. In order to prevent extreme slippage of øs12.7 bars at the contra-flexure section, all øs12.7 bars were connected by extruding anchors and fixed on both sides of a 10 mm thick steel plate.

The test set-up is shown in figure 5 to deform the specimen in a double curvature pattern. The cyclic lateral force was applied through Electro-hydraulic Servo Actuator, which has capacities of 500kN in pulling and pushing. The constant axial load was applied by using a 1500kN vertical hydraulic jack. The axial and lateral loadings were controlled by two independent loading systems, respectively. The lateral loading was controlled by the drift ratio $R(=\Delta/L)$ of column, where $\Delta$ is the lateral displacement measured by a Laser Displacement Sensor (LDS), and $L$ is the length of shear span. At each amplitude of drift ratio (0.25%, 0.5%, 0.75%, 1%, 1.5%, and 2%) the lateral force was repeated twice. From drift ratio of 2.5% on, only one cycle of lateral loading was repeated at each drift ratio amplitude till 4% with increment of 0.5%.

4. Numerical analysis method

To verify validity and accuracy of the proposed analytical method for concrete columns reinforced by UHS PC strands, the predicted results of this method were compared with the measured results of the test mentioned above. In addition, the proposed method and the code provisions were used to calculate the flexural and shear capacity of the columns, respectively, and to evaluate the failure mode of the columns.

Figure 6 shows comparisons between the experimentally measured hysteresis curves and the theoretically predicted envelope curves for five concrete columns with normal-strength deformed rebars and UHS PC strands. The solid and dotted lines in the figure represent the measured results of the test and the predicted results of the proposed method, respectively. As shown in Figure 6, difference between the measured value and the predicted value of the peak point of the envelope curve was within 20% up to large deformation, except for the specimens at $R=0.25%$. Table 3 shows comparisons of the test values and predicted values of the feature points (yield strength, ultimate strength and failure strength [13]) of envelope curve for the specimens. As listed in table 3, the errors of ultimate strength and failure strength for the columns No.1–No.3 and No.5 were within 5%, and the
errors for the columns No.4 were within 10%. The errors of yield strength of each column were within 20%. Therefore, the proposed method can give a reasonable prediction about the degradation in lateral resistance of the envelope curve after the yield of the longitudinal reinforcement for the column No.1 and drift-hardening behavior for the column No.2~No.5.

![Figure 6. Lateral force-drift responses of columns, (a) No.1, (b) No.2, (c) No.3, (d) No.4, (e) No.5.](image)

### Table 3. The measured and predicted values of the feature points of envelope curve.

| Notation | Yield strength | Ultimate strength | Failure strength |
|----------|----------------|-------------------|-----------------|
|          | Measured value $V_Y$ (kN) | Predicted values $V_{YA}$ (kN) $V_Y/V_{YA}$ | Measured value $V_u$ (kN) | Predicted values $V_{UA}$ (kN) $V_u/V_{UA}$ | Measured value $V_d$ (kN) | Predicted values $V_{DA}$ $V_d/V_{DA}$ | |
| No.1     | 252            | 267               | 0.94            | 314            | 303               | 1.04            | 267            | 258               | 1.04            |
| No.2     | 257            | 304               | 0.85            | 309            | 321               | 0.96            | 263            | 273               | 0.96            |
| No.3     | 249            | 309               | 0.81            | 314            | 332               | 0.95            | 267            | 282               | 0.95            |
| No.4     | 249            | 303               | 0.82            | 327            | 361               | 0.91            | –              | –                 | –              |
| No.5     | 238            | 299               | 0.80            | 355            | 357               | 1.00            | –              | –                 | –              |

Table 4 shows the results of the ultimate capacity of the specimens. For the column No.1, the flexural capacity $V_{dC}$ calculated by the code [12] equation (6) was in good agreement with the measured capacity $V_{dE}$, i.e., $V_{dE}/V_{dC} = 1.03$. However, for the columns No.2~No.5, the flexural capacity $V_{dC}$ calculated obviously overestimated the measured capacity $V_{dE}$, i.e., $V_{dE}/V_{dC} = 0.71$~0.82. The overestimation might lead to a wrong prediction about the failure mode of concrete columns reinforced by UHS PC strands. The flexural capacity $V_{dC}$ calculated by the method proposed in this paper was in good agreement with the measured capacity $V_{dE}$, i.e., $V_{dE}/V_{dC} = 0.91$~1.04. The shear capacity $V_s$ calculated by the code [12] equation (7) was 5%~33% larger than the flexural capacity $V_{uA}$ calculated by the proposed method, and it is indicated that the test columns shall be dominated by flexure, and coincides with the measured hysteretic responses. Therefore, the proposed method and the code equation can be used to reasonably calculate the flexural and shear capacity of concrete columns reinforced by UHS PC strands, and reasonably evaluate the failure mode of the columns.
Table 4. Primary measured and predicted results of ultimate capacities.

| Notation | $V_{uE}^{a}$ (kN) | $V_{uC}^{b}$ (kN) | $V_{uE}/V_{uC}$ | $V_{uA}^{c}$ (kN) | $V_{uE}/V_{uA}$ | $V_{s}^{d}$ (kN) | $V_{s}/V_{uA}$ |
|----------|-------------------|-------------------|-----------------|-----------------|-----------------|-----------------|----------------|
| No.1     | 314               | 305               | 1.03            | 303             | 1.04            | 355             | 1.17           |
| No.2     | 309               | 379               | 0.82            | 326             | 0.95            | 355             | 1.09           |
| No.3     | 314               | 440               | 0.71            | 338             | 0.93            | 355             | 1.05           |
| No.4     | 327               | 440               | 0.74            | 361             | 0.91            | 452             | 1.25           |
| No.5     | 354               | 440               | 0.80            | 357             | 1.00            | 476             | 1.33           |

\(a\) The measured maximum lateral force.  
\(b\) The ultimate flexural capacity by code provisions.  
\(c\) The ultimate flexural capacity by proposed method.  
\(d\) The ultimate shear capacity by code provisions.

\[ M \leq \alpha_1 f_c b x (h_0 - x/2) + f_y A_s (h_0 - \alpha_s) \quad (6) \]

\[ V \leq 1.75 f_t b h_0 / (\lambda + 1) + f_y v A_v h_0 / s + 0.07 N \quad (7) \]

Where \(M\) is ultimate moment capacity of concrete columns, \(f_c\) is concrete prism compressive strength, \(\alpha_1\) is the equivalent rectangular stress block coefficient, \(b\) is thickness of the column, \(x\) is concrete compressive height, \(h_0\) is effective depth of cross-section, \(f_y\) is longitudinal steel compressive strength, \(A_s\) is area of the longitudinal rebars, \(\alpha_s\) is distance from the longitudinal rebars force point of the compression zone to the edge of the compression zone, \(V\) is shear capacity of concrete columns, \(f_t\) is concrete prism tensile strength, \(\lambda\) is shear span ratio, \(f_y v\) is tensile strength of stirrups, \(A_v\) is stirrup areas arranged in the same cross-section, \(s\) is spacing of stirrups, \(N\) is axial force.

5. Conclusion

This paper presents an analytical method for evaluating the seismic behavior of resilient concrete square columns with UHS PC wire strands and deformed rebars. To verify validity and accuracy of the proposed method, the predicted results by the method were compared with the measured results by the test. The following conclusions can be drawn.

(1) Difference between the measured values and the predicted values of the peak points of the envelope curve was generally within 20%, the errors of ultimate strength and failure strength were generally within 10%. The errors of yield strength of each column were within 20%.

(2) The proposed method can predict the development trend and feature points of the envelop curves of the concrete columns until large deformation. In addition, the method can consider the steel amount of UHS PC strand and the confinement configuration of transverse reinforcement.

(3) The calculated flexural capacities by the proposed method show very good agreement with the test results. Utilizing the proposed method and the current design code, which are used to evaluate the ultimate flexure and shear capacities, respectively, can give a reasonable evaluation of the failure mode of concrete columns.

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