Seismic Response Evaluation of High Strength Concrete Circular RC Columns wrapped with CFRP

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Abstract: Seismic design and construction of high-rise structures besides need for high-strength materials makes the role of high strength concrete (HSC) and CFRP undeniable. Current study deals with strength and seismic ductility assessment of HSC reinforced concrete wrapped with CFRP columns. In order to evaluate the seismic performance, existing experimental work is assumed as verification pilot that consists of four columns subjected to cyclic lateral displacement. Column members differ in the concrete strength, axial load level, number of plies and rebar ratio. The mean HSC strength is 75.2 MPa and 90.1 MPa with crushing strain of 0.3%. Longitudinal and transverse reinforcement is designed in experimental procedure according to ACI 318 regulations. Nonlinear fiber-element Software, SeismoStruct, is used for modeling and analysis procedure of column models. Parametric study of numerical models revealed that the seismic energy dissipation in HSC wrapped with CFRP members is controlled mainly by the longitudinal reinforcement ratio and CFRP wraps thickness amount. Since CFRP confinement effect than the spiral transverse reinforcement is very high, it was observed that the adding transverse confinement in the normal strength concrete lead to no improvement on cyclic behavior, however, HSC observed lower than 4% improvement.

Keywords: High strength concrete; Seismic assessment; Cyclic loading; Nonlinear geometry; Reinforcement ratio; Adding confinement

1. Introduction

Primarily, it is suitable to have a short definition of HSC according to valid regulations. ACI Committee 363 [1] defined HSC as a concrete material with crushing strength (f’c) higher than 41 MPa. HSC is used in high-rise and special structures such as dams and hydropower sub-structure. Various research works is conducted in the field of HSC wrapped with CFRP and its feasible potential to be used in civil structural systems.

Kabir and Shafei [2] conducted studies on the lateral confining of HSC using FRP jackets subjected to eccentric axial loading in advance. The acquired results revealed that FRP confinement is also effective in strength and ductility enhancements of high strength columns. However, strengthening is much effective in normal strength concrete (NSC) material than HSC and the reason is due to brittle nature of HSC as dilation of concrete is inadequate to activate FRP confinement in compression. Ozbakkaloglu has conducted research about behavior of square and rectangular ultrahigh strength concrete-filled FRP tube (UHSCFFT) columns under axial compression [3]. Study revealed that sufficiently confined square and rectangular columns could exhibit highly ductile compressive behavior. However, the behavior of members is highly sensitive to the effectiveness of confining tube, and tubes with low confinement effectiveness may not provide sufficient confinement to allow columns to maintain their load carrying capacity beyond the initial peak load. This sensitivity increases with the increase in concrete strength.

Ozbakkaloglu and Saatchigolu have conducted research about FRP stay-in-place formwork for seismic resistant high strength concrete columns [4]. Study revealed that HSC columns confined by CFRP stay in place formwork can develop ductile behavior under simulated seismic loading. The use of FRP formwork as confinement reinforcement

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substantially increases deformability of circular and square columns. The ratio of corner radius to column dimension ($R/D$) has significant impact on the effectiveness square FRP stay in place formwork. Increased corner radius promotes effectiveness of FRP, while preventing premature material failure associated with sharp corner. Columns with three plies of FRP, tested in the experimental program, were able to develop 6% prior to significant strength decay when the $R/D$ was 1/6, whereas the column with sharper corner ($R/D=1.34$) was able to develop a limited drift ratio of approximately 2%. There exists design-oriented research for confined concrete conducted by Kabir and Shafei with theoretical approach and detailed calibrations.

2. Research Significance

The main criteria in the seismic application feasibility of HSC wrapped with CFRP construction is the stability and ductility levels during quake excitations. On the other hand, the design regulations require unified material response curves for extraction of governing strength equations. There is a need to provide the preliminary material constitutive curve based on the seismic loads beside the static load regimes. HSC wrapped with CFRP columns are the primary members that resist the quake-imposed energy during seismic action in moment frame systems, and therefore they are to be designed in dimension and material to do so. There is a serious lack in determination of initial design dimensions because there is not a clear regulation for HSC material level.

The HSC wrapped with CFRP columns ductility and its interaction with demand seismic performance is not specified in recent research works and therefore the goal of current study is to evaluate existing material models and modify them, if required in order to satisfy the design prerequisite performance levels. Primary target of study is to assess the HSC wrapped with CFRP compressive strength and FRP casing effects on the hysteretic load-deflection response and the dissipated energy under defined displacement protocols. Four circular and square columns with HSC material, which is tested, by Ozbakkaloglu and Saatcioglu [4] is the basis of numerical simulation and should be calibrated according to presented experimental data.

3. Response Characterization

3.1 Experimental Background

Columns accepted as the pilot experimental database are in full-scale size and have circular and square 270 mm cross section with a total height of 1720 mm as tested by Ozbakkaloglu and Saatcioglu. Lateral loading point is elevated at 1720 mm height top of the footing. All columns are reinforced with eight No. 15 (d=16 mm) bars, which provides a flexural reinforcement ratio of 2.8% [4]. The main testing parameters selected as parametric study were the concrete compressive Strength and the axial load ratio. The configuration of HSC columns wrapped with CFRP tested by Ozbakkaloglu and Saatcioglu is as demonstrated in Fig. 1. The details of test members are as in Table 1 reported by the researches.

![Fig. 1. Detail of column specimens tested by Ozbakkaloglu and Saatcioglu [4]](image)

Table 1. Details of HSC Column wrapped with CFRP Members Tested by Ozbakkaloglu and Saatcioglu [4]

<table>
<thead>
<tr>
<th>Column</th>
<th>Cross Section</th>
<th>$f'_c$ (MPa)</th>
<th>FRP casing Number of Plies</th>
<th>$R/D$</th>
<th>Longitudinal steel Reinforcement Arrangement</th>
<th>$f_y$ (MPa)</th>
<th>$\rho_t$</th>
<th>$P$ (KN)</th>
<th>$P/P_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC-1</td>
<td>Circular</td>
<td>90.1</td>
<td>4</td>
<td>1/2</td>
<td>8-no.15</td>
<td>500</td>
<td>2.79%</td>
<td>1580</td>
<td>0.31</td>
</tr>
<tr>
<td>RC-2</td>
<td>Circular</td>
<td>75.2</td>
<td>2</td>
<td>1/2</td>
<td>8-no.15</td>
<td>500</td>
<td>2.79%</td>
<td>1480</td>
<td>0.34</td>
</tr>
<tr>
<td>RS-4</td>
<td>Square</td>
<td>75.2</td>
<td>3</td>
<td>1/6</td>
<td>8-no.15</td>
<td>500</td>
<td>2.79%</td>
<td>1760</td>
<td>0.34</td>
</tr>
</tbody>
</table>
The bases of all columns were anchored to rigid base which is assumed as full restraint in numerical model. In experimental procedure, due to restriction of axial load application, the value of vertical gravity load was changing as column was laterally displaced. However, this phenomenon is modeled exactly as occurring in real nature of structural columns since vertical load does not have any direction change in small drifts. Therefore, the second order effect of axial load \((P-\Delta)\) is expressed in an acceptable way in simulation of current study than as applied in the experiments. The axial load is constant over the period of testing although the lateral displacement has cyclic regime with increasing amplitudes. The time history of applied lateral relative displacement \((\Delta/L)\), drift, is according to Fig. 2 which consists of twelve successive cycles with 0.5% drift increase at first followed by 1% three drift cycles up to rupture of member.

![Fig. 2. Time history curve of lateral drift applied to columns [4]](image)

**3.2 Numerical Simulation**

The mathematical expression of governing response is defined using SeismoStruct environment [5]. The nonlinear material response is integrated in internal integration point of elements and then is assembled in nodal regions considering geometrical nonlinearities. The members are modeled using forced-based beam column elements. Rebar and stirrup reinforcements characteristic is expressed STL-MP uniaxial material proposed by Menegotto and Pinto [6]. The elastic modules, initial yield strength and post-yield hardening ratio are 208.750 GPa, 500 MPa, and 0.5% respectively as reported in the original experimental data. The physical model used for HSC material is assumed as nonlinear concrete Con-hs proposed by Kappos and Konstantindis [7], which is calibrated using compressive test data. Parameters needed for above equations are elastic modules \((E_c)\) as Eq. (1) proposed by ACI committee 363 [1].

\[
E_c = 3320\sqrt f_y + 6900
\]

The regarding basic experimental data reported by Ozbakkaloglu and Saatcioglu, the initial calculated input values for HSC column wrapped with CFRP are as Tables 2 to 3.

<table>
<thead>
<tr>
<th>Fibers</th>
<th>Nominal Thickness (mm/ply)</th>
<th>Ultimate tensile Strength (MPa)</th>
<th>Elastic Modulus (GPa)</th>
<th>Ultimate Rupture Strain (%)</th>
<th>Areal Weight (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.165</td>
<td>3800</td>
<td>227</td>
<td>1.67</td>
<td>300</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bar size</th>
<th>Sress-strain relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_y (MPa)</td>
<td>(\varepsilon_y)</td>
</tr>
<tr>
<td>No. 15</td>
<td>500</td>
</tr>
</tbody>
</table>

Based on the calculations the input parameters for numerical model are also evaluated and reported in table. However, calculated values are the preliminary data for analysis because HSC has lower ductility than NSC. Geometric nonlinear response of column is to be modeled exactly as applied in experiment. For this purpose \(P-\Delta\) effect is considered value by axial load equal to 0.31 for RC-1 and 0.34 for RC-2 and RS-4 of nominal axial strength are columns respectively. Axial load is applied at ultimate elevation of column in numerical model and its time history is defined as constant over analyses domain. Integration of internal forces for column section is developed by longitudinal fiber approach. Current method discretizes section into finite areas where strain is calculated according to defined uniaxial curve data and strain distribution along section domain. The patches for reinforcement and concrete volume are defined separately according to dimensional properties of test members.
Generated element for HSC members is nonlinear beam with hinges with five integration points. The load pattern of the lateral displacement is linear with respect to time and has cyclic regime. Calculation loops are defined for lateral load cycles, which have displacement control theory for integrator module and repeats three times for drift ratios.

3.3 Simulation Results and Verification

Based on primary numerical results, the cyclic response of RC-1, RC-2 and RS-4 members are calculated as Fig. 3-5. In order to compare the accuracy and validity of proposed model the experimental data acquire by Ozbakkaloglu and Saatcioglu is plotted along with the figure. RC-1 curve have conforming estimation for peak resisted base shear ($V_f$) equal to 167 kN and 11.4% lateral drift and these parameters for RC-2, RS-3 are 147.72 kN and 11.2%, 185.77 and 2% respectively.
4. Parametric Study

4.1 Axial Force Effect

One of the important parameters in assessment of energy dissipation is axial load level. In order to estimate energy-dissipation capacity of columns and its hysteretic behavior, variable axial load is applied with respect to section nominal strength that is estimated as 5096.8 kN in Ozbakkaloglu and Saatcioglu research. The calculation of ($P_0$) is according to Eq. (2).

$$P_0 = 0.85f'_c (A_y - A_i) + A_i f_y$$

![Graphs showing the effect of axial load on hysteretic behavior of HSC columns wrapped with CFRP](image)

Fig. 6. Axial load effect on hysteretic behavior of HSC columns wrapped with CFRP

The value of these loads is beginning from up to with 10% increase step. For the accurate and better evaluation of columns behavior, authors applied one logistic qualification for strength decay that this value in current study is...
20% of peak shear force ($0.2V_0$). The extracted data curves for RC-1 are demonstrated in Fig. 6 with respect to axial load increase. In the first step, the peak resisted base shear is 111.7 kN for axial load level within 12% lateral drift, which is also stable for further deflection values. The ultimate dissipated energy for this case is 328.86 kN.m without any strength loss up to 12% drift. Further increase in axial load up to 20% leads to 142.89 kN shear capacity of column at 12% lateral drift.

Here the axial load increases the load carrying capacity and ductility of HSC column wrapped with CFRP within simultaneous concrete crushing and CFRP yielding. In advance, later increase in axial force value up to results in apparent decrease in peak shear of member to 166.11 kN and ultimate reached drift to 12%. Although the shear strength is increased up to 321.16 kN.m Further increase of axial force to and just lead in shear capacity to 178.48 kN and 181.24 kN respectively along with dissipated energy decrease to 155.48 kN.m and 48.48 kN.m in that order. It is observed that axial load increase affects the energy dissipation capability of HSC members in a major manner and therefore such members are sensitive to P-Δ effect. The drop ratios of absorbed energy value in last two axial load cases are 53% and 85% consequently, regarding P-Δ case. In order to analyze the sensitivity of HSC columns wrapped with CRFP to rebar ratio and axial force value, further numerical models are generated and are compared to the analogous case with NSC columns with 40 MPa concrete crushing strength.

### 4.2 Rebar Ratio and Crushing Strength Effects

In order to have a better understanding of the effect of concrete compressive strength on the hysteresis curve, additional data with normal strength concrete is provided. NSC models obey Mander et al. [9] proposed model. The longitudinal reinforcement ratio ($\rho$) is also considered as 1%, 2% and 2.8% values in order to consider the interaction of concrete and steel strengths in calculation of columns shear capacity and feasible energy dissipation value during quakes. In addition, the axial load level is considered as values in dimensionless form, not the same as considered in previous section, in order to investigate ductility sensitivity of HSC and NSC columns wrapped with CFRP. In this study, transverse reinforcement added to models but since confinement effect of CFRP wraps is more than spiral or transverse reinforcement, there is no improvement on hysteretic behavior.

The extracted data for assumed parameters are generated in Fig. 7 for shear force history of HSC and NSC columns wrapped with CFRP with analogous rebar and axial load levels versus lateral applied cyclic drifts. Data are reported considering various concrete crushing strengths, but for the same rebar and axial load ratios as Table 4.
With study about the effect of concrete compressive strength, it was seen that NSC in the constant rebar qualification has better energy-dissipation than HSC and the pinching of HSC is increased. This issue is shown as mentioned figure. In this section of research in order to evaluate the rebar ratio effect on seismic performance, dimension and \( \left( \frac{P}{P_n} \right) \) ratio is taken constant, and rebar ratio is variable. Rebar ratios is 1\%, 2\%, and 2.8\%. With study about the effect of rebar ratio, it was seen that rebar ratio is one of the significant parameters in HSCs. This result is referring to \( \rho_{\text{max}} \) in concrete elements that in the HSC the upper limit for \( \rho_{\text{max}} \) should increase.

![Fig. 8. Shear strength of HSC and NSC columns wrapped with CFRP with respect to axial load and rebar ratios](image)

![Fig. 9. Peak Drift of HSC and NSC columns wrapped with CFRP with respect to axial load and rebar ratios](image)
5. Conclusions

Ultimate shear strength ($V_u$), peak lateral drift ($\Delta$) and total dissipated seismic energy ($U$) are plotted in Fig. 8-10 respectively versus variations in concrete grade (NSC and HSC), axial force ($P/P_0$) and rebar ratio ($\rho$). As shown in figure, in the first stage with increment of concrete strength, shear strength of column is increasing. In the second stage with the increment of axial force level, it was seen that the shear strength of column is increased but the effect of force factor level is more intuitive in the high rebar ratio, which means that with the increasing force level in the high rebar ratio, columns have better seismic performance. In the third stage with the increment of rebar ratio, shear strength of column is increased, but with the difference that the effect of rebar ratio factor about HSC is too much, which means that if HSC have acceptable reinforcement, HSC can have better act than NSC.

As shown in Fig. 9, the effect of three factors that mentioned above is investigated on peak lateral drift. In the first stage, it was seen that in the one constant rebar ratio with the increment of concrete grade because of the FRP wraps, HSC have better performance than NSC. In the second stage with increment of axial force level, it was seen that peak lateral drift in the HSC decreasing while this subject is reverse in NSC and this subject in 2% rebar ratio is more excessive. In the third stage with the increment of rebar ratio, it was seen that peak lateral drift in both of the concrete types improved and this subject in the 2% and 2.8% rebar ratios is more obvious than the other scenarios. As shown in Fig. 10, the effect of mentioned factors on absorbed energy is investigated. In the first stage, it was seen that with increment of concrete grade, energy absorbing is decreasing but this subject in the 2% rebar ratio and axial force ratio equal to 0.31 is reverse, that's means the effect of rebar ratio in the energy absorbing is more than CFRP. In the second stage with increment of axial force level, absorbed energy in HSC is decreased but this subject in the NSC is reverse. In the third stage with increment of rebar ratio, energy-absorbing capacity of members is increasing but in the 2.8% rebar ratio, it was seen that HSC and NSC have equal behavior.

At last with the investigating of all factors that influences in mentioned curves and since the energy dissipation capacity and maximum drift ratio in a seismic-resistant structural member is more important, it can be concluded that if HSC have appropriate design and good reinforcement, the behavior of HSC is more better than NSC. However, if not have an appropriate condition, maybe have unexpected and weak behavior. The general conclusions made from the current research work can be mentioned as following topics.

1. Rebar ratio effect on energy absorbing is more than CFRP wraps.
2. CFRP effect on peak lateral drift is more than rebar ratio.
3. Rebar ratio effect on shear capacity is more than CFRP.
4. Increase in concrete grade and axial load ratio results in shear strength enhancement, however peak lateral drift and absorbed seismic energy is decreased. Providing higher longitudinal reinforcement ratio waives the undesired effects of concrete grade.
5. With increase of rebar ratio, base shear strength, peak lateral drift, ductility and absorbed energy are increased which approved higher rebar ratio usage for HSC.
6. HSC can be appropriate choice in current situation structures only if concrete design and reinforcement are according to code regulations.
7. Assuming analogous rebar ratio for HSC and NSC columns, NSC members can be more efficient than HSC in dissipating seismic energy.

References


