EXPERIMENTAL STUDY ON A NEW RETROFITTED SCHEME FOR SEISMICALLY DEFICIENT RC COLUMNS

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ABSTRACT

This paper introduces a new scheme to retrofit seismically deficient reinforced concrete (RC) columns or piers with square section using prestressed steel jacket (PSJ). In the present study, six half-scale short RC column specimens were tested under cyclic loading, and the failure mechanism, strength, ductility, hysteretic character, and energy dissipation capacity were examined. The main parameters of the present test were axial compressive ratio of the columns and the prestressed level applied in the PSJ. Based on the test results, it was concluded that the seismic performance of the retrofitted specimens can be successfully enhanced by the proposed method for a transverse confinement is effectively applied on column concrete by PSJ. The expected retrofitted efficiency shows a little undesirable when the prestressed level in SJ is equal to or less than 0.15. Test results also revealed that the proposed retrofitted techniques can also effectively improve the seismic performance of columns with high axial compressive ratio. Though test results indicated that the proposed retrofitted scheme can efficiently enhance the shear strength of shear deficiency columns, further test study on shear resistant mechanism of columns retrofitted by the proposed PSJ is still needed to predict the shear strength of columns retrofitted by PSJ.

Keywords: Prestressed steel plate hoop, Concrete columns, Transverse confinement, Seismic retrofit, Seismic performance

INTRODUCTION

Due to damages by earthquake, changes in codes, rezoning of seismic intensity, poor detailing practice, and wrong design et al, many existing reinforced concrete buildings are seismically deficient. A large number of seismic appraisals of existing buildings and bridges have indicated that the major deficient of reinforced concrete (RC) columns and piers is the lack of sufficient transverse reinforcement.

Transverse reinforcement in concrete columns is used to fulfill three main functions. These functions include restraining longitudinal reinforcement against buckling, increasing shear resistance, and confining concrete for improved deformability. The lack of sufficient transverse reinforcement in short columns (columns with small height-to-depth ratios) may lead to a brittle shear failure due to inadequate shear strength under earthquake excitations. These have been evidenced by the numerous brittle shear failures of columns in the most recent earthquakes, and clearly demonstrated a need for their retrofit.

Various retrofit schemes have been developed for strengthening of concrete columns with seismic

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deficiency, such as concrete jackets, steel jackets, and fiber reinforced polymer composite jackets. The use of steel jackets or tubes to enhance the strength of columns and to improve deformability has been well studied since the 1980s. In the recent studies, emphasis has been directed on the confinement effect of the steel jackets on column concrete. Tomii, Sakino, and Xiao (1987) investigated steel-tube short columns in building structures as a scheme to prevent shear failure and to improve ductility. In their study, gaps were deliberately located from the steel tube ends to the column ends to avoid the buckling of the steel tube. It was found that this scheme was ideal for circular columns, but a deterioration of strength and stiffness was inevitable for rectangular columns, particularly for columns with a compression ratio exceeding 0.30.

Chai et al. (1994) proposed a circular/elliptical jacket method to retrofit square/rectangular columns. In their studies, the square/rectangular columns were enclosed by grout-injected circular/elliptical jackets to enhance the shear strength of the columns and to improve their deformability. This technique, however, is not always suitable when significant changes to the size or shape of the column are not desirable, and the augment of the section may attract more seismic force. Xiao et al. (2003) developed another improvement jacketing method to retrofit square columns by using welded rectilinear steel jackets and stiffeners. Their test results validated the efficiency of the partially stiffened rectilinear steel jacketing, which not only prevented brittle shear failure but also greatly improved the ductility of the column with achieving an ultimate drift ratio of more than 8%. Wu et al. (2003) investigated the composite partial interaction retrofit method to improve the strength and ductility of rectangular reinforced concrete columns. Their study results confirmed that the approach could successfully delay concrete crushing in the plastic hinge region and the strength and ductility of concrete columns could be increased.

Though the efficiency of steel jacket retrofitting RC columns is confirmed by a wealth of experimental studies, problems still exist as follows: (1) severe stress-lag between the retrofitted part and the original part usually exists; (2) the stress transfer capacity between the interface of the retrofitted and the original part depend to a large extent on the performance of the composite grout injected in the gap between the steel jacket and the concrete core of the retrofitted column; and (3) the steel jacket acts as passive confinement, and the confinement action lies on the dilation of the concrete during subsequent loading or on the dilation of flexural compression zone under transverse earthquake excitations.

Externally applied lateral prestressing of RC columns or piers not only improves the mechanisms of transverse confinement, but serves a good approach to solve those problems denoted above as well. Researches on external prestressing of RC columns or piers as a seismic retrofit methodology have been reported since 1990s. Experimental investigation had been underway at the Structures Laboratory of the Univ. of Ottawa since 1993 to develop a new retrofit technique for improved seismic shear resistance of existing concrete bridge columns (Yalcin 1997). The results indicated that the retrofit methodology could suppress shear failure, promote flexural behavior, and increase inelastic deformability substantially (Saatcioglu 2003).

Munawarz (2004) investigated into the behavior of externally confined columns under monotonic concentric loading and simulated seismic loading, with and without axial load. In their studies, a significant initial pretensioning force was applied to the bolts of the external steel hollow structural sections (HSS) collar. The test results showed that the effective core area of externally confined columns was significantly larger than that of conventional columns and could be taken as the full cross sectional concrete area, and the collared columns showed very good seismic behavior under severe cyclic loading.

From the limited experimental studies, it is recognized that the technique of transverse prestressing of columns or piers is an efficient seismic retrofit technique for RC structures. The main objectives of the present experimental study are as follows: (1) to propose an economical and practicable retrofit technique using prestressed steel jacket(PSJ) and to verify its retrofitted efficiency; (2) to obtain information on strength, ductility, deformation characteristics, hysteretic characteristics, drift capacity, and failure mechanisms of seismically deficient column specimens retrofitted with PSJ when
subjected to severe cyclic loading; and (3) to obtain information on the effect of the prestressed level of a steel jacket on the strength and seismic performance of a column retrofitted with PSJ.

**EXPERIMENTAL PROGRAM**

**Description of Specimen**

The retrofitted objective of the present test involves those RC short columns which have been designed seismically deficient and a shear failure rather than flexural failure would be expected. Six half-scale column specimens involving one “as built” column and five retrofitted columns were designed. These specimens have a 250-mm square cross-section, and the shear span-to-depth ratio of specimens is 2.0. Fig. 1 shows the reinforcement details and the geometric characteristics of the test specimens. The main test variables include the prestressed level $\alpha$ applied on steel jacket and the axial compressive ratio $n$, in which $\alpha$ represented the ratio of prestressed jacket strain to its yield strain. The corresponding test variables of specimens are listed in Table 1.

**Table 1. Main test variables**

<table>
<thead>
<tr>
<th>No.</th>
<th>$n$</th>
<th>$N$ (kN)</th>
<th>$\alpha$</th>
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</thead>
<tbody>
<tr>
<td>PC1-29</td>
<td>0.29</td>
<td>234</td>
<td></td>
</tr>
<tr>
<td>PC2-29-55</td>
<td>0.29</td>
<td>234 0.55</td>
<td></td>
</tr>
<tr>
<td>PC3-44-35</td>
<td>0.44</td>
<td>354 0.35</td>
<td></td>
</tr>
<tr>
<td>PC4-53-35</td>
<td>0.53</td>
<td>434 0.35</td>
<td></td>
</tr>
<tr>
<td>PC5-29-15</td>
<td>0.29</td>
<td>234 0.15</td>
<td></td>
</tr>
<tr>
<td>PC6-29-35</td>
<td>0.29</td>
<td>234 0.35</td>
<td></td>
</tr>
</tbody>
</table>

A new type of prestressed steel jacket (PSJ) is adopted to retrofitted the specimens, which is composed of two part of U-shape steel straps. Two strengthened plate are welded at each end of U-shape steel strap, and a gap is intentionally remained between two U-shape straps after they were installed on a column for the purpose of prestressing the steel jacket. The prestressed force is applied by screwing two high strength bolts on the two suits of strengthened plate of a PSJ simultaneously with two spanners. The details and configuration of the prestressed steel jacket (PSJ) used in the present test is shown in Fig. 2, and a uniform configuration and dimension of SJ is adopted in all five retrofitted specimens. During the transverse prestressing, a real time data of strain gauges on the steel strap is monitored to control the prestressed level.
To lubricate the stress transmission in different side of a steel jacket during prestressing, the four corners of a specimen column were chamfered (See Fig.3a), and four arc-shape steel plates were glued to each corner of the column by structural adhesive (See Fig.3b). After having completed above processing, the steel jackets were installed on the corresponding positions and prestressed force were applied (See Fig.3c).

Material Properties

To reflect the characteristic of low concrete strength in an aged structure, the design cube strength of concrete is controlled under 20.0 MPa. The ingredients of the concrete were ordinary cement, irregular gravel of 25 mm maximum size. The mix proportions by weight are given in Table 2. The average cubic (150×150×150mm³) compressive strength is 19.70 MPa after 28 days standard curing. All reinforcing bars used in specimens were rolled out of normal mild steel. The yield stress fy is obtained by tension test. The mechanical properties of the steel plate and reinforcing bars are listed in Table 3.
Table 3. Material properties of steel

<table>
<thead>
<tr>
<th>Material type</th>
<th>$f_y$ (MPa)</th>
<th>$f_b$ (MPa)</th>
<th>$E_s$ (MPa)</th>
<th>$\varepsilon_y$ (µε)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforcing bar</td>
<td>351.6</td>
<td>569.9</td>
<td>$2.0 \times 10^5$</td>
<td>1758</td>
</tr>
<tr>
<td>φ6</td>
<td>393.4</td>
<td>593.7</td>
<td>$2.1 \times 10^5$</td>
<td>1873</td>
</tr>
<tr>
<td>Steel Jacket (t=4)</td>
<td>337.6</td>
<td>451.0</td>
<td>$1.46 \times 10^5$</td>
<td>2306</td>
</tr>
</tbody>
</table>

Test Setup and Loading Procedure

Axial load was applied to the column end by a vertical oil jack, and the horizontal load was imposed by a bidirectional actuator fixed on the reaction frame. The test setup is shown in detail in Fig. 4.

The loading procedure is as follows. First, a predetermined axial load was applied to the column, and then the transverse load was applied. The axial load was held constant during the application of the transverse load. The horizontal loading process was controlled by displacement method. Before the drift ratio of specimens reached 1/75, one cyclic loading was performed under each displacement level of 1/500, 1/200, and 1/150; after the drift reached 1/75, the horizontal load was applied according to the following drift amplitudes, 1/75, 1/50, 1/35, 1/25, 1/20, and 1/15, and at each drift level, three loading cycles were performed.

The whole loading procedure finished when the bearing capacity of the specimen was reduced to 85% of the maximum load ($P_{max}$) or the hysteretic curves appeared distinctly unstable.

Instrumentation

The horizontal and vertical loads were measured using two calibrated load cells. The horizontal displacement was measured using two LVDT with a travel stroke of 100 mm, which were mounted on both sides of the column top. The strain gauges were used to measure the strains of longitudinal bars, stirrups, and steel jackets. The detailed layout of all the strain gauges is shown in Fig. 5.

![Fig. 4. Test setup](image)

![Fig. 5. Layout of the LVDT and strain gauges](image)
EXPERIMENTAL RESULTS AND DISCUSSION

Final Failure Modes

It can be easily observed that the occurrence of shear cracks in those retrofitted specimens were suspended when compared to the as built specimen’s (PC1), and that the occurrence of shear crack could be further suspended by increasing the prestressed level of SJ in those retrofitted specimens.

Although all the specimens reached their maximum bearing capacity after the longitudinal bar yielded, the final failure modes had clearly difference between the as built specimen’s (PC1) and other retrofitted specimens (PC2–PC6) (Fig.6). For specimen PC1, a dominant diagonal crack developed quickly after the yielding of the longitudinal bars, and a typical shear failure happen during the loading cycle of 1/35 drift ratio(Fig. 6a). For those retrofitted specimens PC2, PC3, PC4, and PC6, whose prestressed level $\alpha$ is larger than 0.35, their final failure modes were bending failure mode, although many shear cracks were found in the critical region of the column(Fig. 6b, 6c and 6d). For the specimen PC5 with a low prestressed level ($\alpha=0.15$), although its final failure mode showed bending failure, it could be found that a severe transverse expansion of concrete in the mid-height of the column existed (Fig.6e), which finally resulted the yield of SJ.

Strains of Steel Jacket

The Strains of Steel Jacket (SJ) developed in good agreement with the global failure phenomena of the specimens. Fig.7 shows different relationships of load-strains of SJ with different prestressed level in the retrofitted specimens. From Fig.7a, it can be found that the SJ of PC5 with low prestressed level($\alpha=0.15$) attained its yielded strain at a displacement level of 4$\Delta_y$, and quickly increased with the development of displacement amplitude. This result is consistent with the severe transverse bulging failure phenomenon in PC5 (Fig. 6e). For the other retrofitted specimens PC2, PC3, PC4, and PC6, whose prestressed level $\alpha$ is larger than 0.35, the strains of SJ still remained in elastic range when they reached ultimate failure because the core concrete of the columns were all effectively confined by PSJ, (Fig.7b), and no obvious transverse deformation was observed during the entire test process even under a high axial load.
Strains of stirrups

The load-strain hysteretic curves of stirrups are shown in Fig.8. From Fig.8, it can be found that the load-strains curve of SJ exist obvious difference between retrofitted and unretrofitted specimen. It can be found that the stirrup strain of PC1(unretrofitted) increased abruptly when the drift ratio reaches 1/200, developed continually under subsequent loading and finally yielded when the drift ratio reaches 1/75 (Fig.8a). Fig. 8b indicates that the stirrup strains of the retrofitted specimens developed slower than that of the unretrofitted specimen PC1, and no yielding of stirrup was observed until final failure happened.

Character of the hysteretic curves

The typical $P - \Delta$ hysteretic curves are shown in Fig.9. The hysteretic loop of PC1 (un-retrofitted specimen) shows bow shape and pinching due to the effect of shear crack during cyclic loading (Fig.9a). The degradation of strength and stiffness in PC1 is severe when the amplitude drift exceed 1/35 and a brittle failure is accompanying.

The hysteretic loop of the retrofitted specimens on whom the prestressed level of SJ is equal to or large than 0.35 (PC2, PC3, PC4 and PC6) shows a favorable plump model (Seeing Fig.9b and Fig.9c) and indicate a satisfactory ductility and hysteretic energy dissipation capacity. For the specimen PC5 on whom the prestressed level is controlled under 0.15, the hysteretic loop under large deformation shows pinching due to the effect of severe transverse expansion of concrete (Fig.9d). Compare to those specimens with larger prestressed level, the energy dissipation capacity of PC5 shows a little undesirable.
Test results indicated that the columns retrofitted with PSJ can get an excellent seismic performance provided that an appropriate prestressed level is applied on the steel jackets, and no obvious transverse deformation was observed during the entire test process even under a high axial load. Note that PC4 has a high axial compressive ratio 0.53, the hysteretic loop still show plump and stable (Fig. 9c), even under those large deformation cycles (loading drift index is larger than 1/15). This result indicated that the proposed retrofitted techniques can effectively improve the seismic performance of both the short columns with substandard shear details and those columns with high axial compressive ratio.

**Skeleton curves**

By comparing the $P-\Delta$ curves shown in Fig. 10, it can be seen that there exists a distinct difference between specimens PC1 and retrofitted specimens PC2-PC6. The failure mode of PC1 is obviously shear failure, and thus their strength degenerates earlier than the other specimens. Note that the skeleton curves of those retrofitted specimens experience a longer plastic phase and show a much better ductility than that of un-retrofitted specimen PC1. As for the specimen PC5 with lower prestressed level, at large levels of displacement, the strength degenerates more obviously and earlier than that of specimens with higher prestressed level (PC2-PC4, and PC6), and this indicated that an increase of prestressed level in SJ helps to reduce strength degradation in large deformation range.
The experimental results of the key points for all of the skeleton curves are shown in Table 4, where the units of load and displacement are kN and mm, respectively, and the variables $P_c$ and $\Delta_c$ respectively represent the load and the displacement of the specimens when the shear crack first occurs.

Table 4. Test results of key points in skeleton curves (kN, mm)

| Specimens | $n$ | $\varepsilon$ | $P_c$ | $\Delta_c$ | $P_y$ | $\Delta_y$ | $P_m$ | $\Delta_m$ | $P_{m,i}$/|P_{m,1}| | $\mu$/$\mu_1$ |
|-----------|-----|-------------|------|-----------|------|-----------|------|-----------|------|---------|------------|
| PC1       | 0.28| -           | 57   | 1.0       | 106  | 1.00      | 125  | 1.00      | 120  | 8.68    | 1.00       |
| PC2       | 0.28| 0.55       | 90.6 | 2.5       | 117  | 1.10      | 138  | 1.93      | 40   | 25.43   | 2.94*      |
| PC3       | 0.44| 0.35       | 103.5| 2.5       | 141  | 1.21      | 151  | 4.00      | 30   | 40.00   | 3.21       |
| PC4       | 0.53| 0.35       | 84.5 | 1.47      | 150  | 1.37      | 177  | 37.15     | 127  | 4.60    | 2.46       |
| PC5       | 0.28| 0.15       | 28   | 0.64      | 110  | 1.10      | 138  | 32.39     | 117  | 40.14   | 4.62       |
| PC6       | 0.28| 0.35       | 41   | 0.65      | 111  | 1.09      | 136  | 40.14     | 119  | 4.62    | 10.67      |

Note:\* the measuring process of PC2 was interrupted due to a too small travel stroke of LVDT.

From the Table 4, it can be found that the deformability of the columns with substandard shear strength and shear details could be largely improved by the proposed prestressed SJ scheme. The ultimate deformation and displacement ductility ratio of the retrofitted specimens increased over 3 times than that of the unretrofitted specimen. The specimen PC4 still showed a favorable ductility even when the design compressive ratio reached 0.8.

CONCLUSIONS

Test indicated that the proposed retrofitted scheme can efficiently postpone the occurring and mitigate the developing of diagonal cracks of shear deficiency columns, increase their shear capacity, and turn a threatening brittle shear failure to a favorable failure mode.

From test results, it can be concluded that the seismic performance of the retrofitted specimens can be successfully enhanced by the proposed retrofitted scheme, provided that the shear strength and the shear details of the existed columns are substandard design.

Test results also revealed that the proposed retrofitted techniques can also effectively improve the seismic performance of columns with high axial compressive ratio.

The prestressed steel jacket can effectively confine the column concrete and thus a favorable seismic behavior can be expected, provided that a suitable prestressed level is applied in it. The expected retrofitted efficiency shows a little undesirable when the prestressed level in SJ is equal to or less than 0.15.
The ductility ratio of the retrofitted specimens increased over 3 times than that of un-retrofitted specimen, and the ductility ratio could be further enhanced by increasing the prestressed level applied in SJ.

Test results indicated that the proposed retrofitted scheme can efficiently enhance the shear strength of shear deficiency columns. Problems still exist in calculating the shear strength of columns retrofitted by proposed PSJ, for no shear failure occurred in all retrofitted specimens. Further test study on shear resistant mechanism of columns retrofitted by proposed PSJ is still need to predict the shear strength of columns retrofitted by PSJ.

The proposed scheme has the advantage of environmental and durable over other retrofitted method, for neither chemosynthesis glue nor wet construction work is needed in the retrofitted process.

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REFERENCES


