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SEISMIC RETROFIT OF REINFORCED CONCRETE BUILDINGS WITH COMBINATION OF COLUMN-JACKETING AND SUPPLEMENTAL BEAMS

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Abstract

To assure the structural safety of existing structures during earthquakes, the National Center for Research on Earthquake Engineering (NCREE) in Taiwan developed an analytical procedure, known as TEASPA, to evaluate the seismic performance of these buildings. For buildings not meeting the safety criteria specified by TEASPA, NCREE recommends several retrofit techniques such as construction of shear walls, wing-walls, and column-jacketing. Among these techniques, column-jacketing is usually preferred by school officials due to its less obstruction to both ventilation and natural light. Unfortunately, the structural benefit provided by column-jacketing drops quickly as building height increases. One way to resolve this problem is to connect adjacent jacketed columns with additional beams constructed between floor levels. As preliminary analysis indicated that such measure will greatly improve the effectiveness of column-jacketing, a quasi-static experiment on three full-scale specimens was conducted for verification. Result of the experiment shows that the lateral-force resistance of the retrofitted frame is significantly increased, making the proposed technique a worthy option for the seismic retrofit of concrete buildings

Keywords: TEASPA, seismic retrofit, column jacketing, supplemental beam, pushover analysis

1. Introduction

In Taiwan, seismic retrofit of existing buildings is being considered one of the most critical works in the mitigation of natural disasters. Recognizing that failure of school buildings often cost more lives than average structures, the Taiwan Department of Education has been promoting seismic evaluation and retrofit of elementary and high school buildings in recent years. In order to evaluate the seismic performance of existing buildings, NCREE developed an analytical procedure known as Taiwan Earthquake Assessment for Structures by Pushover Analysis, or TEASPA [1], based on the capacity-spectrum method proposed by ATC-40 [2]. Following such procedure, engineers will be able to determine the seismic resistance coefficient, A_P, of a building, which corresponds to the greatest peak ground acceleration it can sustain under the “life safety” performance level [3], through push-over analysis. If the value of A_P is equal to or greater than the seismic demand of the building, A_T, defined as 40% of its design short-period spectral acceleration, S_{DS}, the seismic resistance of this building is considered adequate; otherwise, retrofit will be necessary. Details on how to calculate A_P and A_T of a building can be found in Ref. [1].

For buildings not meeting the above criteria, NCREE recommends several retrofit solutions such as construction of shear walls, wing-walls, and column-jacketing. Among these techniques, column-jacketing is often favored by both engineers and school authorities since it contributes to the lateral strength of buildings in two orthogonal directions with less interference to ventilation and natural light. In such technique, however, the strength increase mainly comes from the flexural strength of the jacketed columns at it base. As the building height rises, the overturning moment at the column base builds up quickly, and the structural bonus provided by column-jacketing would soon be compromised. To fix this problem, a simple engineering solution is proposed by connecting adjacent jacketed columns with supplemental beam constructed between floor levels. With additional resisting moment generated at both ends of the beam during lateral deformation of the structure, the flexural demand on the column will be reduced. By converting the retrofit plan from strengthening of isolated columns into a much-more-effective moment-frame action, the seismic resistance of the building will be significantly improved.

To check out the performance of the proposed technique, a push-over analysis was conducted on three structural models which represent the as-built, retrofitted with column-jacketing, and retrofitted with combination of column-jacketing and supplemental beams conditions of a typical elementary school building in Taiwan. For verification purpose, a quasi-static experiment was performed on three full-scale concrete frames at NCREE to observe the actual strength, ductility, and failure behavior of these specimens. With both analytical and experimental results, the application value of the proposed technique can be examined.

2. Structural Analysis

The typical configuration of an elementary school building in Taiwan consists of a straight aisle with classrooms located on the same side of the aisle (see Fig. 1). These buildings usually have better seismic resistance in the direction perpendicular to the aisle thanks to the in-plane strength provided by the masonry infills constructed between classrooms. If retrofit is required in this direction, it can be easily accomplished by replacing some of these masonry infills with reinforced concrete shear walls. In the other direction (i.e., the longitudinal direction of the building), however, the masonry infills are constructed under the windows, which tends to restrain the lateral deformation of columns during an earthquake and cause shear failure (see Fig. 2). As a consequence, the seismic resistance in this direction of the building is much lower and relatively vulnerable. For this reason, the following analysis was mainly targeted on the seismic behavior of the building in the longitudinal direction.

Fig. 1 – Typical configuration of an elementary school building in Taiwan

Fig. 2 – Shear failure of columns in a school building during the 2016 Kaohsiung Earthquake

Table 1 shows the dimensions and reinforcement details of the beam and column sections in the structure described above. Material strengths in the structural components are given in Table 2. To calculate the seismic resistance of this building, a push-over analysis was performed based on TEASPA. Result of the analysis indicates that the maximum lateral load (base shear) the building can carry in the longitudinal direction is 373 tf, corresponding to an A_P of 0.241g (see Fig. 3), which falls short of the specified demand (A_T) of 0.28g. Therefore, it is necessary to conduct a seismic retrofit for this building.

Table 1 – Beam and column sections in the original structure

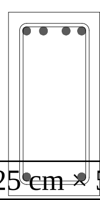
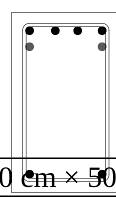
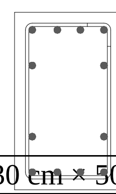
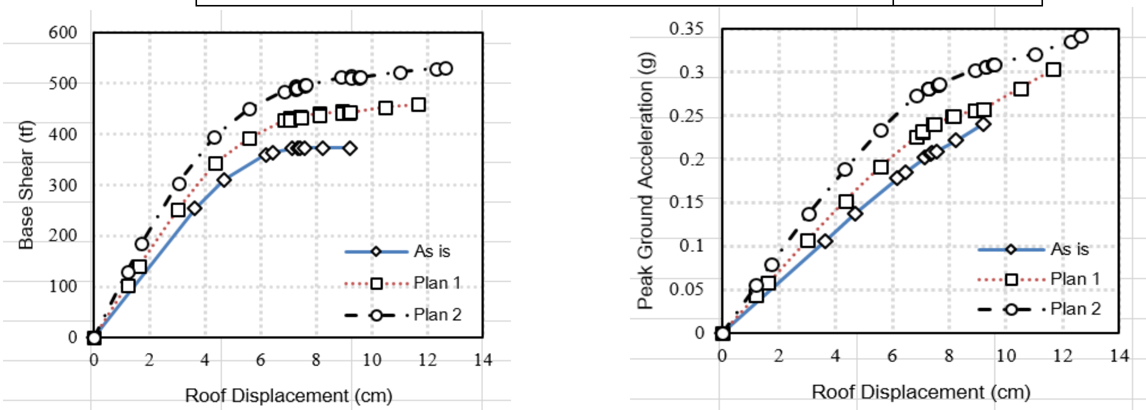
Beam-EW	Beam-NS	Column
		
25 cm × 50 cm	30 cm × 50 cm	30 cm × 50 cm
Top: 4 - No.6 Bottom: 2 - No.6	Top 1: 4 - No.7 Top 2: 2 - No.6 Bottom: 2 - No.7	12 - No.6
Trans: No.3@25 cm	Trans: No.3@25 cm	Trans: No.3@25 cm

Table 2 – Material strengths in the original structure

Specified compressive strength of concrete, f_c'	15.7 MPa
Specified yield strength of reinforcement, f_y	274 MPa
Specified compressive strength of clay masonry units, f_{bc}	14.7 MPa

Specified compressive strength of mortar, f_{mc}	9.8 MPa

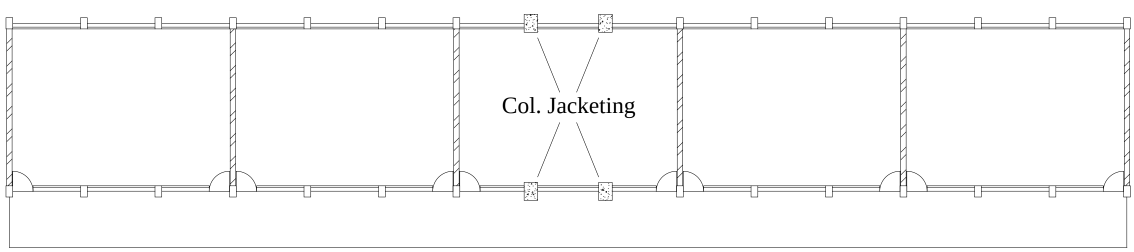


Capacity Curves

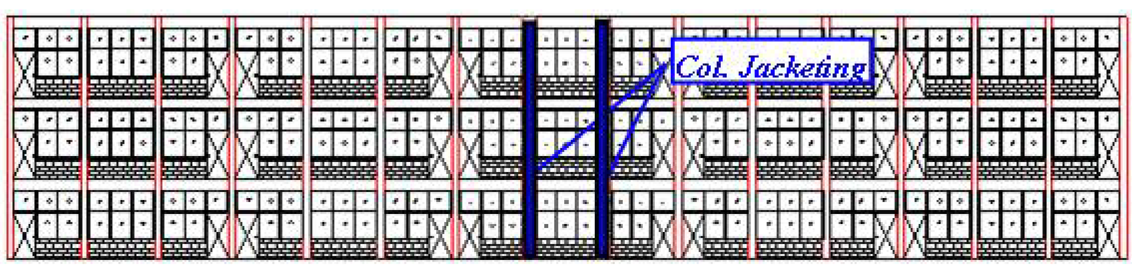
Corresponding PGA curves

Fig. 3 – Seismic performance of the building before and after the retrofit

To improve the seismic performance of the building, two retrofit schemes, one using the traditional column-jacketing technique (Plan 1) and the other using the combination of column-jacketing and supplemental beams (Plan 2), were analyzed. Locations of the retrofit components in the building are shown in Figs. 4 and 5, and the section properties are given in Tables 3 and 4. Result of analysis shows that the lateral strength of the building is increased from 373 tf to 459 tf (+86 tf) and 531 tf (+158 tf) in Plans 1 and 2, respectively, with corresponding A_P rising from 0.241g to 0.303g (+0.062g) and 0.342g (+0.101g). While both retrofit plans meets the seismic demand (A_T = 0.28g), it can be found that the benefit of retrofit (the increase in lateral strength or A_P) of column jacketing is enhanced by 63% (lateral strength) or 84% (A_P) with the addition of supplemental beams, giving quite a boost to the seismic performance of the building.



PLAN



ELEVATION

Fig. 4 – Locations of column-jacketing in Plan 1

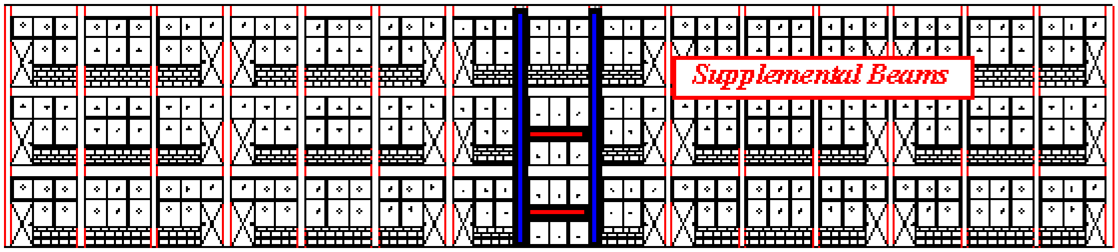


Fig. 5 – Locations of column-jacketing and supplemental beams in Plan 2

Table 3 – Beam and column sections of the retrofitting elements

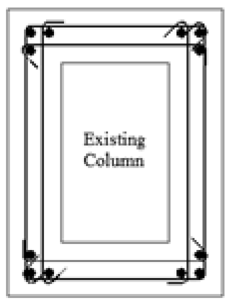
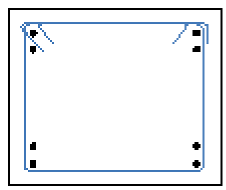
Column Jacketing	Supplemental Beam
	
60 cm × 80 cm	60 cm × 50 cm
12 – No.8	Top：4 - No.7 Bottom：4 - No.7
Trans. No.4 @ 10 cm	Trans. No.4@10 cm

Table 4 – Material strengths in the retrofitting elements

Specified compressive strength of concrete, f_c'	27.4 MPa
Specified yield strength of reinforcement, f_y	412 MPa

3. Experimental Program

To examine the actual performance of the proposed technique, a quasi-static experiment on three full-scale concrete frames, as indicated in Table 5, was performed at the structural laboratory of NCREE. The labels Prototype, CJ, and CJB represent the prototype (the unretrofitted frame), the frame retrofitted with column jacketing, and the frame retrofitted with both column jacketing and supplemental beam, respectively. Both retrofitted frames were constructed with exactly the same design and materials at the same time with the prototype at the first stage of construction, and then retrofitted with respective schemes after 28 days. Dimensions and reinforcement details of the frames are shown in Fig. 6, and the material strengths are given in Table 2.

Table 5 – Full-scale specimens constructed in this program

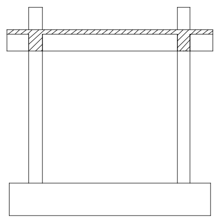
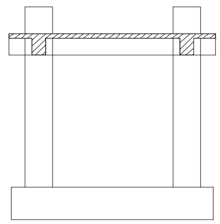
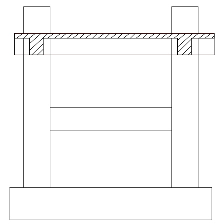
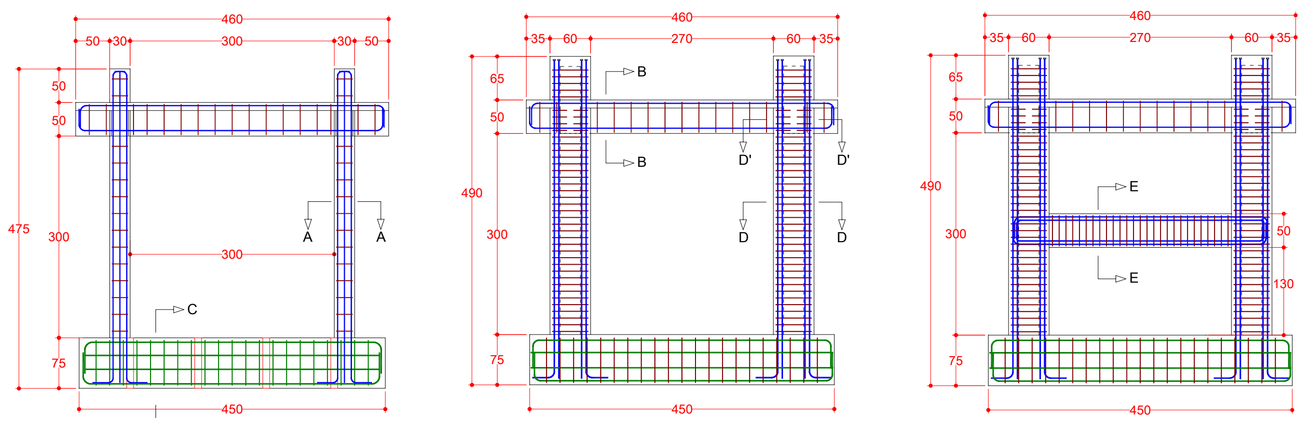
Prototype	CJ	CJB
		

Table 6 – Material strengths in the specimens

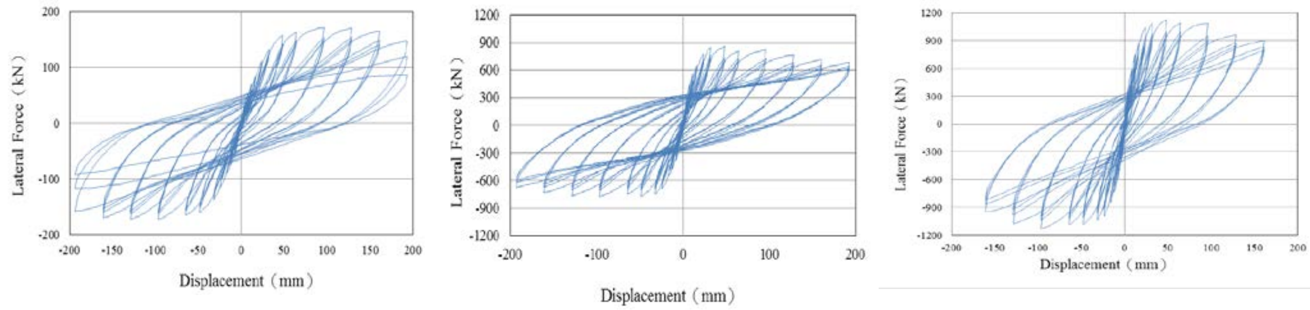
		Specified	Test
f_y	No.3 bars	275 MPa	341 MPa
	No.4 and larger bars	412 MPa	454 MPa
f_c'	Prototype Frame	15.7 MPa	19.3 MPa
	Retrofit Components	27.4 MPa	36.7 MPa
	Foundation	412 MPa	42 MPa



Frame Prototype Frame CJ Frame CJB

Fig. 6 – Dimensions and reinforcement details of the frame specimens

Fig. 7 shows the hysteresis loops of the three specimens under prescribed reversed loading cycles [5]. The corresponding backbone curves, as shown in Fig. 8, are constructed by taking the average readings of the lateral loads obtained at the same drift ratios in the positive and negative loading cycles. From the backbone curves, it can be observed that the lateral strength of the (prototype) frame was increased from 145 kN to 682 kN (+537 kN) and 945 kN (+800 kN) when retrofitted with column-jacketing and combination of supplemental beam and column-jacketing, respectively. In other words, the retrofit benefit (strength increase) of column jacketing was improved by 49% with the addition of supplemental beams, concurring with the conclusion obtained from the analytical results.



Frame Prototype　　Frame CJ　　Frame CJB

Fig. 7 – Hysteresis loops of the tested frames

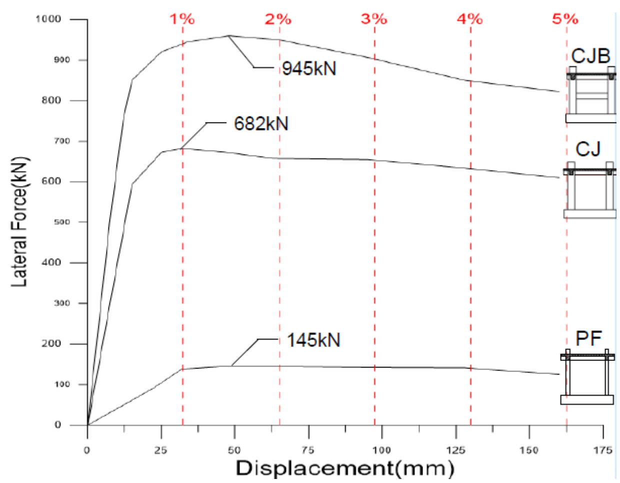


Fig. 8 – Backbone curves of the frame before and after the retrofit

4. Conclusions

In an effort to improve the effectiveness of column-jacketing in the seismic retrofit of buildings, an enhancement scheme is proposed with construction of supplemental beams between adjacent columns. To evaluate the performance of this scheme, a push-over analysis was conducted on a typical Taiwanese elementary school building based on TEASPA. Result of the analysis indicates that the retrofit benefit of column-jacketing could be significantly increased with the addition of supplemental beams. For verification, a quasi-static experiment on three full-scale frames was also performed at NCREE. It was observed that the strength increase of the frame was enhanced by 49% after the supplemental beam was added, justifying the conclusion obtained from the analytical results. Considering that the construction of supplemental beams normally cost less than 10 % of the retrofit project, it would provide a cost-effective options for the seismic retrofit of buildings.

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6. References

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