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TEST OF REINFORCED CONCRETE BEAM-COLUMN JOINTS RETROFITTED WITH CARBON FIBER-REINFORCED POLYMER STRANDS

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ABSTRACT

This study is on a new seismic retrofitting method with carbon fiber reinforced plastics (CFRP) composite for a critical reinforced concrete beam-column joints over reinforced. The method of seismic retrofit used in this study is based on a new concept to increase the strength of a beam-column joint resulting from passive vertical confinement in joints. This idea is implemented by four CFRP bundled strands placed vertically. To make it easy to apply to most three-dimensional beam-column joints with transverse beams, the bundled strands are placed at the four corners of a column. Four one third scale reinforced concrete beam-column joint sub-assemblages were loaded to failure by statically cyclic loading simulating earthquake loading. The test parameters are with and without a retrofit using CFRP Strands and width of the beams. Test results show that the method used here improved the story shear to the level of calculated story shear at flexural capacity of beams. It is verified that the new retrofitting method is one of the practical solutions for seismic retrofits of critical beam-column joints.

Introduction

Architectural Institute of Japan introduced design guidelines which incorporates seismic provisions for reinforced concrete beam-column joints based on the capacity design concept for the first time in 1991 (AIJ 1991). The building standard law enforcement was revised in 2007 such that the design of the beam-column joint should be more strictly enforced than before. As a result, the existing buildings should conform to the enforcement order which adopts the seismic provisions for beam-column joints in the newer AIJ Guidelines (AIJ 1999). New building should conform to the seismic provisions, and existing beam-column joint which do not have enough safety margin for joint shear strength due to negligent design of beam-column joint. Such deficient beam-column joints need seismic retrofit.

The most straightforward method for a retrofit is to increase the size of the column with additional cast-in-place concrete and additional longitudinal and transverse reinforcements to decrease joint shear demand. But this method has a very limited range of applicability due to the

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difficulty of construction and architectural restrictions. Moreover, the relation of seismic performance of such over reinforced beam-column joints and other design parameters which do not conform to current seismic provisions have not been well established.

Application of externally placed FRP composite is one of the simpler solutions. Several methods have been proposed and the performance have been investigated by Pampanin et al. (2006), Silva et al. (2007), Karayanis et al. (2008) and Engindeniz et al. (2008). Engindeniz et al. (2005) wrote that externally bonded FRP composites can eliminate some of the important limitations (for example, difficulties in construction or increase in member sizes) of other strengthening techniques, and still improve the joint shear capacity and shift the failure towards ductile beam hinging mechanisms. However the FRP-strengthened joints mainly consists of simplified two-dimensional test and the detailing is not necessary applicable to three-dimensional joint with transverse beams and floor slab.

The purpose of this study is to propose a new seismic retrofitting method with CFRP composite and to experimentally verify the effectiveness of the method for a longitudinally over reinforced concrete beam-column joints and it could shift the critical part of the structural system from the beam-column joints to the beam ends to ensure a beam-hinging mechanism and increase the story shear capacity. This paper reports the test results and compares the performance of beam-column joint with and without the retrofit.

A New Method of Joint Retrofitting

The idea of the new method for strengthening of beam-columns joint came from a failure mechanism. It is based on the observation from tests by the author (Shiohara 2001). The shear deformation of beam-column joint observed in the tests is mainly represented by the rotational movement of triangular segments. The shear failure of a joint is associated with the rotational movement accompanied by yielding of longitudinal bars passing through a joint. Thus the vertical confinement by elastic elements with sufficient stiffness connecting the upper and lower part of a joint enhances the strength of the joint. As shown in Fig. 1, vertical elements exert vertical force as increasing of the joint deformation. For the elastic element for confining the joint, carbon fiber reinforcing plastic (CFRP) composite is used here.

To facilitate the method applicable to wide range of three dimensional beam-column joints with floor slab and transverse beams, carbon fiber composite strands are bundled and are placed vertically at the four corners of a joint. The two ends of the bundled carbon strands composite are spread out such that it should form a fan shape to transfer the tensile force developed in the strands to the surface of concrete by epoxy resin. This arrangement makes it possible to ease the application of the CFRP. The bundled CFRP composite with fan shape anchor is a proprietary product called CF Anchor available in Japan.

The procedure of the application of the CFRP composite is shown in Fig. 2.

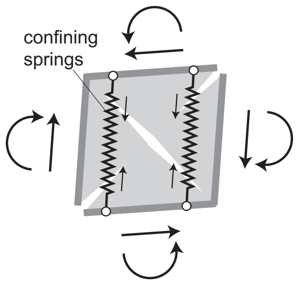


Figure 1. Deformation and moment resisting mechanism in a beam-column joint

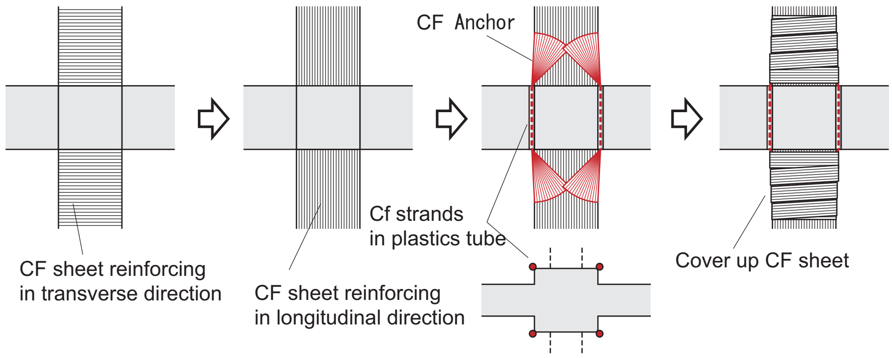


Figure 2. CFRP layout and procedure for retrofitting of beam-column joint

Test Program

Test Specimens

Four specimens of one third scale reinforced concrete beam-column joints were constructed to be subjected to statically cyclic lateral loading simulating earthquake. They were designed to show joint failure. The main parameter of the test is with and without a retrofit using CFRP composite. The other parameter of the test is the width of the beam.

Table 1 lists the properties of the specimens. Figure 3 shows the geometry and the dimension of the specimens. The specimens C02 and C04 are the strengthened specimens while the specimens C01 and C03 are control specimens without strengthening. The section of the column is 240 by 240 mm and is common to all the specimens and the tensile reinforcement ratio is 1.22 percent. The section of the beam of the specimen C01 and C02 is 240 by 240 mm while those of the specimen C03 and C04 is 120 by 240 mm. The amount of reinforcement in the beams are common to all the specimens, thus the tensile reinforcement ratio of specimens C01 and C02 is 1.31%, while the that of specimens C03 and C04 is 2.62%. The ratio of the effective depth to the full depth is 0.84. Two sets of hoops of D6 are placed in beam-column joint; the joint shear reinforcement ratio is 0.28 %.

The concrete is normal concrete with compressive strength of 31.0 MPa. The reinforcements are deformed bars with yield point of 378MPa for D13 longitudinal reinforcing bars and 399 MPa for D6 transverse reinforcing bars.

Based on the mechanical properties of the material by tests, the values of joint shear demands are calculated as 0.9 times and 1.2 times for specimen C01 and C03 respectively compared to the nominal joint shear strength calculated by the equations specified in AIJ Guidelines (1999).

Each CFRP composite bundle consists of 94 strands of 24K-3400 MPa class fiber. The tensile strength of each bundled CFRP composite is estimated to be equivalent to 2.8 times of a D13 longitudinal steel bar used for the specimen in the columns by assuming the Young's modulus of the carbon fiber is 230 GPa and the strain at the fracture of the carbon fiber is 0.7%.

Table 1. Mechanical properties of Specimens

Specimen			**C01**	**C02**	**C03**	**C04**
Beam	Width	mm	240		120	
	Depth	mm	240			
	Longitudinal reinforcement		3+2-D13 (SD345)		3+2-D13 (SD345)	
	Tensile reinforcement ratio	%	1.31		2.62	
	Stirrups		D6 (SD295A) stirrup @ 50			
	Shear reinforcement ratio	%	0.53		1.06	
Column	Width	mm	240			
	Depth	mm	240			
	Longitudinal reinforcement		5-D13 (SD345)			
	Tensile reinforcement ratio	%	1.22			
	Hoops		D6 (SD295A) hoop @ 50			
	Shear reinforcement ratio	%	0.53			
	Carbon fiber sheet (longitudinal direction)		N/A	2 layers of 300 g/m^2	N/A	2 layers of 300 g/m^2
	Carbon fiber sheet (transverse direction)		N/A	1 layer of 300 g/m^2	N/A	1 layer of 300 g/m^2
Joint	Joint hoops		2 sets of D6 (SD295A) hoop			
	Transverse reinforcement ratio	%	0.33			
	Carbon fiber strands retrofit (vertical direction)		N/A	4 bundles of 96 x 24K strands	N/A	4 bundles of 96 x 24K strands

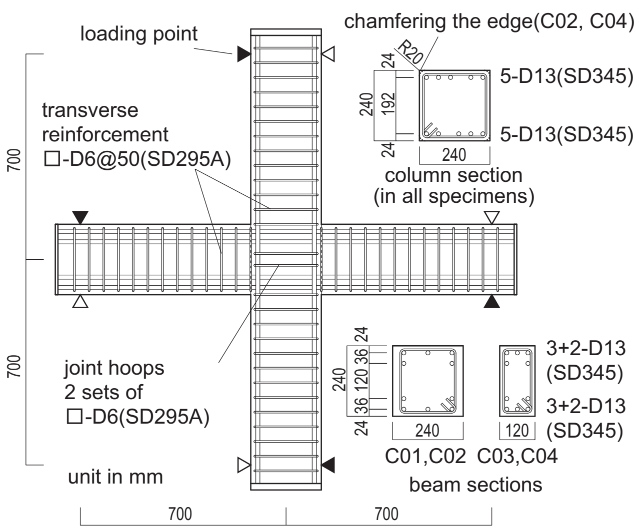


Figure 3. Geometry and reinforcing detail of the specimens

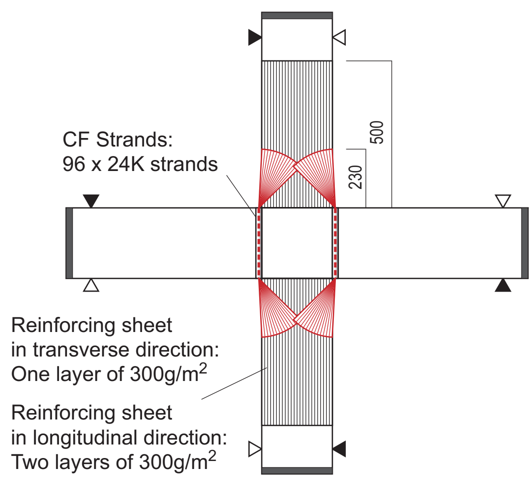


Figure 4. Retrofitting detail

Loading Method

Figure 5 shows the loading setup and the instrumentation of story drift. The specimens are connected to the steel loading frame with PC bars. The lateral load was applied with a horizontal oil jack to a horizontal loading beam supported by two loading columns with pin joints at the both ends. By the loading setup, the lateral deformation in a moment resisting frame is forced to occur in the specimens. The story shear is measured by load cells which monitor tensile forces in the PC bars.

Statically reversed cyclic load with increasing amplitude was applied simulating earthquake load. The loading history is shown in Figure 6. The maximum story drift ratio of the control specimens are 3.0% while the maximum story drift ration of the strengthened specimens are 4.0%. No axial force is applied to the column.

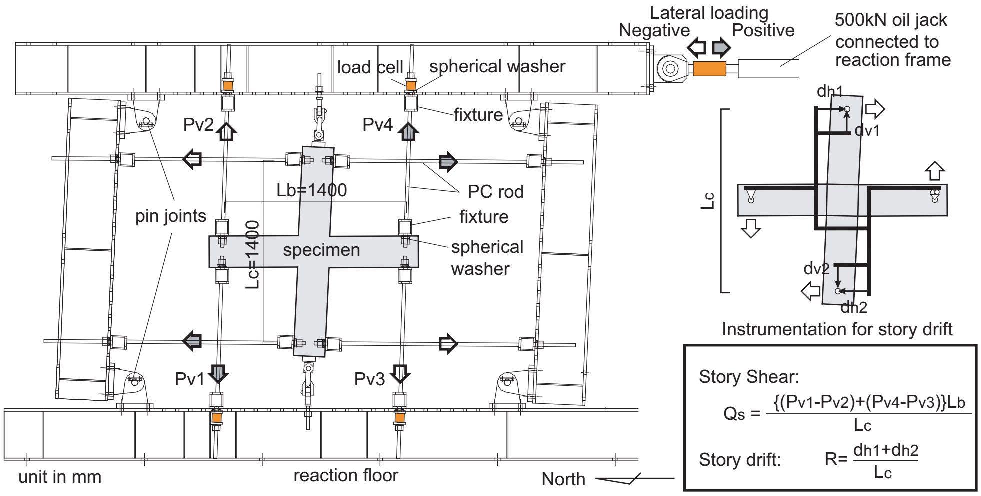


Figure 5. Loading set up and instrumentation for story drift

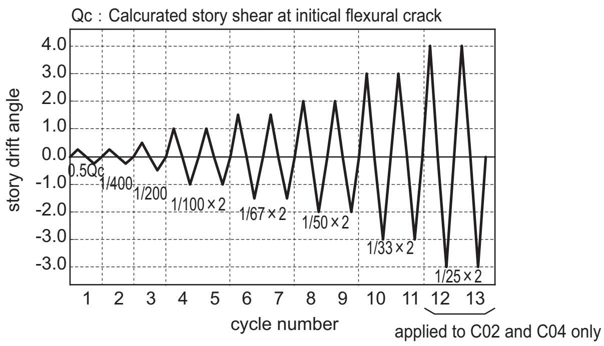


Figure 6. Loading pattern

Test Results

Development of cracks

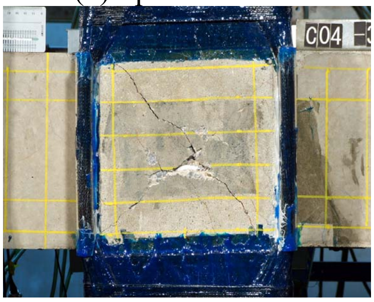
Photo 1 shows the failure pattern observed at the end of the cycles with story drift ratio of 3.0%. In all the specimens, diagonal cracking at two corners of the joint panels were observed at the load cycle of 0.25% story drift ratio. Then diagonal cracking at the center of joints were observed at the same load cycle except the control specimen C03 with small beam width. The diagonal cracking of specimen C03 started at story drift ratio of 0.5%.

In all the specimens, the concrete spalling at the center of the joints were negligible at story drift of 2.0% and became distinct at story drift of 3.0%

(a) Specimen C01

(b) Specimen C02

(c) Specimen C03



(d) Specimen C04

Photo 1. Failure pattern of the specimens at the cycle of 3% story drift ratio

Story shear-story drift relationship

Figure 7 shows the story shear-story drift ratio relationships. Table 2 lists the observed strengths and deformations at major events including initial cracking, yielding of longitudinal steel, yielding of joint hoops and maximum story shear. The calculated story shear are compared in Figure 7. The calculations are by the flexural theory using mechanical properties of materials.

In the control specimens C01 and C03, yielding of joint hoops were observed at story drift ratio of 1.0% to 1.5%. The yielding of the longitudinal bars in both beams and columns were observed and the maximum story shear were attained at story drift of 1.5% to 2.0%. The maximum story shear of the control specimens C01 and C03 are 8% and 12% smaller than their calculated story shear respectively.

The retrofitted specimens C02 and C04 show larger stiffness after joint concrete cracking than the control specimens. The story shear at yielding of joint hoops and longitudinal bars in beams were almost identical to those of the control specimens, while the story drift at the yielding were smaller than the control specimens. No yielding of longitudinal bars in columns was observed in the strengthened specimens.

The maximum story shear of the retrofitted specimens C02 and C04 attained or exceeded the calculated story shear. They are 6% and 13% larger than that of the control specimens respectively. The story drift ratio at the maximum story shear is 3% except in negative loading in specimen C02, which are larger than that of the control specimens.

In all the specimens, the shape of the hysteresis loop is thin and slipping with little energy dissipating capability. One of the reasons of the pinched loops should be no axial load on the columns. With axial load on the columns, the regions of slipping on the hysteresis loops would be short due to the vertical confinement by axial load. The improvement of the hysteresis loops due to the retrofit is little.

Figure 8 compares the equivalent viscous damping ratio obtained from the story shear-story drift relations. The values of the equivalent viscous damping of the retrofitted specimens of the first cycles are similar to those of the control specimens while those of second cycle at the same story drift amplitude are improved to around 1.3 times of those of the control specimens.

Table 2. Story shear and story drift observed in the tests

Specimen		**C01**		**C02**		**C03**		**C04**	
Direction		P	N	P	N	P	N	P	N
Cracking	diagonally at a joint corner	10.4 0.05	-6.6 0.02	7.6 0.03	-10.6 -0.01	7.3 0.05	-4.3 0.02	6.1 0.03	-3.4 0.03
	at a column end	11.7 0.07	-8.8 -0.01	—		14.4 0.14	-7.2 -0.02	—	
	diagonally at the center of joint	24.5 0.25	-14.9 -0.10	14.1 0.08	-12.6 -0.04	15.2 0.19	-27.1 -0.36	16.9 0.14	-15.0 -0.10
Yielding	Beam longitudinal bar in the first layer	62.5 1.00	-61.4 -0.95	67.5 1.00	-62.4 -0.80	61.4 1.41	-59.8 -1.30	61.5 1.16	-58.9 -0.95
	Beam longitudinal bar in the second layer	72.0 1.30	-68.6 -1.25	73.0 1.21	-70.6 -1.00	63.1 1.75	-62.0 -1.71	67.3 1.35	-68.0 -1.31
	Column longitudinal bar	72.0 1.30	-64.0 -1.15	75.5 1.71	-75.1 -1.92	57.7 1.30	-56.8 -1.20	55.1 2.60	-67.7 -2.33
	Joint hoop	57.8 0.90		-56.7 -0.70		-49.4 -0.90		48.7 0.76	
Maximum story shear		75.3 1.50	-73.4 -1.50	80.5 2.92	-77.8 -1.53	67.4 2.00	-65.8 -2.01	76.4 3.01	-74.2 -3.01

upper row : story shear in kN, lower row : story drift ratio in percent

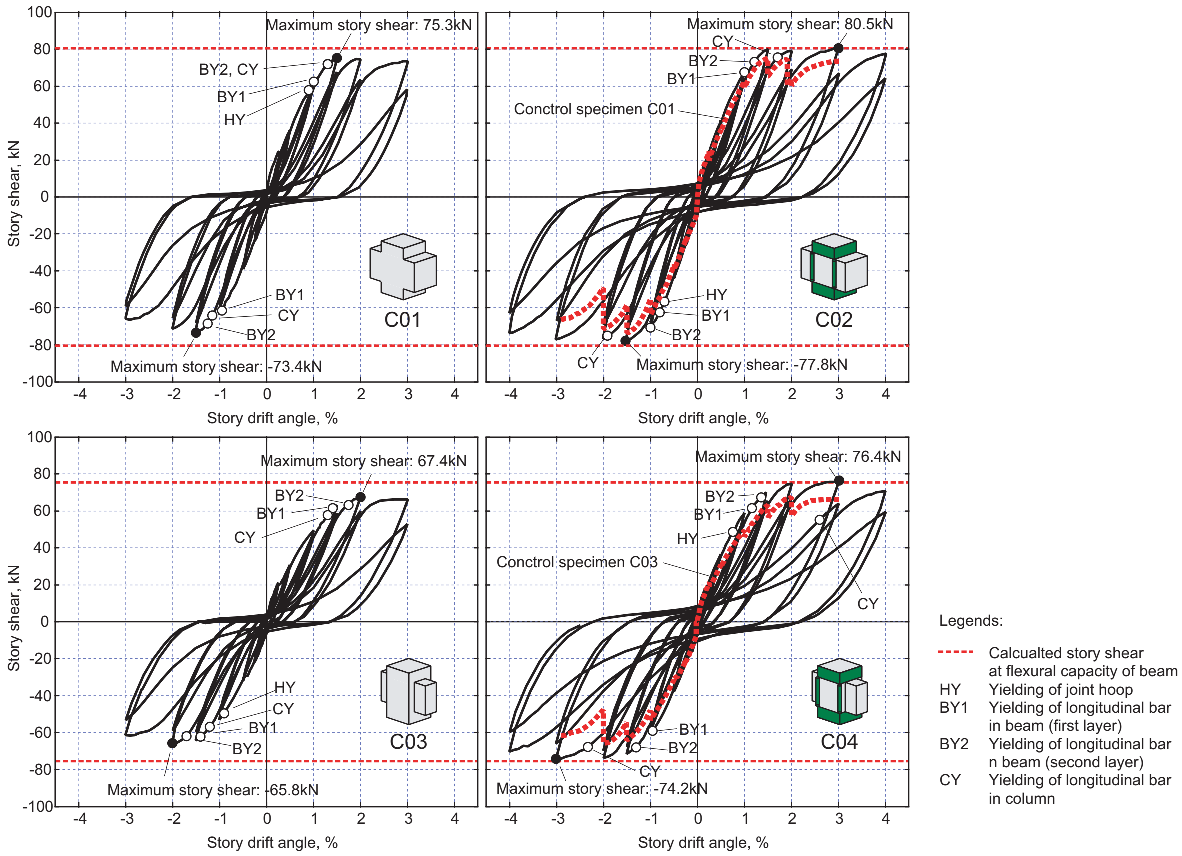


Figure 7. Story shear - story drift relationships

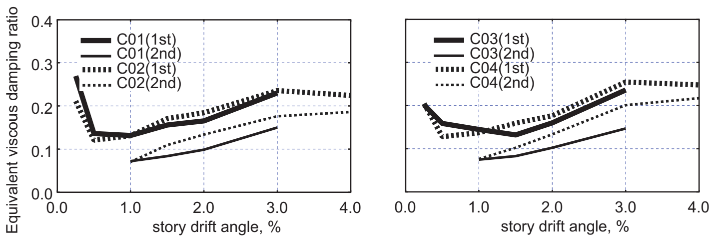


Figure 8. Equivalent viscous damping

Subcomponents of deformation

Figure 9 shows the subcomponents of story drift (Kusuhara 2006) observed in the tests of Specimen C01 and C02. The story drift were divided into deformations due to the chord rotations of beams and columns, the rigid-body-rotations of beams and columns, the joint shear deformation and the rotations of triangular segments of beams-column joint panels.

In retrofitted specimen C02, subcomponents due to the chord rotations and the rigid rotations of columns decreased compared with the results of control specimen C01. Moreover, subcomponents due to joint shear deformation and the rotations of triangular segments were reduced. And on the one hand, the subcomponents due to the chord rotations and the rigid rotations of beams increased. That shows that the retrofitting method made the joint failure alter to a beam-hinging mechanism. However, the dominant component was joint deformation including the joint shear deformation and the rotations of triangular segments of joint panel even in retrofitted specimen C02.

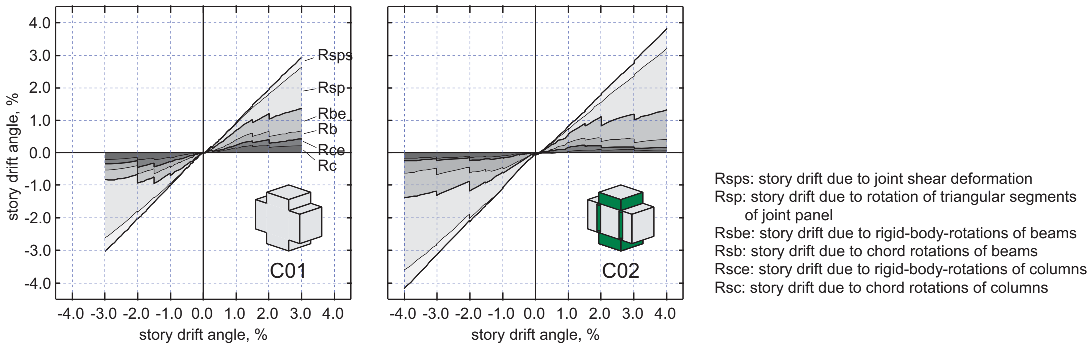


Figure 9. Subcomponents of story drift

Conclusions

A new seismic retrofitting method with CFRP composite is proposed for improvement of the story shear capacity to the value calculated based on the flexural strength of beam sections. The effectiveness of the method was investigated by the lateral loading tests of two pairs of interior beam-column joint specimens with and without the retrofit. The ratio of joint shear input to nominal joint shear capacity of the control specimens were 0.9 and 1.2 respectively and the control specimens showed joint failure accompanied by yielding of longitudinal bars in beams and columns passing through the joints. Their original maximum story shears without the retrofit were from 88 to 92 % of the story shear calculated based on flexural capacity of the beam sections.

From the comparison of the specimens with and without retrofit, preliminary conclusions are derived that,

(1) The maximum story shear increased by 6 to 13 % by the retrofit and attained the calculated values based on the flexural theory of the beam section,
(2) A little improvement of the shape of the hysteresis loop is observed,
(3) The yield stiffness increased by 8 to 22 % due to the retrofit and,
(4) No significant effect to reduce the damage to the joint concrete is obtained due to the retrofit.

It is revealed that the seismic retrofit of the beam-column joint shown here is an effective and practical seismic retrofit of critical beam-column joints. The further investigation on the development of the scope of this retrofitting method is necessary. Development of a mechanical model quantifying the performance of reinforced concrete beam-column joint as well as the effect of the additional mechanical elements improving the performance is necessary toward a more rational performance evaluation and design for seismic retrofit.

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