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Seismic Shear Strengthening for Short Columns

Renforcement de colonnes endommagées par rupture fragile lors de séismes

Verstärkungtechniken für Stützen unter Erdbebenbeanspruchung

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SUMMARY

To develop an effective method for strengthening the existing reinforced concrete short columns which are expected to fail in brittle shear mode during several earthquakes, experimental studies have been conducted. Test results demonstrate that, if the short column is strengthened by a welded steel square tube, then brittle shear failure does not occur and the colunm can develop its ultimate flexural moment capacity. The proposed method is also applicable for repair and rehabilitation of damaged short columns failed in shear mode during severe earthquakes.

RÉSUMÉ

Afin de développer une méthode judicieuse pour le renforcement des colonnes en béton armé faiblement élancées, lesquelles risquent, durant quelques séismes, une destruction par rupture fragile, des études expérimentales on été conduites. Les résultats ont montrés que les ruptures fragiles peuvent être évitées lorsque les colonnes courtes sont renforcées à l'aide d'un tube rectangulaire en acier soudé. Dès lors, la colonne peut développer sa pleine capacité de résistance vis-à-vis des moments de flexion. La méthode proposée est applicable pour la réparation et pour la réadaptation des colonnes faiblement élancées, dont les dommages furent causés par une rupture fragile liée à l'action de séismes.

ZUSAMMENFASSUNG

Zur Entwicklung wirksamer Verstärkungstechniken für kurze Stützen, welche unter Erdbebenbeanspruchung ein sprödes Schubversagen aufweisen, wurden experimentelle Untersuchungen durchgeführt. Die Resultate zeigen, dass mit einer Umhüllung aus Stahlblech kein sprödes Versagen auftritt und der volle Biegewiderstand entwickelt werden kann. Die Methode eignet sich auch zur Instandstellung erdbebengeschädigter kurzer Stützen.

1. INTRODUCTION

Numerous examples of shear failures in reinforced concrete (R/C) short columns have been reported during recent earthquakes in Japan and other earthquake countries. In Japan a new design code provisions for R/C columns was proposed in 1970 in order to prevent the short columns from brittle shear failures. On the contrary, a large number of R/C building structures having short columns which were designed in accordance with the old design provisions are still in use throughout the country. Preliminary analysis by authors indicates that most of those old short columns and some of the new short columns, especially in school buildings, are expected to fail in brittle shear failure modes during strong earthquakes. Therefore, it is one of the important engineering problems to be solved to develop an effective method for strengthening, repair and rehabilitation of those existing structural members at minimum cost. Herein, seismic shear strengthening, repair and rehabilitation methods by using steel plates are proposed to improve the seismic behavior of R/C short columns in the existing building structures practically, easily and inexpensively.

2. SPECIMENS

Test specimens adopted in the present study are 1/3-scale models of 1.5-story beam-column subassemblage belonging to lower levels of 4-story R/C school buildings. Overall dimensions of a typical subassemblage (Specimen CE) are shown in Fig.1 together with cross-sectional details of the first-story short column and spandrel beams of test specimens of Group E in Table 1. Shear-span-to-depth ratio of the first-story short column is 1.0 for all of the specimens. Nine different specimens tested are listed in Table 1, where expected failure modes determined by theory are also schematically illustrated. Each of the test specimen is classified into three groups; Group E (Existing), Group S (Strengthening) and Group R (Repair and Rehabilitation) as shown in Table 1. Specimens CE and BE in Group E are model subassemblages of two existing R/C school buildings which were designed and constructed in accordance with the current aseismic design provisions in Japan. Both of the specimens have the same cross-sectional details in their short columns, where area of longitudinal reinforcement is p_g=2.50 percent of gross area of the column section and shear reinforcement ratio is p_w=0.33 percent. Only difference in details between two specimens is total amount of longitudinal reinforcement in the spandrel beams.

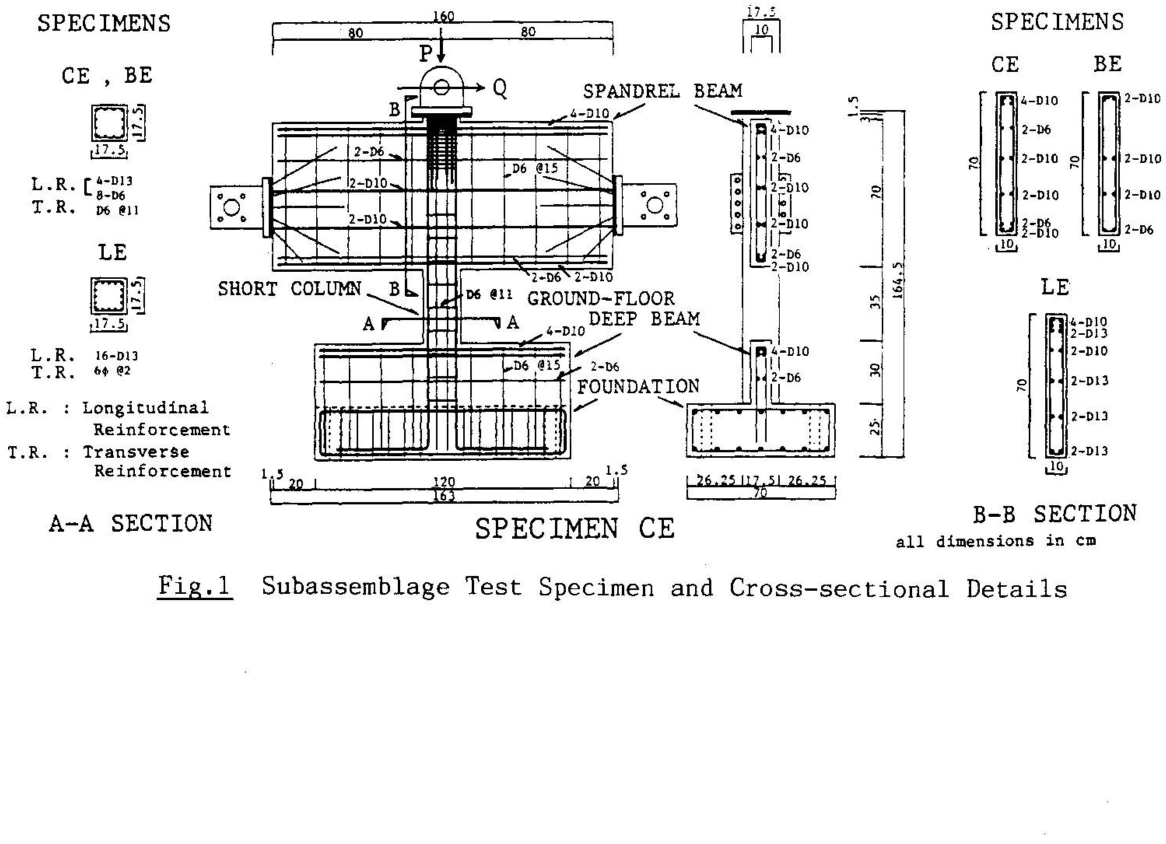

Fig.1 Subassemblage Test Specimen and Cross-sectional Details

In addition to these two specimens, Specimen LE was constructed to investigate validity of a repair and rehabilitation method proposed in this paper. In Specimen LE, quite large amount of longitudinal and shear reinforcements are provided in its short column, that is, p_g=6.64 percent and p_w=1.64 percent respectively. According to a preliminary analysis against severe earthquakes, both of the first-story columns of Specimens CE and BE had been expected to fail in brittle shear mode. In order to prevent these short-columns from shear failure during strong motion earthquakes, same specimens with the test Specimens CE and BE in Group E were constructed, and their first-story short columns were strengthened by a welded steel square tube, which are designated as Specimens CE-S and BE-S respectively. Since all of the tested short columns of the three specimens in Group E had failed in brittle shear modes and had not been able to develop their ultimate flexural moment capacities, damaged first-story short columns were repaired and rehabilitated also by using a welded steel square tube in order to recover the lost seismic capacity. The name of these specimens repaired has a letter "R" after the specimen number in Group E, such as CE-R and BE-R as shown in Table 1.

	Test Group					
	E (Existing)		S (Strengthening)		R (Repair and Rehabilitation)	
Specimen Number and Expected Failure Mode	CE	8.2 SF	CE-S	13.1 FF	CE-R	?
	BE	8.9 SF	BE-S	12.2 FF	BE-R	?
	LE	13.3 SF	LE-S	24.9 FF	LE-R	?

SF : Shear Failure in First-story Short Column
FF : Flexural Failure
○ : Location of Plastic Flexural Hinge

all dimensions in 10^4 N

Table 1 List of Test Specimens and Expected Failure Modes

3. STRENGTHENING METHOD (TEST GROUP S)

Strengthening method and procedure provided into first-story short columns in the test Group S is in the following:
(1) Machine a flat mild-steel plate into L-shape plate by using a press-machine. Steel plates used are 6 mm in thickness. (2) Weld each corner of faced two L-shape plates to form a square tubular section as shown in Fig.2. Clearance between steel tube and short column surface is approximately 5 mm. (3) After fixing the steel tube by spacers, top and bottom of the welded steel tube were sealed by inorganic sealer allowing no liquid leakage, and at the same time, aluminium pipes with 10 mm diameter were buried in the top and bottom sealing materials. (4) By using the bottom aluminium pipes, inject epoxy-based polymer cement under pressure into the clearance between steel tube and R/C column surfaces. Role of the top aluminium pipes is to exhaust the air from the clearance during injection of polymer cement. (5) After curing, cut off the inorganic sealer at top and bottom of the strengthened short column. This is to make the steel tube not to carry longitudinal stresses but only to carry transverse stresses during lateral loading reversals. Compressive strength of the polymer cement injected was 28.5 MPa at the time of experiment. Provided that shear failure does not occur in those strengthened short columns during lateral loading reversals, failure mechanism at their ultimate state of the Specimens CE-S and BE-S become ductile flexure modes, that is, column mechanism in CE-S and beam mechanism in BE-S respectively as shown in Table 1.

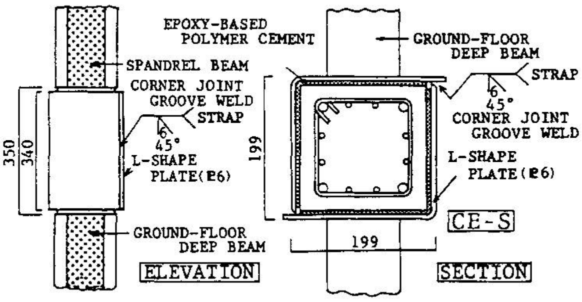

Fig.2 Details of Strengthened Short Column

4. REPAIR AND REHABILITATION METHOD (TEST GROUP R)

Repair and rehabilitation technique provided into damaged short columns in the test Group E is as follows (see Fig.3): (1) Remove residual interstory displacement occurred in the first-story short column. (2) Cut off cracked cover concrete around core of each short column. (3) Surround the naked short column with a welded steel square tube as mentioned in the strengthening method in the test Group S. (4) After sealing bottom of the steel tube by inorganic sealer and burying aluminium pipes in the sealer, put round coarse aggregate into clearance between steel tube and concrete core of the short column. Maximum size of the coarse aggregate is 10 mm in diameter. (5) Seal the top of steel tube and also bury the aluminium exhaust pipes. (6) Inject epoxy-based polymer cement under pressure from the bottom pipes. (7) After curing the polymer cement more than two-weeks, cut off the top and bottom sealer. Compressive strength of the polymer concrete was 25.3 MPa at the time of experiment. (8) By using epoxy resin adhesive (epoxy-based putty adhesive), repair and recover the cracked and lost sections in cover concrete near the top and bottom of short column (see Fig.3).

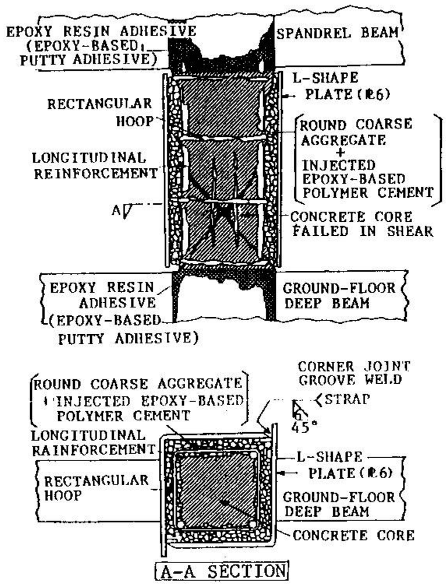

Fig.3 Details of Repaired Short Column

5. EXPERIMENTAL TEST-SETUP AND PROCEDURE

All of the specimens were tested by using a test setup shown in Fig.4, in which all of boundary conditions required in testing such types of the cruciform beam-column subassemblages as shown in Fig.1 are taken into consideration. Details of this test setup are discussed in Ref.1. Axial load to the column and alternately repeated lateral forces were applied at mid height of a second-story short column by using hydraulic jacks 1 and 2 in Fig.4. Since vertical reactions and displacements at left and right supports of the spandrel beam should be always kept equal respectively, "VERTICAL REACTION AND DISPLACEMENT EQUALIZER" is installed, and by using "MOMENT AND ROTATION EQUALIZER", bending moments and rotation angles at the left and right beam supports can be equalized, respectively. All of the tests except for Specimens, CE-S and CE-R, were conducted under a constant gravity load: $P/(A_c f_c) = 0.1$, where P, A_c and f_c are axial load, gross-area of column and compressive strength of concrete in each specimen, respectively. Value of the applied gravity load is a corresponding value of axial load to which first-story columns of low- and medium-rise school buildings are

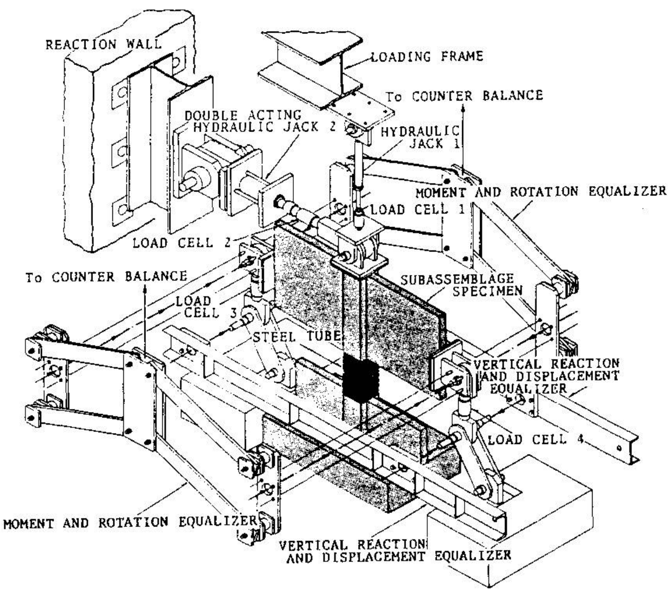

Fig.4 Experimental Test-Setup

subjected. In the Specimens, CE-S and CE-R, initial values of column axial load, $P/(A_c f_c) = 0.1$, varied and increased to about 0.2 at larger lateral displacements because of elongation of short columns due to cracking (refer to Figs.6(a) and 7(a)). Displacement-controlled procedure was adopted for loading program and lateral displacement amplitude of each loading cycle was gradually increased.

6. EXPERIMENTAL RESULTS

Applied lateral-load,(Q) versus interstory displacement,(Δ) relations observed in all the specimens are shown in Figs.5, 6 and 7. Fig.5 shows that all test specimens in Group E failed in brittle shear mode when interstory displacements in the first-story was not larger than 0.5 % rad., and these specimens were not able to develop their ultimate flexural moment capacities, which are determined by a theory and are shown by solid lines parallel to a horizontal axis in each figure. On the contrary, specimens in Group S whose short columns were strengthened by a steel square tube did not fail in brittle shear mode but were able to reach to ductile flexure mechanism showing their ultimate moment capacities as shown in Fig.6.

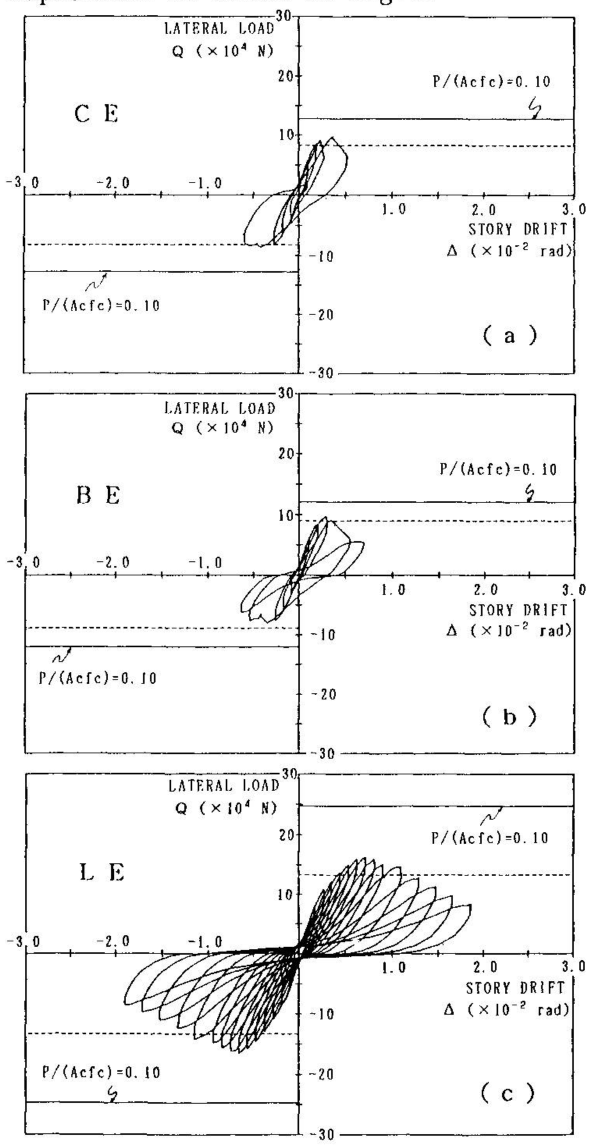

Fig.5 Q-Δ Relations (Group E)

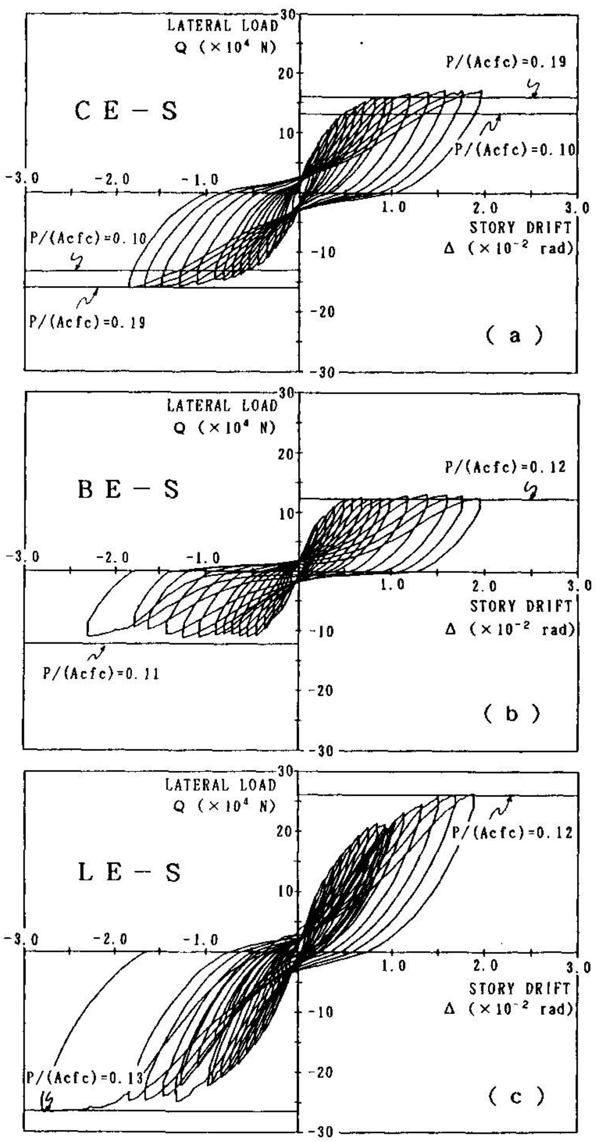

Fig.6 Q-Δ Relations (Group S)

It is worthy of note that, by repairing and rehabilitating the damaged short columns in Group E specimens by a welded steel square tube, repaired specimens (Group R) did no longer fail in brittle shear mode and showed large ductility. Although the short column in Specimen, LE-R, could not develop its ultimate flexural moment capacity, it was able to show excellent and ductile deformability as shown in Fig.7(c). Main reason to this cause is by a local bond deterioration occurred in the longitudinal reinforcement bars at top and bottom of the short column. In addition, these repaired specimens, except for Specimen, LE-R, were able to develop their ultimate flexural moment capacities as can been seen in Figs.7(a) and (b), and furthermore, these repaired specimens showed very close load-carrying capacities to the strengthened specimens shown in Figs.6(a) and (b), respectively. As the result, it may be concluded that the proposed strengthening, and/or repair and rehabilitation method by a steel tube is quite effective to improve the seismic behavior of R/C short columns which are expected to fail or damaged in brittle shear mode during severe earthquakes.

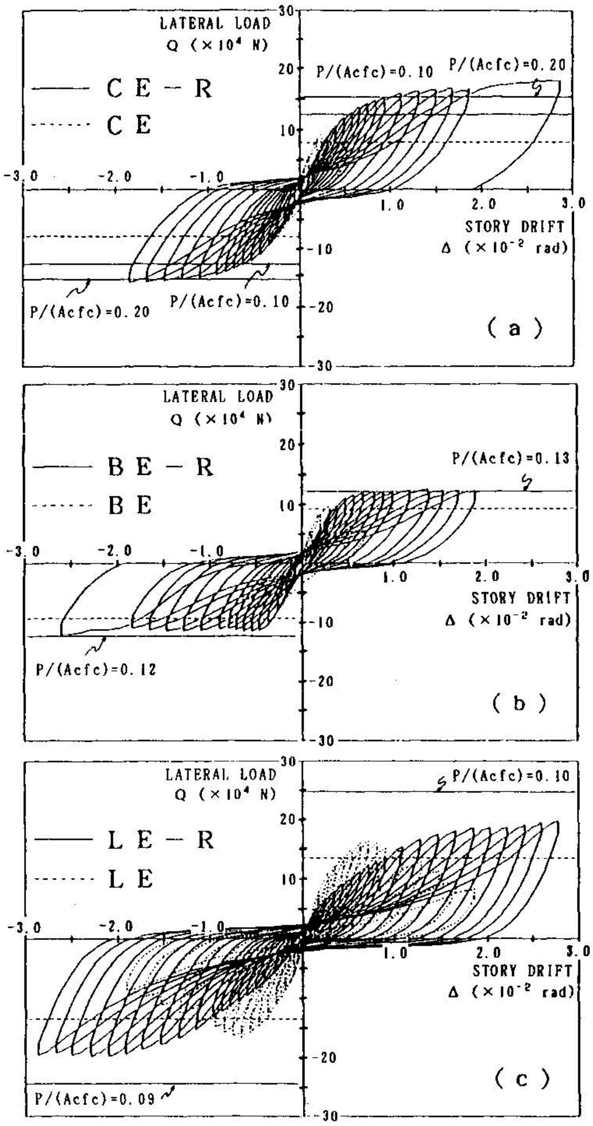

Fig.7 Q-Δ Relations (Group R)

7. CONCLUSIONS

By using a welded steel square tube, strengthening method for R/C short columns which are expected to fail in brittle shear mode was proposed, and validity of the proposed method to improve the seismic behavior of R/C short columns in existing building structures was verified by the experiment. In addition, this reinforcing method by using steel plates is also applicable to repair and rehabilitate the damaged short columns during strong motion earthquakes. This method proposed is quite practical because of being effective, inexpensive and very easy.

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