Seismic Performance Evaluation for Retrofitting Steel Brace of Existing RC Building with Low-Strength Concrete

Mitsuyoshi ISHIMURA
Ishimura Architects and Engineering, Japan

Kazushi SADASUE
Hiroshima Institute of Technology, Japan

Yasuyoshi MIYAUCHI
Takenaka Corporation, Japan

Tsuyoshi YOKOYAMA
Constec Engineering, Japan

Toshiki FUJII & Koichi MINAMI
Fukuyama Univercity, Japan

SUMMARY
There is a widely used method where existing RC buildings are provided with earthquake-resistance reinforcement using steel braces with frameworks, but this method has not been adequately verified for buildings whose concrete compressive strength is below 13.5 N/mm^2. In this research, a component experiment to investigate the shear strength of joints, and a loading experiment to investigate the ultimate strength and toughness of the reinforced frame, were conducted for the method where steel brace reinforcement is provided by joining the existing building frame and steel framework using a combination of post-installed anchors and epoxy resin adhesive. As a result, ultimate strength was confirmed using previous proof strength evaluation methods, and tenacity of the frame after reinforcement was clarified. It was shown that improvement in earthquake-resistance can be achieved, even for buildings with low-strength concrete, by joining the existing building frame and the steel framework using these techniques.

Keywords: Earthquake-resistance reinforcement, steel brace, post-installed anchor, epoxy resin, joint component experiment, building frame experiment

1. INTRODUCTION

One method of earthquake-resistant reinforcement for existing, disqualified reinforced concrete (RC) buildings is the method shown in Photo 1.1. where the proof strength and toughness of the building are improved by mounting steel braces with frameworks inside the frame of columns and beams comprised of RC members. A design method for earthquake-resistant retrofitting using this reinforcement method has been presented in the Earthquake-resistant Retrofitting Design Guidelines for Existing RC Buildings by the Japan Building Disaster Prevention Association (referred to below as the "Earthquake-resistant Retrofitting Design Guidelines"), with the condition that the concrete compressive strength σB must be 13.5 N/mm^2 or more. However, there are many buildings for which σB is less than 13.5 N/mm^2, and since these are outside the scope of the Earthquake-resistant Retrofitting Design Guidelines, almost no earthquake-resistant retrofitting of these buildings is being done at present.
The Earthquake-resistant Retrofitting Design Guidelines present a method using post-installed anchors (referred to below as the "post-installed anchor method") as the typical method for joining the steel brace framework to the existing RC frame. Furthermore, various methods have been proposed to reduce noise and vibration during work and shorten the construction period, such as a method using epoxy resin (referred to below as the "adhesive method") and a method using post-installed anchors and epoxy resins in combination (referred to below as the "anchor + adhesive method"). However, design documentation is not available with any of these methods for low-strength concrete with a

compressive strength less than 13.5 N/mm^2, and the only case where work has been done on the adhesive-type post-installed anchor method is the experimental research by Yamamoto et al.
Therefore, in this research, reinforcement effectiveness was verified by conducting component experiments and building frame experiments for the 3 methods: post-installed anchor method, adhesive method and anchor + adhesive method (see Figure 1.1.). The experiment for the anchor + adhesive method only was conducted separately, and thus there are some differences in factors such as strength of the material used.

Photo1.1. Steel brace reinforcement of existing RC frame (during installation)

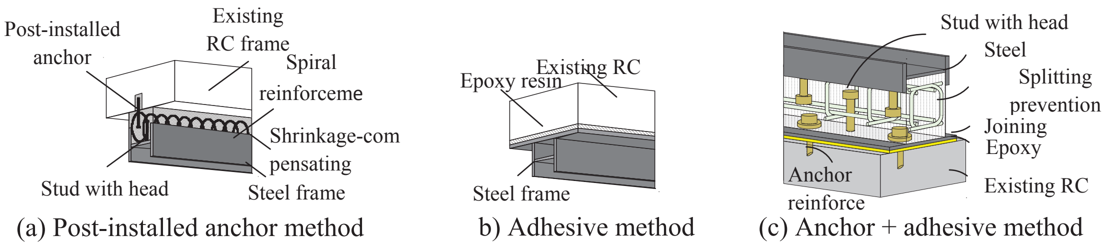


Figure 1.1. Joints between steel brace framework and RC frame

2. JOINT COMPONENT EXPERIMENTS

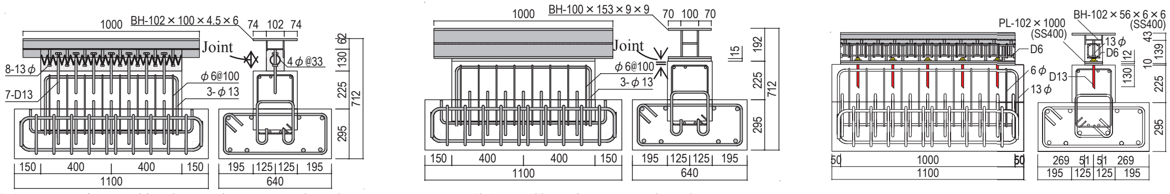
With the post-installed anchor method in Figure 1.1.(a), post-installed anchors are driven into columns and beams, and after placing spiral reinforcement, the joint is filled with shrinkage-compensating mortar, and then the existing RC frame is integrated with the steel brace with framework (to which studs are welded). With the adhesive method in Figure 1.1.(b), the steel brace framework is adhesively joined to columns and beams using epoxy resin, and with the anchor + adhesive method in Figure 1.1.(c), a combination of anchor reinforcement and adhesive (epoxy resin) is used. For this section, experiments were conducted to confirm shear strength of these three types of joining methods. The test pieces have the same structural details as the member form, reinforcement arrangement and joining method of the test pieces for the building frame experiments using in the next section.

2.1. Experiment plan

Figure 2.1. shows the test piece form for each method; Table 2.1. shows the test piece plan; Table 2.2. shows the material test results for concrete etc.; and Table 2.3. shows the material test results for steel. Two test pieces each were fabricated for the post-installed anchor method and adhesive method, and the presence of tensile force acting on the joint was taken to be the experimental variable. For the anchor + adhesive method, the spacing between anchor reinforcements was taken to be the experimental variable, and a total of 9 test pieces were fabricated, with 3 copies of each test piece. The part corresponding to the existing RC frame was mix designed taking the concrete design standard strength FC to be 9 N/mm^2.

2.2. Loading system and displacement measurement

The system equipped with a parallel holding unit shown in Figure 2.2. was used for loading. Hydraulic jacks were aligned with the position of the joint, and a reverse cycling shear force Q was applied in a state where a bending moment does not act. Reverse cycling incremental loading was performed while performing displacement control of the relative shift displacement j δs of the steel frame part with respect to the existing building frame. Figure 2.3. shows the method of measuring displacement for the anchor + adhesive method.



(a) Post-installed anchor method

(b) Adhesive method

Anchor reinforcement spacing 200
(c) Anchor + adhesive joint method

Figure 2.1. Test piece form (units: mm)

Table 2.1. Test piece plan

Test piece name	Loading method	Joint method
AT00	Pure shear	Post-installed anchor method
AT10	Tension + shear	
BT00	Pure shear	Adhesive method
BT10	Tension + shear	
H21	Pure shear	Post-installed anchor method Anchor spacing 200 mm
H31	Pure shear	Post-installed anchor method Anchor spacing 300 mm
H61	Pure shear	Post-installed anchor method Anchor spacing 600 mm

Table 2.2. Concrete material strength

Use point	Compressive strength (N/mm^2)	Tensile strength (N/mm^2)	Remark
Concrete	8.58	0.94	Post-installed anchor method Adhesive method
	8.15	1.02	Anchor + adhesive method
Shrinkage-compensating mortar	57.3	2.57	Post-installed anchor method
	54.6	4.79	Anchor + adhesive method
Epoxy resin	79.1	60.2	Adhesive method
	91.1	56.9	Anchor + adhesive method

Table 2.3. Steel material strength

Use point	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
D13 anchor reinforcement	370(341)	504(501)	23.7(17.0)
13φ stud	352(332)	478(481)	35.6(36.7)
4φ spiral reinforcement	657	852	41.3
13φ beam main reinforcement	323(345)	470(422)	31.2(30.1)
6φ beam stirrup reinforcement	621(354)	657(525)	9.8(14.4)
D6 splitting prevention reinforcemer	(325)	(553)	(12.5)

Parentheses indicate the anchor + adhesive method case

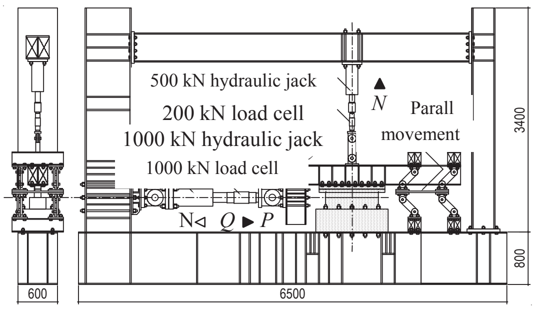


Figure 2.2. Loading system for joint component experiment (units: mm)

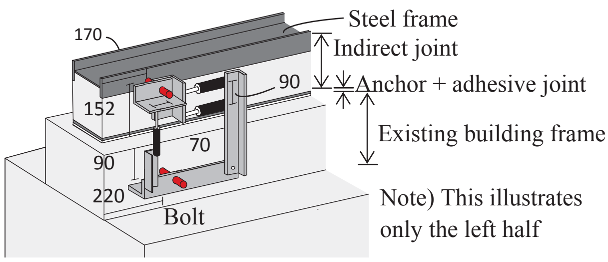


Figure 2.3. Displacement measurement (units: mm)

2.3. Hysteresis curves

Figure 2.4. shows hysteresis curves in which in the vertical axis is taken to be the shear force Q acting on the joint, and the horizontal axis is taken to be the relative shift displacement δu between the RC beam part and the steel framework.

2.4. Evaluation of sheer strength

(1) Post-installed anchor method

The shear strength $_aQ_u$ of the joint with the adhesive type post-installed anchor method is given by Equation (3) and Equations (4.a and 4.b) in the Earthquake-resistant Retrofitting Design Guidelines.

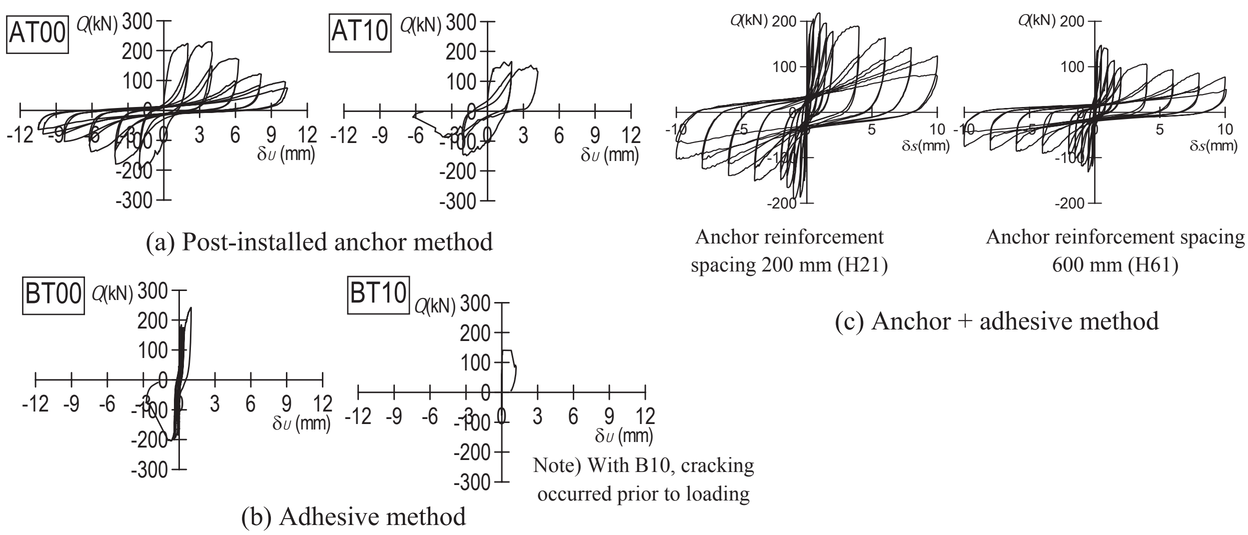


Figure 2.4. Load-deformation relationship

$$_aQ_u = \min\left({}_aQ_{u1},\ {}_aQ_{u2}\right) \tag{3}$$

$$_aQ_{u1} = 0.7\,{}_a\sigma_y \times {}_aa_e \quad \text{(case determined by shear strength of anchor reinforcement)} \tag{4.a}$$

$$_aQ_{u2} = 0.4\sqrt{E_c \cdot \sigma_B} \times {}_aa_e \quad \text{(case determined by bearing pressure of concrete)} \tag{4.b}$$

$$_aQ_u = \tau_{mg} \cdot {}_aa_e \cdot {}_an \tag{5}$$

$$\tau_{mg} = (0.0602 + 0.019\,\sigma_B) \cdot {}_a\sigma_y \cdot \varphi_1 \cdot \varphi_2 \cdot \varphi_3 \tag{6}$$

$$\varphi_1 = 0.84 - 0.05(d_a - 22) \tag{7.a}$$

$$\varphi_2 = 0.85(c/100)^{0.15} \ \text{(here, } \varphi_2 \leqq 1.0\text{)} \tag{7.b}$$

$$\varphi_3 = 1.0 \ \text{(=1.15 if } l_e = 10d_a\text{)} \tag{7.c}$$

Here, aσy is the yield strength of the anchor reinforcement (N/mm^2); aae is the cross-sectional area of the anchor reinforcement (mm^2); and Ec is the Young's modulus of the concrete (N/mm^2)
However, Equation (3) only applies in cases where the concrete compressive strength is 13.5 N/mm^2 or more, and thus the following equations (5) to (7.a, 7.b and 7.c) have been proposed4) to include low-strength concrete (5-15 N/mm^2) of less than 13.5 N/mm^2.
Here,. *da* and *le* are the anchor reinforcement diameter and embedding length, and c is the edge distance dimension. In all cases the units are mm.

(2) Adhesive method
Equation (8) has been proposed for the shear strength bQu of the joint in the adhesive method using epoxy resin. Shear failure of the joint with the adhesive method does not involve failure at the epoxy resin part. It is believed that cohesion failure occurs at the concrete part, and derivation is done using the following equation, based on the tensile strength of concrete.

$$_bQ_u = 0.31\sqrt{\sigma_B} \times {}_bA \tag{8}$$

(3) Anchor + adhesive method
The following equations are provided in related guidelines for evaluating the shear strength jQbu of the anchor + adhesive joint and the shear strength jQsu of the indirect joint, assuming that σB of the existing building frame is 15 N/mm2 or more. Shear strength of the joint is determined by the failure of the part with the smallest shear strength, either the anchor + adhesive joint, or the indirect joint. In this research, the intent is to conduct verification for low-strength concrete, and thus design is carried out so that jQbu＜jQsu.

$$jQbu = 0.08 \cdot \sigma B \cdot Ab + \tau ay \cdot \Sigma aa \tag{9}$$

$$\tau ay = \min(\tau ay1,\ \tau ay2) \tag{10}$$

$$\tau ay1 = 0.5 \cdot \sigma ay \tag{11.a}$$

$\tau ay2 = 0.3 \cdot \sqrt{\sigma B} \cdot Ec1$ (11.b)

Here, σB is the compressive strength of the concrete of the existing building frame; Ab is the epoxy resin adhesion area; Σaa is the total sum of the cross-sectional areas of anchor reinforcement; σay is the yield strength of anchor reinforcement; and Ec1 is the Young's modulus of the concrete of the existing building frame.

2.5. Comparison of experimental and calculated values of shear strength

The maximum values of shear force for each test piece, and the calculated values of shear strength using Equations (3), (5), (8) and (9), are shown in Table 2.4..
Equations (3), (5) and (8) do not take into account the effects of tensile force acting on the joint, and thus the calculated value of shear strength becomes a fixed value, regardless of the existence of tensile force, but in the range of tensile force in this experiment, it was confirmed that the calculated values are evaluated on the safe side regardless of the existence of tensile force.
The calculated value of shear strength for the anchor + adhesive method, obtained using Equation (9), is at or below the shear strength obtained by experiment for all test pieces, and furthermore, a trend was confirmed whereby the greater the number of anchor reinforcements a test piece has, the more the evaluation is on the safe side.

Table 2.4. Experimental and calculated values

Test piece	Tensile force (kN)	Experimental value (kN)	Calculated value（kN）			
			Equation (3)	Equation (5)	Equation (8)	Equation (9)
AT00	0	230	132	95.5	-	-
AT10	75	166	132	85.5	-	-
BT00	0	242	-	-	174	-
BT10	55	-	-	-	174	-
H21～H23	0	204	-	-	-	135.0
H31～H33	0	153	-	-	-	107.0
H61～H63	0	129	-	-	-	94

Note) With BT00, cracking occurred prior to loading, and thus it was eliminated as a subject of comparison.

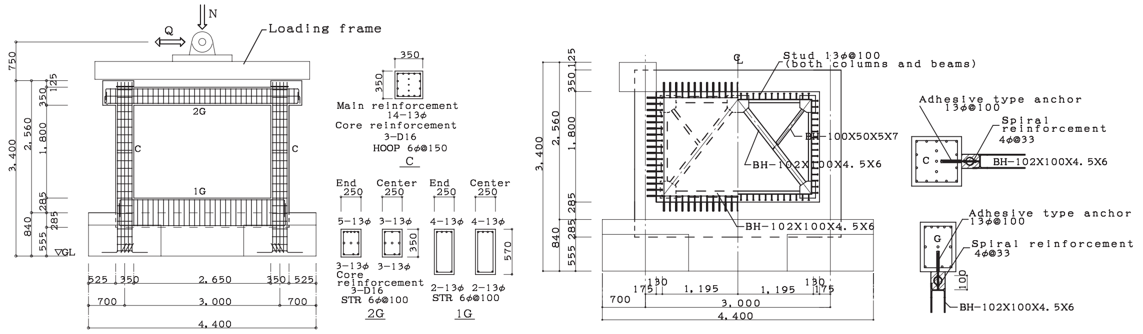
3. FRAME EXPERIMENT

In order to apply each of the methods shown in section 2, and verify the effectiveness of reinforcement in an RC frame reinforced with a steel brace with framework, loading experiments were conducted on an RC frame (unreinforced), and an RC frame reinforced using a steel brace with framework (post-reinforced), which receive a cycling horizontal force while under an axial compressive force.

3.1. Experiment plan

The form of the unreinforced RC frame test piece F1 is shown in Figure 3.1.(a). The test piece is a 1-span-1-layer rigid-framed skeleton which has dimensions of 1/1.75 compared to the actual size building. For the concrete, mixed design with FC=9 N/mm2 is performed for both columns and beams. For the main reinforcement, 13φ(SR235)round steel is used; and for the shear reinforcement, 6φ round steel is used. However, D16 (SD295) core reinforcement is provided for both columns and beams in order to prevent axial direction failure.
Loading experiments were conducted on a total of 4 test pieces: the unreinforced F1 test piece which is used as the basis, the F2 test piece reinforced using steel brace with framework and the post-installed anchor method (see Figure 3.1.(b)), the post-reinforced F3 test piece reinforced using steel brace with framework and the adhesive method, and the F4 test piece reinforced using the steel brace with framework and the anchor + adhesive method. The form of the F3 and F4 test pieces is not shown, but the same brace with framework as in F2 is used, and the joint details are as shown in Figure 2.1.. The material test results are shown in Table 3.1. and Table 3.2..
For buildings in which σB is 13.5N/mm^2 or more, it is known that the failure modes of skeletons reinforced using steel braces with frameworks are the following 3 types.
Failure mode I: Failure of steel brace

Failure mode II: Failure of joint between existing frame and steel framework
Failure mode III: Overall failure
The post-reinforced test pieces F2 and F3 used in this research have their reinforcement designed so that they fail in failure mode I, and the F4 test piece has its reinforcement designed so that it fails in failure mode II to enable confirmation of the shear strength of the joint.



(a) Unreinforced: F1

(b) Post-reinforcement (post-installation anchor method): F2

Figure 3.1. Test piece form (units: mm)

Table 3.1. Compressive strength of concrete etc.

Test piece name	Frame(N/mm^2)	Shrinkage-compensating mortar (N/mm^2)	Epoxy resin (N/mm^2)
F1	9.2	―	―
F2	11.0	62.1	―
F3	8.6	―	60.2
F4	8.4	54.8	99.8

Table 3.2. Steel material strength

Use point		Yield strength σy (N/mm^2)	Tensile strength σu (N/mm^2)
13φ	main reinforcement	323(325)	470(436)
6φ	shear reinforcement	317(291)	518(492)
4φ	spiral reinforcement	657	852
D16	core reinforcement	343	525
PL-4.5	brace	323(343)	451(441)
PL-6	brace	332(293)	443(451)
D13	anchor reinforcement	370(366)	504(552)
13φ	stud	352(364)	478(487)
16φ	core reinforcement	(338)	(461)
D6	splitting prevention reinforcemer	(321)	(512)

3.2. Loading method

Figure 3.2. shows the loading system. The test piece used in this experiment is a 1-layer-1-span fixed foundation frame. There is no orthogonal beam or boundary beam, and reverse cycling incremental horizontal loading was performed, under a fixed axial compressive force (600 kN). In loading, displacement control was performed for the deformation angle between layers R, obtained by dividing the horizontal displacement between layers δby the height L between layers, and incrementing by ±0.2% rad. was repeated for 2 cycles each up to R=±0.8% rad., and incrementing by ±0.4% rad. was repeated for 2 cycles each thereafter up to R=±3.2% rad. Table 3.2. shows the values obtained by converting R to the toughness indicator F value using the method indicated in Earthquake Resistance Evaluation Standards.

Table 3.3. Relationship between deformation angle between layers and F value

Deformation angle between layers$R$ (%rad.)	Horizontal deformation between layers d (mm)	F value
0.2	4	0.8
0.4	8	1.0
0.6	12	1.2
0.8	16	1.5
1.2	24	2.0
1.6	32	2.3
2.0	40	2.6
2.4	48	2.8
2.8	56	3.0
3.2	64	3.2

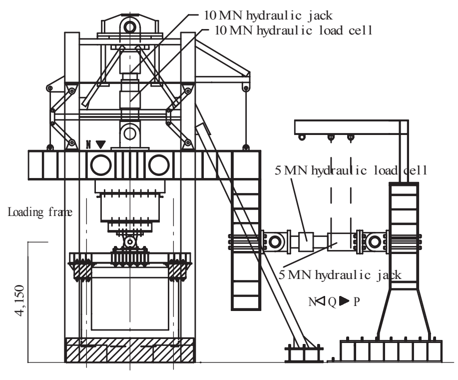
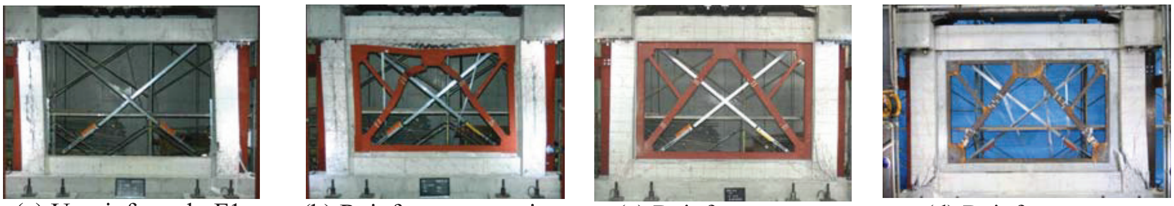


Figure 3.2. Frame experiment loading system (units: mm)

3.3. Failure properties

The final failure situations of each test piece are shown in Photo 3.1..
The F1 test piece experienced shear failure and collapse accompanying inclined cracking of column capitals and bases, as well as bond splitting failure along the core reinforcement of columns.
The F2 test piece experienced shear failure accompanying inclined cracking of columns, and bond splitting along core reinforcement. The steel brace experienced tensile fracture accompanying local buckling, and in addition, conspicuous separation failure occurred between the existing RC frame and steel framework at the brace intersection accompanying steel brace buckling.
The F3 test piece experienced shear slip failure at the adhesive joint between the bottom of the steel framework and the beam, and as a result of this, punching shear failure occurred at the column/beam joint on the column base side.
The F4 test piece used round steel to prevent splitting failure along the core reinforcement, and thus this failure did not occur. At the column/beam joint on the column base side, signs of punching shear failure progressed, and the anchor + adhesive joint failed at the steel frame underside position.



(a) Unreinforced : F1

(b) Reinforcement using post-installed anchor method: F2

(c) Reinforcement using adhesive method: F3

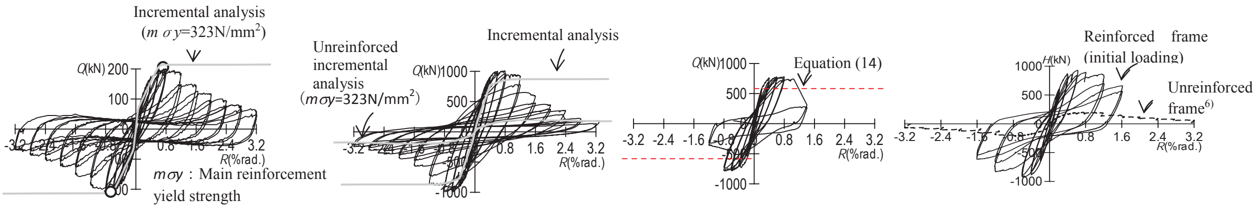
(d) Reinforcement using anchor + adhesive method: F4

Photo 3.1. Final failure situation

3.4. Hysteresis properties

Figure 3.3. shows the relationship between horizontal force Q and the deformation angle between layers R.
For the unreinforced test piece F1 in Figure 3.3.(a), the graph shows the calculated values obtained through load increment analysis using material test results. The ○ marks in the graph are the column shear failure points, but incremental analysis has been conducted assuming that proof strength is maintained even after shear failure. The experiment did not show a decrease in proof strength until 0.8% rad. After that, a decrease in proof strength occurred, but it was confirmed that the calculated proof strength is maintained until about R=±1.0% rad. Subsequently, the proof strength gradually decreased, but axial compressive force of 600 kN was maintained until the end of the experiment at R=±3.2% rad. The form of the hysteresis loop exhibits the slip properties of a reverse S-shape, and it was confirmed that the energy absorbing capacity is small.
For the reinforced test piece F2 in Figure 3.3.(b), the graph shows the calculated values obtained through load increment analysis taking into account the effectiveness of the steel brace. The yield stress intensity of the steel brace $_{s}\sigma_{y}$ is calculated assuming a material strength of 332 N/mm^2. The experiment did not show a decrease in proof strength until 0.8% rad. After that, a decrease in proof strength occurred, but it was confirmed that it remained above the calculated proof strength of the unreinforced frame, and that an axial compressive force of 600 kN was maintained, until the end of the experiment. It was confirmed that the form of the hysteresis loop has the stable hysteresis characteristics of a spindle shape until R=±1.2% rad.
For the reinforced test piece F3 in Figure 3.3.(c), the graph shows the calculated values for ultimate strength, calculated assuming that the adhesive joint experiences shear slip failure. The experiment did not show almost any decrease in proof strength until 0.8% rad. After that, a rapid decrease in proof strength occurred together with punching shear failure of the column/beam joint at R=±1.0% rad, but axial compressive strength of 600 kN was maintained. The experiment was planned so that the test piece would fail in failure mode I, but it actually failed in failure mode II. This is thought be because the actual yield strength of the steel brace was higher than the standard value, and, furthermore, the shear slip strength of the adhesive joint on the low-strength concrete was smaller than the standard value, and therefore punching shear failure of the column/beam joint occurred accompanying shear

slip failure of the adhesive joint.
For the reinforced test piece F4 in Figure 3.3.(d), it is evident that the maximum proof strength of the reinforced frame exceeds the maximum proof strength of the unreinforced frame, but the decrease in proof strength is conspicuous after the maximum proof strength due to the effects of punching shear failure at the column/beam joint on the column base side. Furthermore, the form of the hysteresis loop exhibits intermediate behavior between the F2 and F3 test pieces.



(a) Unreinforced : F1

(b) Reinforcement using post-installed anchor method: F2

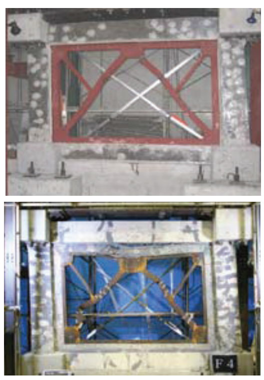
(c) Reinforcement using adhesive method: F3

(d) Reinforcement using anchor + adhesive method: F4

Figure 3.3. Relationship between horizontal force and deformation between layers

3.5. Failure properties and hysteresis characteristics in reloading after repair

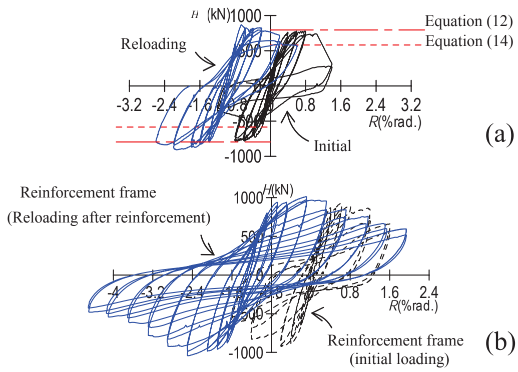
The column/beam joint exhibited punching shear failure in the F3 and F4 test piece and thus these were lacking in terms of toughness. Therefore, epoxy resin was filled into the anchor + adhesive joint and the crack which occurred in the RC frame, while in the state where residual deformation remained after the initial loading experiment was finished, and concrete stub reinforcement was provided to prevent punching shear failure of the column/beam joint on the column base side. Then the same experiment as the initial loading was performed again.
The final failure situations are shown in Photo 3.2., and the Q−R relationships are shown in Figure 3.4.. Figure 3.4. shows the calculated values of ultimate strength (see section 4) calculated assuming that the steel brace yields. With the test piece after repair, punching shear failure did not occur at the column/beam joint. In the F3 test piece, tensile fracture occurred accompanying local buckling of the steel brace, and in the F4 test piece, a large separation appeared between the steel frame and RC frame, at the anchor + adhesive joint near the brace intersection, due to buckling of the steel brace. However, it was confirmed for all test pieces that experimental values exceed calculated values.
When hysteresis curves are compared between the initial loading and reloading after repair, the maximum proof strength in reloading after repair exceeds the maximum proof strength in initial loading. If the state at the start of loading during reloading after repair is set so R=0% rad., then the maximum proof strength is attained at an amplitude of R=±1.2 % rad., and it was confirmed that toughness can be improved if punching shear failure does not occur at the column/beam joint or column.



(a) F3

(b) F4

Photo 3.2. Reloading failure situation



(a) F3 reloading

(b) F4 reloading

Figure 3.4. Relationship between horizontal force and deformation between layers in reloading

4. EVALUATION OF ULTIMATE STRENGTH

4.1. Method of evaluating ultimate strength

Ultimate strength was found using load incremental analysis for the unreinforced frame, and the reinforced frame using the post-installed anchor technique.
Ultimate strength of the reinforced frame using the adhesive method was found using Equations (12) and (14) proposed by Kei et al.

$$Q_{su1} = \sum {}_cQ_u + {}_BQ_{tu} + {}_BQ_{cu} \quad \text{(case where } Qs1>Qsu1 \text{ and adhesion strength is sufficient)} \tag{12}$$
$$Q_{s1} = \sum {}_cQ_u + {}_bQ_u \tag{13}$$

Here, $\sum cQu$ is the proof strength of columns on both sides determined by bending and shear; $BQtu$ is the horizontal proof strength of the brace on the tension side; and $BQcu$ is the horizontal proof strength of the brace on the compression side.

$$Q_{su2} = {}_cQ_u + {}_cQ_{pu} + {}_jQ_f \quad \text{(case where } Q_{s1} \leqq Q_{su1} \text{ and adhesion strength is insufficient)} \tag{14}$$

Here, cQu is the proof strength of the column determined by bending and shear; cQpu is the punching shear proof strength of the column; and jQf is the horizontal load shear force due to frictional force of the adhesive joint.
In this experiment, the ultimate strength of the reinforced frame is calculated in two cases: the case for the F3 test piece in initial loading where Qs1≦Qsu1 and the case for the F3 test piece in reloading where Qs1>Qsu1. bQu is evaluated using Equation (8).
For the ultimate strength of the frame reinforced with a steel brace using both post-installed anchors and epoxy resin, Equation (8) below is provided in related guidelines assuming that σB of the existing building frame is 15 N/mm2 or more. In this experiment, Qu1 and Qu2 are evaluated using Equation (16b) for initial loading case, and using Equation (16a) for the reloading case.

$$Qu = \min(Qu1,\ Qu2) \tag{15}$$
$$Qu1 = Qsu + Qtu + Qcu \tag{16a}$$
$$Qu2 = Qju + Qpc + Qcu \tag{16b}$$

Here, Qsu is the ultimate strength of the steel brace with frame; Qtu is the ultimate strength of the tension side column; Qcu is the ultimate strength of the compressive side column; Qju is the ultimate strength of the joint between the steel framework and existing building frame; and Qpc is the punching shear proof strength of the column capital on the tension side.

4.2. Comparison of experimental and calculated values of ultimate strength

Table 4.1. shows the maximum value of horizontal force *H*max and the calculated value of ultimate strength Qu for each test piece. For all test pieces, it was confirmed that the experimental values exceed calculated values.

5. EVALUATION OF TOUGHNESS

The envelope curve for the first cycle of each test piece is shown in Figure 4.1.. The vertical axis indicates the horizontal force H, and the horizontal axis indicates the deformation angle between layers R.
For test piece F1 and F2, it was confirmed that an F value of 1.5 can be secured when F values are set within a range where there is no decrease in proof strength.
For the test piece F3, it is valid to evaluate the test piece assuming an F value of 1.2. However, in an actual structure, the proof strength of the column/beam joint increases due to the existence of orthogonal beams, boundary beams or slabs, thus resulting in punching shear failure at the column/beam joints, and it may be possible to conduct design with an F value of about 1.5.
For test piece F4, it was confirmed that, when F values are set within a range where there is no decrease in proof strength, the structure has toughness with an F value of 1.2, and in reloading after repair, it has toughness with an F value of 2.0. This is the same result as with test piece F3.

Table 4.1. Experimental and calculated values of ultimate strength

Test piece	Experimental value *Hmax* (kN)	Calculated value *Qu* (kN)	*Hmax* /*Qu*
F1	200	151	1.32
F2	1007	817	1.23
F3	790	583	1.36
F3 (reloading)	870	593	1.47
F4	936	720	1.30
F4 (reloading)	1043	828	1.26

Note) *Hmax*: absolute value of the maximum applied

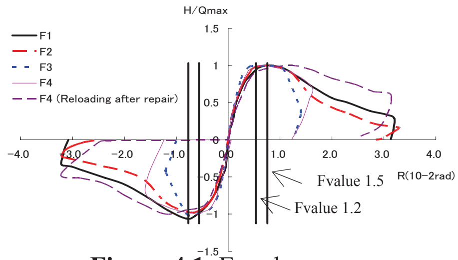


Figure 4.1. Envelope curve

6. CONCLUSIONS

The following conclusions were reached regarding each of the methods indicated in this paper for earthquake-resistant reinforcement of existing, disqualified RC buildings with low-strength concrete using steel braces with frame.

1) The shear strength of joints using each method can be evaluated on the safe side using equations in Earthquake-resistant Retrofitting Design Guidelines or previous evaluation equations.

2) The ultimate strength of building frames reinforced with steel braces using each method can be evaluated on the safe side using load incremental analysis or previous evaluation equations.

3) An F value of 1.5 can be secured for a frame reinforced with steel braces using the post-installed anchor method. Similarly, an F value of 1.2 can be secured with the adhesive method, and an F value of 1.2 can be secured with the anchor + adhesive method. If the column/beam joint does not fail, an F value of 1.5 to 2.0 can be secured.

However, there are reports that low-strength concrete in actual structures has a low Young's modulus, and that there is a conspicuous decrease in strength subsequent to the maximum compressive strength. In addition, it is likely that stress will concentrate on floors with low-strength, and thus a careful response will be required.

ACKNOWLEDGMENTS

Parts of these experiments were conducted by the Low-strength Concrete Special Research Committee WG (Chairman: Koichi Minami, Fukuyama University) established by the Chugoku Branch of the Japan Concrete Institute. This research was also supported by a 2009 Grant-in-aid for Scientific Research (representative researcher: Hideo Araki, Associate Professor, Graduate School, Hiroshima University). Here, the authors would like to express their gratitude.

REFERENCES

Japan Building Disaster Prevention Association.(2001).Earthquake-resistant Retrofitting Design Guidelines for Existing RC Buildings and Commentary

Kei, Takahiro, and Miyauchi, Yasuyoshi.(2001). Dynamic Characteristics of Adhesive Joined Steel Brace Reinforced Frames, Journal of Construction Engineering, Architectural Institute of Japan, No. 539, pp. 103-109.

Masao, Kiyoshi, and Komiya, Toshiaki.(2000). Reinforcement Effect of Braces with an Expanded Steel Frame using a Method combining Adhesive Bonding and Indirect Bonding, Concrete Research and Technology, Vol.22, No.3, pp. 1651-1656.

Yamamoto, Yasutoshi, Katagiri, Taichi, Akiyama, Tomoaki, and Thompson, J.F. (2000). Load Transfer Capability of Adhesive-type Anchor Reinforcement in Low-strength Concrete, Concrete Research and Technology, Vol.22, No.1, pp. 553-558.

Earthquake-resistant Reinforcement System Construction Group.(2001). Design and Installation Guidelines for Steel Braces with Frameworks using the Hybrid Earthquake-Resistant Reinforcement Method.

Japan Building Disaster Prevention Association .(2001). Earthquake-Resistance Evaluation Standards for Existing RC Buildings and Commentary.