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Analysis of reinforced concrete frames retrofitted with steel brace

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ABSTRACT: This paper describes the results of a ststically non-linear analysis of existing reinforced concrete frames which were retrofitted with a steel brace enclosed with steel rim, with focus on the effect of the mortar joint connecting the reinforced concrete member and steel member. The retrofitting method discussed herein is a unique one using a steel brace system enclosed with steel rim which has already proved effective in Japan. The frames which were subjected to the analysis were one-bay, one-story specimens approximately one-third of the full scale. With respect to the specimens which have already been subjected to experiments, the analytic results are compared with the experimental results. For the specimens which have not the experimental results, various strengthening effects of joints are subjected to a comparative study.

1 INTRODUCTION

Strengthening a existing reinforced concrete (r/c) frame with a steel system offers several advantages.

The seismic strengthening method analyzed in this paper is an indirect joining method in which headed chemical anchors are embeded around the inner surroundings of a existing r/c frame, steel rim with headed studs are fitted thereto, and the gap between them is filled with injected mortar to join them.

Computer program used in this analysis employs the step-by-step displacement incementation and corresponding iteration procedure developed primarily to analyze steel structure.

Table 1. Properties of tested specimens

	Yield strength of steel σ_y (MPa) PL-4.5 ⇨297, PL-6.0⇨305	F_c * (MPa)	F_M ** (MPa)
RC-1	Nothing of steel rim & brace	20.7	—
RCS-1	Rim: h-80x80x4.5x6.0	21.2	31.9
X-1	Rim: h-80x80x4.5x6.0 Brace: H-80x80x4.5x6.0	28.5	36.5
V-1	Rim: h-80x80x4.5x6.0 Brace: H-80x80x6.0x6.0 Stopper: H-80x40x6.0x6.0	22.1	33.0
M-1	Rim: h-80x80x4.5x6.0 Brace: H-80x80x6.0x6.0 Stopper: H-80x40x6.0x6.0	21.2	31.9

*Compressive strength of concrete ** Compressive strength of mortar

2 SPECIMENS

Table 1. summarizes the properties of those specimens already been confirmed by experiments. A specimen [RC-1] is the existing r/c portal frame before strengthening, [RCS-1] is a r/c frame strengthened with steel rim alone and specimens [X-1, V- 1 and low V-1] are strengthened with rim and brace. The outline of tested speci-men [V-1] is showen in Figure 1. The section of existing r/c frame and its reinforcement of are common to all specimens.

Moreover, specimen [V-1-S_B] whose upper- and lower-side rims are jointed to the existing r/c frame and specimen [V-1-S_A] which have nothing of anchor in the joint are also analyzed. Finally, [V-1-0] without buckling stopper, [V-1-F] fitted with a thin rim at the top of the opening and [V-1-D_c] and

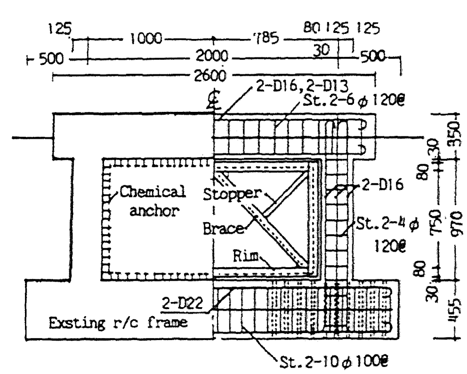

Fig.1 Outline of specimen [V-1]

[V-1-D_T] without the rim and mortar joint at the top of their opening are analyzed (Figure 2).

3 ANALYTIC METHOD

In this analysis, it was necessary to consider the entire strengthened framework, inclding the r/c members, steel members and mortar joints, in terms of steel members.

Figure 3 outlined the modeling of each member. The program used in the analysis considered the bending, shear and longitudinal deformations of r/c members, and the bending, shear and longitudinal deformations and bucking of steel members. The bending element was assumed as a member having rigid and plastic zone at its ends and an elastic zone in the center. The shear and longitudinal elements were assumed as totally deformable parts.

Figure 4 showed how to determine rigidity reduction factors α and β, of the individual elements. The relationship between bending moment(M) and its curvature(ϕ), and the relationship between shearing force (Q) and its strain(γ) were assumed to be tri-linear. It was also assumed that strength after yielding did not decline even when a shear failure occurred. Strain (ε) caused by axial force(N) was assumed to be bi-linear based on the assumption that the yielding strength did not increase after a spring fitted to the center of the member yielded in a state of tension or compression, or reached the Euler's critical load (N_{cr}). Young's modulus ratio (n) of concrete and injected mortar for steel member was assumed as 10. In the figure, symbols E, A, and I mean Young's mod-ulus, sectional area and moment of ineartia, and subscripts c, y and cr mean elastic limit, yieldig and critical state, respectively.

3.1 Modeling of mortar joint

In the actual mortar joint, headed chemical anchors and headed studs were arranged alternately. For the purpose of simplification, they were considered in terms of the imaged anchors which became close to the actual load-deformation curve obtained by direct shear tests of injected mortar joints (Figure 5).

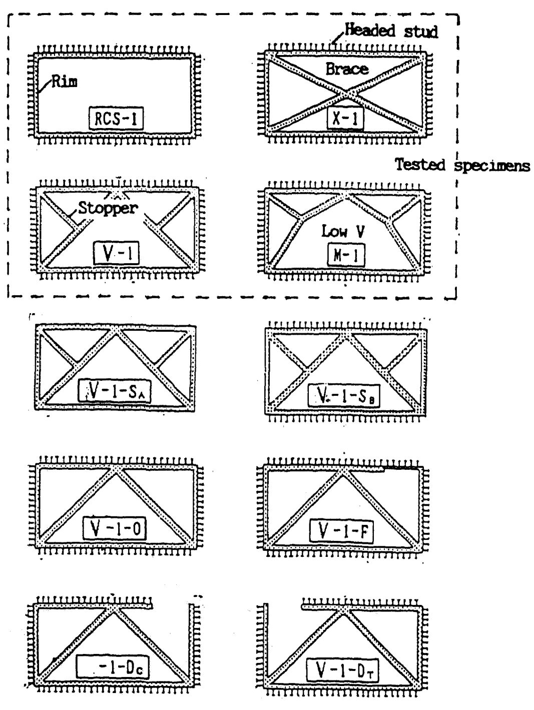

Fig.2 Outline of infilled steel braces

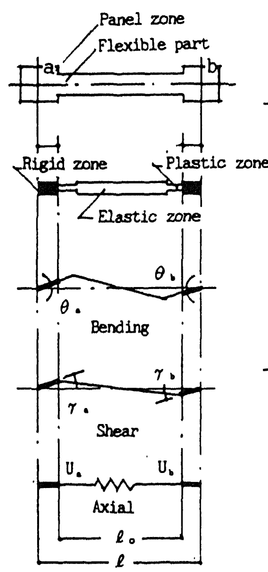

Fig.3 Modeling of a member

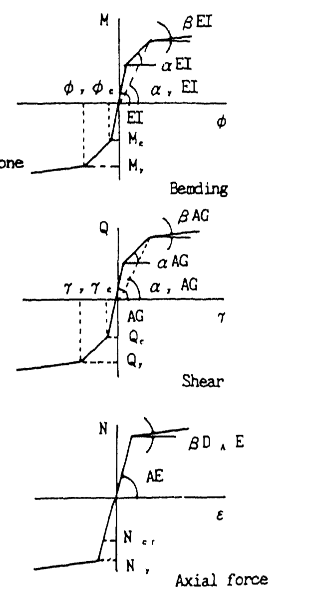

Fig.4 Hysteresis characteristics

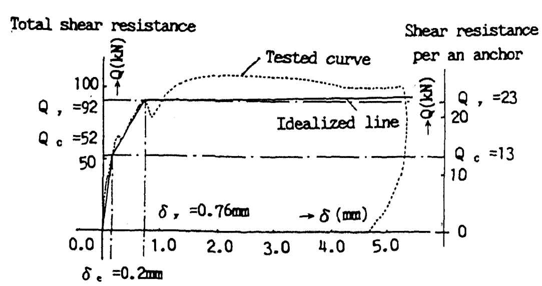

Fig.5 Mechanical properties of imaged anchor

3.2 Modeling of existing r/c frame

The rigid zone was assumed to be up to the surface of a column or beam, and the plastic zone was assumed to be 0.2 of the depth. It was also assumed that the r/c foundation was rigid.

3.3 Steel members

The joint between steel rim and brace was assumed to be rigid, but the rigid zone was left out of consideration.

3.4 Yield strength and ductility of r/c and steel members

The formulas recommended in " Revised Guideline for Repair and Retrofit Design of Existing Reinforced-concrete Buildings " and other data were used to calculate strengths and ductilities of r/c and steel members.

4 PROPERTIES OF MATERIALS

In the present analysis, properties of specimens which have already been subjected to experiments were directly used (Table 1.).

5 COMPARISON BETWEEN ANALYSIS AND EXPERIMENTAL RESULTS

The rigidity, ultimate yield strength, failing process and failure mode of each of the specimens are discussed below.

5.1 Specimen [RC-1] (Fig. 6a)

Though the analysis results showed a higher initial rigidity than did the experimental results, both results indicated a similar shape of curve. Also, the analysis results and experimental results showed similar process of cracking. With respect to the mode of failure, the specimen was subjected to flexural failure in the analysis, whereas it was subjected to shear failure in the experiment. This difference is attributable to the fact that a somewhat higher shearing strength was assumed in the analysis.

5.2 Specimen [RCS-1] (Fig. 6b)

The initial rigidity comfirmed by the analysis almost coincided with that obtained by the experiment. As the degree of cracking increased, the analysis results showed lower rigidity and lower ultimate strength.

In the analysis, the mode of shear failure was such that the r/c column yielded to shear after it cracked due mainly to bending. This coincides with the experimental results.

5.3 Specimens retrofitting with steel brace

[X-1]: The initial rigidity confirmed by the analysis almost coincided with that obtained by the experiment(Fig. 6c). As the specimen began to crack, the analysis results showed lower rigidity and lower yield strength.

Though the upper and lower ends of the r/c column yielded to shear, shear strength of the frame increased and finally the ultimate strength was determined by the flexural yielding of the steel rim and buckling of the brace. Since the shear failure of r/c column and buckling of the brace also occurred in the experiment, and analysis results matched the experimental results in this respect.

[V-1]: The initial rigidity confirmed by the analysis nearly coincided with that obtained by the experiment(Fig. 6d). In the analysis, as in the experiment, yielding to tension and buckling occurred in the brace and shear failure occurred at the right and left r/c columns.

[M-1]: The analysis results showed a lower initial rigidity than did the experimental results(Fig. 6e). In the analysis, a failure similar to the one observed with specimen [V-1] occurred in this specimen. A similar phenomenon was observed in the experiment.

6 COMPARISON OF VARIOUS BRACING METHODS

6.1 Specimens [$V\text{-}1\text{-}S_B$] and [$V\text{-}1\text{-}S_A$]

1. Load-deformation curves (Figure 7a)
When there is no anchor around inside of r/c frame, its initial rigidity was low, especially in case of specimen [$V\text{-}1\text{-}S_A$]. While [V-1] was subjected to tensile yielding at the joint of beam end and shear yielding in the beam center, [$V\text{-}1\text{-}S_B$] was subjected to tensile yielding and compressive yielding at the joint of beam end.

Specimen [$V\text{-}1\text{-}S_A$] was subjected to slippage failure at the tension-side column head. With respect to the ultimate strength, which is defined as the strength at the time when a collapse mechanism occurs, [V-1] showed the largest value, while the ultimate strength of [$V\text{-}1\text{-}S_B$] decreased to 93% of that of [V-1] and the ultimate strength of [$V\text{-}1\text{-}S_A$] decreased to 41% of that of [V-1]. The drift angle at ultimate strength was 1/ 115 for [V-1], while [$V\text{-}1\text{-}S_B$] showed a drift angle of 1/40, approximately three times that of [V-1]. By contrast, [$V\text{-}1\text{-}S_A$] showed a small drift angle of 1/216.

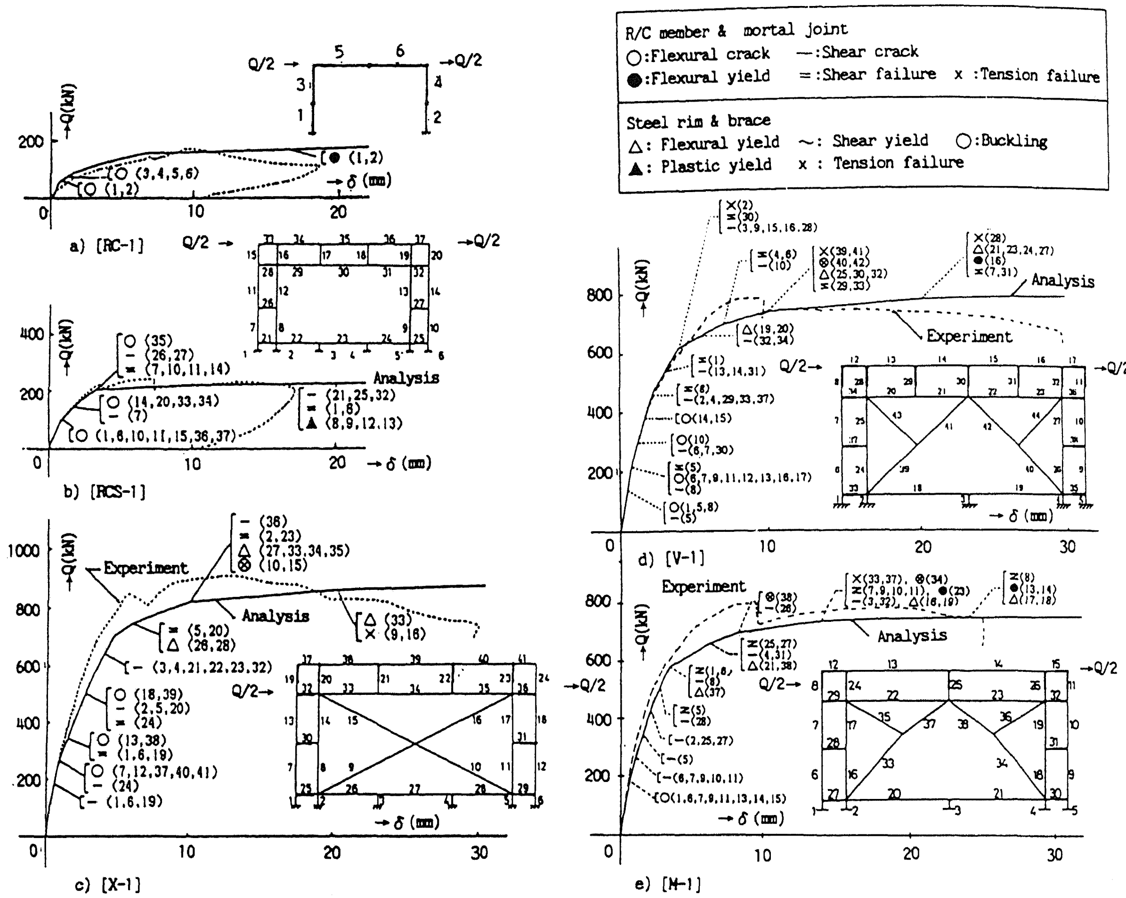

Fig. 6 Comparison with tested and analyzed results
(Number in frame shows member's posision)

2. Failure mechanism
Specimen [V-1-S_B] showed a gradual expansion of shear yielding zone in the tension-side r/c column and the brace buckled ultimately. However, the tensile brace did not yield. In the ultimate condition, specimen [V-1-S_A] was subjected to slippage failure at the tension-side r/c column top and compression-side column bottom. Because of this, the specimens was subjected to brittle failure.

3. Load-bearing ratio of brace (Figure 7)
The ratio of shear force shared in brace to the total shear force in the whole strengthened frame is defined here as load-bearing ratio of the brace. Specimens [V-1] and [V-1-S_B] showed a large brace load-bearing ratio. They also showed a tendency that the tensile and compressive load-bearing ratios became equal. By contrast, specimen [V-1-S_A] showed a small brace load-bearing ratio. Especially, the load-bearing ratio of the tensile brace was small.

6.2 Specimen without buckling stopper [V-1-0]

1. Load-deformation curves (Figure 8a)
The initial rigidity of [V-1-0] was almost the same as that of [V-1]. In the analysis, the rigidity and yield strength remained the same. The ultimate strength was the same as that of [V -1] obtained in the experiment.

2. Failure process
There was little difference in the process of falure between [V-1-0] and [V-1]. Namely, both r/c columns were subjected to shear failure, then the brace yielded to tension and buckling. The buckling occurred with [V -1-0] somewhat earlier.

3. Load-bearing ratio of brace (Figure 8b)
The results of analysis showed very little difference between [V-1-0] and [V-1].

6.3 Specimen [V-1-F]

1. Load-deformation curves (Figure 9a)
The results of analysis of both specimens [V-1] and [V-1-F] were nearly the same with respect to initial rigidity, ultimate strength and deformation at the ultimate.

2. Failure process
With respect to the process of failure, [V-1-F] was almost the same as [V-1]. However, in the case of [V-1-F], the rim at the opening under the r/c beam yielded to bending before the brace buckled.

3. Load-bearing ratio of brace (Figure 9b)
There was very little difference between [V-1-F] and [V-1].

6.4 Specimens [V-1-D $_c$] and [V-1-D $_T$]

1. Load-deformation curves (Figure 10a)
Both specimens showed lower initial rigidity than [V-1]. Also, they showed lower ultimate strength, approximately 78.4%for [V-1-D $_c$] and approximately 67.5% for [V-1-D $_T$].

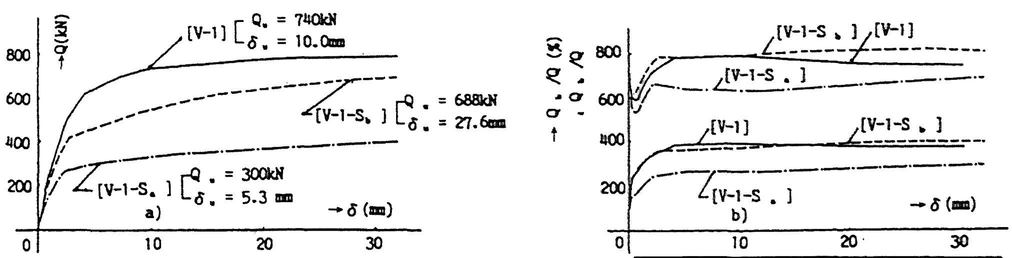

Fig. 7 Arrangement of anchor in mortar joint

Q : Total shear load (MPa)
Q $_b$: Load shared by brace (MPa)
$_t$Q $_b$: Load shared by tensile brace(MPa)

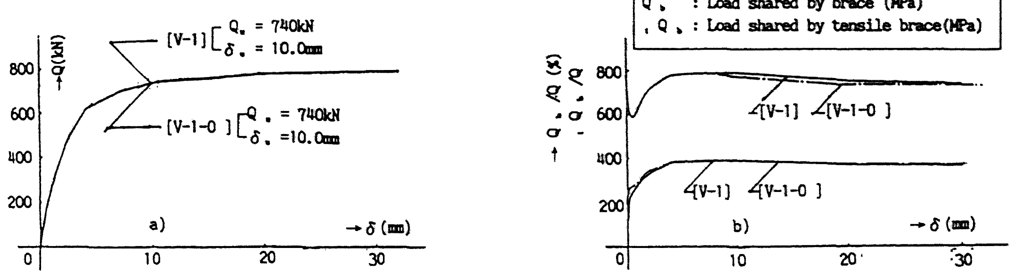

Fig. 8 Effect of the buckling stopper

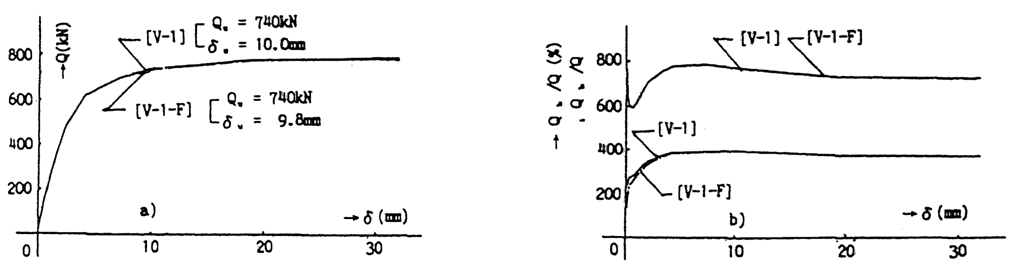

Fig. 9 Changes of rim and mortar joint

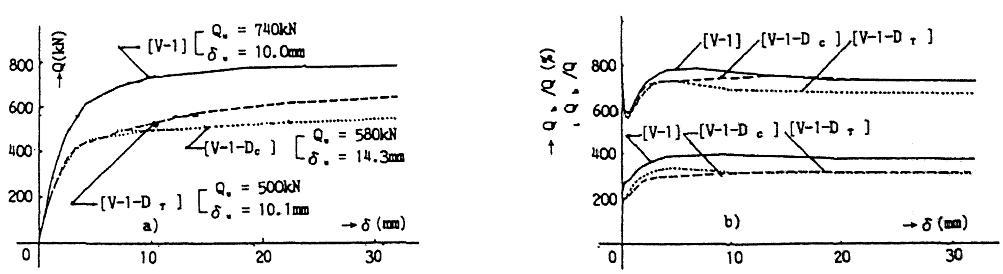

Fig.10 Partial lacking of rim and mortar joint

2. Failure process
Specimen [V-1-D_c] was first subjected to a shear failure at the tension-side column top, compression-side column bottom and left end of the beam, respectively. Then, a bending failure occurred in the rim and a shear failure occurred in r/c beam and tension-side r/c column anchors. In addition, bending failure occurred in the leg of the tension-side r/c column. On the other hand, [V-1-D_T] was subjected to shear failure at the compression-side r/c column leg. Shear failure also occurred at the tension-side column top and anchors under the r/c beam. Then, the tension-side column was subjected to shear failure, when the ultimate strength was reached. Thus, when the mortar joint was partly lost, the absolute amount of anchor under the beam became insufficient to secure adequate yield strength, causing a shear failure. A failure mechanism occured when the tension-side column top, anchor under the r/c beam and compression-side column bottom were subjected to shear failure. The mode of collapse was column shear failure type, not column slippage failure type.

3. Load-bearing ratio of brace (Figure 10b)
Since the yield strength was determined by the shearing force of the anchor under the beam, the brace could not fully display its strength. Even so, the brace load-bearing ratio of [V -1-D_T] was approximately 10% smaller than that of [V-1], whereas the brace load-bearing ratio of [V-1-D_c] remained nearly the same as that of [V-1]. This is due largely to the fact that the efficiency of the tensile brace of [V-1-D_T] deteriorated.

7 CONCLUSION

The applicability of an indirect joining method for strengthening the existing reinforced concrete structure with a steel brace system was studied by a statically non-linear analysis. As a result, it was found that the initial rigidity, ultimate strength, collapse mode, etc., of structures could be predicted with fair accuracy when reference experimental results are available.

From the results of an analysis of joints arranged around the truss enclosed with rim, the following facts were found.

1) The initial rigidity and ultimate strength increase when anchors are arranged at inner four sides of the existing reinforced concrete frame. When anchors are arranged only at the upper and lower beams, the initial rigidity becomes somewhat inferior and the ultimate strength decreases to approximately 90 percent. Neverthless, the latter may be applicable as a simple seismic retrofitting method. Employing no anchors at all is not recommendable because the strengthening effect deteriorates markedly.

2) When the brace is strong, as in specimen [V-1], it may be said that the absence of buckling stopper has negligible effect on the ultimate strength, failure characteristics, etc.

3) Even when a part of the steel frame around the beam has a small cross-sectional area, it has small effect on the entire structural characteristics. However, if the beam has sections which are not strengthened with steel rim and anchors, the brace can not fully display its strength because of insufficient shearing strength of the anchors.

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