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MULTI-DIRECTIONAL FLEXURE BEHAVIOR AND NONLINEAR ANALYSIS OF RC COLUMNS SUBJETED TO ECCENTRIC AXIAL FORCES

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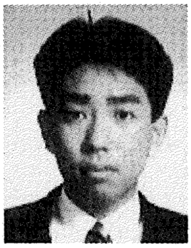 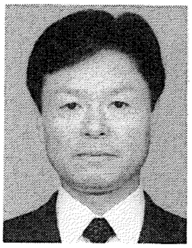 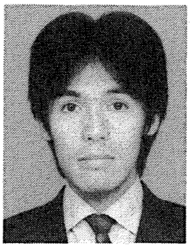 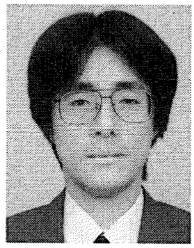 

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Experiments are carried out in which it is observed that RC columns under eccentric axial loading accumulate considerable deformation in the direction of the eccentric permanent moment when reversed-cyclic loading is applied perpendicular to the moment. This deformation exceeds the allowable value given in the design code. This behavior is investigated analytically using the 3D-fiber technique in order to gain an understanding of the mechanism. It is verified that the response is caused by strain hardening of the steel under the influence of eccentric axial forces, and that it is strongly related to the complex nonsymmetrical loading path. This result indicates that a three-dimensional approach is invaluable as a means to obtain the residual displacement of RC piers.

Keywords: *eccentric axial forces, reversed-cyclic loading, residual displacement, 3D FE analysis*

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1. INTRODUCTION

In order to reduce the potential for secondary disasters and allow effective search-and-rescue operations, major transport facilities such as highways need to be designed such that serviceability immediately after a large earthquake is ensured. The Hyogoken-Nanbu Earthquake of 1995 demonstrated the need to control residual displacement after a seismic event. Residual displacement needs to be verified as one of the limit states used in design practice, along with the shear limit. This need arises from the experience that many RC piers had to be demolished as beyond repair, even though they had enough residual capacity to bear emergency traffic [1].

Shear failure can be prevented by providing sufficient stirrup reinforcement. However, no accurate method of estimating residual displacement has yet been established, and this has become an urgent topic of research. The reason for this sudden interest is that RC piers subjected to seismic motion may accumulate residual deformation in the moment direction due to the eccentric axial forces [1][2][3].

For RC piers under eccentric axial compression, little understanding has been accumulated and their dynamic response is not yet well quantified. This study is an attempt to investigate, both experimentally and analytically, the nonlinear behavior that arises when horizontal forces in a direction perpendicular to the moment are applied as a result of eccentric axial forces.

Japan is shifting from limit-state design to performance-based methods [4][5], as described in the JSCE's Standard Specification for Design and Construction of Concrete Structures [6]. There is a clear role for nonlinear analysis in performance-based methodologies, and it has two obvious applications: to the processes of determining structural dimensions and verifying the required performance [7]. As a result, there is presently considerable urgency in efforts to extend the applicability and accuracy of numerical simulations. Mutsuyoshi and Machida have shown that strain rate scarcely affects static and dynamic restoring properties under uni-axial bending [24]. Although the authors deal with experiments on bi-axial static bending, the influence of strain rate may be ignored just as with uni-axial bending. Consequently, the computing of multi-directional static behavior has close parallels with the verification of seismic performance during an earthquake. A three-dimensional nonlinear FE analysis based on a fiber technique is also performed in this study, and its accuracy and effectiveness are verified.

For the purpose of this paper, an "eccentric pier" is defined as a pier subjected to eccentric axial forces, as shown in Fig. 1. Similarly, the "eccentric moment" is the moment due to eccentric axial forces, and the "eccentric direction" is as the orientation of the eccentric moment. Generally, the eccentric direction accords with the transverse axis, and the perpendicular to the eccentric direction accords with the longitudinal axis.

The target RC column used to investigate residual displacement is a flexure-prone column, so it is not necessary to carry out a verification for shear failure. The column is reinforced with adequate web reinforcement as given by the current specifications [8]. The second, third, and fourth authors are responsible for planning the experiments and analysis, while the fifth author takes the initiative in developing the numerical tools. The first author is in charge of calculating and investigating the nonlinear behavior.

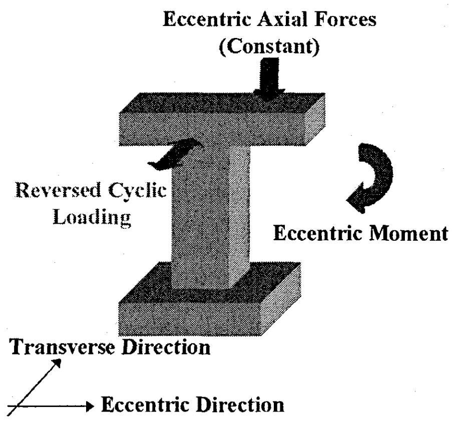

Fig. 1 Loading Direction

2. MULTI-DIRECTIONAL FLEXURE/SHEAR OF RC COLUMN SUBJECTED TO ECCENTRIC AXIAL FORCES

2.1 Target Column and Experimental Specimen

An inverse L-shaped RC column with a comparatively large permanent eccentric moment is selected as a model, and a scaled-down specimen is made. Reversed-cyclic static horizontal loading is applied perpendicular to the eccentric moment. Initial results of this experiment have already been reported [9]; it is one of a series of experiments originally designed to investigate the effects of eccentric axial forces and torsion on seismic performance.

The specimen is developed by scaling down a real structure with a coping in the transverse direction to about 1/5. The dimensions and cross section are shown in Fig. 2. The main reinforcement consists of D10 bars, with D6 as stirrups and multi-legged stirrups. The ratio of cover thickness and bar diameter to the cross section is matched as closely as possible by considering the embedded length of reinforcing bars and concrete compactability, etc.

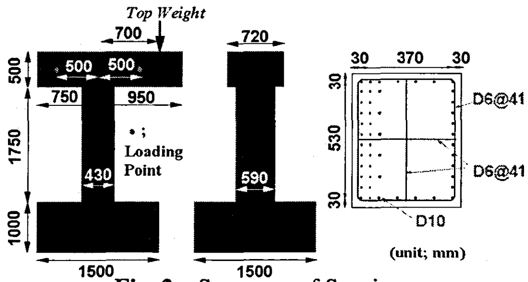

Fig. 2 Summary of Specimen

Table 1 Specimen and Real Structure [9]

	Real	Specimen	Ratio
cross section (cm*cm)	220*300	43.0*59.0	5.09
top weight (kN)	1990	140	
base axial forces (kN)	4270	165	
compress. stress (MPa)	0.648	0.648	1.00
f'c design strength (MPa)	29.4	29.4	
cover thickness (mm)	100	30.0	3.33
Gmax (mm)	20.0	10.0	2.00
main reinf. Cross section area (cm^2)	D32*112 = 890	D10*48 = 34.2	
main reinf. ratio	1.35	1.35	1.00
stirrups volume ratio (%); eccentric direct.	1.10	1.10	1.00
stirrups volume ratio (%); orthogonal direct.	1.54	1.54	1.00

Table 2 Material Properties [9]

Concrete	f'c (MPa)	38.5
	Ec ($*10^4$MPa)	2.63
	ft (MPa)	3.47
	Poisson's ratio	0.164
D10	fy (MPa)	409
	Es ($*10^5$MPa)	1.97
D6	fy (MPa)	396
	Es ($*10^5$MPa)	1.98

The real structure on which the model is based contains adequate stirrup reinforcement, as shown in Table 1. Thus, it passes the test of the Ductility Design Method based on the current edition of Seismic Design Specification for Highway Bridges [8]. The spacing of the stirrups is 41 (mm). A summary of the specimen, and a comparison with the real structure, are given in Fig. 2 and Table 1, respectively [9]. The material properties are given in Table 2 [9].

2.2 Loading Method

Eccentric axial forces are applied as initial loadings. The eccentricity is 700 (mm) and the axial force is 140 (kN), where eccentricity is defined as the distance between the center of the column cross section and the axial force loading position. Compressive stress at the base of the specimen is made equal to that in the real structures, or 118 (MPa). Therefore, the permanent eccentric moment due to the dead load is 103 (kN*m).

Horizontal reversed-cyclic forces are applied to the RC column specimen by displacement control in the direction perpendicular to the eccentric moment. Two cycles of induced displacement are applied. Generally, a clear difference in restoring force characteristics is observed between the first and second loops, since the stress paths of the concrete and reinforcing bars are very different. However, little difference is observed as the number of cycles is increased [10], this simply leading to reinforcement rupture due to low-cycle fatigue. This is not the objective of the research, however, so it is not pursued here. Yield displacement δ_y is set to 8.0 (mm) according to the Seismic Design Specification for Highway Bridges.

Displacement-controlled horizontal loading is applied using two hydraulic jacks attached between the coping and a reaction wall. Induced torsion is carefully avoided by placing universal joints at the ends of the jacks. A hydraulic jack running on guide rails with a friction coefficient of $1.0*10^{-3}$ is used for vertical loading in order to prevent restraining forces in the horizontal direction. A summary of this experimental arrangement is shown in Fig. 3.

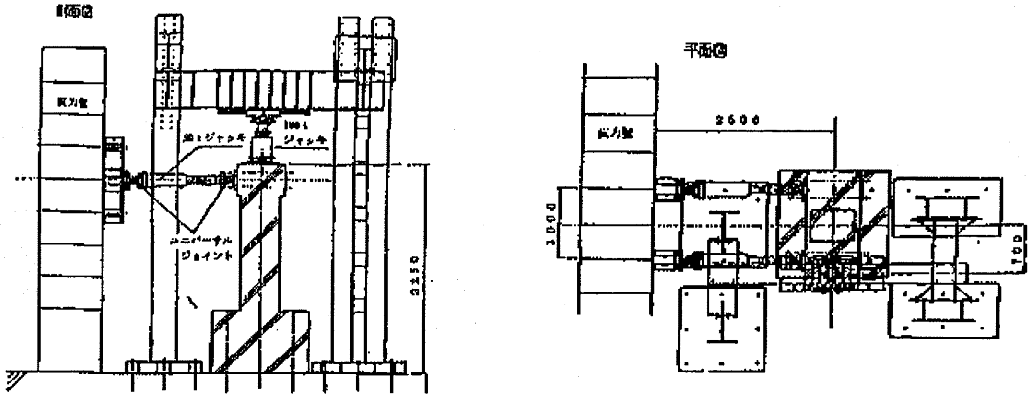

Fig. 3 Summary of Experimental Device [9]

2.3 Experimental Results

Figure 4 shows the experimental relationship between load and displacement in the horizontal loading direction. It indicates considerable energy absorption and superb seismic performance. However, significant deformation is accumulated in the eccentric direction when cyclic horizontal loading is applied in the direction perpendicular to this moment, as shown in Fig. 5.1. Ultimately, this accumulated deformation in the eccentric direction reaches 120 (mm). At this point, the deformation exceeds the limits of the experimental equipment, and loading is terminated at the $7\delta_y$-1 cycle. Although the maximum forced displacement in the horizontal direction is just 56 (mm), the residual displacement in the eccentric direction rises to more than 120 (mm), which is twice the induced displacement in the orthogonal direction.

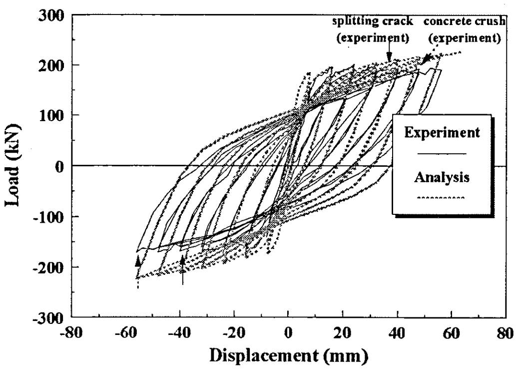

Fig.4 Load-Displacement Relationship in the Transverse Direction

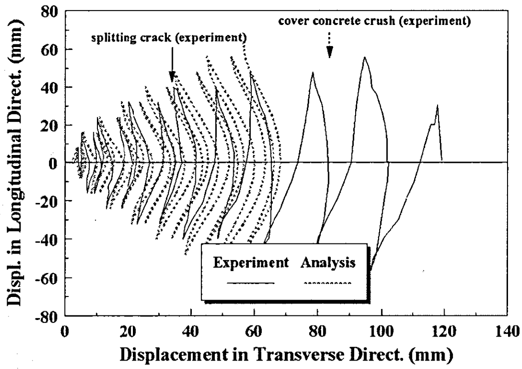

Fig. 5.1 Displ. in the Orthogonal Direct. – Dipl. in the Eccentric Direct. Relationship

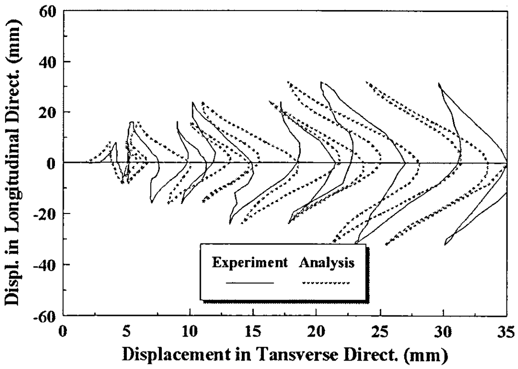

Fig. 5.2 Displ. in the Orthogonal Direct. – Dipl. in the Eccentric Direct. Relationship (enlarge)

This experimental result clearly indicates that an investigation of the eccentric direction is necessary, even where the input motion is in the orthogonal direction. The Seismic Design Specification for Highway Bridges [8] defines the allowable residual displacement as 1/100 of the height between the bottom of the column and the center of gravity of the superstructure. Thus, the allowable value for this specimen is just 25 (mm).

Splitting cracks are observed along the main reinforcement bars at the base of the column after 5 δ_y cycles and crushing of the cover concrete occurs at 6~7 δ_y cycles. No obvious symptoms of buckling are seen. The post-loading specimen is shown in Photos 1 and 2.

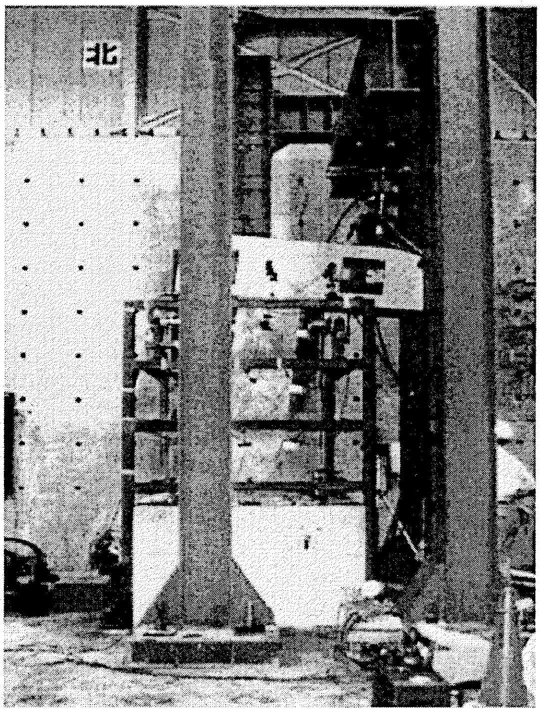

Photo 1 Damage to Specimen (whole)

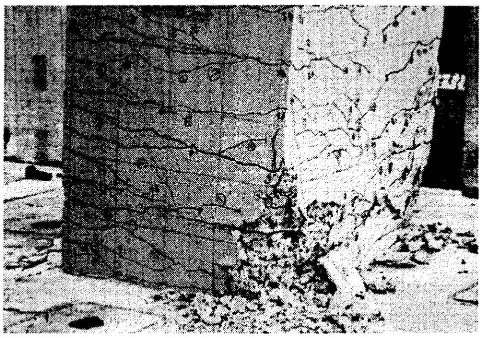

Photo 2 Damage to Specimen (base)

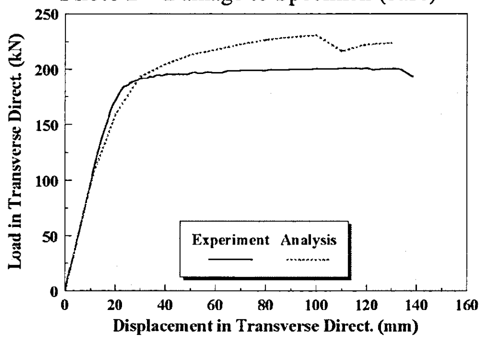

Fig. 6 Load – Displ. Relationship in the Eccentric Direction (after Damage)

Next, horizontal forces are applied in the eccentric direction after removal of the eccentric axial forces in order to check the residual capacity of the heavily damaged column. In spite of the deformation and inclination in the loading direction, the damaged column is found to possess sufficient strength to allow the passage of emergency traffic, as illustrated in Fig. 6.

The phenomenon of residual deformation accumulating in the eccentric direction after horizontal reversed-cyclic loading may be brought on by the existence of an eccentric axial force. However, there is a limit to lead the mechanism from the experiment only. Therefore, in order to obtain the multi-directional behavior of residual displacement, a numerical simulation is carried out in the next chapter to investigate the mechanism by which residual displacement accelerates in a direction perpendicular to the applied force.

3. MECHANISM OF RESIDUAL DISPLACEMENT ACCUMULATION IN THE NON-PRINCIPAL AXIS DIRECTION

3.1 Outline of Analytical Tool [11][15]

The target structure exhibits a three-dimensional nonlinear response, where the residual displacement is perpendicular to the primary horizontal load. This means that a two-dimensional numerical approach is not sufficient. In this numerical investigation, three-dimensional frame analysis based on the fiber technique of in-plane theory [7][15] is adopted. This analytical method is able to deal with reinforced concrete as well as elastic materials and interfaces between different materials. Although a full three-dimensional analysis based on three-dimensional constitutive models [12][13][14] could be applied to the target column, a simplified approach is chosen since shear deformation can be ignored. In the fiber technique, the sectional forces and moments in two directions are calculated from average axial strains and curvatures in two directions according to Euler's assumption, which states that a plane section remains plane. Because this reduces the number of degrees of freedom, well-convergent and stable numerical calculations can be carried out. With the use of suitable material constitutive models, this analytical tool is able to yield the flexure behavior of RC structures with greatly reduced analysis time [7][15][22].

Path-dependent nonlinear constitutive models of the concrete and reinforcing bars, including the unloading/reloading loops, are adopted as shown in Figs. 7 and 8 [11]. These models are based on the smeared crack model with an averaged relationship between strain and stress. The following adjustments are made to the conventional three-dimensional constitutive models of reinforced concrete:

1) Cracking criteria according to loading path are adopted;

2) The elastic-plastic fracture model is used for concrete compressive zones [11][16] and the fall in unloading stiffness is considered;

3) A tension-stiffening model representing the bonding effect is considered for the concrete tension zone and a smooth connection between compression and tension in the concrete model is assumed [11][17];

4) The zoning method, in which RC members are divided into a bond-affected area and an unaffected area, is introduced to enhance representation of the flexure response after cracking [18].

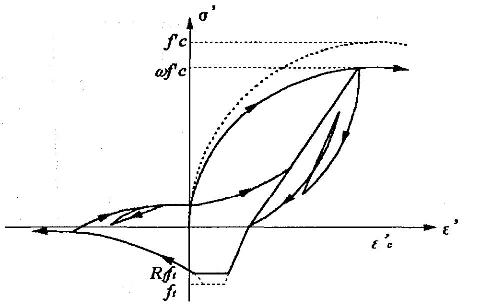

Fig. 7 Concrete Material Model [16][17]

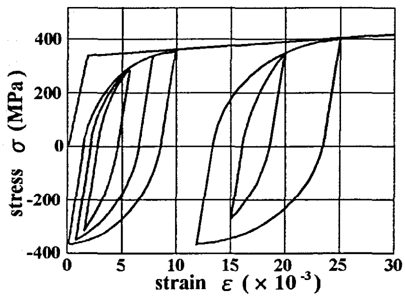

Fig. 8 Steel Material Model [17][18]

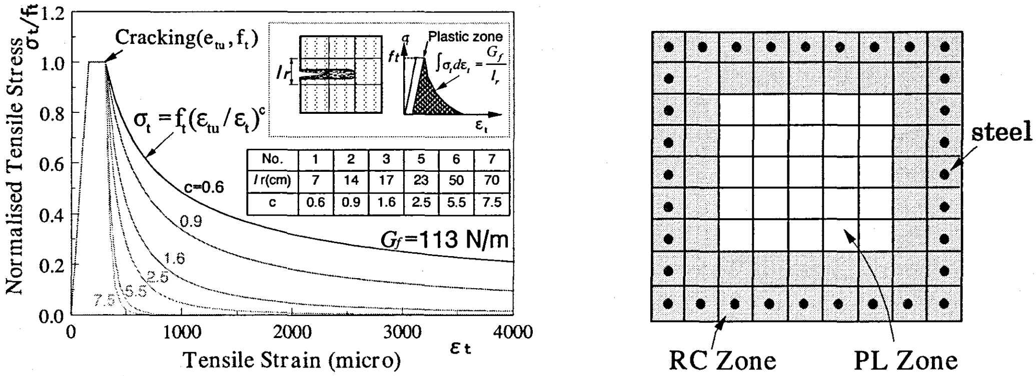

Fig. 9 Tension Softening and Zoning [15][18]

Zoning implies a means of dividing up the cross sections of an RC structure. Each cross section is divided into a bond-affected area (RC zone) and a bond-unaffected area (plain concrete zone). In the RC zones, bonding cracks occur in a dispersed distribution around reinforcing bars and concrete between the primary bending cracks still restrains elongation of the reinforcing bars. In this case, tensile stress develops in the concrete between the bending cracks. On the other hand, no tensile stress transfer can be expected between concrete and steel in the bond-unaffected area (plain concrete zone) or where the cracks run nearly parallel to the reinforcing bars. Stress falls dramatically after cracking, and insufficient tension force is present (tension softening) (Fig. 9).

In order to consider this effect, An et al. proposed the zoning method based on the limit reinforcement ratio [18], and their method is adopted in this study. Timoshenko beam theory is used in the analysis tool, and shear stiffness is assumed to be very large in the fiber technique. As a result, shear deformation is extremely small and can be ignored. In fact, this condition is irrelevant, since the target specimen is a flexure-prone RC column.

In the analysis reported here, pull-out of reinforcing bars from the footings is not considered. It has been reported that the ratio of deformation attributable to pull-out totals no more than approximately 10 (%), corresponding to the full-scale structure, for specimens of this scale if the cross section and reinforcement are scaled as closely as possible [21]. The displacement value in the experimental results represents the total response value, including any pull-out effects.

Constitutive models for behavior in the highly inelastic range, such as spalling of the cover concrete and buckling of the reinforcing bars, are not taken into account. For this reason, it can be expected that the experimental residual displacements will be larger than the analytical values. Additional research will be necessary to establish constitutive models for the highly inelastic range [23]. If accurate spalling and buckling models do become available, they can be incorporated into this analysis tool. In this study, the investigation proceeds by focusing on the mechanism of accumulated residual displacement due to material nonlinearity, and by intentionally excluding uncertainties.

A bi-linear model is adopted for steel in tension to represent the bond effect and the localization of plasticity [19] (Fig. 8). By considering the geometrical nonlinearity, the P- δ effect is taken into account.

As shown in Figs. 7 and 8, stiffness reductions and deterioration in materials due to repeated loading are not considered [10]. Thus, the stress path returns independently to the original value when strain goes back to the maximum experienced value. The reason for ignoring the stiffness reduction is that accurate models have not yet been proposed, as is the case for spalling and buckling. The focus is on the mechanism of accumulated residual displacement due to material nonlinearities, and any other uncertainties are ignored. The material models in this analysis tool are formulated from material tests subjected to static loading. Thus, creep behavior at short periods is automatically included in the analysis.

3.2 Analytical Results

Numerical simulations [20] are carried out for the experiments described in the previous section. The analysis mesh is illustrated in Fig. 10. Torsion is avoided as in the experiment, and reversed-cyclic loading is applied by static displacement control. The analytical results are shown superimposed on the experimental ones in Figs. 4, 5.1, and 5.2. Figure 4 shows the relationship between load and displacement in the horizontal loading direction, while Figs. 5.1 and 5.2 show the relationship with displacement in the loading direction and displacement in the eccentric direction, respectively. Figure 5.2 is an extended chart focusing on deformational behavior before the occurrence of splitting cracks at the base of the column.

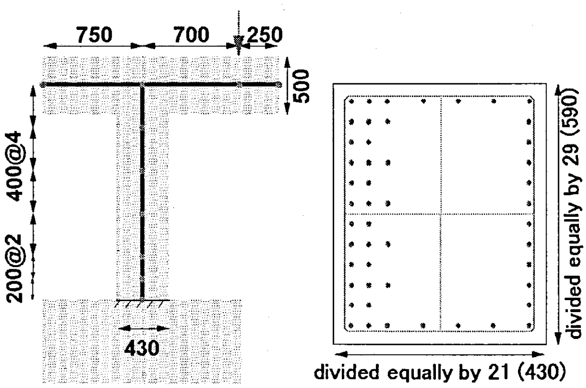

Fig.10 Summary of Mesh Definition

The comparison in Fig. 4 indicates that the analytical results comparatively agree with the experimental ones up to yielding. However, the analytical results indicate greater post-yield bending capacity than the experimental ones, and they begin to diverge from the experiment. This may be mainly due to the spalling of the cover concrete, the buckling of reinforcing bars, and bond deterioration, which are not taken into account in the constitutive models. The primary reason for the slightly increased capacity after yielding may be the simplified bi-linear model used for the steel. Whatever the reason, the RC column clearly possesses great energy absorption and superb seismic performance.

On the other hand, it is also clear from the analytical result that deformation in the eccentric direction is accelerated when reversed-cyclic static loading is applied in the orthogonal direction (see Figs. 5.1 and 5.2). The stiffness reduction arising from repeated loading is not considered in the computation. This leads to the conclusion that such complex deformation behavior does not result from material deterioration under repeated loading, but depends on some mechanism of the combined material system following different stress paths [10].

The experiment and analytical results agree well, especially up to 4 δ_y (Fig. 5.2). Although the residual displacement increases ever faster after 5 δ_y in the experiment, the analysis underestimates the displacement. The main reason for this may be deterioration of the bonds after yielding, spalling of the cover concrete, or buckling of reinforcing-bars — phenomena that are not taken into account in the constitutive models. To enhance the accuracy of these computations, it will be necessary to consider such factors in the models. Although no obvious buckling was observed in the experiments, lateral deformation takes place gradually rather than suddenly. Consequently, highly plastic steel behavior may also be thought as a factor that modifies the analytical estimate.

Horizontal forces are applied in the eccentric direction after removing the eccentric axial force, as in the experiments. As shown in Fig. 6, although the analysis slightly overestimates capacity, the flexure behavior is stable and sufficient residual capacity is indicated, as in the experiments. The reason for the slight overestimation of capacity may also be spalling of the cover concrete. While the analytical method is based on material models that take into account the full bond effect, spalling arises because of horizontal loading in the orthogonal direction in the experiment. This may cause the observed divergence.

Incidentally, it is difficult to link crack distributions and damage information obtained in the experiments with the physical values resulting from computations, since the analytical method is based on a reduced number of degrees of freedom. To deal with this problem, the authors are separately proposing a full three-dimensional analysis that deals directly with all cracks and compressive plasticity/fracture behavior, in which the degrees of freedom are completely preserved. By comparing the local crack distribution and the stress profile of the steel, etc. in the experiment with full three-dimensional analytical results, these verifications for linking damage conditions with the numerical values are conducted.

From this discussion, it can be concluded that the analytical results qualitatively agree with the experimental observations up to the inelastic range, and that the mechanisms at work in reality are incorporated into the analysis. Conversely, it is possible to make assumptions about constitutive models not yet incorporated into the analysis by comparing the analytical results and actually observed phenomena. In order to investigate the nonlinear response that residual displacement accumulates in the direction perpendicular to applied forces, two parametric studies are conducted:
1) Repetitions for the same forced displacement cycle are set to four;
2) Initially, horizontal forces are applied up to +8 δ_y without axial load, and then eccentric axial forces are applied. Each strain path and stress distribution is examined in detail after the calculations.

3.3 Parametric Study and Considerations

The analytical results for four repetitions are illustrated with those for two repetitions in Figs. 11 and 12. There is no difference between the four and two repetitions in the load displacement relationships although repeated number is increased (Fig. 11).

However, deformation in the eccentric direction gradually accumulates with the number of cycles (Fig. 12). In the case of RC columns subjected to axial forces at the center of the cross section, deformation does not progress beyond three cycles in the analysis. The influence of repeated loading is evident in the overall structural response, even though damage models at the material level are neglected. This behavior arises from the combination of different materials with different nonlinear stress-strain paths.

These analytical results are the key to understanding the mechanism of the experimentally observed phenomena. However, a detailed consideration of the number of repeated cycles is presented in the next section along with a description of the mechanism of residual displacement in the eccentric direction.

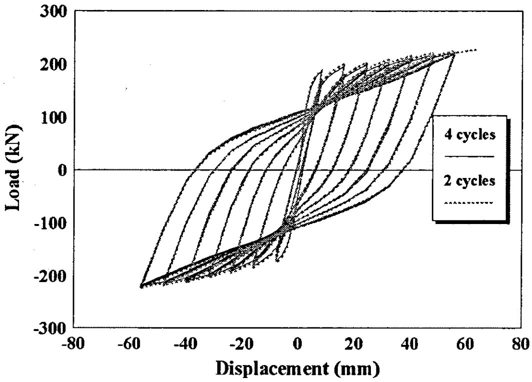

Fig. 11 Load – Displacement Relationship in the Orthogonal Direct. (repeat 4)

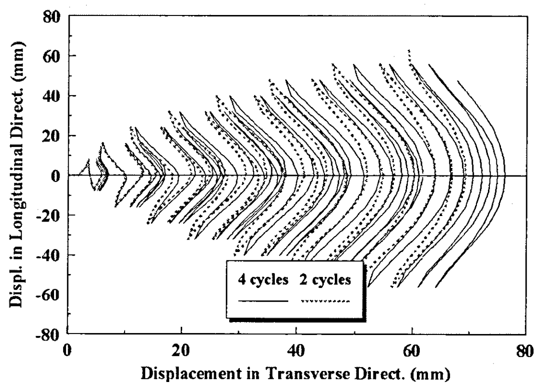

Fig. 12 Displ. in the Orthogonal Direct. – Displ. in the Eccentric Direct. Relationship (repeat 2)

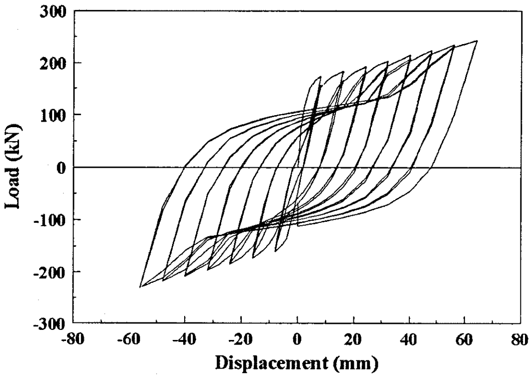

Fig. 13 Load–Displ. Relationship (horizontal only)

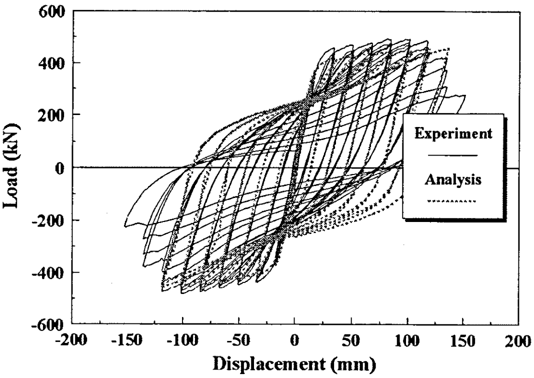

Fig. 14 Load–Displ. Relationship (without eccentricity)

We now move on to the second parametric analysis. The horizontal force is applied up to $+8\,\delta_y$ without an axial load. Then eccentric axial forces are applied. The object of this loading pattern is to evaluate the influence of different loading paths on the overall structural response. For this parametric analysis, the present verification method that judges seismic performances individually for eccentric axial forces and horizontal loading are supposed. As illustrated in Fig. 13, restoring behavior in the horizontal loading direction exhibits an inverse S-shaped loop after yielding of the main reinforcement when horizontal forces are applied without axial compression. Usually, the relationship between load and displacement of RC columns without eccentricity has a similar S-shaped form, too. A past experiment that used specimens similar to those used here indicates this pinching behavior [21]. These results are shown in Fig. 14. Its simulation is also carried out, for reference.

This pinch effect is a result of bending compression forces on the steel. The reinforcing bars in the both compressive and tensile sides become highly plastic locally at the crack plane due to reversed-cyclic loading. The crack plane then penetrates all cross sections, and the bending moment is resisted by the reinforcing bars alone when the applied forces are small. At this time, the stiffness of the member is also low. When a relatively larger forced displacement is added, the concrete begins to undergo compression and stiffness increases rapidly. This explains the analytical result that shows up as an inverse S-shaped restoring property. A similar situation may happen to RC columns without eccentricity [21].

In contrast, cracks opened up by horizontal loading always keep in touch somewhere due to the existence of the eccentric moment in the case of eccentric RC columns. In this case, the situation where reinforcing bars alone resist the bending compression forces is not observed in the analysis, and the concrete contributes to resist part of the compression force. Consequently, the relationship between load and displacement in the direction perpendicular to the eccentric moment takes on a spindle shape and energy absorption is excellent. This is made clear by comparing Figs. 13 and 14.

On deformation in the eccentric direction, the RC column deforms in the negative direction with horizontal loading only. It then deforms in the positive direction after the application of eccentric axial forces (Fig. 15). However, this deformation is very small, less than 1/3 of that shown in Fig. 5.1. The edge, which contains little reinforcement, first begins to yield due to the non-symmetric cross section when horizontal forces are applied without an axial load. Thus, the column cross section takes on a curvature in the opposite direction to the eccentric moment, and exhibits the deformation path shown in Fig. 15. Horizontal flexure loading alone is unable to take the side reinforcement to the yield point. This is in striking contrast to the case of coupled loading, when most of the side reinforcement is susceptible to yielding. This demonstrates clearly that plasticity, stress, strain, etc. of the materials comprising a structure are affected greatly by different loading paths.

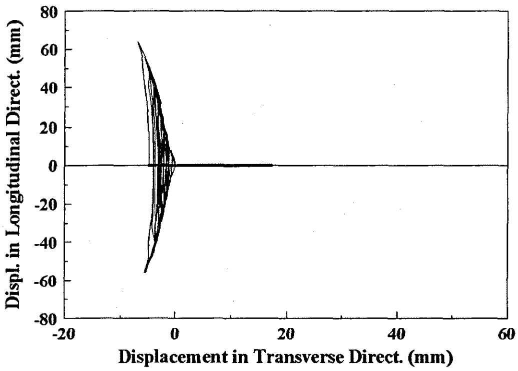

Fig. 15 Displ. in the Orthogonal Direct. – Displ. in the Eccentric Direct. Relationship (horizontal forces→eccentric axial forces)

3.4 Mechanism Elucidation and Verification

The application of reversed-cyclic loading to an eccentric RC pier in the direction perpendicular to the eccentric moment causes irreversible deformation. The analysis suggests that this phenomenon is strongly related to complex interactions between tension and compression due to bending as well as between tension and compression due to eccentric axial forces. Here, we consider the mechanism behind the phenomenon based on the experimental and analytical results.

Focusing first on the group of reinforcing bars under tension as a result of permanent eccentric axial forces (group *A* in Fig. 16), these do not reach the yield point if eccentric axial forces alone are applied. When horizontal forces are applied in the orthogonal direction, some of group *A* move into flexural compression while others move into flexural tension. Consequently, some reinforcing bars in the tension zone supporting the eccentric moment undergo plastic deformation and the re-bars group elongated by orthogonal horizontal forces causes a rotation in the eccentric direction.

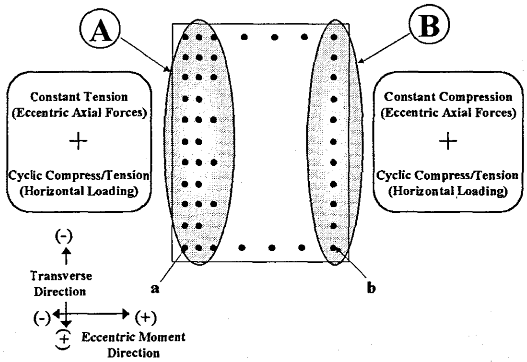

Fig.16 Re-bar Groups at Cross Section

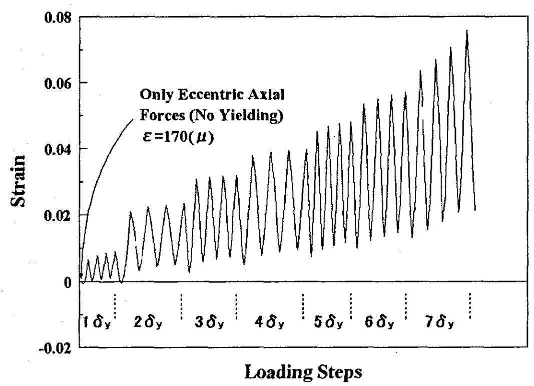

Fig.17.1 Steel Strain History of Point a

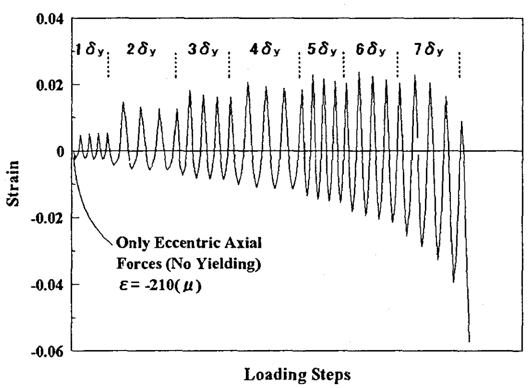

Fig.17.2 Steel Strain History of Point b

In group *B*, which are uniformly compressed due to the eccentric moment, some steel bars are compressed by the horizontal forces and some are placed under tension, as with group *A*. If compression forces due to the eccentric moment is applied to the re-bars elongated to the plastic range by the horizontal forces, only the re-bars in group *B* have to support compressive forces until opening cracks start touching again. At this time, the stiffness is considerably low.

As this makes clear, the analysis shows that reinforcing bars that do not yield under the eccentric moment alone experience a plastic loading history when horizontal forces are applied in the direction perpendicular to the eccentric moment. This causes a decrease in the cross-sectional stiffness in the eccentric direction.

Typical strain histories of two reinforcing bars, *a* and *b* in the analysis, are shown in Figs. 17.1 and 17.2 for four cycles. Even in the same forced displacement value in the loading direction ($\pm n\,\delta_y$), an increase in absolute strain value is observed. Thus, deformation accumulates more in the eccentric direction as the number of cycles increases. This type of loading history is not generally observed for RC columns without eccentricity.

After reinforcing bars in group *B* are elongated to the plastic range in tension by horizontal forces, they experience compressive plasticity by the eccentric moment when the horizontal forces are close to zero. Accordingly, the concrete compression zone decreases its domain as shown in from Fig. 18.1 to Fig. 18.8. The plasticity influences strain paths of reinforcing bars in group *A* and the overall strain path. The multiplication of the arbitrary loading path and the strain paths of composite materials causes plastic deformation of reinforcement to increase continuously and the concrete compression zone decreases under bi-axial bending. Figure 18 describes stress conditions at the base of the column, at the maximum displacement of $\pm 2\,\delta_y$ from the first to the fourth cycle in the longitudinal direction. The same tendency is observed in other loading cycles except $\pm 2\,\delta_y$. The circular stress distribution at the center of the cross section is the remains of stress flow towards the corner. In the case of bending, compressive stress is not uniformly distributed in the loading direction, and a stress flows towards the corner of the rectangular cross section.

It is observed that the relationship between displacement in the horizontal loading direction and displacement in the eccentric moment direction progresses in a bow-shape, as seen in Figs. 5.1, 5.2, 12, and 15. Displacement in the eccentric direction is higher when the applied horizontal forces are small, whereas it becomes smaller when the forces increase. This phenomenon is closely related to the positions of reinforcing bars that become plastic under a combination of the eccentric moment and the orthogonal horizontal forces.

Most reinforcing bars in group *B* in the compression zone due to the eccentric moment move into the tension zone when large orthogonal horizontal forces are applied. Because these reinforcing bars undergo severe pulling, curvature in the eccentric direction is reduced. Thus, displacement in the direction of the eccentric moment becomes smaller when horizontal forces are large.

Here, reinforcing bars in group *B* in the tension zone mostly shift into the compression zone when the horizontal forces return close to zero. Because these reinforcing bars are under compression, curvature in the eccentric direction becomes larger. Accordingly, displacement in the direction of the eccentric moment becomes larger.

When horizontal forces are applied in the reverse direction, similar behavior takes place on the opposite side, and displacement in the eccentric direction becomes smaller. The bow-shaped history results from this behavior.

It is now evident that RC piers subjected to eccentric axial forces undergo accumulating displacement in the eccentric direction when subjected to reversed-cyclic loading in the direction perpendicular to the eccentric moment. During an earthquake, structures are exposed to multi-directional ground motion. Three-dimensional response analysis has suggested that the maximum response displacement and residual displacement of an RC column, even a flexure-prone one, under multi-directional ground motion may be greater than when the ground motion is in one direction [15]. While it is necessary to investigate the dynamic response of eccentric RC columns under multi-directional ground motion, especially focusing on residual displacement, this problem will be discussed in a future paper.

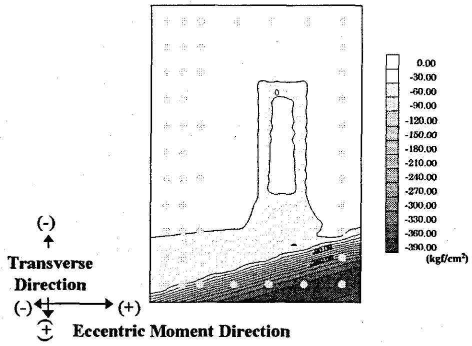

Fig. 18.1 Concrete Stress at +2 δ y (1)

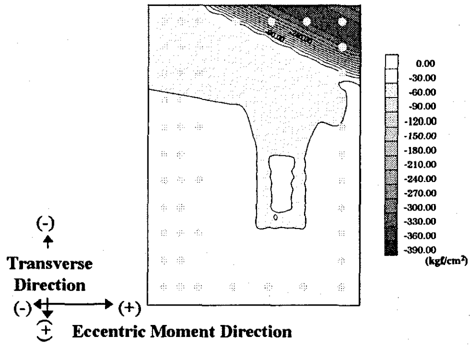

Fig. 18.2 Concrete Stress at -2 δ y (1)

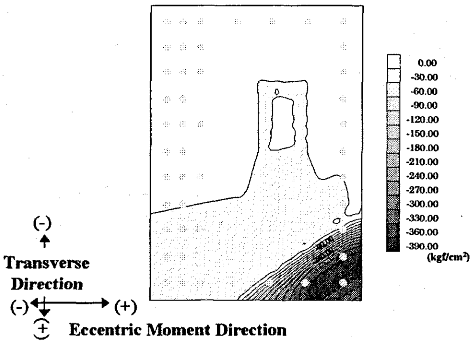

Fig. 18.3 Concrete Stress at +2 δ y (2)

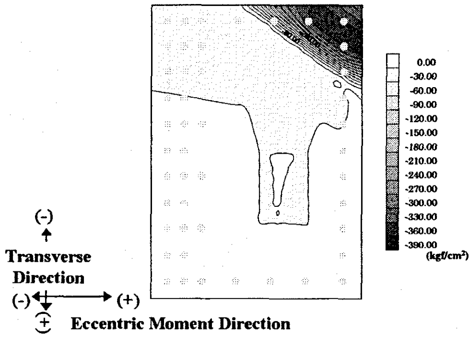

Fig. 18.4 Concrete Stress at -2 δ y (2)

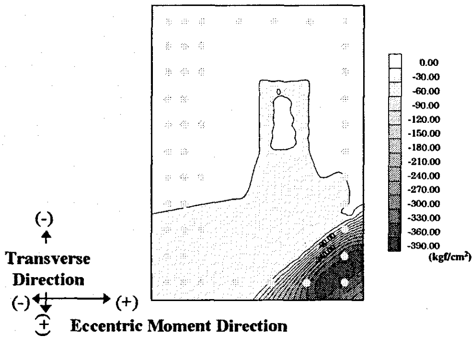

Fig. 18.5 Concrete Stress at +2 δ y (3)

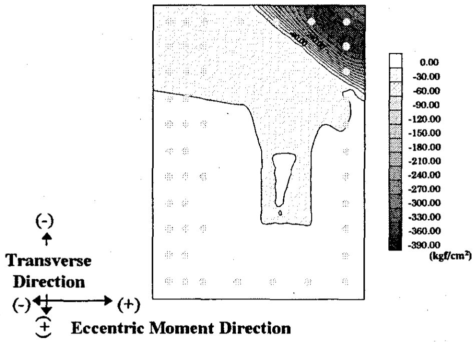

Fig. 18.6 Concrete Stress at -2 δ y (3)

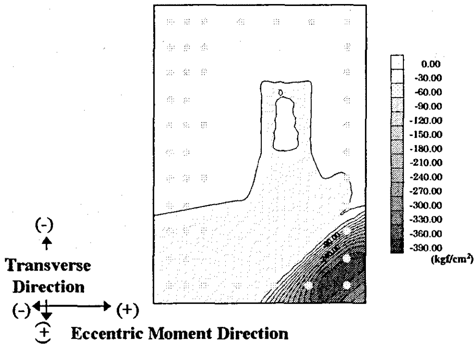

Fig. 18.7 Concrete Stress at +2 δ y (4)

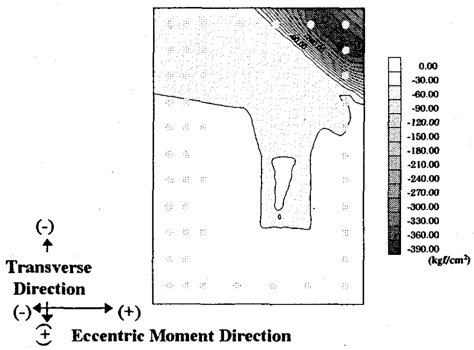

Fig. 18.8 Concrete Stress at -2 δ y (4)

4. VERIFICATION OF RESIDUAL DISPLACEMENT

After the Hyogoken-Nanbu Earthquake, the importance of ductility design for RC piers was, once again, recognized, particularly with respect to rare but very large earthquakes (level two earthquake). Simultaneously, the need for residual displacement control in the case of important RC structures also became obvious. In the design and verification process used for RC piers, seismic performance is usually judged independently by dividing it into transverse and longitudinal behavior. It is very difficult to consider the interactions resulting from a multi-directional input motion with such a method. Where the dimensions of the structure are non-symmetric and loading is eccentric, as is the case in this study, it may be difficult to carry out an independent verification, especially for residual displacement estimation. This is because the residual displacement increases beyond 120 (mm) when reversed-cyclic loading is applied in the orthogonal direction under constant eccentric axial forces, while displacement caused by permanent eccentric axial forces only is about 30 (mm) (Fig.5.2). Residual displacements differing by a whole order of magnitude cannot be directly derived from the individual verifications in two directions. A verification method based on three-dimensional dynamic response analysis with a three-dimensional model and input motions seems to be desirable. It would be difficult to carry out an equivalence operation that would allow us to consider multi-directional effects in two-dimensional analysis. Nowadays, three-dimensional nonlinear dynamic analysis has become established as a practical tool However, at the process determining structural dimensions and materials in the performance verification, it is important to give priority to designer's personality and choice. The uniform decision for any infrastructures at design process is not an objective of the performance-based design methodology at all.

For enhancement of dynamic response analysis for eccentric RC piers under multi-directional ground motion, it is necessary to install a support model between a pier and a girder, a interaction effect of adjacent piers and an interface model between soil and piles. It is again recognized that repeated material property of steel after buckling is essential to enhance residual response analysis as well.

5. CONCLUSIONS

It is experimentally observed that an RC column under eccentric axial loading accumulates a residual displacement in the direction of the eccentric permanent moment when horizontal reversed-cyclic loading is applied perpendicular to the eccentric moment. The mechanism of this residual displacement is explained using three-dimensional analysis based on the fiber technique of in-plane theory. Parametric analysis suggests that the residual displacement increases orthogonal to the force direction as the number of cycles of loading is increased.

Regarding the residual displacement of RC piers subjected to eccentric axial loading, this is difficult to evaluate independently along the orthogonal principal axes, and to argue the rationality of the independent estimation. A verification based on a three-dimensional model and direct input motions is more rational than the equivalent two-dimensional approach.

It is recognized, through a comparison of experimental and analytical results, that three-dimensional frame analysis using the fiber technique is accurate enough to yield capacity and (residual) displacement values. There remain problems in modeling spalling and buckling, etc. in the highly inelastic range. The analytical results, which may underestimate response displacement due to these factors, can be useful by taking the present ability of numerical simulations into consideration because their effects is relatively smaller in real scaled structures.

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