



SF-I

Introductory Report
INELASTIC RESPONSE OF 3-D STRUCTURES AND
MULTI-DIRECTIONAL SEISMIC FORCES ON STRUCTURAL COMPONENTS

Akenori SHIBATA

Faculty of Engineering, Tohoku University, Sendai, Japan

SUMMARY

The paper reviews the state-of-the-art of analyzing the inelastic earthquake response of 3-D reinforced concrete frames subjected to multi-components of earthquake motions. The importance of member-by-member analysis is emphasized for the purpose of understanding the inelastic behavior of each constituent member in 3-D frames. Various inelastic member models are reviewed, especially with regard to biaxial bending and varying axial force combined with bending. Discussed are the problems related to the inelastic earthquake response behavior of 3-D frames, such as column over-design factor for biaxial bending, effect of varying axial force to frame behavior, and inelastic torsional response.

INTRODUCTION

Realistic assumption in the modeling of actual frame structures under earthquake excitation is representing structures by three-dimensional frame models subjected to multi-component earthquake motions. With the rapid progress in computer capabilities, analysis of inelastic 3-D frame models with large degrees of freedom has been made possible. Also, many experimental studies on the inelastic behavior of structural elements under multi-directional forces have developed realistic modeling of structural members for 3-D frame analysis.

Detailed understanding of 3-D behavior of frames and individual members enables more realistic assessment of earthquake resistance capacity of structures. Many examples of damage are found in recent earthquakes which can only be interpreted by the complex 3-D behavior of frames subjected to multi-dimensional earthquake excitations. Further research on 3-D inelastic response under 3-D earthquake excitations is strongly needed for advanced seismic analysis and design of structures. In this report, giving primary attention to reinforced concrete frames, current trends and problems regarding the inelastic earthquake response analysis of 3-D frames are discussed.

MODELING OF 3-D FRAMES

Planar Frames

In the earthquake response analysis of framed structures, planar frame models subjected to one-component earthquake excitation have been generally used. Planar frame analysis is the basis of 3-D frame analysis, and accumulation of knowledge

and techniques on planar frame response analysis has been abundant.

In the early days of inelastic response research, modeling by multi-mass shear system was used, in which the inelastic lateral resistance properties of frames were represented by equivalent inelastic springs expressing the story shear-interstory deflection relation [1]. However, one cannot grasp the inelastic behavior of each constituent member during an earthquake by the story-level analysis using the shear system.

Member-by-member modeling of frames which takes account of the damaging process of each constituent element such as column, beam or shear wall, is needed in order to consider the earthquake resistance capacity on the member behavior level. Response behavior of beam-yielding frames which is considered to be preferable in seismic design can only be rationally evaluated using member-level modeling (Fig. 1). Up to now, many researches on the member-level analysis of planar frames have been presented [2],[3],[4],[5],[6]. Member-level analysis of RC frames requires inelastic member models representing the actual mechanical behavior of RC member elements under various stress conditions.

3-D Frames

Behaviors of actual frame structures under strong earthquake excitations are best represented by 3-D inelastic space frame models subjected to multi-component ground motions (Fig. 2).

Two methods have been generally used for the analysis of 3-D frames. The one is decomposing a framed structure into planar frames in two perpendicular directions, evaluating stiffness matrix of each frame independently, and then constructing the equilibrium equations of total 3-D frame by combining the stiffnesses of planar frames. This method, sometimes called pseudo 3-D analysis, has been extensively used in the research of torsional vibration. Rigid floor assumption is generally adopted. The interaction between planar frames in two directions is sometimes neglected or is considered in approximate ways.

The other is constructing 3-D equilibrium equation directly based on the 3-D member stiffness matrices of constituent elements, which is the orthodox way of analyzing 3-D frames, though it requires much computational efforts [7].

Clarifying the effects of biaxial bending interaction, varying axial force-bending interaction, and deterioration in beam-column joints on 3-D inelastic frame response under strong earthquake excitation is among the major concerns in the earthquake resistant design of RC frames.

Behavior of shear walls combined with open frames needs to be investigated by means of 3-D frame analysis (Fig. 3). Difference in the deformation properties of shear walls and open frames causes interaction between them, which can be properly evaluated by 3-D frame analysis taking account of both in-plane and out-of-plane frames simultaneously [10],[11].

INELASTIC MEMBER MODELS

In order to predict the inelastic dynamic response of frames under earthquake excitation by member-by-member analysis, pertinent inelastic member models have to be developed which can represent the characteristic mechanical properties of each member element such as columns, beams, and walls.

Member Models for Planar Frame Analysis

In member models usually adopted in planar frame analysis, only uni-directio-

nal bending is considered. Shear or axial resistance property is usually treated independently, without considering interaction between multi-component stresses.

Inelastic spring model (one component model) is a member model having two concentrated inelastic springs at both ends of an elastic line element (Fig. 4). Giberson[4] discussed the use of this model and it has been widely adopted for the analysis of RC frames. This model can incorporate arbitrary moment-rotation relations in the end springs which can simulate the cyclic bending behavior of RC members including cracking, yielding and stiffness degradation [13],[14]. For elements with moment distribution different from anti-symmetric distribution such as shear walls, multiple-spring model can be used [12].

Parallel element model (two component model) is a member model consisting of elastic element and inelastic element producing plastic hinges at both ends arranged in parallel. This model was originally used by Clough[3] for bilinear member property (Fig. 5a). Aoyama[8] used multi-element parallel model to express trilinear force-displacement relation (Fig. 5b), and Takizawa considered modified parallel model which can be applied to wider classes of force-displacement relation [9].

Assumption regarding the flexibility distribution along the member is an important problem for inelastic member models. Inelastic spring model assumes concentrated inelastic rotation at spring positions. Takizawa assumed parabolic flexibility distribution along the member axis in order to obtain inelastic member stiffness matrix. Detailed discussion on the comparison of member models was made by Takizawa[9].

Member models including inelastic shear property have to be used for members such as shear walls, short columns and beams (Fig. 6). Shiga et al.[15] used a member model considering shear failure for the analysis of the Engineering Building, Tohoku University, which experienced the 1978 Miyagi-ken-oki earthquake. Kabeyasawa[11] proposed several inelastic member models for shear walls.

Behavior of beam-column connections is also a problem of concern. Inelastic panel zone stiffness and bond deterioration in beam-column joint affects the total stiffness of frames. Effect of bond deterioration within panel zones can be included in inelastic springs of beam model.

Member Models for Biaxial Bending

Modeling of inelastic behavior of columns considering biaxial bending is indispensable for the analysis of the inelastic behavior of 3-D frames under bi-directional earthquake motions. Column damages of Hachinohe Library in the 1968 Tokachi-oki earthquake and of Olive View Hospital in the 1971 San Fernando earthquake gave impetus to the research of biaxial bending behavior of RC columns [16],[17],[18].

Two types of analytical model are generally used for the biaxial bending problem. The one is a model utilizing plasticity theory. Bi-directional restoring force characteristics considering interaction is defined by analogy with the plasticity theory considering yielding condition, associated flow rule and hardening rule in the two dimensional stress state.

Nigam[19] discussed this problem for the first time assuming elasto-plastic uniaxial property, and analyzed the inelastic response of one mass system to two directional ground motions. Takizawa[22] applied the Nigam's method to the case with trilinear uniaxial property which is the characteristics of RC frames (Fig. 7). Earthquake response analyses utilizing the biaxial bending model by plastic theory have been done by many researchers [24],[25].

The other is a model by discretized section. A section of RC member is divided into small elements characterized by uniaxial inelastic stress-strain relation, and the moment curvature relations in two perpendicular directions are obtained assuming linear strain distribution (Fig. 8). This model is called filament model or fiber model. Member stiffness matrix is obtained by assuming various curvature distribution or flexibility distribution along the member. This method is applied to arbitrary section shape, and can consider realistic stress-strain properties for concrete and steel. The method also takes account of the varying axial force together with biaxial bending.

Aktan[26] analyzed inelastic RC columns under biaxial bending using filament method, and studied the one-mass column response to bi-directional earthquake motions. Okada[29] conducted the dynamic tests on the biaxial bending of RC columns, and compared the test results with the analytical results using discretized section model.

Lai, Wilson and Otani[30] proposed a multi-spring model which consists of two inelastic elements at the two ends of RC member sandwiching a linear elastic element. Each inelastic element has four inelastic springs at the four corners of the section representing effective stiffness of steel and concrete, with a fifth spring at the center of section for concrete (Fig. 10). This model seems to provide a useful practical tool for analyzing 3-D RC frames well into inelastic range. Lai[31] also compared the multi-spring model and plasticity based model with regard to test specimens.

A somewhat different macro model for inelastic bi-directional response is given by Wada and Kinoshita[32], which is a story-level model consisting of many inelastic springs arranged in multi-direction. Shibata, Shibuya and Satake[33] extended this model to member model for biaxial bending which has two multi-directional inelastic rotation springs at the both ends of elastic linear member, and applied it to bi-directional earthquake response of RC frames (Fig. 11).

Member Models for Varying Axial Force and Bending

For incorporating the effect of varying axial force in inelastic member model, discretized section models are frequently used. Emori[35] used a layered model for the bottom story column consisting of an elastic line element and a finite length of layered region at the end of column.

Kaba and Mahin[36] presented a multi-slice fiber model which can account for varying axial force and bending. This model considers several slices along the member axis at which the inelastic moment-curvature relationships are calculated and evaluate member stiffness matrix assuming linear variation in flexibility between slices (Fig. 9).

Ristic, Yamada and Iemura[37] used a model which considers several interface elements along the member assuming linear variation in flexibility between interfaces. Complex stress-strain relations for steel and concrete are used to represent realistically the actual nonlinear behavior. Results of the on-line hybrid loading tests of RC columns under constant and varying axial forces are compared with the computed force-displacement relations by the analytical model.

Li, Otani and Aoyama[40] compared the experimental inelastic behavior of RC columns under 3-dimensional stress state of biaxial bending and varying axial force with the calculated behavior using multi-spring model. The method to determine the parameters included in the model is studied.

Application of plasticity theory to the problem of varying axial force-bending moment interaction in RC frames has also been made. Kobori, Minai and Fujiwara[24] considered both biaxial bending and varying axial force in 3-story

space frame analysis assuming bilinear uniaxial property. Fukuzawa[41] made earthquake response analysis of a 30 story reinforced concrete highrise apartment utilizing the axial force-resisting moment interaction curve of RC column and the plasticity theory considering trilinear uniaxial property.

Sophisticated nonlinear 3-D finite element models considering triaxial state of concrete by plasticity theory have been made for analyzing the behavior of RC columns under biaxial bending and axial force, and the static cyclic behavior of columns could be satisfactorily simulated [42]. For dynamic frame analysis, however, use of inelastic 3-D finite element is costly and simplified member models are preferably used.

EARTHQUAKE RESPONSE BEHAVIOR OF 3-D FRAMES

Column Behavior for Biaxial Bending

In designing ductile beam-yielding frames, special care has to be taken to avoid the excessive damage in columns caused by biaxial bending moments. Even if beam yielding mechanism is guaranteed for one component of earthquake motion, column failure may arise under the simultaneous action of two components of earthquake. It is necessary to use column over-design factor taking account of biaxial bending in order to give appropriate redundant strength in columns. Higher mode effect causes the increase in dynamic moments and shears in columns compared to static case, thus affecting column over-design factor.

Yoshimura[43] studied bi-directional inelastic response of one column model representing middle column of 3 story RC building designed with base shear coefficient of 0.3, using member model by plasticity theory with trilinear characteristics, and showed that in order to realize beam-yielding design in which beam damage is always greater than column damage, column over-design factor should be 1.3 to 1.4. Halim[44] studied one column model for 4 to 12 story building under similar conditions and showed that column over-design factor to prevent column yielding is 1.5 to 1.6 for short period for the earthquake of 0.4G or beam ductility factor of 4 or less and that the over-design factor decreases with the increase of natural period (Fig. 12).

Effect of Varying Axial Forces

Outer columns in building frames are subjected to large varying axial forces accompanied by horizontal earthquake forces. In case of 3-D frames under two components of horizontal earthquake motions, corner columns sustain direct sum of large axial forces from two perpendicular frames. In side columns except corner columns, varying axial forces due to one direction of earthquake motion are dominant, but these forces also give influence to the column behavior in the perpendicular direction.

Restoring force characteristics of outer columns exhibit unsymmetrical features due to compressive and tensile axial forces accompanying lateral forces. The effect of unsymmetric restoring force property is usually canceled for the overall behavior of frames, but it gives considerable effect on the local damage in columns.

Takizawa[45] investigated the behavior of planar frame considering the effect of varying axial force in outer columns through an approximate approach using the method of equivalent S.D.F. system, and pointed out that the effect of varying axial force in outer columns is small for behavior of total frame, whereas it cannot be neglected for member-level damage evaluation.

The influence of varying axial force in columns produced by the bending of

shear wall in the transverse direction on the inelastic behavior of column in the longitudinal direction was investigated by Handou, Shibuya and Shibata[46], using simplified analytical model, in which the lower half of the first story column is modeled by a cantilever column having fiber slice at the bottom, the remaining upper part of longitudinal frame is modeled by an inelastic S.D.F. system assuming beam yielding, and the predetermined varying axial force obtained from shear wall response is applied to the top of cantilever column (Fig. 14). Earthquake response behavior of column is largely affected by the presence of axial force from the perpendicular direction.

Inelastic Torsional Response

Torsional vibration is induced by eccentricity in stiffness and mass. In case of inelastic response, unbalance in strength also causes torsional response. Though elastic torsional response problem has been studied extensively, inelastic torsional response of 3-D frames still has rooms for further research, partly for large variations in parameters to be included, and partly for large computational efforts.

The damage to Hachinohe Library in the 1968 Tokachi-oki earthquake was studied by Okada et.[16]. The building was one-story reinforced concrete building with strongly eccentric shear walls and suffered heavy damage in columns at the far end from shear walls due to the large displacement caused by torsion. Inelastic torsional analysis was made for this building assuming circular yield condition for the biaxial bending of columns.

The damage of Maruyoshi building in 1978 the Miyagi-ken-oki earthquake was studied by Shiga et.[47]. This building is a 3 story reinforced concrete building and has eccentricity in the first floor which caused heavy damage in corner columns. Inelastic torsional response was studied by the so-called pseudo 3-D member-level analysis without taking account of biaxial bending nor varying axial force. Analytical results could explain the overall damage.

Yamazaki[48] investigated the effects of biaxial bending of columns on the inelastic torsional response by parametric study using simple one-story space frames, assuming biaxial bending model based on plasticity theory with elasto-plastic uniaxial property (Fig. 13). Comparison of response results shows that biaxial interaction does not always increase the response values, and responses in two directions are influenced each other, sometimes causing averaging effect.

Tso and Sadek[49] also investigated the effect of bi-directional input and the biaxial interaction effect using single story model with four equal columns having mass eccentricity, and showed that biaxial interaction tends to give smaller response compared to the case neglecting interaction and that for eccentric system bi-directional response could be estimated based on uni-directional response. However, more studies are needed to obtain general conclusion on the inelastic torsional behavior.

The effect of the eccentricity by shear walls on the inelastic torsional response was studied by Nishikawa[50]. Analytical models consist of one-story frames with various number of spans in longitudinal direction. Shear walls were provided in transverse direction at different positions to yield various eccentricity. Wall resistance is provided only for one direction and column resistance in two directions with consideration of biaxial bending, assuming bilinear force-displacement relation for walls and frames. It is pointed out that for the range of relatively small eccentricity, the existence of shear walls can decrease the maximum frame displacement in eccentric building as compared with the case of pure open frame.

In designing irregular-shaped buildings, inelastic 3-D response behavior

should be examined. For example, setback type buildings can undergo significant torsional vibration during earthquakes. Satake et.[51] analyzed the inelastic torsional response of a 11-story reinforced concrete apartment building with setback subjected to two components of earthquake motions by pseudo 3-D member-level analysis and recommended appropriate distribution of strength based on the elastic shear distribution (Fig. 15).

MULTI-DIMENSIONAL EARTHQUAKE MOTIONS

The importance of research on the characteristics of multi-component earthquake motions must be emphasized for realistic understanding of the inelastic response behavior of 3-D frames.

General characteristics on the correlations between three components of recorded ground motions as well as the characteristics of each motion must be studied in order to predict accurately 3-D structural response to future earthquake[52],[53]. Effect of vertical motion to structural damage in nearfield earthquake needs to be studied.

Though horizontal and vertical components of recorded strong motions are being used for response calculation at present, 3-D simulated earthquake motions will have to be considered for 3-D frame response analysis in the future. The concept of principal axes for the 3-D ground motions is often utilized for generating 3-D simulated earthquake motions [54],[55],[56],[57].

Strong earthquake motions may differ at different points of which distance is the order of the plan dimension of buildings. Spacial variation in the characteristics of earthquake motions and its effect on structural response must be investigated both theoretically and experimentally [58]. Array measurements aiming at clarifying the earthquake input mechanism are strongly needed. One of the causes of phase difference in earthquake motions will be the generation of surface waves due to discontinuous irregularity in soil layers [59]. Topographical conditions including irregularities of soil layers around the site will have to be considered when considering simulated earthquake inputs.

CONCLUSIONS

The state-of-the-art of analyzing the inelastic earthquake response of reinforced concrete 3-D frames based on the inelastic behavior of constituent members has made remarkable advance in recent years with the rapid advance of computer capability and the development of useful member models to rationally simulate the inelastic behavior of RC members under multi-directional seismic forces. A number of experimental researches have been conducted on the biaxial bending and combined varying axial load - bending, and analytical member models reflecting the inelastic behavior have been proposed.

Though methods of analysis and computer programs have been developed greatly, our understanding on the behavior of inelastic 3-D frames under strong earthquakes is still limited and more response studies for various cases and parameters have to be made to understand how the 3-D effect influences the gross behaviors as well as local damages in reinforced concrete frames.

The inelastic 3-D analysis should also be utilized in the earthquake resistant design of complex structures, and the results of parametric studies on inelastic 3-D earthquake response has to be incorporated in design procedures, by which rational safety factors will be secured in each part of structures.

REFERENCES

1. J.Penzien, "Elasto-Plastic Response of Idealized Multi-Story Structures Subjected to a Strong Motion Earthquake," Proc. of the 2nd World Conference on Earthquake Engineering, Tokyo, 1960.
2. G.V.Berg and D.A.Dadeppo, "Dynamic analysis of elasto-plastic structures," Proc. of ASCE., Vol.86, No.EM2, 1960.4, pp.35-58.
3. R.W.Clough, K.L.Benuska and E.L.Wilson, "Inelastic Earthquake Response of Tall Buildings," Proc. of the 3rd World Conference on Earthquake Engineering, New Zealand, 1965.
4. M.F.Giberson, "Two Nonlinear Beams with Definition of Ductility," Proc. of ASCE., Vol.95, No.ST2, 1969, pp.137-157.
5. W.R.Walpole and R.S.Shepherd, "Elasto-Plastic Seismic Response of Reinforced Concrete Frame," Proc. of ASCE., Vol.95, No.ST10, 1969, pp.2031-2055.
6. S.Otani, "SAKE - A Computer Program for Inelastic Response of R/C Frames to Earthquakes," Civil Engineering Studies, Structural Research Series, No.413, University of Illinois, Urbana, Nov. 1974.
7. A.G.Gillies and R.Shepherd, "Three Dimensional Inelastic Building Response to Seismic Loading," Proc. of the 7th World Conference on Earthquake Engineering, 1980, Vol.5, pp.391-398.
8. H.Aoyama and T.Sugano, "A Generalized Inelastic Analysis of Reinforced Concrete Structures Based on the Tests of Members," Recent Researches of Structural Mechanics- Contributions in Honour of the 60th Birthday of Prof. Y.Tsuboi, Uno-Shoten, Tokyo, 1968, pp.15-30.
9. H.Takizawa, "Notes on Some Basic Problems in Inelastic Analysis of Planar R/C Structures (Part 1 & 2)," Trans. of the Arch. Inst. of Japan, No.240, 1976.2, pp.35-46, and No.241, 1976.3, pp.135-147.
10. S.Aboshi and T.Nishikawa, "Study on Behaviors of Three Dimensional Frames with Shear Walls during Earthquakes," Proc. of the 7th Japan Earthquake Engineering Sympo., Tokyo, Dec. 1986, pp.1783-1788.
11. T.Kabeyasawa, H.Shiohara, S.Otani and H.Aoyama, "The Full Scale Experiment of a Seven-Story Reinforced Concrete Building (Part 3)," Proc. of the 6th Japan Earthquake Engineering Sympo., 1982, pp.1161-1168.
12. T.Takayanagi and W.C.Schnobrich, "Computed Behavior of Reinforced Concrete Shear Walls," Civil Engineering Studies, Structural Research Series, No.434, University of Illinois, Urbana, Dec. 1976.
13. R.W.Clough and S.B.Johnston, "Effect of Stiffness Degradation on Earthquake Ductility Requirements," Proc. of Japan Earthquake Engineering Sympo., 1966, pp.227-232.
14. T.Takeda, M.A.Sozen and N.N.Nielsen, "Reinforced Concrete Response to Simulated Earthquakes," Proc. of ASCE., Vol.96, No.ST12, Dec.1970, pp.2557-2573.
15. T.Shiga, A.Shibata, J.Shibuya and J.Takahashi, "Performance of the Building of Faculty of Engineering, Tohoku University, during the 1978 Miyagi-ken-oki Earthquake," Trans. of the Arch. Inst. of Japan, No.301, 1981.3, pp.119-130.
16. T.Okada, M.Murakami, K.Udagawa, T.Nishikawa and H.Tanaka, "Analysis of the Hachinohe Library damaged by '68 Tokachi-oki earthquake," Trans. of the Arch. Inst. of Japan, No.167, 1970.1, pp.47-58.
17. L.G.Selna, K.B.Morril and O.K.Ersong, "Earthquake response analysis of the Olive View Hospital Psychiatric Day Clinic," Earthquake Engineering and Structural Dynamics, Vol.3, No.1, July 1974, pp.15-32.
18. D.A.W.Pecknold and M.A.Sozen, "Calculated inelastic structural response to uniaxial and biaxial earthquake motions," Proc. of the 5th World Conference on Earthquake Engineering, Rome, June 1974, pp.1792-1795.
19. N.C.Nigam, "Inelastic Interactions in the Dynamic Response of Structures," Earthquake Engineering Research Laboratory, Calif. Inst. of Technology, 1968.6.
20. N.C.Nigam, "Yielding in framed structures under dynamic loads," Journal of Engineering Mechanics Division, ASCE., EM5., Oct. 1970, pp.687-709.
21. N.C.Nigam, and G.W.Housner, "Elastic and inelastic response of framed structures during earthquakes," Proc. of the 4th World Conference on Earthquake

- Engineering, Chile, June, 1969, Vol.11, pp.(A-4)89-104.
22. H.Takizawa and H.Aoyama, " Biaxial Effects in Modeling Earthquake Response of R/C Structures," *Earthquake Engineering and Structural Dynamics*, Vol.4, No.5, July, 1976, pp.523-552.
 23. H.Takizawa, " Biaxial and gravity effects in modeling strong-motion response of R/C structures," *Proc. of the 6th World Conference on Earthquake Engineering*, 1977, Vol.3, pp.49-54.
 24. T.Kobori, R.Minai and T.Fujiwara, " Earthquake response of frame structures composed of inelastic members," *Proc. of the 5th World Conference on Earthquake Engineering*, 1974, pp.1722-1781.
 25. M.Yoshimura, H.Aoyama and M.Kawamura, " Analysis of Reinforced Concrete Structure Subjected to Two-Dimensional Forces (Part 1 Analysis of RC Columns Subjected to Bi-Axial Bending)," *Trans. of Arch. Inst. of Japan*, No.298, 1980.12, pp.31-41.
 26. A.E.Aktan, D.A.W.Pecknold and M.A.Sozen, " Effect of two-dimensional earthquake motion on a reinforced concrete column," *Civil Engineering Studies, Structural Research Series*, No.399, University of Illinois, Urbana, May 1973.
 27. A.E.Aktan, D.A.W.Pecknold and M.A.Sozen, " R/C column earthquake response in two dimensions," *Journal of Structural Division, ASCE.*, Vol.100, No.ST10, Oct. 1974, pp.1999-2015.
 28. K.Takiguchi, S.Kokusho and K.Kobayashi, " Analysis of Reinforced Concrete Sections Subjected to Bi-Axial Bending Moments," *Trans. of Arch. Inst. of Japan*, No.250., 1976.12, pp.1-8.
 29. T.Okada, M.Seki and Y.K.Park, " A Simulation of Earthquake Response of reinforced concrete building frames to bi-directional ground motion by IIS computer-actuator on-line system," *Proc. of the 7th World Conference on Earthquake Engineering*, 1980, pp.41-48.
 30. S.S.Lai, G.T.Will and S.Otani, " Model for Inelastic Biaxial Bending of Reinforced Concrete Members," *Journal of Structural Division, ASCE.* Vol.110, ST11, Nov. 1984, pp.2563-2584.
 31. S.S.Lai and G.T.Will, " R/C Space Frames with Column Axial Force and Biaxial Bending Moment Interaction," *Journal of Structural Engineering, ASCE*, Vol.112, No.7, July 1986, pp.1553-1572.
 32. A.Wada and M.Kinoshita, " Elastic Plastic 3-Dimensional Response Analysis by Using a Multiple Shear Spring Model(Part 1,2)," *Summaries of Technical Papers of Annual Meeting, Arch. Inst. of Japan*, vol. B, October 1986, pp.167-170.
 33. A.Shibata, J.Shibuya and N.Satake, " Inelastic Earthquake Response Analysis of 1-Story Model Building with Eccentricities Considering Bi-Axial Bending of Columns," *Proc. of Tohoku District Sympo., AIJ*, No.48, 1986.10.
 34. A.Shibata and N.Satake, " Inelastic Earthquake Response Analysis of RC Building Considering Bi-Axial Bending Interaction," *Proc. of Tohoku District Sympo. AIJ*, No.49, 1987.
 35. K.Emori and W.C.Schnobrich, " Analysis of Reinforced Concrete Frame-Wall Structures for Strong Motion Earthquakes," *Civil Engineering Studies, Structural Research Series*, No.457, University of Illinois, Urbana, Dec. 1978.
 36. S.A.Kaba and S.A.Mahin, " Refined Modeling of Reinforced Concrete Columns for Seismic Analysis," *Earthquake Engineering Research Center, University of California, Berkeley Report*, No.UCB/EERC-84/03, April 1984.
 37. D.Ristic, Y.Yamada and H.Iemura, " Stress-Strain Based Modeling of Hysteretic Structures under Earthquake Induced Bending and Varying Axial Loads - Development and Verification," *School of Civil Engineering, Kyoto University, Research Report*, No.86-ST-01.
 38. Y.Yamada, H.Iemura and D.Ristic, " Stress-Strain Based Modeling of Inelastic Moment-Rotation Relations of RC Members with Varying Axial Forces," *Proc. of the 7th Japan Earthquake Engineering Sympo.*, 1986, pp.1213-1218.
 39. H.Ukon, T.Wada, T.Matsumoto, D.Ristic, C.Miura and S.Nakae, " Stress-Strain Based Inelastic Earthquake Response Analysis of RC Frame Structures with Varying Axial Forces," *Proc. of the 7th Japan Earthquake Engineering Sympo.*, 1986, pp.1471-1476.
 40. Kang-Ning Li, S.Otani and H.Aoyama, " Analytical Model of Reinforced Concrete

- Columns under Triaxial Loading," Journal of Structural Engineering, Vol.33B, 1987.3, Arch. Inst. of Japan.
41. E.Fukuzawa, Y.Isozaki and K.Fujisaki, " Elastic-plastic earthquake response analysis of reinforced concrete frame in consideration of fluctuation of axial forces on columns," Summaries of Technical Papers of Annual Meeting, Arch. Inst. of Japan, 1987.10.
 42. T.Sugano, T.Miyashita and N.Inoue, " 3-Dimensional Study of Nonlinear Behavior of Reinforced Concrete Column under Repeated Lateral Forces," Proc. of the 7th World Conference on Earthquake Engineering, vol.5, 1980, pp.497-504.
 43. H.Umemura, " Dynamic Aseismic Design of Reinforced Concrete Buildings (Part 2)", Gihoudou Pub. Co., 1982.
 44. J.Halim, " Design of Column in Weak Beam R/C Frames against 2-Directional Earthquake Motion," Proc. of the 7th Japan Earthquake Engineering Sympo., Dec. 1986, Tokyo.
 45. H.Takizawa and Y.Seki, " Effects of Varying Axial Compression in Modeling Flexural Behavior of Reinforced Concrete Columns," Proc. of the 6th Japan Earthquake Engineering Sympo., 1982.
 46. M.Handou, A.Shibata and J.Shibuya, " Earthquake Response Analysis of R.C. Columns with Varying Axial Forces by means of Fiber Model," Summaries of Technical Papers of Annual Meeting , Arch. Inst. of Japan, 1987.10.
 47. T.Shiga, A.Shibata, J.Shibuya and N.Satake, " Inelastic Torsional Earthquake Response Analysis of a Damaged Reinforced Concrete Building," Summaries of Technical Papers of Annual Meeting, Arch. Inst. of Japan, 1985.10, pp.397-398.
 48. Y.Yamazaki, " Inelastic Torsional Response of Structures Subjected to Earthquake Ground Motions," Trans. of the Arch. Inst. of Japan, No.300, 1981.2, pp.61-69.
 49. W.K.Tso and A.W.Sadek, " Inelastic Response of Earthquake Buildings Subjected to Bi-Directional Ground Motions," Proc.of the 8th World Conference on Earthquake Engineering, Vol.4, pp.203-210.
 50. T.Nishikawa, " Inelastic response behavior of torsion in buildings subjected to strong earthquake," Proc. of the 7th World Conference on Earthquake Engineering, Sept. 1980, Vol.5, pp.657-664.
 51. N.Satake and A.Shibata, " Inelastic Torsional Earthquake Response Analysis of a Setback-Type Building - Seismic Performance of R/C High-rise Frame Structures with Wall Columns," Technical Papers of Annual Meeting, Arch. Inst. of Japan, 1987.10, pp.267-268.
 52. Y.Matsushima, " Variation in Characteristics of Horizontal Ground Motions with regard to Direction," Trans. of Arch. Inst. of Japan, No.226, 1974.12, pp.39-44.
 53. T.Tanaka, Y.Fukushima, M.Sakaue and S.Yoshizawa, " Statistical Investigation on Peak Acceleration Data of the Strong-Motion Accelerograph Records," Proc. of the 7th Japan Earthquake Engineering Sympo., 1986.12, pp.439-444.
 54. J.Penzien and M.Watabe, " Characteristics of 3-dimensional earthquake ground motions," Earthquake Engineering and Structural Dynamics, Vol.3, 1975, pp.365-373.
 55. T.Kubo and J.Penzien, " Analysis of Three-dimensional Earthquake Ground Motion along an Orthogonal Set of Principle Axes," Pro. of the 5th Japan Earthquake Engineering Sympo., 1978, pp.97-103.
 56. M.Hoshiya and R.Isoyama, " Simulation of Multi-dimensional Nonstationary Earthquake Accelerations," Pro. of Japan Society of Civil Engineers, NO.269, Jan. 1978, pp.41-52.
 57. M.Watabe and M.TODO, " Research on the Design Earthquake Ground Motions, Part 3, Generation of three-dimensional simulated earthquake ground motions for practical seismic design," Trans.of Arch.Inst.of Japan, Vol.321, Nov. 1982.
 58. Y.Inoue and M.Kawano, " Inelastic Response of Building Structures by Traveling Earthquake Wave Motions," Pro. of the 7th World Conference on Earthquake Engineering, Vol.5, pp.553-560.
 59. J.Shibuya, "Analysis of Earthquake Motions on Soft Ground Considering Surface Waves," Summaries of Technical Papers of Annual Meeting, vol. B, Arch. Inst. of Japan, October 1987.

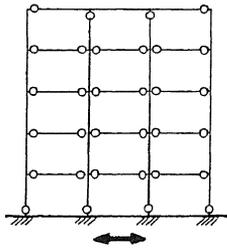


Fig.1 Planar Frame

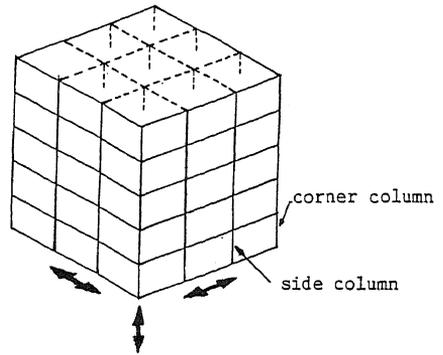


Fig.2 3-D Frame

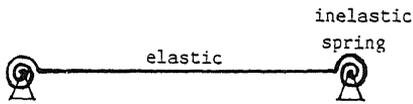


Fig.4 Inelastic Spring Model

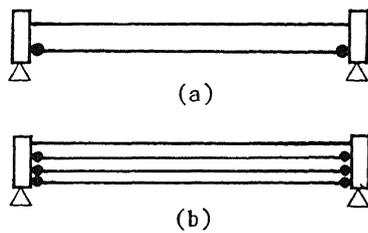


Fig.5 Parallel Element Model
● ; rigid plastic

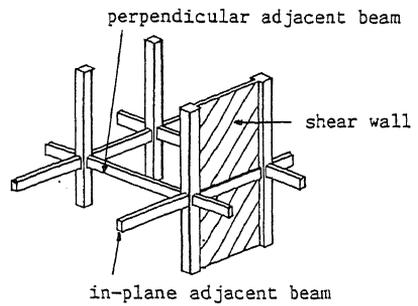


Fig.3 Frame-Wall Interaction

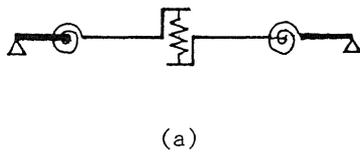


Fig.6 Models for Inelastic Shear Behavior

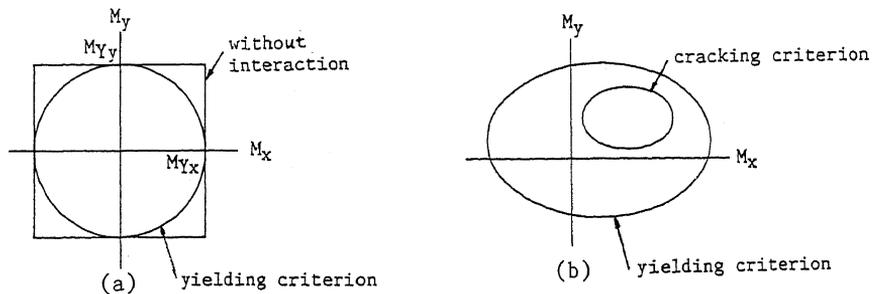
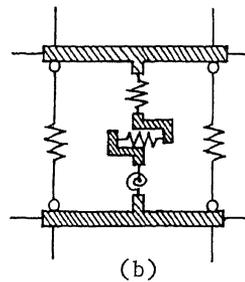


Fig.7 Biaxial Member Model by Plasticity Theory

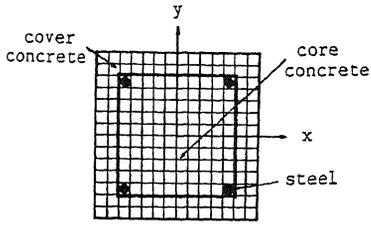


Fig.8 Fiber Model

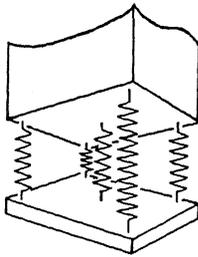


Fig.10 Multi-Spring Model

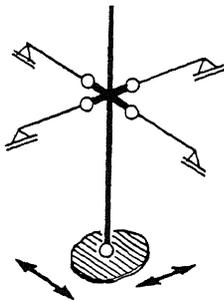


Fig.12 Column Overdesign Factor under Biaxial Bending

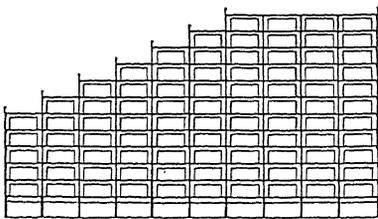


Fig.15 Set-Back Building

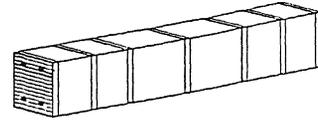


Fig.9 Member Model with Fiber Slices

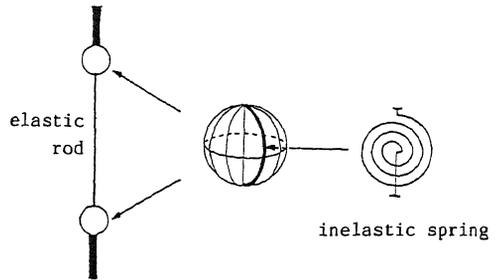


Fig.11 Multi-Rotational Spring Model

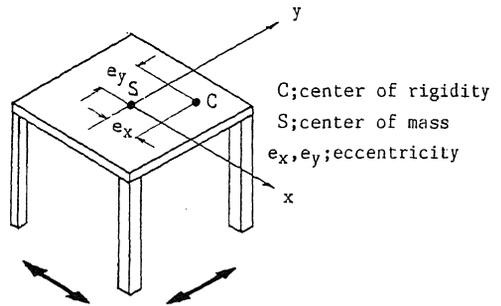


Fig.13 Inelastic Torsional Response

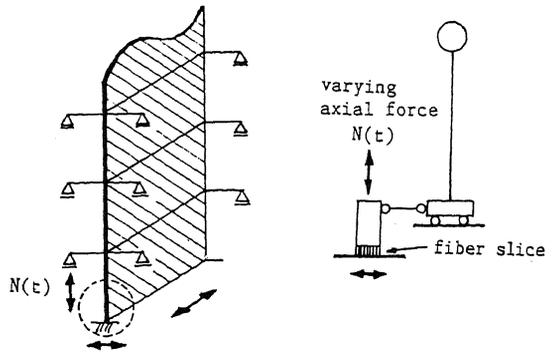


Fig.14 Effect of Axial Force from Perpendicular Direction