INELASTIC BEHAVIOR OF STEEL FRAMES SUBJECTED TO CONSTANT VERTICAL AND ALTERNATING HORIZONTAL LOADS

by

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Introduction. For the study of the behavior of a structure under earthquake excitation, the restoring force characteristic has first to be known upto large deformation stage. In general, the loading situation on framed structures during earthquake motion is characterized by alternating repeated horizontal loading. Moreover, in the case of multi-story frames, the existance of large vertical loads in columns of lower stories becomes important to understand the true behavior of a structure. This induces the unstable feature of a structure and affects greatly on the behavior of unbraced steel frames. Under these circumstances, the behavior of the unbraced frames has been fairly well clarified under monotonic horizontal loading (1-4), but comparatively less studies on the frame behavior under the alternating horizontal loading have been performed (5-9).

A bracing member is an effective earthquake-resisting element in steel frames, so that many kinds of bracing system are often adopted in designing multi-story frames in Japan. The hysteretic behavior of a braced frame is more complex due to the behavior of braces than that of an unbraced frame. A few studies have been reported on this behavior of braced frames under large amplitudes of inelastic deformation (10-13).

In view of these facts, an experiment was carried out to study the inelastic behavior of both braced and unbraced steel frames under alternating horizontal loading, using four full scale models. Two of them simulated the lower story of a multi-story building frame. The behavior under monotonic horizontal loading is also presented here for comparison with that under alternating loading. Theoretical analysis was made so as to study the hysteretic behavior of both braced and unbraced frames tested. Theoretical results well predict the experimental behavior.

Test Program and Experimental Behavior. The test program consisted of eight one-story portal frame specimens built up with rolled wide flange sections and was composed of two series, each containing four specimens. One series was prepared for unbraced frames and the other for braced frames. The test frames and the loading program are shown in Fig. 1 and Table 1, respectively. The material is mild steel called SS41, having proved yield point stress above 2.5 t/cm^2 and ultimate stress scattering from 4.1 to 5.2 t/cm^2. The nominal beam-to-column stiffness ratio is 0.73 and the nominal ratio of the column height to the radius of gyra-

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tion is 34.7 in all specimens. The experimental arrangement is shown in Fig. 2. The details of the experiment may be referred to Ref. (11).

The test results are shown in Figs. 5(a) to 5(e). The following experimental behavior could be observed from these figures.
Unbraced frame: The shape of the horizontal load-displacement hysteresis loops is greatly affected by the amount of the vertical loads on columns. When the vertical loads are large, the instability phenomenon appears in the hysteretic behavior. However, the maximum horizontal restoring force recorded in each cycle increases. This phenomenon is based on the facts that the axial compressive strain cumulated in columns associated with the alternating plastic bending under the constant axial force results in the increasing resisting moment of column sections due to the strain hardening (11), and in addition, that the residual $P \cdot \Delta$ moments exist in the frame when reversed loading bigins (8). On the other hand, when the vertical loads are not applied, the frame instability does not occur and the hysteresis loop which is similar to Masing's model is observed.
Braced frame: The hysteresis loops are quite different from those of an unbraced frame owing to the effect of the post-buckling behavior of a compressive brace and of the behavior of a tensile brace which has residual buckled deflection. The instability effect of the constant vertical loads on the overall behavior of a frame does not seem to be significant in comparison with the case of an unbraced frame, since the restoring force of a braced frame is much larger than that of an unbraced frame because of the tensile brace.

In both the braced and unbraced frame tests, it was observed that the restoring force did not decrease when the local buckling appeared in members, but decreased owing to the out of plane deformation of frame members induced by the local buckling after a few subsequent cycles of loading.

Theoretical Analysis. Theoretical analysis is performed in order to study the hysteretic behavior of both braced and unbraced frames. For the analysis of an unbraced frame, two types of the cyclic moment-curvature relations, the one under no axial force and the other under some axial force, are assumed as to be shown in Figs. 3(a) and 3(b). The assumption seems to be appropriate according to the analytical results based on the bi-linear stress-strain relation of the material (14). The strain hardening factor τ is assumed to be 1/100. Based on the above moment-curvature relations, the load-displacement hysteresis loops of an unbraced frame are strictly analyzed, taking account of spreading yield zones in the direction of member axes, of the shearing deformation of members. The connection panels are assumed not to yield.

For the analysis of a braced frame, it is discomposed into an unbraced frame and bracing members, and then the behavior of each element is independently analyzed. The restoring force of a braced frame is assumed to be equal to the sum of the restoring force of an unbraced frame and the horizontal component of axial force in bracing members at the same displacement. The behavior of a brace under repeated loading is analyzed by Nonaka's theory (15), assuming that the effective length of a brace is L/2 in Fig. 1 (b). The feature of the theory is to take into account the axial deformation at a plastic hinge based on the flow rule of plasticity, at which plastic bending and axial deformations interact with each other. The analysis of an unbraced frame is based on the plastic hinge method which takes account of the effect of the constant vertical loads and the axial force in frame members due to the axial force in braces, on the strength and rigidity of the frame. The axial force in braces is assumed in an approximate manner as to be shown in Fig. 4. In the figure, Nt is the yield load in tension and Nc is assumed to be one fifth of the buckling strength, Ncr, of a member with the same effective length used in brace analysis.

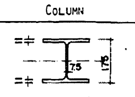
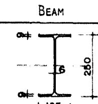
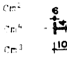
The results of above mentioned analysis are shown in Figs. 5(a) to 5(e). In the analysis, actual section properties and actual material properties of each frame member were used. They very well predict the experimental behavior for both braced and unbraced frames.

Summary. The experimental behavior of braced and unbraced frames under alternating horizontal loading is described, and the effect of vertical loads on the hysteretic behavior of the frame is discussed. The frame behavior under monotonic horizontal loading is also presented for comparison with that under alternating loading. The theory can predict the experimental behavior.

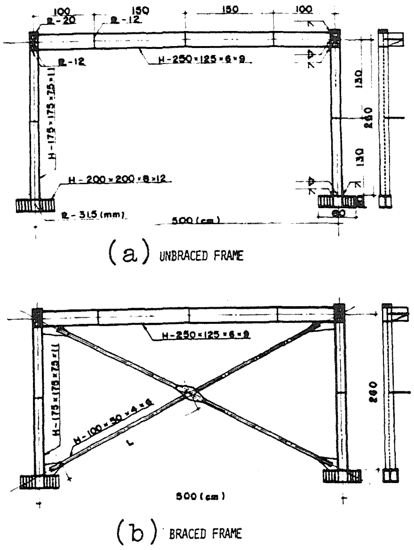
References

1) Wakabayashi, M., "The Restoring Force Characteristics of Multi-Story Frames", Bull. of Disaster Prevention Research Institute, Vol.14, Part 2, No.78, Kyoto University, Feb., 1965, pp.29-47.
2) Arnold, P., Adams, P.F. and Lu, L.W., "Experimental and Analytical Behavior of a Hybrid Frame", Fritz Engineering Laboratory Report 297.18, Lehigh University, Bethlehem, May 1966.
3) Wakabayashi, M., Nonaka, T. and Matsui, C., "An Experimental Study on the Horizontal Restoring Forces in Steel Frames under Large Vertical Load", Proc. of 4th World Conference on Earthquake Engineering, Santiago, Chile, Vol.I, B-2, Jan., 1969, pp.177-193.
4) Wakabayashi, M., Nonaka, T. and Morino, S., "An Experimental Study on the Inelastic Behavior of Steel Frames with a Rectangular Cross-Section Subjected to Vertical and Horizontal Loading", Bull. of Disaster Prevention Research Institute, Vol.18, Part 3, No.145, Kyoto University, Feb., 1969, pp.65-82.
5) Arnold, P., Adams, P.F. amd Lu, L.W., "The Effect of Instability on the Cyclic Behavior of a Frame", RILEM International Symposium on Effect of Repeated Loading on Materials and Structural Elements, Mexico City, sept., 1966.
6) Igarashi, S., Taga, N., Takada, S. and Koyanagi, Y., "Plastic Behavior of Steel Frames under Cyclic Loadings", Trans. of Architectural Institute of Japan, No.130, Dec., 1966, pp.8-15.
7) Fujimoto, M., Hakura, H. and Matsumoto, Y., "Experimental Study on Inelastic Behavior of Steel Structures under Repeated Loading", Proc. of Annual Meeting of Architectual Institute of Japan, Oct., 1968, pp.931-932(in Japanese).
8) Carpenter, L.D. and Lu, L.W., "Repeated and Reversed Load Tests on Full Scale Steel Frames", Proc. of 4th World Conference on Earthquake Engineering, Santiago, Chile, Vol.I, B-2, Jan., 1969, pp.125-136.
9) Wakabayashi, M., Matsui, C. and Mitani, I., "Experimental Studies on the Elastic-Plastic Stability of Steel Frames (Part 4) Subassenblages with Wide Flange Sections Subjected to Alternating Horizontal Force", Trans. of Architectural Institute of Japan, No.195, May 1972, pp.25-37 (in Japanese).
10) Wakabayashi, M., and Tsuji, B., "Experimental Investigation on the Behavior of Frames with and without Bracing under Horizontal Loading", Bull. of Disaster Prevention Research Institute, Vol.16, Part 2, No.112, Kyoto University, Jan., 1967, pp.81-94.
11) Wakabayashi, M., Matsui, C., Minami, K. and Mitani, I., "Inelastic Behavior of Full Scale Steel Frames", Annuals, Disaster Prevention Research Institute, No.13A, Kyoto University, Mar., 1970, pp.3[illegible]-363 (in Japanese).
12) Wakabayashi, M., "The Behavior of Steel Frames with Diagonal Bracings under Repeated Loading", Proc. of U.S.-Japan Seminar on Earthquake Engineering with Emphasis on the Safety of School Buildings, Sendai, Japan, 1970, pp. 328-359
13) Fujimoto, M., Aoyagi, T., Ukai, K., Wada, A. and Saito, K., "Structural Characteristics of Eccentric K-Braced Frames", Trans. of Architectural Institute of Japan, No.195, May 1972, pp.39-49 (in Japanese).
14) Igarashi, S., Matsui, C., Yoshimura, K. and Matsumura, K., "Inelastic Behaviors of Structural Sections under Alternative Loading", (1) Method of Analysis and Examples, Trans. of Architectural Institute of Japan, No.169, Mar., 1970, pp.53-62, (2) Final State of Resisting Moment and Experimental Study, No.170, Apr., 1970, pp.39-50.
15) Nonaka, T.,"An Elastic-Plastic Analysis of a Bar under Repeated Axial loading", Submitted to Inter. Jour. of Solids and Structures.

Table 1 TEST PROGRAM AND NOMINAL SECTION PROPERTIES

Name of Test Frame	Loading Conditions			Nominal Section Properties		
	Vertical		Horizontal			
	P (ton)	P/P_Y		Column	Beam	Brace
FMO	0	0	Monotonic			
FM5	70	0.489	Monotonic			
FCO	0	0	Repeated			
FC5	70	0.516	Repeated			
BMO	0	0	Monotonic			
BM5	70	0.542	Monotonic	A=51.21 cm^2	A=37.66 cm^2	A=9.94 cm^2 
BCO	0	0	Repeated	I=2880 cm^4	I=4050 cm^4	I=12.6 cm^4
BC5	70	0.557	Repeated	Z_p=368.9 cm^3	Z_p=365.9 cm^3	Z_p=8.0 cm^3

P : column load P_Y : yield load of a column A : cross-sectional area I : sectional moment of inertia Z_p : plastic section modulus



(a) UNBRACED FRAME

(b) BRACED FRAME

Fig. 1 TEST FRAMES

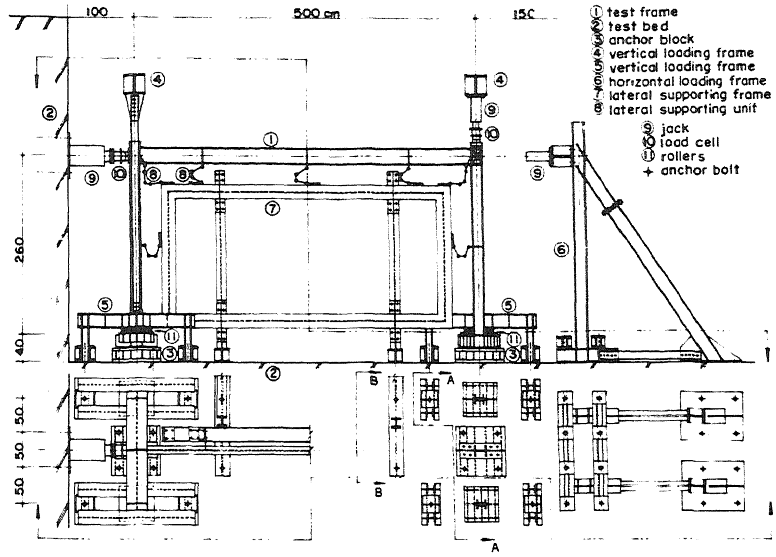
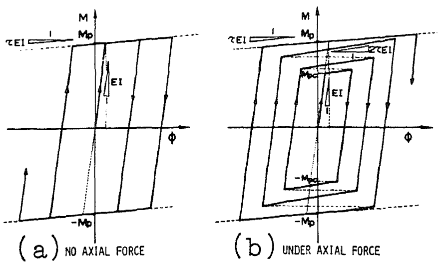


Fig. 2 LOADING ARRANGEMENT



(a) NO AXIAL FORCE

(b) UNDER AXIAL FORCE

Fig. 3 ASSUMED MOMENT - CURVATURE RELATIONS

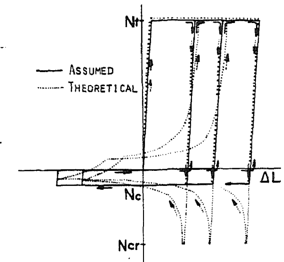
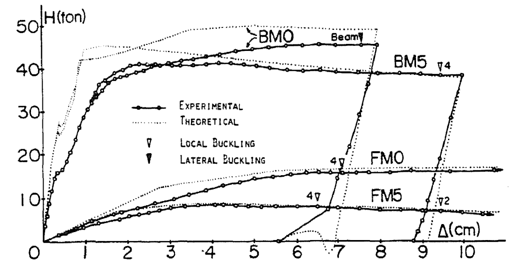
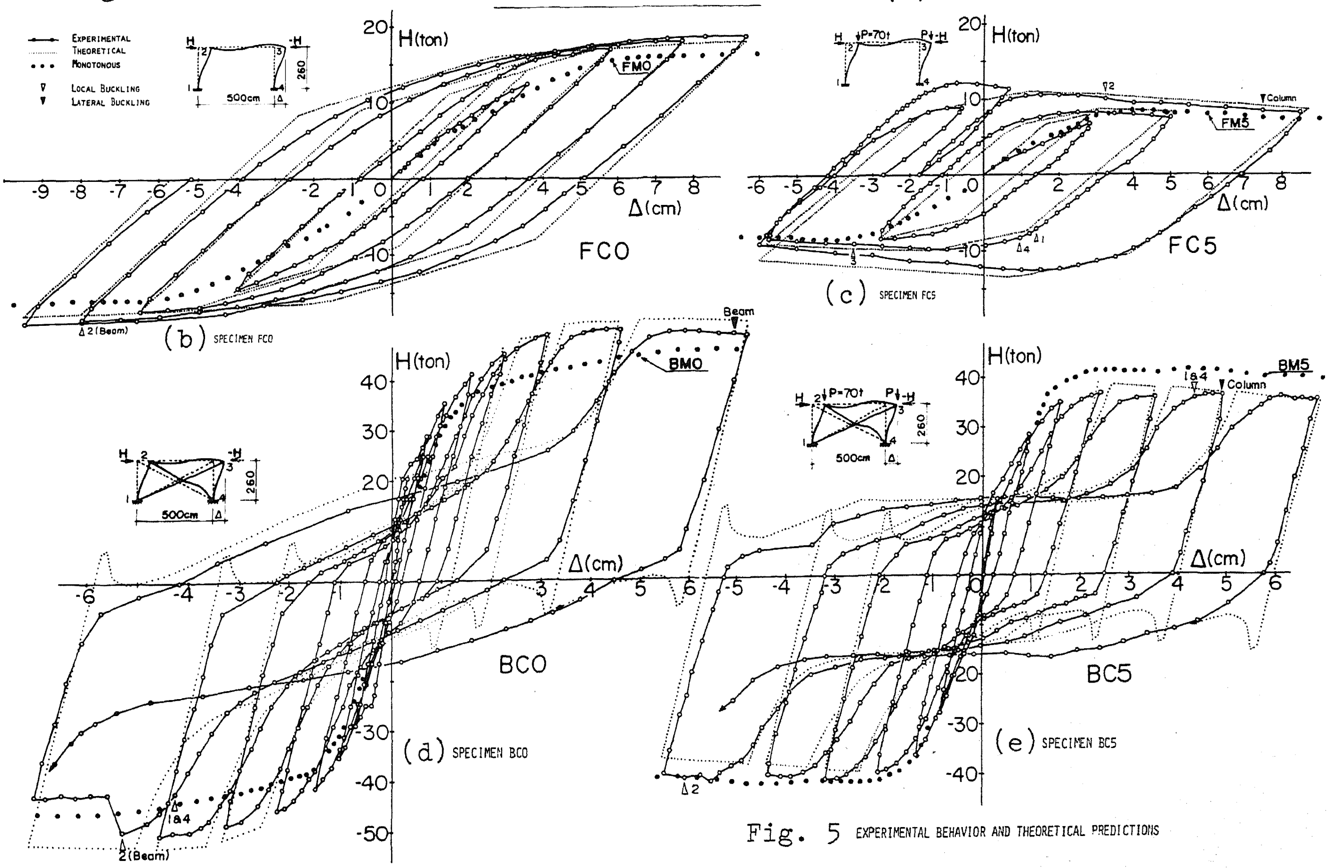


Fig. 4 ASSUMED AXIAL FORCE OF A BRACING FOR FRAME ANALYSIS



(a) BEHAVIOR UNDER MONOTONIC HORIZONTAL LOADING



(b) SPECIMEN FC0

(c) SPECIMEN FC5

(d) SPECIMEN BC0

(e) SPECIMEN BC5

Fig. 5 EXPERIMENTAL BEHAVIOR AND THEORETICAL PREDICTIONS