Final Report

INELASTIC HYSTERESIS BEHAVIOR OF STEEL BRACING MEMBERS AND SEISMIC BEHAVIOR OF BRACED FRAMES

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16. Abstract (Limit: 200 words)

A modeling study of the hysteresis behavior of several steel braced frames subjected to severe earthquake motion is reported. Preliminary investigations were conducted to develop appropriate methods for computing the inelastic dynamic response of complex structures. The theoretical study utilized a model to represent a bracing member. Results show that optimum post-buckling behavior is obtained when yielding occurs simultaneously in the connections and at mid-length of the member. This study of bracing members identified the effective slenderness ratio as being the most influential parameter in determining their hysteresis behavior. Experiments also demonstrated that differences in static and dynamic hysteresis loops are increased, and that experimental hysteresis loops compare well with theoretical results. Based on these member studies, a mathematical model and a physical model were developed to compute the response of braced frame structures to severe earthquake motion. These two models have been programmed for use with the DRAIN-2D program. Nonlinear building response by the characteristics method and studies of torsion in 3-dimensional structures are described.

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Shear stress	Earthquake resistant structures
Torsion	Bracing

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DRAIN-2D program

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INTRODUCTION

This research project had two distinct phases. The first was to perform an analytical and experimental study of the hysteresis behavior of steel members subjected to cyclic axial loading combined wtih restraining moments due to end connections. The findings of this study led to development of a simple and realistic model to represent the hysteresis behavior of steel bracing members. In the second phase, this hysteresis model was used to compute the response of several braced frames due to severe earthquake motion. Preliminary investigations were also made in this phase to develop approximate methods for computing the inelastic dynamic response of complex structures. This included application of the method of characteristics in structural dynamics and representation of a 3-dimensional structure by an equivalent 2-dimensional model.

RESEARCH

Hysteresis Behavior of Bracing Members

In the theoretical study a bracing member was represented by a model with rotational springs at the ends and a prescribed initial out-of-straightness in order to simulate, respectively, the efforts of restrained rotation due to end-connections and transitional yield-buckling in compression. Elastic-plastic behavior was assumed for the member and end-connections. The variables included connection strength and stiffness, and length, size and shape of the member. The study concluded that the optimum post-buckling behavior of the member is obtained when yielding occurs simultaneously in the connections and at mid-length of the member. Further, for such a member (called the balanced connection strength member) the hysteresis behavior can be predicted by using a pin-connected member of equivalent slenderness ratio.

Experimental work was performed by using small size 1"x1" square tube specimens with welded gusset plates for end connections. The slenderness ratio of these specimensranged from 30 to 160. Cyclic axial displacement-controlled loading was applied both statically and dynamically. Effect of local buckling on the hysteresis behavior and fatigue life of the specimens were studied. The most significant conclusions are; (1) the effective slenderness ratio is the most influential parameter in determining the hysteresis behavior of these members, (2) the differences in the static and dynamic hysteresis loops are minimal, and (3) the experimental hysteresis loops generally compared well with the theoretical results except for the residual elongation which could not be predicted theoretically.

Response Of Braced Frame Structures

Based on member studies a simple mathematical model and a physical model (consisting of two rigid links and a plastic hinge) have been derived for the hysteresis behavior of axially loaded bracing members for use in computing the response of braced frame structures when subjected to severe earthquake motion. These two models have been programmed for use with DRAIN-2D program which was originally developed at the University of California, Berekeley. Response of several braced frame structures was studied to learn about the effects of such factors as hysteresis behavior and different arrangements of bracing members, uplift of columns, and vertical component of ground motion on the total response of these structures. Bracing patterns that have been considered are K, V, X and split-K types.

The results show that a realistic representation of post-buckling behavior of bracing members is important and must be included for an accurate prediction of the response of braced frames. Results also indicate areas of concern such as large premanent deformations in the floor girders of K-braced frames and that overall displacement response may not indicate adequately the inelastic deformation in certain members and locations. It also is concluded that the inelastic activity in frame members can be reduced by allowing partial uplift of column bases.

Nonlinear Building Response by the Characteristics Method

Weak-girder type structures are generally recommended for earthquake resistant design rather than weak-column type in order to prevent concentration of damage which could lead to collapse. The conventional lumped-mass shear model, however, does not accurately model the weak-girder type. The characteristics methods has been shown to accurately represent this weak-girder type of structures at a significant cost saving. In this method the structure is treated as a continuous shear beam with distributed mass coupled with a lumped-mass bending beam. The resulting hyperbolic partial differential equations for the shear beam are solved by the method of characteristics.

Torsion in 3-Dimensional Structures

A study has been initiated which deals with developing simpler 2-dimensional models to represent moment frames and coupled shear walls or bracings wtih respect to their linear and non-linear stiffness characteristics and eccentricities. The effects of torsion-translation frequency ratio and the eccentricity-polar radius of gyration ratio, and orthogonal-strength interactions in conjunction with torsion are being studied with respect to ductility requirements. The phenomenon of progressively increasing eccentricity with nonlinearity will also be studied.

UTILIZATION

Bracing members are used in a wide variety of structures to resist earthquakes, wind and sea storms. The hysteresis behavior of these members under reversed cyclic loading is, however, quite complex because of combined influence of buckling and yielding. Hysteresis models proposed in the past have been either too simple but unrealistic, or too complex for use in practical procedures.

Study of bracing members in this research project singled out the effective slenderness ratio as being the most influential parameter in determining their hysteresis behavior. This led to the development of a simple and reasonable mathematical model. A subroutine package along with a user's manual was written for this model to be used with the DRAIN-2D program. Bechtel Power Corporation, San Francisco, California, is already using this subroutine package in their work related with analysis and design of steel structures in power plants. Brown and Root Company, Houston, Texas, has also shown interest in using this model in the design and analysis of off-shore towers. We are forwarding this package to the NISEE for a broader distribution to all potential users.

FURTHER RESEARCH

The study of hysteresis behavior of bracing members in this research project was based on idealized deformation and end conditions, and tests of small scale specimens. Extention of this study including tests on full scale members and connections is now under way with support by NSF/RANN Grant No. ENV76-82209 and a grant from the American Iron and Steel Institute as Project 301. Past studies and results from this research project will be used to refine the hysteresis model for bracing members for use in practical computation of dynamic response of braced steel structures. Emphasis is being placed on developing recommendations for earthquake resistant design of braced frame structures. A study of inelastic torsional response of 3-dimensional structures including bracing will be completed in this new project.

GRANT ACTIVITIES

A. Publications

1. Nishikawa, T., M.E. Batts and R.D. Hanson, "Nonlinear Building Response by the Characteristics Method," Proceedings, U.S.-Japan Cooperative Research Program Meeting, Honolulu, Hawaii, August, 1975.

2. Goel, S.C., "Inelastic Response of Multistory K-Braced Frames Subjected to Strong Earthquakes," Proceedings, Fourth Japan Earthquake Engineering Symposium, Tokyo, Japan, November 1975.

3. Kahn, L.F. and R.D. Hanson, "Inelastic Cyclic Behavior of Axially Loaded Steel Members," Proceedings, Fourth Japan Earthquake Engineering Symposium, Tokyo, Japan, November, 1975, pp. 959-966.

4. Prathuagsit, D., "Inelastic Hysteresis Behavior of Axially Loaded Steel Members with Rotational End Restraints," Ph.D. Thesis, UMEE 76R5, The University of Michigan, Ann Arbor, Michigan, April, 1976.

5. Kahn, L.F. and R.D. Hanson, "Inelastic Cycles of Axially Loaded Steel Members," Journal of the Structural Division, ASCE, Vol. 102, No. ST5, May, 1976, pp. 947-959.

6. Goel, S.C., "Seismic Behavior of Multistory K-Braced Frames Under Combined Horizontal and Vertical Ground Motion," Proceedings, VI World Conference on Earthquake Engineering, New Delhi, India, January, 1977.

7. Kaldjian, M.J., "Inelastic Cyclic Response of Split K-Braced Frames," Proceedings, VI World Conference on Earthquake Engineering, New Delhi, India, January, 1977.

8. Prathuangsit, D., S.C. Goel and R.D. Hanson, "Inelastic Hysteresis Behavior of Axially Loaded Steel Members with Rotational End Restraints," Proceedings, VI World Conference on Earthquake Engineering, New Delhi, India, January, 1977.

9. Jain, A.K., S.C. Goel and R.D. Hanson, "Static and Dynamic Hysteresis Behavior of Steel Tubular Members with Welded Gusset Plates," UMEE 77R3, Department of Civil Engineering, The University of Michigan, Ann Arbor, Michigan, June, 1977.

10. Singh, P., "Seismic Behavior of Braces and Braced Steel Frames," Ph.D. Thesis, (UMEE 77R1), The University of Michigan, Ann Arbor, Michigan, July, 1977.

11. Jain, A.K., S.C. Goel and R.D. Hanson, "An Experimental Verification of Hysteresis Behavior of Axially Loaded Steel Members," Accepted for Central American Conference on Earthquake Engineering, San Salvador, El Salvador, C.A., January, 1978.

12. Batts, M.E., "Inelastic Torsional Building Response due to Bi-directional Ground Motion," Ph.D. Thesis, The University of Michigan, Ann Arbor, Michigan, (Under Preparation).

B. Presentations

S.C. Goel

1. "Inelastic Response of Multistory K-Braced Frames subjected to Strong Earthquakes," Paper by S.C. Goel, Fourth Japan Earthquake Engineering Symposium, Tokyo, Japan, November 27, 1975.

2. "Inelastic Cyclic Behavior of Axially Loaded Steel Members," Paper by L.F. Kahn and R.D. Hanson, Fourth Japan Earthquake Engineering Symposium, Tokyo, Japan, November 28, 1975.

3. "Inelastic Behavior of Bracing Members and Braced Frames Subjected to Earthquakes," Seminar, Disaster Prevention Institute, Kyoto University, Kyoto, Japan, December 1, 1975.

4. "Inelastic Behavior of Bracing Members and Braced Frames Subjected to Earthquakes," Seminar, School of Research in Earthquake Engineering, University of Roorkee, Roorkee, India, December 15, 1975.

5. "Inelastic Behavior of Bracing Members and Braced Frames Subjected to Earthquakes," Seminar, Departments of Aeronautical and Civil Engineering, Indian Institute of Technology, Kanpur, India, December 18, 1975.

6. "Seismic Behavior of Multistory K-Braced Frames under Combined Horizontal and Vertical Ground Motion," Paper by S.C. Goel, VI World Conference on Earthquake Engineering, New Delhi, India, January 11, 1977.

7. "Inelastic Hysteresis Behavior of Axially Loaded Steel Members with Rotational End Restraints," Paper by D. Prathuangsit, S.C. Goel and R.D. Hanson, VI World Conference on Earthquake Engineering, New Delhi, India, January 14, 1977.

8. "Effect of Foundation Uplift on Building Response," Paper by P. Singh, S.C. Goel and R.D. Hanson, ASCE Annual Meeting, San Francisco, California, October 18,1977.

9. "An Experimental Verification of Hysteresis Behavior of Axially Loaded Steel Members," Paper by A.K. Jain, S.C. Goel and R.D. Hanson, Central American Conference on Earthquake Engineering, San Salvador, El Salvador, C.A., January 1978.

R.D. Hanson

1. "Nonlinear Building Response by the Characteristics Method," Paper by T. Nishikawa, M.E. Batts, and R.D. Hanson, U.S.-Japan Cooperative Research Program Meeting, Honolulu, Hawaii, August, 1975.

2. "Behavior of Bracing Members and Braced Frame Structures," Seminar, Chief Engineers' Monthly Meeting, Bechtel Power Corporation, Ann Arbor, Michigan, June, 1976.

3. "Reducing Damage from Earthquakes," RANN2 Symposium on Transferring Earthquake Research into Practice, Washington, D.C., November 7, 1976.

4. "Dynamic Structural Analysis and Design," American Iron and Steel Institute Earthquake Engineering Conference, Berkeley, California, April 13, 1977.

C. <u>Staff Involved in this Research Project</u>

Students

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