EARTHQUAKE-INDUCED PERMANENT DISPLACEMENTS IN SMALL SHEAR-TYPE STEEL STRUCTURES

by

Dixon Rea[I] and Alvar M. Kabe[II]

SUMMARY

The results from a series of shaking table experiments performed to investigate inelastic behavior in steel frames during earthquakes are described. The experiments were conducted on small steel structures designed to reproduce the overall behavior of three story shear-type buildings. The columns of the structures had 1/2 in by 1/4 in rectangular cross-sections and clear heights of 8 in; each floor weighed 44 lb. The structures were subjected to earthquake motions derived from the N21E component of the Taft (1952) record.

INTRODUCTION

Moment resistant steel frame buildings are capable of undergoing large inelastic deformations during earthquakes. However, such deformations may threaten the stability of the structures and may be related to the damage, both structural and nonstructural, they incur. Furthermore, the magnitude of the permanent deformation remaining in a structure after an earthquake may be a significant factor in the cost of repairing the damage. Thus, the development of reliable methods of calculating earthquake-induced deformations, including permanent deformations, is of economic importance.

Computer programs have been developed for analyzing the response of buildings to earthquake motions, even when the motions have sufficient intensity to cause nonlinear inelastic behavior (1,2). However, it has been necessary to incorporate simplifying assumptions about structural behavior into such programs, and it has been difficult to check the significance of these assumptions because of the lack of suitable experimental data. Although inelastic deformations have been produced in an essentially full-scale three story steel frame by subjecting it to earthquake motions by means of a shaking table (3), the magnitudes of the deformations were limited to strain ductility factors of 5 and to displacement ductility factors not much greater than 1. As a consequence the experimental data does not provide a rigorous test for nonlinear computer programs. The experimental data that is available for steel structures undergoing large inelastic cyclic deformations have been obtained either by imposing slowly-varying deformations to the boundaries of full-scale components (e.g.4) or by applying harmonic forces to small steel structures (5). Thus experimental data pertaining to steel structures undergoing large inelastic deformations during earthquake motions is sparse.

A series of shaking table experiments in which small steel frame structures were subjected to earthquake motions of sufficient intensity to cause large inelastic deformations were completed recently (6). The

[I] Associate Professor, University of California, Los Angeles, CA, USA
[II] Member Technical Staff, Aerospace Corporation, Los Angeles, CA, USA

objectives of the experiments were to accumulate experimental data to be used to check the accuracy of nonlinear computer programs and to identify more clearly the mechanisms by which earthquake motions induce large inelastic deformations in steel structures. The results of the experiments pertaining to the latter objective are presented below.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

The small steel structures were designed to reproduce the overall behavior of three story shear-type buildings in which the flexural stiffnesses of the beams are large compared to those of the columns. The floors consist of 2 in x 1/2 in rectangular steel bars bolted together to form 12 in x 24 in rectangular frames. The columns, which had 1/2 in x 1/4 in rectangular cross-sections and clear heights of 8 in, were machined from bars of hot-rolled steel with a minimum yield stress of 36 ksi. The structures were assembled so bending would take place about the weaker axes of the columns. The dimensions of the structures are shown in Fig. 1. Fig. 2 shows a structure after an experiment in which substantial permanent deformations were induced in the first story column.

Earthquake simulation experiments were conducted on a total of 20 structures differing only in the material properties of the columns. The yield stress of the column steel varied among the 20 structures in the range 37.9-47.2 ksi, but was kept constant for individual structures by cutting all the columns for each structure from the same length of bar stock. The fundamental natural frequencies of the structures, with steel plates bolted to the floor assemblies to increase the weight of each floor to 44 lb, ranged from 8.15 to 8.32 Hz. The damping factors for the fundamental modes of vibration were slightly less than 1% of critical damping.

The structures were tested on a shaking table consisting of a 400 lb steel grillage measuring 6 ft x 3 ft in plan. The table, which can be seen in Fig. 2, is supported on four linear bearings that permit table motion in one horizontal direction. The electro-hydraulic actuator that drives the table has a dynamic force rating of 7.5 kips and a stroke of 6(±3) in. The actuator is equipped with a 90 gpm servo-valve. The maximum test specimen weight for the table is 1,500 lb. Fully loaded the table has a maximum acceleration of 3.5 g and a maximum velocity of 100 in/sec.

The earthquake motions used for the experiments were derived from the N21E component of the Taft (1952) earthquake record. The lower frequency components were removed from the original motion in order that motions of sufficient intensity to cause inelastic deformation could be generated within the limited stroke of the actuator. This was accomplished by means of a high-pass digital filter with the corner frequency set at 3.0 Hz. The resulting motion, designated Motion I, contained most of its energy in the frequency band 3.0-8.5 Hz. Two more motions were derived from Motion I by decreasing and increasing its duration by 25% and 15% respectively. Thus Motion II contained most of its energy in the frequency band 3.7-10.0 Hz, and Motion III in the range 2.5-6.8 Hz.

Each structure was subjected to one of three motions at two or three levels of intensity. The lower levels of intensity were chosen so the response of the structure would remain within or just outside the linear range of behavior. The highest intensity level for each structure was chosen to produce inelastic, including permanent, deformations. In all the experiments the acceleration of the table, first and third floors, and the displacement of the first floor relative to the table were recorded by strip chart recorder. In some experiments, the above quantities as well as the second floor acceleration, second and third story relative displacements and the strain in a first story column at a point just below the first floor were recorded in digital form on magnetic tape.

EXPERIMENTAL RESULTS

The acceleration time history for the shaking table undergoing Motion I, and the response of a structure to this motion in terms of the first floor's relative displacement and the third floor's acceleration are shown in Fig. 3. In this experiment the table acquired a maximum acceleration of 3.0 g, the maximum first floor relative displacement was 1.5 in, and the maximum acceleration of the top floor was 5.8 g. A relative displacement of 0.6 in remained in the first story at the end of the experiment. This permanent displacement is the accumulation of a number of steps in the mean position of the floor. Each step coincides with a predominant pulse in the table's acceleration time history, positive acceleration pulses producing negative steps in displacement and vice versa. The maximum table acceleration, maximum first floor displacement, and maximum third floor acceleration all occurred simultaneously at 10.0 seconds. In the first experiment on this structure, when the response remained within the linear range of behavior, the maximum response was just prior to six seconds.

The maximum and permanent displacements induced in the first stories of 10 structures by various intensities of Motion I are shown in Fig. 4. The displacements are expressed as drift indices, that is, they are divided by the column lengths. The relationships for both maximum and permanent displacements are essentially bilinear. The first segment of the relationship for maximum displacement passes through the origin and extends to a maximum table acceleration of 2.5 g. The slope of the second segment is about seven times the slope of the first segment. The relationship for the permanent displacement is similar to the one for the maximum displacement except that the first segment does not commence until a maximum table acceleration of 1.5 g is reached, and then it continues to an acceleration of about 3.0 g. The scatter in the data shown in Fig. 4 is attributable to experimental error, residual stresses, and the variation in yield stress among structures. The yield stress of the columns in the 10 structures varied from 37.9 to 47.2 ksi.

In order to eliminate the effects of variable yield stresses in subsequent graphs a dimensionless parameter $M\ddot{y}_m/P_p$ has been chosen to express the intensity of the table's motion. The individual terms in this parameter are: M - the total mass of the structure, $\ddot{y}_m$ - the maximum acceleration in the table's motion, and P_p - the first story's lateral plastic limit load. The maximum displacements induced in structures by various intensities of Motions I, II, and III are shown in Fig. 5. The curve for Motion I is nearly bilinear, and although there is insufficient experimental data to completely define the curves for Motions II and III, they also appear to be nearly bilinear. The first segments of the bilinear curves for Motions I and II pass through the origin and extend to values of $M\ddot{y}_m/P_p$ of about 1.0 and 1.8 respectively. Due to the lack of experimental data the first segment for Motion III has not been defined, but the second segment commences at a value of $M\ddot{y}_m/P_p$ less than 1.2. The first segment for Motion II extends to a much greater level of intensity than the first segments for Motions I and III. Furthermore, the first three data points as shown in Fig. 3 do not really lie on the same straight line as the remaining six points in the first segment of Motion II. The reasons for the differences between the curve for Motion II and those for Motions I and III have not been identified. The slope of the second segment of Motion I is 7 times greater than the slope of the first segment. The maximum first story drift index for Motion I is 0.49 which corresponds to a displacement ductility factor of 31 since the drift index corresponding to the yield displacement for that structure is 0.016.

The permanent displacements remaining in the first story columns of the structures after they were subjected to various intensities of Motions I, II, and III are shown in Fig. 6. The curves for permanent displacements are also bilinear with the first segments commencing at values of $M\ddot{y}_m/P_p$ between 0.4 and 0.5 and extending up to values of 1.1, 1.2, and 1.7 for Motions I, II, and III respectively. The slopes of the second segments are from 4 to 12 times greater than the slopes of the first segments. The permanent displacements are about 75% of the maximum displacements in experiments with the highest intensity motions. Motions with an intensity $M\ddot{y}_m/P_p$ equal to unity cause permanent displacements of between 25 and 50% of the maximum displacement.

The ratios of the maximum third floor to maximum table acceleration for all the experiments are shown in Fig. 7. The magnification factors for Motions I, II, and III were about 4, 6, and 9 respectively if the motions did not cause the steel in the columns to yield. Motions for which $M\ddot{y}_m/P_p$ exceeded 0.1 or 0.2 caused yielding so the magnification factors decrease with increasing intensity above these levels. The magnification factors are only one-half to one-third of their maximum values for motions with $M\ddot{y}_m/P_p$ equal to 1.0, and they decrease to values between 1 and 2 for the motions with largest intensities.

CONCLUSIONS

High performance shaking tables can be used to investigate the overall behavior of steel buildings under earthquake motions of sufficient intensity to cause large inelastic deformations. Relative displacements up to 31 times the yield displacement were induced in the first story of small steel structures designed to reproduce the overall behavior of 3 story shear-type buildings. As much as 80% of the maximum first story relative displacement remained after an earthquake motion had ceased. The permanent displacement was the result of a number of steps in the mean position of the first floor, each step coinciding with a predominant pulse in the table's acceleration time history.

The earthquake motions used in the experiments were derived from the N21E component of the Taft (1952) earthquake. These motions caused permanent deformations if the dimensionless intensity parameter $M\ddot{y}_m/P_p$ exceeded 0.4, and the permanent deformation became relatively large when this parameter exceeded unity.

ACKNOWLEDGMENT

The financial support provided by the University of California, Los Angeles, through the Academic Senate, the School of Engineering and Applied Science, and the Mechanics and Structures Department is gratefully acknowledged.

REFERENCES

1. R.W. Clough, K.L. Benuska, and E.L. Wilson, "Inelastic Earthquake Response of Tall Buildings," 3WCEE, New Zealand, 1965.
2. A.E. Kanaan and G.H. Powell, "DRAIN-2D A General Purpose Computer Program for Dynamic Analysis of Inelastic Plane Structures," Report No. EERC 73-22, Univ. of Calif., Berkeley, August 1975.
3. D.T. Tang and R.W. Clough, "Shaking Table Earthquake Response of Steel Frame," J. Struct. Div., ASCE, Vol. 105, No. ST1, January 1979.
4. E.P. Popov and V.V. Bertero, "Cyclic Loading of Steel Beams and Connections", J. Struct. Div., ASCE, Vol. 99, No. ST6, June 1973.
5. R.D. Hanson, "Post-Elastic Dynamic Response of Mild Steel Structures," Ph.D. Thesis, Calif. Inst. Tech., Pasadena, Calif., June 1965.
6. A.M. Kabe and D. Rea, "Earthquake-Induced Inelastic Deformations in Small Shear-Type Steel Structures," Univ. of Calif., Los Angeles, 1980.

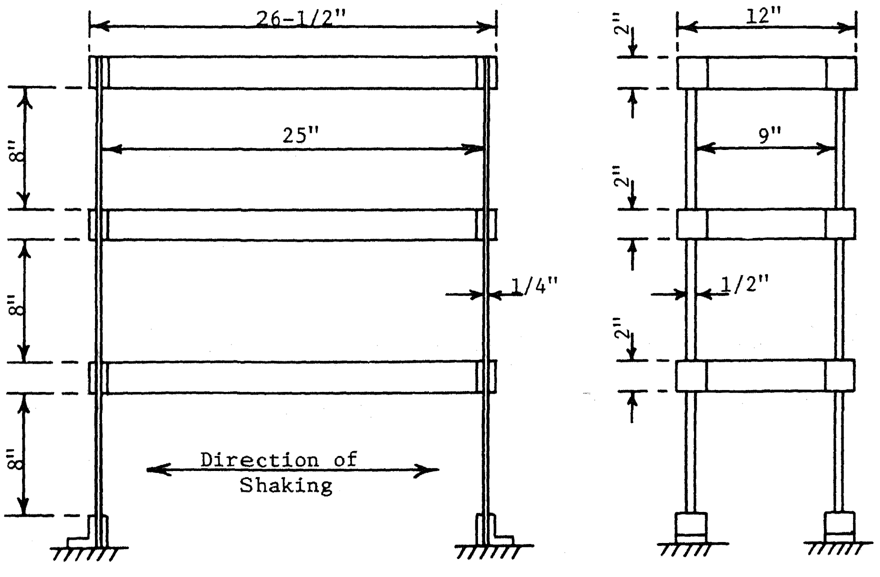

FIG. 1 DIMENSIONS OF STRUCTURES

FIG. 2 STRUCTURE AND SHAKING TABLE

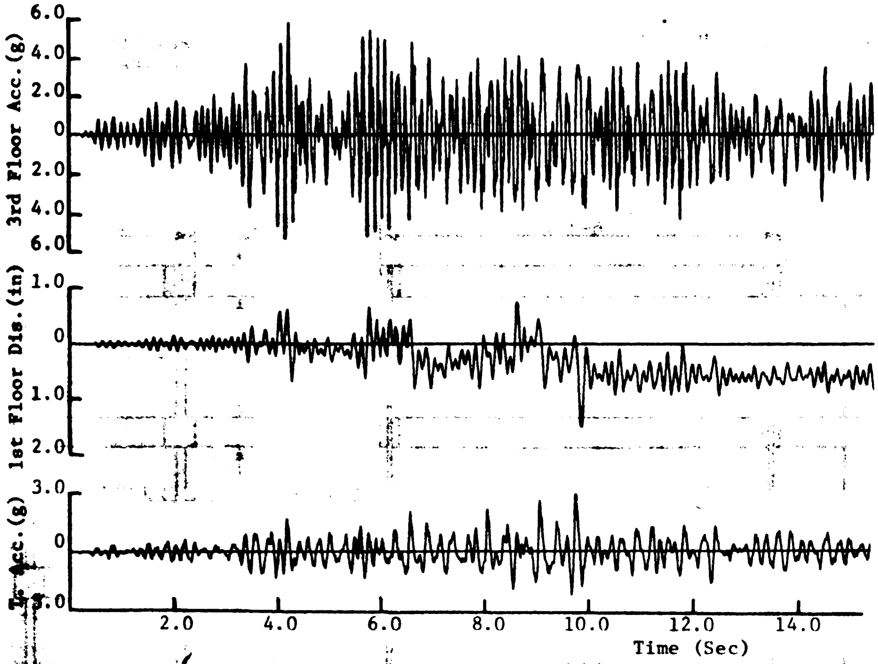

FIG. 3 TIME HISTORIES

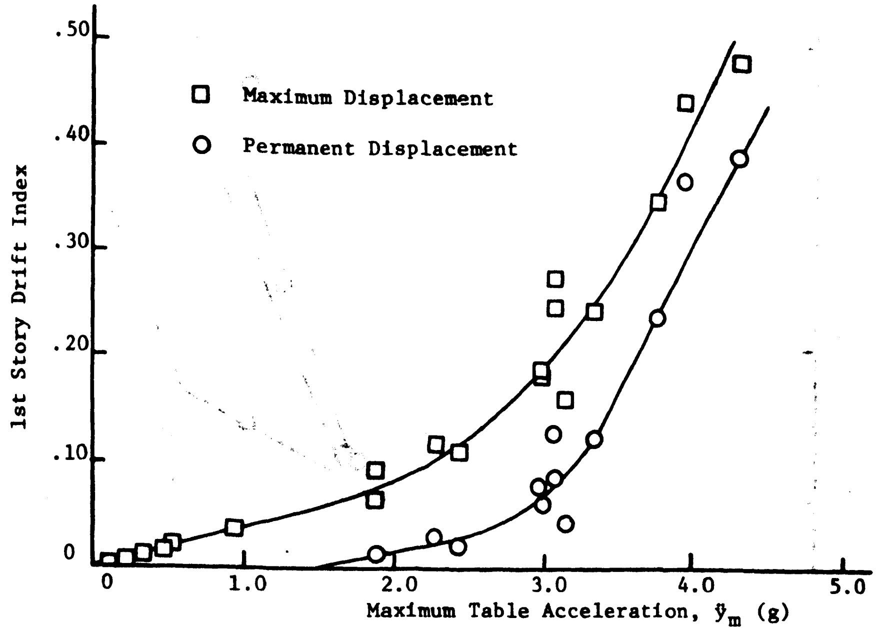

FIG. 4 1st STORY MAXIMUM AND PERMANENT DISPLACEMENTS - MOTION I

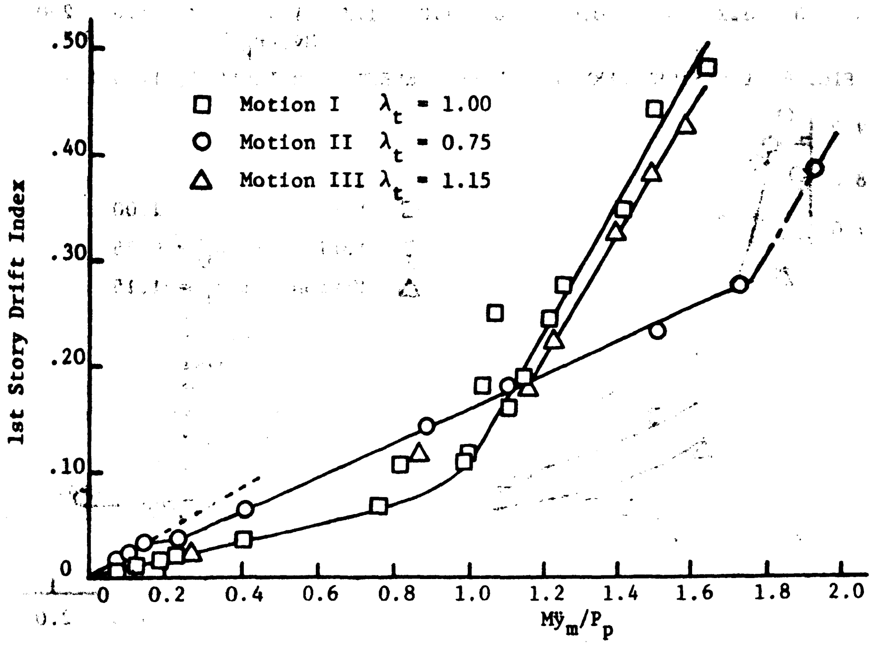

FIG. 5 1st STORY MAXIMUM DISPLACEMENTS - MOTIONS I, II & III

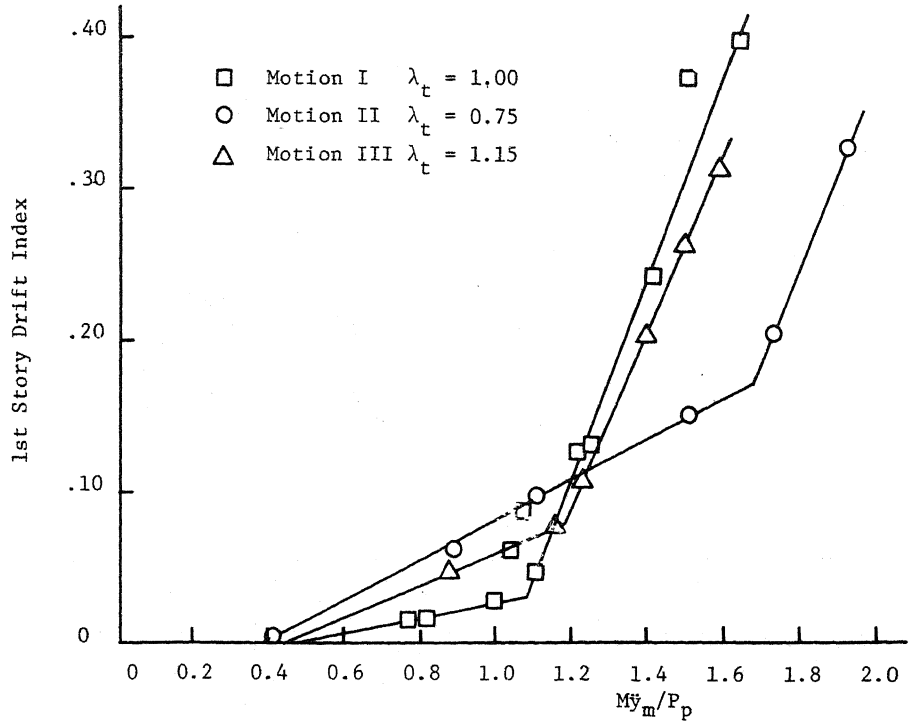

FIG. 6 1st STORY PERMANENT DISPLACEMENT - MOTIONS I, II & III

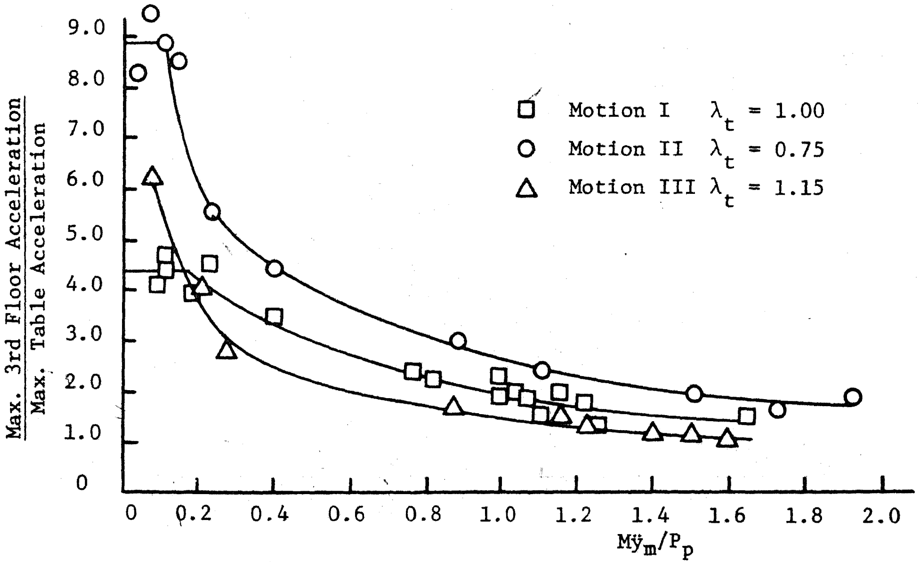

FIG. 7 3rd FLOOR/TABLE ACCELERATION TRANSMISSIBILITY