SHAKING TABLE STUDIES OF AN ECCENTRICALLY X-BRACED STEEL STRUCTURE

Ming-San Yang (I)

SUMMARY

A 5-story, one-third-scaled, eccentrically X-braced steel structure weighing about 50 tons was tested on the 20' x 20' shaking table at the Earthquake Engineering Research Center (EERC) of the University of California, Berkeley to observe its seismic behavior. The results indicated that the test structure could effectively resist an El Centro type table motion with a peak acceleration of 1.15g, and a ductility factor of about 100 was recorded in shear yielding of beams. A simplified mathematical model was formulated for response calculation to compare with the experiment results and a fairly good correlation was achieved.

INTRODUCTION

The eccentric bracing system, which shifts the inelastic behavior of a braced frame from conventional tension yielding and compression buckling of braces to shear or bending yielding of beams, gives a structure the necessary stiffness and strength for frequent events while its ductility for major earthquakes is ensured by inelastic behavior of girders. Figure 1 shows some examples of eccentricity arrangements. All have been tested by quasi-static experiments to have excellent seismic resistant potential (Ref. 1, 2, 3, 4, 5, 6). They all possess high strengths and large stiffnesses, and are ductile if their yielding capacities are exceeded. Especially, other than imminent destruction, unlike conventional bracing, they demonstrated no pinching of hysteresis curves and deterioration of strength and stiffness. However, no dynamic investigation was known to have been done previously.

The purpose of this study is to investigate the earthquake resistive efficiency of eccentric X-bracing by studying the responses of a test structure (see Fig. 2) to simulated earthquakes, and to acquire true seismic data for correlation with results calculated by computer to investigate and improve the effectiveness of computer codes. The experiment was carried out on the 20' x 20' shaking table of the earthquake simulator laboratory at the EERC (Ref. 7).

The experimental results depicting the seismic performance and the result of correlation between experiment and analysis will be presented. The complete detailed presentation of this study is in Ref. 8.

(I) Senior Engineer, NCT Engineering, Inc., California, USA

TEST STRUCTURE AND SEISMIC INPUT

The test structure was made of upper portion of the 9-story steel building frame designed for a previous study (Ref. 9). As shown in Fig. 2, the structure has 4 one-bay plane frames. The eccentric X-bracing was added into the structure in the lower two stories of the two exterior plane frames. The detailed layout of the eccentric X-bracing is shown in Fig. 3. A total of 45 tons of concrete blocks were distributed among the stories in a pattern of 24-18-18-18-12 kips from top to bottom to induce inertia forces. The structure was oriented such that the bracing was parallel to the direction of table motion. It should be noted that the two interior plane frames were disabled to reduce the base shear requirement. Thus the total lateral load was essentially resisted by the two exterior braced plane frame only.

As shown in Fig. 3, the eccentric part of the beam, which will be referred to as 'shear link' because it took mainly shear forces, was designed to be replaceable. Three different sets of links were fabricated and tested to destruction. From here on, the test structure will be referred as Specimen 1, 2, or 3 depending on which set of shear links were installed in it. The strength of links are increasing as specimen numbers, i.e., Specimen 1 had the weakest links.

The source signals of the table motions were the S00E component of the El Centro 1940 and the S74W component of the Pacoima 1971 earthquake records, denoted by EC and PAC, respectively. Because the test structure was presumed one third of a prototype in length scale, the table signals were speeded up by a factor of 1.73, to maintain similitude. And the intensity was adjusted by the control console's span setting. Thus, a table motion was designated by a combination of these three factors. For instance, 1.73*EC 400 denotes a time scaled El Centro type table signal with a control console span setting of 400. This typical table motion was shown in Fig. 4.

EXPERIMENTAL RESULTS

During the tests, the structure experienced no damage except buckling and fracture of the shear links. Figure 5 shows the damaged links of Specimen 2 and Figures 6 and 7 show the shear link and the associated global structural hysteresis loops. It is obvious that they are strongly correlated.

Maximum Base Shears and Overturning Moments

The maximum values of the overturning moments and base shears observed are shown in Fig. 8. As shown, specimens with weaker links produced smaller forces. For example, subjected to 1.73*EC 200, Specimen 3 generated 47% more overturning moment and base shear than Specimen 1. This is because Specimen 1 experienced tremendous link yielding, the structure was thus effectively isolated from the earthquake excitation.

Energy Dissipation Efficiency

The amount of energy dissipated by one of the two links and the total energy input are shown in Table 1. Their unit is inch-kips.

Energy Input and Energy Disspation				
Table Motion	peak acceleration	Total Energy Input (1)	Dissipated by one Link (2)	(3)= (2)/(1)
		Specimen 1		
1.73*EC 200	.43g	152.9	73.3	48%
		Specimen 2		
1.73*EC 200	.43g	142.3	49.7	35%
1.73*EC 400	.98g	516.3	215.5	42%
		Specimen 3		
1.73*EC 200	.43g	151.3	22.0	15%
1.73*EC 400	.98g	556.9	122.3	22%
1.73*PAC300	1.11g	390.9	51.9	13%
1.73*EC 450	1.16g	664.8	129.9	20%

Table 1. Energy Input and Dissipation

Some observation can be concluded from the tabulated results: (a) Subjected to the same table motion, weaker links dissipated more energy. (b) A stronger link dissipated a smaller portion of total energy input. (Thus, a greater response can be expected for a specimen with stronger links.) (c) With comparable peak accelerations, the El Centro motions gave more energy to the structure than did the Pacoima motions because the former have a longer duration.

Maximum Brace Strains

The maximum brace strains measured from all tests plotted against the corresponding peak table accelerations are shown in Fig. 9, The unit of brace strains is milli-inch per inch (mil/in). This figure shows that all specimens had the similar maximum elastic responses when they were excited by small motions, 1.73*EC 50's. It also shows that because of link yielding the brace strains did not increase proportionally with the table intensities.

Displacement Envelopes

Figure 10 shows the maximum displacement responses of all three specimens. Consistently, Specimen 3 had the greatest response. The soft-story effect is obvious in Specimen 1's envelope.

DATA CORRELATION

Since the structure was symmetric, only one quarter of the structure was modeled as shown in Fig. 11. In addition, the elastic upper three stories, which remained elastic in all tests, were modeled by a single shear story. The height, column stiffness, and mass of this shear story were determined such that the first mode overturning moment, base shear, and frequency of the original three stories would be preserved. Table pitching was considered by Element 16. The only inelastic element is Element 11, which was to model the shear yielding behavior provided that its tensile capacity was equal to the shear capacity of the link. This model has only 17 displacement unknowns.

The nonlinear computer code, DRAIN-2D (Ref. 10), was used to do the calculation. A typical comparison between the calculated and measured results is given in Fig. 12. As shown, the peak responses were overestimated at link yielding because of numerical algorithm. A smaller step size is required to reduce the overshooting. In addition, the model damping used, which was 2.8%, was more than reality.

CONCLUSION

This investigation yielded the first available dynamic data of seismic behavior of an eccentrically braced frame. The data shows that the responses of this test structure was governed essentially by the strength of the shear links. A linear relationship between force responses and link strength was observed. The floor displacements were also related strongly to the link shear deformation.

It was interesting to observe from the structural hystereses that the test structure had a tendency to regain its lateral stiffness after yielding. This is because the bracing system always had two braces in tension to align with the deformed link to function as a single diagonal brace accross the first story girder.

More study is required to achieve better correlation between experimental and analytical results. The test structure is of a strong girder-weak column design category. To understand the seismic behavior of an eccentrically X-braced structure which has strong columns and weak girders, more dynamic study is required.

ACKNOWLEDGEMENTS

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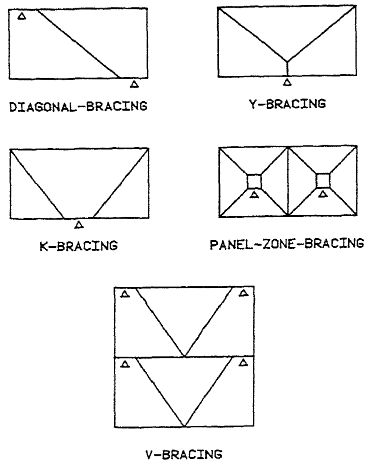

FIG. 1 EXAMPLES OF ECCENTRIC BRACING

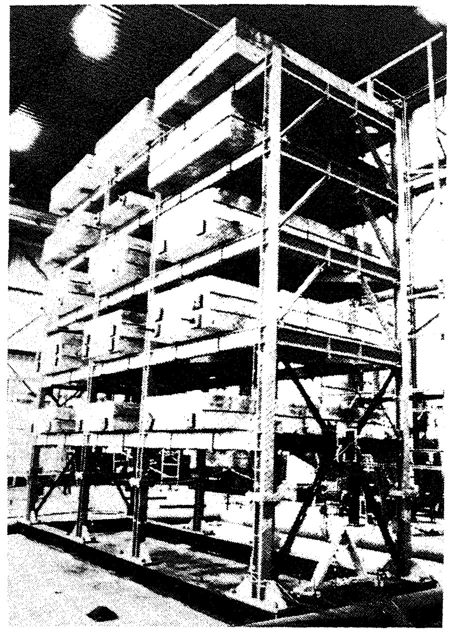

FIG. 2 THE 50-TON TEST STRUCTURE

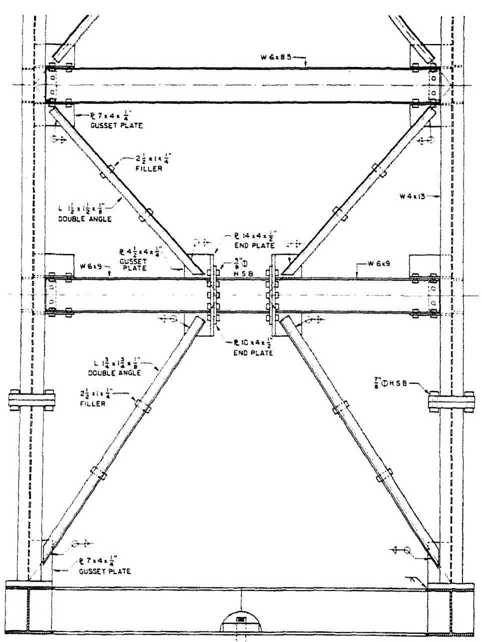

FIG. 3 DETAILS OF ECCENTRIC X-BRACING

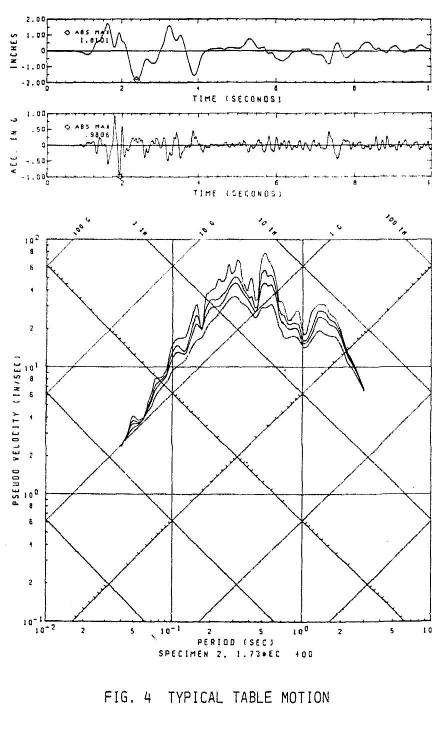

FIG. 4 TYPICAL TABLE MOTION

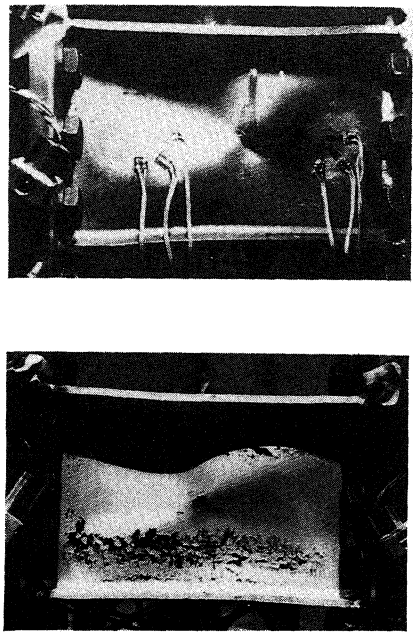

FIG. 5 DAMAGED LINKS (SPECIMEN 2)

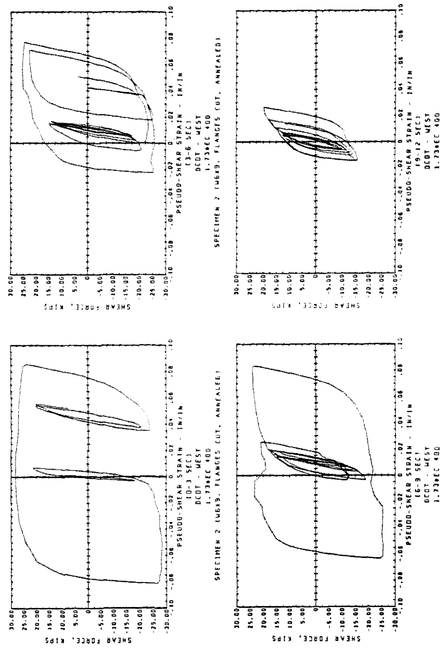

FIG. 6 SHEAR LINK HYSTERESIS LOOPS

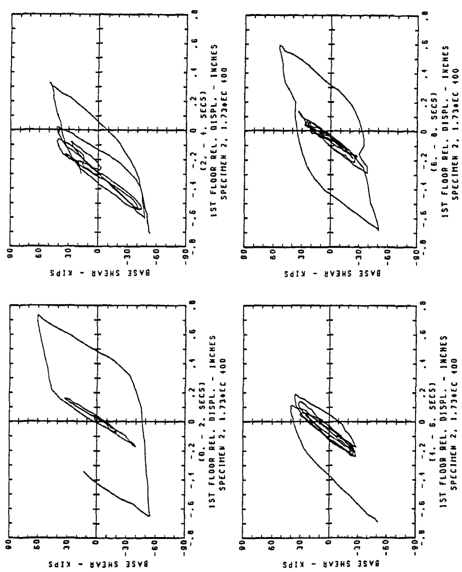

FIG. 7 STRUCTURAL HYSTERESIS LOOPS

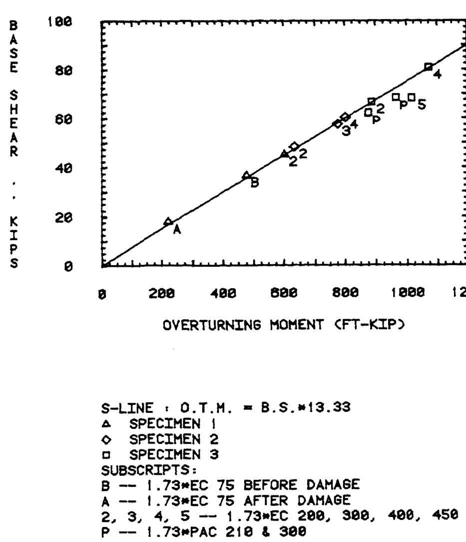

FIG. 8 MAX BASE SHEARS AND OVERTURNING MOMENTS

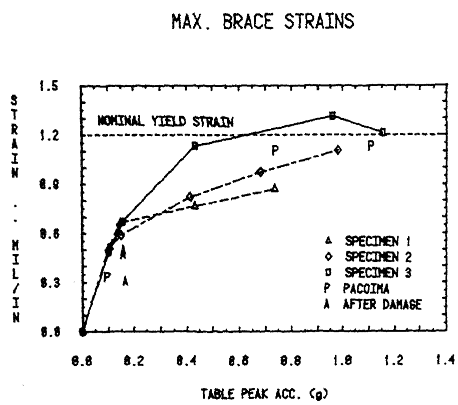

FIG. 9 MAX. BRACE STRAINS

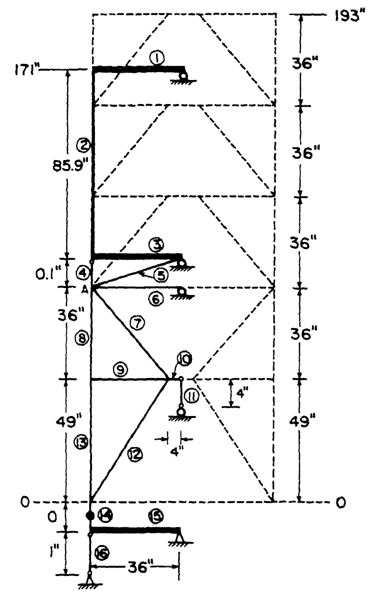

FIG. 11 SIMPLIFIED MATHEMATICAL MODEL

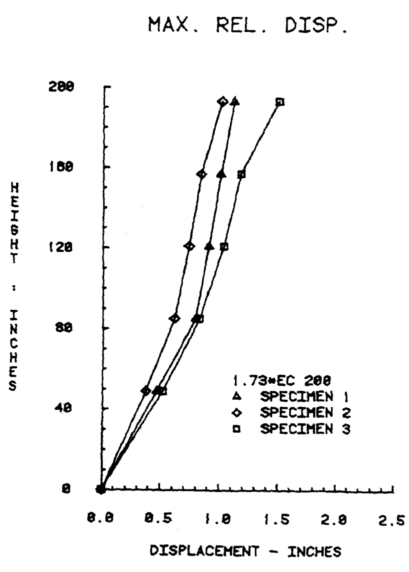

FIG. 10 DISPLACEMENT ENVELOPES

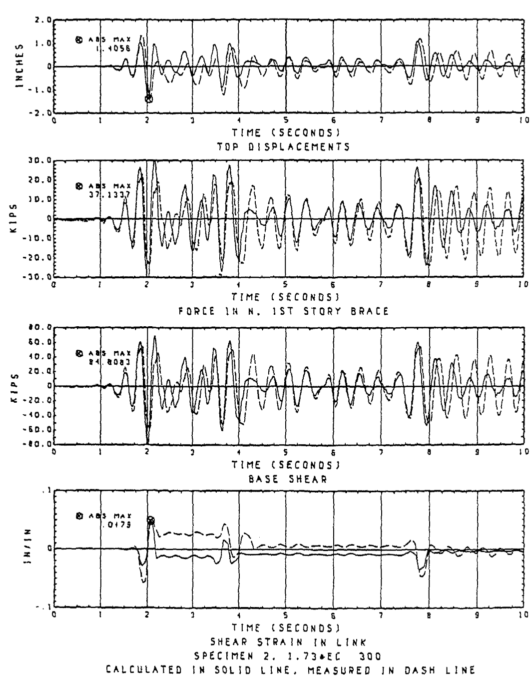

FIG. 12 ANALYSIS AND EXPERIMENT COMPARISON