EXPERIMENTAL STUDIES OF MULTIPLE SUPPORT SEISMIC RESPONSE OF PIPING SYSTEMS

by

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ABSTRACT

An extensive series of experiments on the seismic response of a model piping system in a structure has been completed on the shaking table in the Earthquake Simulator Laboratory at the Earthquake Engineering Research Center of the University of California. The purpose of these experiments is to provide data for the assessment of the accuracy of current multiple support response spectra methods of prediction of the seismic response of piping systems. The piping system tested is a half scale model. The structure in which it was located comprised two steel frames which could be interconnected to act as a single structure or unconnected to act as separate structures. The piping system was attached to several points of each structure and spanned the gap between them.

The combined structure piping system model was subjected to a variety of earthquake inputs on the earthquake simulator including both historical and artificial records. The input to the model included both horizontal and vertical components simultaneously. Three different connection systems were studied including rod hangers only and rod hangers in conjunction with snubbers and springs.

During each test a wide range of response quantities were recorded. These included structure accelerations and displacements; accelerations and displacements on the pipe and on simulated valves; forces and relative displacements at the hangers, snubbers and springs, and strains in the pipe walls at several locations.

This report describes the experiments and gives some preliminary assessments of the results.

INTRODUCTION

The seismic analysis of piping systems continues to be a large part of the structural design of power plants and is a major part of the reanalysis of existing plants.

The current methods of seismic analysis are the single-response spectrum methods, multiple-response spectrum methods and the time-history methods. In all three methods, the analysis begins with the piping system, neglecting the interaction between the piping and the structure. In the first method, a single input response spectrum for the piping system is employed, which is the envelope to the spectra to all attachment points. This method is widely used but is known to give overly conservative results in most cases, (1), (2). In the second method, the spectra at all attachment points are utilized. These floor spectra are generated through time-history analysis of the primary structure using an artificial ground motion history which is compatible with the design spectrum for the site. In the first two methods the response of the piping system to the attachment point excitations is obtained by combining the modal components of the piping response through approximate ad hoc procedures. Numerical studies (3), (4), comparing results from these approximate methods with that of the third method, which is obtained from complete time-history analysis of the piping system response and is presumed to be accurate, have indicated that they can be excessively conservative. On the other hand, the third method requires a large amount of computation and is impractical for economic reasons.

In view of these shortcomings, it is surprising that there has been very little experimental study of realistic piping systems which could be used to assess these methods. The purpose of the research to be reported are such experiments, which may in the future be used for improvement of response spectra methods in the seismic analysis of piping systems.

A large model of a piping system weighing roughly 1360 kg (3000 lbs) was constructed for the tests and incorporated into two large structural models placed side by side on the large shaking table at EERC. The structural models could be connected by a rigid bracing system which could be removed so that the piping system could be seismically tested as if it were located in a single structure or in two separate structures thus allowing the study of piping connected to two different buildings. The piping system was a fairly realistic model and was attached to the frame at several points. It incorporated a variety of hangers, spring supports and in certain tests, snubbers. The combined structure-piping system was subject to a wide variety of earthquake inputs on the earthquake simulator. The inputs to the model included horizontal and vertical components simultaneously. Response data which were monitored were accelerations at various points of the piping system and the structure, stresses in the pipe wall at several sections, relative displacements between pipe and frame, and displacements of the frame.

The input signals included several records of historical earthquakes, and artificially generated records. Peak acceleration levels were selected to ensure that the system response was linear.

The results of this test series will be described. These results may be used to assess the accuracy of current methods and it is hoped that they will suggest simplified approaches to seismic analysis of piping.

SHAKING TABLE TESTS

Test Facilities

The experiments reported here were carried out on the shaking table at the Earthquake Engineering Research Center (EERC) of the University of California, Berkeley, at Richmond Field Station. The table is 6.1m x 6.1m (20' x 20') in plan dimensions and may be used to apply simulated seismic ground excitation to structures weighing up to 45,000kg (100 kips) in one horizontal direction and vertically with maximum accelerations of 1.5g horizontally and 0.5g vertically.

It is constructed of a combination of reinforced and prestressed concrete. The table plate is driven horizontally by three hydraulic actuators and vertically by four such actuators. During operation the dead weight of the table and the test structure is carried on air pressure, so that the actuators only apply the seismic accelerations and do not carry the gravity loads. The shaking table is electronicaly controlled in five degrees of freedom. The sixth degree of freedom, horizontal translation in the other horizontal direction, is controlled by a sliding mechanism. Normally, the pitch, roll and yaw (twist) commands are zero, and the horizontal and vertical command signals represent the displacement time histories of the earthquake record.

Test Model

Frames. Two steel structural frame models were used in these tests. One frame was a four story, three bay frame. This frame is welded using 4 WF 13 columns and 6 WF 8.5 beams. The dimensions of the frame are shown in Fig. 2.1. The lower story is 1.210m (4'-0") high and the others 0.903m (3'-0") high, the central bay is 1.525m (5'-0") wide and the outside bays are 1.955m (6'-6") wide. The frame is one bay deep with a depth of 1.8055m (6'-0") between the column centers. The model is roughly one third full scale of a typical steel structure and to increase the inertia the model was loaded by eight concrete blocks each 1815 kg (4000 lbs) located in each of the outside bays.

The second frame is a three story single bay steel frame which is taller than the four story frame but lighter. The model has 5 WF columns and 6 WF beams. The lower story is (6'-8") high and the upper stories are 1.600m (5'-4") high. The entire frame is (17'-4") high.

This frame is normally used with three 3630 kg (8000 lbs) blocks of concrete on each floor; but in this test, to produce different frequencies for each frame, the two lower floors were loaded by 1815 kg (4000 lbs) concrete blocks and top floor unloaded.

These two frames were located side by side on the shaking table. The location of the frames on the table was dictated by the spacing of the tie down system on 0.903m (3'-0") centers on the table. There was consequently a gap of just under 0.903m (3'-0") between frames. Due to the different story heights of the frames, the top floor of the four story frame was a few inches above the second floor of the three story frame and the first floor of the three story frame was almost at the same level as the second floor of the four story frame. The frames were tied together at these two levels by two rigid frameworks of heavy angles as shown in Figs. 2.1, 2.2. It was found in the testing program that the bracing between the two frames was very effective in forcing the two frames to act as a single structure.

Piping System. In an effort to make the piping system as realistic as possible consistent with the limitations imposed by the table and the available frames, a model piping system was designed based in part on a portion of an actual piping system from a Bechtel Power Corporation project. The prototype piping system involved 15.24 cm (6") and 10.16 cm (4") diameter pipes. To fit realistic span lengths within the table dimensions, it was necessary to reduce the model diameters to 7.62 cm (3") and 5.08 cm (2"). To enable the model piping system to fit into the two frames, certain connections were reorientated. Thus the model is not a precise half scale model of the prototype system but it bears a general resemblance to the prototype and has as many elbows and connections.

The model system used 3S40 and 2S40 pipe. There are two runs of 2S40 pipe entirely within the four story structure. One of these lengths of pipe is rigidly attached just under the first floor level, the other just under the fourth floor level. These two lengths of pipe are connected through a reducing Tee to the 3S40 pipe which is directed downward in the four story frame, then upward between the frame, then into the three story frame, through this frame and ends up at a rigid attachment point at ground level.

Connections Between Pipe And Frame. An important aspect of the experimental work was the assessment of the seismic response of different pipe support systems. Three different pipe support systems were studied involving horizontal and vertical rod hangers either along or in conjunction with snubbers or with spring hangers.

The selection of the locations and orientations of the rod hangers was not entirely unconstrained since it was essential that a hanger could be attached to a part of the structural system. The hanger system is shown in Fig. 2.4. Each hanger was comprised of a clevis end attached to the pipe, a load cell and a variable length of 1.27 cm (1/2") diameter threaded rod which was attached to a convenient point on either frame.

Three hangers were replaced by snubbers in some tests. In later tests these hangers were replaced by spring hangers. The snubbers used were mechanical shock arrestors model PSA 1/2 supplied by the Pacific Scientific Company. The maximum load of this model is 650 lbs and the allowable travel is 6.33 cm (2.5").

The spring hangers 2 and 3 used were standard items (No. 4) with spring rates of (94 lbs/in.) for spring hangers 2 and 3 and a spring rate of (224 lbs/in.) for spring hanger 1 (No. 7).

The location of the snubbers and the spring hangers is shown in Figs., 2.5 and 2.6, respectively.

Instrumentation

The structures and the piping system were equipped with a large number of measurement devices during the test program. In all, 75 channels of data were accessed by the shake table acquisition system.

The first seven channels (0 through 6) were used to monitor table input. The instrumentation for the table is permanently incorporated and records average vertical and horizontal table displacement and acceleration and the pitch roll and twist accelerations. Channels 8 through 19 (except 18) record accelerations in all three directions of points on the piping system. The points selected for monitoring were the valve locations and at the top and bottom of the long run of pipe between the frames. The next six channels 20 through 26 (25 is blank) were used for horizontal frame accelerations. The next eleven channels (28 to 38) recorded the forces in each hanger. The hanger forces were measured by load cells inserted into the hanger. The load cells were aluminum tubes instrumented with strain gauges.

Frame displacements measured by linear potentiometers and relative to a fixed frame mounted outside the shake table were recorded by channels 40 to 46, and hanger displacements measured by DCDT's inserted parallel to the hangers themselves were recorded by channels 48 to 52 (47 is blank).

Strains in the pipe at several different locations were measured by strain gauges. These were attached so that the bending moments and torsional moments on the pipe at five different locations on the pipe could be determined. These use channels 56 to 75. The final channel 76 was used to record the acceleration of the structure in the cross horizontal (z) direction.

Data Acquisition and Data Reduction

The Earthquake Simulator Laboratory is equipped with a NOVA-1200 minicomputer operating in conjunction with a Diablo-31 moving head magnetic disc unit. A maximum of 128 data channels can be samples at rates up to 100 samples/channel. The analog signals are fed to amplifiers, multiplexers and to an analog-digital converter. The digitized data are temporarily stored on magnetic disc before being transferred to tape.

After each test run, the positive and negative extreme values of each data channel can be searched and printed with the corresponding times when they occurred.

EARTHQUAKE SIMULATOR TEST PROGRAM

Earthquake Inputs And Response Spectra

In the test program six different earthquake inputs were used. These are:

1. El Centro S00E, Vert. (1940)
2. Taft S69E, Vert. (1952)
3. Pacoima Dam S14W, Vert. (1971)
4. Parkfield N65E, Vert. (1966)
5. San Francisco S80E, Vert. (1957)
6. CalTech A & B artificial

In preparing the published signal data for use on the shaking table, some distortion of the records is inevitable. The table is displacement controlled and the peak displacement during a particular input signal is controlled by the span setting. A span of 1000 corresponds to the maximum table displacement which is 5 in. horizontally and 3 in. vertically. A span setting of less than 1000 corresponds to a proportionally smaller peak displacement, e.g. SPAN 200 refers to an input with a peak displacement of 1 in. horizontally and 0.6 in. vertically.

The acceleration time history produced by the table is not exactly that measured by the strong motion accelerometer. The process of integration to determine displacement, the manipulation of this displacement history to fit the table control system and the frequency response characteristics of the table all result in an alteration of the signal. However, the actual input of the table is recorded in each case.

The input signals can be scaled both in time and in displacement. For the purpose of these experiments, the time scales of the records were decreased by a factor of $\sqrt{2}$ to correspond to the geometrical scale of the model. The intensity was scaled as indicated above by use of the span setting. This was selected to give an input peak horizontal acceleration around 0.5g for all six input signals. In addition, some were run at smaller and larger span settings to give a series of results for increasing intensity of the same signals and to verify the linearity of the response.

Test Program Matrix

The test program involved two different structural systems. In the first system, the frames were separate and acted independently and the second was produced by connecting the two frames by the two rigid bracing systems which forced the frames to behave as a single structure.

There were three separate piping systems depending on whether the connection was rod hangers, snubbers or spring hangers.

The test matrix comprised, therefore, six earthquakes, two structures, and three piping support systems. In addition, on completion of the test program, the piping system was removed and the frames were subjected to the six inputs when both connected and disconnected. This was done to assess to what extent the response of the structures was modified by the presence of the piping systems.

The damping factors associated with the various components used here, have been estimated during previous tests in determining these components as individual items. The three story frame was studied in great detail by Clough and Tang (5) and they report a damping factor of 0.5% in the first mode and 0.15% in the second mode. The four story steel frame is of similar construction and the damping may be estimated to be roughly the same as the three story frame. The damping in the piping system, independent of the structures, can be estimated from the results of an earlier test (6). There the piping system was held in a rigid structure and tested. During these tests the damping factor was estimated to be 1.2%.

TEST RESULTS

The data reduction for the complete test program has not yet been completed; but several useful conclusions can be drawn from the results which are at present available. The data from the test runs will eventually be available in the form of: i) extreme value results for each channel and every run; ii) time history plots of every channel for a selected number of earthquake inputs; iii) time history plots for selected channels of all max earthquake inputs for the six records; iv) response spectra of all earthquake inputs; v) floor response spectra for the frames in the connected and in the independent configurations for all earthquake inputs; vi) Fourier transform plots of the acceleration response of the piping system for selected inputs.

The test program is listed in Table I. In this table the test run is identified by file number and the earthquake input; structural system connection system and peak input horizontal and vertical accelerations are listed. The data associated with each file will be available on tape from the Electric Power Research Institute.

CONCLUSIONS

This paper has described a very extensive series of experimental results which may be used to assess the accuracy of multiple support response spectra methods for the seismic analysis of piping systems. The experiments involved two different structural systems and three different systems connecting the piping to the structures. Six different earthquake signals were used and each of these were run at different displacements.

The very large quantity of experimental data collected during this test program makes it difficult to draw general conclusions on the response of the piping system, at this point, when much of the data reduction is incomplete; but it is clear that the response of the structure is not strongly dependent on the presence of the piping system.

The presence of springs in the connection between pipe and frame is beneficial in that it reduces the accelerations in the pipe, the forces in the connection system and the strains in the pipe as compared to the case when rigid hangers are used. The presence of snubbers in the piping system appears to have the opposite effect. The results seem to argue for more flexible systems that connect piping systems to the structures housing them.

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TABLE I TEST PROGRAM

FILE	STRUCTURE	PIPE SUPPORT	EARTHQUAKE	SPAN	PEAK HORIZ. ACCELN.	PEAK VERT. ACCELN.
110582.01	Braced	Rod Hangers	6.0Hz Sine		0.55	
.03			El Centro	200		
.04				500	0.55	0.13
.05				750	1.00	0.17
.06			Taft	200	0.16	0.07
.07				500	0.43	0.19
.08				750	0.60	0.21
120582.02	Braced	Rod Hangers	El Centro	200	0.21	0.10
.03			Pacoima	200	0.21	0.10
.04				500	0.57	0.22
.05				750	0.93	0.31
.06			Parkfield	200	0.16	0.06
.07				500	0.47	0.16
260582.01	Braced	Rod Hangers	San Francisco	200	0.51	0.10
.02				250	0.63	0.14
.03			Parkfield	200	0.15	0.07
.04				500	0.43	0.15
.05				750	0.70	0.26
080682.01	Braced	Rod Hangers	Cal Tech AB	200	0.13	0.05
.02				500	0.33	0.10
.03				750	0.43	0.16
090682.01	Unbraced	Rod Hangers	Cal Tech AB	200	0.15	0.05
.02				500	0.47	0.12
.03				750	0.65	0.17
.04			Parkfield	200	0.17	0.07
.05				500	0.46	0.17
.06				750	0.79	0.25
.07			San Francisco	200	0.50	0.11
.08				200	0.51	0.11
100682.01	Unbraced	Rod Hangers	San Francisco	250	0.65	0.08
.02			Taft	200	0.17	0.08
.03				500	0.46	0.18
.04				750	0.62	0.23
.05			Pacoima	200	0.26	0.10
.06				500	0.73	0.22
.07				750	1.07	0.32
.08			El Centro	200	0.26	0.07
.09				200	0.28	0.08
.10				500	0.81	0.15
.11				750	1.11	0.18
.12	Unbraced	Snubbers	El Centro	200	0.27	0.08
.13				500	0.79	0.14
.14				750	1.13	0.18
.15			Pacoima	500	0.72	0.22
.16			Taft	500	0.37	0.16
.17			Parkfield	500	0.45	0.16
.18			Cal Tech	500	0.38	0.11
110682.03	Unbraced	Snubbers	San Francisco	250	0.60	0.12
.04	Braced	Snubbers	San Francisco	250	0.61	0.11
.05			Taft	500	0.43	0.19
.06			Pacoima	500	0.57	0.22
.07			El Centro	200	0.20	0.05
.08				500	0.57	0.11
.09				750	0.97	0.17
.10			Parkfield	500	0.47	0.18
.11			Cal Tech AB	500	0.27	0.08
160682.01	Braced	Springs	El Centro	200	0.20	0.08
.02				500	0.62	0.15
.03				750	0.99	0.15
.04			San Francisco	250	0.56	0.11
.05			Taft	500	0.40	0.17
.06			Pacoima	500	0.56	0.23
.07			Parkfield	500	0.43	0.17
.08				750	0.75	0.25
230682.01	Braced	No Pipe	El Centro	200	0.17	0.06
.02				500	0.39	0.13
.03				750	0.54	0.17
.04				750	0.90	0.15
.05			San Francisco	250	0.61	0.10
.06			Taft	500	0.38	0.21
.07			Pacoima	500	0.56	0.21
.08			Parkfield	500	0.42	0.14
.09			Cal Tech	500	0.26	0.07
.10	Unbraced	No Pipe	Cal Tech	500	0.36	0.10
.11			Parkfield	500	0.46	0.16
.12			Pacoima	500	0.64	0.25
.13			Taft	500	0.35	0.15
.14			San Francisco	250	0.64	0.07
.15			El Centro	200	0.25	0.07
.16				500	0.71	0.11
.17				750	1.05	0.14

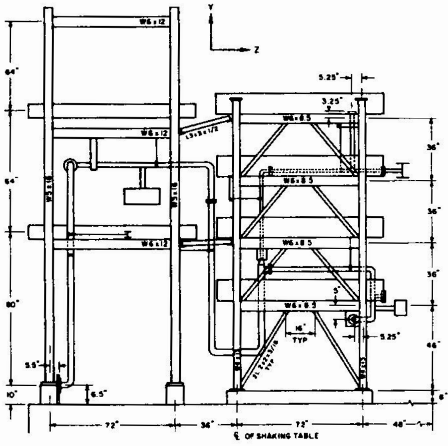

FIGURE 2.1 ELEVATION SHOWING FRAMES SIDE BY SIDE ON TABLE

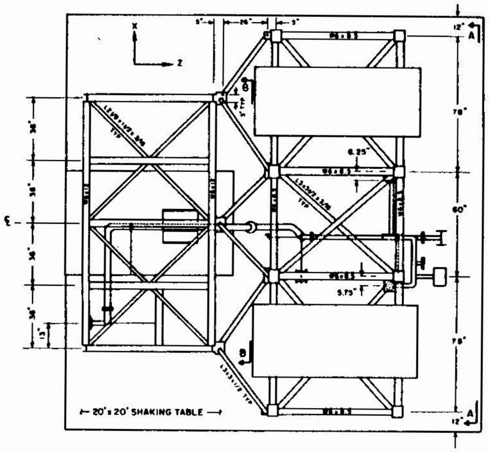

FIGURE 2.2 PLAN VIEW OF FRAMES ON TABLE, SHOWING LOCATION OF CONNECTING BEAMS

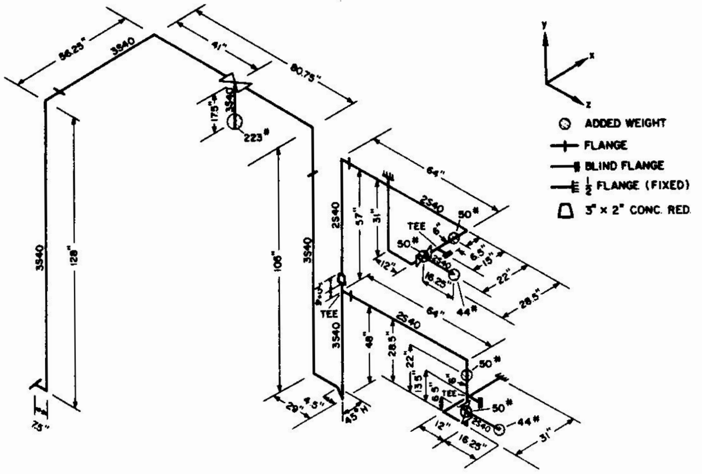

FIGURE 2.3 PIPING SYSTEM MODEL SHOWING DIMENSIONS AND LOCATION OF ADDED WEIGHTS SIMULATING VALVES AND VALVE OPERATORS

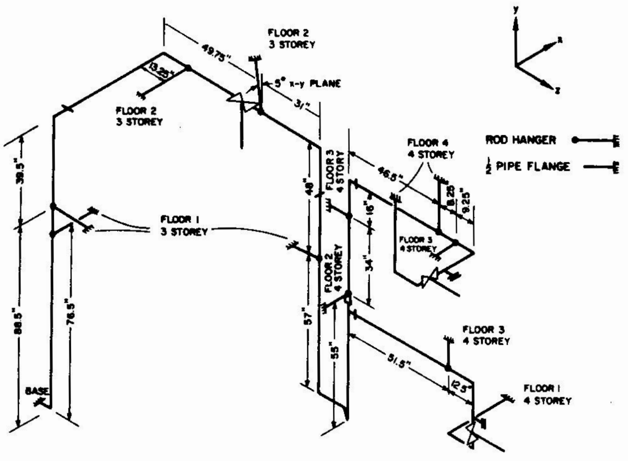

FIGURE 2.4 LOCATIONS AND ORIENTATIONS OF ROD HANGERS

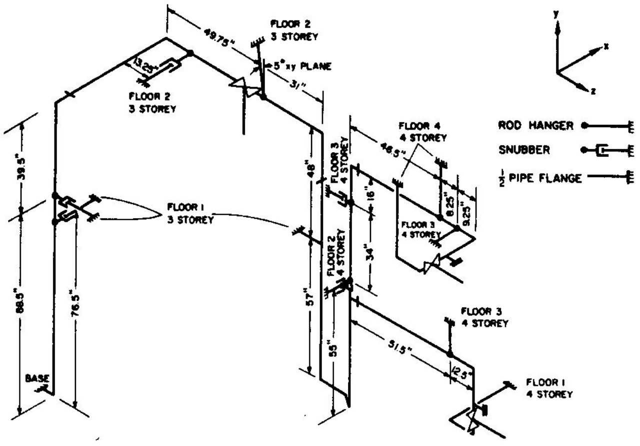

FIGURE 2.5 LOCATIONS OF SNUBBERS

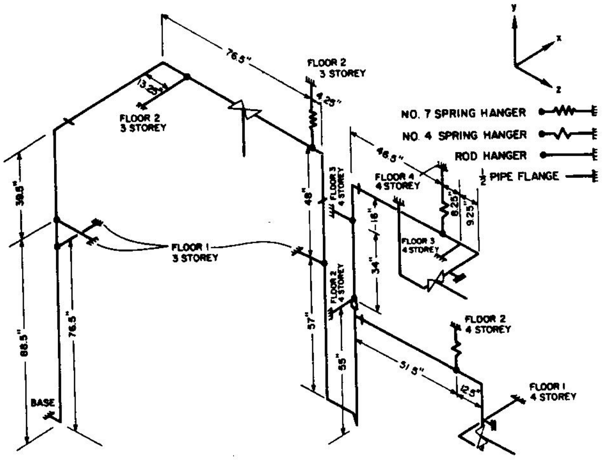

FIGURE 2.6 LOCATIONS OF SPRING HANGERS