

STRONG-MOTION INSTRUMENTATION PROGRAM FOR STATE HIGHWAY BRIDGES

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The State Bridge Seismic Network, supported by the Federal Highway Administration, was established in spring 1974 to instrument highway bridges in seismically active regions. This network is being integrated into the existing National Strong-Motion Instrumentation Network operated by the U.S. Geological Survey. Six bridges in California, Alaska, and Nevada have been instrumented. The most recently installed instrumentation uses a central recording system that permits greater flexibility in locating transducers. For bridge structures with numerous expansion joints, adjacent sections are instrumented so that relative motion across the joints can be interpreted. The response during the 1971 San Fernando earthquake of a seven-story, reinforced concrete building supported by a moment-resistant frame is used to illustrate a simplified interpretation of results from such systems. Instrumentation of representative types of structures will lead to improved modeling and analysis of the response of bridge structures to earthquakes.

•IN SPRING 1974, the Federal Highway Administration established a program to encourage the highway departments of states in seismically active regions to instrument representative types of highway bridges. This program was motivated by the failure of several freeway interchange and overpass bridges during the 1971 San Fernando earthquake (1, 2). Prior to that event, bridge failures during earthquakes in the United States had not caused serious alarm, although the impact of earthquakes on transportation systems had been pointed out as a potentially serious problem (3), and several cases of failure of bridge abutments or displacement of bridges from their piers during earthquakes had been reported (4, 5, 6, 7).

The State Bridge Seismic Network supported by FHWA is to be incorporated into the existing National Strong-Motion Instrumentation Network operated by the U.S. Geological Survey (USGS) for the National Science Foundation and several other cooperating agencies at the federal, state, and local levels. A brief review of the existing network, of concepts for instrumentation of bridges, of the nature of the results to be expected, and of the interpretation of such results is appropriate.

ORGANIZATION OF THE NETWORK

In 1932, the U.S. Coast and Geodetic Survey inaugurated a program of strong-motion seismology intended to furnish data considered essential to the design of earthquake-resistant structures (8). The responsibility for establishing an instrumentation network to achieve this objective was assigned to the Seismological Field Survey (SFS). After several administrative changes that first placed the SFS under the Environmental Science Services Administration (ESSA) and then the National Oceanic and Atmospheric Administration (NOAA), in 1973 NSF was assigned the responsibility for the SFS program. NSF subsequently requested that the USGS operate the program and coordinate it with the strong-motion instrumentation programs of other agencies and organizations. The USGS established the Seismic Engineering Branch to perform this function.

The strong-motion instrumentation program was initiated with the installation of nine low-sensitivity, short-period seismographs (accelerographs) at locations selected by

local engineers. Less than 8 months later, instruments installed at Los Angeles, Vernon, and Long Beach recorded ground motions from the 1933 Long Beach earthquake. These first useful records of damaging earthquake motions indicated amplitudes as large as $0.25\ g$ and provided the impetus for additional instrumentation. The network rapidly expanded to 50 instruments, located primarily in the San Francisco Bay area and the Los Angeles basin but including other seismically active areas of the western United States.

During the succeeding 30 years, there were a gradual increase in the number of instruments and several improvements in the instrumentation. The principal instrument used in the network was the strong-motion accelerograph designed and developed by the C&GS in cooperation with the National Bureau of Standards. A few displacement meters were developed and included in the network. The original accelerograph was relatively large and required extensive and frequent maintenance. Consequently, by 1962 the network had only expanded to 70 accelerographs.

In 1958, a low-cost instrument, the seismoscope, was developed to supplement the accelerographs in evaluating ground motion. The seismoscope record can be interpreted to yield a single point on the relative velocity response spectrum of the ground motion. Because the cost of accelerographs has decreased, the seismoscope is no longer considered an appropriate instrument for further expansion of the network.

In 1963 the first commercially designed accelerograph featuring numerous design improvements was marketed. These instruments overcame many of the inadequacies of the earlier accelerographs and consequently accelerated the expansion of the strong-motion instrument network. By 1974 the network (Figure 1) had increased to approximately 1,200 accelerographs.

From its inception, the program has received the cooperation of numerous outside organizations and individuals. The original advisory board to the SFS subsequently evolved into the Earthquake Engineering Research Institute, a professional organization of engineers, seismologists, and regulatory officials. In the early years, housing and facilities for the instruments were provided by public and private organizations. In recent years, a majority of the accelerographs incorporated into the network have been purchased by outside organizations. Approximately half of the 1,200 accelerographs at the present time are in high-rise buildings as a result of the numerous building codes that require instrumentation at several levels in such buildings.

The recent rapid expansion of the network has brought about the initiation of concerted effort to develop a rational plan for the national network as a coordinated program among cooperating agencies and organizations at the federal, state, and local levels. A balance is to be achieved between the networks designed to determine the nature of the strong ground motions in different regions of the country and those designed to determine the response of representative types of structures. The emphasis is on research that can be applied to improving the process of design of earthquake-resistant structures and facilities.

SELECTION OF STRUCTURES AND INSTRUMENTATION

Because of the importance of understanding structural response to earthquakes at the damage threshold and above and because such information will have an immediate impact on design criteria for structures throughout the country, the structures to be instrumented should be located in areas where the rate of potentially damaging seismic activity is high. On this basis, the highest priority is to instrument structures in California, Alaska, and Nevada, areas about five times more active than the northern Rockies, about 10 times more active than either the Puget Sound region or the lower Mississippi valley, and about 15 times more active than the East Coast (9). On the other hand, a modest investment in instrumentation in all seismically active regions is a prudent hedge given the uncertainty in the historic record of damaging earthquakes.

The structures selected should represent the current predominant construction types within each state, but special or new types of construction should also be considered. The structures should be relatively simple in design so that the records obtained may

be readily interpreted and the knowledge gained may provide significant insight into the response of bridge structures in general. Preferably, the structures selected should be those for which the dynamic characteristics of the structure, the foundation system, and the local soils are known. In any event, the instrumentation scheme must be based on known or estimated mode shapes for the particular type of structure being instrumented.

The FHWA program has been defined such that proposed and current bridge construction in zone 3 (as defined in the Uniform Building Code) may be considered as candidate structures. The criteria on which the limits of zone 3 were defined are being reviewed with a view to revising the seismic risk map. In the meantime, the existing map is being used as a guideline, and more recent geologic or seismic data are also considered.

Six bridges located in California, Alaska, and Nevada have been instrumented. In four cases, the instrumentation is of the type used in ground installations and for the instrumentation of buildings. Although this instrumentation is most appropriate for ground installations and may be used effectively in buildings, the dynamic characteristics of bridge structures and the relative inaccessibility of the desired measurement points make this instrumentation undesirable for use on bridges. The most recently installed instrumentation on bridge structures uses a central recording station tied to appropriately located remote accelerometers. This system has the following advantages:

1. The periodic maintenance is confined to the central recording station, which may be located for convenient access;
2. Single- or multiple-axis accelerometers may be located at specific and perhaps relatively inaccessible locations;
3. Appropriate acceleration traces may be placed on the same record for interpretation of the phase relations between traces; and
4. The same system may be used to record "down-hole" accelerations if this is desired because of the site conditions.

One remote transducer-central recording system has proved suitable for bridge instrumentation, and others are being evaluated.

Early accelerographs recorded on paper, but the newer instruments record on film. Film recording provides a record that is more permanent than paper and is adaptable to automatic digitization, which could be important in processing the records from a large bridge structure. The analog tape recording accelerograph systems that have been developed were found to have a smaller dynamic range than the film recording systems. Two direct digital recording systems have been commercially developed specifically for measuring strong-motion accelerations. The suitability of these systems is being evaluated, and they may be found to be the most appropriate systems when numerous channels of data are to be obtained from a structure in a seismically active area.

INTERPRETATION OF ACCELEROGRAPH RECORDS

The primary purpose of installing strong-motion instrumentation in structures is to provide a means to verify and improve the techniques for analytically modeling the dynamic characteristics of the structures. In particular, it provides the only means for evaluating the appropriate levels of modal damping to be used for modeling this parameter at the levels of response experienced during a strong earthquake (10).

With the limited number of installations, only one record of small-amplitude response of a bridge structure to an earthquake has been obtained to date. Instruments on the interchange of I-5 and Calif-14 near San Fernando, California, recorded the motion at ground level and at the top of one column of this structure during the 1973 Point Mugu earthquake. These records are shown in Figure 2. This structure was damaged during the 1971 San Fernando earthquake and had not been completed at the time of the Point Mugu earthquake. Imbsen and Gates (11) have attempted to correlate the measured

Figure 1. National Strong-Motion Instrumentation Network, 1974.



Figure 2. Accelerograms from interchange of Interstate and Calif-14 during Point Mugu earthquake.

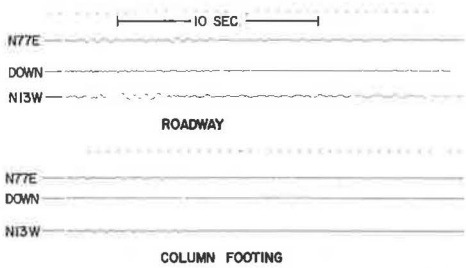


Figure 3. Accelerograms from 8244 Orion Boulevard during San Fernando earthquake.

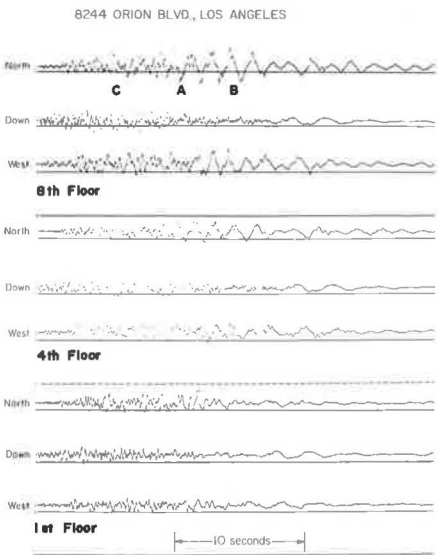


Figure 4. First mode shape for 8244 Orion Boulevard during San Fernando earthquake.

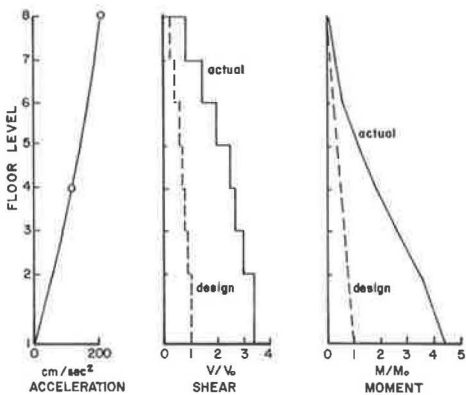
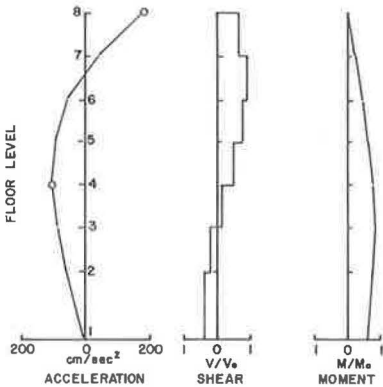


Figure 5. Second mode shape for 8244 Orion Boulevard during San Fernando earthquake.



response with the response calculated from a dynamic analysis of the structure by using the measured input. Although the correlation was not so close as desired, the results did suggest methods for improving the modeling of the structure, particularly damping and modeling of the intermediate hinges at expansion joints. Since completion of the structure, the instrumentation is not accessible for maintenance.

As an illustration of the nature of the records to be expected from this instrumentation program and a simple interpretation that can be made if the structure is adequately instrumented, the response during the San Fernando earthquake of a seven-story reinforced-concrete building with a moment-resistant frame in the exterior walls is discussed. Accelerograph records from the roof (eighth level), the fourth floor, and the ground floor are shown in Figure 3. The maximum ground accelerations at this site were 0.27 g in the north-south direction, 0.14 g in the east-west direction, and 0.17 g in the vertical direction. In the later part of the ground motion record, a long period wave with strong vertical and east-west motion and lesser north-south motion is clearly a strong surface wave.

The records from the fourth floor and the roof contain more distinct frequency components than the record from the ground, inasmuch as the building amplifies the motion at frequencies corresponding to its natural frequencies. In the earlier parts of the records of lateral motion from the roof and fourth floor, the response is entirely in the higher modes. The first mode response becomes apparent about 8 sec after the start of the record. In the north-south record from the roof, a change in the first mode period may be noted at the point labeled A about 11 sec from the start of the record. At this point, the response is a combination of the first and second modes. The first mode period lengthens from about 1.0 to about 1.5 sec. It is thought that the damage to the building occurred at this point in time. The maximum response in the first mode occurs somewhat later in time at about point B.

For response in the north-south direction, the maximum accelerations in the first mode of 0.21 g at the roof and 0.12 g at the fourth floor were used to draw a first mode shape (Figure 4). By multiplying the indicated accelerations at each level by the values of floor weight used in the design, the lateral forces that correspond to first mode response are obtained and story shears and moments may be determined. A comparison of shears and moments to the values used in design is shown in Figure 4 for each floor level and indicates that the structure experienced first mode forces significantly greater than the design values.

The maximum response in the second mode was estimated to have occurred at point C (Figure 3). A procedure similar to that used to obtain first mode response was used to obtain the lateral forces corresponding to the maximum response in the second mode (Figure 5). The results for the second mode should not be added to those for the first mode because the two maximums did not occur at the same point in time, although both were close to their maximums at point A (Figure 3).

This interpretation points up the importance of understanding the dynamic characteristics of the system, in particular the mode shapes, when the locations for the instrumentation on a structure are selected. Because the response can be characterized by the natural modes of vibration, the instrumentation must be located away from the node points of any of the modes that may contribute to the column shears and moments. Although not illustrated by this example, it is important to locate the instrumentation such that lateral and torsional modes can be separated. The modal frequencies are generally more closely spaced in bridge structures than in buildings. This factor can complicate the analysis and implies that more extensive instrumentation is required. For bridge structures with numerous expansion joints, adjacent sections should be instrumented so that the relative motions across the expansion joints can be evaluated. This motion may be associated with the damping of the systems response. For long-span structures, intermediate locations along the deck may have to be instrumented.

CONCLUSION

If structures are to be monitored through use of strong-motion instrumentation, their

dynamic response must be understood when the instrumentation program is planned, although certain standard procedures for instrumentation of each class of bridge may evolve from a coordinated program. The coordination of the various state programs into a Highway Bridge Seismic Network to form a part of the existing National Strong-Motion Instrumentation Network is expected to provide the data necessary to improve seismic design practice for bridge structures.

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