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Linear analysis of R/C buildings for the Whittier earthquake

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ABSTRACT: The seismic design forces for three irregular reinforced concrete structures which had been subjected to the Whittier earthquake of 1987 were studied. The number of stories ranged from 7 to 20. The results of the study showed that the requirement that "irregular" structures be analyzed using a dynamic (response spectrum or response history) analysis may not be necessary for all buildings having abrupt change of stiffness or mass.

1 INTRODUCTION

On October 1, 1987, a Richter magnitude 5.9 earthquake occurred in the Whittier area which is located at about 15 km northwest of downtown Los Angeles, California. Nearly 360 medium to high rise buildings in the area were instrumented with strong motion accelerometers. The majority of the instruments were triggered by the earthquake. The measured data have provided researchers and engineers with ample opportunity to evaluate the response of structures and to assess the validity of structural design assumptions for moderate earthquakes.

Since 1988, the seismic provisions of the Uniform Building Code (UBC) have provided specific guidelines to determine if a building should be analyzed based on static or dynamic method, ICBO (1991). According to the provisions, "irregular" structures located in highly seismic regions need to be analyzed using a dynamic method if the height exceeds certain limits. The object of this article is to examine this requirement for three "irregular" buildings which were subjected to the Whittier earthquake, and to determine if the requirement is justified.

2 DESCRIPTION OF THE BUILDINGS AND RESPONSES

Three reinforced concrete buildings were selected for this study: (i) the California State University at Los Angeles (CSULA) Administration Building, (ii) the Sheraton-Universal Hotel at North Hollywood, and (iii) the Holiday Inn Hotel at Van Nuys. Only the response in the transverse (narrow) direction of these structures was considered. All three buildings have at least one feature that places them in the "irregular" category as defined in UBC. The 1987 Whittier earthquake caused minor structural damage in the first building and only non-structural damage in the other two.

A brief description of each building and its response is presented in the following sections. More detailed information about the geometry and the recorded motions are presented by Abdel-Ghaffar, et. al. (1990).

2.1 The CSULA administration building

This is an eight-story building which was designed in 1967 and constructed in 1969. Figure 1 shows the second floor plan for this structure. The overall dimensions of the upper floors are the same as those of the first floor. The structural system consists of a slab systems composed of reinforced concrete columns, beams, and slabs. The first story columns consist of four wide-flange steel sections encased in circular concrete columns, and ten spiral columns. In the transverse direction, two exterior shear walls extend between the second floor and the roof. The specified concrete compressive strength in 28 days was 4,000 psi (27.6 MPa) for all structural elements.

The structural irregularity in this building is the "soft-story" as defined in the UBC. In the transverse direction, the horizontal stiffness of the columns in the first story is approximately one-twentieth of the combined stiffness of the columns and the shear walls in the second story. According to the UBC, when the stiffness ratio falls below 0.7, the structure is "irregular", unless the story drift ratio is less than 1.3 times the story drift ratio of the story above. For the CSULA structure, the ratio was 5.1.

Fifteen accelerometers were triggered by the 1987 Whittier earthquake. These sensors measured the response of the structure in both the transverse and the longitudinal directions at different floors including the ground level and the roof. The peak transverse acceleration was 31 percent of gravity at the ground level and 49 percent of gravity at the roof.

Taly (1988) reported that during the earthquake, the building experienced relatively high accelerations but suffered only minor damage to structural and non-structural elements. The structural damage was in the form of cracks in the first-story columns, the second floor slab-wall connections, and the shear wall at some of the floors. The non-structural damage consisted of cracking of partitions and breaking of some of the window glasses.

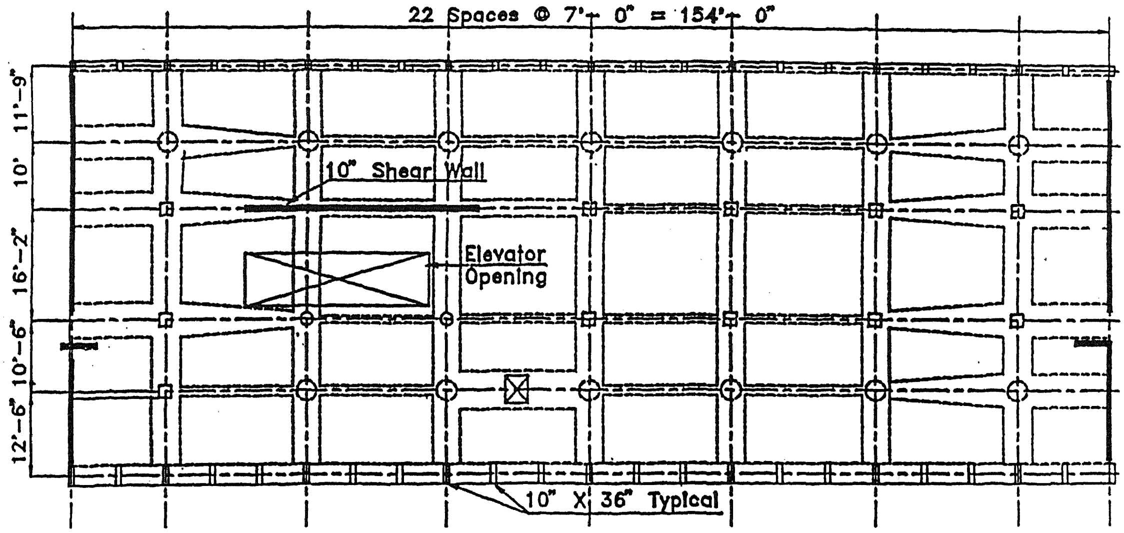

Fig. 1 Plan view of the second floor in the CSULA Administration building (1 ft.=0.305 m, 1 in.=25.4 mm).

2.2 Sheraton-Universal Hotel

This building has three main sections, including a twenty-story tower which is the subject of this paper. It was designed in 1967 and built in 1968. The tower consists of a slab system the elevation of which is shown in Fig. 2. Except for the roof and parts of the hallways, the floors include beams at all column centerlines. The specified compressive strength of concrete is 3,000 psi (20.7 MPa), except for the columns in the lower ten stories for which the specified strength is 4,000 psi (27.6 MPa).

The tower has three types of vertical irregularity as defined in UBC. The first is the length of setback from the third to the fourth floor (Fig. 2). According to UBC, if the ratio of the length of one floor to the length of an adjacent floor exceeds 1.3, the structure has geometric irregularity. In addition, the lateral stiffness of the columns in the third story is only 29 percent of the fourth story columns, thus making the former a "soft story." The third type of irregularity is due the ratio of the effective weight of the third floor to that of the fourth floor which exceeds 1.5 and leads to an irregular weight distribution.

The structure was instrumented with 16 accelerometers which were installed at the basement, third floor, ninth floor, sixteenth floor, and the roof. Two components of horizontal acceleration were measured at all the instrumented floors. An additional sensors was installed at the basement to measure the vertical acceleration.

The measured peak ground acceleration at the basement of the Sheraton-Universal Hotel was eleven percent of gravity during the Whittier earthquake. The maximum transverse roof acceleration was 17 percent of gravity. No significant structural damage was reported.

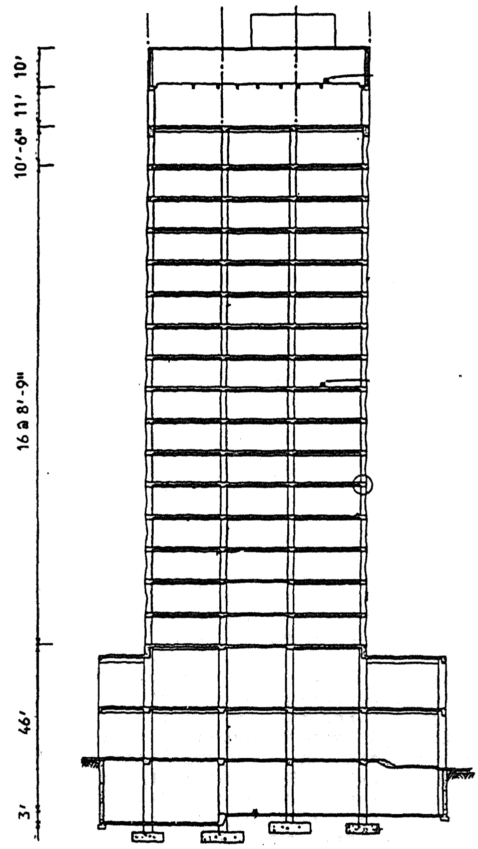

Fig. 2 Transverse section of the Sheraton-Universal Hotel Tower.

2.3 The Holiday Inn Hotel

This hotel is a seven-story flat plate system with spandrel beams (Fig. 3). The exterior frames form the main lateral load carrying system. The building was designed in 1966 and constructed in 1967. The specified concrete compressive strength for the first-story columns was 5,000 psi (34.5 MPa) and for the beams, slabs, and the columns in the second floor was 4,000 psi (27.6 MPa). A compressive strength of 3,000 psi (20.7 MPa) was specified elsewhere in the structure.

The cause of irregularity in the structure is the ratio of the lateral stiffness of the first story columns to that of the second story which is 0.36. Based on the provisions of UBC, a ratio of less than 0.7 would place the structure in the vertically 'irregular' buildings category. The ICBO allows to treat the structure as a regular system if the story drift ratio is less than 1.3 times the story drift ratio of the story above. This condition was met for the Holiday Inn Hotel.

During the Whittier earthquake, thirteen accelerometers collected data at the ground level, the second, third, and sixth floors, and the roof. The maximum acceleration in the transverse direction was 17 percent of gravity at the ground level and 20 percent of gravity at the roof. No structural damage was reported for the building despite the relatively significant peak ground acceleration (PGA).

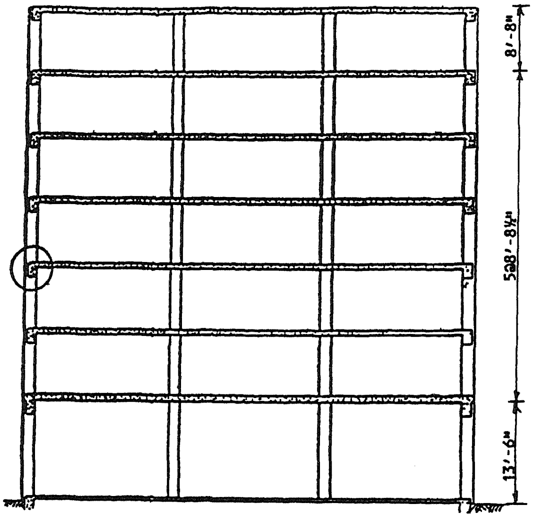

Fig. 3 Transverse section of the Holiday Inn Hotel.

3 ANALYSIS OF STRUCTURES

The analysis of the structures described in the previous sections consisted of static and dynamic analyses. The dynamic analyses included in this study incorporated the response spectrum technique and a time-step response history method, both in the linear range.

3.1 Equivalent static analysis

The equivalent static analysis method to determine earthquake forces and displacements is relatively simple. Although, this method is not allowed for irregular structures, it was used to compare the results of static and dynamic analyses. Many factors such as the seismicity of the region, site characteristics, occupancy type, structural configuration, and structural system affect the magnitude of the earthquake forces.

ICBO (1991) specifies the following equation to determine the service base shear due to earthquake:

$$V = (Z\ I\ C\ /\ R_W\ )\ W \qquad (1)$$

In this equation, Z is the seismic zone factor, I is the importance factor, C is the response spectrum factor specified in Eq. 2, R_W is a coefficient related to the ductility of the structure, and W is the dead load of the frame including a portion of the partition loads.

$$C = 1.25\ S\ /\ T^{2/3} \qquad (2)$$

In this equation, S is the site coefficient, and T is the fundamental period of vibration of the structure. The shear in Eq. 1 is distributed to different floors using a weighted method which is based on the product of the weight and height from the base at each floor.

3.2 Response spectrum analysis

This method is specified as one of the dynamic analysis methods by ICBO (1991), and involves a modal analysis of the structure in which the vibration periods and mode shapes are determined based on the elastic properties of the structure. Only the modes that contribute significantly to the response are considered. The number of modes should be selected such that at least 90 percent of the participating mass of the structure is included in the response. Based on the periods, a spectral acceleration which is normalized relative to the peak ground acceleration is determined using the spectra in ICBO (1991). The modal forces are then determined using a routine procedure. Because the forces so determined ignore the inelastic action of structural members, they are reduced by the R_W factor specified in the previous section.

The structure is analyzed for the reduced forces obtained for each significant mode. The results are then combined to obtain the maximum response. An appropriate mode superposition procedure for structures with well-separated periods is the square root sum square method (SRSS). According to ICBO (1991), the base shear for an irregular structure analyzed using the response spectrum method shall not be less than the shear in Eq. 1. Otherwise, the base shear needs to be amplified to match that from Eq. 1 and other internal forces need to be proportionally increased.

3.3 Response history analysis

According to ICBO (1991), the dynamic analysis may be in the form of a modal superposition analysis for a specified response spectrum, or it may be a direct integration technique of the equation of motion for a representative ground acceleration. The structure in either case is treated as a linear system. In the study presented in this article, the modal superposition method was utilized using the ground acceleration records obtained for each building during the Whittier earthquake.

4 RESULTS OF THE ANALYSIS

For the purpose of static analysis, the fundamental period of vibration for each structure was determined using Eq. 3 in ICBO (1991).

$$T = C_t \ (h_n)^{3/4} \qquad (3)$$

In which, C_t was taken equal to 0.02 for CSULA Administration building and 0.03 for the other two. The parameter h_n is the height of the building in feet. The Z factor in Eq. 1 was 0.4 and the I factor was 1 for all the structures. All the frames were treated as intermediate moment-resisting frames. A value of 9 was used for R_w for the CSULA structure and 8 for the other two. A site coefficient (S) of one was used for all the buildings, because they were built on relatively stiff soil.

The number of lowest significant modes used in the response spectrum analysis was three for the CSULA and the Holiday Inn structures and was four for the Sheraton-Universal Hotel. For all three buildings, the base shear determined from the response spectrum analysis was lower than that from Eq. 1 and had to be amplified by a factor of 1.43, 2.19, and 1.71 for the CSULA structure, the Sheraton-Universal Hotel, and the Holiday Inn Hotel, respectively.

A time interval of 0.02 sec. was used for all the response history analyses. The damping ratios were set at 6.8 percent for the CSULA and the Holiday Inn structures, and at 6.2 percent for the Sheraton-Universal Hotel. These values were the effective damping ratios for the structures during the 1987 Whittier earthquake (Abdel-Ghaffar, et. al. (1990)).

According to UBC, the input earthquake record used in dynamic analysis needs to represent the historic earthquake activities in the area in terms of frequency content, amplitude, etc. The development of ground motion records to satisfy this requirement for each site was beyond the scope of the study discussed in this paper. In the absence of such records, it was deemed to be logical to utilize the ground acceleration data obtained during the 1987 Whittier earthquake in the dynamic analyses.

To evaluate the adequacy of static analysis, the story shears determined using different methods are presented in the following sections for each buildings. A more comprehensive comparison of the responses is presented by Feng, et. al. (1992).

4.1 Results for the CSULA structure

Shown in Fig. 4 is a comparison of the story shears obtained from different methods. It can be seen that the results from the dynamic

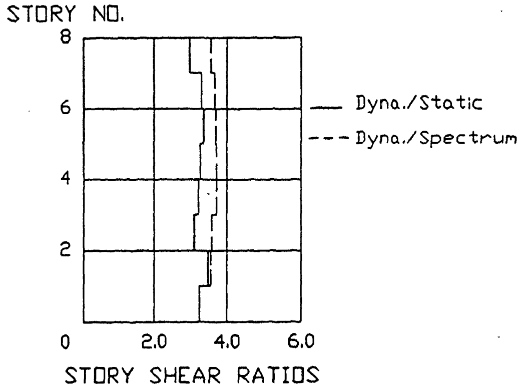

Fig. 4 Earthquake shear ratios for different methods for CSULA structure.

analysis are considerably higher than those from the static and response spectrum analyses. Note that the static and response spectrum results have incorporated the R_w factors, and hence may be viewed as "service earthquake forces." However, the dynamic results are for a peak ground acceleration of 31 percent of gravity, which is too large for a "service" level earthquake. If the PGA were normalized to ten percent of gravity, the ratios would be 1 to 1.2.

The most important observation in this figure is that the results for the static and the response spectrum method have very similar distribution along the height, thus indicating that the static analysis method would have been sufficient for finding the earthquake forces even though the structure is "irregular."

4.2 Results for the Sheraton-Universal Hotel

The measured earthquake record which was used in the dynamic analysis of this hotel had a PGA of eleven percent of gravity. Results in Fig. 5 indicate that the dynamic analysis led to considerably lower story shears than the other two methods. The difference may be because the amplitude of the Whittier earthquake recorded at the ground floor of this building is lower than what would be expected in a service level earthquake. Regardless of whether this is the case or not, the figure shows that the distribution of shear forces from the static analysis is identical to that from the response spectrum analysis.

4.3 Results for the Holiday Inn Hotel

The measured ground acceleration history during the Whittier earthquake in the transverse direction of this hotel was 17 percent of gravity. The ratios of story shears for three different analyses are shown in Fig. 6. It can be seen that the three different analysis methods led to close values for shear for the lower five stories. in the upper two stories, the dynamic results were more than fifty percent higher than the other results. This may be attributed to the relatively low story shear that is normally predicted using the static method. Similar

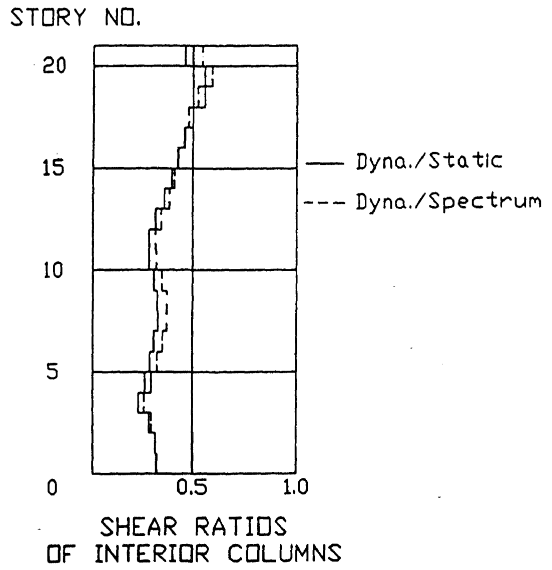

Fig. 5 Earthquake shear ratios for different methods for the Sheraton-Universal Hotel.

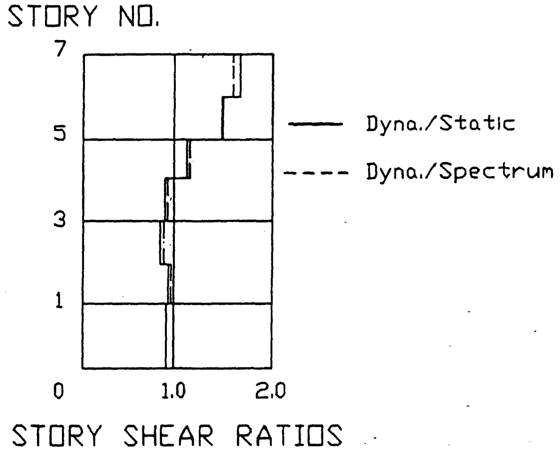

Fig. 6 Earthquake shear ratios for different methods for the Holiday Inn Hotel.

to the other two buildings, the distribution of story shears along the height of the structure was very close for the static and response spectrum methods.

CONCLUSIONS

The study presented in this article indicated that the ICBO requirement that 'irregular' structures be analyzed using a dynamic (response spectrum or response history) analysis may not be necessary for all buildings with abrupt change of mass or stiffness along the height. The internal forces based on the response spectrum analysis for all three buildings were significantly less than those of the static analysis and, hence, they needed to be amplified. Even though the final outcome of the analyses was that the static method controlled, the requirement that a dynamic analysis be performed increased the design time with no apparent justification.

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