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EXTRACTING EMPIRICAL CAPACITY CURVES: A CASE STUDY OF THE SEVEN-STORY HOTEL IN VAN NUYS, CA

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Abstract

After strong earthquakes, damage detection methods can be used on instrumented buildings to provide quick feedback on the status of the structural system of a building. One such damage detection method is the empirical capacity curve extraction method. An empirical capacity curve is a force-displacement curve developed from recorded response data of a particular event. The information from an empirical capacity curve is used to quantify damage to the structural system; depending on the type of empirical capacity curve obtain, damage quantification parameters could include stiffness degradation, strength degradation, ductility ratios, and changes to the fundamental period. For a case study, the empirical capacity curve extraction method has been applied to the seven-story hotel located at 8244 Orion Avenue in Van Nuys, CA. This building is instrumented with accelerometers at the ground, roof, and some intermediate floors. Historical response records are available for the 1971 San Fernando and 1994 Northridge earthquakes. Using these response records, a fundamental mode empirical capacity curve can be extracted for each of the two events by using only the respective roof and ground recorded acceleration records. For fundamental mode empirical capacity curves, stiffness degradation, changes in the fundamental period and if the yield point can be estimated, ductility ratios are the best parameters for damage quantification. For the 1971 earthquake, only the east/west acceleration response records are available. For the 1994 earthquake, both the east/west and north/south response records are available. After the 1971 earthquake, the east/west direction fundamental period appears to decrease by half yet after the event, the building was deemed to only suffer nonstructural damage. For the 1994 earthquake, the initial fundamental period was close to that of the fundamental period after the 1971 earthquake; at the end of the 1994 earthquake, the fundamental period was less than half of the post 1971 earthquake fundamental period. Substantial structural damage was noted on the fourth floor columns. Many researchers such as Freeman, Lepage, and Luna have developed their own capacity curves for this building using the response data. The resulting empirical capacity curve has been compared with the results of the other researchers. While generally similar, there are differences between each researcher's capacity curves for this building. If the empirical capacity curve extraction method was employed at the time immediately after the events, an alert could have been triggered to notify first responders had the fundamental period or stiffness of the system decreased below a certain threshold.

Keywords: Empirical Capacity Curve; Earthquake Response;

1. Introduction and Background

The empirical capacity curve extraction method is applied to historical records from the seven-story hotel located at 8244 Orion Ave. in Van Nuys, California [1]. Acceleration response is available only for a select few of the seven total elevated floors [2].

The seven-story hotel, pictured in Figure 1, was designed in 1965 as a reinforced concrete flat plate structure. The plan dimensions of the structure are 151 feet in the east-west direction and 63 feet in the north-south direction. Column spacing is approximately 20 feet center to center. The floor slabs vary in thickness from eight to ten inches. The total height of the building is approximately 65 feet from the ground to the roof concrete slab. In 1971, an earthquake, referred to as the San Fernando earthquake, with epicenter located 13.8 km away from the hotel damaged the building; damage sustained was deemed non-structural after the event. Some analytical evaluations were performed and found the building to experience some inelastic behavior [3]. At the time of the 1971 San Fernando earthquake, the building was instrumented with nine accelerometer instruments. In 1980, its instrumentation was upgraded with 16 accelerometer instruments at the ground, 2nd, 3rd, 6th, and roof floors. The upgraded instrumentation layout is shown in Figure 2. In 1994, the building experienced the Northridge earthquake with an epicenter located 6.1 km away from the hotel; after the earthquake column shear cracking was observed at the 4th story.

Fig. 1 – Seven-story hotel in Van Nuys, CA [2]

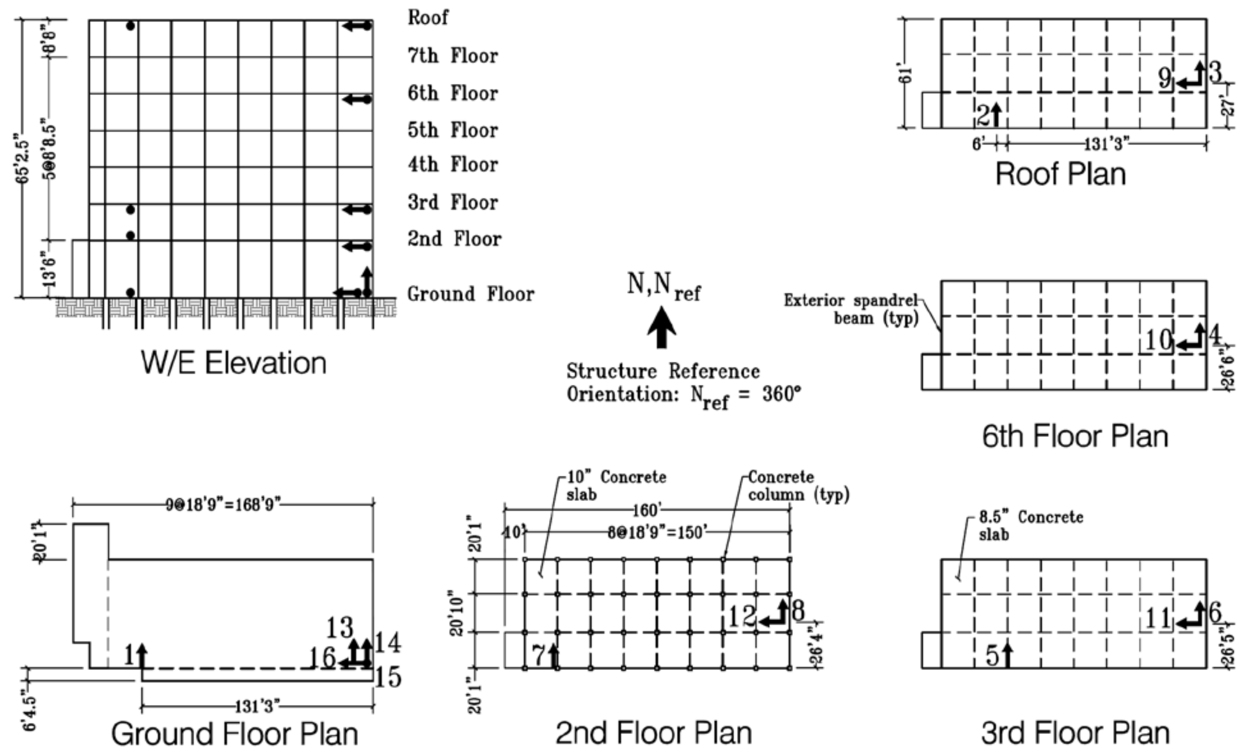

Fig. 2 – Seven-story hotel sensor location information [2]

2. Empirical Capacity Curve Extraction

For this particular sensor layout shown in Figure 2, only a fundamental mode empirical capacity curve can be extracted from the response data [1]. Story empirical capacity curves would require sensors at each story [1]. Therefore, only the ground and roof sensor response data is used to extract a fundamental mode empirical capacity curve. With sensors in both the north-south and east-west directions, a fundamental mode empirical capacity curve can be found for each direction. Additionally, the ground and roof sensor layouts have a north-south sensor on the west side (sensors 1 and 2) and on the east side (sensors 3, 13, and 14) which provides a unique opportunity to compare the performance of each side of the building.

2.1 1971 San Fernando Earthquake Response

Response data for the seven-story hotel recorded during the 1971 San Fernando earthquake are available at the Center for Engineering Strong Ground Motion Data website database [2]. Sensors installed on the roof and ground levels recorded acceleration response data at a sampling frequency of 50 Hz from the 1971 San Fernando earthquake in the east-west direction. Unfortunately, these available data are not raw data and have been processed and baseline-corrected. Only the fundamental mode empirical capacity curve extraction method can be implemented on these data [1]. As a guideline, multi-story building fundamental mode participation factors are generally between 1.3 and 1.4 [4]. For the seven-story hotel in Van Nuys, California, the fundamental mode participation factor has been calculated as 1.3 in the north-south direction and 1.28 in the east-west direction [5]. A fundamental mode participation factor of 1.3 is used for the building in both directions in this analysis.

In the east-west direction fundamental mode analysis, only roof and ground acceleration data are needed. For this analysis, east is the positive direction. A fourth order zero-phase high-pass Butterworth filter with a 4Hz cutoff frequency is applied to the ground and roof data. The absolute roof acceleration and the fundamental mode acceleration are shown in Figure 3. The mean estimated mass-normalized damping coefficient is 1.5 [1]. Using the upper envelope of the quarter cycle secant stiffness response, an empirical capacity curve is shown in Figure 4. Based on the empirical capacity curve, the maximum roof drift is approximately 0.3% for the east-west direction. Using quarter cycle secant stiffness, stiffness degradation can be estimated throughout the duration of the earthquake as shown in Figure 5. The post-event stiffness is estimated to be 50% of the original pre-earthquake stiffness. Moreover, the fundamental mode period of the building can also be used to quantify damage using the empirical capacity curve estimation; the initial period in the east-west direction is approximately 0.7 seconds and final period is approximately 1.3 seconds. The maximum period throughout the response is approximately 1.7 seconds.

The damage to the building from the 1971 San Fernando earthquake was considered primarily non-structural. According to Freeman et al. (1999), the initial fundamental period of the building is 0.7 seconds. The post-event fundamental period is 1.3 seconds. The largest fundamental period throughout the duration of the response is reported to be 1.5 seconds. These estimated periods completely correlate with the results from the empirical capacity curve extraction method.

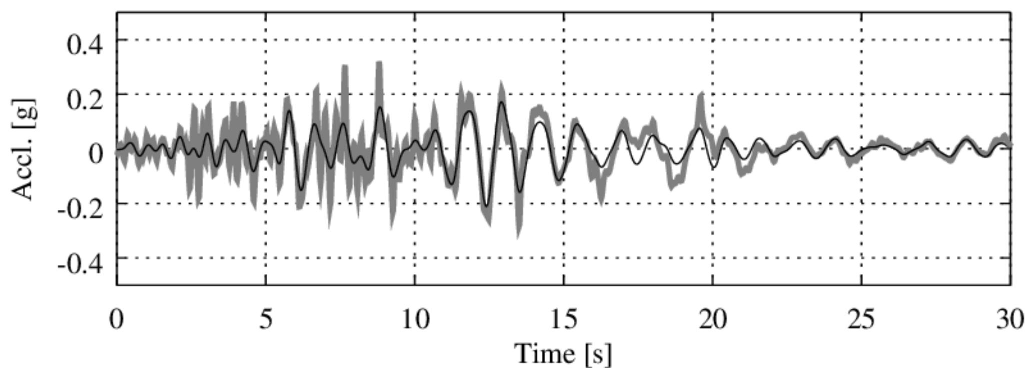

Fig. 3 – 1971 – East-West direction – Acceleration response (grey) and fundamental mode response (black)

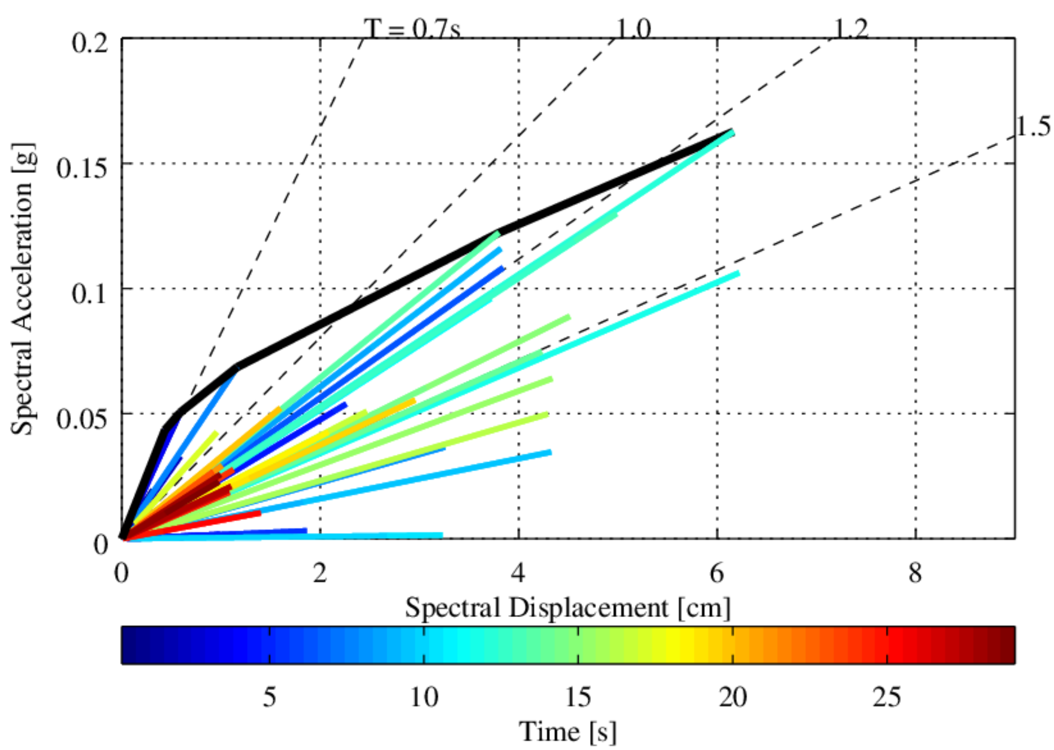

Fig. 4 –1971 – East-West direction – Empirical capacity curve estimation (black)

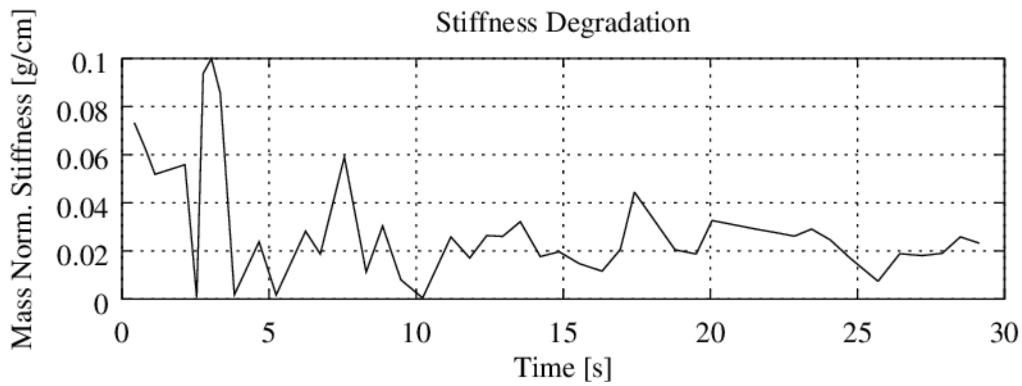

Fig. 5 – 1971 – East-West direction – Stiffness degradation estimation

2.2 1994 Northridge Earthquake Response

Response data for the seven-story hotel recorded during the 1971 San Fernando earthquake are available at the Center for Engineering Strong Ground Motion Data website database [2]. The acceleration data from the roof and ground are available from the east-west direction and north-south direction at the west and east sides of the building. The sampling frequency of the data is 50 Hz. Sensors installed on the roof and ground levels recorded acceleration response data at a sampling frequency of 50 Hz from the 1994 Northridge earthquake. Unfortunately, these available data are not raw data and have been processed and baseline-corrected. Only the fundamental mode empirical capacity curve extraction method can be implemented on these data [1]. A fundamental mode participation factor of 1.3 is used for the building in both directions [5].

For the east-west direction analysis, channel 9 is used as the roof response, and channel 16 is used as the ground input acceleration. West is the positive direction. A 4th order zero-phase high-pass Butterworth filter with a 1.35Hz cutoff frequency is applied to the acceleration data. The absolute roof acceleration and the fundamental mode acceleration are shown in Figure 6. The mean estimated mass-normalized damping coefficient is 0.60 [1]. Using the upper envelope of the quarter cycle secant stiffness response, an empirical capacity curve estimation is shown in Figure 7. The maximum roof drift is 0.8% for the east-west direction. Using quarter cycle secant stiffness, stiffness degradation can be estimated throughout the duration of the earthquake as shown in Figure 8. The estimated post-event stiffness is estimated to be 33% of the original stiffness of the system. The fundamental mode period of the building can also be used to quantify damage using the empirical capacity curve estimation; the initial period in the east-west direction is estimated to be 1.0 seconds, the final period is estimated to be 2.0 seconds, and the maximum period throughout the response is estimated to be 2.4 seconds.

For the north-south direction (west side) analysis, channel 2 is used as the roof response, and channel 1 is used as the ground input acceleration. North is the positive direction. A 4th order zero-phase high-pass Butterworth filter with a 1.7Hz cutoff frequency is applied to the acceleration data. The absolute roof acceleration and the fundamental mode acceleration are shown in Figure 9. The mean estimated mass-normalized damping coefficient is 0.66 [1]. Using the upper envelope of the quarter cycle secant stiffness response, an empirical capacity curve estimation is shown in Figure 10. The maximum roof drift is 0.8% for the north-south (west side) direction. Using quarter cycle secant stiffness, stiffness degradation can be estimated throughout the duration of the earthquake as shown in Figure 11. The estimated post-event stiffness is estimated to be 33% of the original stiffness of the system. The fundamental mode period of the building can also be used to quantify damage using the empirical capacity curve estimation; the initial period in the east-west direction is estimated to be 1.0 seconds, the final period is estimated to be 2.0 seconds, and the maximum period throughout the response is estimated to be 2.2 seconds.

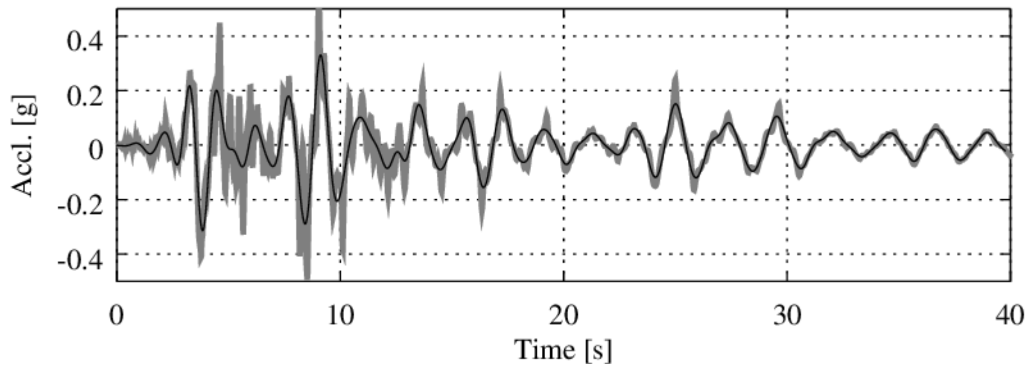

Fig. 6 – 1994 – West-East direction – Acceleration response (grey) and fundamental mode response (black)

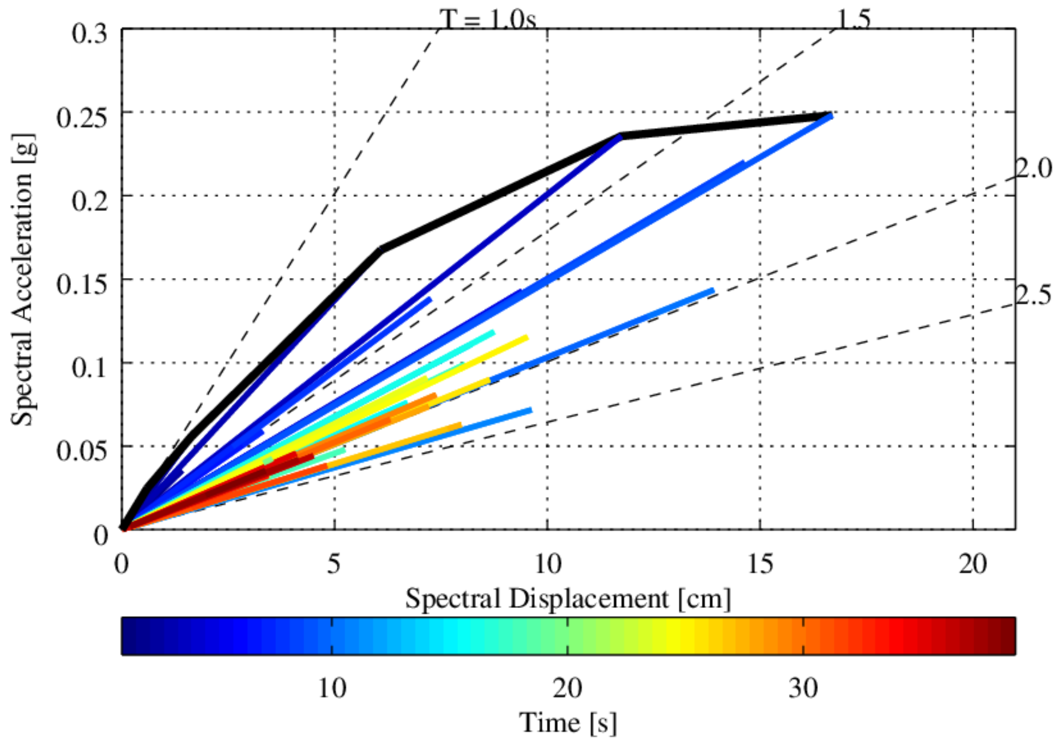

Fig. 7 – 1994 – West-East direction – Empirical capacity curve estimation

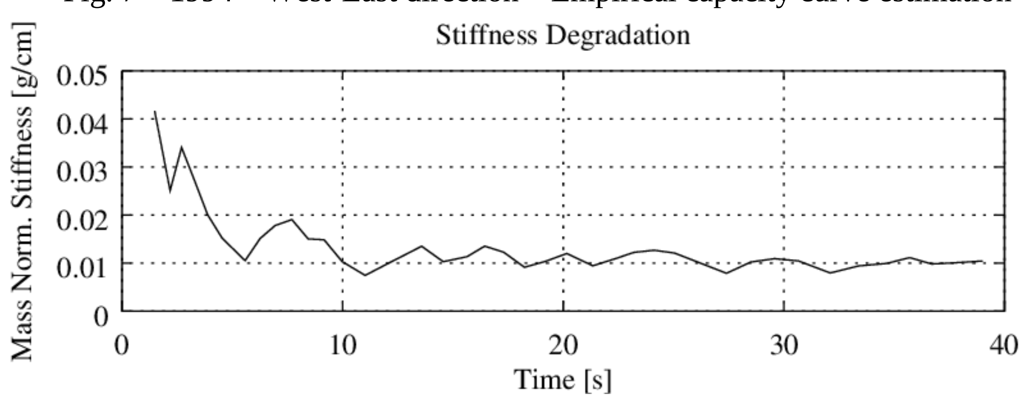

Fig. 8 – 1994 – West-East direction – Stiffness degradation estimation

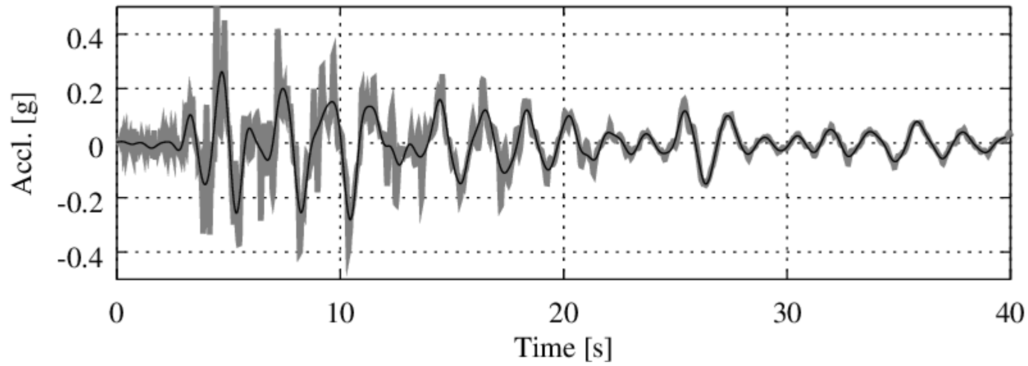

Fig. 9 –1994 – North-South direction (West Side) – Accel. response (grey) and fund. mode response (black)

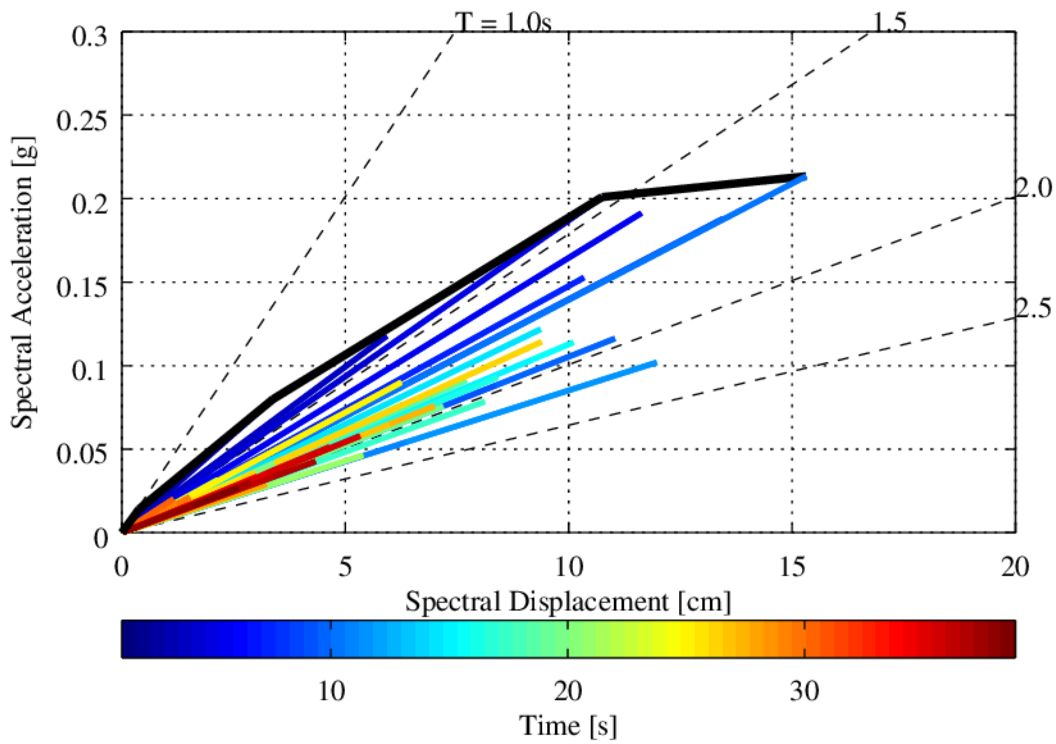

Fig. 10 – 1994 – North-South direction (West Side) – Empirical capacity curve estimation

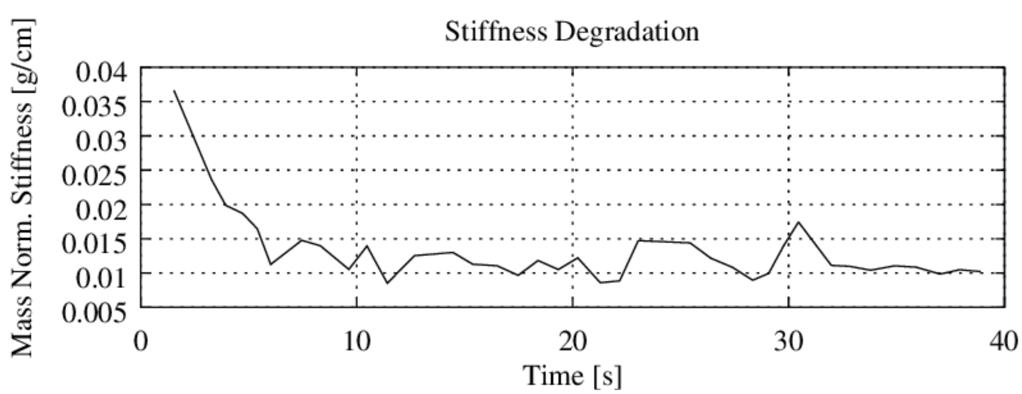

Fig. 11 – 1994 – North-South direction (West Side) – Stiffness degradation estimation

3. Discussion

The empirical capacity curve plots shown in Figures 7 and 10 provide useful information for engineers regarding the capacity curve from the overall building structural system. These particular plots would be useful to engineers for calibration of their nonlinear analyses. However, these figures do not provide the quick quantification of structural damage the stiffness degradation figures provide.

For the response of this building in the 1994 and 1971 earthquakes, the stiffness degradation plots provide the most readily apparent visual evidence of structural damage. Although the fundamental empirical capacity curves are not able to locate damage within the structure, the empirical capacity curves would have been able to provide engineers information that the post-event building stiffness is appreciably reduced from the pre-earthquake stiffness. The engineer implementing this method as a means to quickly determine whether this building warrants additional inspection would have to decide the appropriate percent stiffness degradation trigger. In Figures 8 and 11, notice should be taken to the variance of stiffness over time after the strong motion portion of the excitation. Due to this variance, any type of trigger would be best implemented on average stiffness over the time after the strong motion portion of the excitation has ceased.

After the 1994 earthquake, structural damage was observed to be most severe in the east-west direction with five of the nine south elevation columns on the fourth story undergoing shear failures [7]. Ultimately, these column shear failures not only had an impact on the reduction of stiffness in the east-west direction but also the north-south direction by evidence of the similarities in stiffness reduction in each direction.

If acceleration responses at each story were available, the location of structural damage within the building may have been further narrowed down to the fourth story. Unfortunately, the results are for only the global structural system. Therefore, the entire building would have to have been inspected for structural damage. In this case, the shear cracking in the columns could be easily seen from outside of the building. For cases where structural damage is not so easily visible from a casual walkthrough of the building, this particular method could help investigators decide whether removal interior finishes is necessary for inspection.

A comparison of the estimated empirical capacity curves for each direction and each earthquake is shown in Figure 12. The comparison shows the similarity of the empirical capacity curves for both the north-south and east-west directions for the 1994 Northridge earthquake. Of particular note is the difference in initial stiffness between the 1971 response and 1994 response. As mentioned previously, the observed damage after the earthquake was deemed non-structural. Therefore, any repairs were most likely cosmetic based on the building’s stiffness immediately after the 1971 earthquake being very near the initial stiffness of the 1994 earthquake.

Comparisons of the fundamental mode empirical capacity curve to capacity curves generated by other researchers for the 1994 Northridge earthquake in the east-west direction is shown in Figure 13. At first glance, the capacity curves appear similar. This is true for the initial linear behavior of the system. As the structure becomes nonlinear, the capacity curves deviate in similarity. Two capacity curves, Curves 1 and 2, were generated by use of the response data while Curve 3 was generated using numerical simulation. Of particular note is that Curves 1 and 2 were generated by response data and exhibit strength degradation of the system. Curve 3 does not show a stiffness degrading system response. The empirical capacity curve shown does not exhibit stiffness degradation. However, this does not necessarily mean the system did not undergo strength degradation. Per the method procedure, fundamental mode empirical capacity curves are the upper envelope of the secant stiffnesses of each quarter cycle and are terminated at the largest spectral acceleration response due to the uncertainty of the local peak responses beyond the largest local peak [1].

Numerous other capacity curves were generated by various researchers for the east-west direction of the building for the 1994 Northridge earthquake [6]. Unfortunately, the data presented does not provide sources or the methods or assumptions used to generate the capacity curves. Visual observations of the empirical capacity curve and these capacity curves, shown in Figure 14, indicate the curves have a variance in initial linear behavior and even more variance in nonlinear behavior. None of these various researchers’ capacity curves exhibit any strength degradation of the system. These capacity curves were generated using structural analysis software which requires many assumptions to be made to predict the behavior of the building. The difference of assumptions made between various researchers is evident by the variance in linear and nonlinear behavior of the capacity curves.

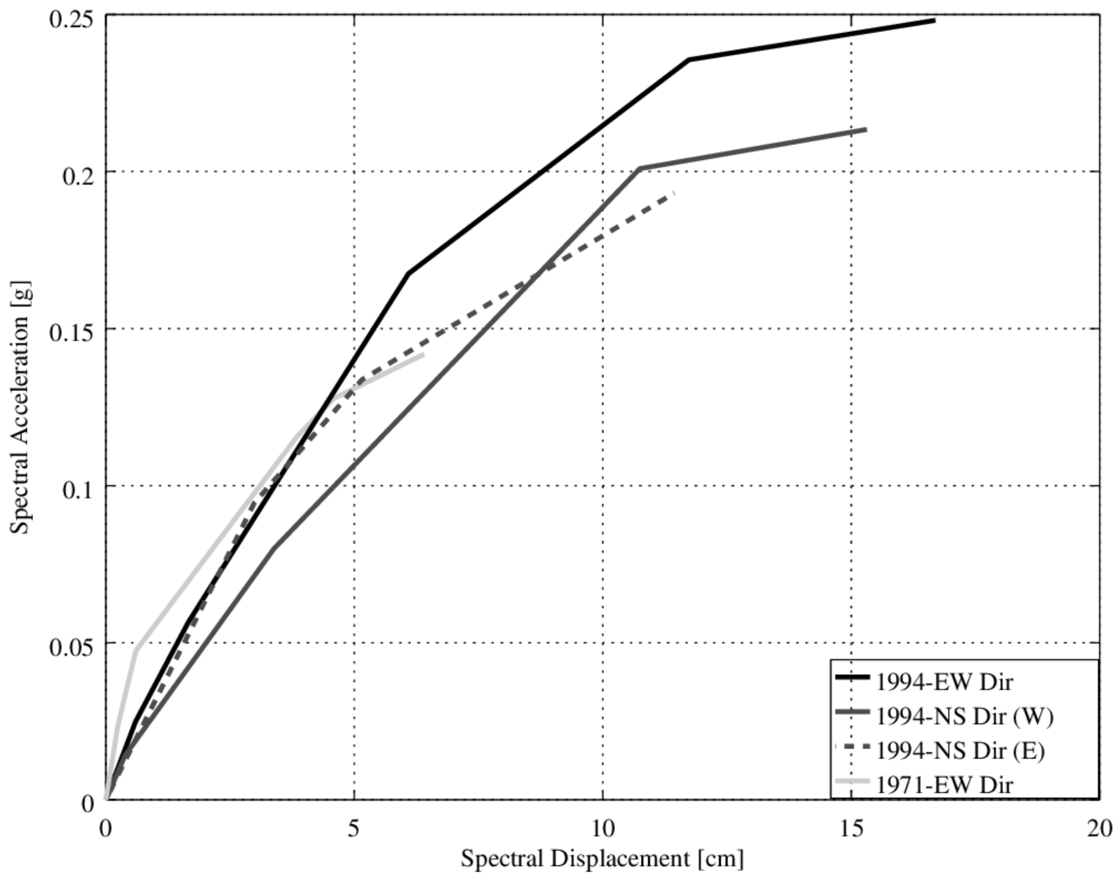

Fig. 12 – 1971 San Fernando and 1994 Northridge earthquakes – Empirical capacity curve comparison

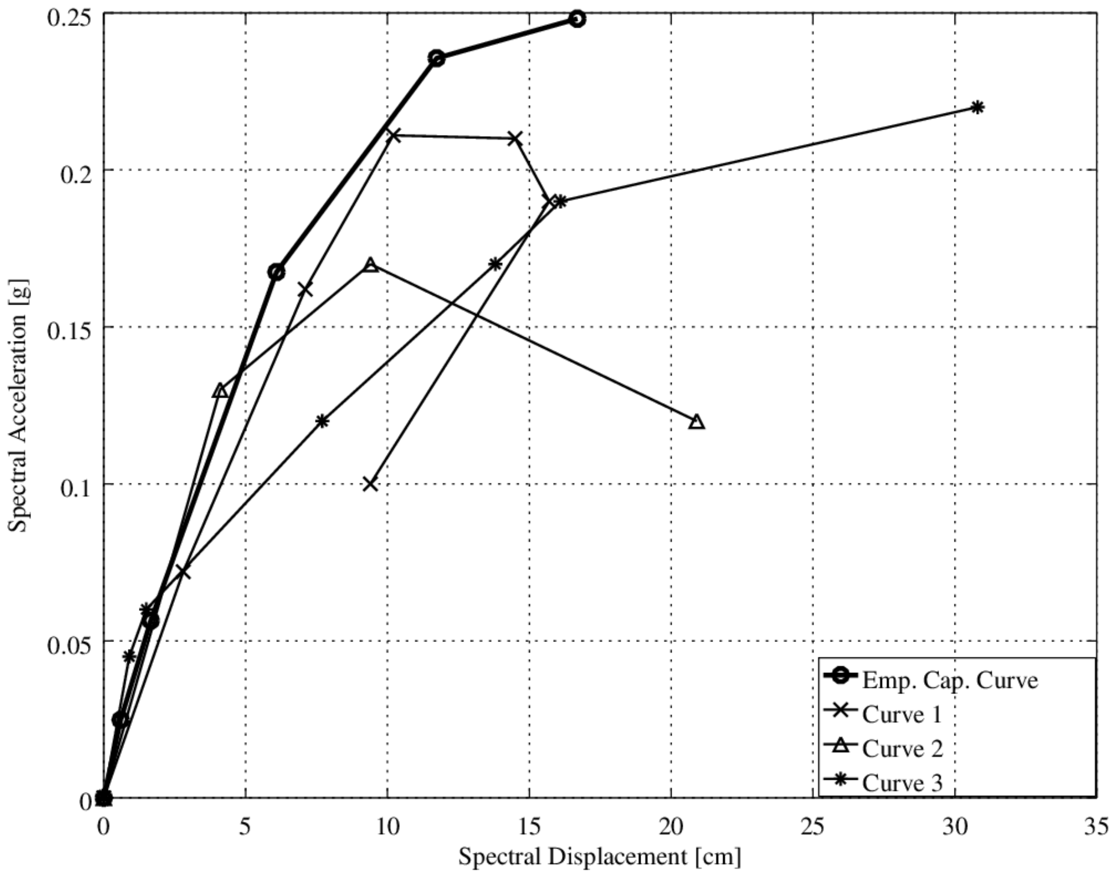

Fig. 13 – 1994 Northridge East-West direction – Capacity curve comparison
Curve 1 [6], Curve 2 [7], and Curve 3 [8]

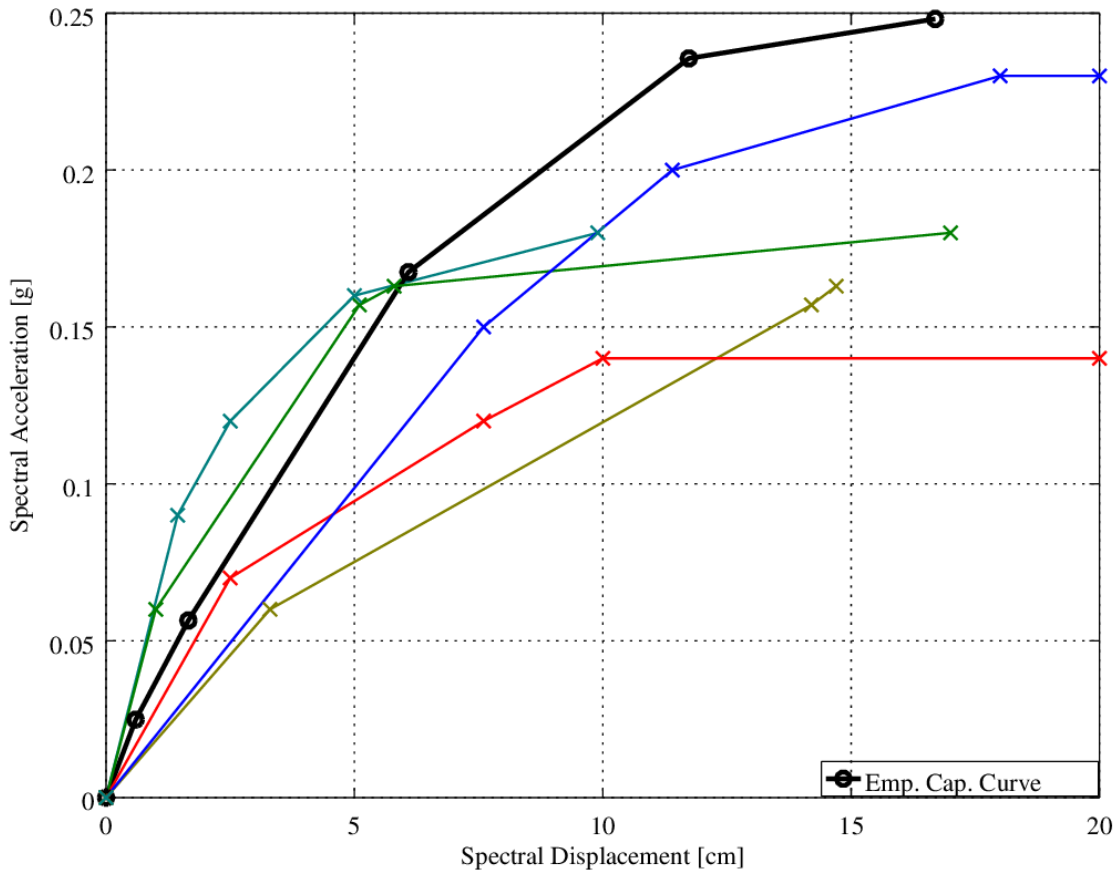

Fig. 14 – 1994 Northridge East-West direction – Capacity curve comparison with various researchers [6]

4. Conclusion

Historical response data from the seven-story hotel in Van Nuys, CA, specifically from the 1971 San Fernando and 1994 Northridge earthquakes, is used to generate empirical capacity curves from the response data. The building is instrumented only at select floors limiting the empirical capacity to the global structural system's fundamental mode. An empirical capacity curve for the fundamental mode and stiffness degradation are provided for the east-west direction for the 1971 San Fernando earthquake and east-west and north-south directions for the 1994 Northridge earthquake. These empirical capacity curves are studied and compared with other researchers' fundamental mode capacity curves developed either from the same response data or computer modeling. The stiffness degradation information is useful for quickly identifying the amount of the global system's structural softening sustained.

The empirical capacity curve from the 1971 earthquake (east-west direction) indicates to post-earthquake global system stiffness is approximately 50% of the initial stiffness. After the earthquake, visual observation indicated only non-structural damage to the building was sustained and no structural repairs were necessary. The 1994 earthquake response data indicates the initial building stiffness was nearly similar with the post-earthquake stiffness of the 1971 earthquake confirming no significant structural repairs were made that would increase the stiffness of the building. The demand of the 1994 earthquake was larger than the 1971 earthquake and resulted in the stiffness being reduced to 33% of the pre-1971 earthquake stiffness (east-west direction). Taking into consideration the initial stiffness of the building prior to the 1971 earthquake, the post-1994 earthquake stiffness is approximately 17% of the pre-1971 earthquake stiffness. Visual observation of the building after the 1994 earthquake verified column shear failures occurred at the fourth story of the building. Had instruments been installed on all floors of the building, locating damage using the empirical capacity curve extraction method may have narrowed down the building damage location to the fourth floor.

If implemented correctly, the empirical capacity curve extraction method is a useful tool for post-earthquake analysis of buildings. Extracting a fundamental mode empirical capacity curve only requires acceleration response data from the roof and ground floors. For the seven-story hotel in Van Nuys, CA, damage could be quickly quantified using stiffness degradation of the global structural system for both directions of the building.

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