DAMAGE DETECTION IN A 6-STORY REINFORCED CONCRETE BUILDING USING WAVELETS

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ABSTRACT

The former Imperial County Services Building—a 6-story RC building severely damaged by the 1979 Imperial Valley earthquake, is a rare example of a well instrumented building that has been damaged by an earthquake. Analysis is presented of damage detection by a method based on detection of abrupt changes in the response using wavelet basis expansion. The changes in system frequency, determined from the ridge of the Gabor transform, are also analyzed. It is shown that most of the detected abrupt changes are consistent with the degree and spatial distribution of damage. Some smaller abrupt changes can be explained as high frequency pulses of the input motion that have propagated through the building. However, there are also prominent abrupt changes (usually in the roof records) that cannot be explained by the reported damage, or by the input motion.

Keywords: structural health monitoring; damage detection; wavelets.

1. INTRODUCTION

The ability to monitor the health of the instrumented structure, detect damage as it occurs, and issue an early warning after the earthquake, before physical inspection is possible, is one of the most significant potential uses of structural monitoring data. This requires structural health monitoring methods that are sufficiently sensitive, and robust when applied to earthquake data. Most vibration methods detect shifts in natural frequencies or changes in mode shapes. To be detectable, the changes caused by damage have to be larger than those due to environmental factors (e.g. temperature, soil-structure interaction, rain, etc.; Trifunac *et al*, 2001ab; Todorovska *et al*, 2004). Because of the high level of redundancy of civil engineering structures, these changes are small when the damage is localized. The changes in the mode shapes (e.g. curvature) are less sensitive to such factors, but are more difficult to detect and require more extensive instrumentation than what is usually available (Trifunac and Todorovska 2001).

Other difficulties include: reliance on baseline data, for which just a model based estimate may be available, or a measurement under different environmental conditions, and reliance on a model and analytical tools for prediction of response, which are only idealizations of the real structure and its behavior at the time when damage occurs. A recent review of research on this topic can be found in Chang *et al* (2003). This paper summarizes a study of damage detection in a rare example of a well-instrumented structure damaged by an earthquake—the former Imperial County Services Building in El Centro, California, severely damaged by the 1979 Imperial Valley earthquake and later demolished. Results are shown of frequency changes, determined from the ridge of a time-frequency transform using Gabor wavelets, and of analysis of high frequency response using expansion of the recorded accelerations in wavelet series, which enables detection of abrupt changes in the response.

2 METHODOLOGY

The method consists of analysis of the high frequency part of structural response (e.g. 12.5 to 25 Hz for analog data), away from the frequency of the first few modes of typical buildings and bridges, where the response is amplified by the structure. The method is based on the assumption that damage would cause some abrupt change in the response, which can be effectively detected using an expansion of the motion in this high frequency band in wavelet series. The abrupt changes will be seen as spikes in the plots of the square wavelet coefficients versus the central time of the corresponding wavelet. Applications to numerically simulated response of simple models with postulated damage (Sone *et al*, 1995; Wang and Deng, 1998; Hou *et al*, 2000; Hera and Hou, 2004) have shown that this method *can point out very precisely to the time of damage*, but the changes are detectable only if the spikes in the wavelet coefficients are above the noise. Also, the detected changes are more prominent if the sensor is closer to the location of the damaged member, *and may be difficult to detect if the sensor is far from the damage*. Hence, this method requires a relatively dense array of sensors, and its spatial resolution depends on the density of sensors. Two applications to earthquake response data (Rezai *et al*, 1998; Hou *et al*, 2000) have shown that there are such abrupt changes in the acceleration response of damaged buildings, but have not considered and eliminated causes of the detected changes other than damage. Todorovska and Trifunac (2005a,b) for the first time critically analyzed this method and its noise for actual earthquake data (the high frequency part of structural response). Their analysis revealed that the noise actually contains very useful information on high frequency wave travel times in the building.

The procedure consists of splitting the signal into a high and a low frequency component. The former is a smooth approximation of the signal, and shows the *trend* in the data, while the latter is the detail that has been removed, and shows *novelties* or *surprises* in the data (e.g. abrupt changes), as viewed at the finest resolution level (Todorovska and Hao, 2003). Then, the two components are decomposed in wavelet series. The coefficients of expansion are the discrete wavelet transform of the signal with respect to the corresponding wavelet (for orthonormal bases) or its dual (for bi-orthogonal bases), and are computed using the pyramid algorithm (also called fast wavelet transform). For this analysis, we chose a basis of bi-orthogonal wavelets (bior 6.8 wavelet), because they can be both symmetric and smooth, which avoids phase distortions, and smoothes smaller spurious peaks in the wavelet coefficients, emphasizing the most significant abrupt changes. The "surprises" are identified in the distribution of the *squared* coefficients of the detail subband, $d_{1,k},\ k = 1,...N/2$, where N is the signal length, which represent the energy distribution in the subband – ideally 12.5 - 25 Hz for data sampled at 0.02 s (Todorovska and Hao, 2003).

3 RESULTS AND ANALYSIS

The Imperial County Services (ICS) building was a 6-story reinforced concrete structure located in El Centro in Southern California. It was designed in compliance with the 1967 Uniform Building Code, and its construction was completed in 1969. It had plan dimensions 41.70×26.02 m and height 25.48 m. The foundation system was composed of pile groups and pile caps directly located under the columns and walls. Up to depth of 9 m, the underlying soil consisted of soft to medium-stiff damp sandy clay with organic materials, with inter-layers of medium dense moist sand, and beneath 9 m it consisted of stiff, moist sandy clay and silty clay. The structure was made of reinforced concrete, with minimum ultimate compressive strength of 27.6 MPa—for the walls, beams and slabs, 34.5 MPa—for the columns, and 20.7 MPa—for the foundation elements, and reinforcement steel of 276 MPa. The structural configuration in the NS (transverse) direction consisted of two concrete panels at the east and west ends of the building (Fig. 1), extending only from the second floor to the roof, and were supported by cantilever parts of the frame beams. At the ground level, four panels were located between axis 2 and 3 along lines A and C through D. In the EW (longitudinal) direction, the structural system consisted of four beam-column frames (Kojić et al. 1984). The building apparent frequencies determined from ambient vibration tests were 2.2–2.8 Hz for NS vibrations, and 1.5 Hz for EW vibrations (Pardoen 1979).

The 16-channel seismic monitoring array (installed by the California Division of Mines and Geology) consisted of a 13-channel structural array of force balance accelerometers (FBA-1) with a central analog recording system, and a tri-axial SMA-1 accelerometer in the “free field,” approximately 104 m east from the northeast corner of the building (Fig. 1).

The Imperial Valley earthquake of October 19, 1979 (M_L = 6.6, depth H=8 km) occurred on the Imperial Fault near El Centro in southern California, at epicental distance of about 26 km southeast from the building. From the hypocenter, the dislocation propagated northwest with velocity near 2.5 km/s, and after about 9 s it passed by the closest distance from the fault to the building – at 7 km southwest from the fault (Jordanovski and Trifunac 1990a,b). Thus, during the first 9 s, the building was receiving larger than average power of strong motion, due to strong fault directivity. The building was severely damaged, and was later demolished (Kojić et al., 1984). Fig. 2 shows a schematic representation of the main damage. The principal failures occurred in the columns of frame F (at the east end of the building) at the ground floor. The vertical reinforcement was exposed and buckled, and the core concrete could not be retained, resulting in shortening of the columns which caused cracking of the floor beams and slabs near column line F on the second, third and higher floors. Columns in lines A, B, D and E also suffered damage. Columns in frames A and E did not suffer such extensive damage, but large cracks in the concrete and exposed reinforcement could be seen near the base. In the columns of interior frames B through E, there were visible cracks and spalling of the concrete cover.

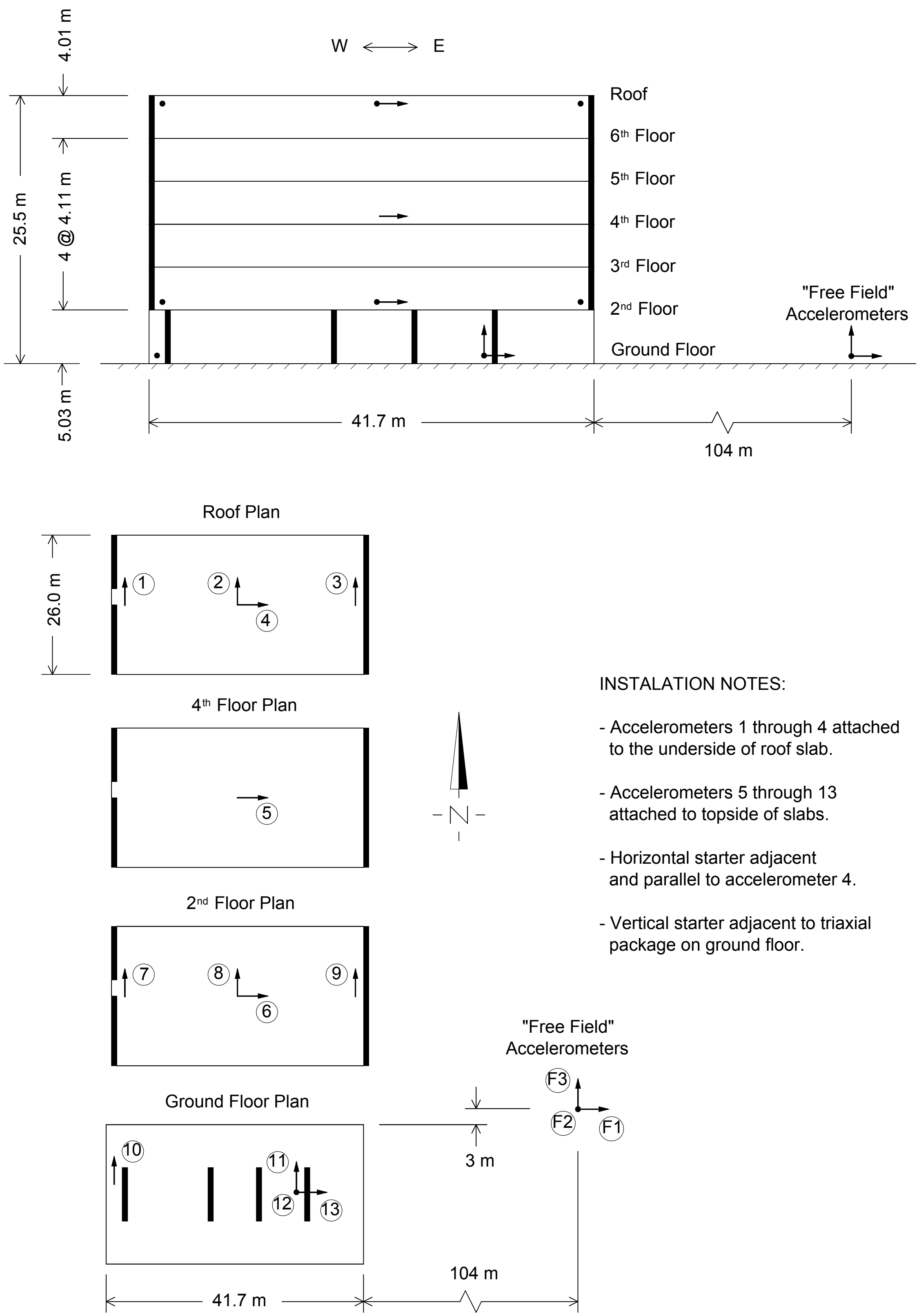

Figure 1: A layout of the seismic monitoring array.

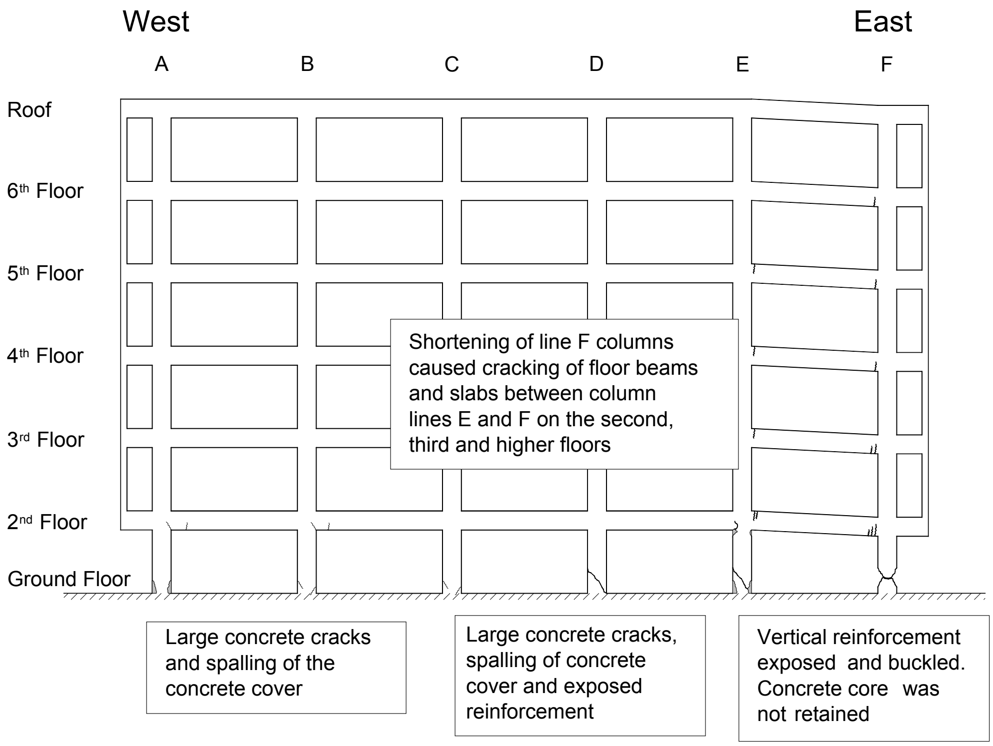

Figure 2: Schematic representation of the earthquake damage.

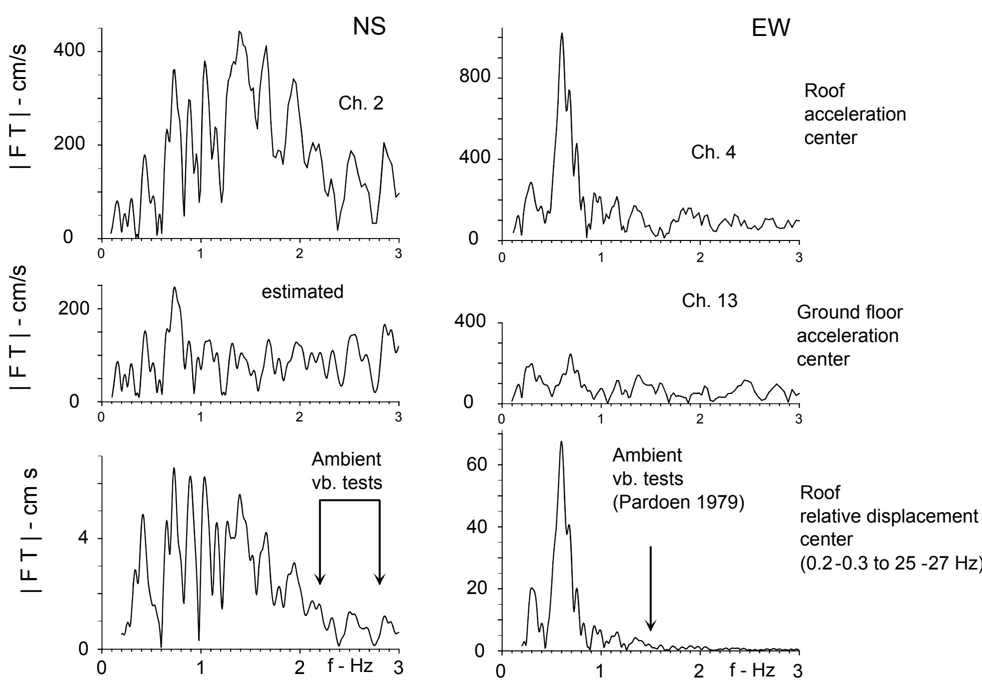

Figure 3: Fourier transform amplitudes of NS (left) and EW (right) response: roof acceleration (top), ground floor acceleration (middle) and relative displacement (bottom), at the center of the building.

The roof and ground floor peak accelerations of the recorded motions were 571 cm/s^2 and 339 cm/s^2 in the NS and 461 cm/s^2 and 331 cm/s^2 in the EW direction. The film records were digitized and processed at USC (Trifunac and Lee, 1979) and the data released was band pass filtered between 0.1-0.125 and 25-27 Hz. Fig. 3 shows Fourier spectra for the NS (left) and EW (right) responses of the roof acceleration (top), ground floor acceleration (middle) and relative displacement (bottom), all at the center of the building. This suggests a wide variation of the NS system frequency (0.7 to about 2 Hz), and EW system frequency near 0.6 Hz during most of the duration of shaking. An analysis of the computed drifts (sum of the drift due to *deformation* of the building and due to *rigid body rocking*, which could not be separated because of inadequate instrumentation) suggests "soft" first story in both NS and EW directions, larger flexibility in the EW direction, and significant torsional response, excited by the wave passage, and amplified by the asymmetric distribution of stiffness in the NS direction at the soft first story (Todorovska and Trifunac, 2005a,b). In the EW direction, the drift exceeded 1.5%, and in the NS direction it exceeded 0.5%. The NS first story drifts were larger at the east side, probably initially as a result of the smaller stiffness, and later due to the damage.

Figs 4a,b show squared detail wavelet coefficients of acceleration for the NS and EW responses. The shades highlight time intervals with large amplitude coefficients. The plots at the bottom show instantaneous system frequency estimated from the ridge of the Gabor transform of the roof relative horizontal response with $\sigma = 1$ (Todorovska, 2001). It can be seen that the NS frequency dropped from about 2 Hz to 0.8 Hz, and the EW frequency - from about 1 Hz to 0.6 Hz. In the analysis of surprises, we first identify the largest peaks in the squared coefficients. We label by T1, T2, … those surprises believed to be due to damage (i.e. consistent with the distribution of reported damage), as G1, G2, … those believed to be due to high frequency pulses of the input motion that have propagated through the building (i.e. with amplitude and time delays consistent with wave propagation with velocity estimated from the building frequency), and as F1, F2, … those that we could not explain.

By far the largest peak (T1) occurs at about 11.2 s in the NS acceleration of channel 9, on the 2nd floor at the east end of the building, *consistent with the location of the most severe damage* (failure of the first story columns of frame F; see Fig. 2). This peak is more than an order of magnitude larger than all other peaks. There is also a large peak at this time in the NS acceleration on the roof at the east side of the building (T2), also consistent with the description of damage. The next largest magnitude surprise, consistent with the damage, is T3, on the 2nd floor at the west side of the building (channel 7) at about 6.3 s, followed by smaller surprises between 8.2 to 9.2 s after trigger, marked as T3a. Both are consistent with the reported smaller damage at the 2nd floor at the west side of the building. Smaller surprises (T4) at about 6.3 s are also observed on the 2nd floor at the center of the building (channel 8), followed by surprises T4a, which also can be related to reported damage in that part of the building. In these two channels, some small surprises are also seen within the third highlighted time interval. These are identified respectively by T3b and/or I-T1, and T4b and/or I-T1, and explained as possible additional local damage (to the one identified by surprises T3 and T4), or as an effect (or "influence") of the most severe damage identified by surprise T1, felt also at the center. Within the first and second highlighted time intervals, smaller surprises are seen also in channel 9, preceding surprise T1. These are marked by T1a (at 6.8 s), and T1b (between 8.2 and 9.2 s). The former can be interpreted as initiation of the damage in the first story columns at the east side of the building, and the latter—as additional damage, leading to the failure of these columns at about 11.2 s (T1).

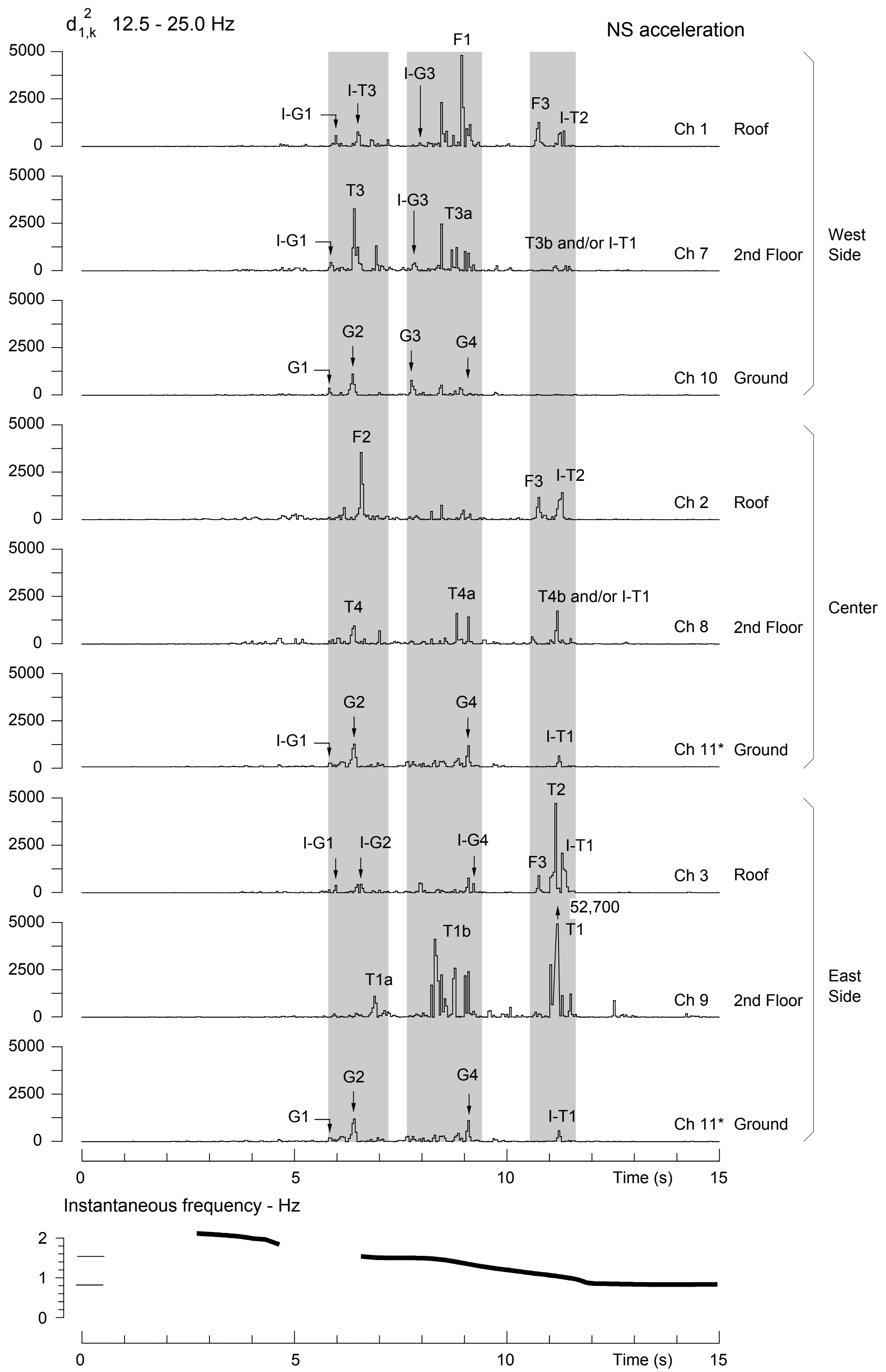

Figure 4a: Squared detail coefficients of NS acceleration (top) and instantaneous frequency (bottom).

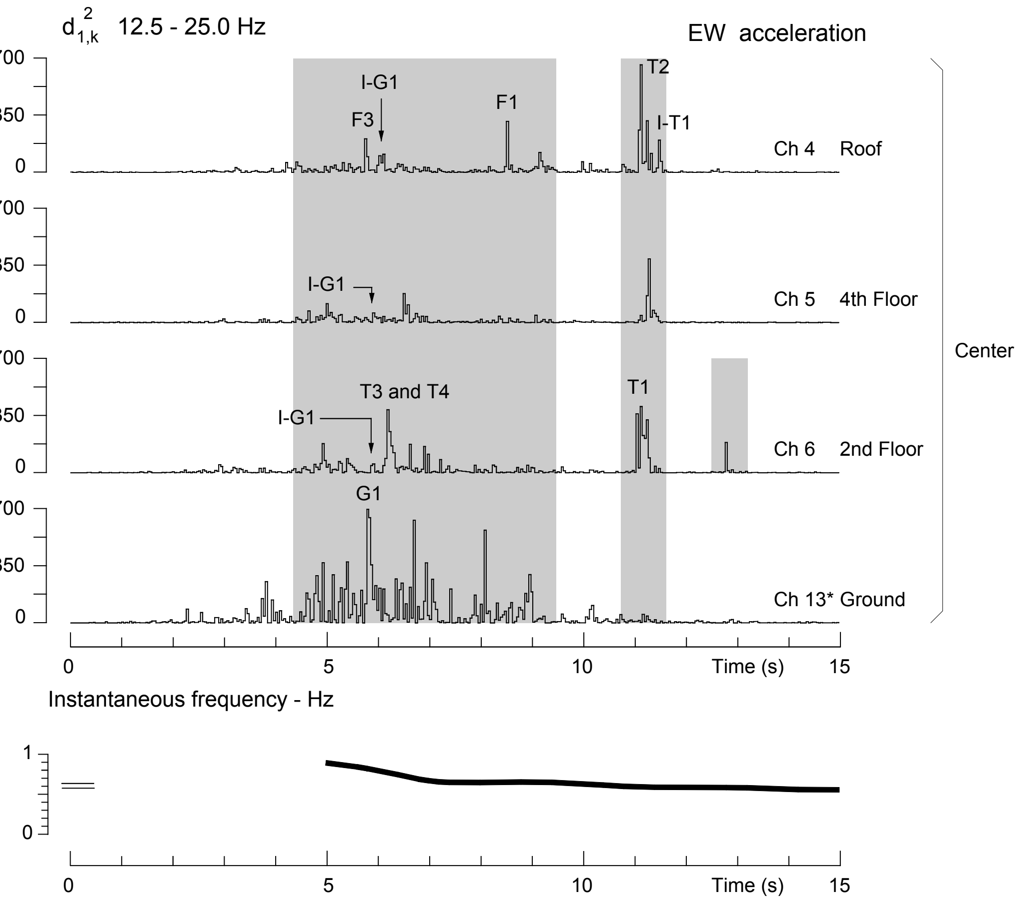

Figure 4b: Squared detail coefficients of EW acceleration (top) and instantaneous frequency (bottom).

Next, we analyze the surprises in the roof response at the west side and at the center of the building (channels 1 and 2). Large surprises are observed at the west side within the second highlighted time interval, and at the center within the first highlighted interval. These cannot be related to severe reported damage, and hence are interpreted as "false positive" and marked by F1 and F2. The smaller surprises in these channels are interpreted as influences of damage that occurred further away from these sensors. In channel 1, these surprises are marked as I-T3 and I-T2, and interpreted to be possibly due to the damage identified by T3 and T2.

In the EW accelerations, recorded only at the center of the building, prominent "true" surprises are seen at about 11.2 s, on the 2nd and 4th floors, and at the roof, all consistent with the observed damage. Those observed at the 2nd floor and roof are interpreted to be due to the damage identified by surprises T1 and T2 in the NS response, and are named by the same symbols as for the NS response. Surprises are also seen at the second floor, between about 5 and 7 s, interpreted to be due to the damage identified by surprises T3 and T4. At the roof, two "false positive" surprises are identified, F1 and F2.

The analysis of the surprises suggests that severe damage in this building started to occur at the west side of the building at about 6.4 s after trigger, and was most significant in the first story columns. The damage at the east side of the building started to occur later, at about 6.8 s after trigger. Additional severe damage occurred between 8.2 to 9.2 s, which further weakened the building, and *finally lead to failure of the first story columns at the east side of the building at about 11.2 s, which was felt throughout the building.*

The plots of instantaneous frequency (bottom of Fig. 4a,b) suggest that the NS frequency dropped from about 2 Hz in the early stage of response (at about 3 s) to about 1.55 Hz (Δf =0.45 Hz or 22.5%), was constant in the interval 6.5–8 s, and further dropped to 0.8 Hz (Δf =0.75 Hz or 48%) in the interval 8–12 s. The EW frequency dropped from 0.9 to 0.65 Hz (Δf = 0.25 Hz or 28%) in the interval 5–7 s, was approximately constant in the interval 7–9.5 s, and dropped gradually to 0.55 Hz (Δf =0.1 Hz or 15%) in the interval 13–14 s. Possible causes for the drops are the effects of soil-structure interaction, and degradation of stiffness due to damage, but the degree to which each one contributed to the overall effect cannot be determined from the recorded response alone, because the soil-structure interaction effects could not be separated due to inadequate instrumentation. It is also noted that the estimation of the time of the change is limited by the finite time resolutions of the method. For Gabor transform with σ= 1, an "instant" is the time interval σ_t = 2*0.71=1.4 s.

A comparison of the times and magnitudes of the drops in system frequency with the times and magnitudes of the "surprises" associated with damage shows that the most severe damage (failure of the first story columns at the east side of the building at 11.2 s) cannot be identified from changes of the EW frequency. The 48% drop of the NS frequency was most likely, at least in part, due to the structural damage. The timing of the occurrence of the damage can be estimated more precisely from the analysis of the "surprises."

4 CONCLUSIONS

The analysis of abrupt changes in the response of the Imperial County Services building to the 1979 Imperial Valley earthquake, which severely damaged the building, showed that: (1) this method, applied to the acceleration records, could identify the time of occurrence and general location of the major damage (with spatial resolution equal to the spacing of the sensors), and (2) the relative magnitudes of the surprises were proportional to the degree of damage. (3) This method was more effective in the analysis of NS response than in the analysis of the EW response, as the former was recorded by a spatially denser array - along three vertical lines, while the latter was recorded only along one line – at the center of the building. Further research is required to find out if this method works for less severe damage, to further understand the nature of the "noise" of the method, and how to differentiate the abrupt changes caused by damage from those caused by other processes.

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