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Proposed Approaches to Fracture Damage Detection for Sparsely Instrumented Steel Moment-framed Buildings

Janise E. Rodgers[1,*], Stephen A. Mahin[2] and Mehmet Çelebi[3]

[1]*GeoHazards International, 200 Town and Country Village, Palo Alto, California 94301 USA*
[2]*Department of Civil and Environmental Engineering, University of California, Berkeley, California 94720 USA*
[3]*US Geological Survey, Menlo Park, California 94025 USA*

Abstract

Several recent earthquakes, most notably the 1994 Northridge, California and 1995 Kobe, Japan earthquakes, caused significant damage to steel moment-framed buildings, including brittle fractures at beam-to-column connections. In a number of Los Angeles-area buildings strongly shaken by the Northridge earthquake, numerous connection fractures resulted in little non-structural damage or other visible evidence, and were thus not revealed by standard post-earthquake walk-through visual inspections. As a result, significantly more costly and time-consuming intrusive inspections involving the removal of interior finishes are currently required for post-earthquake detection of connection fractures. Due to the time required to conduct intrusive inspections, methods that provide information on potential connection fracture damage very soon after an earthquake can give owners valuable information. This paper describes research exploring the effects of connection fractures on building's dynamic response and the possibilities for using fracture-induced changes in dynamic response to detect damage. Fracture damage causes several specific structural responses, such as sudden changes in local stiffness and deflected shape, sudden changes in global acceleration and a sudden release of energy in the form of elastic waves. These responses can be used to develop new methods specifically for fracture damage detection. This paper proposes two related approaches based on the effects of fractures on global accelerations. Connection fractures were observed to cause high-frequency, transient signals in global accelerations in shaking table experiments and analytical simulations, and the proposed approaches seek to detect such signals in recorded accelerations from real buildings. The proposed approaches show promise when tested using the limited strong shaking data available from sparsely instrumented steel moment-framed buildings that experienced the Northridge earthquake.

Keywords: Moment Resisting Frames, Damage Detection, Fracture, Seismic Behavior

1. Introduction and Background

1.1. Connection fractures in steel moment frames

Brittle fractures observed in steel moment connections following the 1994 Northridge earthquake (Bertero *et al.*, 1994) raised significant concerns amongst engineers, building owners, and building officials, leading to a large research effort to determine the causes of connection fractures, the effects of fractures on structural behavior, and means of preventing fractures (FEMA, 2000a). Experimental research efforts focused on performing quasi-static cyclic tests of both new "post-Northridge" and older "pre-Northridge" full-size beam-column connection subassemblages to the point of failure (FEMA, 2000b). Connection hysteretic behavior observed in these experiments was then incorporated into phenomenological connection models for use in analytical studies of the effects of fracture on moment frame system response (experimental testing of full frames was considered too costly). Much of the analytical work on systems focused on determining peak values of deformation quantities and evaluating analytical capabilities for predicting connection fracture locations. Connection fracture was explicitly modeled in numerous dynamic analyses (e.g. Maison and Kasai, 1997; Foutch and Shi, 1998; Cornell and Luco, 2000), but the transient effects of fracture, particularly on global accelerations, were not included in the published results. However, several studies mention the transient effects of fracture. Nakashima *et al.* (2000) demonstrated the process of static moment redistribution after fracture, and noted that transient effects on acceleration were expected in the dynamic case (but such effects were not explored). Uetani and Tagawa (1998) studied the transient response of a beam with a fracture at one end using a distributed mass model and a simpler model, and determined that the simpler model captured the overall trend of the response well. Quantitative effects of fractures on the global accelerations were not presented, however, in either of

*Corresponding author
Tel: 1-650-614-9050, Fax: 1-650-614-9051
Email: rodgers@geohaz.org

these studies. To date, little emphasis has been placed on local or transient behaviors caused by fracture, their implications for system behavior, or potential applications for damage detection.

1.2. Fracture damage detection approaches

Damage detection methods for moment-framed buildings based on recorded data are particularly desirable due to the fact that a large number of connection fractures may produce little non-structural or other visibly evident damage. Since walk-through visual inspections failed in many cases to find fracture damage following the Northridge earthquake, the FEMA 352 guidelines (FEMA, 2000c) were developed for future post-earthquake inspections of welded steel moment-frames (WSMFs). For strongly shaken buildings without severe or visually apparent damage, detailed evaluations with intrusive inspections are required. The FEMA 352 guidelines permit a representative sample of connections to be inspected, with the intent that such a sample will reveal significant fracture damage if it exists. The sample can be selected randomly, by rational analysis (for instance, based on dynamic analysis), or by a prescribed combination of the two (20% of the connections to be inspected are selected by rational analysis, and the remainder randomly). Even if the simplest approach (a random sample) is used, weeks or even months may pass before the inspections are complete and the presence or absence of fracture damage confidently determined. The amount of time required for the intrusive inspection process also depends on factors not related to engineering such as the earthquake preparedness level of the building owner (for example, a retainer agreement with an engineer in place prior to the earthquake can significantly shorten the process), the availability of engineers and contractors, and local regulatory actions. Therefore, information on fracture damage that can be obtained very quickly after an earthquake is desirable for decision-making purposes and could aid the FEMA 352 rational analysis method of selecting connections for inspection.

Digital strong motion accelerographs commonly installed in instrumented buildings can provide such key information on building response within a very short time after the earthquake, even as quickly as near-real time (Çelebi *et al*., 2004). Tools which harness recorded accelerations for the detection of damage are highly desirable because they can provide valuable early information on building performance using sensors that are commonly provided in instrumentation systems. Some other promising ideas for fracture damage detection such as acoustic emission require specialized sensors. As a result, a number of more theoretical damage detection methods that perform various types of analyses on recorded acceleration response data have been proposed recently. Many proposed approaches use changes in a structure's vibration properties to detect damage, and were developed as general-purpose methods applicable to most structural systems. For example, proposed methods of identifying and/or classifying deviations from undamaged behavior include statistical pattern recognition (e.g. Sohn and Law, 1997, Köylüoğlu *et al*., 1998, Sohn *et al*., 2001), neural networks (e.g. Nakamura *et al*., 1998, Masri *et al*., 2000), wavelet analysis (e.g. Hou *et al*., 2000, Kim and Melhem, 2003), and combination approaches (e.g. Marwala, 2000, Sun and Chang, 2002). However, many of these methods are computationally intensive or require substantial work prior to the earthquake to mathematically characterize the system, which may limit their practicality for real buildings, especially large ones. Wavelet-based methods are a notable exception, since the major effort required consists of the engineer learning to understand wavelet analysis and apply it to signals. These methods could potentially be applied immediately following an earthquake if the owner were willing to invest in the time and computing power needed for advanced damage detection approaches, in addition to an extensive digital instrumentation system. Most building owners (with the exception of a few innovators) are not currently willing to make such investments. In the interim, it may be prudent to develop approaches that require less pre-earthquake investment on the part of the owner, but can still provide in improved damage information quickly.

1.3. Scope

Structural dynamics theory predicts that sudden changes in structure properties, such as those caused by steel moment connection fractures, will result in a transient dynamic response. This paper summarizes the results of three studies examining transient dynamic responses caused by connection fracture or their use in proposed damage detection approaches. The first study (Rodgers and Mahin, 2006a) examines the effects of connection fracture on accelerations theoretically, analytically, and experimentally. A selection of experimental results are presented to demonstrate the transient effects of connection fracture on global response. The second study (Rodgers and Çelebi, 2005) describes the development of two proposed approaches for fracture damage detection using transient acceleration signals caused by fracture, and testing of those approaches on a set of data recorded in steel moment-framed buildings during the Northridge earthquake. The third study (Rodgers and Çelebi, 2006) applies one of the approaches from the second study, along with other simple damage detection approaches, to a Los Angeles-area office building with a large dataset of strong motion recordings.

2. Experimentally Observed Indicators of Connection Fracture in Global Accelerations

2.1. Experimental setup and specimen

Thirty-two shaking table tests were performed to assess the effects of connection hysteretic behavior on global

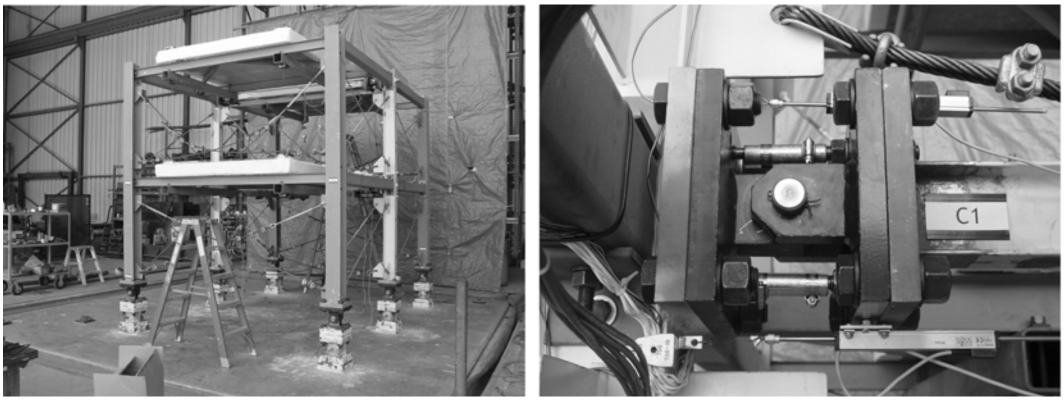

Figure 1. Experimental test specimen (left) and mechanical clevis connections (right).

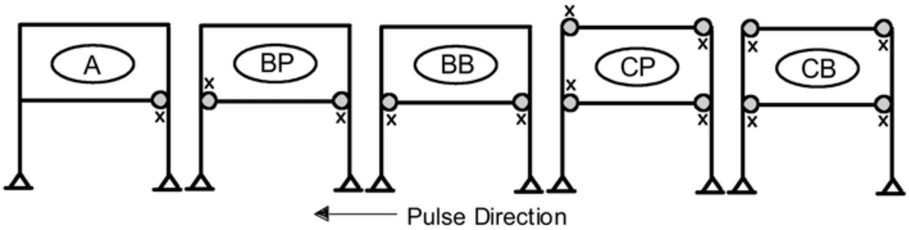

Figure 2. Connection configuration patterns used in shaking table test application, with 'x' denoting fracture locations.

response of a steel moment frame. The experiments employed the simple one-third scale, two-story, one-bay steel moment frame test specimen in Fig. 1, where only the center frame is moment-resisting. To satisfy design constraints, including the need to perform a large number of tests economically, and difficulties in achieving fracture in reduced scale connections, the idealized, mechanical connection shown in Fig. 1 was provided at each of the four beam-to-column connections in the center frame of the test specimen. Replaceable steel coupons placed above and below the clevis pin provide a force couple to resist moment. These connections are described in detail elsewhere (van Dam, 2000).

Different numbers and types of coupons were used to produce ductile baseline (DB) or brittle fracture (BF) connection hysteretic behavior. Fracture-capable connections were arranged in combination with the ductile baseline connections to investigate spatial patterns of interest, shown in Fig. 2. Circles represent connections exhibiting degradation and 'x' indicates a fracture. Locations without circles have ductile baseline connections. The frame itself was designed to remain elastic during testing, with damage limited to the replaceable coupons in the idealized connections. Data from the shaking table tests confirmed that the frame and connections behaved as designed.

2.2. Experimental results

Sudden acceleration changes in the directions shown in Fig. 3 are expected following fracture based on theory and analysis (Rodgers and Mahin, 2006a). Longitudinal (in-plane) accelerations for the 1.2 second cosine pulse excitation are compared in Fig. 4 for the ductile baseline case (no fractures) and the brittle fracture BP connection configuration pattern, which features two near-simultaneous fractures in the first story (see Fig. 2). The direction of acceleration at the top of the 2nd story (the sign convention is given in Fig. 3) shows that the structure is quickly accelerates in the direction of frame motion immediately following fracture. The direction of first motion after fracture at the top of the 1st story shows that the second mode of the structure is excited by the

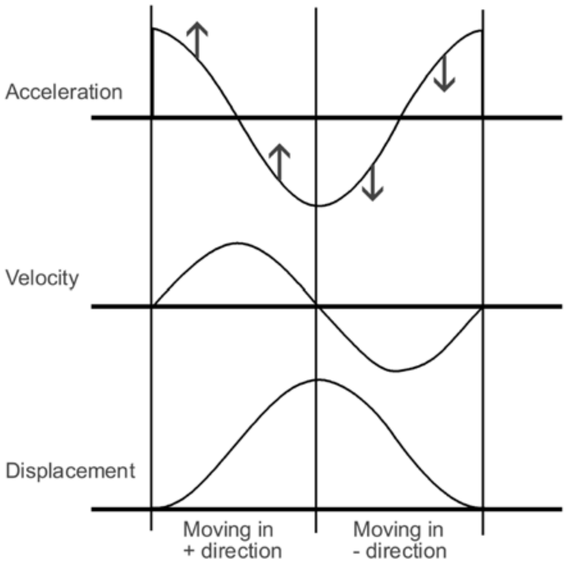

Figure 3. Sign convention for sudden acceleration changes caused by fracture for a cosine pulse excitation. Arrows indicate acceleration in the direction of motion.

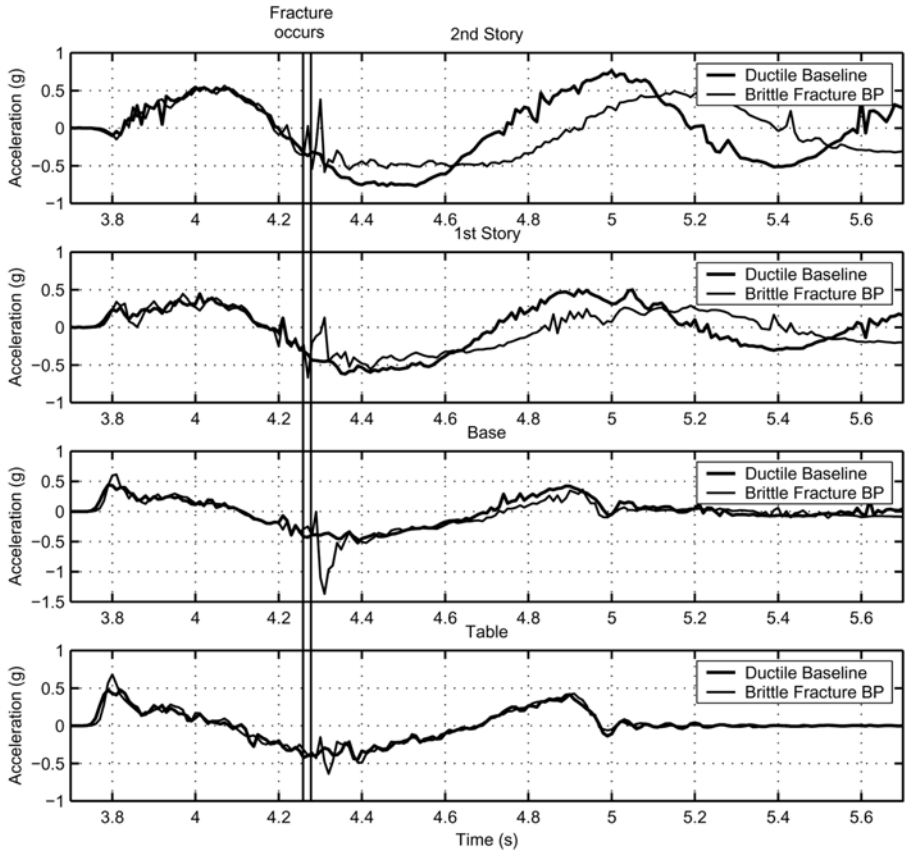

Figure 4. Experimental results for the 1.2s cosine acceleration pulse excitation, brittle fracture BP and ductile cases.

fracture. These results are similar to those obtained from analysis (Rodgers and Mahin, 2006a). Though not shown here, the global displacement response does not show any sudden changes following fracture (Rodgers and Mahin 2006b).

Sudden changes in acceleration were also observed immediately following fractures for case of the brittle fracture CB (BF CB) pattern (brittle fractures at all bottom "flanges" only) for the modified Tabas, Iran earthquake excitation. The longitudinal accelerations during the portion of the motion where fractures occurred are compared with the corresponding accelerations for the ductile baseline (DB) case in Fig. 5. Transient signals with high frequency content relative to the underlying signal occur immediately after each fracture. Directions of first motion following fracture are consistent with the sign convention in Fig. 3.

High-amplitude transient signals were not typically observed at other times during the experiments (with the exception of transient signals caused by the engagement of the safety catch cables). Thus, it is reasonable to conclude that the observed transient signals were caused by fracture. Due to their typically brief duration and oscillatory nature, plus the fact that they do not affect the displacement response of the structure, the overall effects of fracture-caused transient accelerations on system behavior are typically small.

3. Fracture Damage Detection Using Northridge Acceleration Records from Steel Moment-framed Buildings

3.1. Study design and datasets

The objective of the second study was to determine whether particular high-frequency (>25 Hz) features in recorded accelerations can indicate the presence of brittle fractures in WSMF connections. Structural dynamics theory predicts, and the study discussed in the previous section shows, that steel moment connection fractures result in transient dynamic signals with high frequency content that should be observable in the global lateral accelerations. Presumably, such signals can be used to identify the possibility of fracture damage. However, transient signals can be caused by a number of other factors, such as instrument malfunctions, so a method of determining likely transient cause is necessary.

Using a set of 10 instrumented WSMFs with known damage states following the Northridge earthquake, a method was developed for discerning between transient signals likely caused by fracture and those likely due to other sources (Rodgers and Çelebi, 2006). A systematic process was used to rule out transient signals caused by sources other than damage. The method was then evaluated using a second set of 14 instrumented WSMFs, for which damage information was available but not examined

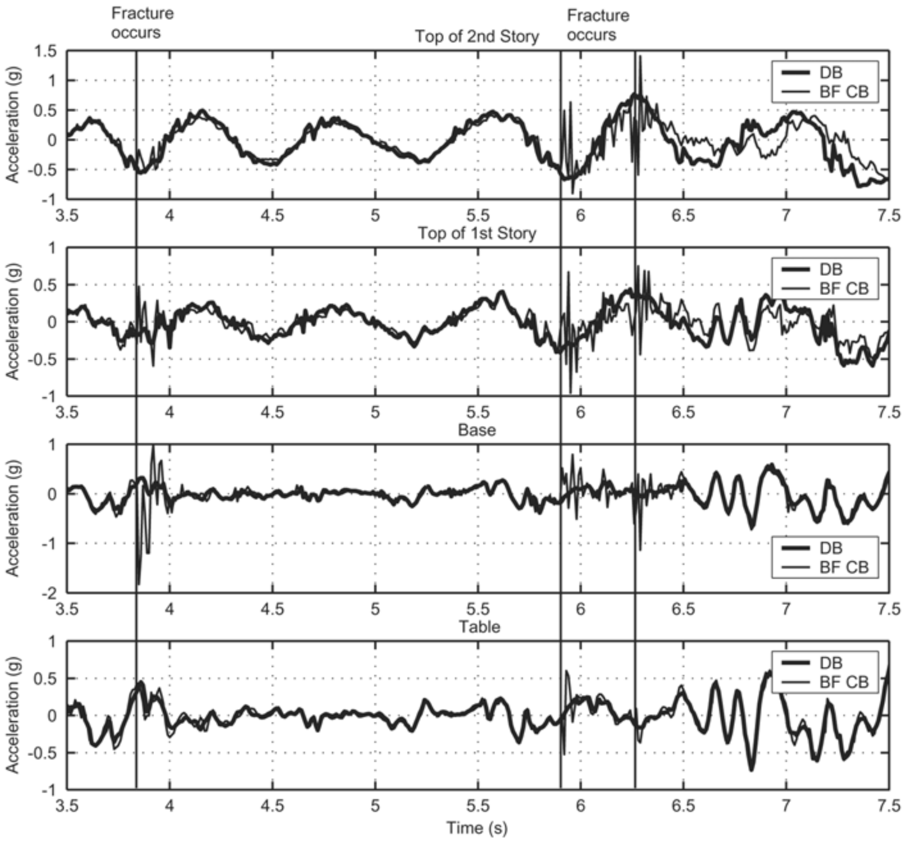

Figure 5. Experimental results for the modified Tabas, Iran excitation, brittle fracture CB and ductile cases.

beforehand. Method performance was evaluated by comparison with a basic damage ratio from the results of intrusive inspections. Two damage detection approaches using the proposed method are discussed herein. These two approaches use the presence of likely fracture-caused transients either (a) alone, or (b) in combination with other damage indicators, such as the amplitude of ground motion (measured or estimated), peak building response, and changes in building vibration properties.

The strong motion dataset used in this study is limited to records from the Northridge main shock and was assembled from three sources: (a) code-instrumented buildings with data retrieved and disseminated by the California Strong Motion Instrumentation Program (CSMIP) under an agreement with the City of Los Angeles, (b) code-instrumented buildings maintained as strong motion stations by the US Geological Survey (USGS), and (c) one USGS extensively-instrumented building (>6 channels of instrumentation which can measure both translation and torsion). Buildings were included in the dataset only if reliable damage information was available and measured accelerations were large enough that damage was considered likely (at least 0.15 g measured at the roof). The dataset is heavily biased towards taller buildings due to its composition of primarily code-instrumented buildings, with the median building height being 12 stories. In contrast, the SAC database developed for loss estimation studies (Bonowitz and Maison, 2003) has a median building height of 4 stories, which is much more representative of the regional WSMF population. However, no strong-motion data were available from low-rise WSMF buildings.

3.2. Example of a record containing high-frequency, transient signals

An 8-story instrumented office building in Burbank provides an example of an acceleration record containing high-frequency, transient signals (hereafter simply transients). The building suffered moderate connection fracture damage (8% of inspected connections had fractures) during the Northridge earthquake. A scanned image of the portion of the original analog record containing several transients is shown in Fig. 6, while the uncorrected, digitized record is shown in Fig. 7. Two large-amplitude and several smaller-amplitude transients are present in this portion of the record, and are easy to detect by visual inspection in both the analog and uncorrected data. The peak value and waveform are easier to determine in the digitized version, though it is clear that some high-frequency information is lost during digitization.

Determining the likely cause of the transients requires a process-of-elimination approach detailed elsewhere (Rodgers and Çelebi, 2005). The results of that procedure indicate that the transients present in the Burbank building record are much more likely to be due to fracture damage than other possible causes. While details are not provided here, it is instructive to illustrate how the process-of-elimination

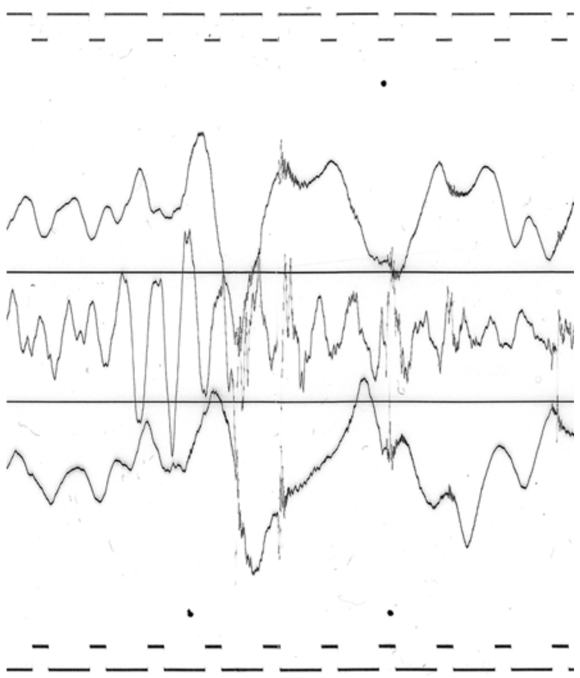

Figure 6. Digital image of a portion of the original analog record from the roof of an 8-story building in Burbank.

procedure distinguished between likely fracture damage and another commonly suspected culprit, falling object impact. It can be difficult to distinguish between signals caused by damage and those caused by falling object impact when examining digitized data, since both cause high-amplitude one- or two-sided pulses. The original analog record shown in Fig. 4 contains additional information that was used to determine that falling object impact was an unlikely source for the transients in the record. During impact experiments conducted as part of this study, several key indicators of falling object impact were observed (Rodgers and Çelebi, 2005). If a transient as large as the largest one in the record were the result of object impact, one would expect to see disturbance of both the fixed traces (the two solid horizontal lines) and the timing traces (the dashed lines at the top and bottom of the film), large amplitude signals in the longitudinal and transverse components, and beating in the response following the transient. None of these indicators are present.

3.3. Results

The results of visual inspection for identifying transients and the process-of-elimination procedure for determining the likely cause of transients (collectively termed the method) are shown in Table 1. The method's overall success rate was 67%. The success rate of the high-frequency transient method for detecting fractures was found to be high (88%) in buildings with heavy damage. The method was somewhat less successful in buildings with moderate damage (50%) or with no damage at all (75%). However, the method failed completely for buildings with light damage (<2% of connections fractured).

The idea of using high-frequency transients to detect fracture in welded steel moment-frame buildings shows promise. However, the use of the process-of-elimination procedure described in the previous section or a similar procedure is recommended before proceeding to use observed high-frequency transients as a potential damage

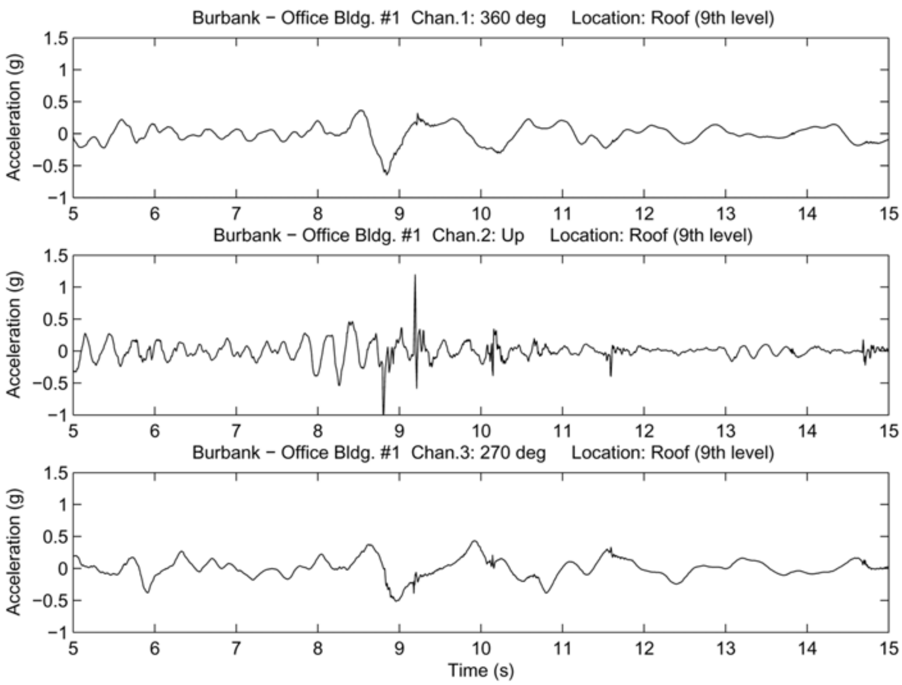

Figure 7. Uncorrected data obtained from digitization of the analog record for the 8-story Burbank building.

Table 1. Results of method for transient detection and evaluation

Building Name	Transient Present	Attributed to fracture	Cause if not fracture	Damage Bin	Damage Ratio	Inspection Ratio	Method Successful
Set 1							
N. Hollywood - Lankershim #2	Yes	Yes	-	None	0.00	0.18	No**
Sherman Oaks - Ventura #6	No	N/A	-	None	0.00	0.23	Yes
Alhambra - Office #1	No	N/A	-	None	0.00	0.06	Yes
Tarzana - Ventura #10	Yes	No	Higher modes	Light	0.02	0.13	No*
Burbank - Office Building #1	Yes	Yes	-	Moderate	0.08	0.92	Yes
Encino - Ventura #12	Yes	Yes	-	Moderate	0.04	1.00	Yes
Woodland Hills - Canoga #1	Yes	No	Noise	Moderate	0.09	1.00	No*
Woodland Hills - Oxnard #4	Yes	Yes	-	Moderate	0.09	1.00	Yes
Woodland Hills - Canoga #2	Yes	Yes	-	Heavy	0.12	1.00	Yes
Los Angeles - Olympic #2	Yes	Yes	-	Heavy	0.17	0.99	Yes
Set 2a							
Los Angeles - Olympic #1	Yes	Yes	-	None	0.00	0.14	No**
Los Angeles - Olympic #3	Yes	No	Instrument	Moderate	0.06	0.86	No*
Los Angeles - Olympic #4	Yes	Yes	-	Heavy	0.14	0.99	Yes
Los Angeles - Wilshire #1	Yes	No	Noise	None	0.00	0.10	Yes
Woodland Hills - Office Bldg. #1	Yes	Yes	-	Heavy	0.17	1.00	Yes
Set 2b							
Encino - Office Bldg. #1	Yes	No	Noise	Light	0.01	0.25	No
Los Angeles - Office Bldg. #3	Yes	No	Noise	None	0.00	0.14	Yes
Los Angeles - Office Bldg. #4	Yes	No	Noise	None	0.00	0.10	Yes
Los Angeles - Wilshire #7	Yes	No	Higher modes	None	0.00	0.31	Yes
Northridge - Oakdale #1	Yes	Yes	-	Heavy	0.23	1.00	Yes
Sherman Oaks - Ventura #7	Yes	No	Instrument	Heavy	0.17	0.60	No*
Woodland Hills - Oxnard #1	Yes	Yes	-	Heavy	0.11	1.00	Yes
Woodland Hills - Oxnard #2	No	N/A	-	Moderate	0.03	0.97	No*
Woodland Hills - Oxnard #5	Yes	Yes	-	Heavy	0.15	1.0	Yes

*Failure is false negative
** Failure is false positive

indicator. If high quality digital recorded response data from frames with connection fractures becomes available, advanced signal processing techniques can be incorporated to improve the method. The results of this study also lead to the recommendation that transients be used as a potential damage indicator in conjunction with other tools for damage detection. A combined approach using transients and other indicators, such as peak ground acceleration and fundamental period elongation, had a higher overall success rate at predicting damage occurrence (80%) than either the transients-only approach described above or an approach which omitted transients and only considered the other indicators.

4. Practical Challenges: Trying to Detect Damage in a Real 13-story Steel Moment-framed Building

4.1. Building and dataset description

The Alhambra building is a 13-story office building located east of downtown Los Angeles. The building has a perimeter moment-resisting frame structural system with "pre-Northridge" connections. The building was designed according to the 1967 Uniform Building Code (ICBO, 1967), constructed in 1970, and instrumented in 1971. At the time, Los Angeles County mandated instrumentation for taller buildings consisting of one tri-axial accelerograph per floor at basement, mid-height, and roof levels. Table 2 lists the earthquakes for which the building's instrumentation system recorded data, along with maximum response information. Engineering drawings and results of post-earthquake inspections (Black & Veatch, unpublished report, 1997) are also available. Since the building has been strongly shaken by several earthquakes and has a substantial amount of data and supporting information available, it was chosen for a case study exploring its seismic response and attempting to determine if structural damage had occurred in any of the recorded earthquakes (Rodgers and Çelebi, 2006).

The Alhambra building also illustrates some of the challenges involved in attempting to detect damage in a large, sparsely instrumented building. Researchers have

Table 2. Earthquakes with building response records and associated maximum shaking parameters

Earthquake	M	A_{max} (g)			A_{max} Level & Direction	D_{max} (cm)	
		Base	12th	Overall		Base	12th
San Fernando	6.6	0.12	0.18	0.18	12th EW	7.7	19.3
Point Mugu	5.3	0.02	0.02	0.03	6th NS	0.2	0.7
Whittier Narrows	6.1	0.29	0.27	0.47	6th EW	2.4	7.5
WN aftershock 10/4/1987	5.3*	0.14	0.18	0.24	6th EW	0.5	1.7
WN aftershock 2/11/1988	5.0*	0.04	0.03	0.05	6th EW	0.1	0.2
Upland	5.2	0.02	0.03	0.05	2nd EW	0.3	1.9
Sierra Madre	5.8	0.13	0.15	0.28	2nd EW	1.8	6.5
Landers	7.3	0.03	0.12	0.12	12th EW	7.5	13.3
Big Bear	6.5	0.02	0.06	0.06	12th NS	1.1	5.0
Northridge	6.7	0.16	0.14	0.54	2nd EW	1.7	12.4
NR aftershock 3/20/1994	5.2*	0.03	0.02	0.09	2nd NS	0.1	0.5
Hector Mine	7.1	0.04	0.10	0.10	12th EW	12.2	16.9
West Hollywood	4.2*	0.02	0.008	0.05	2nd NS	<0.1	0.2
Compton	4.0*	0.008	0.003	0.02	2nd NS	<0.1	<0.1
Big Bear City	5.3*	0.004	0.006	0.01	2nd NS	<0.1	0.1
San Simeon	6.5	0.004	0.03	0.03	12th EW	0.6	3.2

*Denotes local magnitude; moment magnitude used otherwise

recently proposed a number of promising methods for damage detection (Sohn *et al.*, 2003). However, practical difficulties are encountered when trying to apply many of these methods to large buildings like the Alhambra building. Many methods that require a detailed and highly accurate three-dimensional finite element model were ruled out as impractical, due to large computational demands and difficulties involved in obtaining a sufficiently accurate model for a building with approximately 1000 fracture-capable moment-resisting beam-to-column connections, very stiff concrete piers, nonstructural components, and cladding. The building's instrumentation system lacks the spatial resolution necessary to generate an improved model through model updating (Skolnik *et al.*, 2006), or to use methods based on mode shapes. The recorded strong-motion dataset for the Alhambra building is far too small to properly train a neural network despite being among the most extensive available in the US. Thus, the damage detection approaches applied to the Alhambra building were limited to simpler strategies: changes in fundamental frequency, wavelet analysis, and the method based of high-frequency, transient signals discussed in the previous section.

4.2. Results

The simple damage detection methods applied to the structure, including two specifically intended to detect fractures, did not indicate structural damage. This result is consistent with the limited post-earthquake inspections conducted after the Northridge earthquake, which found no structural damage and limited nonstructural damage. No high-frequency, transient signals were identified, even with wavelet analysis, which can detect small discontinuities in the response. The building's fundamental period was not observed to elongate during the stronger events most likely to cause damage (Whittier Narrows and Northridge). However, substantial variations were observed in system vibration properties over time (approximately 20% change in the fundamental period over the 30-plus year instrumented life of the structure). These variations do not show a clear trend and do not appear to be related to structural damage. Such variability may pose difficulties for many vibration-based damage detection methods.

5. Summary

Sudden changes in global lateral accelerations were observed in a series of laboratory experiments on a one-third scale model steel moment frame with fracturing connections. High-frequency, high-amplitude transient accelerations were consistently observed immediately following fracture in all shaking table tests with fracturing connections, and were not generally observed at other times. The sign of the first motion of the observed transient accelerations is consistent with that predicted by theory and analysis. Thus, it is reasonable to conclude that the observed transients were caused by fracture. The effects of these transients on overall system behavior were deemed to be small in most cases. Other consequences of fracture, particularly strength and stiffness loss, generally tend to be responsible for any adverse global behavior observed, especially in cases where many fractures occur and connections continue to lose capacity following fracture. Despite their small impact on system response, the transient acceleration signals were observed to have high amplitudes and high frequency contents relative to the underlying signal, and thus could be useful for damage detection.

Based on this, the second study proposed a method for detecting connection fractures using the high-frequency, transient dynamic response expected to result from fracture. The method was then evaluated using strong motion data and damage information collected from 24 buildings following the 1994 Northridge earthquake. The method has an overall success rate of 67%, but this rate varies significantly with damage level. The method is quite successful in detecting significant fracture damage and in identifying cases where there is no damage, but fails in cases with few fractures. Some improvement in the ability to detect damage is noted when the method is combined with other damage indicators, and when records with excessive noise or instrument response are removed from consideration. This study did not attempt to determine fracture locations due to the very sparse instrumentation in most buildings. It is anticipated that very dense instrumentation schemes utilizing wireless sensors (the cost of cabling for very dense schemes would be prohibitive), or use of additional specialized sensors such as those measuring acoustic emissions, would be necessary to specifically locate fractured connections.

The Alhambra building provides an example of the challenges involved in detecting real building damage using recorded seismic data from a limited number of accelerometers. Many of the recently proposed damage detection methods were impractical for the 13-story Alhambra building due to very heavy computational demands, requirements for a detailed and accurate three-dimensional finite element model, and the need for more closely spaced instruments. The simple damage detection methods employed did not detect structural damage, a finding in agreement with the results of limited intrusive inspections conducted following the Northridge earthquake. The study did reveal significant variations in building vibration properties that did not appear to be related to damage. However, it is possible that low levels of damage are present and have gone undetected, primarily due to the low spatial resolution of data from the instrumentation system. It is anticipated that very dense arrays with wireless sensors would be necessary to detect and locate of low levels of damage in large buildings.

Very dense instrumentation schemes of the kind necessary to detect and locate low levels of damage in large buildings would be prohibitively expensive using conventional wired sensors, primarily due to the high cost of the cabling, and would not be justifiable in most cases because owners are not typically concerned by low levels of damage. Permanent installation of very dense wireless schemes is not currently practical due to the durability and battery life limitations of available wireless sensors, though improvements in wireless technology could make such networks practical and economically feasible in the future. Based on simple probability, temporary deployments of dense arrays using currently available wireless technology are not likely to yield response data from damaging earthquakes, thus limiting their value in damage detection. In the interim, intermediate-density arrays with at least three conventional horizontal sensors at each floor level, though more expensive than traditional "extensive" arrays, have the potential to significantly enhance the utility of recorded response data for damage detection.

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