

ABSTRACT

There has been recent interest in using acoustic techniques to detect damage in instrumented civil structures. An automated damage detection method that analyzes recorded data has application to building types that are susceptible to a signature type of failure, where locations of potential structural damage are known a priori. In particular, this method has application to the detection of brittle fractures in welded beam-column connections in steel moment-resisting frames (MRFs). Such a method would be valuable if it could be used to detect types of damage that are otherwise difficult and costly to identify.

The method makes use of a prerecorded catalog of Green's function templates and a matched filter method to detect the occurrence and location of structural damage in an instrumented building. This technique is different from existing acoustic methods because it is designed to recognize and use seismic waves radiated by the original brittle failure event where the event is not known to have occurred with certainty and the resulting damage may not be visible.

The method is outlined as follows. First, identify probable locations of failure in an undamaged building. In pre-Northridge steel MRFs, which are susceptible to brittle failure of welded beam-column connections, those connections would be the locations of probable failure for this type of building. Second, obtain a Green's function template for each identified location of probable failure by applying a short-duration high-frequency pulse (e.g. using a force transducer hammer) at that location. One underlying assumption of this method is that the Green's function template specific to a potential location of failure can be used to approximate the dynamic response of the structure to structural damage at that location. Lastly, after a seismic event, systematically screen the recorded high-frequency seismograms for the presence of waveform similarities to each of the catalogued Green's function templates in order to

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detect structural damage. This is achieved by performing a running cross-correlation between each Green's function template and a moving window of the continuous data recorded during the earthquake. Damage that occurs at one of the catalogued potential locations is expected to result in a high cross-correlation value when using the correct Green's function template. This method, also known as the matched filter method, has seen recent success in other fields, but has yet to be explored in the context of acoustic damage detection in civil structures.

Preliminary experimental results from tap tests performed on a small-scale laboratory frame are presented. Cross-correlation calculations highlight similarities among events generated at the same source location and expose differences among events generated at different source locations. Finally, a blind tap test is performed to test whether cross-correlation techniques and catalogued Green's function templates can be used to identify the occurrence of and pinpoint the location of an assumed-unknown event.

INTRODUCTION

Acoustic damage detection methods rely on the comparison of a recent signal to an archived baseline response function, known as a template. The template is recorded at a time when the structure is undamaged. The sensor network must have a high sampling rate to capture the propagation of waves throughout the structure. Acoustic techniques have been explored experimentally and numerically for thin plates and beams (Park et al. 2007, Wang and Rose 2003, Wang et al. 2004), which serve as waveguides that effectively carry information from the location of structural damage to a receiver. This information, namely differences in waveform and amplitude between the current signal and the template, are used to diagnose damage.

Acoustic methods can be passive or active, and sensor networks can be permanently installed or temporary. Giurgiutiu (2005) reviews current techniques, including embedded ultrasonic non-destructive evaluation (NDE), which uses a transmitter to interrogate the structure while a receiver records the structural response.

1) *Pitch-catch*: A pulse is emitted by a transmitter and travels through the material to a receiver. Differences in guided wave shape, phase, and amplitude are used to detect damage in the medium between the transmitter and receiver.

2) *Pulse-echo*: A pulse is emitted by a transmitter, which also acts as a receiver to detect damage in the form of additional echoes.

3) *Time-reversal*: A signal sent by a transmitter arrives at a receiver, where the signal is time-reversed and reemitted. Structural damage that causes linear reciprocity to break down leads to discrepancy between the original signal and the final signal received by the transmitter.

4) *Migration*: Recorded waves are back-propagated through the material by systematically solving the wave equation to image reflectors in the medium.

In this paper, a complementary acoustic method is presented, that makes use of a prerecorded catalog of Green's functions and a matched filter method to passively detect the original failure event. This technique is different from existing acoustic methods as it is designed to recognize seismic waves radiated by the original brittle failure event. The matched filter method has been successfully used in other fields

(Gibbons and Ringdal 2006, Anstey 1964), but the method has yet to be explored in the context of acoustic damage detection of civil structures.

METHOD

The proposed method would make use of a prerecorded catalog of Green's functions for an instrumented building to detect structural damage during a later seismic event. Continuous data collected on a passive network is screened for the presence of waveform similarity to one of the Green's function templates. The method is outlined below.

1) Identify probable points of failure in an instrumented building before structural damage has occurred. As pre-Northridge steel MRFs are susceptible to the brittle failure of welded beam-column connections, these would be the locations of probable failure for this type of building.

2) At each labeled location, apply a short-duration high-frequency pulse (e.g. using a force transducer hammer). The response of the building at each instrument site is the Green's function specific to that source location-receiver pair. The Green's functions are archived in the catalog of templates to be used later to screen the high-frequency seismogram for a damage signal.

3) For each possible source location k , perform a running cross-correlation between the Green's function templates for that source location and a moving window of the seismogram that recorded the shaking event, stacking over the receivers. Cross-correlation between the k^{th} Green's function template x_i^k recorded by the i^{th} receiver and the seismogram x_i recorded by the i^{th} receiver is given by

$$C_i^k(t) = \frac{\int_0^T x_i^k(\tau) x_i(t+\tau) d\tau}{\left(\int_0^T (x_i^k(\tau))^2 d\tau \int_0^T (x_i(t+\tau))^2 d\tau \right)^{1/2}}. \quad (1)$$

Time T is the duration of the template, and the cross-correlation is normalized by the autocorrelation values for the given time window.

Compute the stacked cross-correlation function by summing over the R receiver locations to obtain

$$C^k(t) = \frac{1}{R} \sum_{i=1}^R C_i^k(t). \quad (2)$$

4) If damage occurred at or near the k^{th} source location, the stacked cross-correlation function given by Eq. (2) should peak at a value close to one at the correct time of the structural damage event. In the case of multiple locations of damage, then the stacked cross-correlation functions should each peak at a value close to one at the corresponding times, provided the correct Green's function templates are used. This procedure could be extended to the three-dimensional case.

Figure 1. Instrumented steel frame (right) and beam-column connection (left).



EXPERIMENTAL TESTING

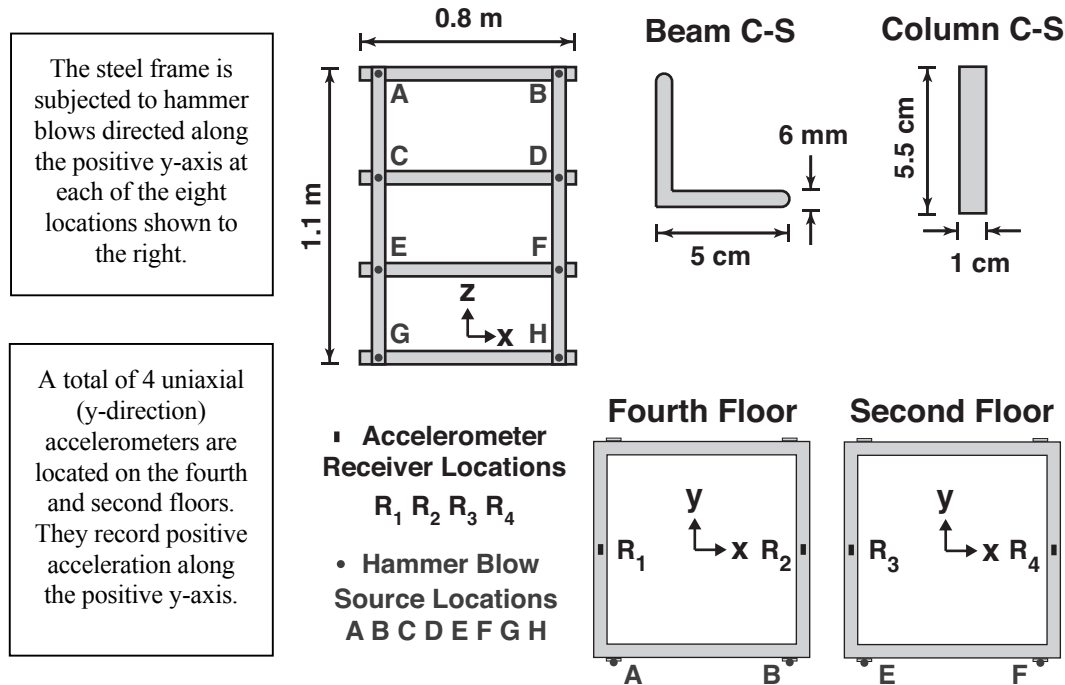
Tap tests were conducted on a small-scale steel frame to study the feasibility of the proposed method. Resulting Green's functions were analyzed using cross-correlation techniques to verify the similarity between events generated at the same source location and to expose the difference between events generated at different source locations. Finally, a blind tap test was performed to confirm whether the prerecorded Green's functions could be used to determine where and when a later hammer blow occurred.

Experimental Setup

A small-scale steel frame instrumented with four accelerometers, as shown in Fig. 1 and 2, was subjected to hammer blows at beam-column connections by using a force transducer hammer. The experimental setup includes:

- Small-scale steel frame with a pinned base and bolted beam-column connections
- High sensitivity low mass accelerometers and power supply
- Force transducer hammer and power supply
- USB multifunction data acquisition device
- Laptop for data logging

Figure 2. Steel frame dimensions and accelerometer locations.



Experimental Method

Green's functions were generated by using a force transducer hammer to apply an impulsive force load at each of the eight connections shown in Figures 1 and 2 above. Four accelerometers captured the response of the frame. The sample frequency was 200kHz and the record time duration was 2.5 seconds. A total of 7 trials were repeated at each source location. The recorded Green's functions were then cross-correlated by using autocorrelation normalization and stacking over the four receivers, as was done in Equations 1 and 2. The time delay from the cross-correlation is compared to the relative time difference of the hammer blows, to see how precise the cross-correlation timing is. A blind tap test was performed to determine whether the prerecorded Green's functions could be used to pinpoint the locations of the taps. A sample recording is shown in Figure 3.

Figure 3. Recorded hammer data (top) and R_1 acceleration (bottom) for source location A.

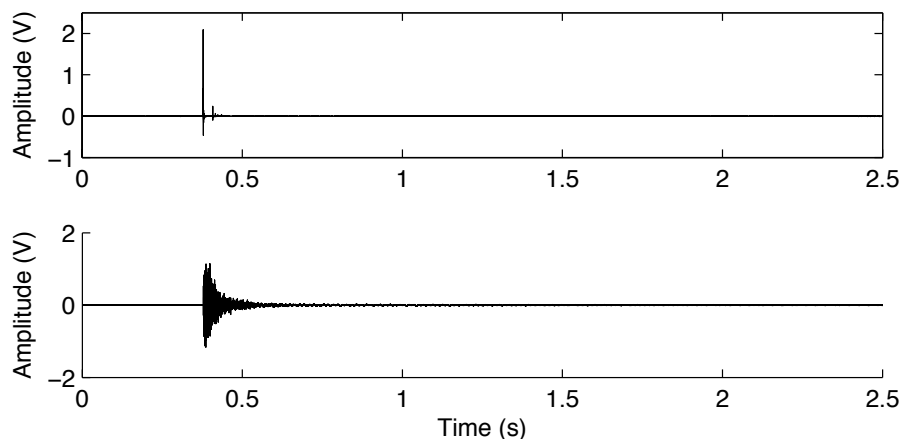
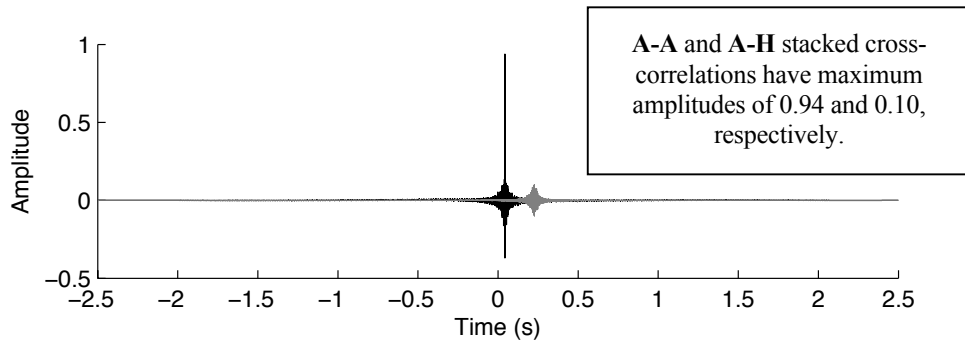


Figure 4. Comparison of **A-A** and **A-H** stacked cross-correlations.



Experimental Results

The cross-correlation statistics were computed and shown in Tables I and II on the following page. The maximum amplitude of the cross-correlation, as shown in Figure 4 above, is used as an indicator of how similar the two waveforms are. The maximum amplitude is highest when comparing Green's functions generated at the same source location. The hammer time series is used to compute the reference time difference between the two taps, and the time error is calculated as the difference between the reference time difference and the cross-correlation time delay. The time error is smallest when the same source location is used for the two signals.

A blind tap test, shown in Figure 5 below, was performed using three taps in unknown locations. A number of tap tests were performed. One of these tap tests was selected at random, and analyzed to see if the tap locations could be determined. Stacked cross-correlations between the test data and the Green's function for each source location were computed and compared to determine the three locations. Three cross-correlation peaks stand out in the comparison: B, A, and A. The actual locations were revealed at the end, after the selection had been made. The chosen locations were indeed the three locations used for the blind test. Note that the cross-correlation values no longer range from 0 to 1 due to the multiple peaks in the blind tap test record. The time errors fell between $-10\ \mu\text{s}$ and $10\ \mu\text{s}$.

Figure 5. Blind tap test consisting of three taps at unknown locations. Recorded hammer data (top), R_1 acceleration (middle), stacked cross-correlation comparison (bottom).

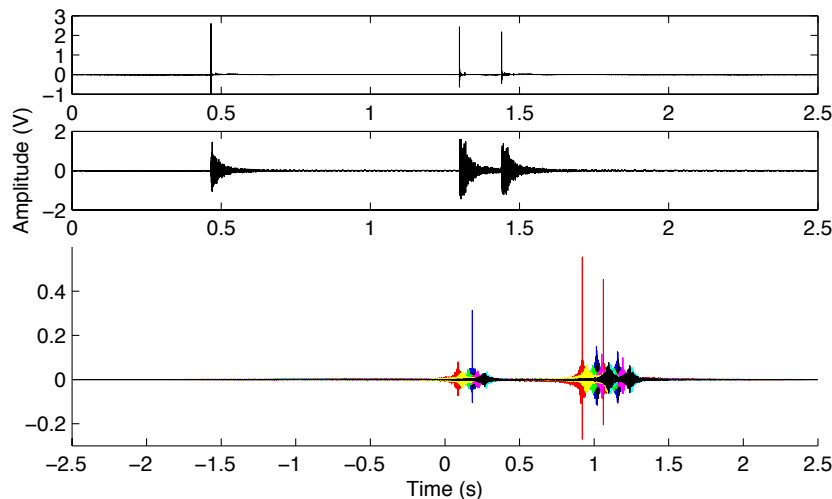


TABLE I. STACKED CROSS-CORRELATION MAXIMUM AMPLITUDE VALUE: MEAN, STANDARD DEVIATION, AND NUMBER OF PAIRS

			Source Location							
			A	B	C	D	E	F	G	H
Source Location	A	μ	0.85	0.22	0.12	0.10	0.12	0.09	0.09	0.10
		σ	0.06	0.01	0.02	0.01	0.01	0.01	0.01	0.01
		N	21	49	49	49	49	49	49	49
	B	μ	0.22	0.83	0.10	0.12	0.10	0.10	0.10	0.09
		σ	0.01	0.06	0.01	0.03	0.01	0.01	0.01	0.01
		N	49	21	49	49	49	49	49	49
	C	μ	0.12	0.10	0.86	0.12	0.19	0.12	0.19	0.12
		σ	0.02	0.01	0.05	0.01	0.01	0.01	0.01	0.01
		N	49	49	21	49	49	49	49	49
	D	μ	0.10	0.12	0.12	0.83	0.09	0.18	0.11	0.15
		σ	0.01	0.03	0.01	0.05	0.01	0.02	0.01	0.02
		N	49	49	49	21	49	49	49	49
	E	μ	0.12	0.10	0.19	0.09	0.82	0.11	0.17	0.14
		σ	0.01	0.01	0.01	0.01	0.05	0.01	0.03	0.01
		N	49	49	49	49	21	49	49	49
	F	μ	0.09	0.10	0.12	0.18	0.11	0.78	0.13	0.16
		σ	0.01	0.01	0.01	0.02	0.01	0.06	0.01	0.04
		N	49	49	49	49	49	21	49	49
	G	μ	0.09	0.10	0.19	0.11	0.17	0.13	0.80	0.18
		σ	0.01	0.01	0.01	0.01	0.03	0.01	0.06	0.02
		N	49	49	49	49	49	49	21	49
	H	μ	0.10	0.09	0.12	0.15	0.14	0.16	0.18	0.80
		σ	0.01	0.01	0.01	0.02	0.01	0.04	0.02	0.04
		N	49	49	49	49	49	49	49	21

TABLE II. STACKED CROSS-CORRELATION TIME ERROR: MEAN AND STD DEVIATION

			Source Location							
			A	B	C	D	E	F	G	H
Source Location	A	μ (μ s)	-7	1370	-1900	2500	-620	-840	2600	470
		σ (μ s)	15	15	2300	930	840	2700	5900	2200
	B	μ (μ s)	1370	5	-2100	2500	-2100	-1600	-2100	900
		σ (μ s)	15	17	1800	3900	2400	5400	1600	5800
	C	μ (μ s)	-1900	-2100	-20	-1200	190	-40	600	-2000
		σ (μ s)	2300	1800	33	2000	250	2100	30	1900
	D	μ (μ s)	2500	2500	-1200	14	-140	330	-830	420
		σ (μ s)	930	3900	2000	24	2700	27	2000	58
	E	μ (μ s)	-620	-2100	190	-140	4	950	280	-2300
		σ (μ s)	840	2400	250	2700	23	2700	69	1100
	F	μ (μ s)	-840	-1600	-40	330	950	-3	1300	520
		σ (μ s)	2700	5400	2100	27	2700	25	890	760
	G	μ (μ s)	2600	-2100	600	-830	280	1300	-1	1400
		σ (μ s)	5900	1600	30	2000	69	890	23	332
	H	μ (μ s)	470	900	-2000	420	-2300	520	1400	7
		σ (μ s)	2200	5800	1900	58	1100	760	332	12

DISCUSSION

Experimental results support the feasibility of the proposed method. However, it remains to be seen whether waveform cross-correlation will be successful when the source mechanism is different from a hammer blow, as is the case for structural damage at a beam-column connection. It is possible that a different cross-correlation method will be more robust, especially one that is weighted based on the amplitude of the acceleration record.

CONCLUSION

Preliminary experimental results from tap tests performed on a small-scale laboratory frame are presented. Cross-correlation calculations highlight similarities among events generated at the same source location and expose differences among events generated at different source locations. Finally, a blind tap test was performed. Cross-correlation techniques and catalogued Green's function templates were used to successfully identify the occurrence of and pinpoint the location of an assumed-unknown event. Experimental results pave the way for damage event detection experiments that cross-correlate pre-recorded Green's function templates with the response of the structure to damage.

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