

A Damage Detection Method for Instrumented Civil Structures Using Prerecorded Green's Functions and Cross-Correlation

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ABSTRACT

Automated damage detection methods have application to instrumented structures that are susceptible to types of damage that are difficult or costly to detect. The presented method has application to the detection of brittle fracture of welded beam-column connections in steel moment-resisting frames (MRFs), where locations of potential structural damage are known a priori. The method makes use of a prerecorded catalog of Green's function templates and a cross-correlation method to detect the occurrence, location, and time of structural damage in an instrumented building. Unlike existing methods, the method is designed to recognize and use mechanical waves radiated by the original brittle fracture event, where the event is not known to have occurred with certainty and the resulting damage may not be visible. An experimental study is conducted to provide insight into applying the method to a building. A tap test is performed on a small-scale steel frame to test whether cross-correlation techniques and catalogued Green's function templates can be used to identify the occurrence and location of an assumed-unknown event. Results support the idea of using a nondestructive force to characterize the building response to high-frequency dynamic failure such as weld fracture.

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 has a sampling rate that is high enough to capture the propagation of waves throughout the structure. Acoustic techniques have been explored experimentally and numerically for thin plates and beams, which serve as waveguides that effectively carry information from the location of structural damage to a receiver [1-3]. 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. Existing methods include pitch-catch, pulse-echo, time-reversal, and migration [4]. 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. It is similar to the matched filter method, which has been successfully used in other fields [5-6]. The method has yet to be explored in the context of acoustic damage detection of civil structures.

DESCRIPTION OF METHOD

The proposed method makes 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 are 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 Eq (1).

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

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 Eq (2).

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

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 unity 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 unity at the corresponding times, provided the correct Green's function templates are used. This procedure could be extended to the three-dimensional case.

EXPERIMENTAL STUDY

To study the feasibility of the proposed method, experimental tests were conducted on the small-scale steel frame shown in Fig. 1. Three different source mechanisms were applied to beam-column connections: impulsive hammer blow, bolt fracture, and impulsive hammer blow to a frame with a “damaged” beam-column connection. The similarities and differences between the three cases were analyzed using waveform cross-correlation normalized by the autocorrelation value and stacked over the eight receiver locations. Results were averaged over 15-25 trials.

Experimental Setup

A small-scale steel frame instrumented with eight uniaxial (y-axis) accelerometers, shown in Fig. 2, was subjected to hammer blows and bolt fracture at beam-column connections. A sample frequency of 100kHz and record duration of 2.0 seconds were used. The experimental setup included:

- 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

Experimental Method and Results

Green's functions were generated by using a force transducer hammer to apply an impulsive force load along the y-axis to each of the eight beam-column connections (A-H) shown in Fig. 2. A total of



Fig. 1. Instrumented steel frame (left), close-up of bolted beam-column connection (top right), and notched bolts before and after failure (bottom right). Dimensions are shown in Fig. 2.

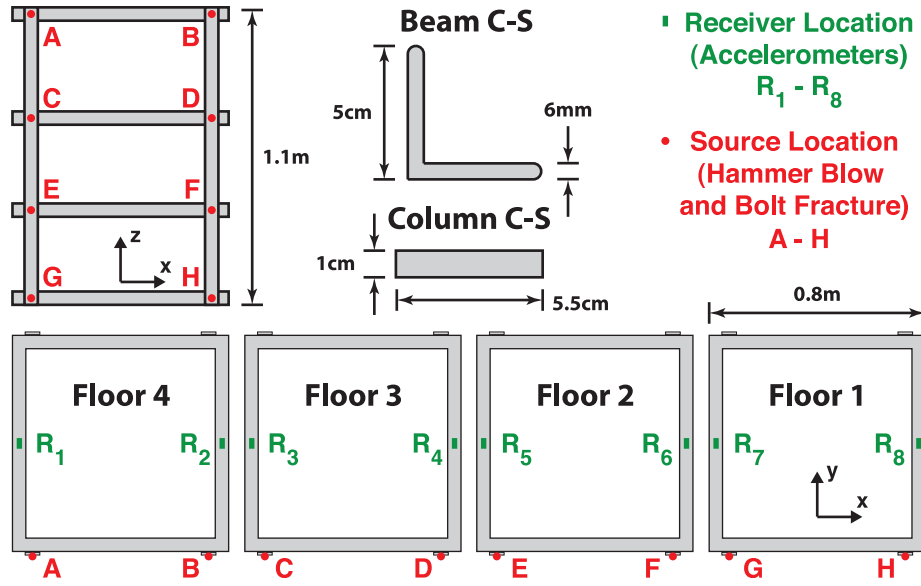


Fig. 2. Experimental Setup: Steel frame dimensions, receiver (accelerometer) locations, and source (hammer blow and bolt fracture) locations

five hammer blows were delivered at each source location. Fig. 3 displays the Green's function that was generated by applying an impulsive hammer blow at source location C. The cross-correlation of each possible pair of Green's functions was computed. Cross-correlations were first calculated at each receiver location, using the two different records and autocorrelation normalization, as in Eq. (1). The cross-correlations were then stacked, or summed, over all eight receivers, as in Eq. (2). An example is presented in Fig. 4, where the cross-correlations of Green's functions generated by impulsive hammer blows applied at identical source locations C-C are plotted on the left, and those generated by hammer blows applied at different source locations are plotted on the right. The maximum amplitude of the stacked cross-correlation is recorded, averaged over the total number of pairs (20 total for pairs consisting of two identical source locations and 25 total for pairs consisting of two distinct source locations), and presented in Table 1. In Fig. 4, the maximum value of the stacked cross-correlation is 0.87 for source location pair C-C, and 0.11 for source location pair C-F.

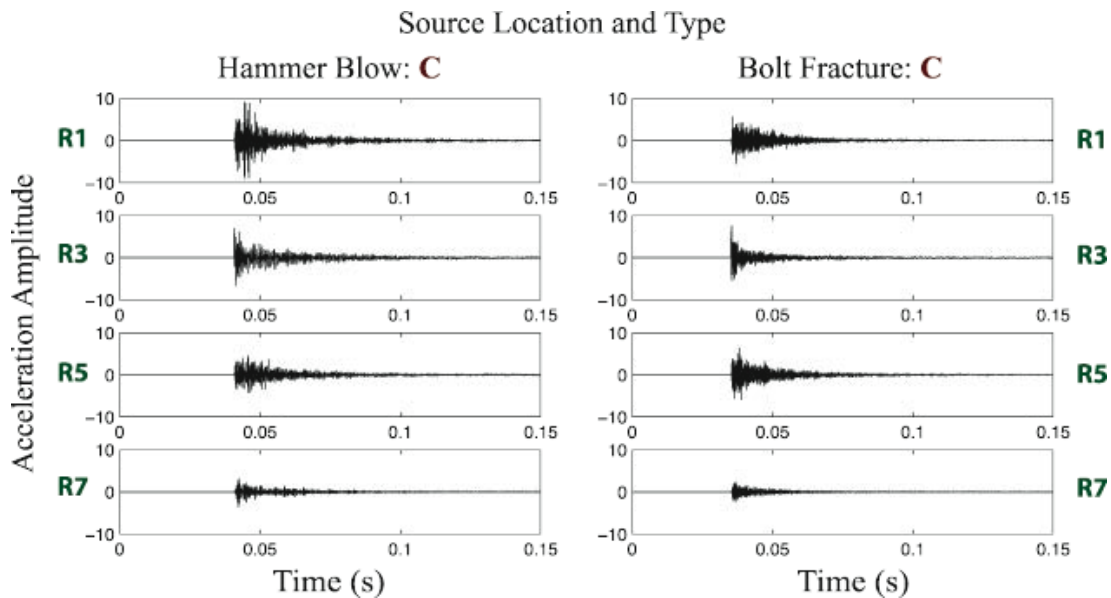


Fig. 3. Acceleration time series for a hammer blow (left) and a bolt fracture (right) shown for four receiver locations (R₁, R₃, R₅, R₇) and the same source location (C).

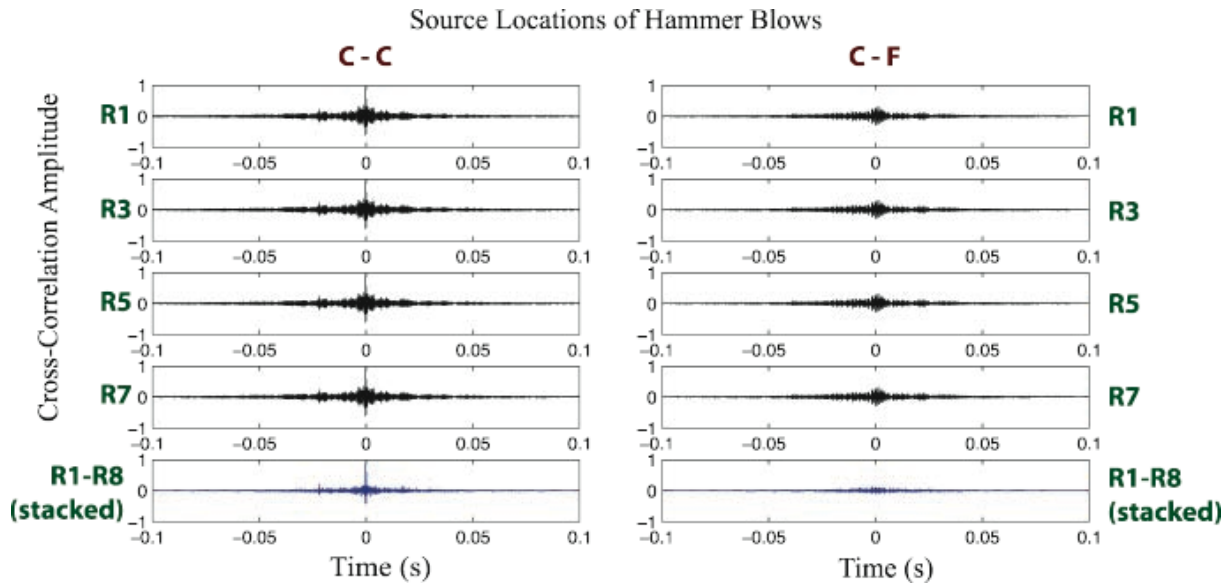


Fig. 4. Cross-correlations of Green's functions generated by hammer blows at the same source location (left) and of Green's functions generated by hammer blows at two different source locations (right) shown at four receiver locations, as well as the stacked cross-correlations (bottom).

Further experimentation was conducted to determine whether prerecorded Green's functions could be used as an approximation to the frame's response to structural damage (i.e. a fracture event) at the same source location. A notched stainless steel socket cap screw was introduced into a beam-column connection. The screw replaced the bottom bolt shown in Fig. 1. It was then loaded by torque tightening to the point of failure, and the response of the frame to the fracture was recorded on the eight accelerometers. An example acceleration time series generated by bolt fracture is shown in Fig. 3. Three trials were repeated at each of the four source locations A, C, E, and G. Cross-correlations were computed to determine the similarity between the prerecorded Green's functions and the frame's response to bolt failure. Specifically, the frame's response to the prerecorded Green's functions was cross-correlated with the response of the frame to bolt failure. Each possible pair of bolt failure source location and Green's function source location was considered. Results presented in Table 2 were averaged over 15 total pairs.

Finally, a tap test was performed on a frame with a "damaged" beam-column connection. Damage was introduced by removing all three bolts from the connection (A, C, E, or G), with the stiffness of the rest of the structure holding the beam and column in place. An impulsive hammer blow was applied to each of the eight source locations, for each of the four damaged connection cases. This was performed a total of three times. To highlight differences in structural response before and after damage occurred, the prerecorded Green's functions were cross-correlated with the response of the damaged frame to an impulsive hammer blow applied at the same source location, for each of the four damaged connection cases. Results were averaged over 15 total trials and are presented in Table 3.

Table 1. Stacked cross-correlation of Green's functions: averaged maximum value over 20-25 trials. The table is symmetric.

		Hammer Blow Source Location							
		A	B	C	D	E	F	G	H
Hammer Blow Source Loc	A	0.78	0.17	0.14	0.09	0.15	0.10	0.13	0.10
	B		0.85	0.09	0.15	0.08	0.08	0.08	0.07
	C			0.80	0.14	0.16	0.10	0.20	0.11
	D				0.83	0.09	0.22	0.10	0.11
	E					0.81	0.10	0.30	0.10
	F						0.83	0.12	0.18
	G							0.80	0.13
	H								0.85

Table 2. Stacked cross-correlation of Green's function and structural response to bolt failure: averaged maximum value over 15 trials.

		Hammer Blow Source Location							
		A	B	C	D	E	F	G	H
Bolt Fracture Source Loc	A	0.17	0.07	0.11	0.07	0.07	0.06	0.08	0.05
	C	0.07	0.05	0.16	0.06	0.12	0.05	0.09	0.05
	E	0.08	0.06	0.07	0.07	0.17	0.06	0.14	0.07
	G	0.06	0.05	0.07	0.06	0.11	0.07	0.15	0.07

Table 3. Stacked cross-correlation of the Green's function generated by applying a hammer blow at one source location and the response of the damaged frame to a hammer blow applied at the same location. Four different damaged connection cases are shown: averaged maximum value over 15 trials.

		Hammer Blow Source Location							
		A	B	C	D	E	F	G	H
Damaged Connection	A	0.11	0.44	0.46	0.53	0.51	0.56	0.51	0.56
	C	0.52	0.50	0.41	0.48	0.44	0.51	0.51	0.51
	E	0.60	0.57	0.46	0.54	0.33	0.45	0.47	0.53
	G	0.60	0.60	0.52	0.60	0.45	0.54	0.31	0.50

DISCUSSION

The maximum value of the stacked cross-correlation record is used as an indicator of how similar the two correlated waveforms are, e.g. how similar the building responses are to different source mechanisms and locations. Stacked cross-correlation values range from -1 to 1, with a higher value corresponding to a higher degree of similarity. In Table 1, the stacked cross-correlation values are greatest along the diagonal, where the two Green's function source locations are the same. Off-diagonal terms, where two different source locations are used, have a much lower stacked cross-correlation value. The reason for this is illustrated in Fig. 4, which compares the

cross-correlation records for source location pairs C-C and C-F. For source location pair C-F, the unstacked cross-correlations computed at each receiver location have lower peak values than the corresponding C-C unstacked cross-correlations. Furthermore, the stacked C-F cross-correlation attains a peak value of 0.11, which is lower than each of the peak values of the unstacked C-F cross-correlations, which range from 0.15 to 0.32. There is a relatively large time difference (0.0087 sec) at which the peak values occur in the unstacked C-F cross-correlations. For comparison, the maximum time difference between unstacked C-C cross-correlation peaks is 0.00002 sec, which results in much more coherent stacking. Differences in both waveform as well as arrival time contribute to the smaller off-diagonal terms.

The stacked cross-correlation values in Table 2 are greatest when the bolt fracture source location is the same as the Green's function source location. Hence, the Green's function that best approximates the frame's response to bolt fracture is the one with the same source location. This is a necessary condition for the proposed method to be successful. However, the stacked cross-correlation values in Table 2 are much lower than those in Table 1. Alternative cross-correlation techniques will need to be explored, as a high cross-correlation value will be essential for robust detection of structural damage. Future work will investigate which provides a better approximation to the structural response to bolt failure: the prerecorded set of Green's functions or the post-event set of structural responses to hammer blows. This will be accomplished by cross-correlating the damaged structure's response to an impulsive hammer blow with the structure's response to bolt failure.

The change in the response of the frame to an impulsive hammer blow at the same source location after damage has occurred is apparent in Table 3. The values in Table 3 are much lower than the values along the diagonal in Table 1, falling from an average value of 0.82 to 0.49. The values along the diagonal in Table 3, where the location of the damaged connection is the same as the source location of the hammer blow, give the lowest cross-correlation values, an average of 0.29 compared to the off-diagonal terms, which have an average of 0.52. Thus, there is significant change in the response of the structure to a hammer blow after damage has occurred, and this change becomes more evident when the hammer blow is applied at the location of the damaged connection.

CONCLUSION

An experimental study was conducted to provide insight into a damage detection method that makes use of a prerecorded catalog of Green's function templates and a cross-correlation method to detect the occurrence and location of structural damage in an instrumented building. Impulsive hammer blows and bolt fracture were applied to a small-scale steel frame to test the feasibility of applying the method to a building. Results indicate that the Green's function that best approximates the frame's response to bolt fracture at a beam-column connection is the Green's function generated by a hammer blow applied to the same connection. However, alternative cross-correlation techniques will be explored, as a higher stacked cross-correlation value than the one obtained via waveform correlation will be essential for robust detection of structural damage. Successful damage detection could be accomplished by employing a mixed approach that analyzes both recorded seismograms for the presence of a brittle fracture event as well as post-event tap tests that expose changes in building response. Results support the idea of using a nondestructive force to characterize the building response to high-frequency dynamic failure such as weld fracture.

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