DETECTING FAILURE EVENTS IN BUILDINGS: A NUMERICAL AND EXPERIMENTAL ANALYSIS

V. M. Heckman[1] M. D. Kohler[2] and T. H. Heaton[3]

ABSTRACT

A numerical method is used to investigate an approach for detecting the brittle fracture of welds associated with beam-column connections in instrumented buildings in real time through the use of time-reversed Green's functions and wave propagation reciprocity. The approach makes use of a prerecorded catalog of Green's functions for an instrumented building to detect failure events in the building during a later seismic event by screening continuous data for the presence of waveform similarities to one of the prerecorded events. This study addresses whether a set of Green's functions in response to an impulsive force load can be used to approximate the response of the structure to a localized failure event such as a brittle weld fracture. Specifically, we investigate whether prerecorded Green's functions can be used to determine the absolute time and location of a localized failure event in a building. We also seek to differentiate between sources such as a weld fracture that are structurally damaging and sources such as falling or colliding furniture and other non-structural elements that do not contribute to structural failure. This is explored numerically by comparing the dynamic response of a finite-element cantilevered beam model structure to a variety of loading mechanisms. A finite-element method is employed to determine the behavior of the resulting elastic waves and to obtain a general understanding of the structural response.

Introduction

The 1994 Northridge earthquake caused structural failure, notably fracture of steel frames, in more than one hundred buildings that were designed for the ground motions produced by the earthquake. As a result, civil engineers recognized the potential seismic hazard of brittle fracture of welded beam-column connections in steel frame buildings (Updike 1996). Post-Northridge analysis has shown that weld fracture significantly decreases the ductility of tall steel buildings (Hall 1995). Olsen (2008) report that simulations of 20-story steel buildings with brittle

[1]Graduate Student, Department of Civil Engineering, California Institute of Technology, Pasadena, CA 91125
[2]Professional Researcher, Center for Embedded Networked Sensing, University of California at Los Angeles, Los Angeles, CA 90095
[3]Professor of Engineering Seismology, Department of Civil Engineering, California Institute of Technology, Pasadena, CA 91125

welds are three to five times as likely to collapse in near-source shaking than identical buildings with perfect welds.

According to Rodgers and Celebi (2005), sudden structural failure (such as brittle failure of welded connections) should produce both near and far-field dynamic response that is observable over seismic loading. Rodgers and Celebi further suggest that the frequency content of this dynamic response should be higher than that of the predominant building response for several reasons: 1) the sudden change in the stiffness and strength of damaged members results in sudden changes in global accelerations to satisfy the equations of motion; 2) weld fracture occurs over the span of milliseconds and results in excitation of local member vibration modes; and 3) the sudden release of strain energy creates elastic waves that propagate away from the fracture in connected members.

A sophisticated damage detection system that monitors data recorded by a structure's vibration monitoring array will take into account locations of relatively high probability of failure, such as welded connections, and use waveform data to detect locations of dynamic failure. If it is possible to assemble a database of expected building responses to failure at each of these locations (by using the building response to an impulse load applied at each location, e.g. the Green's function), then data recorded by the structure's seismic array during an earthquake could be screened continuously in real time for the presence of one or more failure events at each of the suspect locations. This would be accomplished by performing a series of cross correlations using both the preexisting database of building responses as well as by running a time-window of seismic data. Application of a high-frequency filter further distinguishes the transient response to dynamic failure from the predominant building response.

Such a damage detection system would be able to sort through a wealth of seismic data in real time as well as store detected locations of probable damage for later use. This information could be used to help guide physical inspection of welded connections after an earthquake. Inspections can be expensive as weld fracture often occurs without accompanying distress to architectural finishing and cladding. The level of spatial coverage and temporal resolution needed by a seismic array to attain a high level of spatial resolution required to distinguish between failure events at different beam-column connections remains to be seen. However, the increasing prevalence of new inexpensive smaller sensors (e.g. MEMS-based USB sensors designed for use at desktop computer sites such as the Quake-Catcher Network; Cochran 2009), and the plans for network installation during new high-rise construction (Los Angeles Tall Buildings Structural Design Council 2008) makes the method proposed here application-realistic.

Methodology

Kohler et al. (2009) show that wavefield properties of linear elastic media provide the basis for a method to determine the location and time of the occurrence of a high-frequency fracture event in a civil structure. First, the structural displacement from a hammer blow (impulse point force load) is expressed in the Green's function for the building. A weld fracture is a more complicated source signal and can be approximated two ways. The first approximation is the one used is this study; it consists of an elastic model with a tensile crack that experiences a step change in normal traction on the crack surface. An alternative way to approximate a weld fracture is a method commonly used in seismology to model an earthquake source. The weld fracture is approximated as a localized region that experiences large elastic tensile strains resulting in finite opening across the strained region. A body-force equivalent source is characterized by a seismic moment tensor that consists of a combination of linear force couples and shear force couples. The response of the medium to these force couples is the spatial derivative of the point force Green's functions.

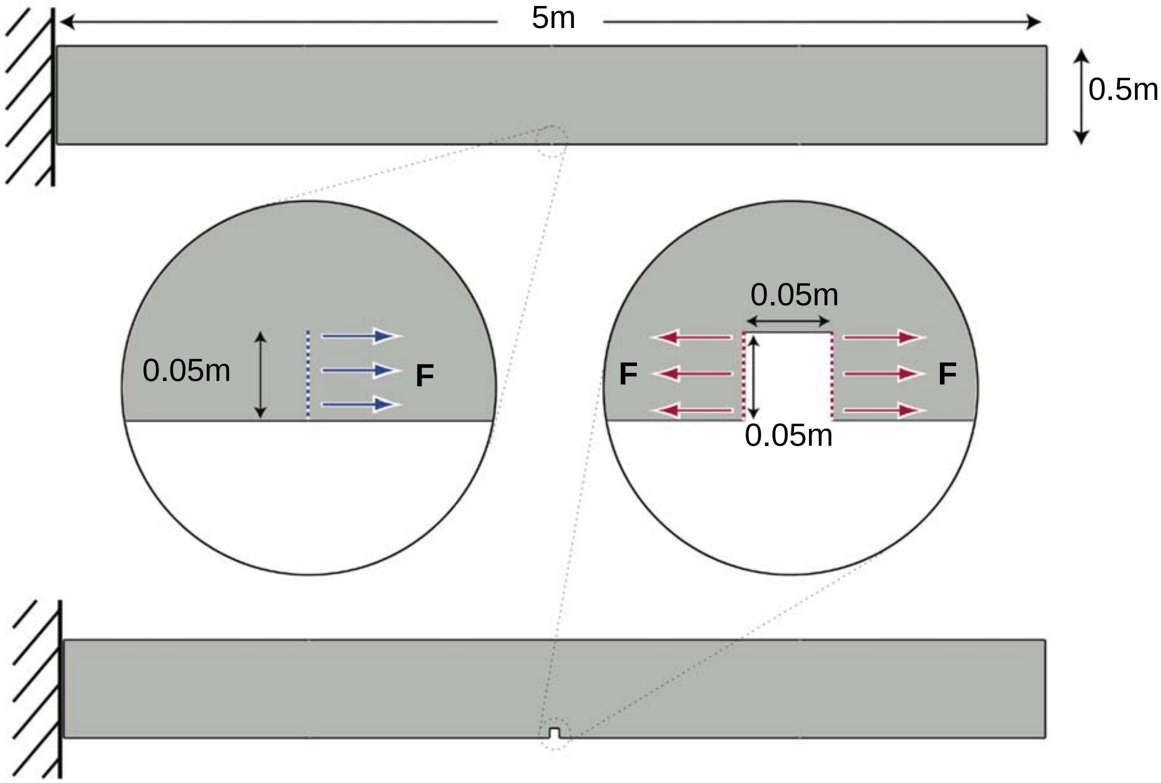
The response of the medium can be decomposed into near-field and far-field terms. The near-field terms are necessary to describe the steady-state solution. The far-field terms are solutions to the homogeneous equation of motion and generally have a time history that is a time derivative of the near-field terms. Kohler et al. (2009) show that if the far-field portion of the Green's function is approximated by a sum of traveling rays, each traveling at a different velocity, then for each ray in the sum the expected similarities between seismograms produced by a hammer blow point source and the seismograms produced by a weld fracture differ only by a constant ratio; this ratio is different for each ray and is a function of the radiation patterns of the different sources. Given these assumptions, the correct location and time of each subsequent fracture source can be inferred by identifying which Green's function has a high cross correlation value when it is cross correlated with a record from an individual station. If the signal from a weld fracture is recorded on several stations, it should produce an impulse at the same time for the cross correlation at each station.

Numerical Method

Finite-element analysis is used to simulate the response of a model structure to various loading mechanisms in order to determine conditions for which a set of Green's functions approximates the response of the structure to a complex failure source such as a weld fracture. Numerical simulations are conducted on a cantilevered beam finite-element model. The goal is to compare a cantilevered beam's response to an impulsive load to that of an opening crack.

Numerical analysis is carried out using Pylith, a finite-element code for the solution of dynamic and quasi-static tectonic deformation problems that runs in either serial or parallel mode (Aagaard 2007). It has the flexibility to work on large and small spatial and temporal scales, and it is well-suited for our problem as it is capable of simulating wave propagation through solids. Material properties (i.e., density, shear-wave and compressional-wave velocities) and parameters for boundary and fault conditions are user-specified through a spatial database. Boundary conditions include the option of applying a force to selected nodes, with force-time histories that can be specified by the user. Nodes are chosen to satisfy a desired boundary condition in Cubit, a full-featured software toolkit for robust generation of 3D finite-element meshes (Benzley 1997).

The cantilevered beam models and accompanying force-time histories, shown in Fig. 1, simulate a horizontal impulsive force (i.e., hammer blow) and a crack subjected to a step change in tensile stress (i.e., weld fracture). The material has the properties of A36 structural steel, with a Young's modulus of 200 GPa, shear modulus of 80 GPa, density of 7850 kg/m^3, and shear-wave and compressional-wave speeds of 3.2 and 5.6 km/s, respectively. We first test our methodology on a simple case; we constrain our mesh to experience displacement only along the a)



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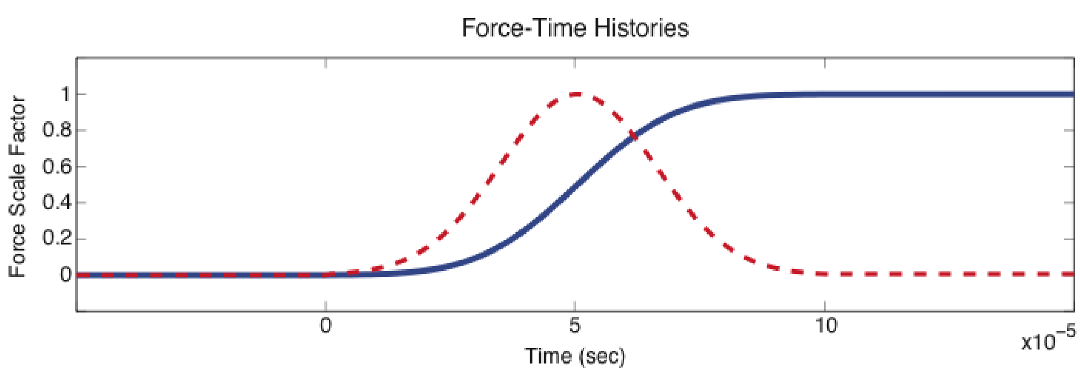

Figure 1. Cantilevered beam model. a) A horizontal impulsive force is applied to an unnotched beam (top). A crack (square notch) is subjected to a step change in tensile stress (bottom). A model mesh size of 2.5 cm and a time step of 1 μs are used. Beam dimensions are 5.0 m × 0.5 m × 0.25 m. The mesh is constrained to experience displacement only along the longitudinal axis. The longitudinal force is distributed over nodes located in each highlighted cross section of the beam. The value of the force applied to each node scales with the amount of surface area contained by the node. b) Force-time histories applied to nodes. The red (dashed) curve simulates an impulsive hammer blow. The black (solid) curve simulates a weld fracture. The maximum force (F = 2 kN) is multiplied by a time-dependent scale factor.

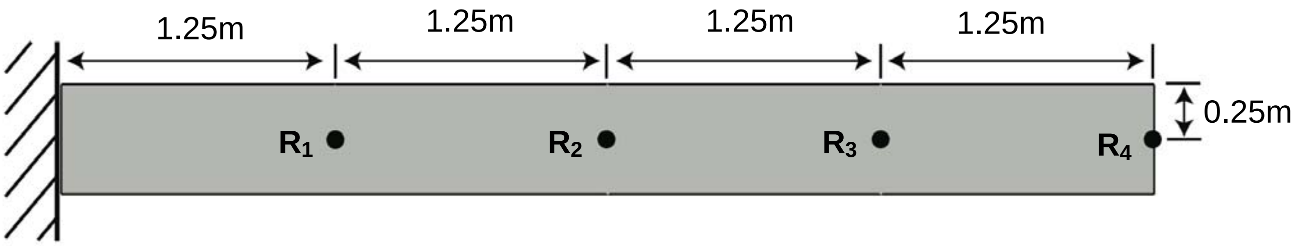

Figure 2. Receiver locations. Receivers are equally spaced along the beam's center axis.

longitudinal axis. This effectively reduces the problem to two dimensions and removes the possibility of dispersion. The resulting displacements, velocities and strains are recorded at the four receiver locations shown in Fig. 2.

Experimental Results

The numerical solution is consistent with the traveling wave solution to the beam equation (Timoshenko 1951). According to Timoshenko, a body's reaction to a suddenly applied force is not present at all parts of the body at once. The remote portions of the body remain unaffected during early times. Deformation propagates through the body in the form of elastic waves. This can be observed in Fig. 3 which shows an elastic wave propagating away from the source. At first the beam reaction is present only in the immediate vicinity of the source. Elastic waves reach the ends of the beam at 450 μs. Reflected waves interfere in a manner consistent with the traveling wave solution for longitudinal vibration of a prismatic beam.

The numerical solution for the unnotched beam is similar to the analytic solution to the longitudinal vibration of a beam with initial conditions of zero displacement and a positive horizontal pulse in velocity along the vertical axis that passes through R_2. The analytic solution consists of the superposition of two waves: a compression wave traveling to the right and a tension wave traveling to the left. If the beam is constrained to move only along the longitudinal axis, then the wave speed will equal the compressional-wave speed,

$$c_p = \sqrt{\frac{\mu(E-4\mu)}{\rho(E-3\mu)}} \tag{1}$$

where E, μ, and ρ are the Young's modulus, shear modulus, and density, respectively. If this constraint is not present, the wave speed will be the longitudinal wave speed in a prismatic beam,

$$c_l = \sqrt{\frac{E}{\rho}} \tag{2}$$

A wave that reflects off the free end of the beam has the same polarity and magnitude as the original forward traveling wave, since the sum of the combined strains must equal zero. A wave that reflects off the fixed end has the same magnitude but opposite polarity as the original backward traveling wave, since the sum of the displacements must equal zero (Timoshenko 1951).

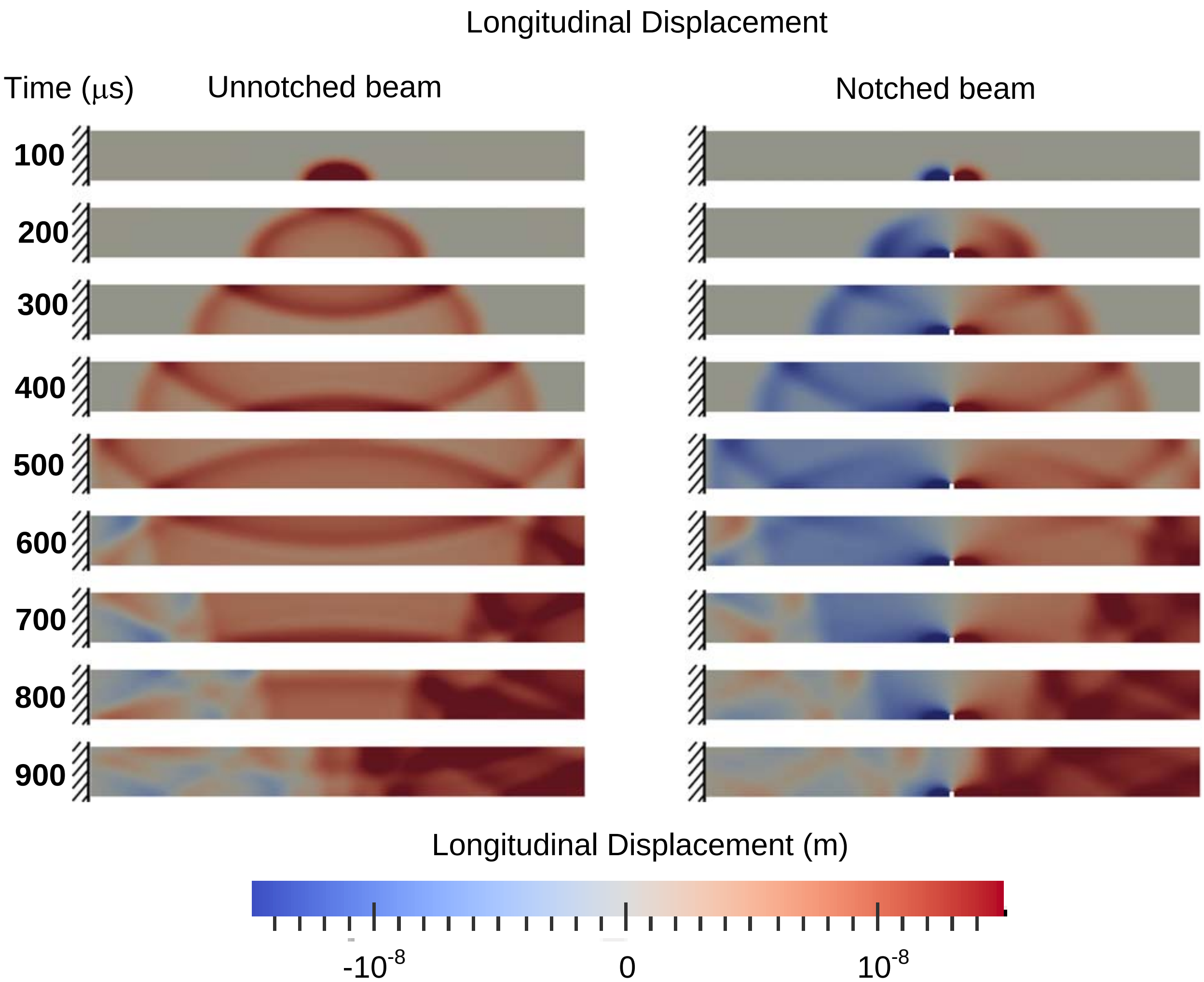

Figure 3. Beam displacements for two source loading cases. Left panels show the response of the unnotched beam to an impulsive horizontal force. Right panels show the response of the square notched beam to a step source applied to open the crack. In both cases, the left end of the beam is fixed and the right end is free. Time is listed along the left. Waves interfere either constructively or deconstructively after reflecting off the right and left ends of the beam in a manner consistent with the traveling wave solution for longitudinal vibration of prismatic beams.

In the left column panels of Fig. 3, an elastic wave begin to propagate away from the source, with compression to the right of the source and tension to its left. The forward propagating wave reflects off the free end of the beam at a time of 450 μs. The average combined displacement of the original and newly reflected waves is twice the displacement of the original wave. At the fixed end of the beam, the resulting average displacement from the original backward propagating wave and its reflected wave is zero. The asymmetric application of the load results in additional complexity in the numerical solution, due to vertical reflections of waves off the top and bottom of the beam. A Gaussian FIR filter is applied to recorded displacements to remove frequencies of high modes of oscillation and reveal the underlying

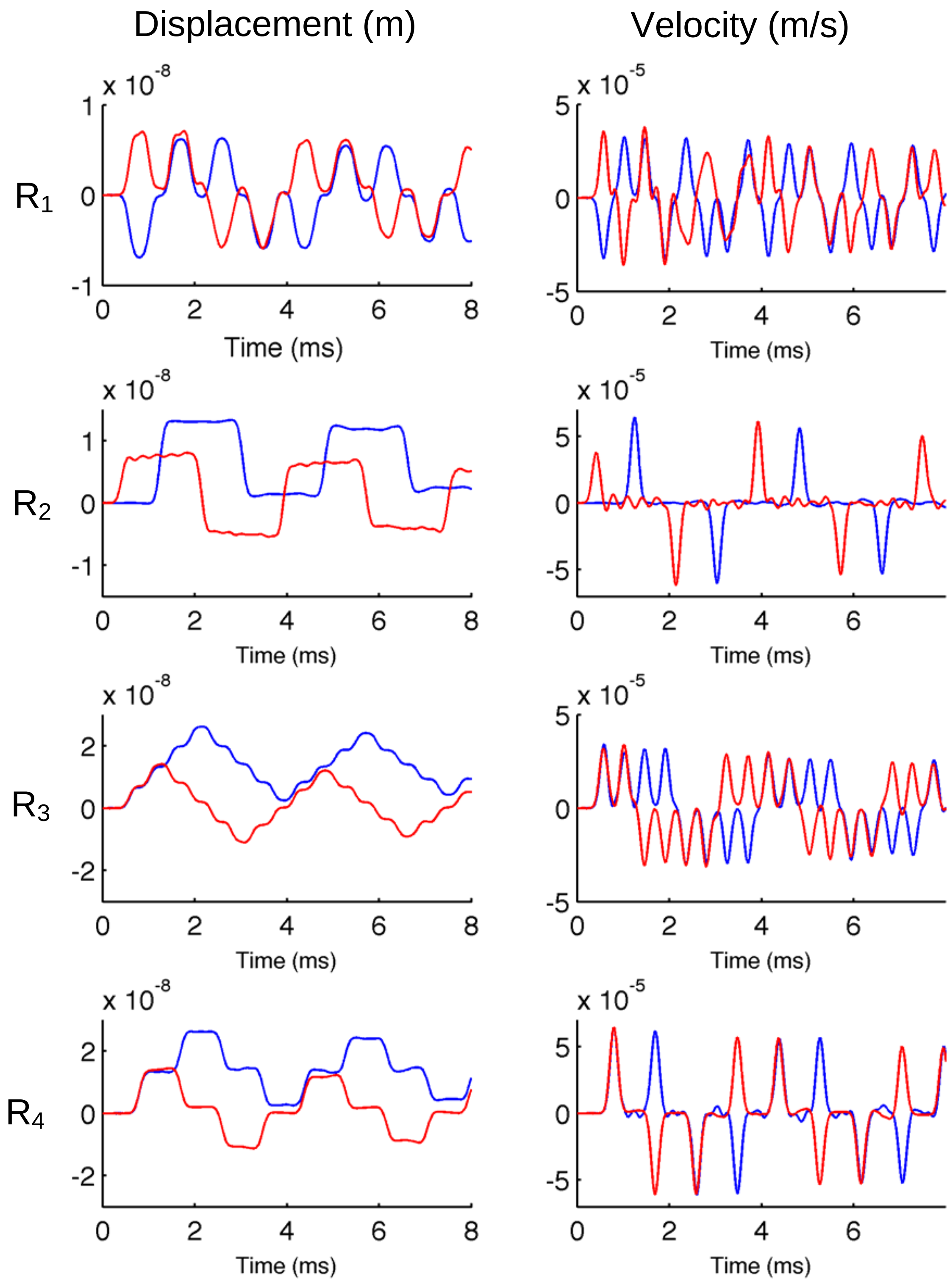

Figure 4. Seismograms for an impulsive force (red) and a tensile crack (blue); each seismogram displays either the filtered displacement (left) or velocity (right) recorded at a given receiver location (labeled along the left). The period is 3.6 ms.

planar wave solution. The filtered displacements and velocities, shown in Fig. 4, are similar to the one-dimensional solution to the longitudinal vibration of a beam subjected to an initial pulse in velocity.

The velocity records in Fig. 4 illustrate how they are better suited for performing cross correlation than displacement records due to their pulse-like nature. The displacement records resulting from the impulsive load do not always give a good approximation to the displacement records resulting from the opening crack. This is due to the fact that the crack source double couple initially leads to compression in both sides of beam, whereas the single impulsive force initially leads to compression in the right half of the beam and tension in the left half of the beam. The pulses in velocity often only differ in polarity, suggesting that the absolute values of the recorded velocities at each receiver location in response to an impulse load can be used to approximate the absolute velocities recorded at a number of locations to a crack in the structure at that receiver location. The reason for the discrepancy between velocity records at R_2 for the two different source loads is that R_2 lies at a node where the two waves originating from the notch deconstructively interfere. For the notched case, R_2, R_3, and R_4 displacements oscillate about a nonzero offset due to tensile deformation across the notch.

Conclusions

We performed a numerical study to gain insight into applying a novel method to detect high-frequency dynamic failure in buildings. A 2D finite-element model of a cantilevered beam that is discretized on a spatial scale of centimeters provides the basis for our numerical tests. The beam's elastic, longitudinal response to two loading cases, impulsive force and opening crack tensile stress, is computed on a temporal scale of microseconds. We find that the velocity waveform of a tensile crack can be approximated by the velocity waveform of a horizontal impulsive force load applied at the proper location. These results support the idea of using an impulse force to approximate a weld fracture damage source to characterize a high-frequency fracture event in the far field. The similarities between impulsive force and tensile crack velocity waveforms is further underscored by the fact that, for traveling waves of either type of source, the strains are proportional to their associated particle velocities. The results pave the way for the use of waveform cross correlation using a pre-event catalog of Green's functions to determine the location and time of occurrence of a subsequent fracture recorded on a network of vibration sensors. It remains to be seen what types of waves, reflections, and interfering wave behavior will occur in three dimensions because of the added complexity due to dispersion and surface waves.

Acknowledgments

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