USING SEISMOMETERS TO DETECT DAMAGE IN BUILDINGS

Tom Heaton, Monica Kohler, Vanessa Heckman, Ming Hei Cheng, Casey Bradford, Brad Aagaard, John Clinton, Javier Favela
Overview

- Wave propagation in instrumented civil structures
  - Harvest useful information from large, complex dataset
    - Before, During, After an Earthquake
  - Application
    - Damage detection
    - System identification
    - Vibration Monitoring

- Methods
  - Seismic Interferometry
    - Deconvolution
    - Cross-correlation
  - Time-reversed reciprocal method
  - Use of impact test to characterize response to structural damage

- Future/potential
  - Community Seismic Network (CSN), iShake
Millikan Library: Background

- Caltech Millikan Library
  - Nine-story reinforced concrete frame and shear wall building

- Observed Change in Natural Frequencies
  - Historical change in natural frequencies after EQs due to softening in system stiffness
    - EW fundamental frequency: currently 1.15 Hz, 20% difference from original value (1.45 Hz)
    - 1971 San Fernando EQ (M 6.6, 31 km): 16.6% decrease from original value
  - Change in natural frequencies due to weather variation
    - 2-3% variation in fundamental frequencies following major rainstorm
    - Forced vibration tests suggest that it is due to changes in the building stiffness, rather than soil swelling

Long Distance Studies

J. Favela, 2004
Long Distance Studies

Finite element modeling of the Pasadena area -- excitation from our forced vibration tests

Radiation damping about 1/3%
There are probably complex modes that involve both the building and the soil
Historical Behavior of Millikan Library

Fundamental EW and NS modes of Millikan Library since construction.

Crosses indicate frequencies from forced vibration tests.

Circles indicate natural frequency estimates from recorded earthquake events, and numbers in italics are peak roof accelerations from the event (cm/s²).

Dashed lines represent the observed natural frequencies of the library, and the shaded region is the likely variance from such factors as weather conditions, weight configuration of the shaker used for forced vibration tests, and experimental error.

1994 M 6.7 Northridge earthquake on E-W for Millikan Library
One Week of Data

A spectrogram of MIK (EW component) consisting of one week of data, with a running FFT of one hour. The vertical stripes in the spectrogram are quiet periods, the AC system turns off nightly from Midnight-4AM.
Dynamic Properties of Millikan Library vary on different timescales:

- Days
- Weeks
- Years

Clinton, 2004
Santa Ana Windstorms

Big Bear Earthquake  
M5.4  Δ=119  22Feb2003

Forced Vibration Testing

![Graph showing frequency domain amplitude over time and frequency.](image-url)
Santa Ana Windstorms

Big Bear Earthquake
M5.4  Δ=119  22Feb2003

Forced Vibration Testing
Weather Conditions

Exmaining data from extreme weather events, we can see that both strong winds and heavy rains can affect the dynamic behavior of the library.

Heavy winds have been observed to temporarily decrease all fundamental frequencies by 2-4%. The building recovers immediately after the wind event.

Rainfall causes an increase in the EW and Torsional fundamental frequencies of 3-5%, the NS mode is less strongly affected by rain. Rain effects persist for 1-2 weeks, gradually reverting to pre-rain levels.
Building stiffness vs. time

Imperial County Services Center

Wigner-Ville
Time/frequency
From Casey Bradford
Time→
Wigner-Ville
Time/frequency
From Casey Bradford

1994 M 6.7
Northridge Earthquake
John Hall’s design of a 20-story steel MRF building

• Building U20
  1994 UBC zone 4
  Stiff soil, 3.5 sec. period

• Building J20
  1992 Japan code
  3.05 sec period

• Both designs consider
  Perfect welds
  Brittle welds
Pushover Analysis

- Special attention to P-delta instability
- Story mechanism collapse
- Frame 2-D fiber-element code of Hall (1997)
10% probability
Background: UCLA Factor Building

- UCLA Factor Building
  - 17-story, moment-resisting steel-frame structure
  - Embedded 72-channel accelerometer array
  - N-S modal frequencies: 0.59 Hz, 1.8 Hz, 3.1 Hz
  - E-W modal frequencies: 0.55 Hz, 1.6 Hz, 2.8 Hz
- Experimental data and numerical model (ETABS)

Kohler, M. Heaton, T., Bradford, C. 2007. BSSA.
Background: UCLA Factor Building

- Impulse Response Function
  - Deconvolution is used to extract the transfer function
  - Bandpass filtered between 0.5 Hz and 10 Hz
  - Stack over small EQs to stay in linear response
- Shear beam: waves travel nondispersively throughout the lower floors of the building \((v = \sim 160 \text{ m/sec})\)
- For bending beams, the waves would disperse with the wave velocity increasing as the square root of the frequency

Kohler, M., Heaton, T., Bradford, C. 2007. BSSA.
Laboratory Example: Uniform Shear Beam

- Experimental Setup
  - Five-story uniform shear model
  - Piezoelectric accelerometers, DAQ
  - Force transducer hammer
  - Shake table, signal generator
  - Damaged/undamaged configuration
Laboratory Example: Uniform Shear Beam

- Consider the structure modeled by a multi-degree-of-freedom system
  \[ M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = f(t) \]

- Compute constants m, k from mass, geometry, and material properties
  - m: Mass of each floor
  - k: Stiffness due to bending plate (column)

- Determine the mode shapes and frequencies of the system from the eigenvalues and eigenvectors of \( M^{-1}K \)

- Damping is found experimentally
  - 1\textsuperscript{st} mode: logarithmic decrement method
  - Higher modes: half-power bandwidth method
  - Neglected: \( \zeta_n < 0.005, n = 1, \ldots, 5 \)

Kohler, M., CE 181 Class Notes, 2010.
Mode Shapes, Frequencies, and Wave Propagation

- Calculated vs. Observed: Good agreement
- Damage: Introduced at the 4th floor
- Damaged vs. Undamaged
  - Significant decrease in frequencies
  - Changes in mode shapes
  - Changes in wave propagation

<table>
<thead>
<tr>
<th></th>
<th>Calculated</th>
<th>Observed</th>
<th>Damaged</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_1$</td>
<td>3.2</td>
<td>3.3</td>
<td>2.6</td>
</tr>
<tr>
<td>$\omega_2$</td>
<td>9.5</td>
<td>9.6</td>
<td>6.2</td>
</tr>
<tr>
<td>$\omega_3$</td>
<td>14.9</td>
<td>15.2</td>
<td>10.8</td>
</tr>
<tr>
<td>$\omega_4$</td>
<td>19.2</td>
<td>20.0</td>
<td>14.6</td>
</tr>
<tr>
<td>$\omega_5$</td>
<td>21.9</td>
<td>22.4</td>
<td>21.2</td>
</tr>
</tbody>
</table>
Using High-Frequency Seismograms to Detect Structural Damage in Instrumented Civil Structures

Vanessa Heckman
Monica Kohler
Tom Heaton
Purpose:
- Detect damage in an instrumented structure using high-frequency seismograms

Method:
- Before an earthquake, identify locations in a structure that have a relatively high probability of failure (e.g. welded BC connections in steel MRFs)
- Assemble a database of expected building response to failure
  - Apply a force impulse (hammer blow) at each location
  - For a true impulse, the recorded responses are the Green’s functions (GFs) of the structural system
- Data recorded by the structure’s seismic array during an earthquake is screened continuously for the presence of one or more failure events
  - Cross-correlate our pre-existing database of building responses with the seismic data
  - If damage occurred at one of the identified locations, there will be a high cross-correlation value

Purpose of the numerical study: Test the feasibility of our method
A Time-Reversed Reciprocal Method: Setup

- **Numerical Model: 3D Steel Frame**
  - Linear elastic material
  - **Impulsive force load along the +x-axis**
  - Fine Discretization
    - $c_{\text{long}} = 5.1$ km/s
    - Hex 8 mesh element ($dx = 2.5$ cm)
    - Time step $dt = 2 \mu$s
- **Receivers at six locations**
  - Located at the central X-section

### Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>7850 kg/m$^3$</td>
</tr>
<tr>
<td>$c_{p\text{-wave}}$</td>
<td>5.6 km/s</td>
</tr>
<tr>
<td>$c_{s\text{-wave}}$</td>
<td>3.2 km/s</td>
</tr>
<tr>
<td>$c_{\text{long}}$</td>
<td>5.1 km/s</td>
</tr>
</tbody>
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Material Properties
  - $\rho = 7850$ kg/m$^3$
  - $c_{p\text{-wave}} = 5.6$ km/s
  - $c_{s\text{-wave}} = 3.2$ km/s
  - $c_{\text{long}} = 5.1$ km/s

Force Time-History

- Time $t = 0$ to $250\ \mu$s
A Time-Reversed Reciprocal Method: Setup

- Numerical Model: 3D Steel Frame
  - Linear elastic material
  - Impulsive force load along the +x-axis
  - Fine Discretization
    - $c_{\text{long}} = 5.1$ km/s
    - Hex 8 mesh element ($dx = 2.5$ cm)
    - Time step $dt = 2$ μs
- Receivers at six locations
  - Located at the central X-section
A Time-Reversed Reciprocal Method: Forward

**Force Impulse**

*Color Scale:* Displacement in X  
*Time:* Slowed down by a factor of 20k

**Displacement Records**

- **R₂:** closest receiver to source
A Time-Reversed Reciprocal Method: Forward

- Reverse each of the displacement records in time
- Interchange the receiver and source locations
- Rerun the simulation prescribing Dirichlet boundary conditions at the six new source locations

Recorded Displacement

<table>
<thead>
<tr>
<th>R1</th>
<th>S1</th>
</tr>
</thead>
<tbody>
<tr>
<td>R2</td>
<td>S2</td>
</tr>
<tr>
<td>R3</td>
<td>S3</td>
</tr>
<tr>
<td>R4</td>
<td>S4</td>
</tr>
<tr>
<td>R5</td>
<td>S5</td>
</tr>
<tr>
<td>R6</td>
<td>S6</td>
</tr>
</tbody>
</table>

Time (ms)
A Time-Reversed Reciprocal Method: Forward

- Reverse each of the displacement records in time
- **Interchange the receiver and source locations**
- Rerun the simulation prescribing Dirichlet boundary conditions at the six new source locations
A Time-Reversed Reciprocal Method: Forward

- Reverse each of the displacement records in time
- Interchange the receiver and source locations
- Rerun the simulation prescribing Dirichlet boundary conditions at the six new source locations
A Time-Reversed Reciprocal Method: Forward

- Take each of the displacement records and reverse it in time
- Interchange the receiver and source locations
- Rerun the simulation prescribing Dirichlet boundary conditions at the six new source locations

Can displacement records be used to determine where the original force was applied?
A Time-Reversed Reciprocal Method: Reverse

**Dirichlet BC**

**Color Scale:** Displacement in X

**Time:** Slowed down by a factor of 20k

**Plate:** original “force plane”
Displacement records can be used to determine the location and application time of an applied force in a linear elastic structure.

**Dirichlet BC**

- **Color Scale:** Displacement in X
- **Time:** Slowed down by a factor of 20k
- **Plate:** original “force plane”
Displacement records can be used to determine the location and application time of an applied force in a linear elastic structure\cite{1,2}. 

**Weakness:**

**Need dense active network**
Use of Impact Test to Characterize Damage

Seismic Interferometry – Time-Reversed Reciprocal – Impact Test (Numerical)
Comparison of Dynamic Response: Numerical Setup

**Unnotched Frame**
Ricker wavelet force applied along +x axis at top left BC connection

**Notched Frame**
Error function force applied to open notch at top left BC connection
Comparison of Dynamic Response: Numerical Setup

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Comparison of Dynamic Response: Numerical Setup

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Ricker wavelet force applied along +x axis at top left BC connection

**Notched Frame**
Error function force applied to open notch at top left BC connection

- $F_1(t)$
- $F_2(t)$
Comparison of Dynamic Response

**Unnotched Frame**
Ricker wavelet force applied along +x axis at top left BC connection

**Notched Frame**
Error function force applied to open notch at top left BC connection

Displacement warped by a factor of: 1e7
Time: Slowed down by a factor of 10k
**Comparison of Dynamic Response**

**Displacement**

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>y</th>
<th>mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>R₁</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>R₂</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R₄</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Velocity**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>R₁</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R₄</td>
<td></td>
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<td></td>
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</table>

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**Unnotched Frame / Ricker Wavelet Force**

**Notched Frame / Error Function Force**

- Differs significantly due to the static offset across the notch
- Early arrival times generally coincide. Due to polarity differences, velocity magnitude is a better approximation.
A stacked cross-correlation method is used to determine the similarity of velocity waveforms generated by a force impulse at one source location and a tensile crack at another source location.

- The envelopes of the velocities are used.
- Results are stacked/summed over all four receivers.

- Cross-correlation values are highest when the location of the tensile crack and force impulse are the same.

<table>
<thead>
<tr>
<th>Tensile Crack Source Location</th>
<th>S₁</th>
<th>S₂</th>
<th>S₃</th>
<th>S₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁</td>
<td>0.92</td>
<td>0.78</td>
<td>0.79</td>
<td>0.84</td>
</tr>
<tr>
<td>S₂</td>
<td>0.78</td>
<td>0.92</td>
<td>0.84</td>
<td>0.79</td>
</tr>
<tr>
<td>S₃</td>
<td>0.77</td>
<td>0.78</td>
<td>0.91</td>
<td>0.81</td>
</tr>
<tr>
<td>S₄</td>
<td>0.88</td>
<td>0.77</td>
<td>0.81</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Concluding Remarks

- There is potentially great value to high-dynamic continuous seismic data from buildings
- Regional seismic arrays and building monitoring networks should be merged
Cross-Correlation is used to indicate similarity between two structural responses.

**Response** of the structure for two different trials:

\[
x = \{x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8\} = \{x_n(t)\}, n = 1, \ldots, 8
\]

\[
y = \{y_1, y_2, y_3, y_4, y_5, y_6, y_7, y_8\} = \{y_n(t)\}, n = 1, \ldots, 8
\]

**Waveform cross-correlation**

\[
C(x_n, y_n)(t) = \frac{\int_0^T x_n(\tau)y_n(t+\tau)\,d\tau}{A(x_n, y_n)(t)}
\]

**Autocorrelation normalization**

\[
A(x_n, y_n)(t) = \sqrt{\int_0^T (x_n(\tau))^2 \,d\tau} \int_0^T (y_n(t+\tau))^2 \,d\tau
\]

**Stacked cross-correlation** over the total number of receivers, and **record the peak value** (over time) into a table:

\[
C(x, y)(t) = \sum_{n=1}^{8} C(x_n, y_n)(t)
\]
Use of Impact Test to Characterize Damage

Seismic Interferometry – Time-Reversed Reciprocal – Impact Test (Experimental)
Description of Proposed Method

• **Purpose:**
  • Detect damage in an instrumented structure using high-frequency seismograms

• **Method:**
  • Before an earthquake, identify locations in a structure that have a relatively high probability of failure (e.g. welded BC connections in steel MRFs)
  • Assemble a database of expected building response to failure
    • Apply a force impulse (hammer blow) at each location
    • For a true impulse, the recorded responses are the Green's functions (GFs) of the structural system
  • Data recorded by the structure’s seismic array during an earthquake is screened continuously for the presence of one or more failure events
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• **Purpose of the numerical study:** Test the feasibility of our method
**Cross-Correlation** is used to indicate similarity between two structural responses.

**Response** of the structure for two different trials

\[
\begin{align*}
x &= \{x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8\} = \{x_n(t)\}, n = 1, \ldots, 8 \\
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**Stacked cross-correlation** over the total number of receivers, and **record the peak value** (over time) into a table

\[
C(x, y)(t) = \sum_{n=1}^{8} C(x_n, y_n)(t)
\]
Experimental Setup

- Small-scale steel frame
- Eight low mass high sensitivity accelerometers
- Sample frequency: 100kHz
- Record duration: 2.0 seconds
- Force transducer hammer, bolt failure

![Experimental Setup Diagram]

- Receiver Location (Accelerometers) \( R_1 - R_8 \)
- Source Location (Hammer Blow and Bolt Fracture) \( S_1 - S_8 \)
### Experimental Method

<table>
<thead>
<tr>
<th>Source Mechanism</th>
<th>Green’s Functions</th>
<th>Response to Bolt Failure</th>
<th>Response of Damaged Frame to Hammer Blow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammer Blow ((S_1-S_8))</td>
<td>Bolt Fracture ((S_1, S_3, S_5, S_7))</td>
<td>Hammer Blow ((S_1-S_8))</td>
<td></td>
</tr>
<tr>
<td>Undamaged</td>
<td>Undamaged -&gt; Damaged ((S_1, S_3, S_5, S_7))</td>
<td>Damaged ((S_1, S_3, S_5, S_7))</td>
<td></td>
</tr>
</tbody>
</table>
## Experimental Method

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<td></td>
<td>Bolt Fracture</td>
<td>Hammer Blow</td>
</tr>
<tr>
<td>(S₁-S₈)</td>
<td></td>
<td>(S₁, S₃, S₅, S₇)</td>
<td>(S₁-S₈)</td>
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<td>Damaged (S₁, S₃, S₅, S₇)</td>
<td></td>
</tr>
</tbody>
</table>

**Structural State**

- **Undamaged**: All bolts are intact.
- **Damaged**: One or more bolts are fractured.

**Diagram**

- The frame is 1.1m in height and 0.8m in width.
- Locations of sensors: S₁, S₂, S₃, S₄, S₅, S₆, S₇, S₈.
## Experimental Method

<table>
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<th>Green’s Functions</th>
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<th>Response of Damaged Frame to Hammer Blow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammer Blow</td>
<td>Undamaged</td>
<td>Bolt Fracture (S1, S3, S5, S7)</td>
<td>Hammer Blow (S1-S8)</td>
</tr>
<tr>
<td>Structural State</td>
<td>Undamaged</td>
<td>Damaged (S1, S3, S5, S7)</td>
<td>Damaged (S1, S3, S5, S7)</td>
</tr>
</tbody>
</table>

### Source Mechanism
- Hammer Blow ($S_1$-$S_8$)
- Bolt Fracture ($S_1$, $S_3$, $S_5$, $S_7$)
- Hammer Blow ($S_1$-$S_8$)

### Structural State
- Undamaged
- Damaged ($S_1$, $S_3$, $S_5$, $S_7$)

### Diagram
- Diagram showing the structural state and bolt locations ($S_1$-$S_8$)
## Experimental Method

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<table>
<thead>
<tr>
<th>Structural State</th>
<th></th>
<th>Undamaged -&gt; Damaged ($S_1$, $S_3$, $S_5$, $S_7$)</th>
<th>Damaged ($S_1$, $S_3$, $S_5$, $S_7$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undamaged</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Diagram

- **Source Mechanism**: Hammer Blow ($S_1$-$S_8$)
- **Bolt Failure**: Bolt Fracture ($S_1$, $S_3$, $S_5$, $S_7$)
- **Hammer Blow**: Hammer Blow ($S_1$-$S_8$)
- **Structural State**: Undamaged
- **Damage**: Damaged ($S_1$, $S_3$, $S_5$, $S_7$)
Source Location and Type

Hammer Blow: **S3**

<table>
<thead>
<tr>
<th>Acceleration</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td></td>
</tr>
<tr>
<td>R3</td>
<td></td>
</tr>
<tr>
<td>R5</td>
<td></td>
</tr>
<tr>
<td>R7</td>
<td></td>
</tr>
</tbody>
</table>

Bolt Fracture: **S3**

<table>
<thead>
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<th>Time (s)</th>
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<tbody>
<tr>
<td>R1</td>
<td></td>
</tr>
<tr>
<td>R3</td>
<td></td>
</tr>
<tr>
<td>R5</td>
<td></td>
</tr>
<tr>
<td>R7</td>
<td></td>
</tr>
</tbody>
</table>
Sample Cross-Correlations

Source Locations of Hammer Blows

**S3 - S3**

- R1
- R3
- R5
- R7
- R1-R8 (stacked)

**S3 - S7**

- R1
- R3
- R5
- R7
- R1-R8 (stacked)

Peak Value: 0.87

Peak Value: 0.11
## Cross-Correlation Values

<table>
<thead>
<tr>
<th>Source Location</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
</tr>
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<td></td>
<td></td>
<td>0.85</td>
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</tr>
</tbody>
</table>

Much higher cross-correlation value along the diagonal for pair of identical source location.
Much higher cross-correlation value along the diagonal for pair of identical source location.
Blind tap test

A blind tap test is successfully performed using waveform cross-correlation:

1) Hammer blow applied at three unknown source locations.

2) Record is cross-correlated with each prerecorded Green’s function.

3) Peak cross-correlation values reveal the correct source locations.
- The GF that best approximates the structural response to bolt failure is the GF with the same source location as the damaged connection.
- Values along the diagonal are not high enough for robust damage detection. Other cross-correlation techniques will be explored.
- The GF that best approximates the structural response to bolt failure is the GF with the same source location as the damaged connection.
- Values along the diagonal are not high enough for robust damage detection. Other cross-correlation techniques will be explored.
Cross-correlation values are much lower when the frame is damaged vs. when the frame is undamaged (bottom row). Moreover, the cross-correlation value is smallest when the hammer blow is applied to the damaged connection.
Cross-correlation values are much lower when the frame is damaged vs. when the frame is undamaged (bottom row). Moreover, the cross-correlation value is smallest when the hammer blow is applied to the damaged connection.
Conclusions: Impact Test

• The velocity (magnitude) record from a force impulse can be used to approximate the velocity (magnitude) record from a tensile crack at the same location.

• Cross-correlation techniques can be used to determine the location/time of damage.

• A blind tap test was successfully performed experimentally using waveform cross-correlation with stacking.

• A mixed approach that analyzes building response both during and after an earthquake could have advantage over one or the other.
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• Rob Clayton, Professor of Geophysics, Caltech

• Hartley Fellowship
• Housner Fund
THANK YOU!

Questions?
Seismic Interferometry

- Seismic interferometry may aid in damage detection by comparing post-event waveforms with pre-event waveforms
  - Changes in wave speed
  - Floor-to-floor reflections
- Forward modeling using a numerical model (ETABS) will be used to test the application to civil structures

Kohler, M., Heaton, T., Bradford, C. 2007. BSSA.
Hayashi, Y., Sugino, M., Yamada, M., Takiyama, N., Onisha, Y. 2012. STESSA