# Full-Scale Shaker Tests of a Non-Ductile Reinforced Concrete Frame Retrofitted with SMA Braces

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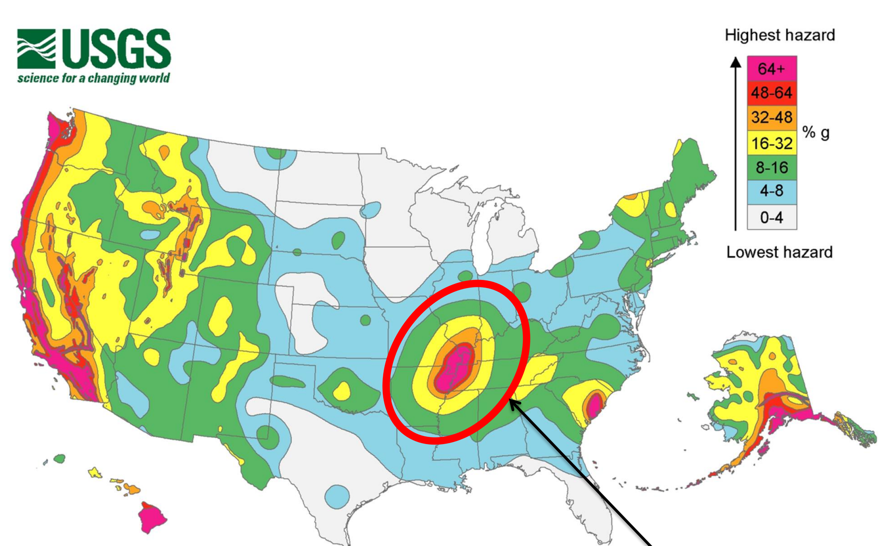
## OVERVIEW

- Non-ductile reinforced concrete (RC) frames present safety and economic problems in areas of moderate seismicity
- Driven by the shift from life-safety to performance based design metrics, this study aims to validate an innovative SMA retrofit scheme that is practical in design and installation, passive in nature, requires minimal maintenance, and can reduce residual deformations following a seismic event
- The results from this study indicate that the proposed SMA device can efficiently enhance the seismic performance of non-ductile RC frame buildings

## BACKGROUND

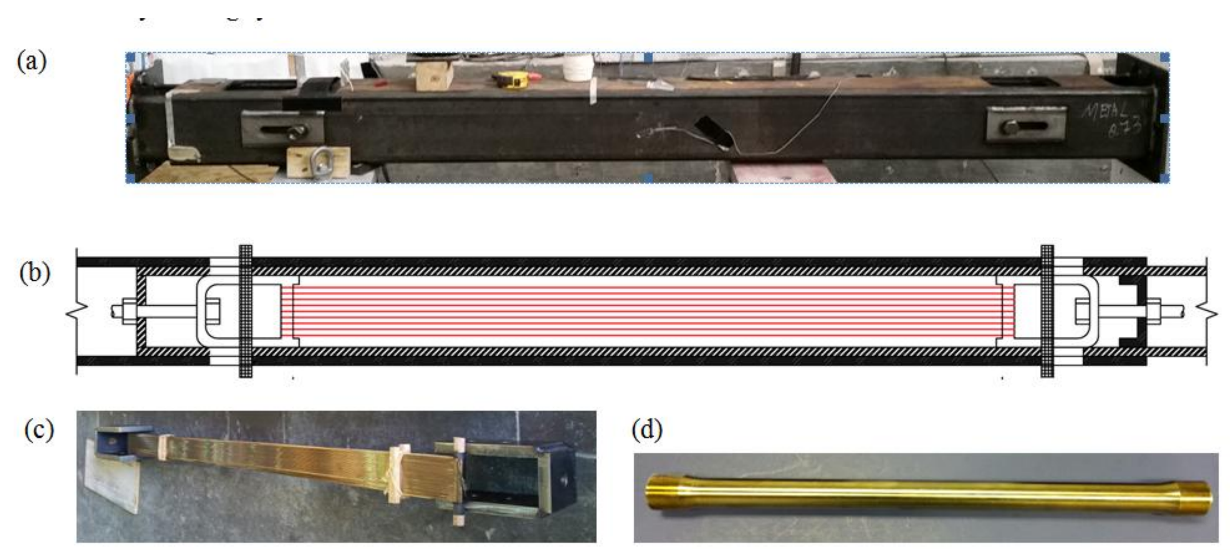



A 7.7 $M_w$ earthquake in the New Madrid Seismic Zone could result in approximately $300 billion in economic losses and nearly 86,000 human injuries and fatalities (Mid-America Earthquake Center)
(Diagram: http://earthquake.usgs.gov/hazards/products/)

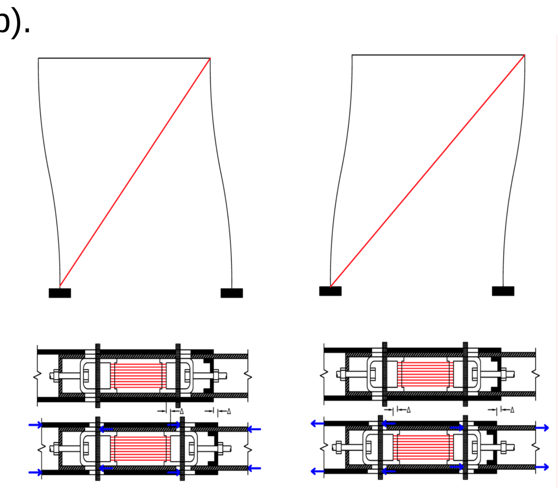
Georgia Tech test structure, designed using the 1963 ACI-318. Design parameters and details did not consider seismic loading, which is typical of older RC construction in the central and eastern US.

## INDIVIDUAL BRACE TESTS & RC FRAME SHAKER TESTS

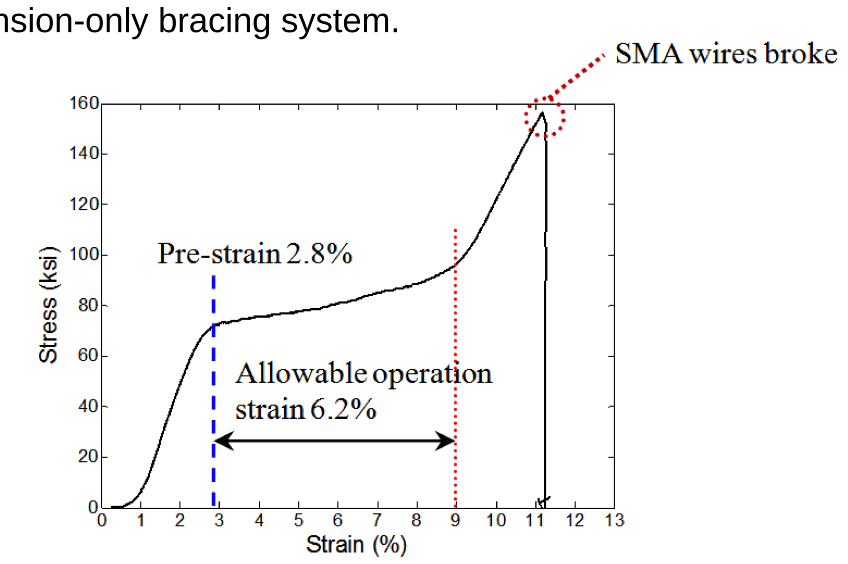
### SMA BRACE DESIGN & ASSEMBLY




The brace device (a) consisted of an SMA component –wires (c) or rods (d)– housed inside two A500 steel hollow structural section (HSS) tubes, as seen in the section drawing (b).



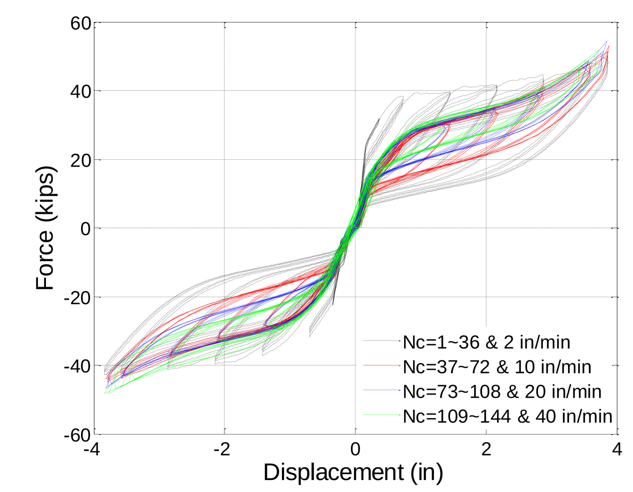
The braces were designed and assembled such that the SMA component remained in tension while the two HSS tubes were pulled apart (brace in tension) or pushed together (brace in compression). This allowed for the use of slender SMA sections, which reduces the required amount of SMA material, relative to a tension-only bracing system.



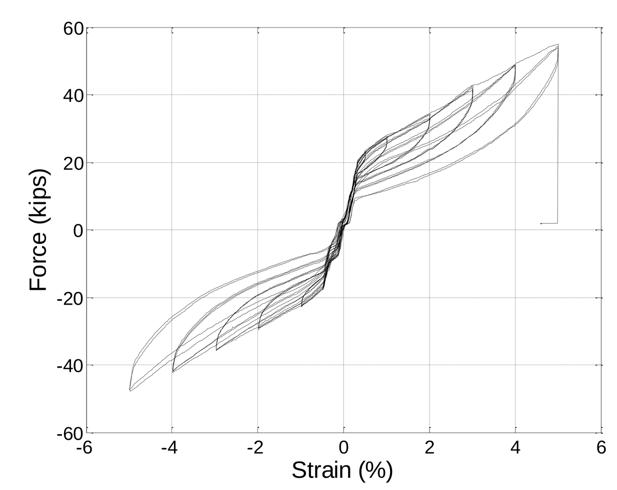

The stress vs. strain relationship of SMA wires under preliminary individual tension tests is shown above. The wires reached the forward transformation yield stress at 2.5% strain, entered the second strain hardening transformation at 9.0% strain, and eventually broke at 11.2% strain.

The post-tensioning was performed by jacking Dywidag bars with a hydraulic hollow cylinder piston. The Dywidag bars were temporarily anchored to the SMA holding piece. After the required pre-strain was reached, a high-strength pin was inserted into the slots on the sides of the two HSS tubes. These pins served as the load transfer between the SMA component and the steel tubes. The slots were cut to a 4" length to allow relative displacement of the tubes. This 4" displacement corresponds to a 5.6% SMA strain, conservatively under the assumed allowable operation strain, 6.2%, shown above.

### INDIVIDUAL BRACE TESTS

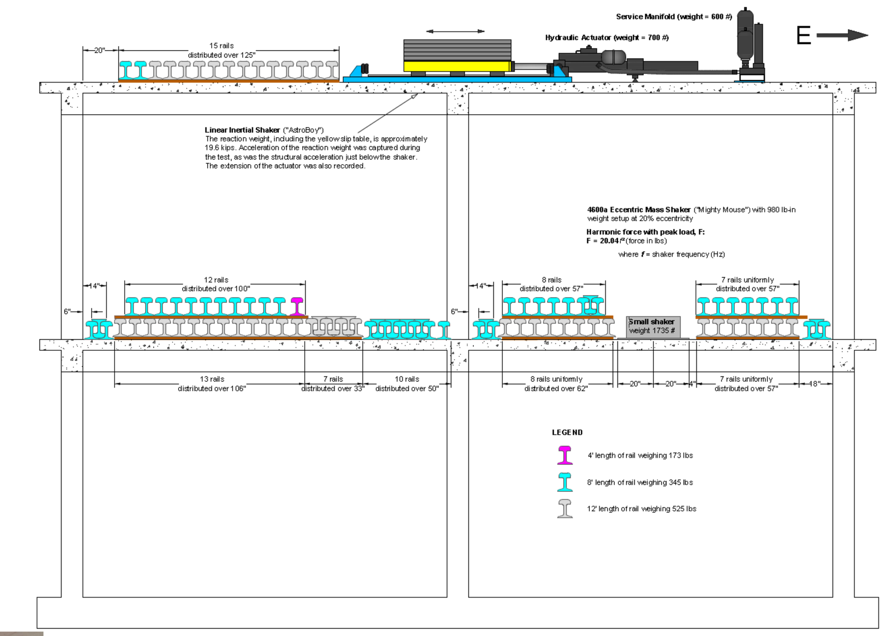



The SMA wire based brace was tested quasi-statically and with faster loading rates. Generally, the brace was able to deliver a certain extent of hysteretic damping ability with almost full recentering. In the first 36 loading cycles (Nc=1~36), the forward and reverse transformation yield strengths of the brace are approximately 38 and 8 kips, respectively. When the number of loading cycles increases up to 72, the forward transformation yield strength significantly decreases to approximately 30 kips; however, the reverse transformation yield strength slightly increases up to approximately 12 kips, resulting in degradation in the hysteretic loop area, that is, the loss of the equivalent viscous damping capacity. In the following cyclic loading (Nc=73~108 and 109~144), the forward transformation yield strength remains approximately 30 kips; however, the reverse transformation yield strength increases up to approximately 18 kips, indicating the consecutive degradation in the damping capacity and the continuous increase in the re-centering capacity.



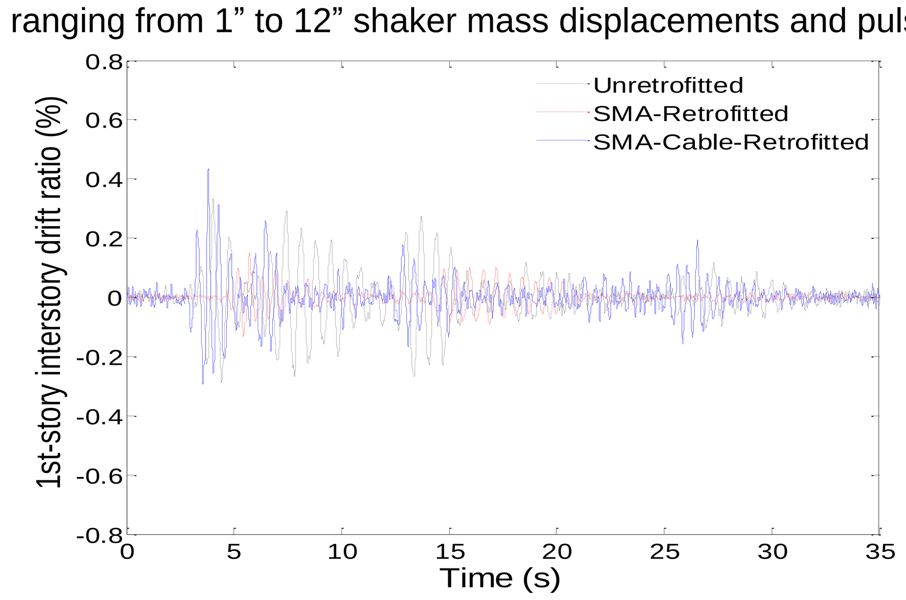

The SMA rod based brace was tested only quasi-statically (2 in/min). A series of subsequent tests were planned, but the SMA rod fractured during the 3rd cycle at the 5.00 % strain level. In contrast to the SMA wire based brace, the forward transformation yield strength is approximately 22 kips, which is much smaller than 38 kips from the SMA wire based brace. The reverse transformation yield strengths for the two types of SMA braces are similar, 8~10 kips. The strain hardening in the SMA rod based brace is much more significant than that in the SMA wire based brace, with the strength increasing from 22 kips to 52 kips during 0.40% strain and 5.00% strain. The maximum residual deformation is approximately 0.20%.

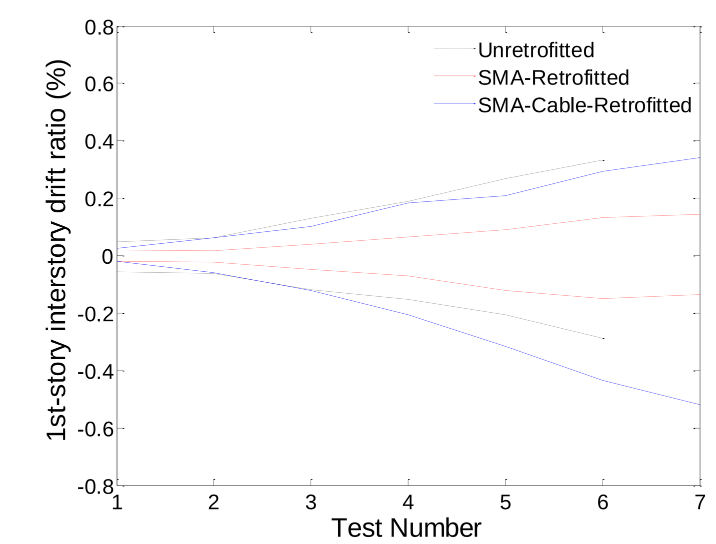
### SHAKER TESTS



| Test Number | Shaker Vibration Type |
|---|---|
| 1 | El Centro scaled to 1" |
| 2 | El Centro scaled to 2" |
| 3 | El Centro scaled to 4" |
| 4 | El Centro scaled to 6" |
| 5 | El Centro scaled to 8" |
| 6 | El Centro scaled to 10" |
| 7 | El Centro scaled to 12" |
| 8 | Pulse 4" |
| 9 | Pulse 8" |
| 10 | Pulse 12" |
| 11 | Double Pulses 16" |
| 12 | Double Pulses 20" |
| 13 | Double Pulses 26" |

Responses of the SMA braced frame and the unretrofitted frame to the shaker excitation were investigated by analyzing floor displacement data. Input excitations included an El Centro ground motion record with amplitudes ranging from 1" to 12" shaker mass displacements and pulses ranging from 4" to 26".




Time histories of interstory drift ratios for all frames under the 10" amplitude El Centro (Test 6) are shown in the left figure. The first-story drift ratio for the SMA braced frame was 0.15%, which was less than 0.33% for the unretrofitted frame. The smaller interstory drift ratio in the first story of the SMA braced frame indicates that the braces effectively suppressed the first story vibration. For all amplitudes of El Centro vibration, the SMA braces successfully limited the first-story drift ratio to less than 0.20%, as shown in the drift envelopes on right figure.

## CONCLUSIONS

- SMA wire based braces were successfully installed in the non-ductile RC frame and used to effectively suppress the story vibrations and recenter the frame upon removal of the external loads.
- Both SMA wires and rods can be applied into braces without breaking as long as the design appropriately limits the peak SMA strain demand to the permissible strain range.
- The brace end connection linked the brace to steel members anchored to a concrete member. It was designed according to the AISC seismic provisions and ACI 'anchoring to concrete' specifications. The connection successfully transferred forces without damage to the steel or concrete members.

## FOR MORE INFORMATION

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