NONDESTRUCTIVE MONITORING OF SUBSURFACE DAMAGE PROGRESSION IN CONCRETE COLUMNS DAMAGED BY EARTHQUAKE LOADING

Katelyn Freeseaman, Lev Khazanovich, Kyle Hoegh, Alireza Nojavan, Arturo Schultz, Shih-Ho Chao

Katelyn Freese
(Corresponding Author)
University of Minnesota
500 Pillsbury Drive SE
Minneapolis, MN 55455
weile068@umn.edu

Lev Khazanovich
University of Minnesota
500 Pillsbury Drive SE
Minneapolis, MN 55455
Khaza001@umn.edu

Kyle Hoegh
University of Minnesota
500 Pillsbury Drive SE
Minneapolis, MN 55455
hoeg0021@umn.edu

Alireza Nojavan
University of Minnesota
500 Pillsbury Drive SE
Minneapolis, MN 55455
nojav002@umn.edu

Arturo E. Schultz
University of Minnesota
500 Pillsbury Drive SE
Minneapolis, MN 55455
schul088@umn.edu

Shih-Ho Chao
University of Texas, Arlington
425 Nedderman Hall, 416 Yates
Arlington, TX 76019
shchao@uta.edu

ABSTRACT

The assessment of the structural integrity of infrastructure after extreme events is an important application of nondestructive technology. Advancements in elastic wave-based methods in recent years have allowed for productive and accurate quantitative analysis which was previously lacking. In this study, ultrasonic array measurements coupled with a modified signature analysis method were implemented for damage detection purposes. Full-scale testing of a reinforced concrete column subjected to simulated earthquake loading was tested using ultrasound nondestructive testing at various stages of loading. A signature analysis technique was adapted to create improved reconstructions and was coupled with a quantitative analysis incorporating Pearson's correlation coefficient. The results demonstrated the ability to detect internal damages and defects prior to appearance on the surface using one-sided access, showing promise for health monitoring applications.

Keywords: Nondestructive testing; ultrasound; reinforced concrete; column; earthquake loading; health monitoring; one-sided access

1. INTRODUCTION

The scale of damage caused by earthquakes has been well documented and portrayed in the media in recent history. While earthquakes can cause severe damage to buildings, there are also cases where there may be no visible damage but the structure has been weakened as a result of the earthquake. Identifying both visible and nonvisible signs of earthquake damage is extremely important in the aftermath of a quake in order to categorize the condition and serviceability of remaining infrastructure. This scenario creates the need for nondestructive

1 evaluation in order to assess the safety and remaining structural capacity. Specifically,
2 reinforced concrete (RC) systems create added complexity due to their heterogeneous nature.
3 Extensive research has been done in the past regarding the response of RC structures to
4 earthquake loading [e.g., 1-4], which shows that damage in concrete structures may occur
5 even under small drifts. Effective repair methods for damaged RC structural members have
6 been developed, as verified by recent RC bridge columns tested using ground motion similar
7 to that of the 1994 Northridge earthquake [5]. However, for proper implementation of repair
8 techniques, it is critical for damage to first be accurately identified, preferably by a
9 nondestructive method.

10
11 Often, structural evaluation can only be conducted using nondestructive techniques that
12 require access to only one side of the structure. Donnelly [6] outlined the accuracy of many
13 nondestructive techniques via the analysis of bridge decks, of which infrared thermography
14 (IT) and impact echo (IE) proved to be the most successful. IT is able to identify less than
15 half of the delaminations present and is highly affected by the depth of the delamination. IE is
16 a common nondestructive testing method that involves generation of compression, shear, and
17 Rayleigh waves using a mechanical impact at the surface. The waves reflected from internal
18 changes in acoustic impedance or external boundaries are recorded on the surface, where the
19 impact was generated to give information about the structure using signal interpretation
20 techniques normally based on spectral analysis. IE has been shown to be effective in
21 detecting layer interfaces for applications such as thickness determination and inclusion
22 detection. However, testing with this method can be time-intensive and only allows for one
23 signal pair to be sent and received per scan. This lack of signal redundancy associated with a
24 single impact signal causes difficulties when complex geometries are present due to the
25 requirements of the spectral analysis method. [7]. In addition, IE is able to detect top and

bottom delaminations, but is not able to detect all cases of damage and in some instances results in false positives. When applied to concrete slabs, IE also proves to be sensitive to the overall dimension and thickness of the slab [8].

Shear wave based ultrasound methods have also been tested for crack detection in uniform concrete elements [9]. This research also identified the effect of rebar, aggregates, or damaged concrete as a complicating factor that needs to be addressed. Shubert and Kohler also found that the presence of aggregate and air voids creates scattering and attenuation of ultrasound signals [10]. Additionally, one-sided nondestructive ultrasound techniques have had difficulty in detecting damage behind dense reinforcement in concrete structures [11].

These methods are able to detect some cases of damage, but the limitations of their applicability highlight the need for a more quantitative nondestructive testing method, especially for thick reinforced concrete elements with one-sided access. To this end, evaluation techniques and hardware such as air coupled impact echo have multiple measurement pairs and allow for more productive measurement acquisition [12]. Highly productive and repeatable measurements are needed to ensure measurement accuracy. To attain this reliability, dry point contact transducers have also been utilized. Dry point contact transducers allow for diagnostics up to 36 in. (914 mm) deep. This device uses low frequency (~50 kHz) stress waves to assess various types of structural systems, including reinforced concrete members [11].

While this high productivity allows for more reliable measurements, the analysis methods involved often require qualitative interpretation. To provide quantitative interpretation, Impact Echo Signature Analysis (IESA) has been proposed. IESA compares one-dimensional (1D) impact-echo signals with a reference signal in either the time or frequency domain. For

time domain analysis, Pearson's correlation equation has been used for comparison of 1D impact-echo signals and is shown in Equation (1) [13]:

$$C_{XY}^j = \frac{Cov[X, Y^j]}{\sqrt{Var[X]Var[Y^j]}} = \frac{\sum_{i=1}^N (x_i - x_{mean})(y_i^j - y_{mean}^j)}{\sqrt{\sum_{i=1}^N (x_i - x_{mean})^2 \sum_{i=1}^N (y_i^j - y_{mean}^j)^2}} \quad (1)$$

Where j is the j -th signal, i is the i -th value within a signal, X and Y^j are the intensity amplitude vectors of the reference and j -th IE scans, respectively; Cov and Var stand for the covariance and variance; x_i is the i -th intensity value within the reference signal and y_i is the i -th intensity value within the current signal, respectively; x_{mean} and y_{mean}^j are the mean intensity of the reference signal and current signal, respectively; N is the number of intensity values in each signal being compared; and C_{XY}^j is Pearson's correlation coefficient, which measures the strength of the linear dependence between IE intensity measurements X and Y^j . Thus, no correlation would result in a C_{XY}^j value of 0, while a linear relationship between signals would have a C_{XY}^j value of 1.0. This quantification of similarity via referencing a signal representative of a "damage-free" position allows for qualitative analysis. The implementation of array technology further improves the nondestructive testing previously outlined by incorporating redundancy and measurement accuracy [14].

The IESA method was generalized for two-dimensional reconstructions to allow for use with ultrasonic linear array technology. The resulting two-dimensional ultrasound tomography signature analysis (2D-UTSA) method has been applied for identification of plain concrete degradation under the surface [15].

This paper presents a modification of the 2D-UTSA method in order to monitor damage progression of a heavily reinforced concrete member and applied for evaluation of full-scale

reinforced concrete moment frame columns that were tested by extreme earthquake loading protocols. These tests are part of a research project sponsored by George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) of the National Science Foundation (NSF). Details of this experimental investigation have been reported by Nojavan et al. [16]

Preliminary findings on the nondestructive evaluation of a reinforced concrete column are presented. In collaboration with the University of Texas at Arlington, columns were tested at the University of Minnesota's Multi-Axial Subassemblage Testing (MAST) Laboratory under simulated earthquake loading. This provided an opportunity to gain insight on the internal behavior of the system before external damage was present through nondestructive evaluation.

2. EXPERIMENTAL INVESTIGATION

Full-scale reinforced concrete (RC) columns were constructed and tested under distinct earthquake loading protocols. These specimens were cast at the University of Texas at Arlington and tested at the Multi-Axial Sub-assemblage Testing (MAST) lab at the University of Minnesota. The columns are representative of a portion of a column bent in double-curvature at the ground floor of a 20-story modern high-rise moment frame building. The specimens had a clear height of 106 in. (2693 mm) between the footing (bottom) and the loading (top) blocks, and were designed in accordance with Chapter 21 of ACI 318-11 [17]. A Perimeter-Frame (PF) column was utilized for the nondestructive ultrasonic array testing described in this paper and had (16) #9 longitudinal bars with a cross-sectional dimension of 36x28 in. (914x711 mm). The column represents a ground level column of a 20-story perimeter moment frame used in modern RC buildings with interior post-tensioned flat slab system. Longitudinal bars were tied with #5 hoops and ties placed at 5 in. (127 mm) spacing. **Figure 1** shows the reinforcement details and the dimensions of the columns.

Fig. 1 – Column specimen assembly and detailing.

2.1 Instrumentation and Loading

The specimens were instrumented to measure deflection, rotation, and strains. Linear variable differential transformers (LVDTs) were installed vertically on opposite faces of the specimen in order to measure curvature along the height of the column. Horizontal LVDTs were also used to measure horizontal deflections. String potentiometers were installed to measure transverse displacement and shear deformations. In addition, strain gages were used to measure longitudinal and transverse steel and concrete core strains at locations along the columns. The specimen was placed on top of a three-piece spacer block and connected to the MAST strong floor and the loading crosshead (**Figure 2**). The columns were then loaded to simulate earthquake activity via a drift history representative of multiple cycles of reversed motion with increasing amplitude. **Figure 3** shows the near-collapse loading protocol in terms of the column drift ratios, while **Figure 4** shows the lateral load vs. drift ratio hysteresis

loops where drift ratio is defined as the lateral displacement at the inflection point of the column (96 in. (2438mm) above the column base) divided by the distance from the column base to the inflection point (96 in., 2438 mm). Testing was truncated once the strength of the column was reduced to 20% of its maximum capacity, as determined by the reduction in peak lateral load resisted by the system in a given cycle. Further details regarding experimental program can be found elsewhere [16, 18].

Fig. 2 – Assembly of the specimen under the loading crosshead at the MAST Lab [16].

Fig. 3 – Near-collapse loading protocol in terms of column drift ratios (MIRA scans were conducted at the points shown after returning from the labelled peak drift locations).

Fig. 4 – (left) Lateral load vs. drift ratio response and (right) enlarged cycles of interest (MIRA scans were conducted at the points shown after returning from the labelled peak drift locations).

2.2 Nondestructive Testing

While the specimen was being tested for earthquake loading, scans were obtained incrementally using the ultrasonic tomography device MIRA [19]. MIRA incorporates 10 channels, with each channel composed of four transmitting and receiving transducers, as seen in **Figure 5**. This linear array allows for 45 time-of-flight measurements in less than three seconds. The change in acoustic impedance causes reflection of the waves traveling from one medium to another (i.e. from concrete to rebar or concrete to air). The recorded wave reflections at the surface from the transducers are processed using the Synthetic Aperture Focusing Technique (SAFT, discussed later) to yield a visual representation of the cross section that was measured. The results can then be analyzed to help gain insight into the inner structure [15, 20, 21]. For example, pavement applications have shown the device to be capable of detecting inclusions and internal flaws [15, 20, 22, 23].

Fig. 5- MIRA ultrasonic linear array device

In this study, ultrasonic array measurements were taken at three discrete times during testing in which the column was brought back to its neutral position (zero drift) for safety reasons. Measurements were taken prior to any loading, once zero drift was attained after loading resulting in 0.5% drift level, and after achieving 1% drift level. These drift levels were selected based upon the observed damage progression of previous rounds of testing. The loading corresponding to these locations was detailed in **Figures 3 and 4**, with purple dots designating when testing took place and red dots designating the point of maximum drift achieved prior to measurement acquisition. A total of 60 ultrasound readings were taken, organized in sets of 6 progressing from left to right with approximately 4 in. (102 mm) between sequential readings. This spacing resulted in 12 in. (305 mm) of overlap from scan to scan due to the 16 in. (406 mm) width of the testing device. **Figure 6** shows the state of the column when the 2nd set of measurements was taken, while **Figure 7** shows the condition of the column when the 3rd set of measurements was taken. As can be seen in the first set of images, there were no external signs of damage when the 2nd set of measurements was taken, but the 3rd set of measurements were taken when external damage was present.

Fig. 6 – Column condition for 2nd set of MIRA measurements (after 0.5% drift ratio was attained).

Fig. 7 – Column condition for 3rd set of MIRA measurements (after 1% drift ratio was attained).

3. ANALYTICAL INVESTIGATION

A signature quantitative analysis method was utilized to collect data at different damage levels. SAFT is an ultrasonic imaging technique that allows for back-propagating of a set of

impulse time-histories to achieve reconstructions with improved resolution. In addition, this technique allows for improvements in signal to noise by reducing the backscattering effects of the concrete material through the natural deconvolution characteristics of the algorithm [24]. The following Equation (2) allows for the formulation of reconstructed images at a point via integration.

$$\hat{\mathbf{o}}(x, z) = \int_{x'_{min}}^{x'_{max}} \alpha(x', x, z) s\left(x', \frac{2}{c} \sqrt{z^2 + (x - x')^2}\right) dx' \quad (2)$$

where $\alpha(x', x, z)$ is the apodization factor that is typically a function of the distance traveled, divergence of the wave propagation, and incident angle of reflecting interface at each reflection point location with respect to the emitted/received signal [25], x'_{min} and x'_{max} are the interval in which the signals are measured, c is the sound velocity, x and z are the horizontal and vertical positions in the region of interest (ROI), x' is the transducer location, and s is the received impulse.

3.1 Qualitative Analysis

SAFT reconstructions at pre-loading, after 0.5% drift ratio, and after 1% drift ratio are shown in **Figures 8 and 9**. **Figure 8** shows an example of readings that indicate little change in relative reflectivity, while **Figure 9** shows an example location that exhibits a large change in relative reflectivity. Lighter (white) areas correspond to areas of high reflectivity, indicating the presence of changes in acoustic impedance. For example, presence of reinforcement, flaws, or layer boundaries cause an increase in reflectivity. In this case, the lighter regions were roughly 2 in. (51 mm) deep and are representative of the #5 transverse bars. These figures show only the first 12 in. (305 mm) due to the limited accuracy at large depths of individual scans. In order to address this and other limitations, as well as utilize the overlapping scans that were captured during data collection, panoramic images were of interest.

Fig. 8 – MIRA reflectivity results for 1st measurement (left) and 2nd measurement (middle), and 3rd measurement (right) for a location with relatively low level of damage with loading.

Fig. 9 - MIRA reflectivity results for 1st measurement (left) and 2nd measurement (middle), and 3rd measurement (right) for a location with relatively high level of damage with loading.

Because there is limited coverage at the edges of individual scans due to the presence of fewer overlapping transducers, panoramic reconstructions allow for a more accurate and redundant form of analysis. This also mitigates the limited aperture effect, allowing for quantitative comparisons of relative reflectivity within a wider region of SAFT panoramic reconstructions [26]. Because the region of interest (the entire cross-section of the column) is larger than the individual SAFT reconstructions, multiple sets of reconstructions can be combined to add redundancy and create a large panoramic cross-section with high resolution.

To achieve this, individual scans are combined in a string formation in which each SAFT scan overlaps with the next to create an encompassing region of interest, or ROI_{PAN} . For those regions in which the SAFT scans overlap one another, the larger value is selected for the panoramic image.

To formulate these panoramic images, each SAFT scan, $\widehat{\mathbf{O}}_I^m$, where m is the index of the current SAFT scan and I denotes that it is an individual scan, is combined in the following manner to form the new ROI_{PAN} . The ROI_{PAN}^m has the same vertical dimension, z , as all of the individual SAFT scans, while the horizontal dimension spans from 0 to x_{PAN}^m . Each individual scan has a horizontal dimension of x_I^m . In this case, ROI_{PAN} has a width of 36 in. (914 mm) and a depth of 30 in. (762 mm), while individual SAFT scans had a width of only 16 in. (406 mm). SAFT scans are merged, with each individual SAFT scan starting a distance D from the global origin (0, 0). The SAFT scans, $\widehat{\mathbf{O}}_{x,z}^m$, are combined according to the following expression for all values of x and z :

$$\widehat{\mathbf{O}}_{PAN}^m(x, z) = \begin{cases} \widehat{\mathbf{O}}_{PAN}^{m-1}(x, z), & \text{if } x < D \\ \max\left(\widehat{\mathbf{O}}_{PAN}^{m-1}(x, z), \widehat{\mathbf{O}}_I^m(x, z)\right), & \text{if } D < x < x_{PAN}^{m-1} \\ \widehat{\mathbf{O}}_I^m(x, z), & \text{if } x > x_I^m \end{cases} \quad (3)$$

For each panoramic reconstruction in this study, six individual SAFT scans were merged, as shown in the schematic in **Figure 10**. The first SAFT scan covers surface areas A-D, the second scan covers areas B-E, and so on with the sixth SAFT scan covering the areas F-I.

Fig. 10- Schematic outlining the merging of 6 individual SAFT scans to create one panoramic reconstruction.

Figure 11 gives an illustrative example cross-section comparing the ultrasound panoramic reconstruction to the designed features along the width of the column at a height of 9 in. (229 mm) from the base. **Figure 11(a)** shows the example panoramic created using Equation (3) at that location. **Figure 11(b)** shows the corresponding designed cross-section. It can be observed that increases in reflectivity occur at the shallower reinforcement locations, as well as the depth of the column along the evaluated cross-section. Even though there is significant attenuation of the wavefront at 28 in. of depth, the change in acoustic impedance at the layer boundary from concrete to air is significant enough to show up in the reconstruction. This is only true if there is not significant enough damage to cause additional scattering of the wavefront. **Figure 11** shows the location of the #9 reinforcing bars, as well as the presence of

the backwall.

Fig. 11 – (a) Panoramic reconstructions for 1st measurement showing location of reinforcement and back wall presence, and (b) corresponding design schematic.

A series of panoramic reconstructions can be seen in **Figure 12**. This figure shows the scans for all three rounds of testing at a location near the base of the column, highlighting the damage progression and subsequent shadowing of the backwall captured by the scans. It can be observed from **Figure 11(a)** that the backwall reflection is strong for the evaluated width of the reconstruction indicating no significant damage. Scattering, referring to any deviation in wave propagation from that which is expected for a homogenous body, can be used as an indicator of the damage level. The backwall on the left side of the reconstruction is not present after the 2nd round of loading, indicating increased scattering of the wavefront toward the left. The backwall is not present after the 3rd round of testing, indicating significant scattering of the wavefront. The increase in scattering (shadowing of the wavefront) indicates the presence of increased damage at a shallower depth [27]. However, since this analysis is qualitative in nature, signature analysis is presented in the following section to

1 quantify the damage caused by loading.

2
3 *Fig. 12 – Panoramic reconstructions for 1st measurement (left), 2nd measurement (middle),*
4 *and 3rd measurement (right) for a location on the bottom of the column.*

5 3.2 Quantitative Analysis

6 While this change in reflectivity can be qualitatively observed via panoramic images, and
7 indicates increased damage of the concrete around the reinforcement as shown in **Figure 10**,
8 these types of interpretations require significant engineering judgment and time. Because of
9 this, an ultrasonic tomography signature analysis (2D-UTSA) method has been adapted to
10 quantify the level of damage by comparing each scan to the corresponding undamaged
11 condition. It has been shown in previous studies that Pearson's correlation is a good indicator
12 of linear dependence, and thus damage, in comparing IE and ultrasound measurements [14,
13 21]. Pearson's correlation coefficient is adapted for comparison of reconstructed intensity
14 matrices from testing conducted before and after loading as follows using the SAFT variables
15 shown below in Equation (4):

$$17 \quad C^{IA,m} = \frac{Cov[\hat{O}^{IA,ref}, \hat{O}^{IA,m}]}{\sqrt{Var[\hat{O}^{IA,ref}]Var[\hat{O}^{IA,m}]}} = \frac{\sum_{i=1}^W \sum_{k=1}^D (\hat{o}_{i,k}^{IA,ref} - \hat{o}_{mean}^{IA,ref})(\hat{o}_{i,k}^{IA,m} - \hat{o}_{mean}^{IA,m})}{\sum_{i=1}^W \sum_{k=1}^D (\hat{o}_{i,k}^{IA,ref} - \hat{o}_{mean}^{IA,ref})^2 \sum_{i=1}^W \sum_{k=1}^D (\hat{o}_{i,k}^{IA,m} - \hat{o}_{mean}^{IA,m})^2} \quad (4)$$

where $[\hat{\mathbf{o}}]^{IA,ref}$ and $[\hat{\mathbf{o}}]^{IA,m}$ are the matrices of reflection intensity for the reference SAFT scan for the preloading condition and SAFT scan taken after loading and damage occurred, respectively; $\hat{o}_{i,k}^{IA,ref}$ and $\hat{o}_{i,k}^{IA}$ are the single intensity values of the reference signal and damaged reconstruction, respectively, with depth increasing with k and the horizontal location of the scan increasing with i ; $\hat{o}_{mean}^{IA,ref}$ and $\hat{o}_{mean}^{IA}$ are the mean intensities of the reference scan and damaged scan, respectively; W and D are the number of width and depth intensity values in the depth and device aperture direction, respectively; and $C^{IA,m}$ is Pearson's correlation coefficient, which measures the strength of the linear dependence between $[\hat{\mathbf{o}}]^{IA,ref}$ and $[\hat{\mathbf{o}}]^{IA,m}$.

In this study, the unloaded scan condition was used as the reference scan (i.e. the left image in **Figure 12**). This quantitative analysis method makes the technique more feasible for routine implementation due to the reduced interpretation time. Thus, flawed concrete locations can be identified due to the similar scan locations of the reference and damaged scan conditions. On the extremes, a $C^{IA,m}$ value of 0 would indicate no correlation and a $C^{IA,m}$ value of 1.0 would indicate that the two SAFT scans are related linearly. Therefore, a higher $C^{IA,m}$ would indicate that the SAFT scan was taken on sound concrete, and a significant decrease in the correlation coefficient would indicate non-uniform SAFT scans, or damaged concrete, especially if observed in a group of adjacent scans. This type of analysis will be referred to as the 2D-UTSA method. Lower UTSA values indicate an increase in damage as compared to the original condition.

To demonstrate the ability of UTSA values to characterize damage, consider an example analysis using a reconstruction from round 1 experimental data serving as a clean condition, and a scan containing random noise, as shown below in **Figure 13**.

Fig. 13 – Experimental reconstruction from round 1 of testing (left), and fabricated reconstruction containing noise (right).

Multiple artificial reconstructions can be generated as detailed in Equation (5):

$$[\hat{\mathbf{O}}]_i = [\hat{\mathbf{O}}]^{IA,ref} + \alpha_i [\hat{\mathbf{O}}]^{IA,noise} \quad (5)$$

where $[\hat{\mathbf{O}}]_i$ is the new matrix, $[\hat{\mathbf{O}}]^{IA,ref}$ is the reference matrix of reflection intensity for the clean case, as shown in **Figure 13** (left), $[\hat{\mathbf{O}}]^{IA,noise}$ is the matrix of reflection intensity containing random noise, as shown in **Figure 13** (right), α is the coefficient of noise intensity for all i cases considered for analysis. If the coefficient α is small, the reconstruction should be similar to the original reference reconstruction, while an increase in α leads to an increase in noise that is often associated with damage.

A sample analysis was performed in which α values of 0.01, 0.05, 0.1, and 0.25 were used to create artificial reconstructions. Each of these artificial matrices were compared with the reference case (**Figure 13**, left) and Pearson's correlation coefficients were computed using Equation (4). The effect of these α values on the resulting Pearson's correlation coefficient is shown in **Figure 14**. It can be observed that for very small α values, the Pearson's correlation

coefficient approaches one, while increasing α leads to very low correlation.

Fig. 14 – Effect of changes in α on the Pearson's correlation coefficient value.

This analysis can be confirmed by visual comparison of the corresponding reconstructions shown in **Figure 15**. As can be seen, reconstructions with high Pearson's correlation coefficient values appeared similar to the reference case, whereas reconstructions with low values show significant deviation from the base case. This same principal holds for the analysis of subsequent rounds of experimental data, and the results of this analysis are shown in the following section.

Fig. 15 – Reconstruction for α of 0.01 (top left), 0.05 (top right), 0.1 (bottom left), and 0.25 (bottom right).

4. EXPERIMENTAL RESULTS AND DISCUSSION

The analysis presented in this study is based on analysis of shear horizontal waves (SH waves) where a portion travels along the surface and a portion reflects from within the medium. Since the 50 kHz shear waves correspond to a wavelength of approximately 2 inches (51 mm), the reconstructions of the first two inches below the surface need to account for both wave paths. Below this point, the surface path of the signal can be ignored. Because damage detection below the surface is of interest in this study, the surface path is not included in this analysis

Figures 16 and 17 show a representation of the 2D-UTSA results comparing the original panoramic scans to those after 0.5% and 1% drift ratios, respectively. For each tested location, the $C^{IA,m}$ value was plotted on a scale with 0 indicated by red and 1 indicated by white, with intermediate values shown in shades of light red and yellow. In this case, darker locations (lower $C^{IA,m}$ values) indicate an increase in subsurface damage from the original condition, while light locations (higher $C^{IA,m}$ values) indicate little change from the original condition. As can be seen from these figures, ultrasonic array testing can identify levels of degradation before there are external signs of failure. When analyzing these two figures, a general trend of higher damage intensity (red coloring) can be seen in the left and lower left portion of the images. This area corresponds to the portion of the column that exhibited external damage first, as seen in **Figure 6**.

Fig. 16 – MIRA gradient results after 0.5% drift ratio.

Fig. 17 – MIRA gradient results after 1% drift ratio.

5. CONCLUSIONS

Advancements in elastic wave methods have allowed for productive and accurate quantitative analysis which was previously lacking. In this study, ultrasonic array measurements coupled with a modified signature analysis method were implemented. The full-scale testing of a heavily reinforced concrete column subjected to simulated earthquake loading demonstrated

1 the ability to detect internal damages and defects prior to appearance on the surface using
2 one-sided access. This meets an important infrastructure health monitoring goal of identifying
3 damage development beneath the surface nondestructively before visual failure occurs.
4 Shadowing analysis of the ultrasonic imaging reconstructions indicated damage below the
5 surface caused by scattering of the ultrasonic wavefronts. The shadowing and other
6 indicators of damage were quantified through the use of correlation coefficient signature
7 analysis. The results of signature analysis showed increased subsurface damage in the areas
8 that failed first after further loading. This demonstrates the ability of ultrasonic array testing
9 and signature analysis to aid in detecting not only damage below the surface, but also to
10 indicate which area of the column will show signs of failure first. It should be noted that the
11 current analysis presented in this paper requires measurements of the undamaged state of the
12 specimen to evaluate the relative damage progression. As such, the techniques can be
13 employed in actual cases if monitoring of structural health begins before damage has
14 occurred. Further work will be done in the future by the authors, in fusion with alternative
15 nondestructive testing methods, to increase the applicability of the current findings for
16 implementation on structures which have not been analyzed in an undamaged state.

17
18 The applicability of ultrasonic methods presented in this paper is promising in the field of
19 health monitoring due to its nondestructive nature and its ability to detect issues that are not
20 visible on the surface at the time of testing. This type of subsurface characterization provides
21 a practical input for improved assessment of the safety and remaining service life of
22 structures since the methods presented in this paper require only one-sided access for data
23 collection and provide quantitative early detection of subsurface conditions.

24 25 **ACKNOWLEDGEMENTS**

1 This research was primarily supported by the NSF under Award No. CMMI-1041633 and the
2 Federal Highway Administration USDOT Grant DTRT13-G-UTC44. The authors also would
3 like to acknowledge the assistance of the staff at the MAST lab of the University of
4 Minnesota and students and technicians at both the University of Minnesota and the
5 University of Texas at Arlington.

6

REFERENCES

- [1] Park, Y.-J., and Ang, A. H.-S. 1985. "Mechanistic Seismic Damage Model for Reinforced Concrete." *J. Struct. Eng.*, 111(4), pp. 722–739.
- [2] Takeda, Toshikazu, Sozen, M. A. and Nielsen, N. Norby. (1970). "Reinforced Concrete Response to Simulated Earthquakes." *Journal of Structural Engineering*, American Society of Civil Engineers, December 1970.
- [3] Bracci, J. M., Kunnath, S. K. and Reinhom, A. M. (1997). "Seismic Performance and Retrofit Evaluation of Reinforced Concrete Structures." *J. Struct. Eng.*, 123(1), pp. 3–10.
- [4] Ghee, A. B., Priestley, M. J. N., and Paulay, T. (1989). "Seismic Shear Strength of Circular Reinforced Concrete Columns." *Structural Journal*, American Institute of Concrete. 86(1), pp. 45-59.
- [5] Vosooghi, A. and Saiidi, M. (2013). "Shake-Table Studies of Repaired Reinforced Concrete Bridge Columns Using Carbon Fiber-Reinforced Polymer Fabrics," *ACI Structural Journal*, V. 110, No. 11, Jan-Feb., pp. 105-114.
- [6] Donnelly, J. (2012). "Means and Methods of Evaluating Reinforced Concrete Structures," *ACI Fall 2012 Convention*, October 21-24; Toronto, ON.
- [7] Carino, N. J. (2001). "The impact-echo method: an overview." *Proceedings of the 2001 Structures Congress & Exposition*, May, 2001, pp. 21-23.
- [8] Azari, H., Nazarian, S., & Yuan, D. (2014). Assessing sensitivity of impact echo and ultrasonic surface waves methods for nondestructive evaluation of concrete structures. *Construction and Building Materials*, 71, 384-391.
- [9] Godinho, L., Dias-da-Costa, D., Areias, P., Júlio, E., & Soares, D. (2013). Numerical study towards the use of a SH wave ultrasonic-based strategy for crack detection in concrete structures. *Engineering Structures*, 49, 782-791.
- [10] Schubert, F. & Koehler, B. (2001). "Three-dimensional time domain modeling of ultrasonic wave propagation in concrete in explicit consideration of aggregates and porosity." *Journal of computational acoustics*, 9, 1543-1560.
- [11] Choi, H., & Popovics, J. S. (2015). NDE application of ultrasonic tomography to a full-scale concrete structure. *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on*, 62(6), 1076-1085.
- [12] Popovics, J. S., Oh, T., and Ham, S. (2012). "Effective visualization of impact-echo data for bridge deck NDE." *AIP Conference Proceedings*, 2012, pp. 1681.

- 1 [13] Schubert, F. and Kohler B. (2008). "Ten Lectures on Impact-Echo." Journal of Nondestructive Evaluation.
2 Special Issue: Acoustic and Electromagnetic Nondestructive Evaluation of Concrete Structures. Volume 27, pp.
3 1-3, 5-21.
- 4 [14] Schubert, F., Lausch, R., and Wiggenhauser, H. (2003). "Geometrical effects on impact-echo testing of
5 finite concrete specimens." Proceedings of International Symposium Non-Destructive Testing in Civil
6 Engineering (NDT-CE), 2003, pp. 16-19.
- 7 [15] Hoegh, K., Khazanovich, L., Maser, K. R., and Tran, N. (2012). "Evaluation of Ultrasonic Technique for
8 Detecting Delamination in Asphalt Pavements." Transportation Research Record: Journal of the Transportation
9 Research Board. Volume 2306 pp. 105-110.
- 10 [16] Nojavan, A., Schultz, A.E., Haselton, C., Simathathien, S., Liu, X., and Chao, S-H. (2015). "A New
11 Dataset for Full-Scale RC Columns under Collapse-Consistent Loading Protocols," Earthquake Spectra, EERI,
12 31(2): 1211-1231.
- 13 [17] ACI Committee 318. (2011). Building Code Requirements for Reinforced Concrete and Commentary (ACI
14 318-11/ACI 318R-11). American Concrete Institute, Detroit, MI.
- 15 [18] Nojavan, A., Schultz, A. E., Chao, S-H., Haselton, C., Simasathien, S., Palacios, G., and Liu, X.,
16 "Preliminary Results for NEESR Full-Scale RC Column Tests Under Collapse-Consistent Loading Protocols,"
17 10th U.S. National Conference on Earthquake Engineering, Anchorage, AK, July 21-25, 2014.
- 18 [19] Shevaldykin, V. G., Samokrutov, A. A., and Kozlov, V. N. (2002). "Ultrasonic Low-Frequency
19 Transducers with Dry Dot Contact and Their Applications for Evaluation of Concrete Structures," IEEE
20 Ultrason. Symp. Proc., Vol. 1-2, 2002, pp. 793-798.
- 21 [20] Hoegh, K., Worel, B., Yu, H. T., and Khazanovich, L. (2013). "Detection of Subsurface Joint
22 Deterioration" Transportation Research Record: Journal of the Transportation Research Board. Volume 2367.
23 Issue 1: pp. 3-12.
- 24 [21] Hoegh, K. and Khazanovich, L. (2012). "Correlation Analysis of 2D Tomographic Images for Flaw
25 Detection in Pavements," Journal of Testing and Evaluation. American Society for Testing and Materials 40(2):
26 pp. 247-255.
- 27 [22] Hoegh, K. and Khazanovich, L. (2012). "Concrete Pavement Joint Diagnostics Using Ultrasonic
28 Tomography," Transportation Research Record: Journal of the Transportation Research Board. Volume 2305:
29 pp.54-61.

- 1 [23] Hoegh, K., Yu, H. T., and Khazanovich, L. (2011). "Ultrasonic Tomography Technique for Evaluation of
2 Concrete Pavements," Transportation Research Record: Journal of the Transportation Research Board. Volume
3 2232: pp. 85–94.
- 4 [24] Langenberg, Karl-Jörg, René Marklein, and Klaus Mayer. (2012). "Ultrasonic Nondestructive Testing of
5 Materials: Theoretical Foundations." CRC Press.
- 6 [25] Lingvall, Fredrik, Tomas Olofsson, and Tadeusz Stepinski. (2003). "Synthetic aperture imaging using
7 sources with finite aperture: Deconvolution of the spatial impulse response." The Journal of the Acoustical
8 Society of America 114.1: 225-234. <http://dx.doi.org/10.1121/1.1575746>.
- 9 [26] Hoegh, K. and Khazanovich, L. (2015). "Extended Synthetic Aperture Focusing Technique for Ultrasonic
10 Imaging of Concrete." NDT & E International. doi:10.1016/j.ndteint.2015.05.001.
- 11 [27] Schickert, M., Krause, M. & Müller, W. (2003). "Ultrasonic imaging of concrete elements using
12 reconstruction by synthetic aperture focusing technique." Journal of Materials in Civil Engineering, 15, 235-
13 246. Permalink: [http://dx.doi.org/10.1061/\(ASCE\)0899-1561\(2003\)15:3\(235\)](http://dx.doi.org/10.1061/(ASCE)0899-1561(2003)15:3(235)).