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Nondestructive monitoring of subsurface damage progression in concrete columns damaged by earthquake loading

Katelyn Freeseman [a,*], Lev Khazanovich [a], Kyle Hoegh [a], Alireza Nojavan [a], Arturo E. Schultz [a], Shih-Ho Chao [b]

[a] University of Minnesota, 500 Pillsbury Drive SE, Minneapolis, MN 55455, United States
[b] University of Texas, Arlington, 425 Nedderman Hall, 416 Yates, Arlington, TX 76019, United States

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A B S T R A C T

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.

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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 evaluation in order to assess the safety and remaining structural capacity. Specifically, reinforced concrete (RC) systems create added complexity due to their heterogeneous nature.

Extensive research has been done in the past regarding the response of RC structures to earthquake loading [e.g., 1–4], which shows that damage in concrete structures may occur even under small drifts. Effective repair methods for damaged RC structural members have been developed, as verified by recent RC bridge columns tested using ground motion similar to that of the 1994 Northridge earthquake [5]. However, for proper implementation of repair techniques, it is critical for damage to first be accurately identified, preferably by a nondestructive method.

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

* Corresponding author.
E-mail addresses: weile068@umn.edu (K. Freeseman), Khaza001@umn.edu (L. Khazanovich), hoeg0021@umn.edu (K. Hoegh), nojav002@umn.edu (A. Nojavan), schul088@umn.edu (A.E. Schultz), shchao@uta.edu (S.-H. Chao).

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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. Schubert 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 Eq. (1) [13]:

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

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 36 × 28 in. (914 × 711 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. Fig. 1 shows the reinforcement details and the dimensions of the columns.

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 (Fig. 2). The columns were then loaded to simulate earthquake activity via a drift history representative of multiple cycles of reversed motion with increasing amplitude. Fig. 3 shows the near-collapse loading protocol in terms of the column drift ratios, while Fig. 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. (2438 mm) 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].

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,

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