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Integrated Visualization for Reinforced Concrete

Using Ultrasonic Tomography and Image-based 3-D Reconstruction

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Abstract

A comprehensive visualization scheme to characterize reinforced concrete structures, based on integrated ultrasonic tomography and 3-D computer vision, is presented. A recently developed hybrid air-coupled/contact ultrasonic transducer system enables the generation of internal tomographic images that characterize the interior condition, for example the presence of voiding defects, of full-scale reinforced concrete elements. Based on tomographic cross-sectional slice images, 3-D volumetric internal images are built up to obtain full stereoscopic analysis. An automated image-based 3-D reconstruction technique is applied to the same structure to visualize external condition. Both internal and exterior visualizations of full-scale concrete column are integrated in a single three-dimensional image. The approach is demonstrated on a reinforced concrete column sample that exhibits exterior geometric inconsistency with the original design and also includes controlled internal defects. The experimental results demonstrate that the proposed integrated visualization technique provides holistic characterization of the interior and exterior of the test sample and thus demonstrates great potential for facilitating inspection of existing structures in the field.

Keywords: Air-coupled; Imaging; Nondestructive evaluation; Structure from motion; Tomography

1. Introduction

Quality assurance and quality control (QA/QC) of the infrastructure has become an important issue based on the American Society of Civil Engineers' report card in 2013 [1], which graded to America's infrastructure D+ overall. Especially for concrete structures, maintenance is a critical factor for enhanced service life because existing damage can promote secondary material degradation processes such as corrosion and alkali-silica reaction [2]. Advances in structural health monitoring (SHM) and non-destructive evaluation/tests (NDE/T) technology can enhance efforts to visually inspect concrete condition and deploy appropriate maintenance procedures [3,4]. However, holistic inspection of civil infrastructure is often hampered by large size and limited access. Computer vision techniques offer a solution to this problem. Computer vision methods provide surface assessment in a virtual 3-D format and thus offer a basis for effective data interpretation by enabling potential for automated robotic image acquisition and automated data interpretation. Image-based 3-D reconstructions and visualization have been applied effectively to monitor construction progress [5] or to diagnose building performance problems [6]. 3-D modeling of civil structures is also possible using a laser scanner, however that method is costly and labor-intensive and requires manual post-processing of raw data to remove noise. Alternatively, computer vision-based 3-D reconstruction can be readily applied by a non-expert and requires only a consumer-level digital camera for data collection [7].

The visualization of internal structure is also needed to fully evaluate the condition of civil infrastructure. For reinforced concrete structures, the application of ultrasonic methods such as tomography and synthetic aperture focusing technique (SAFT) has been studied [8-15]. A hybrid ultrasonic pulse velocity system includes air-coupled transmitter and an array of contact accelerometers, developed by the authors, can collect a large amount of high quality ultrasonic data from a large concrete element [16]. The large data volume measured by air-coupled transmission scanning significantly increases sectional ray coverage, enabling the application of tomography to full-scale concrete structures. Furthermore, it has been demonstrated that the through thickness transmission-based configuration improved internal imaging for reinforced concrete structures with high volumes of embedded steel over one-sided imaging and SAFT-based methods [17].

Despite the benefits provided by true 3-D tomography, the required tests and analysis are computationally expensive. In this paper, we generate 3-D tomographic reconstructions of an object using a set of stacked 2-D tomogram slices [18]. The use of the air-coupled sensing system used in this work significantly increases the amount of ray path data that can be collected, which results in time efficient and cost-effective scanning of large specimens,

with minimal surface preparation needed. Previous ultrasonic tomographic approaches have been applied to small-scale concrete elements because the contact-type sensing configuration is labor-intensive and limits the number of ray data that can be collected [8-10]. Then, an external 3-D reconstruction in the form of a point cloud is built up from individual digital photographs using Structure-from-Motion (SfM) [19] and Multi-View Stereo (MVS) algorithms [20]. This approach automatically generates 3-D geometrical models of objects from unordered collections of digital photographs. The integrated graphical representation of ultrasonic tomograms and point cloud models can provide infrastructure inspectors an intuitive and cost effective approach to assess structural condition powered by a 3-D virtual environment. Prior efforts to apply image-based 3-D reconstruction for concrete structural condition assessment were limited to exterior evaluations, such as surface crack detection [21, 22]. The visualization approach demonstrated here has benefits over previous imaging approaches and provides new diagnostic capability not provided previously, and to the best of our knowledge, such integrated visualization for structural inspection has not yet been reported.

2. Proposed techniques

2.1. Ultrasonic imaging system

A hybrid ultrasonic system that comprises both contactless air-coupled transmitters and an array of contact accelerometers is used [16]. The benefit of this system is that air-coupled transmitters enable the collection of a large amount of data without touching the surface of the specimen. Electrostatic-based transducers (SensComp 600) are used as contactless ultrasonic because they are more efficient in terms of transmitting sensitivity for air-coupled ultrasonic generation as compared to conventional piezoelectric-based transducers. More detail about the sensing technology used in the hybrid configuration can be found elsewhere [23]. On the opposing surface, small sized (9 mm) receiving accelerometers (PCB 352c15) are physically attached to surface using a commercially available instant adhesive to enable high quality through thickness measurements. The entire data acquisition procedure of the hybrid ultrasonic system is fully controlled by a personal computer, including the automated scanning of the air-coupled transducer. A quantitative comparison between a conventional contact ultrasonic system and the hybrid system is represented in Table 1, showing that the automated system significantly improves the speed of the measurement, provides high accuracy, and enables a dense volume of data to be collected from a cross-section thus enabling higher resolution internal images.

Table. 1 Characteristics of two configurations of the ultrasonic method

	Surface Preparation	Couplant	Measurement type	Position accuracy	Data acquisition duration (based on 36 inch scan)	Ray coverage
Contact UPV	Possibly required	gel-type	manual	plus or minus 5mm	1 hour, 64 signal set	Sparse, Every 11 cm
Hybrid UPV	N/A	N/A (transmitters) adhesive (receivers)	automated	minimum 0.1mm	Less than 6 min, 2,720 signal set	Dense, Every 0.25 cm

Internal structures are visualized using tomographic reconstruction built up from through thickness measurements. Based on obtained P-wave arrivals and known geometry of the specimen, velocity tomograms are developed in the form of slowness (inverse of velocity) as

$$t_i = \sum_{j=1}^M p_j d_{ij} \quad (i = 1 \sim N) \quad (1)$$

where d_{ij} is the distance traveled by ray i through pixel j , p_j is slowness (inverse of velocity) at pixel j , t_i is arrival time of wave of ray i , and N and M are the number of observations and pixels, respectively. The mathematical process is illustrated in [fig. 1a](#). The inverse of the slowness matrix can be calculated; however, an insufficient number of data or corrupted data caused by noise content can give rise to singularities. The algebraic reconstruction technique (ART) iteratively solves the matrix inversion as an algebraic problem until the difference between previous and current steps converges to defined threshold level [\[24, 25\]](#). A common iteration solver is the back-projection method using a row-normalized transpose of d_{ij} [\[26, 27\]](#)

$$p_j = \sum_{i=1}^N \frac{d_{ij}^T t_i}{d_i^2} \quad (j = 1 \sim M) \quad (2)$$

In the iterative procedure, the initial assignment of slowness is a key variable to control overall computation time and to ensure minimal errors. In this study, the average of slowness from all measurements is used as the initial assignment of slowness for the tomographic reconstruction. The calculated slowness values from the iterative procedure are assigned to known geometric location as illustrated in [fig 1b](#).

$$\begin{bmatrix} d_{11} & & \\ & \ddots & \\ & & d_{ij} \end{bmatrix} \begin{bmatrix} p_1 \\ \vdots \\ p_2 \\ \vdots \\ p_3 \\ \vdots \\ p_4 \\ \vdots \\ p_j \end{bmatrix} = \begin{bmatrix} t_1 \\ \vdots \\ t_2 \\ \vdots \\ t_3 \\ \vdots \\ t_4 \\ \vdots \\ t_i \end{bmatrix}$$

Distance, d_{ij} (known) Slowness, p_j (unknown) Arrival time of p-wave, t_i (known)

(a)

Fig. 1 Illustration of algebraic reconstruction technique: (a) matrix representation of velocity tomography, and (b) graphical representation relative to the matrix components in (a)

The reconstructed sectional image represents P-wave slowness, which is affected by variations in material properties such as elastic modulus and density. The speed of ultrasonic waves decreases when the wave propagates through lower density or lower modulus regions within the material, which could be set up by the presence of internal cracks or voids. A 50 kHz center-frequency narrow band ultrasonic pulse is employed to avoid scattering losses in concrete, where the corresponding wavelength is around 8cm to 10cm assuming that P-wave velocity of concrete is between 4000m/s and 4700m/s. Although the employed frequency wave limits sensitivity to sub-wavelength reflectors inside concrete, the tomographic algorithm emphasizes the lower velocity regions because of the large amount of data measurements across multiple wave paths. Therefore, the tomograms enable visualization of reflectors that are slightly smaller than the wavelength.

2.2. 3-D computer vision reconstruction

The data and process associated with the image-based 3-D reconstruction are illustrated in [fig 2](#). A consumer-level digital camera is used to collect a set of photographic images of the object under inspection. The SfM process automatically computes the intrinsic (e.g., focal length and radial distortion parameters) and extrinsic (e.g., rotation and translation) camera parameters from a given set of images. In order to reduce the computational cost, a Graphic Processing Unit (GPU)-based SfM implementation is used, [\[28\]](#) which consists of following steps: 1) detecting distinct visual features that are invariant to changes in illumination, rotation, and scale for all images; 2) matching their descriptors across each image pair using a nearest neighborhood matching algorithm; 3) forming the Epipolar geometry between each image pair by estimating the Fundamental matrix within a RANdom SAMple Consensus (RANSAC) loop and fitting the Fundamental matrix in the RANSAC loop [\[29\]](#). By forcing the corresponding features to have consistent transformation, this process minimizes false matches, which typically occur due to similar visual features, that are inconsistent by the general transformation from one camera to another; 4) selecting a pair of images for initializing 3-D reconstruction process based on the selection heuristics [\[30\]](#) and deriving the relative translation and rotation between the initial image pair; 5) incrementally computing the camera parameters and the location of the 3-D feature points starting from an initial triangulation; and 6) optimizing the estimated camera parameters and the locations of the 3-D points using the GPU-based library [\[31\]](#) of the bundle adjustment algorithm [\[32\]](#) to cut the computation time. Then, the resulting intrinsic and extrinsic camera parameters are fed into the MVS algorithm. In this process, distinct visual features detected by Harris and Difference-of-Gaussians (DoG) operators are first matched across all images, yielding a set of sparse patches (possibly including false positives). Then, expansion and filtering steps are iteratively implemented to make the patches denser and remove the false matches. Because the underlying reconstruction process generates a 3-D point cloud until image projections of the feature points cover all the registered images, an increase in the number of target images brings about denser 3-D reconstruction. The final outcome is a dense 3-D point cloud which represents the geometrical base of the given object.

Fig. 2 Flowchart describing the 3-D computer vision technique

3. Experimental evaluation

3.1. Test specimen and data collection

The visualization method is applied to a test sample that represents a full-scale reinforced concrete column that contains a high volume of steel reinforcement. The specimen simulates a plastic hinge zone of a seismic designed concrete column that includes embedded # 4 transverse rebar (12.7 mm diameter) with 4 inch (101.6 mm) and 6 inch (152.4 mm) spacing at the bottom and top parts of the column, respectively. The concrete used for this specimen has a target 28-day compressive strength of 5000 psi (34.4 MPa) and a maximum coarse aggregate particle size of 10mm, representing conventional structural material. The specimen has a rectangular cross-section of 36 inch (914.4 mm) by 28 inch (711.2 mm). As shown in [fig 3](#), the column contains controlled internal defects. Concrete voids, possibly caused by construction errors or insufficient grouting of tendon, are simulated with Styrofoam prisms. Cracked concrete regions, for example damaged by alkali silica reaction or freezing and thawing action, are simulated by pre-cracked concrete prisms. The size of each of the controlled prismatic damage zones is 3×3×9inch (76.2×76.2×228.6 mm) ([fig 3b](#)). Cross-section A-A of the sample includes both types of embedded defects: a void at the center and a pre-cracked prism near the front surface ([fig 3c](#)). It was observed that the bottom part of concrete form popped out during the casting process, resulting in an inadvertent widening on the specimen geometry at the bottom.

Fig. 3 Test specimen detail; (a) Design of the full-scale reinforced concrete column with embedded artificial defects
(b) Detail of artificial defects (c) Cross section A-A (fig 3 is reproduced from ref 16)

Through-thickness ultrasonic measurements were carried out using a hybrid ultrasonic system developed by the authors. The hybrid ultrasonic test set-up is illustrated in fig 4. The test specimen is scanned using a robotic scanning frame. A total 4,800 ultrasonic time signals were obtained from one cross-section of the sample, scanning across the 36 inch face (2,720 signal set) and the 28 inch face (2,080 signal set) of the column. Using 8 receivers, the data acquisition system simultaneously measures 8 signals for each position increment of the air-coupled transmitter, which takes 1 second. Two perpendicular surfaces of one cross-section were scanned providing an orthogonal set of wave paths within the sample, where the total duration of data acquisition for one cross-section was approximately 10 minutes. The total data acquisition time for the twenty separate sections was about 200 minutes. Each individual time signal was time-averaged five times and amplified using a PCB 442c04 signal conditioner unit. The received signals were digitized using a 32-bit digitizer (NI USB-6366) at a sampling rate of 2 MS/s. Figure 5 illustrates the ultrasonic data collection process showing the test configuration at one cross-section including embedded defects in fig 5a, spatially stacked signals obtained from a near-center accelerometer in fig 5b, and an individual time signal with the

1 P-wave arrival indicated in fig 5c. The indentation in the P-wave front marked in fig 5b shows that the transmitted P-
 2 wave arrivals that travel through the internal defects are delayed.

Fig. 4 Schematic drawing of the hybrid ultrasonic test configuration including air-coupled sending transducer on the left and array of receiving accelerometers on the right

Fig. 5 Illustration of ultrasonic tests applied to the concrete column: (a) Section A-A showing measurement configuration; (b) stacked time signal (B-scan) image obtained from one accelerometer attached near the center of section A-A as indicated (yellow line represents arrival of P-wave); (c) an example of transmitted ultrasonic time signal through section A-A

A 3-D computer vision technique is applied to provide an external visualization of the sample. A consumer-level digital camera (Canon EOS 60D) was used to collect 110 digital photos around the concrete column. Each photograph from the camera has a spatial resolution of 3264×2448 pixels. All vertical surfaces of the column were photographed from multiple perspectives. The photographs were collected from unordered camera positions of interest, and the total procedure took less than 10 minutes. The locations and orientations of the camera for each photograph are registered in the 3D virtual environment (Figure 6) where such data are automatically derived from the SfM process (Section 2.2) based on camera extrinsic parameters. Figure 6 shows all camera positions for the photographs. Finally, the photographs are combined to generate a point cloud reconstruction of the surface of the specimen in simulated stereoscopic vision.

Fig. 6 Illustration of image-based 3-D reconstruction from unordered photographs collected around the column

3.2. Integrated visualization

Figure 7 illustrates the process of 3-D visualization by integrating internal and external data. Cross-sectional ultrasonic velocity tomograms are developed using the algebraic reconstruction technique. The developed 2-D tomograms at different vertical positions along the column are stacked along the z-axis with a vertical spacing of 2 inch (5.08 cm) between image slices. The individual image slices are linearly interpolated to produce a 3-D volumetric data set. The external surface of concrete column is reconstructed in a virtual 3-D environment using the SfM-based computer vision technique. Then, multi-view stereo generates a dense point cloud model of the exterior of the concrete

specimen. The resulting 3-D reconstruction is transformed into a real-world coordinate system by using the grid lines marked on the column as reference. Finally, the velocity tomograms and the reconstructed 3-D concrete column are integrated into a single 3-D environment and coordinate system. The tomograms are geo-registered with respect to the underlying reconstructed concrete column in 3-D axes.

Fig. 7 Graphical illustration of the integrated visualization scheme

4. Results

The slowness values calculated by the tomographic algorithm are converted to P-wave velocity in order to indicate velocity differences between defect and sound regions in the constructed tomograms. A pixel-region exhibiting higher P-wave velocity is represented by red colors, while lower velocity is illustrated by blue colors in the jet-color scale format used. Thus, the location of embedded defects should be indicated by dark blue colors. As illustrated in [fig 8a](#), the ultrasonic tomograms nearby section A-A show blue colors in the center of the section where the void defect is embedded. However, the pre-cracked concrete sample near the surface is less clearly identified. This is likely a result of the facts that fewer ray paths intersect through that particular defect area and the pre-cracked

concrete defect exhibits a relatively modest acoustic impedance difference with respect to the sound concrete. Also, the color of the embedded defects in the image is not consistently blue. This is because the tomographic iterative solver incrementally calculates pixel values based on residual comparison to adjacent pixels, which are the solutions of the linear equations shown in Eqn. 1. Furthermore, regions of low velocity (blue color) are found near the corners of the sample and at the locations of the fixed surface receivers. These are likely false indications caused by limited ray coverage that converge to relatively low velocity values and thus may not represent actual low P-wave velocity in those regions. It is also noted that the tomograms do not reveal the presence of embedded steel reinforcing bars. Transmitted P-wave arrivals are not significantly influenced by the relatively small volume of bars along a given ray path. Because the method is largely unaffected by the presence of reinforcing bars, it can be applied to image the interior of densely reinforced concrete structures; in contrast, reflection-based ultrasonic imaging methods such as SAFT can be disrupted by densely placed reinforcing bars [17]. In order to interpret the data across the full column height, each tomogram is stacked and interpolated to create a data volume (fig 8b), and the sections of interest are isolated (fig 8c). Vertical slice images from the data volume also show distinct locations of lower velocity in the expected located of defects.

Fig. 8 Stacked p-wave velocity tomograms: (a) horizontal images around section A-A (b) stacked tomograms through an entire region of the concrete column (c) vertical section images around the center of the column specimen

The external geometry reconstructed using the 3-D computer vision technique illustrates detailed geometric and surface properties of the test column. The 3-D point cloud model and a single photograph of the concrete column from the same viewpoint are compared in [fig 9](#). The surface characteristics, grid lines and marked numbers are indicated in both. However, the 3-D point cloud model offers benefits over the single photograph. For example, detailed dimensional information from the 3-D point cloud image provides geo-spatial references in virtual 3-D space. Furthermore, detail of concrete texture is provided. The 3-D image offers qualitative surface texture information such as color differences and level of roughness (flatness), as shown [fig 9b](#). The as-designed column is compared to the reconstructed model in terms of geometrical accuracy in [fig 10](#). The red box in the figure indicates that the shape of the column as designed ([fig 10a](#)), over which the 3-D point cloud model is overlaid ([fig 10b](#)). The photo insets show the width of the column measured at a horizontal edge, where there is approximately 1cm expansion at the bottom that is attributed to form construction error. [Fig 10c](#) illustrates the mismatch between the original shape of the column and reconstructed 3-D model, showing the construction error on the bottom part of the column. The 3-D model demonstrates high resolution surface visualization and geometric measurement and interpretation not provided by individual photographs.

Fig. 9 Comparison between photograph and 3-D point cloud model: (a) single photograph of the concrete column
(b) 3-D dense point cloud model of the concrete column, where insets show surface texture and coloring detail

Fig. 10 Comparison between the column as designed and 3-D point cloud model: (a) box frame representing originally designed shape; (b) 3-D point cloud model where insets show dimension details (1cm error); (c) 3-D point cloud model overlaid with the box frame, where insets show geometric construction error

In figure 11, the integrated ultrasonic tomogram and the 3-D point cloud image is illustrated for the column. The photo in fig 11a shows the placement of artificial defects before casting concrete. Figure 11b shows the 3-D point cloud image of the cast column with the location of internal defects indicated by green and blue boxes for voids and pre-cracked concrete prisms, respectively. The integrated image is shown in fig 11c where blue colored zones, representing lower P-wave velocity, indicate the presence and location of the internal defects within the boundaries of the as-designed locations. It is noted that the color inside the region of embedded defects is not consistently blue as discussed in section 4. Figure 12 illustrates that the integrated visualization can be manipulated for improved utility, for example by viewing from different perspectives or by extracting portions of the image for detailed analysis. Figure 12a indicates the location of all embedded defects within the column including the two pre-cracked prisms. In fig 12b, a partial cut-away perspective composed of integrated tomogram slides reveals that a part of the embedded cracked region is observed within the marked box, which is not clearly identified in any individual tomogram slice.

Fig. 11 Integrated visualization of tomograms and an image-based 3-D reconstruction ; (a) Photograph of sample before casting concrete, (b) 3-D dense point cloud model of the concrete column where position of defects (green box: Styrofoam, blue box: pre-cracked concrete) are also indicated, (c) integrated interior and exterior images showing relative position of internal defects.

Fig. 12 Integrated visualization fields from different perspectives; (a) side views and (b) top views

5. Discussion

Integrated ultrasonic tomography and image-based 3-D reconstruction visualization provides more information beyond that from the individual visualizations alone. An integrated visualization provides intuitive understanding of positions of internal defects with respect to the external 3-D point cloud. Furthermore, integrated visualization enhances understanding of the nature of internal damage through the use of multiple perspectives or splice cuts. The 3-D virtual space enables users to analyze more data collectively across multiple cross-sections and perspectives, providing benefit over individual 2-D based cross-sectional tomograms.

Although the results of the integrated visualization demonstrate great potential to evaluate reinforced concrete elements, further improvement to the test set-up and visualization analysis approach are needed. In the case of the

1 hybrid ultrasonic configuration, the physical coupling procedure used for the receivers across multiple scan lines
2 increases overall duration of data acquisition. Deployment of an array of dry-coupled point sensors or fully air-coupled
3 receivers would help address this issue. Also, improvements to the tomographic reconstruction and analysis
4 procedures are needed in order to better detect and characterize embedded defects in a quantitative manner. However
5 qualitative analyses procedures, for example setting an arbitrary P-wave velocity threshold values to define a defect
6 region, may lead to misleading or incorrect images [33]. Although the applied technique successfully identifies defined
7 regions associated with lower wave velocity, material degradation processes in concrete are often associated with
8 material cracking. P-wave arrival time may not be sensitive to the presence of distributed cracking damage because
9 the employed wavelength in our case is about 8 cm, which is much larger than the dimension of an individual crack.
10 Although high ray density may compensate to some degree for the wavelength issue, velocity tomography is limited
11 when the internal reflectors have dimensions much smaller than wavelength. Alternate ultrasonic testing parameters,
12 such as propagating wave energy or wave scatter, may better detect small-sized defects such as cracks. Our research
13 group is currently investigating such improvements.

14 The 3-D computer vision techniques employed in this work are broadly applicable in the field. The cost of
15 the required hardware, a consumer-level digital camera, is low compared with laser scanners, which have been used
16 to create 3-D models of civil infrastructure. Because 3-D computer vision data acquisition is simple (i.e., taking a
17 picture) and it does not require a specific sequence of the photos, the measurement procedure can be performed by a
18 basic robotic system. Such an automated data collection process has great potential to visual inspection for large-scale
19 infrastructure with limited access, such as nuclear power plants, bridges or airport pavements. Finally, 3-D computer
20 vision techniques offer potential to empower conventional infrastructure inspections. For example, Torok et al.
21 suggested a 3-D auto-crack detection algorithm as an extension of the computer vision techniques for civil engineering
22 applications [22]. The complete operation is fully automated, from data collection to auto-crack detection in 3-D
23 virtual space, and when implemented should contribute to new visual inspection capabilities of large-scale civil
24 infrastructure.

25 26 **6. Conclusions**

27 This paper presents integrated visualization technology that uses ultrasonic tomography and 3-D computer
28 vision techniques to evaluate a full-scale reinforced concrete column. The data were collected using an ultrasonic

1 system that uses air-coupled transducers and a consumer-level digital camera. Sectional tomograms were
2 reconstructed from through-thickness ultrasonic velocity data and integrated with a 3-D surface model reconstructed
3 from a set of external digital photographs. Internal defects are characterized by ultrasonic tomography identified and
4 assigned in the integrated 3-D reconstruction image of the concrete column. Such integrated visualization techniques
5 have great potential to improve structural condition assessment of large-scale civil infrastructure.

6
7 Based on the work presented in this paper, the following conclusions are drawn:

- 8 • 3-D volumetric internal images based on ultrasonic tomograms can detect embedded defects within concrete,
9 even when the element contains high volumes of steel reinforcement;
- 10 • Image based 3-D reconstruction using computer vision techniques provide accurate information about
11 surface conditions, such as surface color variations, numbers and other markings, and geometrical deviations
12 from the original design;
- 13 • Integrated internal/external visualization offers deeper understanding of the test sample in comparison to
14 the data provided by each method individually. Multi-perspective analysis of the integrated images in a single
15 unified coordinate environment provides powerful holistic information of internal and external condition of
16 the inspected structure.

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List of tables

Table. 1 Characteristics of two configurations of the ultrasonic pulse velocity (UPV) method

List of figures

Figure. 1 Illustration of algebraic reconstruction technique: (a) matrix representation of velocity tomography, and (b) graphical representation relative to the matrix components in (a)

Figure. 2 Flowchart describing the 3-D computer vision technique

Figure. 3 Test specimen detail; (a) Design of the full-scale reinforced concrete column with embedded artificial defects (b) Detail of artificial defects (c) Cross section A-A (fig 3 is reproduced from ref 16)

Figure. 4 Schematic drawing of the hybrid ultrasonic test configuration including air-coupled sending transducer on the left and array of receiving accelerometers on the right

Figure. 5 Illustration of ultrasonic tests applied to the concrete column: (a) Section A-A showing measurement configuration; (b) stacked time signal (B-scan) image obtained from one accelerometer attached near the center of section A-A as indicated (yellow line represents arrival of P-wave); (c) an example of transmitted ultrasonic time signal through section A-A

Figure. 6 Illustration of image-based 3-D reconstruction from unordered photographs collected around the column

Figure. 7 Graphical illustration of the integrated visualization scheme

Figure. 8 Stacked P-wave velocity tomograms: (a) horizontal images around section A-A (b) stacked tomograms through an entire region of the concrete column (c) vertical section images around the center of the column specimen

Figure. 9 Comparison between photograph and 3-D point cloud model: (a) single photograph of the concrete column (b) 3-D dense point cloud model of the concrete column, where insets show surface texture and coloring detail

Figure. 10 Comparison between the column as designed and 3-D point cloud model: (a) box frame representing originally designed shape; (b) 3-D point cloud model where insets show dimension details (1cm error); (c) 3-D point cloud model overlaid with the box frame, where insets show geometric construction error

Figure. 11 Integrated visualization of tomograms and an image-based 3-D reconstruction ; (a) Photograph of sample before casting concrete, (b) 3-D dense point cloud model of the concrete column where position of defects (green box: Styrofoam, blue box: pre-cracked concrete) are also indicated, (c) integrated interior and exterior images showing relative position of internal defects

1 Figure. 12 Integrated visualization fields from different perspectives; (a) side views and (b) top views