CONCRETE CORE DEFECTS TOMOGRAPHIC IMAGINATION FOR MESOSCALE CFST MEMBERS USING STRESS WAVE MEASUREMENT

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To visualize concrete core void defects in concrete-filled steel tube (CFST) members considering the mesoscale heterogeneity and randomness of concrete core is critical in practice. A stress wave travelling time tomography imagination method using piezoelectric-lead-zirconium-titanate (PZT) patches as actuators or sensors is proposed and validated numerically. A two-dimensional (2D) multi-physics and mesoscale coupling CFST-PZT model composed of number of PZT actuators and sensors, steel tubes, and concrete core with randomly distributed circular aggregates is established. The first stress wave arrival times of the mesoscale coupling CFST-PZT model without or with a concrete core void defect are recorded by PZT sensors when a PZT actuator is excited by pulse signals. A random walking algorithm (RWA) with the Snell laws is employed to determine the shortest wave travel path between each PZT actuator and each PZT sensor. Finally, the velocity fields of the mesoscale coupling models are identified using a simultaneous iterative reconstruction technique (SIRT) to minimize the difference between the first arrival time of the stress wave and the shortest wave travel time. Results show that the location and dimension of the void defect in the models with heterogeneous concrete core can be imaged with acceptable resolution.

Keywords: Piezoelectric-lead-zirconium-titanate (PZT), Randomness, Heterogeneity, Multi-physics coupling model, Random walking algorithm (RWA), Simultaneous iterative reconstruction technique (SIRT).

1 INTRODUCTION

In the past two decades, concrete-filled steel tube (CFST) members have been widely used as major vertical and axial load-carrying elements in large-scale engineering structures including skyscrapers and long-span bridges to overcome the limitations of mechanical properties of traditional reinforced concrete (RC) structures. Different types of defects including air void in concrete and interface debonding defects between the steel tube and concrete core in CFST members may occur due to inevitable concrete shrinkage, creep and poor concrete quality control methods during construction. Existing researches show that defects in CFST members lead to a negative influence on structure safety and serviceability in the form of decreases in load-carrying capacity, stiffness and even hysteretic behaviors. Although some traditional non-destructive testing (NDT) methods including X-ray techniques, ultrasonic techniques, acoustic echo methods, etc., are efficient for the detection of concrete cracks and debonding between concrete and reinforcement in RC structures, defects detection and the visualization in CFST is still a challenging task (Chen et

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al. 2021). To avoid the electromagnetic shielding effect of steel tubes, stress wave propagation-based approaches for defect detection of CFST members received great attention in the past decades. As one of the pioneer researchers, Xu and his group members developed an interface debonding defects detection approach for CFST members using the wavelet packet energy of stress wave measured with embedded piezoelectric-lead-zirconium-titanate (PZT) patches and validated the feasibility of the proposed approach numerically and experimentally (Xu et al. 2013, Xu et al. 2017a, Xu et al. 2017b, Xu et al. 2017c, Xu et al. 2018, Wang et al. 2022a, Wang et al. 2022b). Actually, embedded PZT sensors should be installed in the concrete core of CFST members before pouring concrete and are unsuitable for defect detection of existing CFST structures. Surface-mounted PZT actuation and sensing technologies are preferred for existing CFST members. Chen et al. (2019a) and Chen et al. (2019b) verified the viability of an interface debonding detection approach using multi-channel surface wave measurements even the heterogeneity of mesoscale concrete core in CFSTs is considered.

In engineering practice, detecting the size and location of inaccessible defects in CFST members in a visualization way is more attractive. Tomography technology is attractive for reconstructing the internal image using projection data obtained from detection equipment outside the object and can detect defects in a visualization way. Liu et al. (2019) developed a concrete core void and interface debonding imaging method for CFST members according to the travel time of guided waves and numerically validated the validity of the proposed approach. In the study by Liu et al. (2019), the concrete core is modelled as a homogeneous material but the mesoscale heterogeneity and randomness of concrete core are not considered. Moreover, the traditional Snell laws do not work when the wave refraction point is occasionally located at an intersection point of two adjacent imaging elements, which occurs frequently in mesoscale model of concrete core. A more general approach for the determination of the shortest wave travelling path is desired when the mesoscale heterogeneity and randomness of concrete core in CFST members is considered.

In this study, a travelling time tomography imagination method using PZT-based actuating and sensing technologies for the visualization of concrete core void defects in CFST members with mesoscale concrete is proposed and validated numerically. The mesoscale heterogeneity and randomness of concrete core, the multi-physics coupling effect between CFST and PZT patches and the direct and inverse piezoelectric effects of PZT patches in the two-dimensional (2D) multi-physics and mesoscale coupling CFST-PZT model are considered. A random walk algorithm (RWA) is proposed to find the shortest stress wave travelling path from each PZT actuator to each PZT sensor. The velocity field of the CFST member is reconstructed with a simultaneous iterative reconstruction technique (SIRT) to form a tomographic imagination. The accuracy of the tomographic imagination method for concrete core defect visualization in mesoscale CFST members is verified numerically. Results show that the proposed approach can accurately visualize the size and location of concrete core void defects in CFSTs even the mesoscale heterogeneity and randomness of concrete core are considered.

2 CONCRETE CORE VOID DEFECT TOMOGRAPHY IMAGINATION APPROACH IN MESOSCALE CFST MEMBERS

2.1 Random Aggregates Modeling Approach in Mesoscale CFST Members

Firstly, a two-dimensional (2D) rectangular CFST (RCFST) member with randomly distributed circular aggregates in concrete core is established. An ideal gradient curve is used to determine the quantity and dimension of circular aggregates. The interior boundaries of the steel tube of the RCFST member is used as a region for the delivery of randomly generated circular aggregates with the Monte Carlo method. To avoid overlap and contact between any two adjacent circular
aggregates, the distance between their centers of any two aggregates must be greater than the sum of their diameters. The random circular aggregates modeling and delivery method for the mesoscale concrete core in RCFST member can be found in detail in Wang et al. (2022b).

### 2.2 Equations of Multi-physics Mesoscale Coupling RCFST-PZT Systems

The equation of motion for the multi-physics mesoscale coupling RCFST-PZT model can be described by Eq. (1) (Xu et al. 2017a, Xu et al. 2017b, Xu et al. 2017c, Xu et al. 2018):

$$
\begin{align*}
[M] \mathbf{\ddot{u}} + [C] \mathbf{\dot{u}} + [K] \mathbf{\mu} &= \{F\} \\
\end{align*}
$$

where $[M]$ denotes the general mass matrix, $[C]$ represents the damping matrix, $[K]$ is the stiffness matrix, $[K^2]$ stands for the electromechanical coupling matrix and $[K^d]$ is the dielectric matrix, $\{\mu\}$ represents displacement vector and $\{V\}$ is electric potential of the electrode surface, $\{F\}$ and $\{Q\}$ denote the load vector and the electricity of free charge, respectively.

### 2.3 SIRT Tomography Imagination Algorithm with an RWA Method

When the elastic stress wave passes through a discontinuous medium such as heterogeneous concrete in an RCFST, the incident angle of the stress wave shifts as described by the Snell law. Figure 1 shows the Snell law for finding the refraction point, where $V_1$ and $V_2$ represent different wave velocities of the two adjacent elements with different mediums, $K_1$ and $K_3$ are two points located in the two adjacent elements, and $K_2$ is the intersection point, and $\theta_1$ and $\theta_2$ are the angle between the ray and the interface. The shortest wave travelling path point at the interface after refraction is $K_2$, and $\Delta x$ represents the moving distance from $K_2$ to $K_2$.

![Figure 1. Snell law for finding the refraction point.](image1)

![Figure 2. A random walk ray-tracing method.](image2)

![Figure 3. FEM of the mesoscale coupling RCFST-PZT model.](image3)

However, when the refraction point is occasionally located on the intersection of two adjacent finite elements with different wave velocities, which occurs easily when the mesoscale heterogeneous of concrete core is considered, Snell law does not work. In this case, the shortest wave travelling time cannot be detected directly and the imagination for concrete core void might be erroneous. Therefore, in this study, a random walk ray-tracing method combined with the Snell law is proposed as shown in Figure 2. When the refraction point $K_2$ is occasionally located at the intersection of adjacent finite elements as shown in Figure 2, the RWA is adopted to find the shortest wave travelling time path. The refraction point $K_2$ moves randomly along the surrounding finite element boundaries to form four new refraction points $K_2'', K_2''', K_2''''$ and $K_2'''''$, and then the travel times from $K_1$ to $K_3$ passing through each new refraction point is calculated and the shortest wave travelling time path is determined. Then, the travelling time linear equation is established by
using the difference between the propagation time of the stress wave collected by the PZT sensor and the theoretical ray travel time as shown in Eq. (2):

$$A\Delta f = \Delta t$$

where $A$ stands for projection matrix for the length of ray within all imaging elements, $\Delta f$ is the increment matrix for slowness, and $\Delta t$ represents the difference between the travel time of the stress wave collected by PZT sensors and that determined by the theoretical rays.

The SIRT iterative algorithm is used to reconstruct the image of the internal void defect of an RCFST member (Wu et al. 2021). The basic idea of SIRT iterative algorithm is to use the travel time projection error of all rays to correct the wave slowness in each imaging element. The slowness of the $j^{th}$ imaging element $s_j$ can be determined by Eq. (3):

$$s_j = \frac{\sum_{i=1}^{I} t_{ij}(\Delta t_i/\sum_{j=1}^{J} t_{ij})}{\sum_{i=1}^{I} t_{ij}}$$

where $s_j$ represents the slowness of the $j^{th}$ imaging element, $i$ represents the $i^{th}$ ray, $t_{ij}$ stands for the length of the $i^{th}$ ray in the $j^{th}$ imaging element, $\Delta t_i$ denotes the time difference of the $i^{th}$ ray, $I$ means the total number of rays and $J$ stands for the total number of imaging elements.

3 WAVE TRAVEL TIME SIMULATION WITH MULTI-PHYSICS MESOSCALE COUPLING RCFST-PZT MODELS FOR VOID DEFECT IMAGINATION

The finite element model (FEM) of the multi-physics mesoscale coupling RCFST-PZT with randomly distributed circular aggregates is discretized with 2D plane strain elements as shown in Figure 3. An internal void in mesoscale concrete core has a size of 150mm×100mm and the planner size of RCFST member is 410mm×410mm. The steel tube has a thickness of 5 mm. 11 PZT patches with labels of A1-A11 mounted on the bottom surface of the specimen with a horizontal spacing of 35mm are used as actuators and 11 PZT patches labeled as S1-S11 mounted on the opposite side are used as sensors. Each PZT patch has a planner dimension of 10mm×3.3mm. The polarization direction of the PZT patches is in its thickness direction. Concrete is treated as a heterogeneous material. The material properties of mesoscale RCFST members and the equation of the employed pulse excitation signal with an amplitude of 10V can be found in the study of Wang et al. (2022c). For simulation accuracy, the maximum size of each element must not exceed one-fifth of the wavelength (Xu et al. 2018).

Due to the space limitation, only the output voltage time-histories of the eleven PZT sensors in the above mesoscale coupling RCFST-PZT model with and without a void defect when the PZT A6 is used as an actuator under the pulse excitation signal are presented in Figure 4. From Figure 4 (a) and (b), the PZT sensor response amplitude of the healthy mesoscale coupling RCFST-PZT model is obviously higher than them of the model with a void defect. Moreover, the stress wave travelling time delay could be found for the model with a void defect. The stress wave attenuation due to the void defect is clear. As shown in Figure 4 (b), the response of the sensor S6 when actuator A6 is used as the actuator is the largest. When the PZT sensor moves horizontally from the center of the void defect, the amplitude of the collected output time-domain signal reduces gradually and the time delay of stress wave propagation increases. The energy dissipation and attenuation of the stress wave become obvious with the increase of the wave travelling path from A6 to other PZT sensors. From Figure 4, it is worth noting that the output voltage signals of the two PZT sensors with an identical horizontal distance from the center of the upper side are not exactly the same. The effect of the heterogeneity and randomness of the mesoscale structure of concrete core of the RCFST member on the response of two symmetrical PZT sensors is clear.
4 CONCRETE CORE VOID DEFECT IMAGINATION CONSIDERING MESOSCALE HETEROGENEITY AND RANDOMNESS

Using the stress wave propagation and travelling time simulation results determined by the above mesoscale coupling RCFST-PZT models, the concrete core void defect imaging is determined using the SIRT approach based on an initial velocity distribution estimation of the RCFST model shown in Figure 3. The reconstructed imagination by the proposed algorithm is displayed in Figure 5. The void in mesoscale concrete core behaves as a low-velocity region. The solid red rectangle showing the real location of the void is presented in Figure 5 for comparison. It can be found that the boundary of the void defect in the mesoscale concrete core in the RCFST member can be shown clearly. The location and shape of the imagined concrete core void are close to that shown in Figure 3. It is concluded that the location and size of the void defect in RCFST can be determined with acceptable accuracy even the mesoscale heterogeneity and randomness of concrete core are considered. Moreover, as shown in Figure 5, the random distributed circular aggregates in concrete core at mesoscale can also be visualized using the proposed approach and the imagination result of the mesoscale concrete core is close to that shown in Figure 3.

5 CONCLUSION

In this study, a SIRT algorithm for inner void defect visualization in an RCFST member with a mesoscale concrete core model is proposed, and the feasibility of the developed imagination method has been numerically verified with a multi-physics mesoscale coupling RCFST-PZT model where the heterogeneity and randomness of the mesoscale concrete core model, the coupling effect between PZT patches and mesoscale RCFST members, and the direct and inverse piezoelectric effects of PZT material are taken into account. Results show that the location and dimension of concrete core void defect can be imaged with acceptable resolution using the stress wave measurement. The following conclusions can be made:

(1) The influence of the heterogeneity and randomness of mesoscale concrete core on the stress wave propagation in the multi-physics coupling mesoscale RCFST-PZT models is discussed and compared with that of the void defect.

(2) In order to address the difficulty in determining the shortest wave travelling time when the refraction point is located at the intersection of two adjacent imaging elements in the mesoscale coupling RCFST models, the random walking algorithm as an alternative to traditional Snell law is proposed and the theoretical shortest travelling time for stress waves is determined.

(3) By minimizing the difference of the stress wave travelling time collected by PZT sensors and the theoretical shortest travelling time with the SRIT image reconstruction algorithms,
the size and location of the internal void defect and the distribution of the circular aggregates in mesoscale concrete core are visualized. Results show the efficiency and the accuracy of the proposed tomography imagination method for void defect detection of RCFST members even concrete core is considered as a heterogeneous material.

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