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Hasan Mohseni, Ching-Tai Ng

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Rayleigh wave propagation and scattering characteristics at debondings in FRP-retrofitted concrete structures

H. Mohseni and C. T. Ng[1]

School of Civil, Environmental and Mining Engineering, The University of Adelaide,
Adelaide, SA 5005, Australia

Abstract

Structural health monitoring (SHM) is of paramount importance to ensure safety and serviceability of structures. Among different damage detection techniques, guided wave-based approach has been the subject of intensive research activities. This paper investigates the capability of Rayleigh wave for debonding detection in fibre reinforced polymer (FRP) retrofitted concrete structures through studying wave scattering phenomena at debonding between FRP and concrete. A three-dimensional (3D) finite element (FE) model is presented to simulate Rayleigh wave propagation and scattering at the debonding. Numerical simulations of Rayleigh wave propagation are validated with analytical solutions. Absorbing layers by increasing damping (ALID) is employed in the FRP-retrofitted concrete numerical model to maximise computational efficiency in the scattering study. Experimental measurements are also carried out using a 3D laser Doppler vibrometer to validate the 3D FE model. Very good agreement is observed between the numerical and experimental results. The experimentally and analytically validated FE model is then used in numerical case studies to investigate the wave scattering characteristic at the debonding. The study investigates the directivity patterns of scattered Rayleigh waves, in both backward and forward directions, with respect to different debonding size-to-wavelength ratios. This study also investigates the suitability of using bonded mass to simulate debonding in the FRP-retrofitted concrete structures. By enhancing physical understanding of Rayleigh wave scattering at the debonding between FRP/concrete interfaces, this study can lead to further advance of Rayleigh wave-based damage detection techniques.

Keywords: Rayleigh wave, FRP retrofitted concrete, debonding, scattering, guided wave, finite element, experiment, 3D scanning laser vibrometer

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[1] Corresponding author, Email address: alex.ng@adelaide.edu.au

Introduction

Engineering structures provide our cities with crucial services. Therefore, it is highly important to ensure structural integrity, serviceability and safety of our infrastructure. Structural health monitoring (SHM) is defined as the implementation of an integrated sensing/actuating system in engineering structures in order to monitor structural conditions and identify damages through data acquisition and processing[1,2]. In the literature, different non-destructive testing (NDT) methods have been developed, such as magnetic particle testing, dye penetrant testing, radiography, ultrasonics and eddy current technique[3]. While NDT methods mainly provide offline safety inspection of structures, SHM can provide online monitoring and assessment of structural integrity and safety[4].

Among different SHM schemes, guided wave approach has attracted great attention, because it has significant advantages over conventional bulk-wave methods. Guided waves can propagate over relatively long distances[5], while the application of bulk waves is quite local. Other advantages of guided waves include their sensitivity to different shapes and sizes of damages, and their ability to inspect inaccessible structural elements. Research related to guided waves has been extensive over the last two decades[6-10]. A huge amount of research studies have been carried out for guided wave-based damage identification in different types of structures, e.g. cables[11,12], beams[13-17] and plates[18-**Error! Reference source not found.**].

A number of studies utilised guided waves to identify debonding between steel bars and concrete. Wang *et al.*[22] studied on guided wave-based debonding detection between rebars and concrete in reinforced concrete structures using spectral element method and experimental verifications. Ou *et al.*[24] studied on debonding identification between rebars and concrete using guided waves generated and sensed by piezoceramic transducers. Li *et al.*[**Error! Reference source not found.**] employed the guided wave to detect debonding in carbon fibre reinforced polymer concrete beams.

Fibre reinforced polymer retrofitted concrete structures

Reinforced concrete (RC) is one of the commonly used construction materials. As in-service concrete structures age, they may need to be retrofitted for a number of reasons. These include the repair of damaged/deteriorated concrete elements; the correction of design and/or construction errors; and upgrades for higher loading levels[25, 27]. Traditional retrofitting methods involved bonding steel plates or using steel jackets on concrete elements[28]. Those methods required deployment of heavy equipment while the retrofitting steel itself was susceptible to corrosion. The use of fibre reinforced polymer (FRP) composites to retrofit concrete structures has been increasing dramatically[29, 30]. FRPs have high specific strength and stiffness, adjustable mechanical properties, and good resistance to corrosion. However, the long-term performance of FRPs on concrete structures is still a matter of major concern[31, 32].

In FRP-rehabilitated concrete structures, defects can be initiated at any stage of the rehabilitation process. These stages include raw constituent materials, on-site preparation of FRP composites and concrete substrate, installation of FRP composite overlays on concrete elements, and during the service life of FRP-retrofitted concrete structure. For example, epoxy resin defects and the inappropriate installation of FRP composites on concrete substrate can contribute to debonding at the FRP/RC interface[33]. FRP-retrofitted structures will not function properly with the existence of debonding between FRP and the concrete substrate[31]. Therefore, monitoring and inspection of FRP-retrofitted concrete structures need to be done using proper damage detection techniques[28, 34]. So far, some NDT techniques have been employed such as visual inspection, hammer tapping[35] and infrared thermography[36]. However, the literature on damage identification methods in FRP-retrofitted concrete structures is still very limited.

Rayleigh wave

Rayleigh wave is a type of guided waves that propagates along the surface of a semi-infinite solid medium. When a harmonic load or displacement is applied on a half-space, Rayleigh wave will contain the biggest portion of energy when compared to other types of body waves (S-waves and P-waves), and it decays at a much slower rate along the surface[37]. Rayleigh wave propagation characteristics depend on the geometric and mechanical properties of the medium. The characteristics of the wave change in the presence of defects or non-conformities. Therefore, applications of Rayleigh wave to detect surface and near-surface damage in concrete have been considered[38]. A numerical model was developed by Hevin *et al.*[39] to characterise concrete surface crack using Rayleigh wave. Edwards *et al.*[40] used low-frequency, wideband Rayleigh wave for gauging the depth of damage in concrete. Sun *et al.*[41] studied on health monitoring and damage detection in concrete structures using Rayleigh wave generated and received by piezoceramic transducers. A study on the repair evaluation of concrete surface cracks was presented by Aggelis and Shiotani[42] using surface and through-transmission waves. Aggelis *et al.*[43] also deployed surface Rayleigh wave to characterise the depth of concrete surface cracks, which helped evaluate effectiveness of the repair. The aforementioned studies focused on concrete structures only.

In the literature, very limited research has been performed on the use of Rayleigh wave in FRP-retrofitted concrete structures. When Rayleigh wave interacts with debonding between FRP and concrete, wave is scattered and this phenomenon can be used to detect the debonding. To use the Rayleigh wave for identification of debonding between FRP and concrete, it is crucial to gain physical insights into Rayleigh wave propagation and scattering phenomena at the debonding between FRP and concrete. This will help further advance Rayleigh wave-based damage identification methods for the FRP-retrofitted concrete structures.

This paper aims to enhance our understanding of Rayleigh wave propagation and scattering characteristics at the debonding of FRP/RC interface using experimentally verified three-dimensional (3D) finite element (FE) models. In addition, absorbing regions[44, 45] are developed for Rayleigh wave in FRP-retrofitted concrete structures and successfully extended to provide a computational efficient simulation for studying the wave scattering at debonding in the FRP-retrofitted concrete structures in this study.

The organisation of this paper is as follows. The numerical models of the FRP-retrofitted concrete structures are presented in the section ‘Three-dimensional finite element simulations’. Absorbing regions and attenuation due to material damping are also described in this the section. Rayleigh wave propagation properties, such as group and phase velocities and mode shapes, are analytically verified in the section ‘Analytical validation of wave velocity and mode shape’. The experimental validation of Rayleigh wave propagation and scattering is presented in the section ‘Experimental verification’. The experimental setup involves generation of Rayleigh wave with piezoceramic transducers and sensing of signals using 3D laser Doppler vibrometer. Scattering of Rayleigh wave at bonded mass is also investigated and validated using experimental data. The experimentally verified 3D FE model is then used in the parametric case studies to investigate the scattering characteristics of Rayleigh wave at the debonding at FRP/RC interface. The results and discussions are presented in the section ‘Scattering of Rayleigh wave due to debonding at the FRP/RC interface’. Effects of different debonding shapes and sizes on the scattering characteristics of Rayleigh wave at the debonding are also investigated in this section. Finally, the conclusions are drawn in the section ‘Conclusions’.

Three-dimensional finite element simulations

In this study, 3D FE models were developed to simulate Rayleigh wave generation and propagation in FRP-retrofitted concrete structures. The explicit module of ABAQUS, version 6.14, was used to model the FRP-retrofitted concrete, simulate the debonding, generate Rayleigh wave, and calculate the displacement responses at pre-defined measurement locations. The FE simulation results were used to predict the fundamental properties of Rayleigh wave, such as group and phase velocities and mode shapes. These properties were then verified by both analytical solutions and experimental measurements.

Generally, the explicit solution is well suited for short duration, high speed and highly discontinuous dynamic problems. For these types of problems, the explicit procedure offers higher accuracy as well as lower computational cost compared to implicit solution. The central difference method is employed in explicit module of ABAQUS. For wave propagation problems, the time increment required for stability of explicit solution is approximated as $\Delta t_{stable} \approx L_{\min} / c_d$, where L_{min} is the minimum characteristic element dimension and c_d is the dilatational wave speed. In numerical simulations, the stable time increment is automatically chosen by ABAQUS.

Finite element model description

The 3D FE model of the FRP-retrofitted concrete structures consisted of three parts: 1) FRP, 2) concrete, and 3) the absorbing region. This section describes the FRP and concrete modelling. The absorbing region is described in detail in the section 'Absorbing regions by increasing damping for wave scattering analysis'. The dimensions of the FRP used in this study are 300mm×600mm (W×L), and it is attached to the surface of a 300mm×600mm×300mm (W×L×H) concrete block. The 4-ply FRP composite has stacking sequence of [0/0/0/0]. Each lamina is 0.5mm thick. The elastic properties of each lamina are given in Table 1. A mesh converge study was carried out to determine the optimal mesh size. In this study, the FRP is modelled using 2mm×2mm, 4-noded, S4R shell elements with reduced integration. The concrete block is modelled using 2mm×2mm×2mm, 8-noded, C3D8R solid elements with reduced integration. In this study, the geometry of the steel rebars and piezoceramic transducer are also modelled using the C3D8R elements. Tie constraint is used to bond the FRP shell elements and the solid concrete elements. The debonding is created by untying the FRP shell from the concrete solid elements at the disbond area. A schematic diagram of the FE model used in this study is shown in Figure 1.

[Table 1. Elastic properties of FRP lamina]

[Figure 1. Schematic diagram of the FRP-retrofitted concrete FE model]

Based on the literature, a minimum of ten nodes should exist per wavelength to ensure the accuracy of the FE simulated wave signals[46, 47]. In the section 'Analytical validation of wave velocity and mode shape', the wave velocities from 60kHz to 85kHz are validated with the analytical results. After that, 65kHz excitation frequency is considered for the rest of the study. For the excitation frequency ranges from 60kHz to 85kHz, the wavelength is between 24mm and 36mm. Therefore, a mesh size of 2 mm is small enough to ensure the accuracy of simulated Rayleigh wave signals in this frequency range. The Rayleigh wave is generated by applying nodal displacements in radial direction on the nodes located at the circumference of the piezoceramic transducer top surface. The time step is automatically controlled by ABAQUS.

To calculate the group and phase velocities, the out-of-plane nodal displacements are captured at measurement points on the FRP composite. It should be noted that out-of-plane displacement is dominant in Rayleigh wave propagation; therefore, calculations are based on out-of-plane displacements. Group and phase velocity of Rayleigh wave, denoted by C_g and C_p respectively, can be calculated from FE simulations as[48]:

$$C_g = \frac{\Delta x}{\Delta t} \tag{1}$$

$$C_p = \frac{2\pi f_c \Delta x}{\Delta \varphi} \tag{2}$$

where f_c, φ and t denote the central excitation frequency, the phase and the arrival times of signals, respectively. Δx represents the distance between measurement points. The arrival time of a signal is calculated from a signal envelope obtained by the Hilbert transform[14].

Figure 2 presents snapshots of the out-of-plane displacement contours for the Rayleigh wave propagation and scattering waves at the debonding in the FRP-retrofitted concrete structure. Figure 2a displays the propagation of the Rayleigh wave in the FRP-retrofitted concrete model before they reached the debonding at the FRP/RC interface. After the interaction of the incident wave with the debonding, the incident wave is transmitted through and reflected back from the debonding as shown in Figure 2b. Figure 2 demonstrates that the

Rayleigh wave is sensitive to the debonding between the FRP and concrete. Therefore, it is feasible to detect the debonding using Rayleigh wave. This highlights the major importance of investigating characteristics of the scattered Rayleigh wave at debonding at the FRP/RC interface.

[Figure 2. Typical contour snapshots of out-of-plane displacement for numerical FRP-retrofitted concrete model with a circular debonding at FRP/concrete interface, (a) before Rayleigh wave reach debonding and (b) after interaction of Rayleigh wave with debonding, deformation]

Absorbing regions by increasing damping for wave scattering analysis

As discussed in the section 'Finite element model description', the FE element size was set to 2mm, based on the wavelength of the excited Rayleigh wave. However, the numerical study of the scattered wave characteristics needs to be carried out in an FRP-retrofitted concrete model that is representative of real conditions, i.e. large size of a structure. Modelling the actual size of a structure results in a large number of FE elements, which is computationally very expensive. Since the wave propagation is a local phenomenon and the purpose of the study is to examine the characteristics of the wave scattered at the debonding, only a section of the FRP-retrofitted concrete model is modelled in the study. Absorbing regions were employed to avoid the wave reflections from the boundaries of the FRP-retrofitted concrete model, and hence, a small section of the FE model can be used to represent a large structure. Therefore, the computational cost can be significantly reduced for investigating the scattering characteristics of the Rayleigh wave at debonding in the FRP-retrofitted concrete structure.

Absorbing layers by increasing damping (ALID) is proposed and implemented in commercial FE software for guided wave problems[49]. In this method, successive layers with gradually increasing values of damping are added to the extremities of a main structure. According to Rayleigh damping relation, damping can be expressed as a linear combination of mass and stiffness as:

$$[C] = \alpha[M] + \beta[K] \tag{3}$$

where α and β denote mass-proportional and stiffness-proportional damping coefficients, respectively. To employ the ALID in explicit FE simulation, stiffness-proportional damping is to be set to zero in order to limit the effects on stable time increment. Then, mass-proportional damping across absorbing layers can be expressed as[45]:

$$\alpha(x) = \alpha_{max} X(x)^P \tag{4}$$

To implement the absorbing layers in the FRP-retrofitted concrete structure, the ALID was separately applied to the FRP shell element and the concrete solid element models, respectively. For the purpose of the present scattering study, the target of the ALID is to reduce the maximum magnitude of the waves reflected from the boundaries to less than -46 dB. The excitation frequency used in the scattering study was 65kHz. At this frequency, the width of the absorbing region was determined to be 80mm. The absorbing regions were applied to all four sides of the FRP and concrete and also concrete bottom. Each of the absorbing regions had 40 layers of elements with gradually increasing values of damping. The thickness of each layer was 2mm, which was equal to the element size. Using Equation 4, P was set to 3 and α_{max} was 2.5×10^6. A schematic diagram of the ALID in FRP-retrofitted concrete model is shown in Figure 3.

[Figure 3. Schematic diagram of absorbing regions for wave scattering studies]

Figures 4a to 4d show the Rayleigh wave propagation on the FRP-retrofitted concrete with and without absorbing layers. Figure 4a and 4b show the typical out-of-plane displacement contours for the FE model without absorbing layers. In these figures, both incident wave and boundary reflections are obvious. Figures 4c and 4d display the out-of-plane displacements in the FE model with absorbing region and they show that Rayleigh wave gradually diminishes in the absorbing layers.

*[*Figure 4. *Typical contour snapshots of out-of-plane displacement for Rayleigh wave in FRP-retrofitted concrete model without and with absorbing layers. (a) When the incident wave is interacted with the boundary, (b) soon after the wave reflection. (c) When the incident wave is being absorbed by the absorbing region, (d) soon after the wave absorption]*

Material damping

When the waves propagate in composites, the energy of the wave dissipates due to the viscoelasticity of the waveguide[6]. The attenuation coefficient k_i can be determined by fitting the curve of the signal data using the following relationship[50,51]:

$$\frac{A_1}{A_2} = \exp\left(\mathrm{k}_i(x_2 - x_1)\right) \tag{5}$$

where A_1 and A_2 are the wave amplitude at locations x_1 and x_2 respectively. Based on the value of k_i, the mass-proportional and stiffness-proportional damping constants for a particular angular frequency could be calculated as:

$$\alpha_\omega = 2k_iC_g \tag{6}$$

$$\beta_\omega = \frac{2k_iC_g}{\omega^2} \tag{7}$$

where α_ω , β_ω , C_g and ω represent the mass-proportional damping constant, the stiffness-proportional damping constant, the group velocity and the angular frequency, respectively.

Analytical validation of wave velocity and mode shape

The analytical validation of the FE model is achieved by comparing the results of the FE simulations and DISPERSE. DISPERSE is capable of calculating both group and phase velocities, and mode shapes of the guided waves in multi-layer structures. DISPERSE was developed based on global matrix method[52]. In this method, the propagation of waves in each layer can be described and related to displacements and stresses at any location in the layer through a field matrix. The filed matrix coefficients depend on through-thickness position in the layer and mechanical properties of the layer material. The assembly of field matrices form the global matrix. The whole system is modelled by superposition of wave components and the imposition of boundary conditions at the interface of each two adjacent layers. Figure 5a compares the group and phase velocities of the FRP-retrofitted concrete structure calculated using FE simulations and DISPERSE. Figure 5b displays percentage difference between numerical and analytical results of group and phase velocity. As shown, the group and phase velocities calculated using the FE simulations matches quite well with the results calculated from DISPERSE.

[Figure 5. (a) Numerical and analytical values of group and phase velocity (b) Percentage difference between numerical and analytical results]

To further validate the FE results, the in-plane and out-of-plane displacement mode shapes of Rayleigh wave at the frequency of 65kHz are compared and verified with DISPERSE. The results are shown in Figure 6. The mode shapes indicate the deformation along the thickness direction during the Rayleigh wave propagation in the FRP-retrofitted concrete. The Rayleigh wave mode shapes shown in Figure 6 were obtained by capturing both in-plane and out-of-plane displacements at vertical measurement points along a cross-section of the FRP-retrofitted concrete. As expected, the deformation of the Rayleigh wave is concentrated on the surface of the waveguide, which is consistent with the nature of the Rayleigh wave, i.e. wave travel along the surface of the solids. Figures 5 and 6 show that there is good agreement between the results calculated by FE and DISPERSE.

[Figure 6. Analytical and numerical mode shapes for FRP-retrofitted concrete model]

Experimental verification

Experimental setup

To study Rayleigh wave propagation and scattering characteristics at debonding in the FRP-retrofitted concrete structures, two concrete blocks with the Young's modulus of 26.8GPa, density of 2350kg/m^3 and a maximum aggregate size of 10mm were cast and cured. The dimensions of the concrete blocks are 300mm×600mm×300mm (W×L×H). Concrete Specimen 1 has no reinforcement, while Specimen 2 has four 16mm diameter rebars at four corners of the cross section, with 6cm of concrete cover as shown in Figure 1.

Before application of the FRP, the concrete blocks were sandblasted in order to remove laitance and contaminants. Four layers of 300mm×600mm unidirectional carbon fibre with a stacking sequence of [0/0/0/0] were bonded on the concrete surface using a hand lay-up method. Each fibre layer was saturated by BASF MasterBrace 4500 epoxy resin and applied to the concrete block. The constructed 4-ply FRP-bonded concrete was then left at room temperature to cure and harden.

The Rayleigh wave were generated and measured using a piezoceramic transducer and a Polytec PSV-400-3D laser Doppler vibrometer, respectively. The laser Doppler vibrometer system includes a data management system, three sensor heads and vibrometer controllers, and a junction box as shown in Figure 7. The data management system PSV-W-400 incorporates a computer, a built-in signal generator, and a data acquisition unit. The excitation signal was a narrow-band 5-cycle sinusoidal tone burst pulse modulated by a

Hanning window. The central frequency of the excitation signal was 65kHz, which ensures minimum reflections from the concrete aggregates[53]. The signal was generated at 4.3V, which was amplified four times by a Playmaster SERVO amplifier before being sent to the actuator. The actuator was a 10mm diameter circular and 2mm thick piezoceramic transducer bonded on the FRP surface. The Rayleigh wave signals were sensed by three PSV-I-400 sensor heads controlled by the OFV-5000 vibrometer controllers. The interface between the sensor heads, vibrometer controllers, and data management system was provided by a PSV-E-400 junction box. The sampling frequency of the measurement system was set to 2.5MHz. To improve the signal quality and reduce the signal-to-noise ratio (SNR), an averaging of 2000 times of the signals was carried out. The acquired data was fed into the computer, from which output results were obtained.

[Figure 7. Schematic diagram of the experimental setup]

Rayleigh wave propagation in FRP-retrofitted concrete

To experimentally validate the accuracy of the FE model, the 3D laser Doppler vibrometer was used to measure the Rayleigh wave signals. The measured data was then compared with the FE simulation results. To ensure the numerical and experimental results can be compared directly, the maximum absolute amplitude of signals was normalised to be one. As explained in the section ‘Finite element model description’, the FRP-retrofitted concrete was modelled in FE with real dimensions; i.e. four layers of 300mm×600mm FRP bonded on 300mm×600mm×300mm concrete. Since the arrival time and magnitude of the boundary reflections needed to be verified with experiments, absorbing layers were not applied to the FE models in the experimental validation. Concrete Specimen 1, which has no rebar and no debonding at the FRP/RC interface, is used to verify the Rayleigh wave propagation. Based on the Cartesian coordinate system shown in Figure 1, Rayleigh wave was actuated at x = 516mm and z = 190mm. The out-of-plane displacements were measured at x = 376mm and z = 190mm. As shown in Figure 8, there is good agreement between the FE calculated and experimentally measured results.

[Figure 8. FE calculated and experimentally measured Rayleigh wave signals for Concrete Specimen 1 (without rebar)]

Reinforcement in concrete is usually in the form of steel bars; therefore, the FE model with rebar needs to be experimentally verified. Four layers of FRP were bonded onto Concrete Specimen 2, which has longitudinal steel bars. The dimensions of the numerical model and the experimental specimen are the same, and absorbing layers were not applied to the FE model. There was no debonding in the FRP-retrofitted concrete structure. The Rayleigh wave was generated at x = 170mm and z = 120mm. The out-of-plane displacements were sensed at x = 120mm and z = 120mm using the 3D laser Doppler vibrometer. A very good agreement on the arrival time and magnitude is observed between the numerical and experimental signals as shown in Figure 9.

[Figure 9. FE calculated and experimentally measured Rayleigh wave signals for Concrete Specimen 2 (with rebar)]

A polar directivity plot of the maximum absolute amplitude of the incident wave is shown in Figure 10. The out-of-plane displacements were sensed at 36 points, with a circular path of r = 50mm, $0° \leq \theta \leq 360°$, and step increments of 10°. The piezoceramic transducer was located at the centre of the circular path. Figure 10 shows the amplitude of the excited Rayleigh wave in different propagation directions. Since the concrete is retrofitted by 4-ply unidirectional FRP on the surface, the amplitude distribution of the Rayleigh wave has anisotropic behaviour. To compare the numerical and experimental results, the amplitude at each point is normalised to the maximum absolute amplitude of all points. As shown in Figure 10, there is good agreement between the numerical and the experimental results.

[Figure 10. Polar directivity of the normalised amplitude of Rayleigh incident wave measured on a circular path with r = 50mm, $0° \leq \theta \leq 360°$ and the actuator located at the centre]

To investigate the attenuation of Rayleigh wave in FRP-retrofitted concrete, the out-of-plane displacements were measured at $20\text{mm} \leq r \leq 160\text{mm}$ away from the piezoceramic transducer, along the direction $\theta = 0°$. Because of the possible non-uniformity of the FRP-retrofitted concrete specimen, four different locations of the piezoceramic transducer were considered. The wave signal at each measurement point was normalised by the maximum absolute amplitude of the signal at r = 20mm, so that the numerical and experimental results could be compared. Figure 11 shows the normalised maximum amplitude of the incident wave signals as a function of the distance from the piezoceramic transducer. Using Equation 5, the attenuation coefficient for this FRP-retrofitted concrete structure is k_i =2.87Np/m. Considering Equations 6 and 7, the calculated damping constants are α_ω = 12,065rad/s and β_ω = 7.234×10^{-8}s/rad.

[Figure 11. Attenuation of surface waves in FRP-retrofitted concrete]

Rayleigh wave scattering at bonded mass

To further validate the 3D FE model, experimental measurements are also used to validate the Rayleigh wave scattering phenomenon. In this section, the accuracy of the 3D FE model in predicting the scattering waves are investigated by means of the scattering directivity pattern (SDP)[54], which displays the maximum amplitude of the scattered signal as a function of the angular direction of the measurement points. To obtain the scattered wave signals for calculating the SDP, it requires the baseline data obtained from undamaged structures for extracting the scattered wave signals. Although this is practical in real SHM applications, it is hard to obtain the baseline data for delamination/debonding type of damages in the wave scattering study. Therefore, the bonded mass is used to verify the accuracy of the 3D FE in predicting the SDP. In addition, the damage has been frequently simulated bonding masses to surface of the structures for verification of damage detection method[55, 56]. It is still an open question whether or not the debonding can be well represented by bonding masses to the surface of the retrofitted concrete structure. The suitability of using bonded mass to represent the debonding is also investigated in the section 'Scattering of Rayleigh wave due to debonding at the FRP/RC interface'.

Based on the polar coordinate system as shown in Figure 1, the piezoceramic transducer was located at r = 110mm and θ = 180°. The out-of-plane displacements were sensed by the 3D laser Doppler vibrometer at 36 points on a circular path with r = 50mm, 0° ≤ θ ≤ 360° and step increments of 10°. The measurements were obtained before and after a 40mm cubic steel mass bonding onto the FRP with the centre of the mass area located at r = 0mm and mass edges parallel to the x or z axis. The measured signal at each point was normalised by the maximum absolute amplitude of the signal at θ = 180° in the model without the bonded mass. After that, the scattered waves were obtained by subtracting the signals without the bonded mass from the signals with the bonded mass. The magnitudes of the scattered waves at different directions are then calculated and represented by the SDP.

In the FE simulations, the same measurement location and excitation frequency are used. The bonded mass was modelled in FE simulation using C3D8R solid elements with the same dimensions and mechanical properties as the bonded mass used in the experiments. Two simulations, one with bonded mass and the other without the bonded mass, were carried out to obtain the scattered wave signals for calculating the SDP.

Figure 12 compares the FE simulated and experimentally measured signals before and after bonding the mass on the FRP. The numerical results match quite well with the experimental results. As shown in Figure 12, the bonded mass has the maximum effect on the measured signal, from angle $\theta = 60°$ to $\theta = 300°$ (clockwise) with a reduction of up to 50% in wave magnitude. The scattered signal at each measurement point is the difference between the baseline signal (without a bonded mass) and the signal measured with the mass bonded. Figure 13 shows the Rayleigh wave SDP for the 40mm cubic bonded mass. The figure shows amplitude of the scattered wave in different directions, which indicates the energy distribution of the scattered wave signals. There is good agreement between the FE results and the experimental measurements. The results show that the maximum magnitude of scattering waves is around 0.35 and 0.20 for forward and backward scattering direction, respectively. As shown in Figure 13, the scattered wave energy concentrates in the forward scattering direction.

[Figure 12. Normalised polar directivity pattern for the measured signal, with and without cubic 40mm bonded mass.]

[Figure 13. SDP for a cubic 40mm bonded mass.]

Scattering of Rayleigh wave due to debonding at the FRP/RC interface

Experimental verifications of the numerical models have been presented in the section 'Experimental verification'. It has demonstrated that the 3D FE model can precisely simulate the propagation of Rayleigh wave in FRP-retrofitted concrete structures and scattering of wave at the bonded mass. Also, group and phase velocity and mode shapes of Rayleigh wave have been analytically verified in the section 'Analytical validation of wave velocity and mode shape'. The experimentally and analytically validated 3D FE model is then used to study the scattering characteristics of Rayleigh wave at the debonding at FRP/concrete interface in this section.

Effects of rebars

To investigate the effects of embedded steel rebars on Rayleigh wave propagation, two FRP-retrofitted concrete models are considered: one with rebars, and the other without rebars. The Rayleigh wave was generated at x = 170mm and z = 120mm. The out-of-plane displacements were measured at x = 120mm and z = 120mm. In the model with rebars, reflections can come from both rebars and boundaries. As explained in the section 'Absorbing regions by increasing damping for wave scattering analysis', absorbing layers were applied to all boundaries of both models to remove all boundary reflections. Therefore, only the incident waves and the rebar reflections can be seen in the signals. As illustrated in Figure 14, the rebars have a minor effect on the incident waves, and only cause some reflections of body waves. It means that in Figure 9, the first reflected signal coming after the incident wave is a combination of the rebar reflections and boundary reflections. The rebar reflections exist in the signals of both intact model and the model with the debonding. Since the baseline subtraction method[57, 58] is applied to obtain scattered wave signals from the debonding, the rebar reflections have a minimal effect on the scattered waves.

[Figure 14. Effect of rebars on Rayleigh wave propagation]

Effect of debonding shape and size

According to the polar coordinate system shown in Figure 1, Rayleigh wave is actuated at r = 110mm and θ = 180°. For each debonding case, two sets of FE simulations were performed, one without debonding and the other with debonding. The scattered signal was obtained by subtracting the signals of the model without the debonding from the model with the debonding[59]. Absorbing layers were applied in all FE models. Two different shapes of debonding, rectangular and circular debonding, are considered in this study. To examine effects of the debonding size on the scattering wave, results are presented in terms of R_{DW}. For rectangular and circular debonding, R_{DW} is defined as the ratio of the debonding size to wavelength, and the debonding diameter to wavelength, respectively. The wavelength of Rayleigh wave at the frequency of 65kHz is around 32mm. Rectangular debondings with sizes and circular debondings with diameters of 10, 16, 20, 24, 30, 36, 40, 44, 50, 56 and 60mm are considered in this section.

For all rectangular debonding cases considered in this study, the centre of the debonding area is located at $r = 0$mm and debonding edges are parallel to the x- or z-axis. The out-of-plane displacements are measured at 36 points, at $r = 50$mm, $0° \leq \theta \leq 360°$ at intervals of 10°. The signal at each measurement point is normalized by the maximum absolute amplitude of the incident wave at $r = 50$mm and $\theta = 180°$. Figure 15 displays the SDP for 40mm×40mm rectangular and 40mm diameter circular debonding. It has been shown that the amplitude of the forward scattering direction is larger than that of the backward scattering direction. The amplitude distribution of the forward scattering waves is quite similar for both rectangular and circular debonding. The maximum amplitude of the forward scattering wave occurs at $\theta = 0°$ with magnitudes of 0.298 and 0.272 for rectangular and circular debonding, respectively. The maximum amplitude of the backward scattering occurs at $\theta = 180°$, with magnitudes of 0.091 and 0.046 for rectangular and circular debonding, respectively.

[Figure 15. SDP for 40mm×40mm rectangular debonding and 40mm diameter circular debonding]

To demonstrate the effects of debonding size and shape on the scattering phenomenon, the normalized forward and backward scattering amplitude of rectangular and circular debondings are displayed as a function of R_{DW} in Figures 16 to 19. The forward scattering results are presented in Figures 16 and 17 at $\theta = 90°, 60°, 30°, 0°, 330°, 300°$ and 270°. The backward scattering results are presented in Figures 18 and 19 at $\theta = 90°, 120°, 150°, 180°, 210°, 240°$ and 270°.

[Figure 16. Normalized amplitude for the forward scattering of rectangular debonding as a function of debonding size to wavelength ratio]

[Figure 17. Normalized amplitude for the forward scattering of circular debonding as a function of debonding diameter to wavelength ratio]

[Figure 18. Normalized amplitude for the backward scattering of rectangular debonding as a function of debonding size to wavelength ratio]

[Figure 19. Normalized amplitude for the backward scattering of circular debonding as a function of debonding diameter to wavelength ratio]

Figure 16 displays the normalised amplitude of the forward scattering wave for rectangular debonding as a function of debonding size to wavelength ratio. At $\theta = 0°$, the scattering amplitude rises quite sharply to 0.298 at $R_{DW} = 1.25$ and then falls slightly to 0.280 at $R_{DW} = 1.563$. After that, it increases sharply again to 0.397. For $\theta = 30°$ and 330°, the amplitude increases steadily to 0.263 with a small decrease at $R_{DW} = 0.50$. The magnitudes of the scattering amplitude at $\theta = 60°$ and 300°, and $\theta = 90°$ and 270° exhibit moderate fluctuations with R_{DW}.

Figure 17 shows the normalised amplitude of the forward scattering of circular debonding as a function of the debonding diameter to wavelength ratio. The amplitude at $\theta = 0°$ increases constantly to a peak of 0.360. The rise in amplitude is sharper for $R_{DW} \leq 1.375$. For $\theta = 30°$ and 330°, the amplitude rises steadily to 0.193 except for a small decline at $R_{DW} = 0.50$. The forward scattering amplitudes at $\theta = 60°$ and 300°, and $\theta = 90°$ and 270° show a similar trend to those of the rectangular debonding. For both rectangular and circular debondings, the forward scattering amplitudes at $\theta = 60°$ and 300°, and $\theta = 90°$ and 270° are considerably smaller than those at $\theta = 0°$, $\theta = 30°$ and 330° especially for larger values of R_{DW}. Therefore, selecting an appropriate measurement direction is critical in the damage detection.

The normalized amplitude for backward scattering of rectangular debonding as a function of debonding size to wavelength ratio is shown in Figure 18. It is obvious that the overall trend of the backward scattering is quite different to that of the forward scattering. For $\theta = 180°$, which is along the incident wave direction, the backward scattering amplitude first rises to a local peak and then drops to $R_{DW} = 0.625$. The amplitude then increases steeply to a peak of 0.092 at $R_{DW} = 1.25$, and decreases sharply to 0.056. After this point, it increases gradually to 0.070. The trend at $\theta = 150°$ and 210° is of a slow increase with moderate fluctuations. The amplitude at $\theta = 120°$ and 240° shows some variations without a dominant trend.

Figure 19 shows the normalised amplitude of the backward scattering for circular debonding as a function of debonding diameter to wavelength ratio. For $\theta = 180°$, the amplitude rises dramatically and then falls sharply at $R_{DW} = 0.5$. The amplitude then has an increasing trend with fluctuations. The amplitude at $\theta = 150°$ and 210° starts with a rapid increase and a sharp decline at $R_{DW} = 0.5$. Then, an increasing trend is observed and it reaches a peak at $R_{DW} = 1.75$. For $\theta = 120°$ and 240°, the amplitude shows a gradual decrease for R_{DW}

less than 0.938 and then they have moderate fluctuations. In general, the magnitudes of the backward scattering amplitude at $\theta = 120°$ and $240°$ are smaller than those at $\theta = 180°$, $\theta = 150°$ and $210°$.

For both rectangular and circular debondings, a major, increasing trend is obvious for the forward scattering amplitude at the same direction of the incident wave ($\theta = 0°$) and also at $\theta = 30°$ and $330°$. The trend for the backward scattering is complicated and shows some fluctuations. It is shown that Rayleigh wave are sensitive to the debonding between FRP and concrete. However, measurement direction should be chosen appropriately in the damage detection.

Conclusions

This paper has presented a study into Rayleigh wave propagation in FRP-retrofitted concrete structures, and wave scattering at the debonding between FRP and concrete. The 3D FE model has been used for the numerical simulations. The numerical results of group and phase velocity, and of mode shapes of Rayleigh wave, have been verified by analytical solutions. The experimental measurements have been carried out on FRP-retrofitted concrete specimens. Very good agreement has been observed between the numerically simulated and experimentally measured Rayleigh wave signals. Additionally, the numerical results of the Rayleigh wave scattering at the bonded mass have been proved by experiments. By analytical and experimental validation of the numerical results, it has been demonstrated that the 3D FE model can accurately simulate the propagation and scattering of Rayleigh wave in FRP-retrofitted concrete model.

Further numerical case studies in this paper have focused on the directivity pattern of scattered signals at debonding, with regard to R_{DW}. For small values of R_{DW}, magnitudes of forward and backward scattering are close. For larger values of R_{DW}, the forward scattering is more sensitive to debonding than backward scattering, demonstrating larger magnitudes and a less complicated directivity pattern. It has been shown that the forward scattering for rectangular and circular debonding follows a similar trend while rectangular debonding demonstrates slightly larger magnitudes. Rectangular debondings cause larger backward scattering than do circular debondings; however, the trend of backward scattering is complex for both debonding shapes.

The study has gained physical insights into the scattering of Rayleigh at debondings and proved the sensitivity of Rayleigh wave to debonding between FRP and concrete. It has been demonstrated that it is feasible to use the Rayleigh wave to detect the debonding between FRP and concrete. The findings of this study can further advance the research development in this area.

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