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Guided wave propagation for assessment of adhesive bonding between steel and concrete

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Abstract

Adhesive bonding is becoming more increasingly important in joining of structural elements. In civil engineering, there is a growing interest in connection by adhesive bonding in steel-concrete flexural members. This study concerns the guided wave propagation technique applied to condition assessment of an adhesive connection between a steel member and a concrete beam. Various states of degradation were considered by producing several laboratory samples differing in the placement and the length of the adhesive bond. Piezoelectric transducers were used to excite and to register signals of propagating waves. In addition, the finite elements method was used to simulate propagation of guided waves at the bond-line between steel and concrete. Results for the beam with perfect bonding were compared with results obtained for beams with partially degraded connections. The influence of the length of damaged bond and its position on registered signals was investigated.

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Keywords: guide waves, diagnostics, bonding quality, reinforcement structures, debonding detection

1. Introduction

In recent years, significant effort has been dedicated to improve methods of strengthening damaged structures without the need of replacing the entire elements or substructures. One of the ways to strengthen the structural elements, among them prestressing, redesigning a size of their cross-section or a static scheme, is appending external reinforcement. The reinforcement may be in the form of tapes, mats or profiles made of metal or composite

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materials (e.g. [1-4]). The main condition for the effective reinforcement is good quality of adhesive bonding between the reinforcement and a repaired structure. Therefore, there is a need to develop effective methods for assessment of adhesive bonding. Of particular interest are techniques based on elastic wave propagation. Wave propagation techniques have been successfully used in determining the bonding length between a steel bar and concrete [5, 6] or detection of debonding between two steel plates [7-9], however the examples of their usage in diagnostics of bonding quality in strengthened concrete beams are still very limited.

The aim of this study is application of the guided wave propagation method for the condition assessment of an adhesive connection between a steel member and a concrete beam. Various states of degradation are considered by producing several laboratory samples differing in the placement and the length of the adhesive bond. Results for the beam with perfect bonding are compared with results obtained for beams with partially degraded connections. The influence of the length of damaged bond and its position on registered signals is investigated.

2. Wave propagation in structures consist of different materials

Wave propagation in a structure consisting of materials with different parameters is associated with the energy transmitting into bordering medium and wave reflecting from the border of the media. The intensity of wave transferring (leakage) into the surrounding medium depends on acoustic impedances of adjacent media, which are functions of basic material parameters: the density and modulus elasticity. The proportion between the energy of reflected and transmitted waves depends on the relation between impedances. The smaller difference in impedances, the greater amount of energy is transmitted into the surrounding medium. Because of the energy leakage, the use of guided waves in the diagnosis of composite elements (e.g. made of steel and concrete) is significantly more complex than in simple steel structures. The wave leakage is related with the amplitude decrease and therefore the interpretation of signals registered for concrete-steel elements can be complicated because of a lack of isolated amplitude peaks.

3. Experimental and numerical investigations of wave propagation in concrete beams

3.1. Description of specimens

Numerical and experimental investigations were carried out on laboratory models of concrete beams having a cross-section of 4 cm × 4 cm and a length of 16 cm (Fig. 1). The geometry of the typical specimen is presented in Fig. 1. The specimens were made of concrete with a density $\rho = 2362.5$ kg/m^3. Mechanical properties – the elasticity modulus $E = 44$ GPa, the Poisson's ratio $\nu = 0.2$ – were determined using non-destructive methods. Before experimental tests, the beams were left to cure in order to obtain the full strength of concrete.

The beams were strengthened by the external reinforcement in the form of a steel plate with a thickness of 1 mm and dimensions of 4 cm × 16 cm. The material parameters of steel were: $E = 210$ GPa; $\nu = 0.3$; $\rho = 7781$ kg/m^3. The plate was attached to the beam by adhesive bonding using epoxy glue. Different cases of state of adhesive bonding between steel and concrete were analyzed. The test specimens included four beams with variable length of debonding length L_d equal to 0%, 25%, 50% and 75% of total length of the beam.

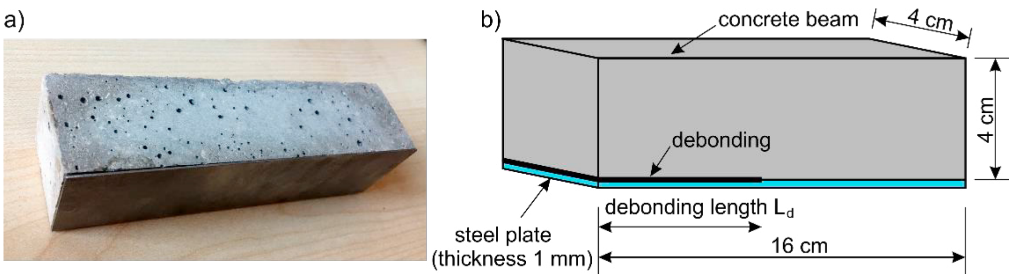

Fig. 1. Investigated concrete beam: (a) general view; (b) geometry and dimensions.

3.2. Numerical model

Numerical calculations of guided wave propagation were performed by the finite element method (FEM) in the Abaqus environment. Three-dimensional FEM model of the concrete beam was developed in the Abaqus/Explit module using 8-node bilinear axisymmetric quadrilateral elements with reduced integration (C3D8R). The connection between the concrete part and steel reinforcement was modelled as a tie constrain. The concrete part was discretized into elements with dimensions 1 mm × 1 mm × 1 mm, while the steel plate was divided into elements of dimensions 1 mm × 1 mm × 0.3 mm. The boundary conditions were assumed as free on all edges. The integration time step was equal to $\Delta t = 10^{-7}$ s.

3.3. Experimental set-up

The instruments used in this study included the PAQ 16000D device for generation and registration of wave signals and the plate piezo actuators Noliac NAC2011 used for both actuation and sensing of guides waves. The excitation signal was a ten-cycle sine function with a carrier frequency of 60 kHz modulated by the Hanning window.

The distribution of measurement points is illustrated in Fig. 2. The waves were induced in the direction perpendicular to the steel plate, thus the sensor measured acceleration of vibrations caused by the motion of antisymmetric waves propagating in the plate. Two configurations were applied in the performed experimental tests. In the first case (configuration #1) the actuator (denoted as *A* in Fig. 2) and sensor (denoted as *S*) were attached to the end with the intact bonding between concrete and reinforcement. In the second configuration (#2) the actuator *A* and sensor *S* were attached at the end with the damaged bonding.

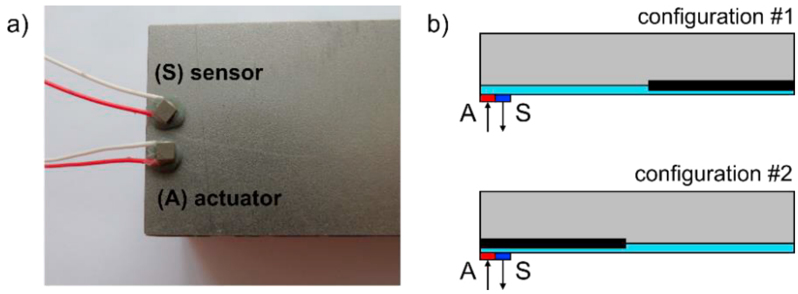

Fig. 2. Measurement points: (a) view of piezo actuators; (b) configurations of piezo actuators.

4. Results

4.1. Numerical results

The snapshots of propagating waves at selected time instants in the specimen with 50% debonding are given in Fig. 3 and Fig. 4. For configuration #1, the wave excited in the steel plate immediately leaks into the concrete part (Fig. 3a and 3b). Because of the perfect bonding, at the interface between steel and concrete the condition of continuity of the stresses and strains must be satisfied. One can see in Fig. 3b that deformation caused by the wave motion at the border of media is the same. The greatest deformation is caused by the surface wave propagation.

For configuration #2, the wave energy leakage is initially impossible and the wave travels only in the steel reinforcement. For this reason the amplitude of deformation is the steel part is larger than in the previous case, while in the concrete part any wave motion is observable (Fig. 4a and 4b). The propagating wave is reflected from side edges of the plate and travels back (Fig. 4b). The part of the energy propagates along the steel reinforcement and it is diffracted at the place where the plate is bonded with the concrete beam (Fig. 4c). The diffracted wave is transmitted into concrete and it starts propagating back and forward along the beam (Fig. 4d). After the wave leakage into the beam, the amplitude of deformation in the plate decreases rapidly (Fig. 4e and 4f).

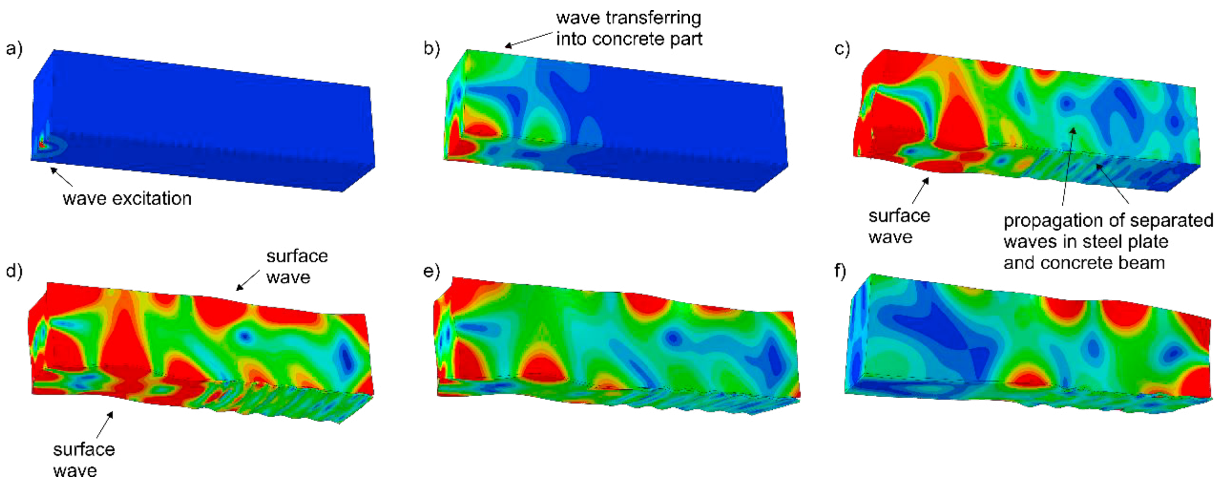

Fig. 3. Snapshots of propagating waves (magnitude of acceleration) in the beam with debonding length equal to 50% (configuration #1 of actuator and sensor) at selected time instants: (a) 0.02 ms, (b) 0.05 ms, (c) 0.10 ms, (d) 0.14 ms, (e) 0.18 ms, (f) 0.21 ms.

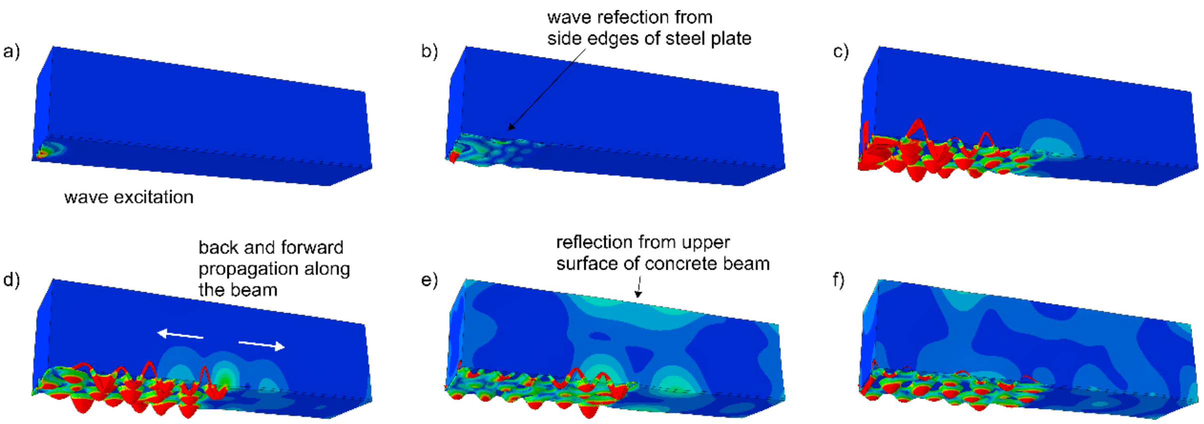

Fig. 4. Snapshots of propagating waves (magnitude of acceleration) in the beam with debonding length equal to 50% (configuration #2 of actuator and sensor) at selected time instants: a) 0.02 ms, b) 0.05 ms, c) 0.11 ms, d) 0.14 ms, e) 0.18 ms, f) 0.21 ms.

4.2. Experimental results

The first analysis concerned results obtained for the variable length of the adhesive bonding. The registered wave propagation signals are given in Fig. 5. For signals registered at the intact end of the beam (configuration #1) the first peak occurred at the same time for all cases of the debonding length, but its value varied for particular specimens (Fig. 5a). The highest values of the amplitude of the first peak was observed for beams with relatively long debonding (50% and 75%), while the signal for the beam with short debonding (25%) was characterized by smaller amplitude value, very close to the amplitude of the signal for fully bonded beam. Moreover, it is clearly visible that the amplitude decayed as the time gone on in every case regardless of the debonding length, but generally the decrease of the amplitude with time was greater for longer deboning lengths. The decrease of the amplitude was caused by the transfer of the wave energy into the concrete part. The wave motion in the beam was damped more intensively than in the plate because of irregular microstructure of concrete. The longer healthy connection was, the more energy was transferred in concrete and in consequence damped.

Results for configuration #2, with the actuator and sensor attached to the damaged end of the beam, are given in Fig. 5b. Contrary to the previous case, the first peak value was not observed at the same time for every debonding length. For configuration #1 single peak was registered at the beginning of the signal, while for configuration #2 two peaks occurred and furthermore the second peak in two cases (debonding of 75% and 25%) was characterized by higher value than the first one. Moreover, there was no clear relationship between the amplitude decay and the debonding length.

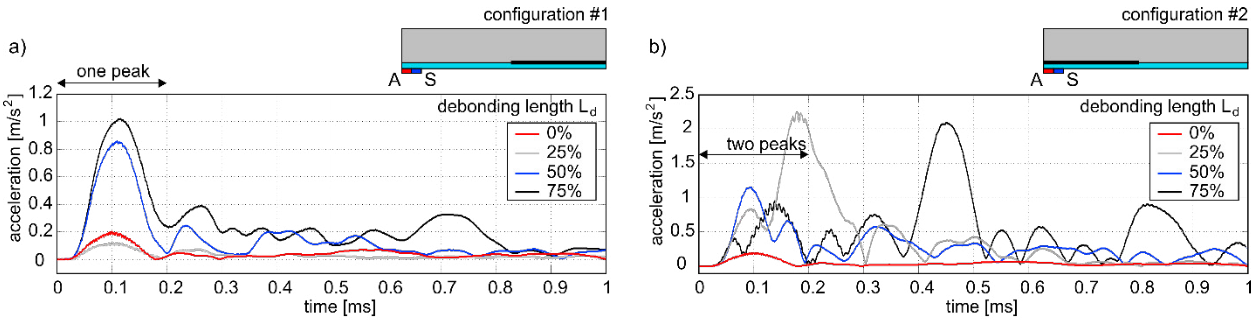

Fig. 5. Envelopes of signals registered for beams with various debonding length: (a) configuration #1; (b) configuration #2.

The aim of the second analysis was to compare the results for the same debonding length but for various configurations of the actuator and sensor. According to FEM visualizations given in Fig. 3 and Fig. 4 it can be observed that the phenomena occurring during disturbance propagation depends on the location of the excitation source. Figure 6 contains three pairs of signals for variable damage level with additionally plotted envelope of the signal for the intact beam. In each case, the signal registered for configuration #2 is characterized by higher amplitude of recorded peaks. As can be seen the most considerable difference was observed for the beam with 25% debonding (Fig. 7c). For this case, the signal registered by the sensor attached the intact end of the beam (configuration #1) is comparable to the signal for the undamaged beam, while the amplitude of the signal for configuration #2 is incomparably greater. Moreover, in each case the wave motion is damped much faster for configuration #1.

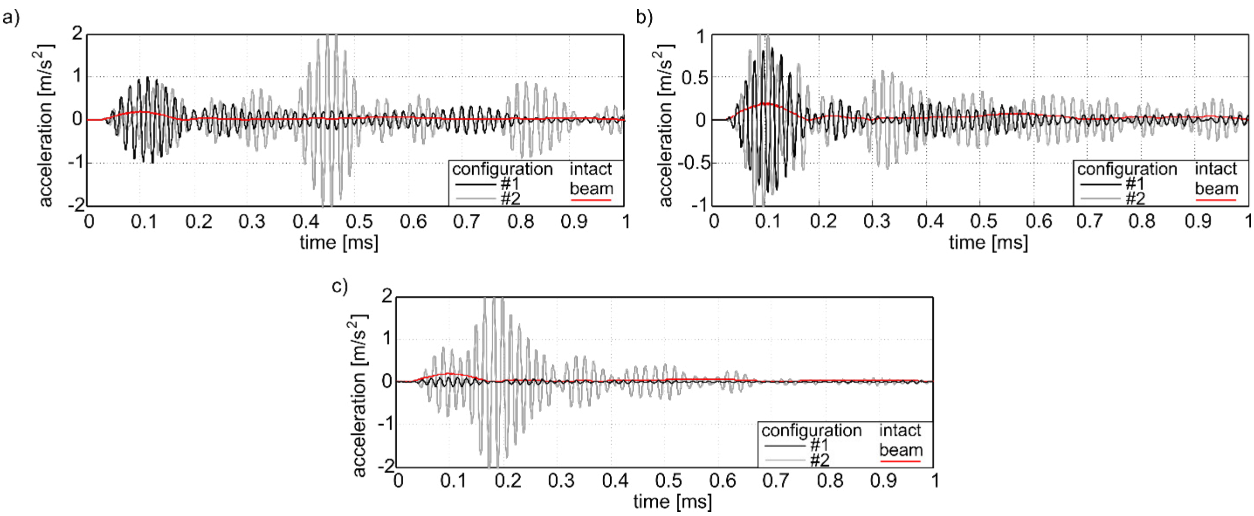

Fig. 7. Signals registered for beams with various debonding length equal to (a) 75%, (b) 50%; (c) 25%.

5. Conclusions

In this paper numerical and experimental investigations of wave propagation in concrete specimens with external steel reinforcement were carried out. The research focused on the condition assessment of the adhesive connection between the steel plate and the concrete beam. Four different debonding lengths at the steel/concrete interface and two configurations of the actuator and sensor were analyzed.

Results in the form of wave propagation field and time signals lead to conclusion that the phenomena of wave propagation in the beam with adhesively bonded steel plate strongly depended on the mutual position of damage and piezo actuators. When the actuator and sensor were attached to the intact end of the connection, the wave leaked into concrete immediately after excitation and in consequence, the disturbance started propagating in the entire volume of the concrete beam. The signal registered for beams with variable level of debonding contained clear single peak, characterized by the declined amplitude with the decreasing debonding length. There was clear relationship between the debonding length and the value of the first peak, so it can be concluded that the amplitude of the signal can be used as an indicator of the quality of bonding between concrete beam and steel plate. If the actuator and sensor were attached to the damaged end of the connection, the wave excited in the steel reinforcement initially did not leak into concrete and at first it was reflected from the edges of the plate. In the initial part of the signal, two peaks were observed, because reflections from the edges interfered with the incident wave.

The study indicated the potential of the wave propagation technique in diagnostics of bonding quality between concrete and external reinforcement, but for more efficient usage various configurations of sensors and actuators should be investigated.

Acknowledgements

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