Lamb wave propagation in a single lap adhesive joint

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ABSTRACT: The aim of the paper is the analysis of Lamb wave propagation in adhesive joints. The research was performed on a single lap adhesive joint of two steel plates. Two types of joints, namely an intact and with defect were considered. In experimental investigations the condition assessment of the joint was performed with the use of antisymmetric Lamb waves excited by a plate piezo actuators and measured by a laser vibrometer. Numerical analysis was carried out using the finite element method in Abaqus/Explicit environment. The results of experimental and numerical investigations indicated the changes in signals collected after passing through the joints with different areas of bonding.

1 INTRODUCTION

Adhesive joints are widely used in many branches of industry (e.g. Adams & Wake 1984, Piekarczyk & Grec 2012, Rudawska 2013). In recent years structural adhesive bonding of metal elements has been made widespread in some particular fields, e.g. automotive or aerospace structures (Cuc & Giurgiutiu 2004). Nowadays, adhesive bonding is gaining new value for many applications in civil engineering, also in metal structures (Piekarczyk, 2012, Piekarczyk & Grec 2012).

One of the simplest kind of a structural connection with the use of adhesive (glue) is a single lap joint (Adams & Wake 1984). It consists of two singular elements, e.g. bars or plates, combined together by a part of their surface. The joint is subjected to shear and its strength is determined by the type of used adhesive, the material of adherends (technical term for adhesively bonded elements) and condition of their surfaces in the area of the overlay before being combined. There are many methods of preparing the surfaces of joined elements, e.g. degreasing, mechanical working, chemical treatment (e.g. Rudawska 2013). The propriety of forming the joint is a significant issue too. Any mistake committed during preparation of the adhesive layer can generate disbond areas, which may cause in catastrophic consequences for the entire structure. Another issue that cannot be neglected is the progressive mechanical degradation of the joint that results in the decrease of its strength features (e.g. Godzimirski et al. 2009).

According to the increasing interest in adhesive bonding, the problems of structural health monitoring, diagnostics and quality assessment have become the subject of intensive research. There exists a number of non-destructive testing (NDT) methods, including visual methods, vibration-based methods and wave propagation-based methods (e.g. Rudawska et al. 2016, Barski et al. 2014). One of the rapidly developing NDT area covers techniques based on propagation of ultrasonic waves. There are two fundamental approaches that might be applied for the inspection of adhesive joints. The first is the ultrasonic method dealing with a pressure wave travelling through the thickness of the joint (Figure 1a). The method requires the movement of an ultrasonic probe over the whole scanned area. As a result, a detailed representation of defects in adhesion profiles can be obtained (Korzeniowski et al. 2014). The second approach is based on the guided wave propagation phenomenon (Cuc & Giurgiutiu 2004, Rokhlin 1991, Lanza di Scalea et al. 2001, Puthillath er al. 2008, Castaings 2014). Lamb waves are specific guided waves of numerous applications in nondestructing testing, e.g. in damage detection. They are dispersive waves that occur in media restrained by two parallel surfaces (e.g. thin plates). At the beginning the wave propagates through one adherend as a single-layer mode and then leaks to another by means of mode conversion resulting in wave propagation in three-layer medium (Figure 1b). Based on the interpretation of signals collected after passing through the joint, the condition of the joint can be assessed.

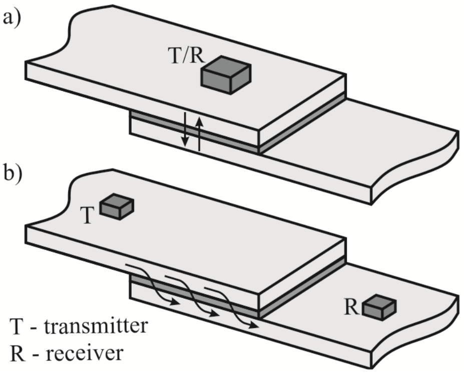

Figure 1. Ideological schemes of diagnostic techniques based on ultrasonic wave propagation for inspection of adhesive joints: a) ultrasonic method; b) guided wave propagation method.

The paper deals with the research of guided Lamb wave propagation in laboratory models of lap joints. The study contains results of experimental and numerical investigations for joints with different areas of bonding. The obtained results are compared and evaluated in terms of a possible application of guided Lamb waves for inspection of adhesive lap joints.

2 EXPERIMENTAL INVESTIGATIONS

2.1 *Object of research*

The object of the study was a single lap adhesive joint of steel plates. Dimensions of a cross-section of each element were 120 mm × 3 mm and the length was 270 mm. The overlap length was assumed equal to the half-width of the plate, i.e. 60 mm. The epoxy-based adhesive Loctite EA 9461 was used to form the joint with the bondline thickness of 0.2 mm.

The investigations were carried out for two types of specimens: one intact and one with a defect in the form of partial debonding. The pristine specimen was prepared with an adhesive layer on the area 60 mm × 120 mm (Figure 2a), while the damaged specimen was made with two adhesive layers on the area 60 mm × 40 mm (Figure 2b) separated by the area 60 mm × 40 mm without glue.

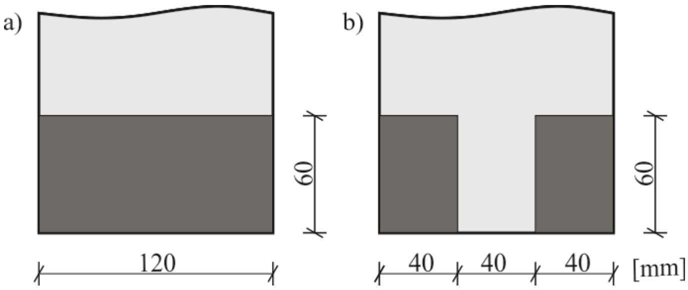

Figure 2. Types of analysed specimens: a) intact; b) with defect.

2.2 *Experimental setup*

Diagnostic tests covered the excitation of antisymmetric Lamb waves in one adherend and collection of signals on the whole area of the joint. The experimental setup is presented in Figure 3, the photograph of an investigated specimen is presented in Figure 4. The experimental setup included the arbitrary function generator Tektronix AFG 3022, the amplifier EC Electronics PPA 2000 and the scanning laser vibrometer Polytec PSV-3D-400-M. Lamb waves were excited by the plate PZT actuators Noliac NAC2024. The excitation signal was a five-peak wave packet obtained from the sinusoidal function of a frequency of 200 kHz modulated by the Hanning window (Figure 5). Velocity signals (out-of-plane velocity components) were recorded in 4225 points distributed over the area of the joint.

Figure 3. Experimental setup for measurements of Lamb wave propagation.

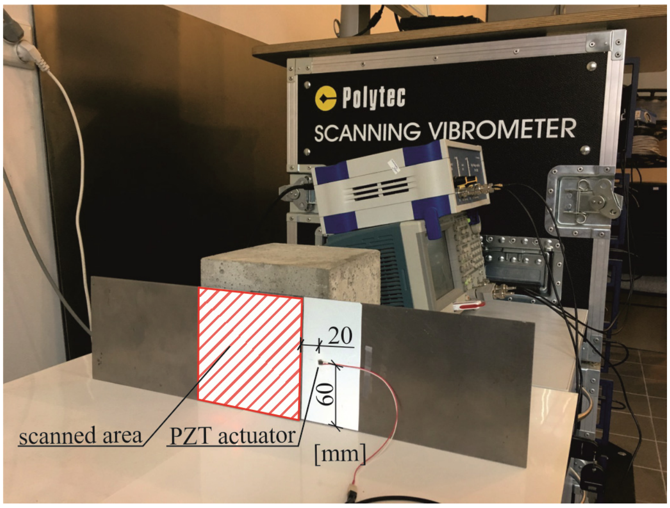

Figure 4. Investigated specimen with PZT actuator and indicated scanned area.

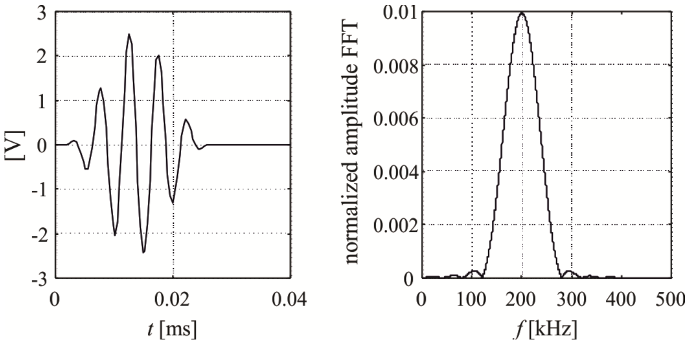

Figure 5. A 200-kHz 5-count Hanning windowed burst in time and frequency domains.

3 FEM CALCULATIONS

Numerical calculations of Lamb wave propagation in the adhesive lap joint were carried out using the finite element method in Abaqus/Explicit software. The numerical model of the intact specimen is shown in Figure 6. The structure was discretized by means of 8-node solid finite elements with reduced integration (C3D8R). The volume of cubic elements was 1 mm^3. The boundary conditions were assumed free at all edges. A homogenous isotropic material model was applied for steel with Young's modulus $E = 210$ GPa and Poisson's ratio $v = 0.3$. Between the plates, a 0.2 mm adhesive layer was applied with Young's modulus $E = 2.757$ GPa and Poisson's ratio $v = 0.35$. The contact between elements was assumed a tie connection on the surface of the adhesive layer. The excitation was applied in the form of the wave packet by means of a concentrated force at the lower plate.

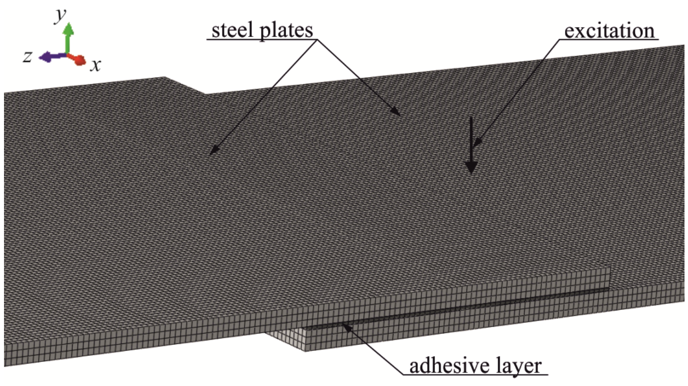

Figure 6. Numerical model of considered joint (intact).

4 RESULTS AND DISCUSSION

Figures 7 and 8 illustrate numerical maps of velocity along the y direction (out-of-plane velocity component), showing both specimens from the top side. At the first selected time instance ($t = 0.03$ ms), the wave is passing through the joint. Dispersive nature of Lamb waves results in differences in propagation in the single-layer and the three-layer plates. This effect appears as the shifts of the wavefront on the edge of the overlap. The comparison of both joints results in a considerable difference in the shape of the wavefronts. A disbond area in the centre of the damaged specimen causes the wave to propagate by two longitudinal areas of the adhesive layer, while in the intact specimen it propagates through the entire width of the connection. At the second time instance ($t = 0.04$ ms) the wave encounters the opposite edge of the joint. No significant disturbance in the wavefront can be observed as it was on the first edge, when the wave was leaking from one plate to another. While passing through the opposite edge the wave propagates mainly in the upper plate.

The comparison of velocity maps attained from experimental investigations (Figures 9 and 10) leads to conclusions coincident with the ones received from numerical results. A disbond area in damaged joint generates changes in the shape of the wavefront. It is also worth noting that the map for the specimen with the defect is not symmetric about its longitudinal axis. The reason may be an inaccurate geometry of defect in the damaged joint.

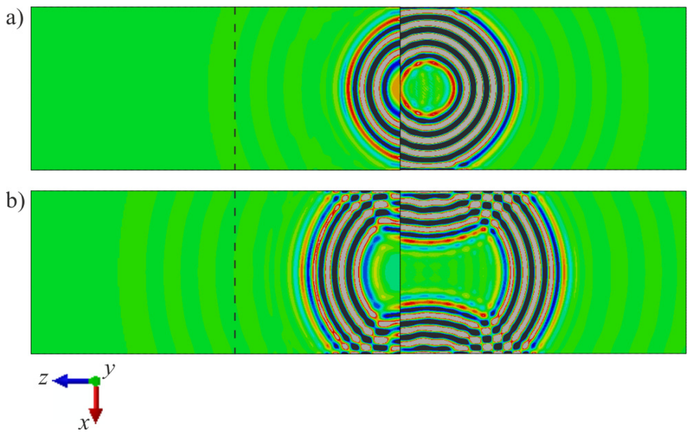

Figure 7. Numerical C-scan of Lamb waves in the intact joint at: a) $t = 0.03$ ms; b) $t = 0.04$ ms.

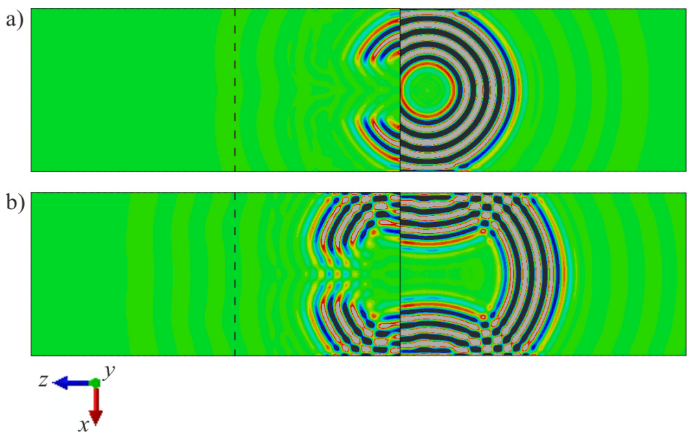

Figure 8. Numerical C-scan of Lamb waves in the in the joint with defect at: a) $t = 0.03$ ms; b) $t = 0.04$ ms.

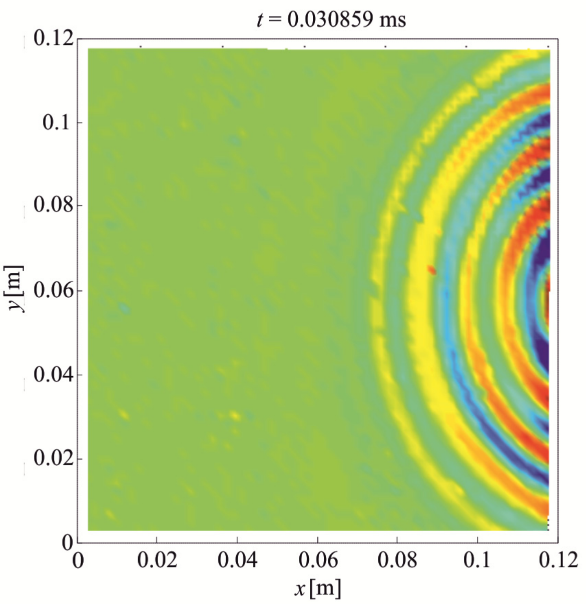

Figure 9. Experimental C-scan of Lamb waves in the intact joint.

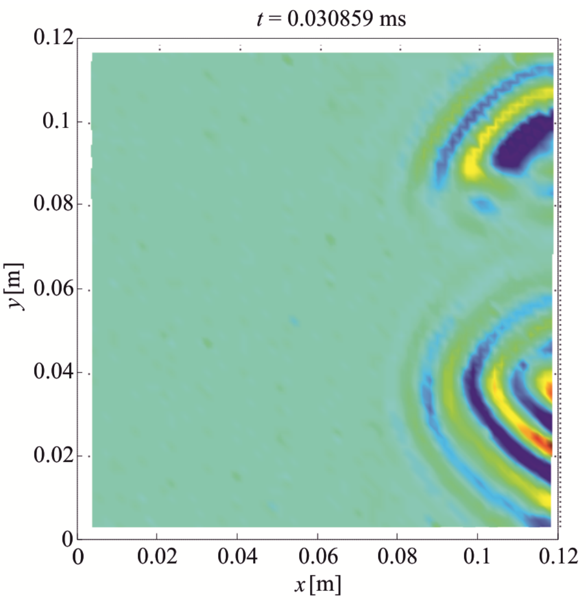

Figure 10. Experimental C-scan of Lamb waves in the joint with defect.

5 FINAL REMARKS

In the paper the phenomenon of Lamb wave propagation in the adhesive lap joint of steel plates was analysed. Both experimental and numerical results indicated qualitative differences in signals of elastic waves depending on the geometry of the adhesive layer. In particular, variation of the area of bonding affected the shape of the wavefront. Moreover, the applied guided wave propagation method allowed to determine the inaccuracies in process of preparation the joint. The executed research is the first step for further works directed to ultrasonic diagnostics of adhesive joints in metal structures.

ACKNOWLEDGEMENTS

The research work was carried out within the project No. 2015/19/B/ST8/00779, financed by the National Science Centre, Poland. Calculations were carried out at the Academic Computer Centre in Gdańsk.

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