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Research on assessment of bolted joint state using elastic wave propagation

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Research on assessment of bolted joint state using elastic wave propagation

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Abstract. The work contains results of experimental investigation of elastic wave propagation in a bolted single-lap joint. Tests were carried out for the excitation perpendicular to the connection plane. In experimental studies, PZT transducers were used for both excitation and registration of ultrasonic waves. The analyses took into account varying contact conditions between the elements of the connection depending on the value of the prestressing force. The influence of loosening/tightening of bolts on the energy dissipation was analysed. The experimental results proved the influence of bolt torque on quantitative characteristics of the signals. To improve the diagnostic possibilities only the initial parts of signals were analysed.

1. Introduction

Joints are integral parts of steel structures, which allow formation of subtle and unconventional structures of buildings. However, due to abrupt stiffness changes, stress concentrations, technical difficulties and susceptibility to atmospheric corrosion, connection points are the places most vulnerable to damage and they are relatively frequently subjected to failures. In building industry welded and bolted joints are the most commonly used forms of connections. Less prevalent are riveted and glued joints. In the group of bolted connections, two types of joint can be distinguished, namely standard and prestressed joints. The second of those subgroups is recently becoming more popular. The main reasons, and also the biggest advantages of prestressed bolted joints, are durability and high load capacity. Besides, they are easy to assemble and do not require expensive equipment during mounting. However, prestressed bolted joints require thorough preparation of connected surfaces and providing a controlled bolt torque value. Additionally bolts may be subjected to loosening under time-varying external loads. This results in the need for continuous monitoring of joints, which are especially important for structural reliability. Therefore in recent years bolted joints have become an area of intensive research associated with diagnostics, in particular in the context of ultrasonic waves. Methods based on the propagation of elastic waves are successfully used to detect defects in many types of structural components, especially in plate-like structures [1–4]. They allow for non-destructive assessment of structural condition. Moreover, they are relatively inexpensive and allow testing of inaccessible areas of structures.

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2. Diagnostics of bolted joints using elastic waves

One of the first approaches to diagnosis of bolted connections using elastic waves was developed by Mita and Fujimoto [5]. They developed an algorithm using the support vector machine which allows to detect loosening of bolts and damage localisation. Similar methodology is presented in [6]. Park et al. described the technique to detect defects simulated as loosening of selected connectors by the means of the time of flight and coefficients based on the wavelet transform. Additionally they used neutron probabilistic networks and support vector machines to assess the state of the connection. Experimental validation of the proposed method showed its high effectiveness in detecting failures of bolts. Yang and Chang [7, 8] proposed attenuation-based system of monitoring of bolted joint in composite thermal protection panels. Doyle et al. [9] showed changes in the phase of registered signals for differing values of a bolt torque in the context of monitoring of space structures. An and Sohn [10] presented a combination of methods using impedance and elastic wave techniques. A completely different approaches based on nonlinear acoustic phenomena are presented by Amerini and Meo [11]. The authors developed three indicators for three different ranges of excitation frequency. These indicators were based on the energy of the signal in the frequency domain, represented by the acoustic moment, sidebands in frequency spectrum and second harmonic generation. Wang et al. [12] investigated the effect of tightening torque on the signal energy in the time domain.

The aim of this study is to analyse the possibilities of using quantitative indicator based on signal energy of propagating elastic waves for assessment of the state of a steel lap bolted joint. The effects of sensor positions, excitation frequency and duration of the analysed time interval were examined.

3. Experimental case studies

3.1. The bolted joint model and experimental set-up

The object of the research was a single lap bolted joint (Figure 1). The model consisted of two steel plates with dimensions 6.2 mm × 59.8 mm × 404 mm which were assembled using two steel bolts of class 5.6. and diameter of 12 mm. The joint was mounted in a steel frame to simulate fixed-fixed boundary conditions and ensure a stable position during tightening and loosening process. The excitation and measurements of elastic waves were carried by the device PAQ-16000D and piezoelectric transducers Noliac NAC2024 with dimensions of 3 mm × 3 mm × 2 mm attached to the structure at selected points. The excitation had forms of five-peak sine modulated by the Hanning window. The output voltage signals were measured with a sampling frequency of 2 MHz. In order to reduce the influence of noise, each measurement was repeated 100 times and averaged.

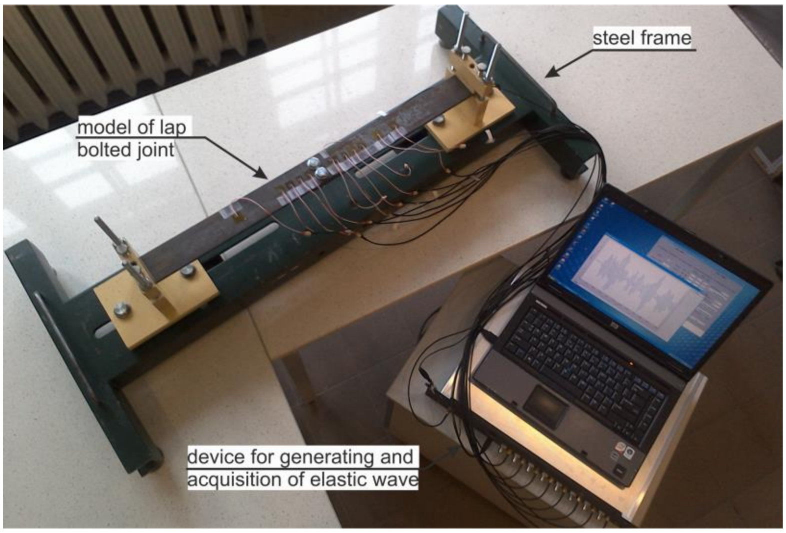

Figure 1. Experimental set-up for lap-joint measurements

3.2. Research program

Ultrasonic waves were excited at one point, at the distance of 8 cm from the axis of connection. Measurements were performed at 8 points located both before and behind the connection area. The arrangement of sensors is shown in Figure 2. Research was carried out for different values of the wave frequency and the bolt torque. The central frequency of excitation varied from 60 kHz to 120 kHz with step of 20 kHz. The controlled value of the bolt torque was ensured by using a torque wrench. The study included variation of the bolt torque in the range from 0 Nm to 100 Nm.

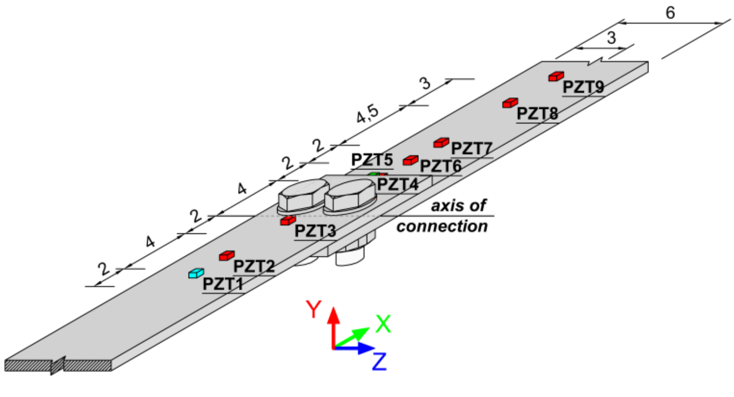

Figure 2. Sensors arrangement in experimental investigation

3.3. Results

The experimental results showed a significant impact of the bolt torque value on the characteristics of ultrasonic waves propagating in the tested joint. Differences between wave propagation signals were caused mainly by the changes of the contact area between the plates in the micro and macro scale. On macro level, this effect is caused by the variations of the radius of area around the bolt where two plates interact with each other [13]. In the micro-scale this phenomenon is associated with the change of the true contact area in dependence on the value of the contact stress and the surface roughness. The relationship between the nominal and true contact area for sinusoidal wavy surface using Hertz contact theory was discussed in paper [7]. Illustration of the changes of the contact surface is shown in Figure 3.The increase of the true contact surface also reduces the dissipation of energy at the interface between the connected plates. Less influence on variability of registered waveforms has the stress and tension state due to bolt tightening process.

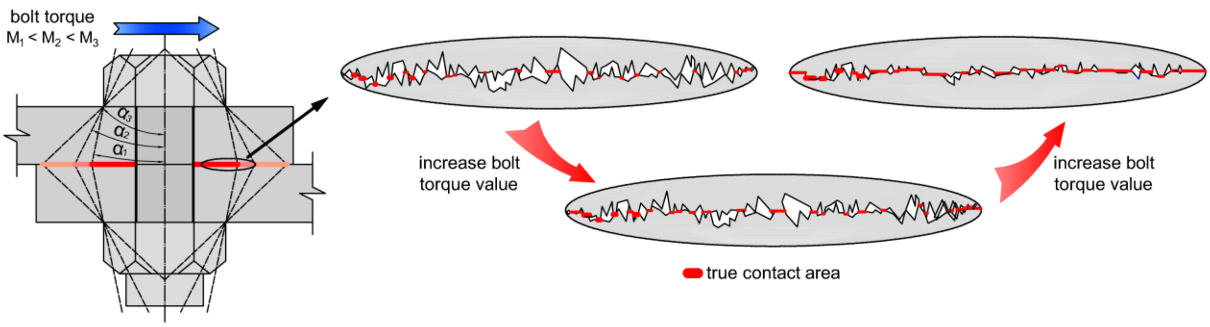

Figure 3. Changes of nominal and true contact area with increasing bolt torque value

The examples of ultrasonic signals acquired by sensors PZT5 and PZT9, for the excitation with the central frequency 60 kHz and 100 kHz, are presented in Figures 4, 5 and 6. It can be seen that there are significant differences between signals registered for different values of bolts pre-load. The registered waveform signals are similar only at the initial time interval, namely 0–0.11 ms for PZT5 and

0–0.15 ms for PZT9. However, despite of resemble in the shape, a slight shift of the registered signals occurred with the increase of the torque value (cf. Figure 5, 6). Analogical results were obtained for the other piezoelectric sensors.

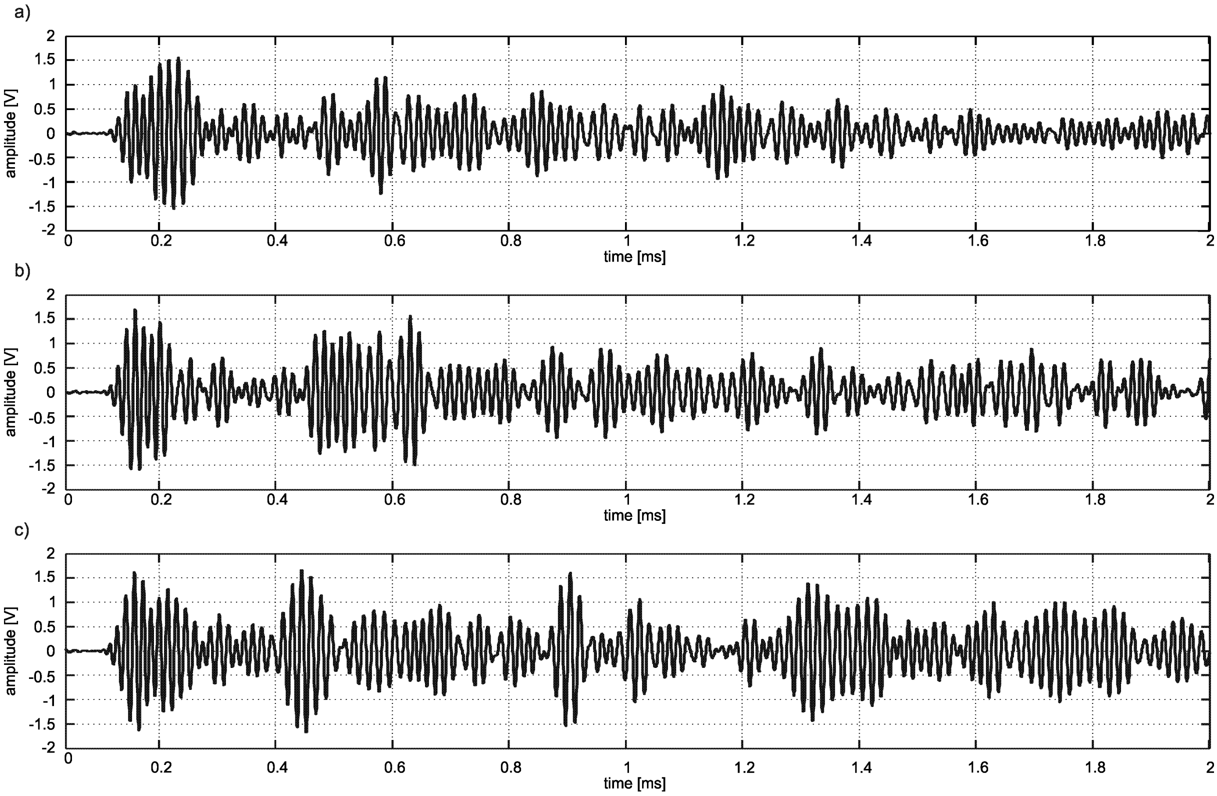

Figure 4 Output voltage signal registered in the case of excitation frequency 60 kHz by PZT9 for different value of bolt torque: a) 20 Nm; b) 60 Nm; c) 100 Nm

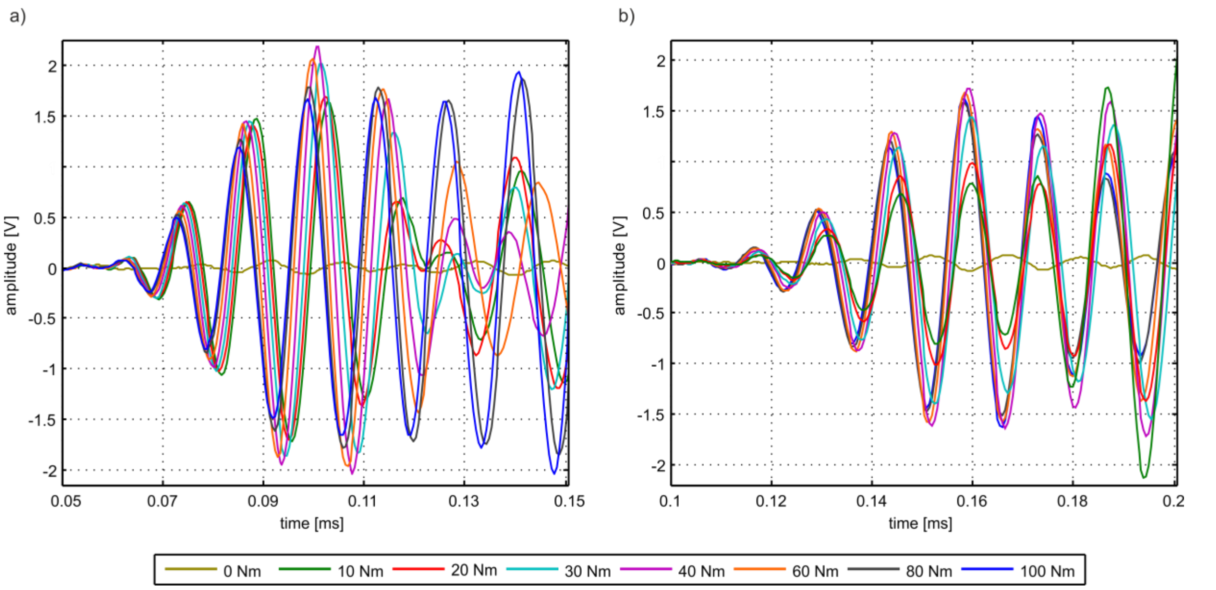

Figure 5. Wave propagation signals for different values of bolt torque in the case of excitation frequency 60 kHz registered by: a) PZT5; b) PZT9

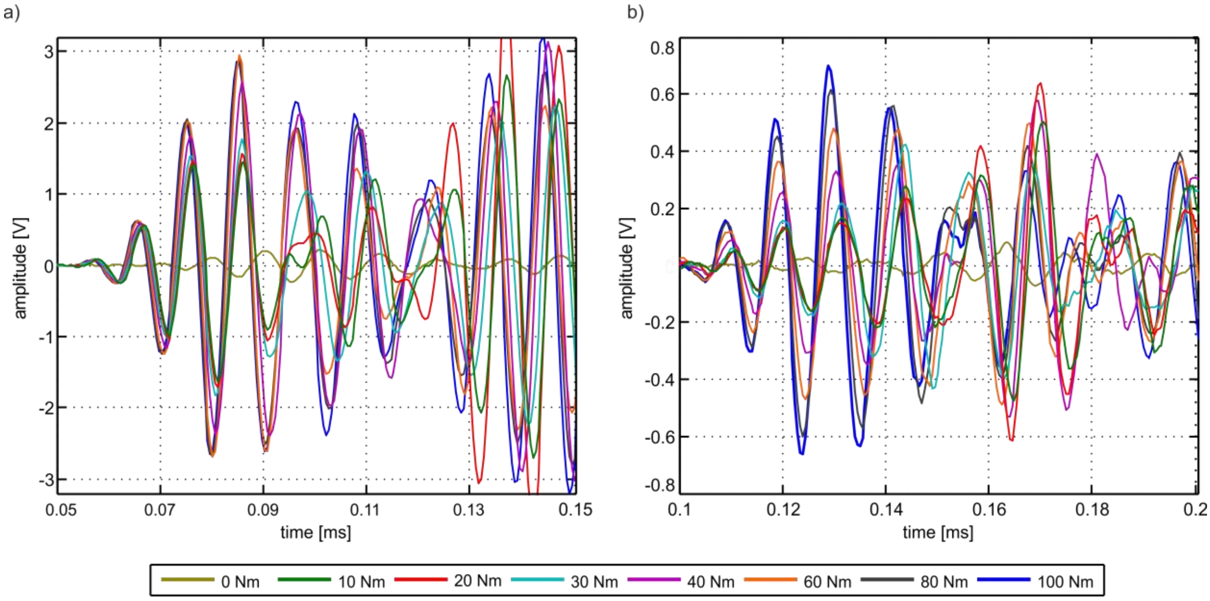

Figure 6. Wave propagation signals for different values of bolt torque in the case of excitation frequency 100 kHz registered by: a) PZT5; b) PZT9

Figure 7 shows the time-frequency characteristics of the signal registered by sensor PZT9 for excitation with the central frequency of 60 kHz. The values of the signal spectrum increased with increasing bolt torque value. Simultaneously, the spectrum was flattened, and few side lobes with similar amplitude appeared. In addition, registered waveforms were highly contaminated by reflections from the edges of the bolted joint model. As a result, the qualitative comparison of signals in wide time range was extremely difficult. Therefore, in this study the energy of signals has been proposed as a quantitative characteristic directed to diagnostic purposes of bolted joints.

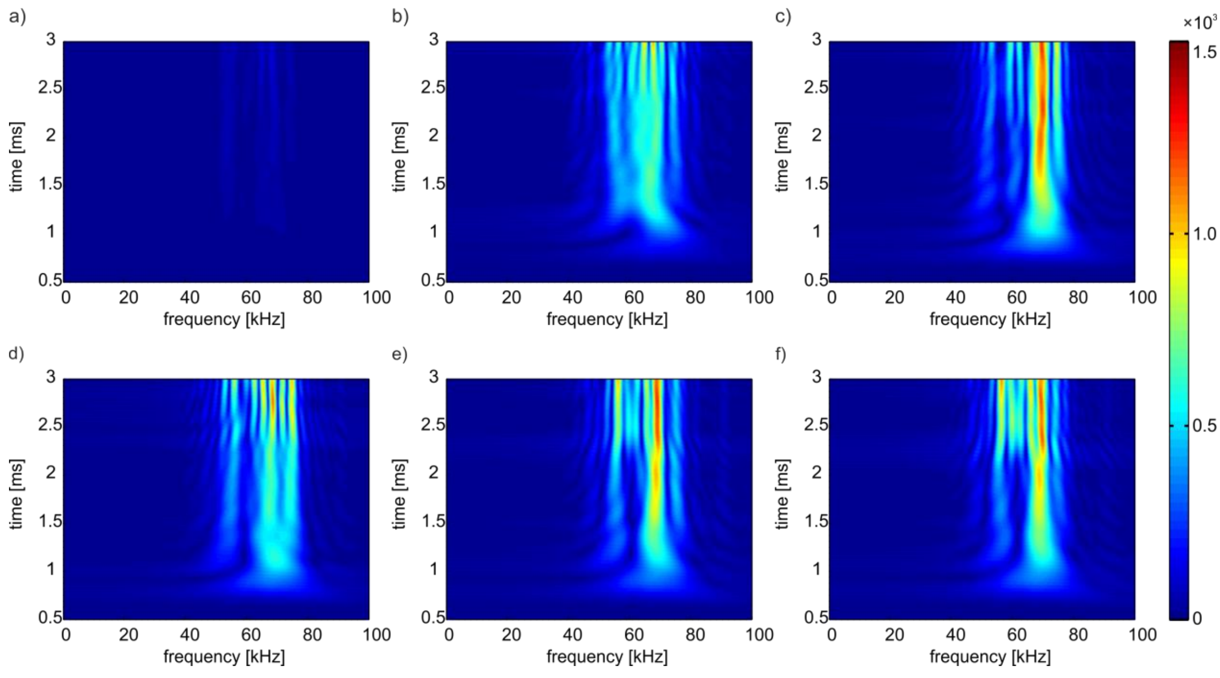

Figure 7. Time-frequency characteristics of signals registered by PZT9 in case of excitation frequency 60 kHz and bolt torque value: a) 0 Nm; b) 20 Nm; c) 40 Nm; d) 60 Nm; e) 80 Nm; f) 100 Nm

The energy of a signal can be defined for continuous and discrete signals in both time and frequency domains. In the theory of signals, the energy of discrete signal can be written as [14]:

$$E_x = \sum_{n=n_0}^{\infty} x_n^{\ 2}, \tag{1}$$

where x_n denotes the value of discrete signal at a given time point. In Equation (1) summation occurs in the infinite range, which is impossible to carry out for experimentally acquired signals. The problem disappears if the recorded signal is periodic. However, it does not occur in this case. To overcome this limitation, we must assume that outside the specified range $\langle n_0; n_1 \rangle$ the signal has only a zero or very close to zero values, so the signal energy in the range $\langle n_1; +\infty \rangle$ is negligible. It is obvious that due to the physical nature of a waveform induced by a single wave packet its amplitude after a certain time significantly decreases. An additional difficulty is the noise in the signal, whose influence can be reduced by using averaging or filtering techniques. After determination of the suitable registration time, the analysed wave signal becomes finite, hence its energy is finite and calculable.

Figure 8 shows the changes of the selected signal energies depending on the time range of the measurement. It may be noted that after significant initial increase, the energy of all signals was stabilized. In the time range of 5–10 ms energy values rose slightly and further measurement was therefore unnecessary.

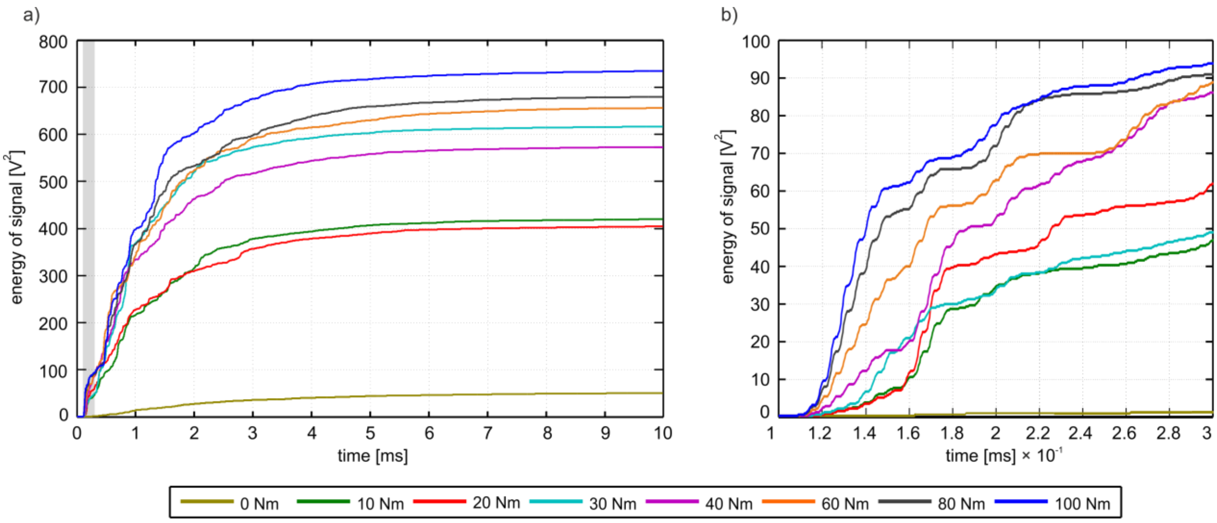

Figure 8. Signal energy changes depending on the measurement time in the case of excitation frequency 100 kHz for sensor PZT9 in the range: a) 0–10 ms; b) 0.1–0.3 ms

Table 1 presents the values of the signal energy for all PZT-sensors at the excitation frequency of 100 kHz normalized with respect to the maximum value obtained for relevant sensor. Only in the case of sensor PZT9 a stable trend between the values of the signal energy and the bolt torque can be observed. For sensors located in the lap area, the decline of the maximum signal energy with the increasing value of prestressing force can be observed. In the cases of excitation frequencies of 60 kHz, 80 kHz and 120 kHz, there was no clear relationship between the signals energy and the bolt torques for any of sensors. It demonstrates that in the case of evaluation of the joint state based on the signal energy over the entire range of its variability, it is necessary to determine accurately both the position of the sensor and the excitation frequency.

Another approach is to assess the state of the connection only on the basis of the energy of the part of the signal, at the certain time internal. In this case, the greatest difficulty was to determine the end of the analysed range. Based on the analysis of the variability of the recorded waveform it was found that analysed time should correspond to half duration of the excitation time. For this purpose, a cross-correlation function of Hilbert spectrums of the excitation signal and waveforms recorded by sensor PZT9 was used. Results obtained in this manner are summarized in Table 2. In this case, the relationship between the increase of the bolt torque and the signal energy in the analysed time range can be observed for all sensors situated outside the connection area except PZT2.

Table 1. Energy of signals registered by various PZT sensors for excitation frequency of 100 kHz

	normalised signal energy [-]							
bolt torque [Nm]	0	10	20	30	40	60	80	100
PZT2	1,0	0,832	0,852	0,892	0,921	0,887	0,926	0,968
PZT3	1,0	0,717	0,703	0,770	0,644	0,651	0,743	0,710
PZT4	1,0	0,613	0,511	0,417	0,466	0,564	0,515	0,499
PZT5	0,059	0,703	0,631	1,0	0,983	0,790	0,861	0,914
PZT6	0,076	0,658	0,752	0,755	1,0	0,832	0,899	0,843
PZT7	0,042	0,768	0,644	0,901	1,0	0,903	0,900	0,824
PZT8	0,072	0,631	0,557	0,675	1,0	0,924	0,933	0,869
PZT9	0,069	0,572	0,551	0,839	0,780	0,893	0,925	1,0

Table 2. Energy of initial part of signals registered by various PZT sensors for excitation frequency of 100 kHz

	normalised signal energy [-]							
bolt torque [Nm]	0	10	20	30	40	60	80	100
PZT2	0,992	0,994	0,995	0,999	1,0	0,999	0,996	0,997
PZT3	0,508	1,0	0,975	0,827	0,858	0,934	0,927	0,891
PZT4	0,658	0,795	0,810	0,574	0,655	1,0	0,841	0,721
PZT5	0,001	0,370	0,397	0,450	0,628	0,883	0,970	1,0
PZT6	0,001	0,425	0,410	0,510	0,705	0,855	0,959	1,0
PZT7	0,001	0,638	0,611	0,622	0,815	0,938	0,982	1,0
PZT8	0,002	0,166	0,161	0,222	0,394	0,716	0,910	1,0
PZT9	0,004	0,048	0,049	0,075	0,198	0,451	0,758	1,0

4. Conclusions

The paper contains experimental investigations of elastic wave propagation in a laboratory model of the single lap bolted joint. The research focused on the changes in the waveforms registered by piezoelectric sensors attached to the structure at several locations. Quantitative signal changes were analysed. It has been shown that based on the signal energy over the entire range of its variability only the full loosening state can be detected. In order to improve the diagnostic possibilities the initial part of signals was analysed. To find the limits of the range, which should be considered, a cross-correlation function of Hilbert spectrums of the excitation signal and waveforms was used. In this case, for sensors located on the opposite side of the joint with respect to the actuator, the regular increase of the signal energy with increasing bolt torque was observed.

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