Methods for diagnosing defects in glued joints - a methods review

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Abstract. The paper presents the applications of glued joints in many industry branches. The advantages and disadvantages of glued joints as well as the methods of detecting weld damage are presented. The methods of damage analysis to the glued joints were divided and explained. The most important detection techniques are the X-ray method, the ultrasonic method, the Laser Ultrasound method, the guided wave method, the electromechanical impedance method and the active thermography method. The advantages and limitations that may allow for the proper selection of the research method depending on the diagnosed material and the conditions accompanying the study were indicated.

1 Introduction

Currently, in many industries, new materials are increasingly used, including composite materials, which replace the raw materials used so far. This situation can be encountered in the aviation industry, where traditional welded joints are replaced with modern glued joints. This situation results from the fact that more and more models of individual aviation manufacturers focus their production on the production of airframes from composite materials. Combining this type of materials with structural elements made of aluminium alloys is practically impossible [1]. For this reason, the above-mentioned elements are joined by means of innovative glued joints, which are often characterized by greater strength than traditional welded joints. In addition to the aviation industry, similar trends can be found in the automotive and railway industries. In this case, glued joints are used to connect composite elements with other materials used in production. These include connecting fairings for trucks with cabins or attaching composite body panels and covers for buses and rail vehicles. The use of glued joints is associated with the reduction of vehicle weight, which is important from the point of view of production economy [2] and ecology, both at the stage of production, operation and disposal of the vehicle. In addition, connections made by arc welding pose many problems, especially in the case of thin-gauge elements, aluminium or stainless steel elements. In these cases, deformation of the bonded elements may occur, spatter sticking and the material properties decrease [3].

Gluing processes are successfully used in the shipbuilding industry. Many elements in modern yachts and boats are assembled with the use of glue. This solution is easy to

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implement as it reduces the number of unnecessary operations in the production process, such as drilling, threading, sealing.

Gluing processes can also be used in the construction of furniture such as kitchen cabinets or wardrobe cabinets in swimming pool changing rooms. Limiting the amount of material, through the use of lighter furniture boards of less thickness, in the creation of modern furniture constructions allows to reduce production costs. In addition, such a solution allows for more effective use of the rooms usable space. However, the limited thickness of the furniture boards eliminates the possibility of using traditional shaped connections, as making through mounting holes in furniture fronts is unsightly and therefore unacceptable in modern furniture cabinets. In such a situation it becomes necessary to make fastenings by means of glued joints.

The glued joint can be encountered most often when joining at least two elements with a layer of adhesive substance and ensuring appropriate conditions for the production of an adhesive joint in the relation between glue and element surface. Glued joints have numerous advantages. The most important ones include [4]:

- glued joint allows to limit the number of technological processes,
- the ability to dampen vibrations,
- the adhesive layer has sealing properties,
- joining different materials without the risk of damaging the surface,
- the adhesive layer does not reduce the strength of the glued materials, which allows for the full strength of the glued material.

Despite the use of modern assembly adhesives, mainly epoxy and polyurethane adhesives [5], as well as bonding techniques of individual elements, some damage may occur in the final joint, which may significantly weaken the joint. Such damages are often not visible and require special methods of their detection. This paper presents methods of performing non-invasive analyses of damage to glued joints.

The division of detection techniques is presented in Table 1.

Table 1. Methods of detection defects in glued joints.

No.	Detection method
1.	X-ray radiography method
2.	Ultrasonic method
3.	Laser ultrasound method
4.	Guided wave method
5.	Electromechanical impedance method
6.	Active thermography method

2 Diagnostic methods of defects in glued joints

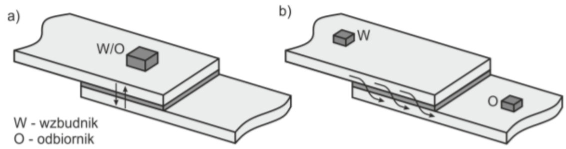
2.1 X-ray radiography method

Currently, multi-layer metal glued plates are successfully used in many industries, ranging from nuclear power, through aviation production, to the automotive industry [6]. One of the methods of detecting voids and pores in the adhesive fraction is x-ray radiography [7]. It is one of the basic industrial techniques through which non-destructive testing is performed. The visualization of the tested material internal structure is the aim of the tests performed with the use of the above-mentioned method. It allows the detection, among others, discontinuities in the tested objects, which were created at the stage of production or operation [8]. This method consists in registering an image of the material to be assessed with the use of X-rays. The operation is performed on a radiosensitive material [9]. The method requires two-sided access to the analysed material. Moreover, the technique is slow and not suitable for the detection of defects which are characterized by zero volume, e.g. delamination. For this reason, ultrasound methods are successfully used to examine these cavities [7].

2.2 Ultrasonic method

One of the assessing adhesive connections methods is ultrasonic testing. This method consists in placing the ultrasound-generating head on the surface of the glued material and recording the impulse systems on the flaw detector screen. Kowalczyk et al. Carried out tests on the joints of a steel sheet with a tape, and an aluminium sheet with a glued-on fragment of the tape using the ultrasonic echo method. For this purpose, a 3M VHB TAPE RP45 Gray tape was glued to the steel sheet and the G20MNX ultrasound head connected to the Krautkramer USM35XS flaw detector with a processing frequency of 20 MHz, diameter 3.6 mm, wavelength in a steel sheet 0.29 mm, near field was applied from the side of the sheet 10.4 mm and a beam width for a drop factor k = 0.87 at a distance of 15 mm from ultrasonic processing 2.2 mm. The tests carried out have shown that this method allows for a non-invasive location of the joint in the strip-sheet relation, which allows its use in production processes [2].

Subsequent tests involved the detection of damage in the glued lap joint of two steel sheets with dimensions of 12 cm x 27 cm and a thickness of 3 mm [10]. Loctite EA 9461 epoxy glue was used to connect both boards at a length of 6 cm. In the study, Lambda waves were excited using the Noliac NAC2024 transducer and the signals from points located on the joint surface were measured using the PSA-3D-400-M laser scanning vibrometer. The excitation was characterized by the frequency of 200 kHz and the form of a wave packet with 5 cycles. The study examined the joints with the use of damage various variants introduced in the form, lack of glue on the surfaces. On one of the sheets, in the place where the damage was assumed, a Teflon tape was glued. The obtained signals, after processing with the use of the weighted quantum average, allowed to obtain values close to the values characteristic for a single plate at the place of the defect. The maps obtained in this way made it possible to diagnose the location of irregularities as well as its dimensions [11]. Figure 1 illustrates the solution principle for the ultrasonic method and guided waves [12].



W – Inductor
O – Receiver

Fig.1. Defect detection using guided waves on the example of a glue joint: a - ultrasonic (local) method, b - guided wave (global) method [12].

2.3 Laser ultrasound method

The conducted research with the use of ultrasound had numerous limitations. Currently, Laser Ultrasound (LU) methods are used to minimize the related difficulties. The use of laser pulses allows for the generation of a broadband signal, which, unlike classical ultrasound methods, allows for a clearly better resolution. When examining composites, longitudinal waves that are detached from individual layers create images of a quality similar to X-ray computed tomography [13].

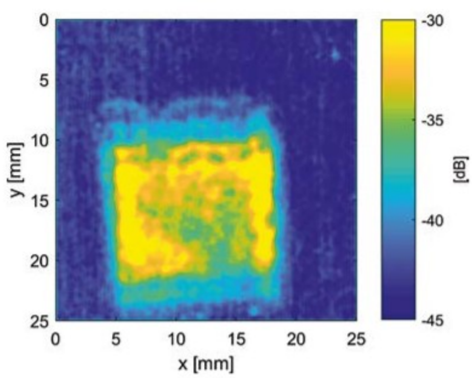


Fig.2. The image of the reflected shear wave amplitude for a Teflon insert [7].

There may be some limitations when using the Laser Ultrasound method in the analysis of metal structures. The use of this technique does not allow for efficient generation of longitudinal waves without ablation of the surface. Therefore, in order to circumvent this limitation, other wave modes can be used successfully. There are known methods of using laser-generated surface waves [14], shear waves [15] or Lamb waves [16]. The tests carried out with the use of the LU scanner consisted of joining together three aluminium plates with a thickness of 1; 1.5 and 3 mm. Between the first and the second layer there is an insert with dimensions of 15 x 15 mm, made of Teflon. The sample prepared in this way was tested by attaching it to a mechanical scanner and analysing the damaged area with a resolution of 0.02 mm. Spatial averaging of the signal was performed using a two-dimensional Gaussian window (15 x 15 points) and a low-pass filter with a cut-off frequency of 9 megahertz. The results obtained by the method of laser excitation and ultrasound measurement allowed to clearly indicate the location of the Teflon insert. To sum up, the presented technique allows for conducting analyses in a non-contact manner, is a relatively quick method of detection and allows for obtaining highly sensitive results. As a consequence, this method can be successfully used in the detection of discontinuities in materials joined with glue. Figure 2 shows a Teflon insert showing the amplitude of the transverse wave that was reflected [7].

2.4 Guided wave method

The guided wave method is one of the global techniques. The wave that is excited at one point propagates throughout the structure. For this reason, its course can be recorded in any location, also outside the excitation area. Unlike ultrasonic methods, this technique is used in a different frequency range. Usually it is in the range from tens to hundreds of kilohertz. Examination of samples without defects in their structure shows only a graph illustrating the reflections of waves that hit the ends of the tested object. On the other hand, in the case of samples characterized by discontinuities in their structure, successive reflections are visible in the graph image. In this case, the wave bundle, when it encounters a defect, is additionally reflected and is visible as a wave bundle with a lower vibration amplitude. The correlation of the resulting reflections location and the time allows for the damage location to the tested material. Obtaining two-dimensional visualizations of wave propagation in a defined time is possible when using this method in the study of surface elements. In this situation, it is necessary to use, for example, a laser vibrometer, which allows to scan the examined area. The consequence of the examination is type C imaging. Figure 3 illustrates an example of the application of the guided wave method in fault detection [12].

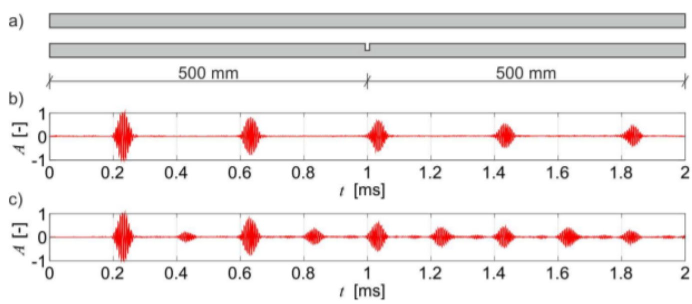


Fig.3. An example of the waves guided method used in the bar damage detection: a - research object without and with damage, b - waveforms in the object without and with damage [12].

2.5 Electromechanical impedance method

The electromechanical impedance method is based on the use of piezoelectric transducers, which are characterized by the use of a simple and inverse piezoelectric effect. Due to the inverse piezoelectric effect, vibrations are induced in the system. Providing an electric field to the system causes the piezoelectric material to deform. Impedance measurements can be made using the simple piezoelectric effect associated with the generation of an electric field as a result of the resulting mechanical deformations. As a result, the response of the system in the area to be detected is converted into an electrical signal. The signal transformation process takes place in the converter. The inference is based on the measured electrical quantities [17]. This method can be successfully used to detect damages to mechanical structures that use glued joints [18]. However, the electromechanical impedance method has its limitations, which are related to the preliminary selection of places where weld damage may have occurred. The use of a high-frequency band makes this method suitable only for the detection of locally occurring defects that are located in close proximity to the transducers. In addition, this technique only allows for a qualitative analysis of the damage caused, as other types of defects show impedance changes with similar values, which makes it difficult to determine a specific type of damage. The electromechanical impedance technique is sensitive to changes in temperature, excitation and boundary conditions, which entails the necessity to monitor the aforementioned parameters [17].

2.6 Active thermography method

One of the youngest methods of detecting defects in glued joints is the active thermography technique [19, 20]. The method is based on a thermal effect on the object to be tested and on thermographic observation of the response. The thermal forcing applied to the tested object causes the formation of local changes in the distribution of temperature values, which is caused by differences in the propagation of thermal waves that encounter defects in the tested structure. All losses, i.e. delamination, cracks and bubbles are characterized by a different heat diffusion. The presence of such an anomaly can be detected by analysing the temperature distribution of the thermographic image. In the described method, the thermal action can be realized with the use of optical, mechanical or electromagnetic techniques. In order to verify the suitability of the method, experimental tests were performed. The research sample consisted of two 1 mm thick body sheets connected with each other with polyurethane glue. This joint has been broken to simulate a weld failure. To increase the emissivity, a layer of black paint was applied to one of the sheet surfaces, followed by thermographic observation. The obtained results confirmed the applicability of the method in the detection of defects in glued joints. The conducted research proved that it is important to choose the right exposure time, and the defect is most visible in the heating phase. This state of affairs allows to reduce the disturbances that accompany the test during cooling. At this time, the image is obtained with the greatest difference in temperature contrast between the defect and the area free from it. Figure 4 shows the specimen geometrical features and the glue location [5].

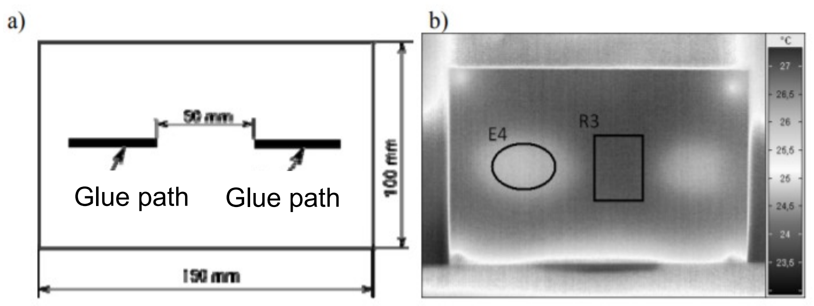


Fig.4. The test specimen characteristics: a - specimen geometrical features and the adhesive layer, b - tomographic image with specific measurement zones made during the heating phase [5].

3 Analysis

Among the presented methods of connection damage detection, the Laser Ultrasound method, the electromechanical impedance method and the active thermography method should be distinguished. The first method is a development of the classic technique of non-contact detection with the use of ultrasound. In addition, it allows to quickly test a defect in the glue joint. Moreover, this method is characterized by high resolution and allows to obtain highly sensitive materials bonded discontinuities with the use of an adhesive layer. Despite numerous advantages, the Laser Ultrasound method has some disadvantages. Due to the inability to efficiently generate longitudinal waves without ablation, the use of the Laser Ultrasound method is limited. Both the electromechanical impedance method and the active thermography method can be an alternative to the Laser Ultrasound method. Both methods are characterized by appropriate sensitivity and allow for the identification of defects in the glue joint. Nevertheless, the electromechanical impedance method is characterized by certain limitations and allows the diagnosis of locally occurring defects, and, consequently, the need to carry out an initial selection of damaged fragments of the adhesive joint. This technique necessitates the control of temperature and boundary conditions. On the other hand, a sufficiently long exposure time can be considered a limitation of the active thermography technique.

4 Conclusion

There are several methods that make it possible to perform a non-invasive qualitative assessment of the joints of glued materials with different mechanical properties. The most important of them are the ultrasonic method, the Laser Ultrasound method, the electromechanical impedance method and the active thermography method. However, each of the techniques presented has its advantages as well as limitations. Therefore, these methods are not universal, and some of them can only be used under strictly defined conditions. Therefore, it is crucial to select the appropriate test method for the materials used in the combination.

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