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Original Research

Experimental Research on the Influence of Structural Modifications of Adherends on the Load-Bearing Capacity of Lap Joints of S235JR Steel Sheets

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Abstract

The paper presents the results of the research determining the impact of structural modifications of adherends on the load capacity of the joints determined in the static shear test. Tests of adhesive lap joints of S235JR steel sheets bonded with Araldite 2014-2 epoxy adhesive are described. The influence of technologically simple structural modifications was investigated; it consisted in making notches and holes at the leading edge of the adherends. These modifications were aimed at bringing about local flexibility of the joint in the sensitive area of stress concentration. Based on experimental studies, it was shown that there is a possibility of increasing the load-bearing capacity of the joint due to the applied modifications; in the most favorable variant, an increase in the load-bearing capacity by 15.9% compared to the base variant was demonstrated. The tests confirmed that the notches filled with the adhesive in the front part of the adherends can significantly improve the strength properties of joint, while the considered modifications in the form of holes do not have a significant impact on the properties of the adherends.

Keywords: adhesive joints, structural modification, static shear test, S235JR steel

1. Introduction

Structural adhesive joints are becoming more and more widely used, as they enable joining materials with different properties. They are used in composite structures combining various material properties (Davis et al., 1999). The type of joints considered is commonly used in the construction of the means of transport, especially in the automotive, aviation or railways, because they enable the production of structures with a relatively low weight. Adhesive joints are not only used in manufacturing of new products, but are also widely used in repairs, including aviation structures (Davis et al., 1999).

The strength of adhesive bonds depends on many factors, such as the method of surface preparation of adherends, the conditions of bonding and hardening the adhesive, and the thickness of the adhesive layer (Bartczak et al., 2013; da Silva et al., 2009; Davies et al., 2009; Kadioglu & Adams, 2015; Karachalios et al., 2013).

The factors influencing the properties of joints also include the geometric features of the adherends (da Silva et al., 2011; Zhao et al., 2011). The most important of them are the geometrical dimensions and the shape of the joint, which translates into the way it is loaded and the stiffness of the adherends (Zhao et al., 2011).

A general recommendation for the design of adhesive joints determines the shape of the joints so that they are dominated by shear stresses.

In reality, however, there is usually no pure shear in lap joints. Usually there appears a complex state of stresses, in which an important role is also played by normal stresses, causing an unfavourable state of peeling (da Silva et al., 2009).

At the front edges of the loaded lap joint, a stress concentration occurs (da Silva et al., 2009), which usually initiates the failure of the joint. The amount of accumulation depends primarily on the stiffness of the adherends and the properties of the adhesive.

In the literature, there are various methods aimed at limiting stress concentration at the leading edges of the joint. Godzimirski (2002) suggests making a groove (undercut) along the edge of the adhesive joint as one of the methods of reducing the concentration of stresses. Such a procedure, despite weakening the adherends, reduces the value of stresses in the joint and moves the maximum stress away from the edge of the joint.

In the adhesive joining technology, if there is no such requirement, it is recommended not to remove the adhesive flashes. Many authors have shown that flashes have a positive effect on stress distribution (Belingardi et al., 2002; Godzimirski, 2002). They unify and reduce the maximum stress values in the near-edge zone of the joint. The authors of research works (Belingardi et al., 2002; Lang and Mallick, 1998; Rispler et al., 2000; Wang et al., 1998) showed that the additional application of adhesive beyond the outline of the main lap joint, which increases the spew, increases the strength.

An additional method of reducing the near-edge stress concentration in lap joints is to increase the thickness of the adhesive layer in this zone. A number of scientific works raise the issue of the appropriate shaping of adherends, which aims to increase the thickness of the adhesive layer locally in the area of stress concentration (da Silva & Adams, 2007; Kaye & Heller, 2002; Kim et al., 2001; Lang and Mallick, 1999; Mazumdar & Mallick, 1998). These modifications may include, inter alia, the application of chamfer or fillet on the leading edge of adherend (Belingardi et al.2002; You et al., 2007; Zielecki et al., 2017). Thanks to this, local flexibility of the joint in the sensitive area is introduced.

The authors of the work (Belingardi et al., 2002) conducted FEM analyzes for bevelled edges of adherends. The analyzes concern the influence of the bevel angle on the distribution of tangential and normal stresses in a single-fold joint of adherends of different thickness. With the proposed modifications, clear benefits can be noticed, related not only to the lowering of the maximum tangential stresses, but also to the uniformity of the distribution in the sensitive zone.

Similar analyzes were carried out by You et al. (2007), who supported these considerations with experimental research. They confirmed the possibility of improving the strength of adhesive lap joints with structural modifications. In the most preferred cases, an increase in the shear strength of about 20% (You et al., 2007) is obtained.

Structural modifications consisting in making a radius in the joint near-edge zones were considered by Lucas (2011). Considerations from the publication (Lucas, 2011) also apply to the shear lap joint. Various dimensions of the radius were considered here, together with adhesives with different modulus of elasticity. In the most preferred variants, an increase in the shear strength of about 40% was demonstrated.

On the basis of the literature review, it what was noticed was the need for relatively simple ways of introducing structural changes that do not require a significant increase in technology costs, which would contribute to the improvement of the properties of the joints.

In this paper, experimental tests were carried out on structural adhesive joints with structural modifications of the front part of the adherends. The modifications consisted in introducing simple notches and holes at the edges of sheets of various sizes. The aim of the study was to show whether this type of relatively technologically simple modification of joints can contribute to the local flexibility of the adhesive joint in the sensitive zone, where stress concentration occurs.

2. Material and methods

The research on the impact of structural modifications aimed at reducing stress concentration in the frontal area of the adhesive joint was carried out for adhesive lap joints with the dimensions shown in Fig. 1a. Both adherends were made of S235JR sheet steel with a thickness of 2 mm. The shape and dimensions of the considered structural modifications in the form of notches at the leading edge of the adherend are shown in Fig. 1b, while the modifications in the form of holes are shown in Fig. 1c. As structural modifications, variants with the indentations of 1 mm, 2 mm and 3 mm widdt and lengths: 1

mm, 2 mm, 3 mm and 4 mm were used. Modifications in the form of holes with the diameters of 2 mm, 3 mm and 4 mm were also tested. A detailed specification of the modification dimensions at the leading edge of the adherends is presented in Table 1. As part of the research, only symmetrical joints were tested, i.e. in each variant, both adherends had identical modifications.

Notches and holes in the front part of the adherends were made by machining. The notches were made using disc cutters with the thickness corresponding to the width of the notches, while the holes were made using drills.

The joint was made using the epoxy adhesive Araldite 2024-2 (supplied by Huntsman Corporation, Texas USA).

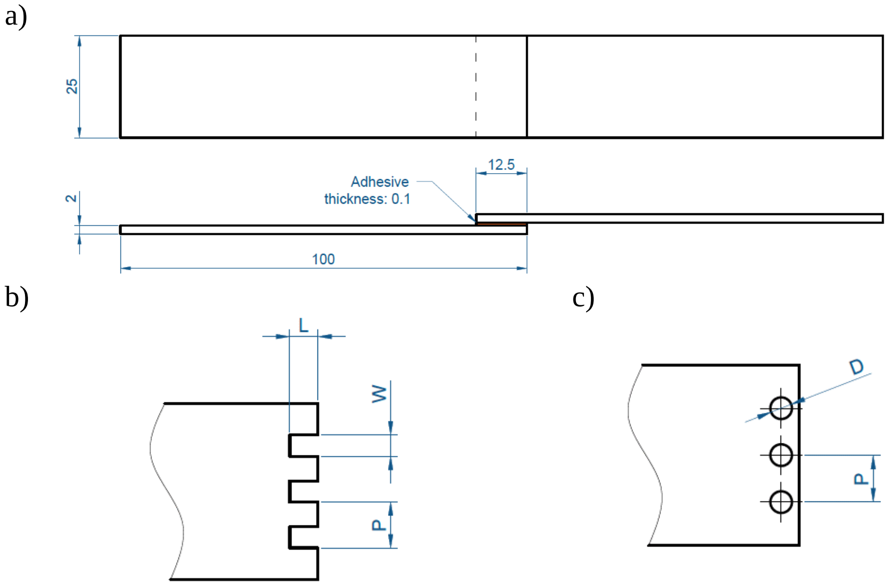

Fig. 1. The shape and dimensions of the samples of adhesive lap joints used in the tests in the basic version (a) and the shape and dimensions of structural modifications in the front part of the adherends in the form of notches (b) and holes (c)

The same methods of surface preparation and hardening conditions of the adhesive composition were applied to all joint variants. Each surface to be joined was subjected to abrasive blasting with aloxite 95A, which contains 96% aluminium oxide (Al_2O_3), ~3% titanium dioxide (TiO_2) and 1-2% other admixtures. Abrasive blasting was performed under the following conditions: grain size w_z = 0.27 mm, air pressure p = 0.8 ± 0.1 MPa, and blasting time t = 60 s.

Table 1. Summary of dimensions of structural modifications for individual variants of samples

Variant		Notch width (W in mm)	Notch length (L in mm)	Hole diameter (D in mm)	Pitch (P in mm)	Location of the holes (L in mm)
Base		-	-	-	-	-
Narrow notch	N-1x1	1	1	-	6.5	-
	N-1x2	1	2	-	6.5	-
	N-1x3	1	3	-	6.5	-
	N-1x4	1	4	-	6.5	-
Medium notch	N-2x1	2	1	-	6.5	-
	N-2x2	2	2	-	6.5	-
	N-2x3	2	3	-	6.5	-
	N-2x4	2	4	-	6.5	-
Wide notch	N-3x1	3	1	-	6.5	-
	N-3x2	3	2	-	6.5	-
	N-3x3	3	3	-	6.5	-
	N-3x4	3	4	-	6.5	-
Hole	H-2	-	-	2	6.5	2
	H-3	-	-	3	6.5	2.5
	H-4	-	-	4	6.5	3

Surface morphology of the adherends was measured with the Talysurf CCI Lite 3D optical profiler (Taylor Hobson Ltd., Leicester, United Kingdom). Figure 2 presents surface morphology of the adherends after the sand blasting process.

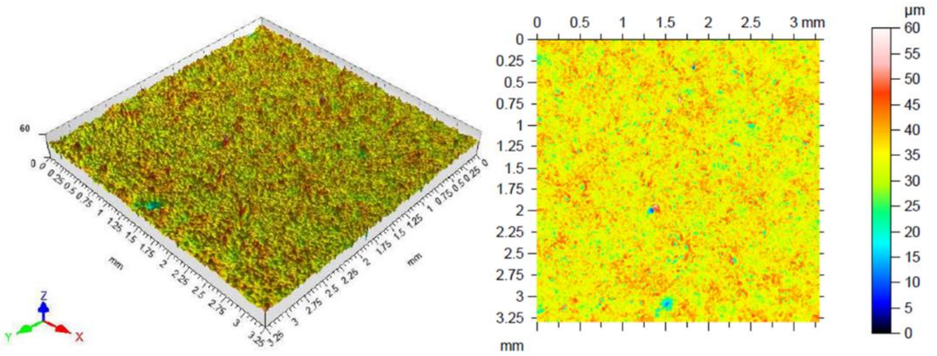

Fig. 2. Surface morphology of the adherends after the sand blasting process

The values of basic surface roughness parameters are as follows: arithmetical mean height Sa = 1.55 µm, root mean square deviation Sq = 3.92 µm, kurtosis Sku = 4.98, skewness Ssk = -0.447, maximum profile peak height Sp = 24.6 µm, maximum height Sz = 60.0 µm and maximum profile valley depth Sv = 35.4 µm.

The hardening process of the adhesive-bonded joints lasted for 24 h at room temperature 20 ± 3 °C under a constant pressure of 0.1 MPa applied to the joint area.

The investigation of the load capacity of the joint by tensile/shear tests was carried out using a ZWICK Roell Z-100 universal testing machine (Zwick/Roell GmbH & Co. KG, Ulm, Germany) with the constant crosshead speed of 5 mm/min at ambient temperature. The research was carried out for five repetitions of each variant.

The morphologies of the fracture surfaces of the adhesive joints were examined using an scanning electron microscope (SEM) Phenom ProX (Nanoscience Instruments, Phoenix, AZ, USA).

3. Results and discussion

Figs. 3a-c show representative curves from static shear tests of joints for each of the variants of the applied modifications in comparison to the basic variant. In Fig. 3a the shear curves of the samples from narrow notch of different lengths were related to the base variant. Herein, in selected cases, a higher load capacity of the joints was observed, and in each variant with a modification, a slightly higher stiffness of the joint in relation to the base variant was also observed. Similar phenomena were demonstrated for the variants of medium notch and wide notch.

On the other hand, in the case of structural modifications consisting in making holes, no significant differences were revealed in the strength and stiffness of joints in relation to the base variant.

The discussion of the possible mechanisms of failure of joints affecting the nature of the mechanism of static shear curves for individual variants will be carried out on the basis of fractographic analyzes.

Diagram shown in Fig. 4 summarizes the individual test results for individual samples along with the mean value for each variant and the value of the standard deviation. The highest increase in the load capacity of the joint in relation to the base variant was demonstrated for the notch medium, specifically for the N-3x1 variant. In this case, the average value of the load capacity of the joint increased by about 15.9%, as for the variant under consideration it was 8634.04 N, while for the base variant, this value is 7446.95 N. It should be noted that the dispersion of the load capacity results was also increased here, because for the variant N-3x1 the standard deviation value was 381.6 N, while for the base variant, the standard deviation was 201.5 N. The increase in the spread of strength results was observed for most variants with structural modifications. The largest scattering of results in relation to the base variant was shown for the variant with holes, namely H-3, where the standard deviation was 982.9 N and the average value of the load capacity for this variant was 7033.12 N.

It should be noted that from the technological point of view, accurate filling of the notches with adhesive is difficult to obtain, hence in many cases quite significant scattering of the strength results was demonstrated. Additionally, filling certain volumes with adhesive mass creates the possibility of the occurrence of voids, air bubbles in these volumes, which may be random, and undoubtedly affect the repeatability of the test results.

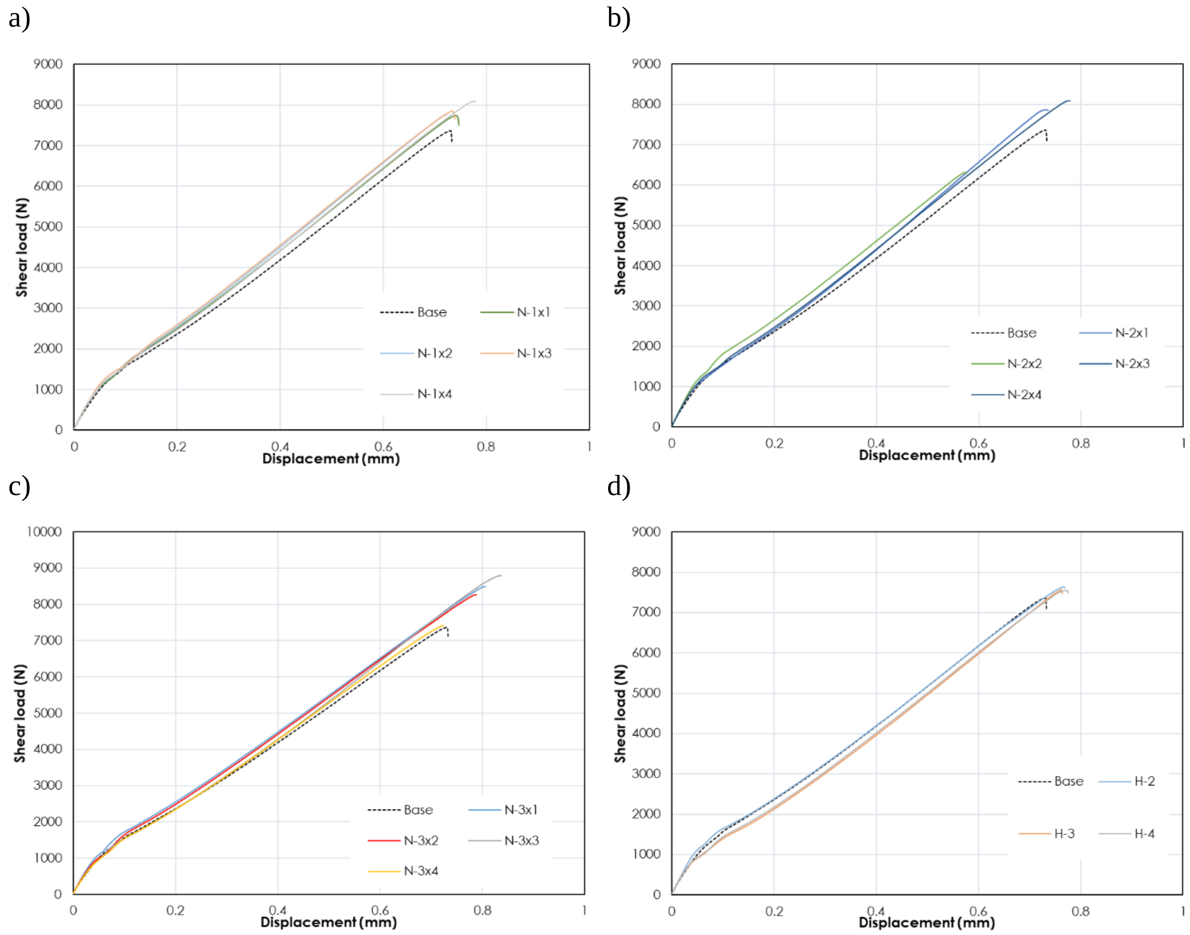

Fig. 3. Shear load-displacement representative static test curves of adhesive joints with structural modifications in relation to the base variant, for the following types of modifications: narrow notch (a), medium notch (b), wide notch (c) and hole (d)

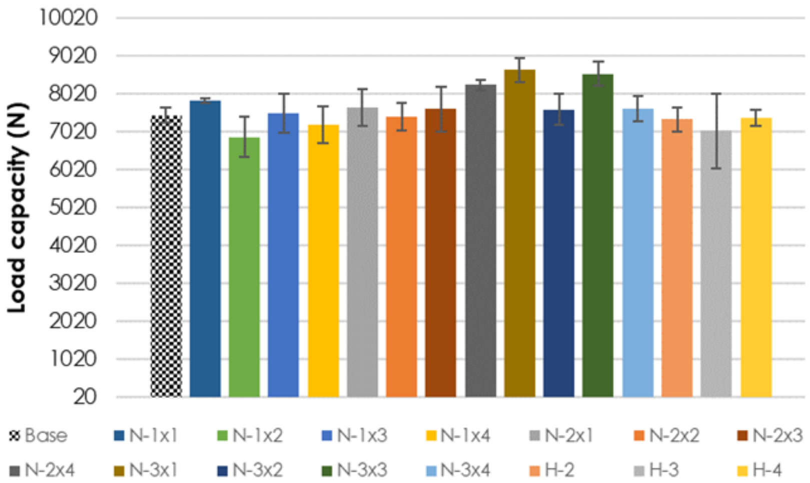

Fig. 4. Effect of the geometry of structural modifications on load capacity of adhesive joints

However, in the case of one of the variants with a structural modification, namely N-1x1, high repeatability of the results was demonstrated during the tests, because in this case the average load capacity of the joint was 7834.13 N with the standard deviation equal to 61.62 N. It should be noted that this is the variant with the smallest notch dimensions that were considered, namely the volume of the notches which is filled with the adhesive, has the dimensions of 1×1×2 mm. With such a small volume, it is easy to completely and repetitively fill the space with adhesive; the probability of defects such as voids occurring in these volumes is reduced, hence the high repeatability of the test results is ensured.

On the basis of fractographic analyzes, an attempt was made to determine the phenomena influencing the increase in strength of the selected joint variants. The analyzes were started with the notched variants, as this modification resulted in a significant increase in the strength of the joint. Fig. 5 shows images of the fracture surface for the N-2x4 variant showing the border between the sheet surface and the notch filled with adhesive. The SEM micrograph shows a clear difference in the nature of the fracture of the adhesive in the area of the notch and the sheet surface. In the case of failure of the joint in the area of the sheet, a typical failure of the adhesive joint was observed due to shearing of a thin layer of adhesive of about 0.1 mm thickness. In this case, there is essentially cohesive failure, although fragments of adhesive failure can also be seen in small areas at the leading edge of the sheet. A similar character of failure occurs with the basic variant (Fig. 6a), while in this case no areas of adhesive failure were observed. A completely different character of the cracking takes place in the notch area; in this case the fracture is characterized by a failure mechanism typical for the stretching of thermosets, where the fracture of adhesive a brittle character. In the area of the notch, the hardened adhesive has a thickness that is much greater than that of the adhesive joint, i.e. close to the thickness of the sheet, i.e. 2 mm. In the considered areas formed by the adhesive-filled notches, a different, lower joint stiffness occurs locally, which results in a change in the stress distribution. The local flexibility of the front joint area is advantageous due to the stress concentration typical of this type of joint. It is in this phenomenon that the increase in strength for variants with notches should be seen. At the same time, as previously observed, the technological problem of uniform filling of the volume of notches and holes with adhesive may translate into an increase in the scatter of test results. On the one hand, the greater the volumes formed by the notches, the greater the flexibility of the joint, but on the other hand, the larger volumes filled with the adhesive mass increase the likelihood of the aforementioned drawbacks, such as air bubbles, voids, etc.

In the case of structural modifications consisting in making round holes at the front edges of the adherends, no significant effect on the strength of the joint was demonstrated. Fig. 6b shows the micrographs of the fracture surface for the H-4 variant. Based on the SEM image, it can be concluded that in this case there was no significant difference in the mechanism of failure of the joint in the area of the sheet surface and the hole filled with adhesive. In the case of notches, the adhesive that fills the notch volume has one degree of freedom, i.e. it stretches in the direction of the joint loading. On the other hand, the adhesive closed in a hole made in steel having significantly higher stiffness than the hardened adhesive material, has no possibility of stretching. Therefore, such a structural modification does not have a significant impact on the stress distribution at the leading edge of the joint - the adhesive filling the holes is sheared in the joint plane.

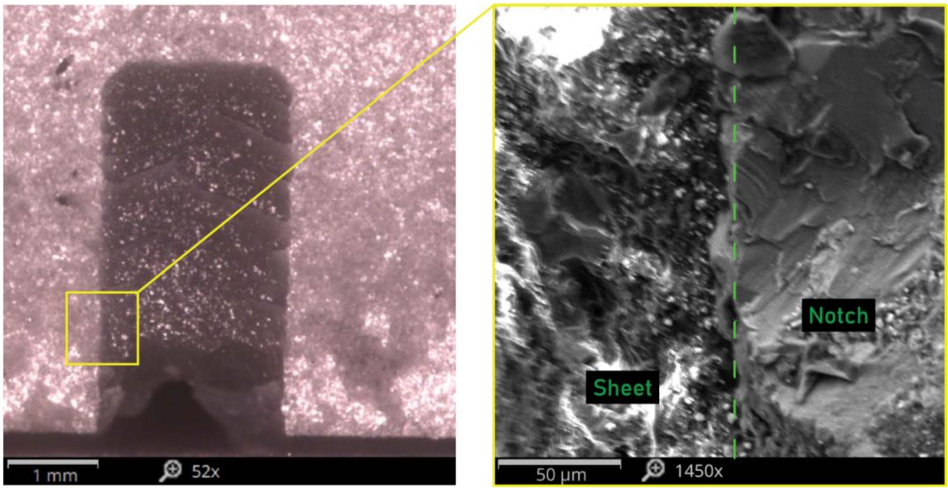

Fig. 5. Micrographs of the fracture surfaces for variant: medium notch 4 mm length

To sum up, a significant potential to increase the static strength of the adhesive joint by several percent thanks to making the front part of the joint more flexible has been demonstrated. The issue requires further optimization studies aimed at indicating the optimal dimensions and shapes of notches. The issue of technology also requires development, because in order to ensure the repeatability of the strength of joints, it is necessary to fill the space in the notches in such a way so as to ensure uniform mechanical properties.

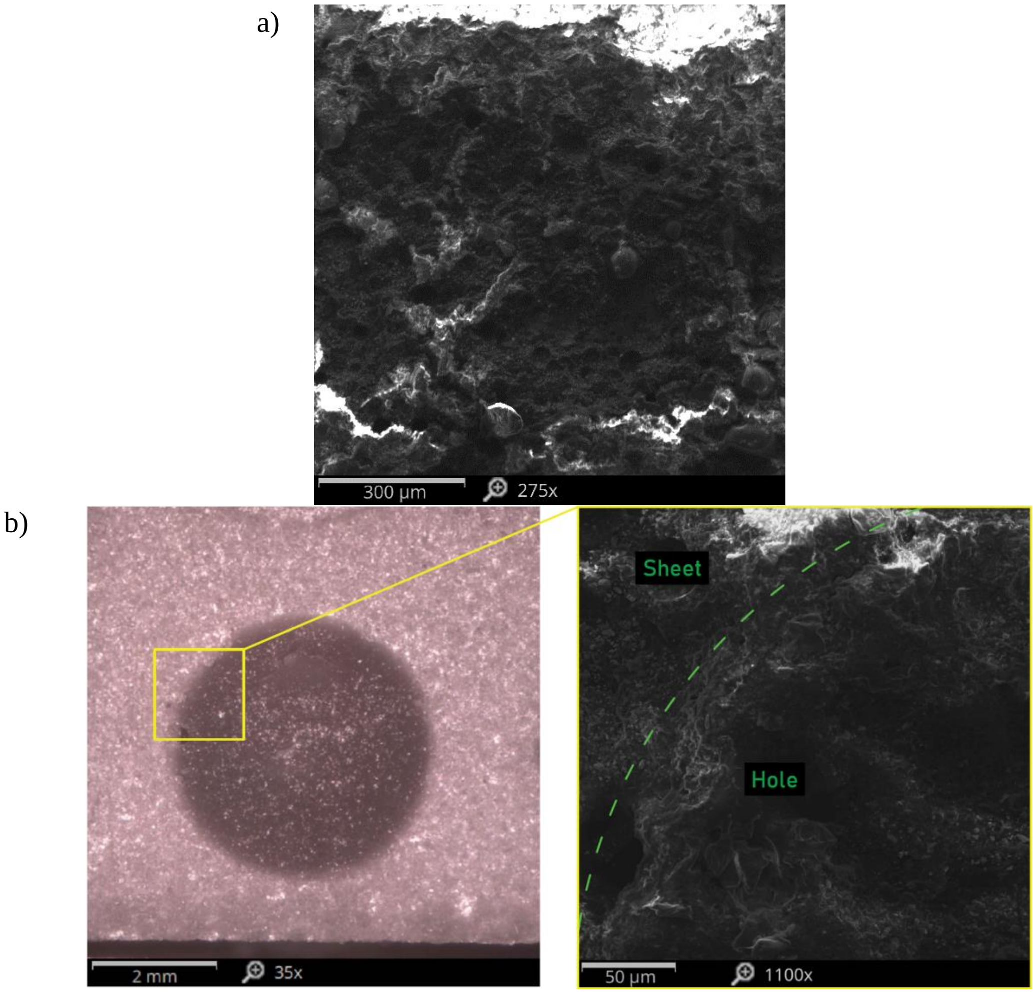

Fig. 6. Micrographs of the fracture surfaces for base (a) and hole with a diameter of 4 mm (b)

4. Conclusions

The aim of the work was to demonstrate, on the basis of experimental studies, the possibility of increasing the structural load-bearing capacity of S235JR steel adhesive joints by making relatively easy structural modifications to the adherends. Based on the research work carried out, the following conclusions were drawn:

- Due to the application of relatively easy-to-implement structural modifications, the load-bearing capacity of adhesive lap joints can be improved. As part of the research, the highest increase was shown for the variant with 3 mm wide and 1 mm long notches. In this case, the average value of the load capacity of the joint increased by about 15.9%, as for the variant under consideration it was 8634.04 N, while for the base variant, this value is 7446.95 N.
- The increase in the load capacity of the joints was demonstrated only for the variants with notches, while no significant changes in the load capacity were observed for the variants with openings at the leading edge of the adherends.
- The increase in load capacity for variants with structural modifications in the form of notches is caused by the local elasticity of the front part of the joint, where stress concentration occurs. In the area of the notches, the adhesive filling undergoes a different destruction mechanism than the thin layer of adhesive sheared between the sheet surfaces.
- In most cases, for variants with structural modifications, the standard deviation of the test results was increased. The largest dispersion of results in relation to the base variant was shown for the variant with holes with the diameter of 3 mm, where the standard deviation was 982.9

N and the average value of the load capacity was 7033.12 N, while for the base variant the value of the standard deviation was 201.5 N for the average value of the load capacity of the joints equal to 7446.95 N.
- Increasing the dispersion of the results is caused by a technological problem, because filling the notches and holes with adhesive mass creates the possibility of the occurrence of voids, air bubbles in these volumes, which may be random and has a significant impact on the repeatability of the test results.

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Badania Eksperymentalne Wpływu Modyfikacji Konstrukcyjnych Materiałów Klejonych na Nośność Złącza Zakładkowego Blach Stalowych S235JR

Streszczenie

W artykule przedstawiono wyniki badań określających wpływ modyfikacji konstrukcyjnych elementów klejonych na nośność złączy wyznaczoną w statycznej próbie ścinania. Opisano badania połączeń klejowych zakładkowych blach stalowych S235JR sklejonych klejem epoksydowym Araldite 2014-2. Zbadano wpływ prostych technologicznie modyfikacji konstrukcyjnych, polegających na wykonaniu nacięć i otworów na krawędzi natarcia elementów klejonych. Modyfikacje te miały na celu doprowadzenie do miejscowego uelastycznienia połączenia we wrażliwym obszarze koncentracji naprężeń. Na podstawie badań eksperymentalnych wykazano, że istnieje możliwość zwiększenia nośności złącza dzięki zastosowanym modyfikacjom. W najkorzystniejszym wariancie zaobserwowano wzrost nośności o 15,9% w stosunku do wariantu niemodyfikowanego konstrukcyjnie. Badania potwierdziły, że wypełnione przez klej nacięcia w przedniej części elementów klejonych mogą znacząco poprawić właściwości wytrzymałościowe złącza, natomiast rozważane modyfikacje w postaci otworów nie mają istotnego wpływu na właściwości elementów klejonych.

Słowa kluczowe: połączenia klejowe, modyfikacja konstrukcyjna, statyczna próba ścinania, stal S235JR