Technologia i Automatyzacja Montażu

Volume 125, Issue 3/2024, Pages 3-11
https://doi.org/10.7862/tiam.2024.3.1

Original Research

A PROPOSAL FOR A NEW METHOD OF TESTING THE IMPACT STRENGTH OF ADHESIVE JOINTS

PROPOZYCJA NOWEJ METODY BADANIA UDARNOŚCI POŁĄCZEŃ KLEJOWYCH

Jan GODZIMIRSKI[1], **Andrzej KOMOREK**[2]

[1] Faculty of Mechatronics, Armament and Aerospace, Military University of Technology, Warsaw, Poland
[2] Department of Aviation, Polish Air Force University Dęblin, Poland

* Corresponding author: jan.godzimirski@wat.edu.pl

Abstract

The usefulness of the proprietary method of testing the impact strength of adhesive joints under shear loads was checked. An adhesively bonded lap sample of flat bars with a thickness of 5 mm, loaded on the side surface of the overlap, was proposed. Numerical calculations have shown that in such a loaded lap joint, shear stresses dominate. Impact tests of such specimens can be performed on conventional Charpy hammers. Experimental tests were carried out on samples made of steel, brass and aluminum alloy bonded with various adhesives: Epidian57/Z1, Raychem S1125, Loctite 9464 and DP 420. The conducted experimental tests showed high reproducibility of the results of such tests and as expected, higher destruction energy of flexible adhesive and adhesive layers of greater thickness was obtained.

Keywords: adhesive joints, impact strength of adhesive joints, new impact testing method

Streszczenie

Sprawdzono przydatność autorskiej metody badania udarności połączeń klejonych obciążonych na ścinanie. Zaproponowano klejoną na zakładkę próbkę wykonaną z płaskowników o grubości 5 mm, obciążaną na bocznej powierzchni zakładki. Obliczenia numeryczne wykazały, że w tak obciążonym złączu zakładkowym dominują naprężenia styczne. Próby udarności takich próbek można wykonywać na konwencjonalnych młotkach Charpy'ego. Przeprowadzono badania eksperymentalne na próbkach wykonanych ze stali, mosiądzu i stopu aluminium klejonych różnymi klejami Epidian57/Z1, Raychem S1125, Loctite 9464 oraz DP 420. Przeprowadzone badania eksperymentalne wykazały dużą powtarzalność wyników takich badań i zgodnie z oczekiwaniami uzyskano wyższą energię niszczenia kleju elastycznego i warstw kleju o większej grubości.

Słowa kluczowe: kluczowe: połączenia klejowe, udarność połączeń klejowych, nowa metoda badań udarności

1. Introduction

Adhesive bonded is one of the methods of joining parts. The factor driving the dynamic development of the adhesive technique is, above all aviation and cosmonautics as well as the automotive industry (Adams 1997, Higgins 2009, Silva 2011) and construction. In addition to testing static properties, for some time now more and more tests have been carried out on the resistance of adhesive joints to impact loads. This especially applies to vehicles exposed to various types of collisions (Grant 2009, Galvez 2017, Machado 2018).

Currently, three methods of testing the impact strength of adhesive joints are recommended:

- Block Shear Test (ISO 9653) (Adams 2016, Taylor 1996, Asgharifar 2014),
- Impact Wedge Peel Test (ISO11343, Blacman 2000, Gyeong-Seo 2020),

- Impact shear method of lap joints subjected to tensile loading (Adamvalli 2014, Raykhere 2010, Komorek 2021).

The first two methods are standardized. The first is like the standard for wood adhesives. It consists in adhesively bonding a plate 3 mm thick, 25 mm wide and 10 mm long (Fig. 1) to a metal block, which is dynamically loaded with a hammer impactor (Fig. 2) during the tests. The result of the experiment depends on the direction of the impact. The destruction energy of the adhesive joint is measured, and divided by the joint surface, it is possible to calculate the impact strength of the tested joint.

The main disadvantage of this method is the low reproducibility of the experiment results, the reasons explained in publications (Adams 1966, Komorek 2016) are difficult to eliminate.

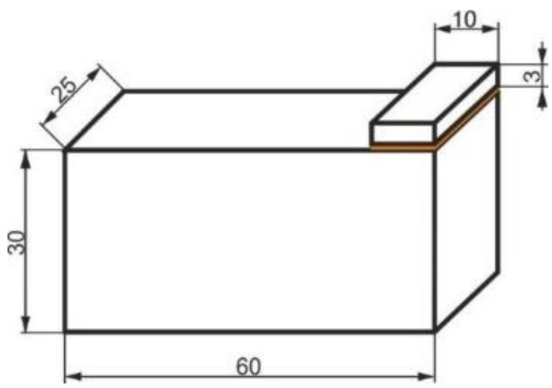

Fig. 1. Block sample

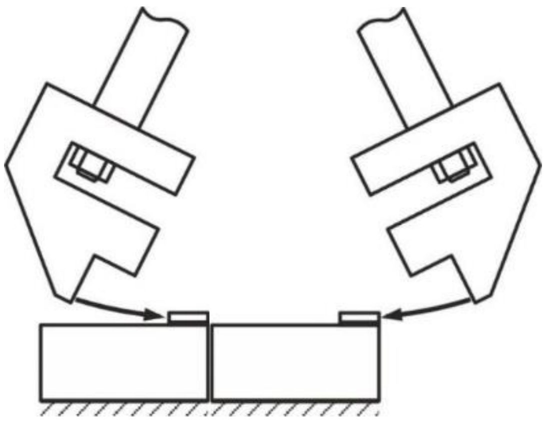

Fig. 2. Block sample load

An attempt to modify this method by changing the shape of the adhesively bonded element to cylindrical (Fig. 3) allowed to reduce the scatter of the test results but led to plastic deformation of the loaded element (Fig. 4), which resulted in the accumulation of stresses in the adhesive layer near the striking edge (Komorek, 2020).

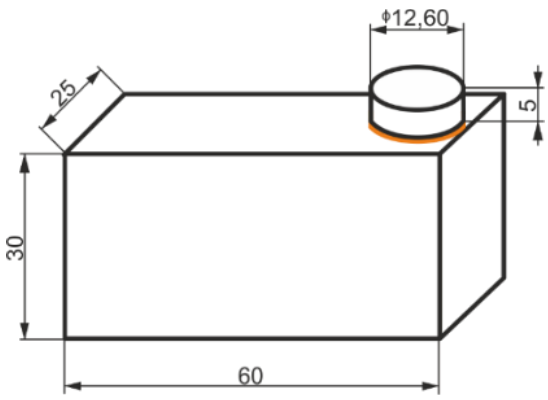

Fig. 3. Modified block sample

Fig. 4. Plastic deformation of the cylindrical plate under dynamically loaded

Due to the disadvantages of the block connection test method, such tests are rarely conducted.

The ISO11343 method, consisting in dynamic cleaving of the adhesive joint with a wedge (Fig. 5), is more widely used.

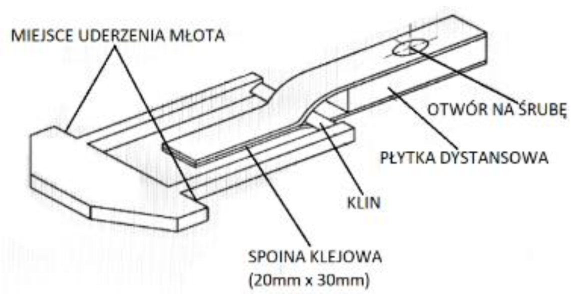

Fig. 5. The method of dynamic cleaving the adhesive joint with a wedge

This method is used in the automotive industry to test the crash test resistance of adhesively bonded car bodies. It requires a specialized device measuring and recording the dependence of force on time or force on displacement, which, after integration, allows the energy to be determined between 25% and 90% of the curve. The results of such tests depend on the properties of the adhesive, the surface treatment of the joined elements (adhesion forces) and the mechanical properties of the bonded materials. Such tests are essentially dynamic peel tests.

Due to the fact, that a properly designed adhesive joint should be mainly stressed for shear, attempts are made to test the impact strength of lap joints. Due to the lack of an appropriate standard, researchers use their own solutions, which makes it difficult to compare the obtained results.

The authors conducted tests on lap specimens made of two plates with dimensions of 20x100 mm and a thickness of 2 mm. A pendulum hammer with a modified striker shape was designed to conduct such research (Fig. 6).

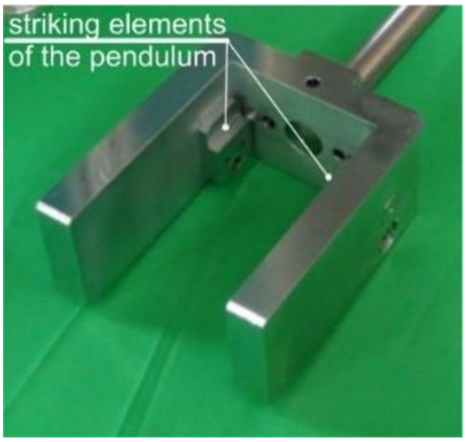

Fig. 6. Modified striker of a hammer

At one end of the adhesively bonded lap sample, a special holder with a wedge was attached (Fig. 7), which prevented the sample from moving in the holder during loading.

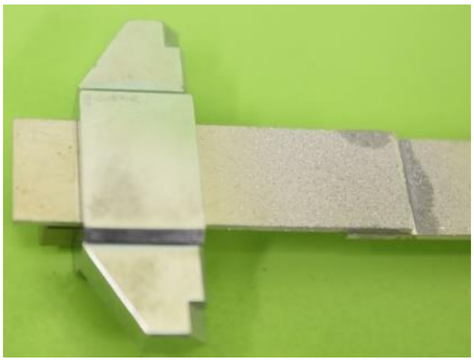

Fig. 7. A lap specimen with a handle

The other end of the sample was fixed in a rigid holder (Fig. 8) and a hammer hit a self-clamping holder fixed on the sample.

The impact tests carried out in accordance with the presented method were characterized by a much greater reproducibility of the results than in the tests of block joints, although it was not possible to eliminate the removal of samples from the holders (about 10%), which resulted in a rapid increase in the measured energy.

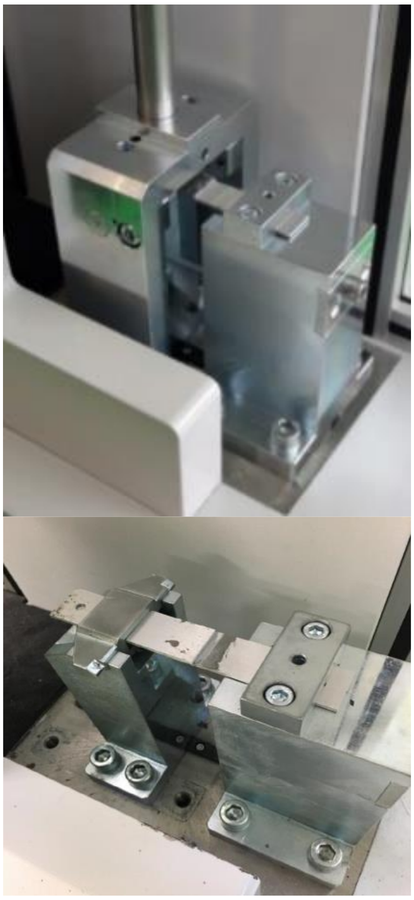

Fig. 8. The sample attached to the impact tests

The presented test method allows to study the effect of the overlap length, the thickness of the adhesive layer, the method of preparing the surface for bonding and the stiffness of the sheets to be bonded on the impact strength of the joints. Its disadvantage is the labor-consumption of such tests resulting from careful assembly of samples and the need to have a pendulum hammer with a modified structure. Considering the limitations of the test method for lap specimens, another method of testing the impact shear resistance of adhesive joints has been proposed. The theory of strength of adhesive joints shows that there are three basic structural systems of such joints, in the adhesive layers of which shear stresses dominate (Silva, 2011) (Fig. 9).

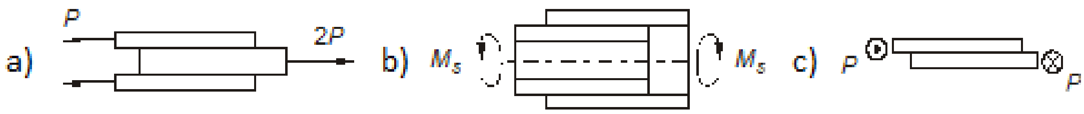

Fig. 9. Models of shear-loaded adhesive joints (a - lap, b - sleeve-twisted, c - lap-stressed along the width of the overlap)

The aim of the analysis was to check the suitability for impact tests of samples loaded similarly to the third load model presented in Fig. 9.

2. Numerical analysis

It was assumed that the sample will have similar dimensions to the samples used in the impact tests of metals and it will be possible to perform the tests on commonly available Charpy pendulum hammers. The sample load model and its numerical model of such a sample is shown in Fig. 10.

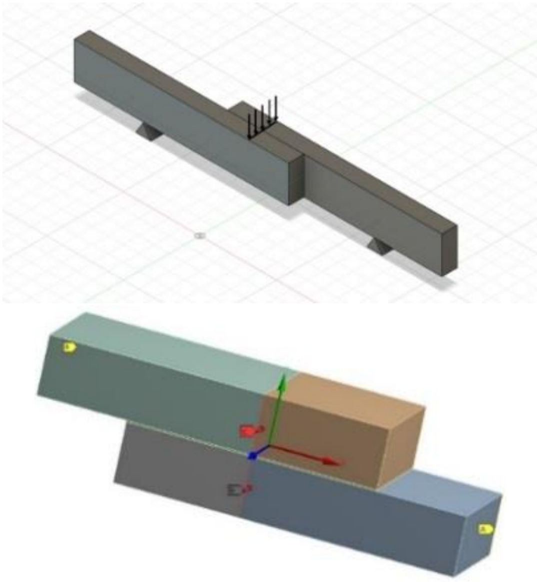

Fig. 10. Model of sample mounting and loading

The adhesively bonded elements were given the properties of an aluminum alloy (E = 72 GPa, ν = 0.33), and an adhesive layer with a thickness of 0.15 mm was given the properties of epoxy adhesive (E = 2 GPa, ν = 0.35). The sample was supported on both sides (spacing of supports 43 mm) and centrally loaded with a total force of 2000 N distributed evenly along the edge. The calculation results are shown in Figs. 11 to 14.

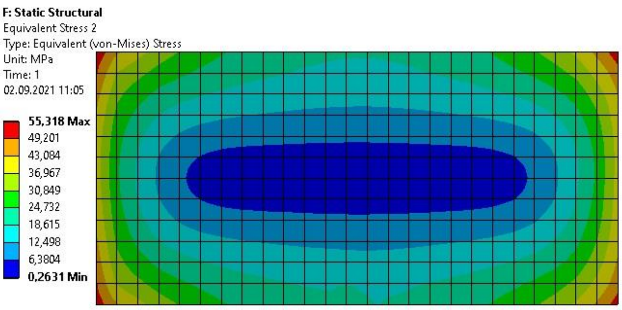

Fig. 11. The von Mises stress distribution in the adhesive layer

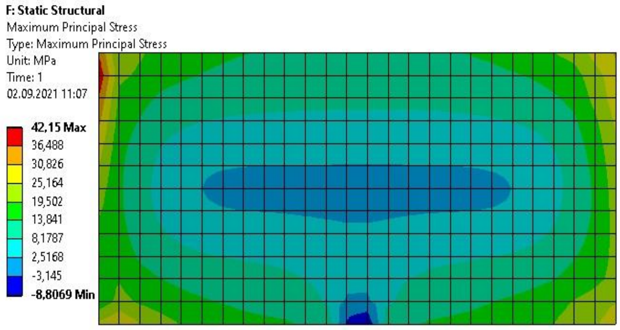

Fig. 12. Distribution of the maximum principal stresses in the adhesive layer

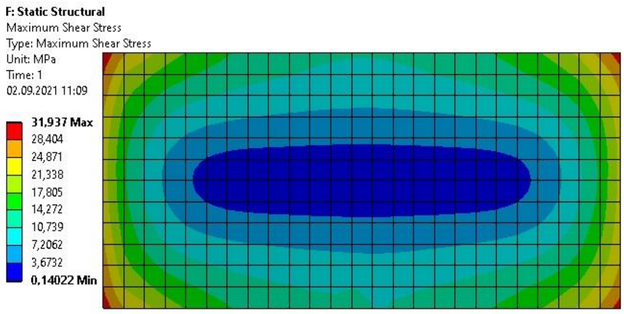

Fig. 13. Distribution of maximum shear stresses in the adhesive layer

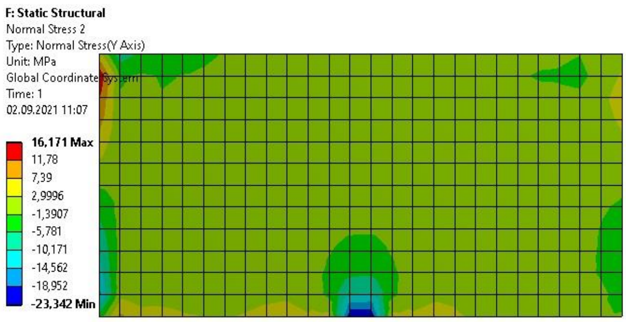

Fig. 14. Distribution of normal stresses perpendicular to the adhesive layer surface

The performed calculations show that shear stresses dominate in the adhesive layer of the analyzed joint, to a greater extent than in lap joints. It follows that the proposed samples meet the criterion of joints loaded in shear and can be used in impact tests.

Additionally, numerical calculations were carried out in which the type of bonded materials (Young's modulus) was changed, the length of the overlap and the thickness of the bonded elements under the same load. The results of these calculations are presented in Table 1.

Table 1. The relationship of stresses in the adhesive layer on the type of joined materials, the thickness of the bonded elements and the length of the overlap

	Thickness of the joined elements 6 mm				Thickness of the joined elements 5 mm		
Overlap	15 mm	25 mm			25 mm		
Material	duralumin	duralumin	brass	steel	duralumin	brass	steel
Stresses [MPa]							
σ_{VM}	68.4	55.3	48.9	41.9	59.7	52.4	44.4
σ_{I}	55.5	42.2	35.0	28.2	45.2	37.3	29.8
τ_{max}	39.5	31.9	28.3	24.2	34.5	30.2	25.6
σ_{Y}	22.8	16.2	11.6	7.5	17.3	12.5	8.1

σ_{VM} – von Mises stress, σ_{I} – maximum principal stress, τ_{max} – maximum shear stress, σ_{Y} – normal stress perpendicular to the adhesive layer surface

The calculations show that in the case of standardization of such a test method, the length of the overlap, the thickness of the bonded elements and their width should be determined. When changing the distance between the supports from 43 to 60 mm, the calculated stresses increased by about 50%. If we assume that the criterion of dynamic failure was only the value of stresses in the adhesive layer, then the highest failure energy should be obtained for steel samples of greater thickness, jointed with a longer lap and with a smaller spacing of support.

3. Research methodology

Rectangular cross-section bars with dimensions of 12x5 or 12x6 mm were cut into 45 mm long sections. On one side of the sample, a surface with a side length of 25 mm intended for adhesive bonding was marked. The joined surfaces were prepared for adhesive bonding using various methods: only degreasing with extraction gasoline, roughening with abrasive cloth No. 80 and degreasing with gasoline, or sandblasting with corundum and degreasing with gasoline. Two elements made of a 12x5 mm flat bar 45 mm long each were adhesively bonded, with an overlap of 25 mm. The bonded elements were made of brass M69, steel C45 and aluminum alloy AW 3035 H12).

Adhesives were applied to both dried surfaces. To obtain the appropriate thickness of the adhesive layers, sewing threads were placed in them or not. Epidian 57 resin was mixed with the Z1 hardener in weight proportions of 100 to 10.5. The ingredients of other adhesives are dosed automatically while squeezing them from the packaging. The samples were bonded in a special device with low contact pressures exerted by springs. The adhesives were cured according to the manufacturers' recommendations (Epidian 57 - 24 h at ambient temperature and 5 h at 80^{o}C, Loctite 9464 – 7 days at ambient temperature, DP 420 – 48 h at ambient temperature, Raychem – 24 hours at ambient temperature).

After the joints had hardened, the adhesive flashes were removed using a metal cutting saw blade and an abrasive cloth. The samples were mounted centrally in swing hammers. The experiment was conducted mainly on a SW – 5 swing hammer with an energy of 50 J and a speed of 3.8 m/s with a support spacing of 43 mm (Fig. 15) and on a pendulum hammer Julietta with the energy of 7.5 J with a spacing of supports 60 mm (only one batch of samples).

Fig. 15. Sample placed on a pendulum hammer

Five samples in each batch were tested and the energy of destruction of joints was recorded (Fig. 16). The results were analyzed statistically by calculating the mean value and confidence intervals at the 95% significance level.

Fig. 16. A batch of brass samples bonded with Epidian 57 / Z1 adhesive

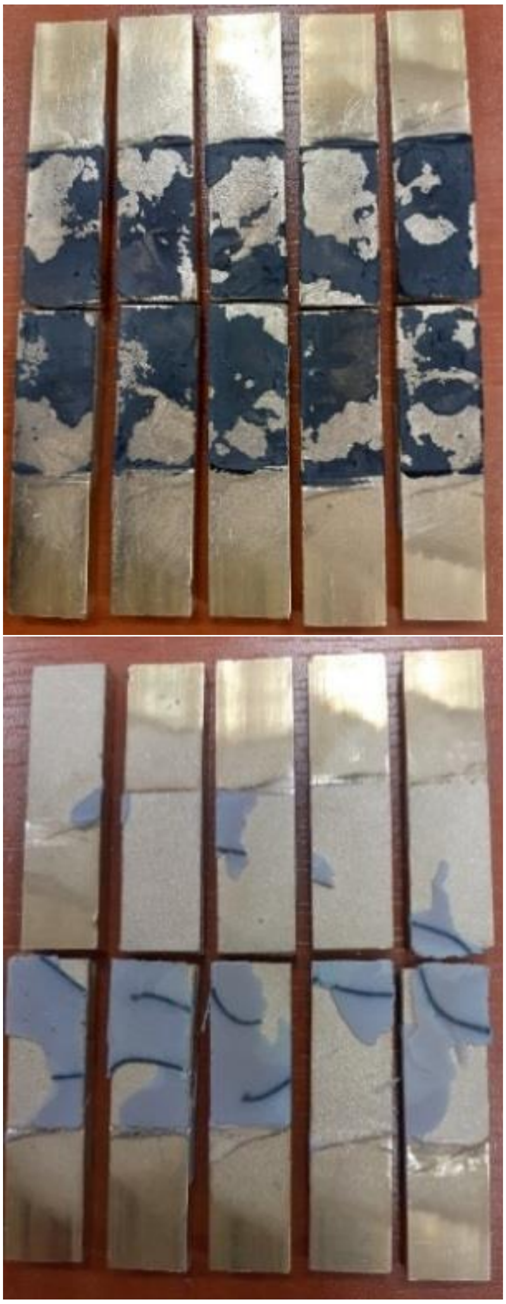

Fig. 17. The nature of destruction of adhesive layers with a thickness of 0.3 mm (Epidian 57 / Z1 adhesive) and 0.25 mm (Raychem adhesive)

4. Experimental tests

In the first stage of the research, the influence of the thickness of the adhesive layers and their stiffness on the impact strength of the joints was estimated. The adhesively bonded surfaces were roughened with abrasive cloth of granulation 80 and washed with gasoline. Three batches brass samples of 5 pieces each, were bonded with adhesive: Epidian57 / Z1 (thickness of adhesive layer 0.04 mm), Epidian 57 / Z1 (thickness of adhesive layer 0.3 mm) and Raychem S-1125 characterized by great flexibility (thickness of adhesive layer 0.25 mm) and one batch of steel and aluminum alloy samples were bonded with Epidian 57 / Z1 adhesive (thickness of the adhesive layer 0.3 mm).

The tests were carried out on a pendulum hammer SW – 5. The nature of the destruction of the adhesive layers of brass samples is shown in Fig. 17.

The results of the tests with confidence intervals for the 95% level of significance are presented in Table 2.

Table 2. Results of impact tests

Adhesive	Epidian57/Z1 g = 0.04 mm	Epidian57/Z1 g = 0.3 mm	Raychem g = 0.25 mm	Epidian57/Z1 g = 0.3 mm	Epidian57/Z1 g = 0.3 mm
Material	brass			steel	AW 3035
Energy [J]	1.8 1.7 1.6 1.7 1.7	2 2 1.8 2.1 2.2	3.5 3 3.6 2.8 3.1	1.5 1.3 1.4 1.5 1.6	2.3 2.4 2.1 1.7 2.3 1.7
Average energy [J]	1.7±0.03	2.02±0.18	3.2±0.46	1.44±0,19	2.08±0,33

The test results are characterized by satisfactory repeatability and as expected, a significant influence of the adhesive layer thickness and adhesive stiffness on the impact strength of the tested joints.

The impact strength of steel and brass specimens adhesively bonded with Loctite EA 9464 adhesive was also compared with different spacing of supports. In this case, the tests were carried out on a pendulum hammer Julietta with a spacing of supports 60 mm. The results of the specified energies are shown in Table 3.

Table 3. Comparison of the failure energy of brass and steel samples bonded with Loctite EA 9464 adhesive, tested at different spacing of supports (steel samples only washed with gasoline, brass samples roughened with cloth 80 and degreased)

Spacing of supports	60	43
Material	Average energy of failure [J]	
steel	1.48±0.22	1.88±0.26
brass	2.43±0.36	4.12±0.22

According to the results of numerical calculations, the increase in the spacing of supports resulted in a decrease in the energy of joint destruction.

Even though in the adhesive layers of steel samples there are lower stresses than in the brass samples under the same static load, their impact strength turned out to be lower. This may be due to the different adhesion of the adhesive to different materials or the lower impact strength of the stiffer joints.

To compare the adhesive properties of steel, brass and aluminum alloy surfaces prepared for bonding by various methods the tension strength tests were carried out on cylindrical samples (Fig. 18) bonded with Loctite EA 9464 adhesive.

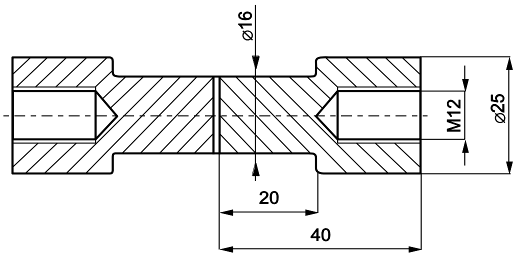

Fig. 18. A sample for testing the tension strength of adhesives

Table 4. Tensile strength test results for Loctite EA 9464 adhesive bonding various materials

Surface treatment	Roughening with cloth 80 and degreasing			Degreasing
Material	AW 3035	Brass	Steel	Steel
Strength, MPa	26.4 ±2.35	37.1 ±2.1	31.5 ±2.3	17.59 ±0.35

The research shows that when the surface preparation for adhesively bonding with Loctite EA 9464 is roughened with cloth no. 80, better adhesive properties are shown by brass than steel and aluminum alloy. Only the degreasing of steel surfaces with gasoline resulted in a significant decrease in the tensile strength of steel samples (about 50%).

Table 5 compares the impact toughness of samples made of different metals bonded with Loctite EA 9464.

Table 5. Comparison of the failure energy of samples made of various materials bonded with Loctite EA 9464 adhesive (surface treatment with abrasive cloth No. 80)

Material	AW 3035	Brass	Steel
Failure energy, J	4.43±0.80	4.12±0.42	5.68±0.27

The impact energy destruction of samples was also tested, the surfaces of which were prepared for bonded by sandblasting with electrocorundum and then washing with gasoline. The test results are presented in Table 6 (tests were performed twice).

Table 6. Comparison of the failure energy of samples made of various materials adhesively bonded with Loctite EA 9464 (sandblasting of bonded surfaces)

Material	AW 3035	Brass	Steel
Failure energy, J	3.00±0.44 2.92±0.26	6.04±0.48 5.06±0.57	4.45±0.28 4.57±0.12

The use of such a method of surface preparation resulted in a significant increase in the destruction energy of steel lap specimens loaded on the side surface as well as brass specimens, but a decrease in the energy of aluminum alloy specimens. This proves the relevant influence of the adhesive forces on the impact strength of adhesive joints.

Considering the high heat capacity of the samples and the speed of performing the impact tests, tests of the influence of temperature on the impact strength of adhesive joints were carried out. The tests were carried out on steel samples, sandblasted, adhesively bonded with two adhesives: Loctite 9464 and DP 420. The destruction energy of joints at ambient temperature and heated in a laboratory oven to 60^{o}C was tested. To eliminate the effect of increased temperature on the hardening of the adhesive, all samples were annealed at 60^{o}C, and some of the samples intended for testing at ambient temperature were then cooled. The test results are presented in table 7.

Table 7. Comparison of the destruction energy of steel samples at ambient and elevated temperature of 60°C

Adhesive	Loctite 9464		DP 420	
Temperature	20°C	60°C	20°C	60°C

For both adhesives, a significant decrease in the impact strength of the tested joints was found at an elevated temperature of 60°C. An inverse relationship was expected, as the adhesive layer will become more flexible with increasing temperature. It was assumed that the reason for the decrease in impact strength may be stresses caused by different values of linear expansion coefficients of steel and adhesives.

Numerical calculations were carried out in the ANSYS 19 system, in which the sample was first loaded with a force of 6600 N (resulting from tests of the static strength of such joints), and then with the same force and a temperature increase of 40°C.

For steel, the value of the linear expansion coefficient α = 1.2 10-5 1/C was declared, and for the adhesive α = 5 10-5 C. temperature change.

Fig. 19 and 20 show the distributions of the maximum principal stresses in the adhesive layers: loaded with force and loaded with force and temperature change.

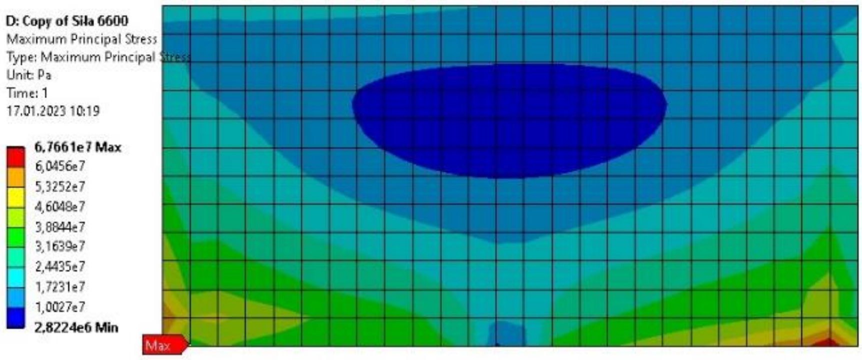

Fig. 19. Maximum principal stresses in the adhesive layer loaded with a force of 6600 N

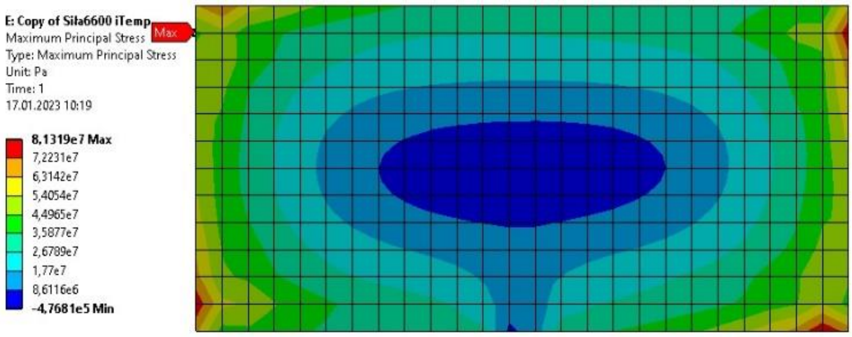

Fig. 20. Maximum principal stresses in the adhesive layer loaded with a force of 6600 N and a temperature increase of 40°C

Even though the load on the joint with only a temperature increase of 40°C generated stresses in the adhesive layer of about 2.5 MPa, the increase in stresses in the adhesive layer loaded with force due to the temperature increase was 13.6 MPa, i.e. it had a significant impact on the joint effort.

5. Conclusion

In the joints of the samples tested according to the proposed method, shear stresses dominate, i.e. those that occur in properly designed adhesive joints.

The impact test in accordance with the proposed method is characterized by a much greater repeatability of results than in the case of testing block or lap samples, which allows to reduce the number of tested samples.

The tests can be carried out on typical pendulum hammers with energies of 10 J, and the adhesively bonded elements can be reused several times in the tests after removing the adhesive from the previous tests.

Considering the relatively high thermal capacity of the proposed samples and the speed of the tests, the proposed method enables the study of the influence of temperature on the impact strength of adhesive joints.

References

Adams R.D., Harris J.A. 1996 "A critical assessment of the block impact test for measuring the impact strength of adhesive bonds" *International Journal of Adhesion and Adhesives* 16: 61-71.

Adams R.D., Comyn J. Wake W.C. 1997. Structural adhesive joint in engineering, Springer Science & Business Media, London.

Adamvalli M., Parameswaran V. 2008 "Dynamic strength of adhesive single lap joints at high temperature" *International Journal of Adhesion and Adhesives* 28: 321-327.

Asgharifar M, Kong F, Carlson, B, Kovacevic R. 2014 "Dynamic analysis of adhesively bonded joint under solid projectile impact" *International Journal of Adhesion and Adhesives* 50: 17-31.

Blackman B.R.H, Kinloch A.J, Taylor A.C, Wang Y. 2000 "The impact wedge-peel performance of structural adhesives" *J. Materials Science* 35: 1867-1884.

Galvez P. Quesada A., Martinez M.A., Abenojar J., Boada M.J.L., Diaz V. 2017 "Study of the behaviour of adhesive joints of steel with CFRP for its application in bus structures" *Composites Part B: Engineering* 129: 41-46.

Grant L.D.R., Adams R.D., da Silva L.F.M. 2009 "Experimental and numerical analisys of single-lap joints for the automotive industry" *International Journal of Adhesion and Adhesives* 29 (4): 405-413.

Gyeong-Seok Chae, Hee-Woong Park, Jung-Hyun Lee, Seunghan Shin 2020 "Comparative Study on the Impact Wedge-Peel Performance of Epoxy-Based Structural Adhesives Modified with Different Toughening Agents" *Polymers* 12, 1549; doi:10.3390/polym12071549.

Higgins A. 2009. "Adhesive bonding of aircraft structures" *Int J Adhesion Adhesive* 20: 367-376, 10.1016/S0143-7496(00)00006-3.

ISO 11343 – Adhesive. Determination of dynamic resistance of high-strength adhesive joints to separation under impact conditions – Wedge impact method.

Komorek A., Godzimirski J. 2016 "The selected aspects of the research into impact loading of adhesive joints in block samples – comparison of different ways of applying the load" *Maintenance Problems* 103 (4): 77-91.

Komorek A., Godzimirski J., Rośkowicz M. 2020 "Analysis of new shape of test specimen for block shear impact test" *Materials* 13 1693, https://doi.org/10.3390/ma13071693.

Komorek A., Godzimirski J. 2021 "Modified pendulum hammer in impact tests of adhesive, riveted and hybrid lap joints" *International Journal of Adhesion and Adhesives* 104, https://doi.org/10.1016/j.ijadhadh.2020.102734.

Machado J.J.M., Marques E.A.S., Silva M.R.G., da Silva Lucas F.M. 2018 "Numerical study of impact behaviour of mixed adhesive single lap joints for the automotive industry" *International Journal of Adhesion and Adhesives* 84: 92-100.

Raykhere S.L., Kumar P., Singh R.K., Parameswaran V. 2010 "Dynamic shear strength of adhesive joints made of metallic and composite adherents" *Material and Design* 31: 2102-2109.

Rośkowicz M, Godzimirski J., Komorek A., Jasztal M. 2021 "The Effect of Adhesive Layer Thickness on Joint Static Strength" *Materials*, 14 (6), 1499; https://doi.org/10.3390/ma14061499.

da Silva L.F.M., Öchsner A., Adams R.D. (Eds.), *Handbook of adhesion technology*, Springer, Heidelberg 2011.

Taylor A. 1996 Impact Testing of Adhesive Joints. *MTS Adhesive Project 2 AEA Technology*, 5 (2).