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IMPACT STRENGTH OF HYBRID JOINTS

UDARNOŚĆ POŁĄCZEŃ HYBRYDOWYCH

Abstract

Hybrid adhesive-mechanical joints compared to only adhesive or only mechanical joints are characterized by many advantages: greater stiffness, greater static strength, greater fatigue life, higher reliability, corrosion resistance. For these reasons, they are eagerly used in aviation structures. The aim of the research was to check the influence of hybridization on the impact toughness of connections. The static strength and the energy of dynamic destruction of lap joints loaded in shear by stretching or bending were compared: adhesive, riveted and hybrid joints. The tested hybrid joints were characterized by higher strength and dynamic destruction energy compared to adhesively bonded or riveted samples. The research also shows that the energy of dynamic failure increases if the failure of the joint is not complete and causes the connected elements to rotate around one rivet.

Keywords: hybrid adhesive-rivet joints, static strength, impact destruction energy

Streszczenie

Połączenia hybrydowe klejowo-mechaniczne w porównaniu do połączeń tylko adhezyjnych czy tylko mechanicznych charakteryzuje wiele zalet: większa sztywność, większa wytrzymałość statyczna, większa trwałość zmęczeniowa, wyższa niezawodność, odporność na korozję. Z tych względów chętnie są stosowane w konstrukcjach lotniczych. Celem prowadzonych badań było sprawdzenie wpływu hybrydyzacji na udarność połączeń. Porównano wytrzymałość statyczną oraz energię niszczenia dynamicznego połączeń zakładkowych obciążonych na ścinanie poprzez rozciąganie lub zginanie: klejowych, nitowych i hybrydowych. Badane połączenia hybrydowe cechowała większa wytrzymałość i energia niszczenia dynamicznego w porównaniu z próbkami klejonymi lub nitowanymi. Z badań wynika również, że energia niszczenia dynamicznego wzrasta, jeśli zniszczenie połączenia nie jest całkowite i powoduje obrót łączonych elementów wokół jednego nitu.

Słowa kluczowe: połączenia hybrydowe klejowo-nitowe, wytrzymałość statyczna, energia niszczenia udarowego

1. Introduction

The hybrid joint can be a combination of a mechanical joint and an adhesive joint. The appropriate configuration of the hybrid connection allows to eliminate the shortcomings of these connection techniques, and thus to obtain a structural node with better strength and operational properties [3, 6, 8, 12, 13, 14, 15, 17]. Many types of hybrid connections have been used in aviation structures: weld-adhesive, rivet-adhesive, clinch-adhesive and screw-adhesive [1, 2, 7]. This is due to the fact that the use of mechanical fasteners causes a high concentration of stresses around the mounting holes or welds [9], and this negative phenomenon can be partially limited by using an adhesive bond in the structural node alongside the mechanical connection.

The combination of mechanical and adhesive joints was also used to relieve the adhesive joint and reduce the negative impact of stress concentration at the edges of the joints. The right places for fasteners installation seem to be the ends of the adhesive joints, where the phenomenon of stress accumulation, especially normal stresses perpendicular to the adhesive joint, causes peeling.

The double system of connections is also a way of securing in a situation where one of the connections - most often the adhesive connection [18] - becomes damaged. Due to the assembly technology, the use of mechanical fasteners usually facilitates the assembly of the adhesively bonded elements and replaces the troublesome process of generating pressures during the hardening of the adhesive joint.

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Hybrid joints compared to only adhesive or only mechanical joints are characterized by [1, 4, 10, 16]: greater stiffness, greater static strength, greater fatigue life, higher reliability, corrosion resistance. Such connections are eagerly used for joining composites [5, 11].

The aim of the research was to check whether the impact strength can also be increased by the hybridization of riveted and adhesive joints.

2. Research methodology

The tests were carried out on two types of lap joints, loaded in shear by tension and by bending. The first type of samples was made by joining plates with dimensions of 70 x 20 x 2 mm made of AW 2024T3 aluminum alloy (material commonly used in aircraft construction) with an overlap of 24.5 mm by the method of adhesive bonding, riveting, adhesive bonding and riveting (Fig. 1).

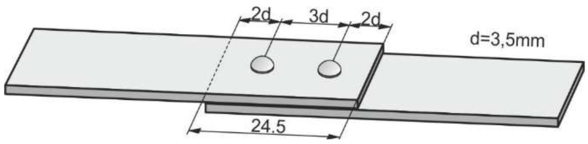

Fig. 1. The spacing of rivets in the lap sample, loaded by tension

Epidian 57/Z1 adhesive was used and two rivets with a diameter of 3.5 mm with countersunk heads made of PA24 alloy. The adhesively bonded surfaces of the samples were sandblasted with aluminum oxide and degreased with extraction gasoline. The adhesive layers were hardened in two stages: 12 hours at the ambient temperature and 5 hours at the temperature of 80ºC. The dimensions of the samples were determined by the capabilities of the Julietta impact hammer adapted to such tests. The samples were loaded in shear by stretching the joined elements. Three batches of samples (adhesively bonded, riveted and hybrid) were prepared, each of 15 pieces, 5 of which were intended for static strength tests, and 10 for dynamic tests. The static tests were carried out on the Hung Ta HT-2402 testing machine with a speed of 2 mm/min. In the impact tests, the holder mounted on the sample (Fig. 2) was hit with the energy of 25 J at a speed of 3.83 m/s.

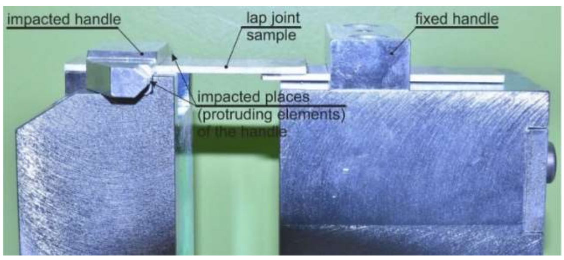

Fig. 2. Method of fixing lap specimens in impact tests

The second type of samples was made by joining steel plates with dimensions of 45 x 12 x 5 mm with an overlap of 25 mm by the method of adhesive bonded, riveting, adhesive bonded and riveting. Steel is a material used in the construction of motor vehicles for which impact strength is an important feature due to the possibility of participating in a collision. Loctite EA 9464 adhesive was used, two rivets with a diameter of 3.5 mm with ball heads made of PA24 alloy, spaced 7-11-7 mm. The adhesively bonded surfaces were roughened with abrasive cloth of granulation 80 and washed with gasoline. The adhesive layers were hardened for 5 days at ambient temperature. The samples were loaded on the wall by symmetrically bending them with double-sided support. The load was applied symmetrically to the surface perpendicular to the edge of the adhesive joint (Fig. 3).

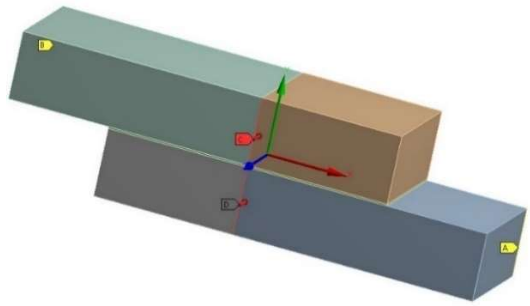

Fig. 3. Model of loading of lap samples by bending

There were prepared 3 batches of samples (adhesively bonded, riveted and hybrid) with the number of 10 pieces, of which 5 were intended for static strength tests, and 5 for dynamic tests. The static bending strength of the samples was determined by pressing them in a special device (Fig. 4) in the Hung Ta HT-2402 testing machine at a speed of 2 mm/min with the supports spacing of 40 mm. Impact tests were performed on a SW-5 impact hammer with a speed of 3.8 m/s, hitting with an energy of 50 J

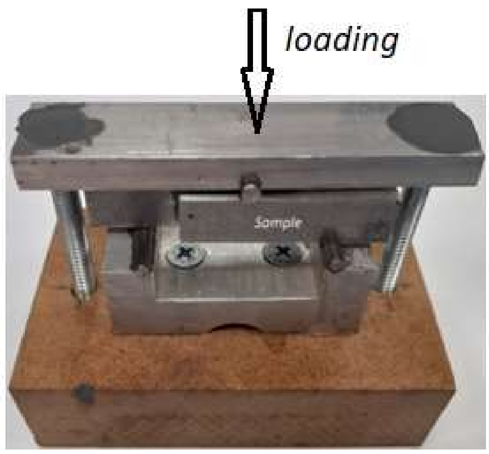

Fig. 4. The sample mounted in the device for testing the static strength by bending

3. Tests results

The lap joints loaded by tension

The results of the static strength tests are presented in Table 1 and Fig. 5 (the results in the tables are given with the confidence intervals calculated for the significance level of 95%).

Table 1. Results of the static strength tests

Joint	Adhesive	Riveted	Hybrid
Destructive force [N]	3593 ± 539	4604 ± 326	5668 ± 684
Average shear stress [MPa]	7.33 ± 1.10	9.40 ± 0.67	11.57 ± 1.40

The shear strength of the rivets was calculated:

$$R_t = \frac{F}{n\frac{\pi d^2}{4}} = \frac{4604}{2\frac{\pi 3{,}5^2}{4}} = 239\ \text{MPa}$$

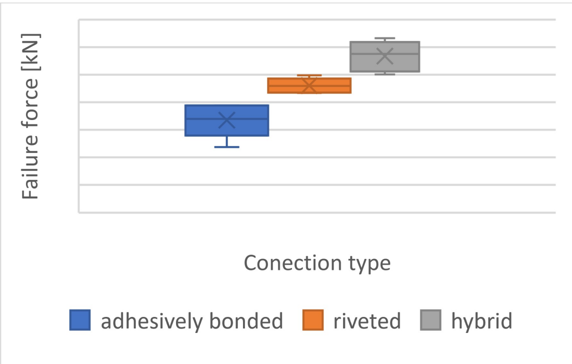

Fig. 5. Comparison of the resistance of different types of joints of lap specimens loaded by tension (X - median, mustache - maximum and minimum value, box - range 50% of the results (difference between the third and first quartile))

The strength of the tested joints differed significantly. The strength of the hybrid joints was the highest, but lower than the sum of the strength of the component connections, which is normal for this type of connection.

The dynamic test results conducted on the Julietta pendulum hammer with an energy of 25 J and a speed of 3.83 m/s are listed in Table 2 and in Fig. 6.

Table 2. Impact test results

Joint	Adhesive	Riveted	Hybrid
Destructive energy [J]	2.61±0.26	6.45±0.72	12.01±1.25
Average impact strength [kJ/m^2]	5.33±0.53	13.16±1.47	24.51±2.55

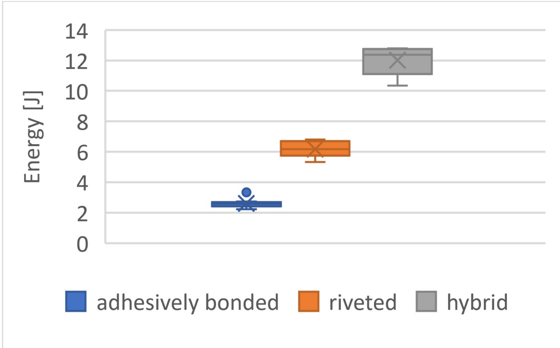

Fig. 6. Comparison of the failure energy of different types of tension lap joints

The destruction energy of hybrid samples turned out to be higher than the sum of the destruction energy of glued and riveted samples.

The lap joints loaded by bending

The results of the static strength tests of bended lap specimens are presented in Table 3 and Fig. 7.

Table 3. Results of the static strength tests

Joint	Adhesive	Riveted	Hybrid
Destructive force [N]	5347±481	3504±467	6662±593
Average shear stress [MPa]	17.82±1.60	11.68±1.55	22.2±21.98

The shearing force of one rivet can be calculated from the formula:

$$F_1 = \frac{F}{4}\left(1 + \frac{l}{2a}\right)$$

where: F - force destroying the connection, l - support spacing, a - rivet spacing.

The mean force calculated from this relationship has the value of 2469 N. It follows that the shear strength of the rivets used in the tests was:

$$R_t = \frac{F}{n\frac{\pi d^2}{4}} = \frac{2469}{1\frac{\pi 3{,}5^2}{4}} = 257\ \text{MPa}$$

The static strength of the adhesively bonded samples loaded in shear by bending was much higher than that of the tensile lap samples, despite the fact that the overlap samples were characterized by a larger area of the adhesive layer. The shear strength of the tested adhesives does not differ significantly, therefore the reason for the higher strength of the bended samples seems to be a lower share of normal stresses in the effort of the adhesive layers of joints loaded by bending and a much higher stiffness of the joined elements.

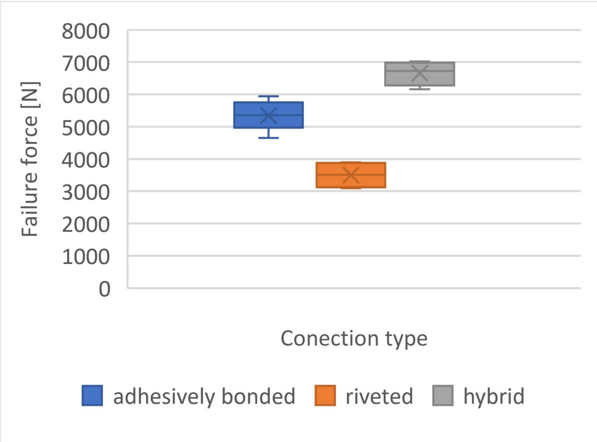

Fig. 7. Comparison of the resistance of different types of joints of lap specimens loaded in shear by bending

The results of the impact tests of the lap specimens loaded by bending are presented in Table 4 and Fig. 8.

Table 4. Impact test results

Joint	Adhesive	Riveted	Hybrid
Destructive energy [J]	3.78±0.49	8.8± 1.17	11.05±0.73
Average impact strength [kJ/m^2]	12.60±1.63	29.33±3.90	36.83±2.43

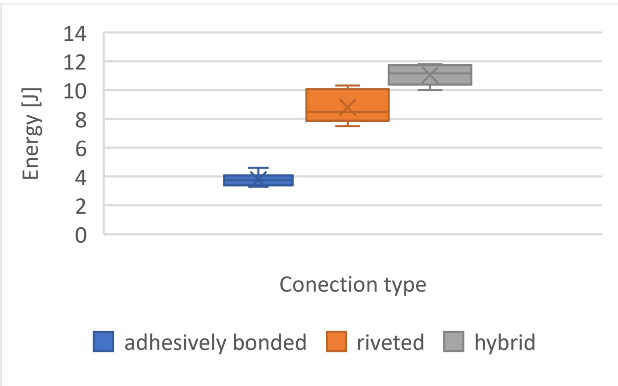

Fig. 8. Comparison of the failure energy of different types of joints of lap specimens loaded by bending

The riveted samples loaded by bending were characterized by a lower static strength compared to the lap samples, which is related to the adopted method of their loading, but the destruction energy was higher than that of the lap samples, despite the fact that in the case of tensile lap samples, two rivets were damaged, and in the case of bent samples, only one (Fig. 9). Therefore, it should be assumed that the rotation of the joined elements along the axis of the undamaged rivet consumed a significant part of the energy. Consequently, the impact strength of riveted and hybrid bend specimens that have undergone such failure is also overestimated. This is evidenced by the fact that four hybrid samples loaded by bending (which were not taken into account in the analysis of the results) were destroyed by cutting both rivets (Fig. 9), and their average failure energy of 7.05 J was lower than the destruction energy of hybrid samples in which only one rivet was damaged. It would also show that the adhesive causes a more even load of the mechanical connectors, which resulted in their simultaneous destruction.

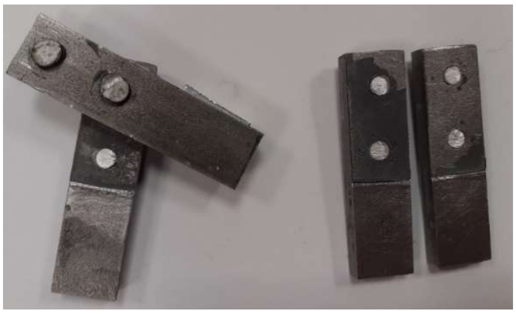

Fig. 9. Two methods of destroying hybrid lap joints of bended samples

The obtained results are difficult to relate to the literature data, as they were carried out on original, non-standardized samples. In addition, the literature data related to impact strength mainly concern combinations of different materials, which combinations are called hybrid, and not different duplicate joint systems.

4. Numerical analysis of samples loaded by bending

Numerical calculations of the statically loaded bended adhesive, riveted and hybrid joints were performed using the ANSYS system. Fig. 10 shows the hybrid connection load model and the mesh of elements. All analyzed joints were first loaded with the same force of 2000 N, because their purpose was mainly to estimate to what extent the adhesive joint would relieve the mechanical joints in a hybrid joint. The calculations were performed assuming linear properties of the adhesive (E = 2 GPa), joined steel elements (E = 200 GPa) and rivets (E = 72 GPa).

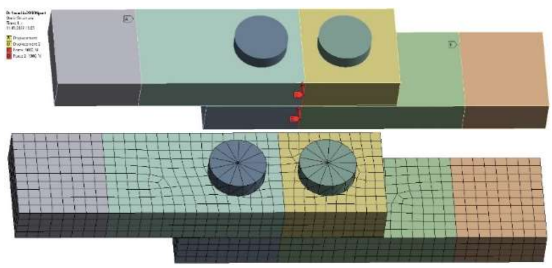

Fig. 10. The way of loading the hybrid connection and the mesh of elements

Figure 11 shows the von Mises stress distribution in the adhesive layer of an adhesive joint loaded by bending with a force of 2000 N.

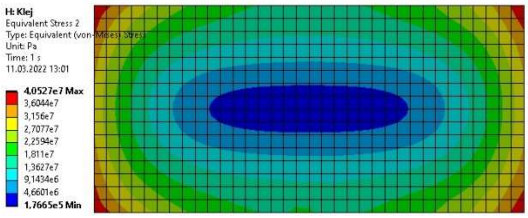

Fig. 11. Mises stress distribution in the adhesive layer of the joint loaded by bending with a force of 2000 N

Figure 12 shows the von Mises stress distribution in the shaft of the mechanical connector of a riveted joint loaded by bending with a force of 2000 N.

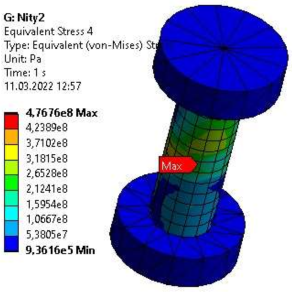

Fig. 12. Mises stress distribution in the shaft of the mechanical connector of a riveted joint, loaded by bending with a force of 2000 N

Fig. 13 shows the Mises stress distribution in the adhesive layer and in the shaft of the mechanical connector of hybrid joint, loaded by bending with a force of 2000 N.

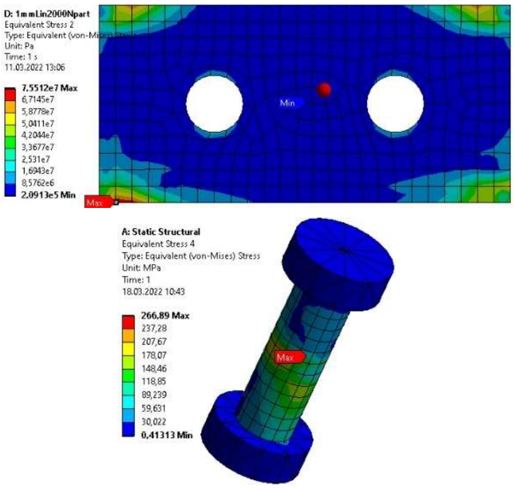

Fig. 13. Mises stress distribution in the adhesive layer and in the rivet body of a hybrid joint loaded by bending with a force of 2000 N

The performed calculations show that in the tested hybrid joint loaded by bending, the adhesive joint reduces the load of the rivet shafts more than twice. The use of rivets even increases the equivalent stresses in the adhesive joint but moves them away from the edge of the joint.

Since the calculated stresses in the adhesive joint exceeded the adhesive strength, additional calculations were made, taking into account the nonlinear properties of EA9464 adhesive (the mutilinaer isotropic hardening model - Fig. 14) and the aluminum alloy from which the rivets were made (bilinear isotropic hardening model - yield strength 330 MPa, strain hardening modulus 650 MPa).

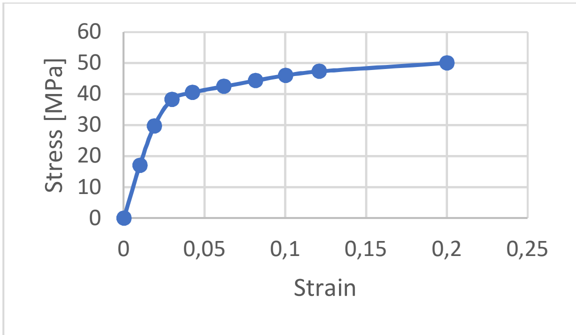

Fig. 14. The curve σ = σ (ε) of Loctite EA 9664 adhesive

In these calculations, the joints were loaded with experimentally determined destructive forces. The calculation results are shown in Figs. 15…17.

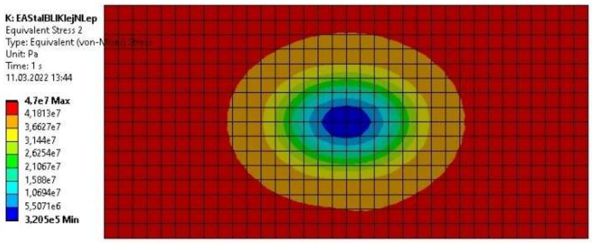

Fig. 15. Mises stress distribution in the adhesive layer of the joint loaded by bending with a force of 5347 N (nonlinear properties of the adhesive)

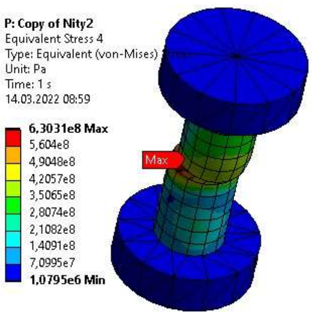

Fig. 16. Mises stress distribution in the shaft of a mechanical connector of a riveted joint loaded by bending with a force of 3504 N (nonlinear properties of aluminum alloy)

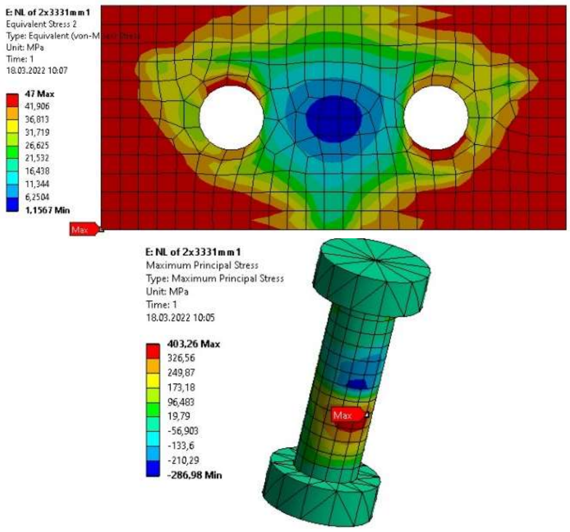

Fig. 17. Mises stress distribution in the adhesive layer and in the rivet body of a hybrid joint loaded by bending with a force of 6662 N (nonlinear properties of the adhesive and aluminum alloy)

Taking into account the non-linear properties of the adhesive resulted in a more uniform loading of the adhesive layer over a larger area. The calculated stresses in the rivet shafts of the riveted joint had values greater than the actual stresses of the alloy they are made of by about 17%, which may result from the too low value of the declared coefficient of friction (f = 0.1) between the joined elements. Taking into account the calculated values of destructive stresses of adhesive and rivet, it can be concluded that the analyzed hybrid joint the adhesive should be destroyed first, and then the rivets.

5. Conclusions

Hybrid joints are characterized by higher strength and impact strength compared to adhesively bonded or riveted ones.

The impact strength and energy of impact failure of the tested adhesively bonded, riveted and hybrid overlapping samples differed significantly. In the case of overlapping samples loaded by tensile stress, the impact strength of hybrid samples turned out to be higher than the sum of the impact strengths of riveted and adhesively bonded samples. In the case of bending samples, the impact strength of hybrid samples was close to the sum of the impact strengths of adhesively bonded and riveted samples.

It can be assumed that in the case of tensile lap samples, the adhesive layer strengthened the rivet joint, which was characterized by a higher load capacity than the adhesive joint. In the case of samples loaded by bending, it was the other way round, and in this case the rivets only slightly strengthened the adhesive joint.

Tensile lap samples seem to be more suitable for the tests of the impact strength of hybrid connections, because both mechanical connectors are always sheared when damaged.

Numerical analysis of adhesively bonded, riveted or hybrid joints loaded with destructive forces requires taking into account the nonlinear material properties of such joints.

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