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NUMERICAL STUDY OF THE PRESTRESSED CONNECTORS AND THEIR DISTRIBUTION ON THE STRENGTH OF A SINGLE LAP, A DOUBLE LAP AND HYBRID JOINTS SUBJECTED TO UNIAXIAL TENSILE TEST

BADANIA NUMERYCZNE DOCISKU W ŁĄCZNIKACH ORAZ ICH ROZMIESZCZENIA NA WYTRZYMAŁOŚĆ POŁĄCZEŃ ZAKŁADKOWYCH, DWUNAKŁADKOWYCH I HYBRYDOWYCH PODDANYCH JEDNOOSIOWEMU ROZCIAGANIU

Prestressed joints are widely used in construction using connectors in the form of screws, whose task is to strong clamping of joined parts, thereby the internal forces in joint are transferred by surface friction contact of the elements. In the automotive and aerospace industries hybrid joints are more widely applied. Mechanical connectors are added to the adhesive joint in form of rivets, screws or clinch increasing its strength properties.

The aim of this study was to determine how the prestressed connectors influence the mechanical response of hybrid, single and double lap joints. The influence of different distribution of the connectors was also investigated. Numerical study was conducted in ABAQUS program. Mechanical connectors were modeled by using fasteners, that allowed for a considerable simplification of the numerical model. In their application, there is no need for an additional submodels for connectors in the form of the rivet or the bolt. Prestressing is activated by direct application of the force to the connector.

In the numerical examples the authors assumed that the diameter of the mechanical connectors was equal to 6mm and shear strength was equal 1kN. Adhesive layers were modeled by using cohesive elements for which maximum shear stresses and fracture energy were specified. The layer thickness was assumed to be equal 0.1mm and it was initially removed from the areas where mechanical connectors were placed.

Two types of joints were analysed in the study: the single lap joint with lap dimensions 40×40mm as well as the double lap joint with lap dimensions 40×20mm, from which it results that theoretical strength of both connections should be the same.

The prestressing of connectors was introduced by the force 1.5kN. For all pure – mechanical joints and for single lap joints positive effects were obtained. For double lap joints additional prestressing did not significantly affect for their strength.

The influence of distribution of mechanical connectors was additionally analyzed by consideration of three configurations, where the rows of rivets were located at distances of 5, 10 and 15mm from the lap edge. The maximum increase of the load capacity by 24% was achieved for single lap joint as well as 35.7% for double lap joint.

The obtained numerical results indicate the positive effects of additional pressure and allows for practical suggestions how to correct and optimize spacing distance of mechanical connectors in hybrid joints to get better mechanical response.

Keywords: prestressed connctors, numerical analysis, single lap joint, double lap joint, hybrid joint

Połączenia sprężone są szeroko stosowane w budownictwie przy wykorzystaniu łączników w postaci śrub, których zadaniem jest silne dociśnięcie do siebie łączonych elementów, wskutek czego siły w złączu są przenoszone dzięki tarciu stykających się powierzchni tych elementów.

W przemyśle samochodowym i lotniczym coraz powszechniej stosuje się połączenia hybrydowe. Do złącza klejowego wprowadzane są łączniki w postaci nitów, śrub lub przetłoczeń podnosząc jego cechy wytrzymałościowe.

Celem przeprowadzonych badań było określenie jak wpływa sprężenie łączników w połączeniach hybrydowych w złączach zakładkowych oraz dwunakładkowych także przy różnym rozmieszczeniu łączników.

Badania numeryczne były przeprowadzone w programie Abaqus. Połączenia mechaniczne były modelowane przy użyciu tzw. fastenerów, które pozwalają na znaczne uproszczenie budowy modelu. Przy ich zastosowaniu nie ma potrzeby wykonywania dodatkowego modelu w postaci łącznika – nitu lub śruby. Sprężenie jest natomiast wywoływane poprzez bezpośrednie podanie wartości siły występującej w łączniku.

Dla łączników mechanicznych została podana siła powodująca ścięcie o wartości 1kN a ich średnica wynosiła 6mm. Warstewka kleju była modelowana przy użyciu elementów kohezyjnych dla których zostały określone maksymalne naprężenia styczne oraz energia zniszczenia. Grubość warstewki wynosiła 0,1mm i wstępnie została ona usunięta z obszarów w których występowały łączniki mechaniczne.

Badaniom poddano dwa typy połączeń: zakładkowe o wymiarach zakładki 40×40mm oraz dwunakładowe o wymiarach zakładek 40×20mm z czego wynika fakt, że teoretycznie wytrzymałość na ścinanie obu połączeń powinna być jednakowa.

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Analizowano połączenia sprężone siłą 1,5kN uzyskując pozytywne efekty dla wszystkich połączeń czysto – mechanicznych oraz dla połączeń zakładkowych. Dla połączeń dwunakładkowych sprężanie nie wpływa znacząco na ich wytrzymałość.

Dodatkowo w pracy analizowano wpływ rozmieszczenia łączników mechanicznych rozważając trzy konfiguracje, gdzie rzędy nitów znajdowały się w odległościach 5, 10 i 15mm od granicy zakładki. Uzyskano tym samym maksymalny wzrost nośności o 24% dla połączeń zakładkowych oraz o 35,7% dla dwunakładkowych.

Wykonane prace świadczą o pozytywnych skutkach sprężania połączeń a także dają wskazówki do prawidłowego – bardziej optymalnego wytrzymałościowo rozmieszczania łączników mechanicznych w połączeniach hybrydowych.

1. Introduction

Continuous requirements of improvements of aircrafts structures create new technological challenges, leading to the application of:

- Modern composites with modified internal structure for critical parts of the airplanes (e.g. elements of engines, wings, fuselages, etc.)
- Improved joining technologies to assure higher level of security of the airplanes (e.g. wings, fuselages etc.)

A relatively new idea is the application of functionally graded materials (FGM) in which the material properties change continuously with space (e.g. [1-5]). Layered composites are other option in gradual change of material features. Introduction of layers between material components (e.g. [6-9]) or joined adherends (e.g. [10-15]) and as TBC covering turbine blades (e.g.[16-19]), etc. are other examples of improvements composites or joining technologies. Novel adhesives with different nano-particles or carbon nano-tubes are next examples of the application of modern particle reinforced composites in aerospace technology (e.g. [20, 21]). Coupling of different phases in materials or joints leads to novelty in designing structural elements in aerospace and higher durability and reliability.

The application of new materials is the basis for improvements of joining technologies of structural parts in aerospace. Instead of using single joining technique as riveting, spot welding, clinching or adhesive bonding, a hybrid joining technique (e.g. [15, 22]) can be applied by combination of two simple ones, e.g.: riveted-bonding (e.g. [23, 24]), spot welded-bonding (e.g. [25, 26], clinched-bonding (e.g. [27-34]), etc.

The aim of this work is to analyse other possibilities of joining technology improvement by prestressing of mechanical fasteners. Modeling of connections using mechanical fasteners (rivets, screws), or hybrid adhesive joints is a complex problem. This is due to several factors: necessity of a dense mesh to represent mechanical fasteners, a large number of contact pairs causing that the problem becomes highly nonlinear, necessity of using damage and fracture criteria (e.g. [35-42]) for both mechanical fasteners and adhesive. In addition, the use of prestressed mechanical fasteners complicates the solution of the problem.

The mentioned above connections are the subject of research for areas such as construction [43, 46, 48] and the aviation industry [45, 23, 24, 26].

In the paper [46], the authors present the results for single lap adhesive joint using combined clamping elements, where additional pressing in connected elements was introduced. In this case, the pressure was not induced by mechanical fasteners but by the uniform pressure from 0 to 5MPa, for which load capacity was received more than four times higher as compared to the connection without the use of pressure.

In the aerospace industry, composite materials in the form of laminates are often used. In paper [45] single lap hybrid joint was subjected to analysis, where in addition to the screws adhesive layer, was used. The influence of such parameters as: the level of pressure from screws, clearance size and the effect of variable geometry of the connector's conical part on the level of damage in the individual layers of the laminate were investigated.

These works demonstrate the need and benefits that come from the use of prestressed and hybrid joints. This type of hybrid joints has not only higher load capacity, but also a much higher level of energy necessary to complete destruction of the joint [47, 23, 24, 26].

It should be mentioned that the simulations are carried out not only for the simple and the double lap joints but also for more complex structures included in the real design [43, 48].

2. Prestressing of joints

A difficult matter is the induction of compression in mechanical fasteners. This can be done in a direct or a simplified way. Methods for direct compression are presented in the paper [48] and [24]. In the paper [48], the authors apply the model of real thread profile for nuts and bolts. If the rotation of the nut is performed an axial force is induced in the bolt. However, to make a discretization about 36 000 finite elements for one set (screw + nut) should be applied. Similarly in the paper [24] real geometry of rivet was applied as well as riveting process was carried out using a displacement of steel core forming the connection. The advantage of this method is an accurate modelling of the internal forces in the joint, while the disadvantages are the extra step in simulation and a very dense mesh causing a significant increase in the duration of the calculation.

Other methods were used by the authors of the papers [44 - 45]. A mechanical connector in the form of a screw is modeled with a strong simplification (without the thread and the hexagonal head), but the main dimensions remain the same. Furthermore, making holes in joined sheets is also necessary. Prestressing of these simplified connections is also made in a separate step, by holding of the screw head and introduction of the axial displacement to the nut. After that, the nut is fixed in relation to the bolt. This method gives a lot of benefits, taking into account the duration of the simulation.

In this paper, completely different technique was applied by using mesh-independent fasteners. This method was described in paper [26], where it was used to model welded joints. The main advantage of this method is the lack of additional models in the form of rivets or bolts which significantly accelerate the computation time. Compression is introduced directly by inputting the forces acting on the joint.

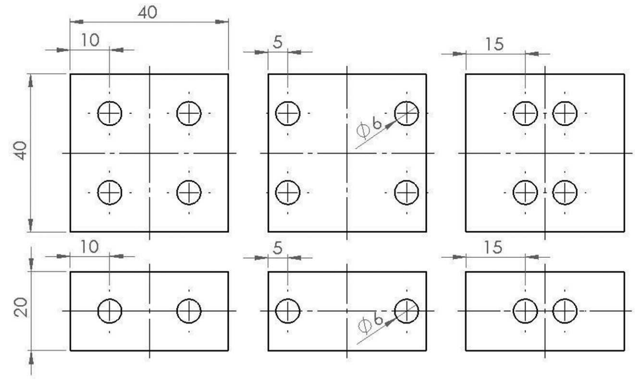


Fig. 3. Configurations of connectors distribution in the: hybrid, single and double lap joints

3. Overview of the analyzed cases and models construction

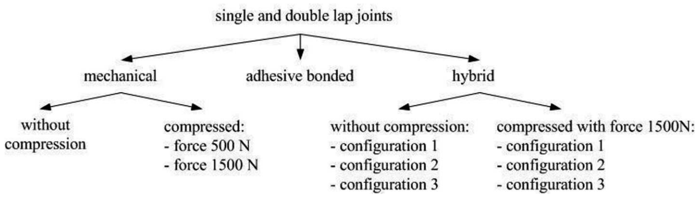


Fig. 1. Analyzed cases according to configurations presented in Fig. 3

In Table 1 the quantity of finite elements used in the single and the double lap models is given. For sheets modelling C3D8R elements were used, while for the adhesive – cohesive ones (COH3D8). In both models a similar total amount elements were applied. In the joined sheets the mesh was condensed at the place of the lap occurrence. For the cohesive layer one element was used at thickness while two elements for sheets.

Fig. 1 shows schematically analysed types of connectors which were tested. Two types of geometric joints were used: the single lap joint and the double lap joint whose basic dimensions are shown in Fig. 2.

TABLE 1

Finite elements quantity used in the single lap and the double lap joints

	C3D8R – joined sheets	COH3D8 – adhesive layer
single lap joint	6400	5094
double lap joint	6000	4812

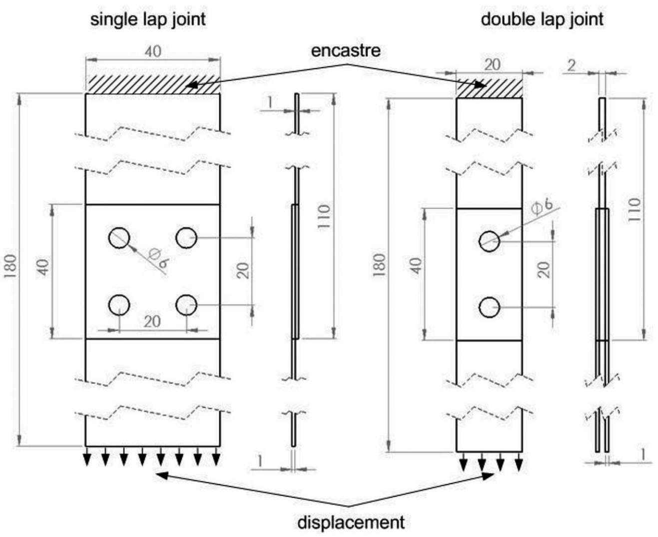


Fig. 2. Types of analysed joints

4. Analysis of the results

4.1. Single lap joints

It is necessary to point out that the marked in the drawings the locations of the connectors with 6 mm diameter do not constitute holes. In simulation these are the cross sections of the fasteners.

Theoretically, the connections capacity (presented in Fig. 2) should be the same, because in both cases there is the same laps area as well as the same shear surface for mechanical connectors. However, numerical results presented below show that there are some differences.

Moreover different distributions of fasteners for the hybrid, single and double lap joints were analysed as was shown in Fig. 3.

Fig. 4 shows the three basic types of connections: the adhesive joint, the mechanical joint and the hybrid joint. In calculations the destructive force of the single mechanical fastener was assumed equal to 1kN. In case of the pure mechanical joint the destructive force was approximately 4kN, which confirms the correctness of the calculations and the construction of the model.

Degradation process of the adhesive layer in the hybrid joint, we can distinguish three characteristic phases:

- stage 1 – a progressive increase of the stresses in the adhesive layer to satisfy the damage criterion. In this stage the level of the currying force is the same as in the purely adhesive joint.
- stage 2 – when the damage criterion is satisfied the strength decreases slightly by about 0.4 kN and start to increase again. The damage zone develops up to the border of the mechanical fasteners. Thus, the mechanical fasteners take on part of the currying load and protect the adhesive layer, located between them.
- stage 3 - this is the stage of the maximum capacity of the joint. At the pick of the plot we observed failure of

the both mechanical fasteners, whereas the adhesive layer remains still currying load. However, dynamic fracture process starts and the force drops to zero.

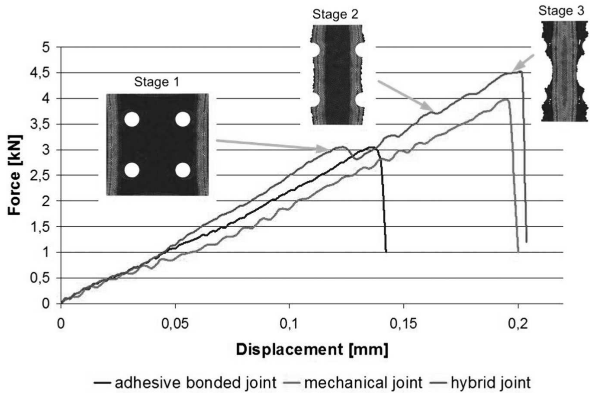


Fig. 4. Comparison of deformation stages of the analysed joints

TABLE 2

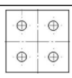
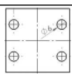
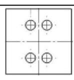
Results for the single lap joints without prestression and with different level of compression force

Prestression	mechanical joint		hybrid joint	
	destructive force [kN]	difference [%]	destructive force [kN]	difference [%]
without compression	3,93	-	4,5	-
compression force 500N	4,16	5,85	4,87	8,22
compression force 1500N	4,73	20,36	5,14	14,22

Table 2 presents the results for mechanical and hybrid single lap joints using compression forces of 500N and 1500N per one connector. A very important parameter in prestressed connections is a friction coefficient. In all simulations this coefficient is equal to 0.1.

TABLE 3

Results for different configurations of the connector distributions (Fig. 3)

configuration	hybrid joint without compression		hybrid joint with compression force 1500N	
	destructive force [kN]	difference [%]	destructive force [kN]	difference [%]
No 1 	4,50	-	5,14	-
No 2 	5,21	15,77	5,87	14,20
No 3 	3,45	-23,33	3,91	-23,93

The analysis of the above Table 2 lead to the conclusion that the increase of the load capacity in average is equal to 13,4% for hybrid joints in comparison with purely mechanical joints, which confirms the validity of this type of connections. Using the hybrid joint with compression force of 1500N in each connector, you can get a capacity increase of 30,7% in relation to purely mechanical joint.

Table 3 shows the results for the hybrid samples without compression as well as with compressed force of 1500N in each connector for different configurations of fasteners distributions, which are shown in Fig. 3.

Although the number of mechanical fasteners and the adhesive surface area in all cases was the same, there is a very large difference in the results for the considered configuration. The obtained results (Table 3) allows to formulate conclusion that mechanical fasteners should be placed as near the border of tabs as possible (configuration 2).

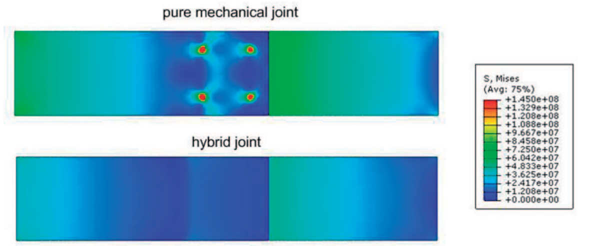


Fig. 5. Huber – von Mises stress distribution for single lap joints

Fig. 5 shows the distributions of the Huber – von Mises stresses for the hybrid and the purely mechanical joints. Both results correspond to displacement of the joint equal to 0,16 mm. That figure shows the great advantages resulting from the use of hybrid joints. In the hybrid joint despite pointwise mechanical fasteners occurrence, there is no visible of stress concentration phenomenon in the lap. The load is carried by both the adhesive and the mechanical fasteners.

4.2. Double lap joints

The difference between single and double lap joint involves symmetrical adding of a single sheet. Furthermore, in order to ensure the same thickness for the whole connection, lap thickness should be half thickness of the middle plate.

Fig. 6 shows the deformation process of the joints: the adhesive bonded, the purely mechanical and the hybrid one. As in the single lap joint, we can distinguish three stages of deformation of the hybrid joint. A common feature of the both joints is that the adhesive layer of located between the connectors is protected from damage until the fasteners reach the critical state. This fact means that the load is carried by both the adhesive and mechanical fasteners.

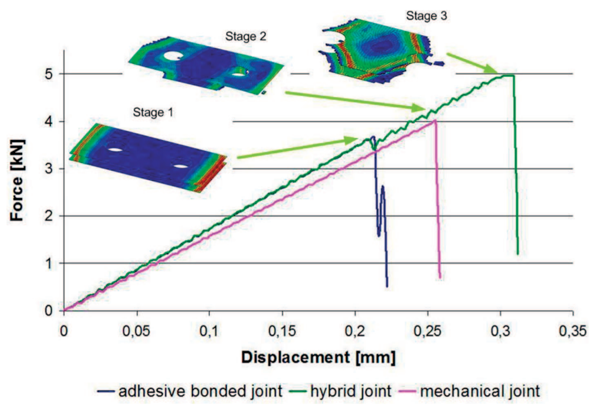


Fig. 6. Stages of deformation of the analysed joints

Numerical tests were also carried out for mechanical and hybrid joints subjected to compression, see Table 4. Using a hybrid joint (without prestression) instead of a purely mechanical, increase of a capacity can be achieved by 23,38% and this is better as compared to hybrid single lap joint.

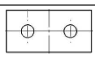
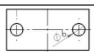
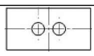
TABLE 4
Results for the double lap joints without prestression and with different level of compression force

	mechanical joint		hybrid joint	
	destructive force [kN]	difference [%]	destructive [kN]	difference [%]
without compression	4,02	-	4,96	-
compression force 500N	4,18	3,98	5,00	0,81
compression force 1500N	4,51	12,19	5,08	2,42

Application of the compression improves the joint capability for the purely mechanical connection, i.e. we can get over a dozen percent increase in capacity. For the hybrid connection the input of additional compressive force does not give as good results.

Positive effects for double lap prestressed connections are hard to find even with variable configurations of mechanical fasteners (Table 5). Only for the unfavorable configuration 3 the decrease in capacity was 8%. For comparison, the decrease for single lap joint was as high as 24%.

TABLE 5
Results for different configurations of the connectors distribution (Fig.3)

configuration	hybrid joint without compression		hybrid joint with compression force 1500N	
	destructive force [kN]	difference [%]	destructive force [kN]	difference [%]
No 1 	4,96	-	5,08	-
No 2 	6,69	34,87	6,80	33,86
No 3 	4,15	-16,33	4,67	-8,07

As in case of single lap joint large benefits come from using the second configuration. Thereby we can achieve the increase of connection capacity of about 35%.

A much smaller impact of compression on the load capacity in the double lap joints than in the single lap joints also requires explanation. The reason for this phenomenon is well explained in Fig. 7, which shows a 10 times larger deformation of joints in their work. In single lap joint during operation an additional bending moment is formed which value is the product of the loading force and the thickness of a single sheet. Bending of joint causes normal stresses that take the maximum value at the end of the lap and additionally weaken the bonding joint. Therefore, the introduction of mechanical fasteners causes stiffening of joints and currying negative normal stress which results in an increase in capacity of the joints.

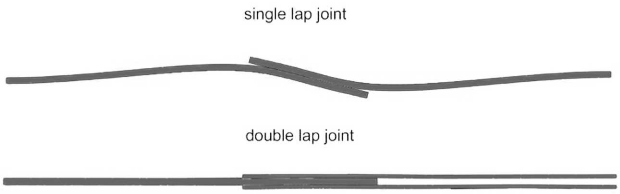


Fig. 7. Joints deformation

5. Results

In this paper 20 different types of connections were studied. Based on the results the following conclusions can be drawn:

- prestression of both types of connections gives better results for the purely mechanical connections than connections with the adhesive layer,
- prestression of hybrid single lap joints increases the capacity by 8,22% for compression force 500N and 14,22% for 1500N,
- compression of hybrid double lap joints does not bring greater benefits and increase in capacity is on the level of 2% - 3%,
- it is preferable to use double lap than single lap joints, where there is no additional bending, their strength can be increased by about 10% to 30% depending on the type of connection,
- important for the strength of connection is fasteners distributions. They should be placed as far away from the lap axis perpendicular to the direction of tensile force.

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