International Journal of Adhesion & Adhesives 30 (2010) 574–582

Contents lists available at ScienceDirect

International Journal of Adhesion & Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh

Adhesive joint strength of hybrid assemblies: Titanium sheet-composites and aluminium sheet-composites—Experimental and numerical verification

Anna Rudawska*

Faculty of Production Engineering, Department of Mechanical Engineering, Lublin University of Technology, ul. Nadbystrzycka 36, 20-618 Lublin, Poland

ARTICLE INFO

Article history:
Accepted 24 May 2010
Available online 10 June 2010

Keywords:
Titanium and alloys
Aluminium and alloys
Composites
Finite element stress analysis

ABSTRACT

This article presents the results of the testing of adhesive joint strength of hybrid assemblies consisting of different materials and joints of the same materials. Both experimental testing and numerical FEM analysis of the joints were applied. This type of joint can be found in the aviation industry, for example, where the use of composites as construction materials, including polymer composites with epoxy matrix, is becoming increasingly popular. One frequently used joint type in the aviation industry is the adhesive joint. The literature generally refers to adhesive joints made from the same materials while there is little information on adhesive joints using materials with different geometries and properties (mechanical, physical and chemical), therefore it would be useful to evaluate joint strengths both experimentally and numerically in terms of joint behaviour under various types of load.

This paper compares experimental data obtained through numerical analysis for adhesive joints made of titanium sheet, aluminium sheet and aramid–epoxy composite using a number of different joint assemblies.

1. Introduction

Gluing is one of the most popular methods of joining elements due to its particular properties which allow elements made of different materials to be joined, which is a common situation in the aviation, automotive and building industries [1–6]. Almost any material type can be joined, including metals with non-metals. In some cases adhesion is actually the only possible bonding method, especially when thin-walled sections or elements with a significant difference in thickness have to be joined. Another advantage of adhesion technology is the possibility of making light constructions in comparison to other assembly technologies, which is highly advantageous in aviation. Moreover, when elements are adhesively bonded, stress concentration in the bonded joints is less uniform than when caused by other means of joining, for example as is the case of pressed or rivet joints. There are no holes left on the surface to weaken the element cross-section and constitute a site of stress concentrations.

Composites are becoming increasingly popular in many sectors of industry as a result of their special properties [1,7], which often make a better alternative to typical construction materials. Composites with a polymer matrix are common in the aviation industry due to their strength resistance characteristics and often having relatively low weight. In many cases composites are combined with other materials, for instance with aluminium or titanium sheet [8–12].

2. FEM numerical analysis

Finite element method (FEM) is being used increasingly as a calculation tool for designing adhesive joints [13–18]. There are no precise calculation methods for adhesive joint strength, which means that the use of adhesion in a design requires a number of destructive strength tests. When designing high-strength adhesive joints one faces many difficulties connected with forecasting the joint strength, which depends on a number of factors.

The current methods of designing adhesive joints are based on experimentally determined average values of adhesive-bonded joint destructive stress, including: apparent shear strength, tear strength and bending strength. They allow comparison of different adhesives to a certain extent; however, as shown in our the adhesive joint strength cannot be forecasted since the current methods have a limited application—only for joints shaped and loaded as described in the standards.

Moreover, analytical methods of determining stress in joints are encumbered with errors resulting from simplified assumptions. The analytical dependencies can be precise when the strength calculations only involve the types of joints closest to the models used when formulating the analytical dependencies.

The finite element method (FEM) enables more complex joints to be analysed with satisfactory precision, hence it is possible to

* Corresponding author. Tel.: +48 081 53 84 232.
E-mail address: a.rudawska@pollub.pl

0143-7496/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijadhadh.2010.05.006

avoid often costly and time-consuming destructive experimental tests.

FEM-based stress distribution analysis was carried out using ABAQUS/Standard software as the numerical tool [19,20]. Thanks to such numerical methods and modern software it is possible to make calculations involving materials and geometrical non-linearity that exert significant influence on the precision of the results, which can provide information crucial for designing adhesive joints.

3. Experimental methods

3.1. Material characteristics

Samples made of the following materials were used:

(1) titanium sheet, CP1 (Grade 1—ASTM B265), thickness 0.4 mm;
(2) aluminium sheet, 2024PLT0 (EN AW-2024-AlCu4Mg1), thickness 0.64 mm;
(3) aramid–epoxy composite, thickness 0.6 mm.

The samples made of aramid–epoxy composite consisting of two layers (2×0.30 mm) of epoxy fabric KV-EP 285 199-46-002 were used for the tests. The fabrics were positioned at a 90° angle and subject to hardening (using a suitable technology).

Some mechanical and physical properties of tested materials are presented in Table 1 [21,22].

The aluminium sheet 2024 is a plated sheet of surface hardening state 0 which is a product that achieves the required properties after annealing by hot moulding.

3.2. Adhesive joint characteristics

The geometry of a single-lap adhesive joint is presented in Fig. 1. The actual joint dimensions varied, depending on the joint type.

The shear loaded single-lap adhesive joint types analysed were as follows (Fig. 2):

type I: titanium sheet–titanium sheet;
type II: aramid/epoxy composite–aramid/epoxy composite;
type III: titanium sheet–aramid/epoxy composite;
type IV: aluminium sheet–aluminium sheet;
type V: aluminium sheet–aramid/epoxy composite.

The joints had the following dimensions: sample length $l=100$ mm, adhesive joint thickness: $g_k=0.1$ mm and sample width: $b=20$ mm. The sample thickness varied, depending on the material, and was: $g_b=0.4$ mm for titanium sheet, $g_b=0.64$ mm for aluminium sheet and $g_b=0.6$ mm for composites. The length of the adhesive joint lap was: $lz=8$ mm (for joint types I–III), $lz=24$ mm for the joint made of aluminium sheets (type IV) and $lz=16$ mm for aluminium sheet–aramid/epoxy composite (type V).

The lap boundary length of the analysed joints was determined from the relation, derived from formula presented by Prof. J. Godzimirski and Prof. J. Łunarski and others in their publications and based on [23]

$$l_{gr}\geq 5\sqrt{\frac{Eg_bg_k}{2G_k}} \tag{1}$$

where E is the Young's modulus of the bonded elements, g_b the thickness of bonded elements, g_k the adhesive joint thickness and G_k the shear modulus of the adhesive.

Degreasing with Loctite 7063 was a surface preparation method. Loctite 3430 epoxy adhesive was used for making adhesive joints, with a setting time of 48 h and humidity $40\pm$ °C. Destructive tests were carried out after the adhesive had set, in order to determine the actual joint destructive force.

The properties of the epoxy adhesive used were as follows [24]: $E=2500$ MPa, $\nu=0.35$; $G=1000$ MPa.

Adhesive joint shear strength tests were carried out using a universal testing machine Zwik 2100.

4. Numerical test method

4.1. Scope of numerical analysis

Numerical analysis of the adhesive joints for different materials involved determining the mean value of the destructive load as recorded in the experimental tests.

With regard to the non-linear properties of the analysed material joints, elastic and plastic models of both materials were

Table 1
Mechanical and physical properties of the tested materials.

No.	Mechanical properties	**CP1 (Grade 1)**	**2024 T0**	**Aramid–epoxy composite**
1	Rm (MPa)	240	275	1400
2	Re (MPa)	172	145	–
3	E (MPa)	102730	700000	760000
4	A (%)	25	10	–
5	ν	0.34	0.33	0.34
6	G (GPa)	41.4	25.5	2.0

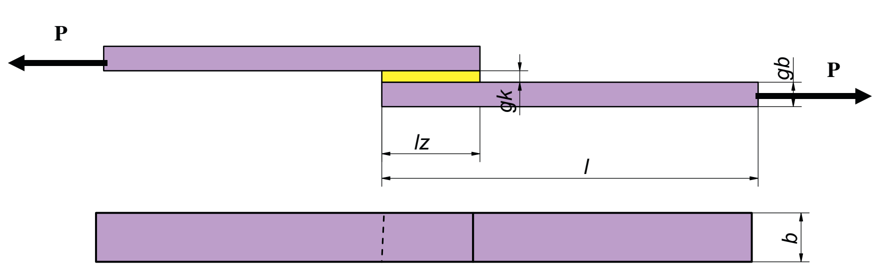

Fig. 1. Schematic representation of single-lap adhesive joint geometry.

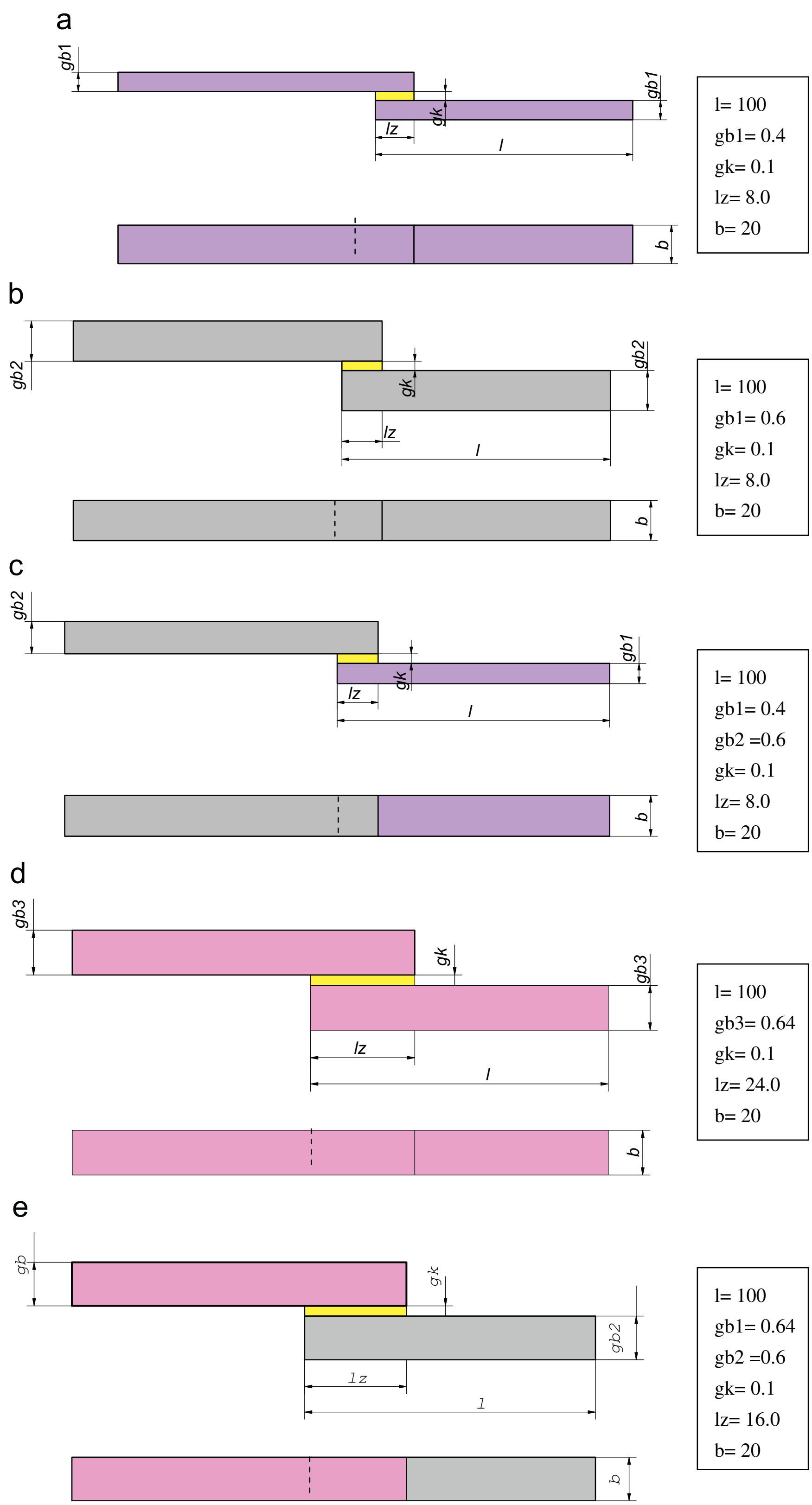

Fig. 2. Schematic representation of the analysed types of single-lap adhesive joints geometry: (a) type I, (b) type II, (c) type III, (d) type IV and (e) type V.

used. The adhesive used was an elastic-traction material, which recorded failure of cohesive elements.

The calculations were also of a non-linear geometrical character thanks to the use of incremental-iterative calculation methods based on the Newton–Raphson method. ABAQUS/Standard software was used as the numerical tool for calculations in order to conduct FEM analyses within physically and geometrically non-linear scope.

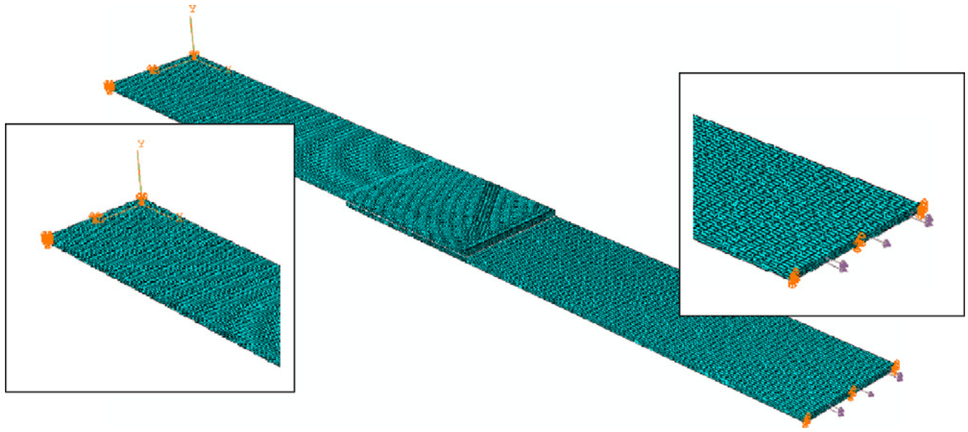

Fig. 3. Numerical model of a single-lap adhesive joint.

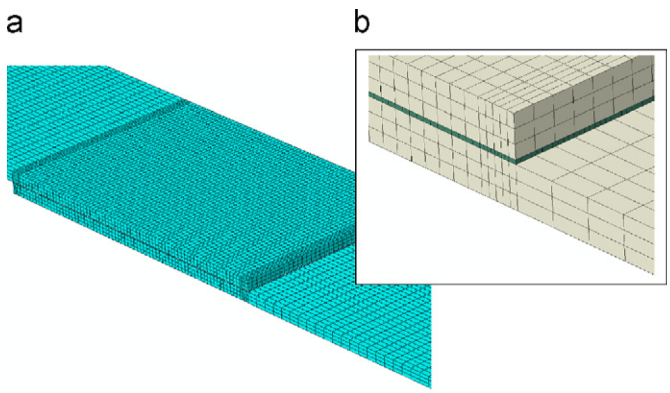

Fig. 4. FEM mesh at the lap end: (a) general view and (b) detailed view.

4.2. Numerical model characteristics

A spatial numerical model of a single-lap adhesive joint based on a structural mesh of hexagonal solid type finite elements—Figs. 3 and 4 was used for the FEM calculations.

The number of elements of tested materials was on average 13,700–15,000 elements for each sample, and about 7250–1350 elements for the adhesive layer. The number of elements for the entire mesh and for the adhesive layer depended on the type of adhesive joints.

Boundary conditions (Fig. 3) were defined by blocking the translational degree of the node freedom located on the front surface of the upper sheet and allowing for displacement of the front surface of the lower sheet only in the load application direction.

Previous tests indicate that the structure of the finite element mesh near the ends of the adhesive joint laps should be marked by strong stress gradients, and are therefore crucial for preparing the numerical model. For this purpose the finite element mesh was concentrated 1 mm from the lap ends, see Fig. 4b.

The adhesive joint was modelled with cohesive type elements COH3D8 characteristic of the specific properties demonstrated by such materials as adhesives. These elements are but a few used in ABAQUS and as such are subject to three-dimensional analyses. Fig. 5 presents some information about the cohesive elements used.

The model presents a situation in which connecting cohesive elements to other components (materials) was realised by applying surface-base tie constraints as there was no match between the meshes of two neighbouring parts (Fig. 6).

Owing to these elements it was possible to model the adhesive joint failure in the analysed adhesive joints. The literature [6,16,17,20] provides increasing amounts of information on modelling adhesive joints using this type of element.

The essential constitutive law describing *cohesive* elements is failure criterion called *traction–separation* (tearing force–maximum separation value) which allows taking into consideration both normal interactions (tearing) and the effects of failure caused by tangential interaction.

Modelling of adhesive-bonded joint with the use cohesive elements requires defining a material whose description contains the failure mechanism. The calculations were performed using a material model/pattern whose characteristics containing a description of damage initiation and damage evolution to the total loss of the element's rigidity were defined on the basis of the traction–separation criterion Fig. 7.

5. Test results

5.1. Adhesive joint strength

The results of strength tests for the analysed variants of joints between titanium sheet and composites, including hybrid joints of the titanium sheet—composite are presented in Fig. 8.

Based on the test results presented in Fig. 7 it could be noticed that the greatest strength was obtained for the adhesive joints involving titanium sheets, and the lowest strength for the ones using composites. A bigger strength increase occurred with titanium sheet–aramid/epoxy composite hybrid assembly in comparison to the joints including only composites. In this case bonding of two different materials has a positive influence on strength in relation to the material with lower strength value.

The results for the joint types using aluminium sheet, composites and aluminium sheet–composite hybrid assembly are presented in Fig. 9.

Among the compared adhesive joint types, the adhesive joint formed from aramid–epoxy composite elements had the greatest strength, while the strength of the aluminium sheet joint was almost half as big (8.27 MPa). The aluminium sheet–aramid/epoxy composite assembly seems particularly interesting; in this case the adhesive joint was not damaged so the strength presented in the diagram (6.26 MPa) is the strength value of the

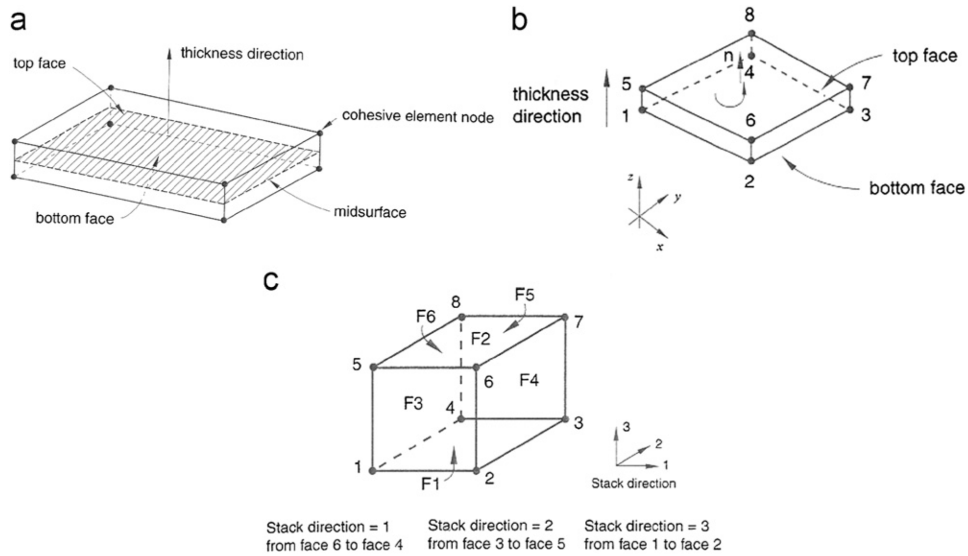

Fig. 5. Cohesive elements COH3D8 characteristic: (a) special representation, (b) default thickness direction and (c) stack directions [20].

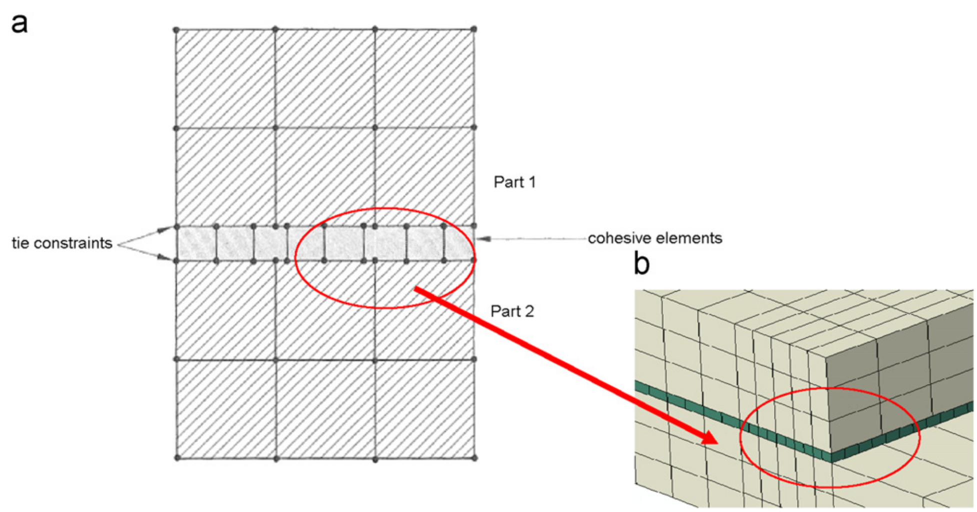

Fig. 6. Independent meshes with tie constraints: (a) pictorial scheme [20] and (b) considering model.

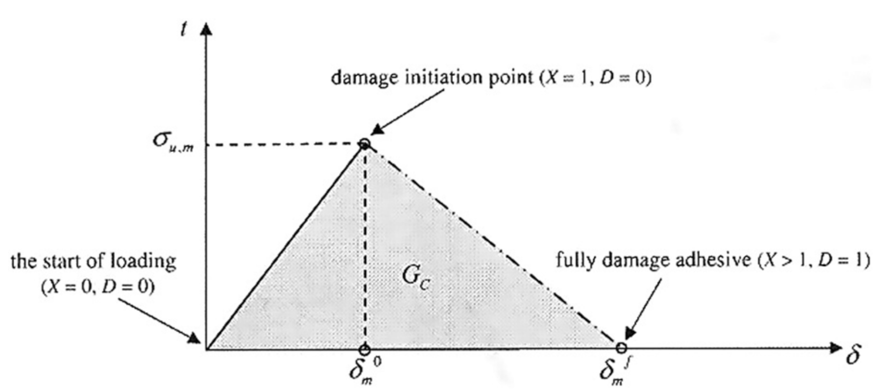

Fig. 7. Schematic representation of constitutive behaviour, damage initiation, and damage evolution of the adhesive [18].

weaker material in the hybrid assembly, which is given in brackets in Fig. 9. The results may also demonstrate that surface preparation and adhesive have been properly applied.

Therefore, when analysing joint strength in hybrid assemblies it appears that using a joint of two different material types is beneficial to improve joint strength in reference to the material for which the lower value of a joint using the same material was obtained. However, a negative result or the destruction of one of the materials is possible, but the achievable joint strength is greater than the strength of one of the connected materials and the joint strength that should be achieved needs to be considered during the adhesive joint analysis.

The stress distribution in the adhesive joints was obtained based on the numerical analysis, the adhesive joint behaviour during destructive tests was evaluated and the force required to damage the joint was calculated.

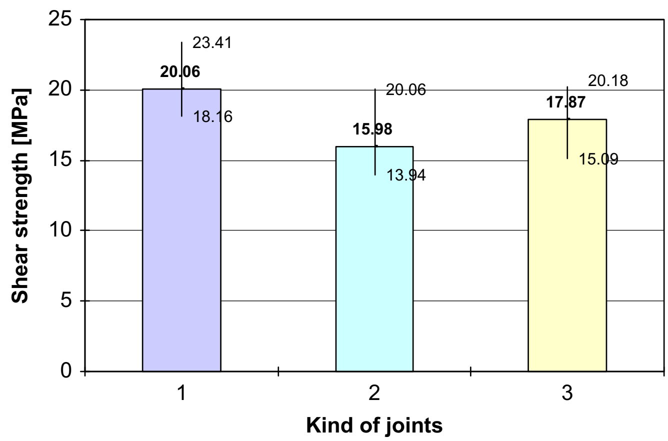

Fig. 8. Adhesive joint strength in shear for: (1) titanium sheet–titanium sheet joint, (2) aramid/epoxy composite–aramid/epoxy composite joint and (3) titanium sheet–aramid/epoxy composite joint.

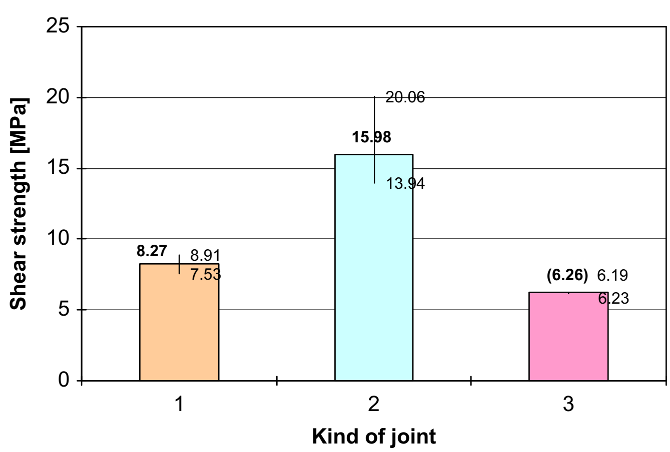

Fig. 9. Adhesive joint strength in shear for: (1) aluminium sheet–aluminium sheet assembly, (2) aramid/epoxy composite–aramid/epoxy composite assembly and (3) aluminium sheet–aramid/epoxy composite assembly.

6. Results of numerical tests

Fig. 10 presents some selected results of the numerical analysis of the adhesive joint behaviour under a load equal to the that of the failure force determined in the experimental tests for one of the analysed joint types (type IV: aluminium sheet–aluminium sheet).

Thanks to the use of cohesive elements for adhesive joint modelling it is possible to visualise the process of adhesive joint failure and obtain the value of the force at which joint failure was initiated. It can be observed that the analysed numerical model presents the actual joint behaviour under the external load. Fig. 11 presents samples of the tested aluminium sheet after adhesive joint failure. The geometry after failure of aluminium sheet samples (in experimental tests) and during numerical analysis visualisation is comparable.

Fig. 12 shows the adhesive joint failure diagram for a hybrid joint: titanium sheet–aramid/epoxy composite.

Fig. 13 presents the stress distribution in an adhesive joint for some selected failure stages and adequately the stress distribution along the adhesive median layer.

Fig. 14 presents one of the stress distributions types in the connected elements of a hybrid joint: titanium sheet–aramid/epoxy composite.

The use of numerical analysis techniques allows stress distributions to be readily visualised in an adhesive joint and in the connected elements at each stage of loading up to failure. The results are useful for designing adhesive joints as it is possible to indicate locations where potential problems may occur by indicating the maximum stress points. Therefore it is possible to design or modify the structure of a joint, or to determine the moment of initiating adhesive joint destruction, which is crucial when using adhesive joints.

6.1. The comparison of the experimental and numerical results

Table 2 presents the comparison of the failure force value obtained in the experimental tests and based on the numerical analysis of the tested joints. In case of numerical analysis the

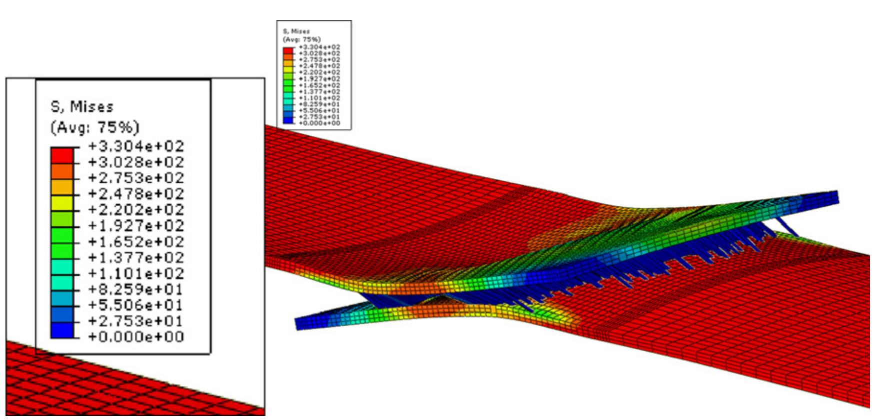

Fig. 10. Visualisation of aluminium sheet–aluminium sheet adhesive joint failure.

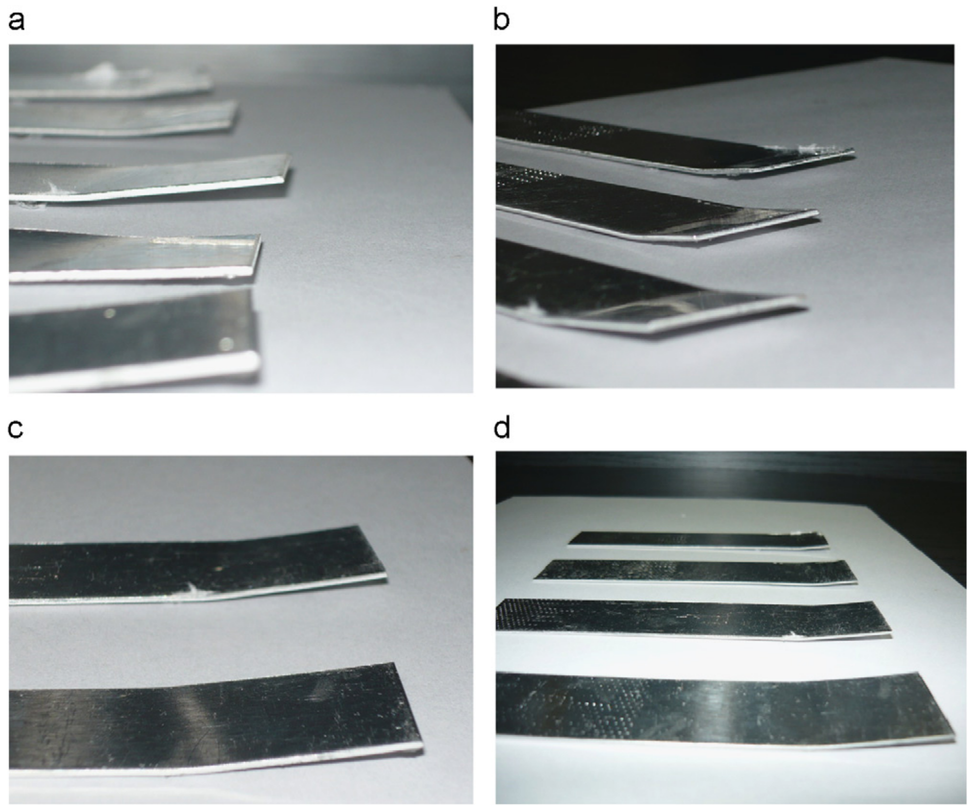

Fig. 11. Varied visualisation of aluminium sheet samples after failure that occurred in experimental tests: (a)–(d).

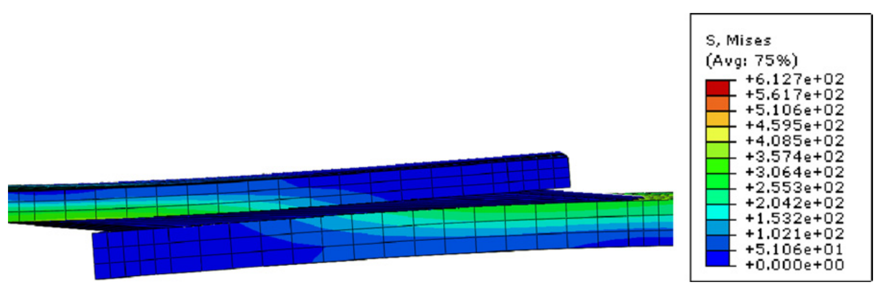

Fig. 12. Visualisation of the failure of a hybrid adhesive joint: titanium–aramid/epoxy composite.

failure force value was obtained at the moment when adhesive elements lost rigidity.

For the analysis of the failure force values for the tested adhesive joints, almost 100% compatibility was achieved between the numerical analysis and experimental test results for the aluminium sheet–aluminium sheet joint. In the case of composite–composite joint the compatibility was over 95%, and for titanium sheet–composite joint over 93%. The greatest difference between experimental and numerical tests was observed for the titanium sheet–titanium sheet joint at about 17%. However, this discrepancy does not seem crucial enough to exclude using numerical analysis for further tests, and the errors in the modelling method and the actual conditions must also be taken into consideration.

It was observed that the values of the failure force obtained from the FEM analysis were lower than those from the experimental tests for almost all the joint types. Therefore it can be concluded that assuming the numerical analysis results (in this case the value of joint failure force) for construction and strength calculations of adhesive joints will constitute a certain safety margin for the actual construction. It assumes a lower value of force required to destroy the joint than occurs in reality. Certainly, the results depend on a number of factors, including the acquired modelling method, material properties of the connected elements, etc.

Using numerical analysis and proper joint modelling methods mean that the stress distribution analysis and adhesive joint failure mechanism can be observed, together with determining the approximate value of the force at which failure is initiated. In many cases this knowledge can be of great importance.

7. Conclusions

Based on the numerical analysis results it can be observed that the acquired method of adhesive joint modelling allows for the

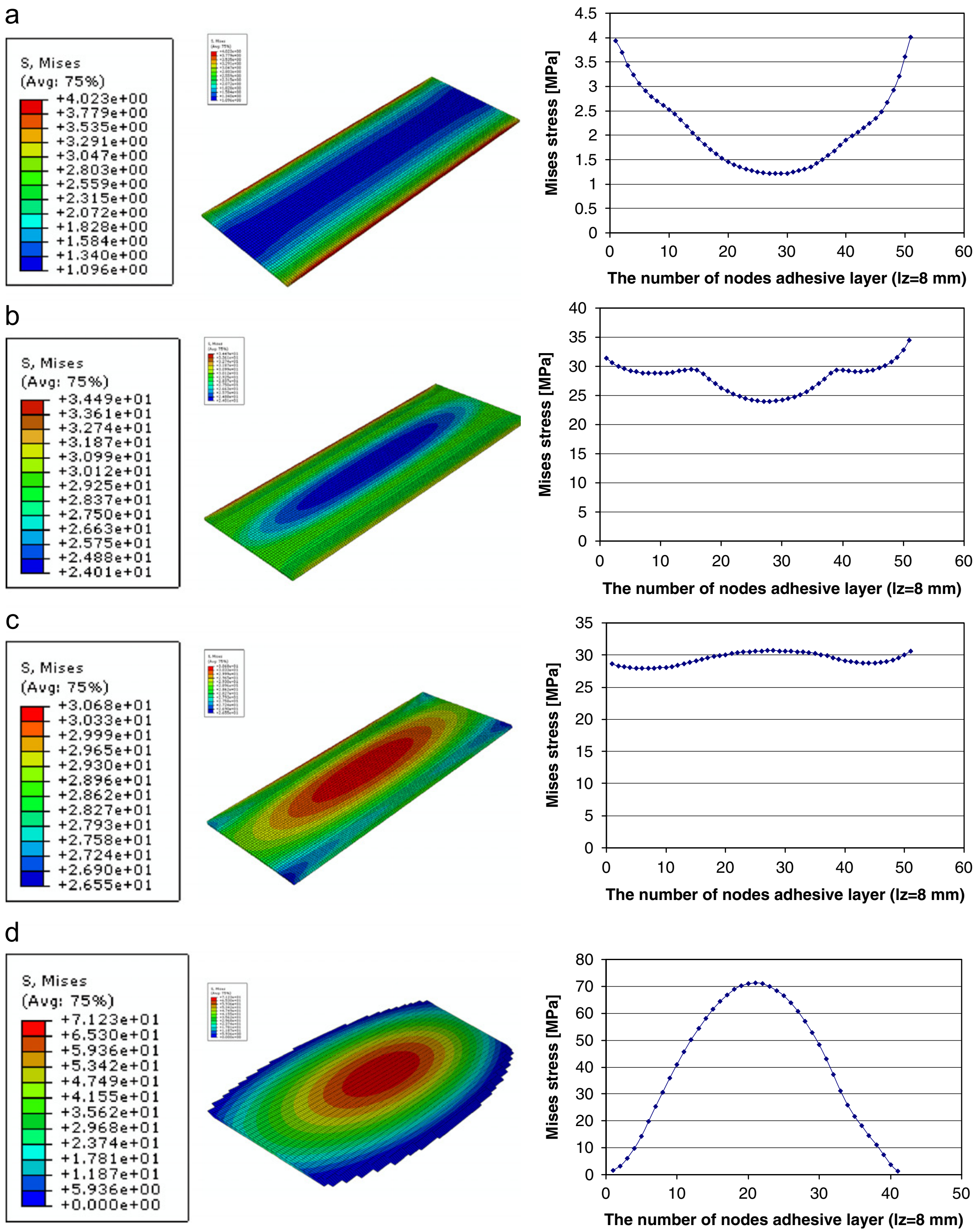

Fig. 13. Stress distribution in a hybrid adhesive joint: titanium sheet aramid/epoxy composite for various stages of adhesive joint behaviour during failure process in adhesives layer: (a) force 165 MPa, (b) force 2550 MPa, (c) force 2669 MPa and (d) joint failure force 2673 MPa.

visualising of adhesive joint deformation, both of the connected materials as well as the adhesive joints together with a load increase, and the failure of the adhesive joint itself. It is possible to observe adhesive degradation as the destructive force increased; the modelled adhesive joint failure method was qualitatively and quantitatively similar to the joint behaviour during the experiment.

The comparison of the destructive force value obtained from the experimental tests and numerical analysis shows that, in the majority of the tested adhesive joint types, the value of the adhesive joint failure force reached a similar value. This may be evidence of correct adhesive joint modelling, as well as the fact that the numerical analysis can be widely used for designing adhesive joints.

Summing up it can be stated that numerical analysis can be a valuable complement to experimental testing, allowing for visualising adhesive joint behaviour during failure when this is impossible through experimental tests using standard experimental methods.

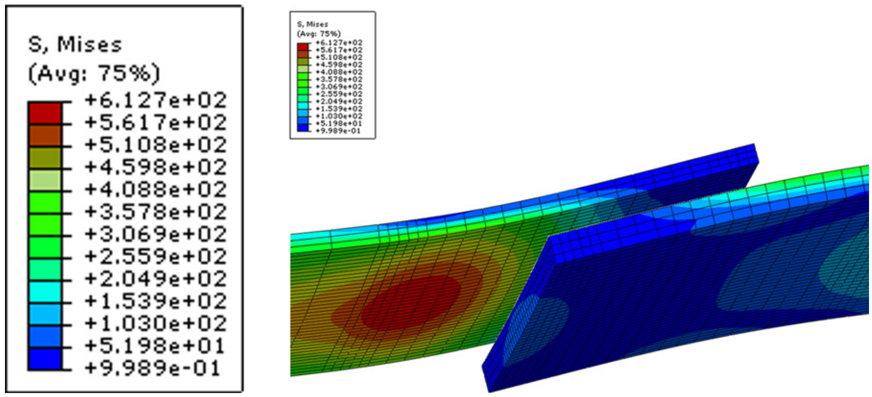

Fig. 14. Sample stress distribution of the connected elements of a hybrid joint: titanium sheet–aramid/epoxy composite.

Table 2
Failure force value obtained in the experimental tests and based on the numerical analysis of the tested joints.

No.	Joint type	Shear strength Rt (MPa)	Failure force value (N)	
			Experimental tests	Numerical analysis
1	Titanium alloy CP1 g=0.40 mm+titanium alloy CP1 g=0.40 mm	20.06	3210	2673
2	Aramid–epoxy composite g=0.60 mm+aramid–epoxy composite g=0.60 mm	15.98	2557	2440
3	Titanium alloy CP1 g=0.40 mm+aramid–epoxy composite g=0.60 mm	17.87	2860	2673
4	Aluminium sheet 2024 PLTO, g=0.64 mm+aluminium sheet 2024 PLTO, g=0.64 mm	8.27	3971	3955
5	Aluminium alloy 2024PLT0 g=0.64 mm+aramid–epoxy composite g=0.60 mm	(6.26)	2004 (failure force of aluminium alloy samples)	~2000

Acknowledgements

The scientific study was funded from education finance for 2006–2009 as research Project no. 3T10C02730.

References

[1] Megson THG. Aircraft structures for engineering students. 4th edition. Elsevier Science Publishers; 2007.
[2] Grant LDR, Adams RD, da Silva LFM. Int J Adhes Adhes 2009;29:405.
[3] Belingardi G, Chiandussi G. Int J Adhes Adhes 2004;24:423.
[4] Goglio L, Rossetto M, Dragoni E. Int J Adhes Adhes 2008;28:427.
[5] Borsellino C, Calabrese L, Di Bella G, Valenza A. Int J Adhes Adhes 2007;27:466.
[6] de Morais AB, Pereira AB, Teixeira JP, Cavaleiro NC. Int J Adhes Adhes 2007;27:679.
[7] Taib AA, Boukhili R, Achiou S, Gordon S, Boukehili H. Int J Adhes Adhes 2006;26:226.
[8] Liljedahl CDM, Crocomble AD, Wahab MA, Ashcroft IA. Int J Adhes Adhes 2007;27:505.
[9] da Silva LFM, Adams RD. Int J Adhes Adhes 2007;27:362.
[10] Taib AA, Boukhili R, Achiou S, Achiou S, Boukehili H. Int J Adhes Adhes 2006;26:237.
[11] Gómez S, Oñoro J, Pecharromán J. Int J Adhes Adhes 2007;27:263.
[12] da Silva LFM, Adams RD. Int J Adhes Adhes 2007;27:216.
[13] You M, Yan Z-M, Zheng X-L, Yu H-Z, Li Z. Int J Adhes Adhes 2007;27: 696.
[14] Borsellino C, Calabrese L, Di Bella G, Valenza A. Int J Adhes Adhes 2007;27:466.
[15] Dean G, Crocker L, Read B, Wright L. Int J Adhes Adhes 2004;24:295.
[16] Li S, Thouless MD, Waas AM, Schroeder JA, Zavattieri PD. Int J Adhes Adhes 2006;26:609.
[17] Khalili SMR, Khalili S, Pirouzhashemi MR, Shokuhfar A, Mittal RK. Int J Adhes Adhes 2008;28:411.
[18] Zadpoor AA, Sinke J, Benedictus R. Int J Adhes Adhes 2009;29:558.
[19] Abaqus Theory Manual version 5.8, Hibbit, Karlsson & Sorensen, Inc. 1998.
[20] Abaqus/Standard User's Manual version 6.5, Hibbit, Karlsson & Sorensen, Inc. 2005.
[21] 〈www.northamericanalloys.com〉 (February 2009).
[22] Gerd Lutjering, Williams James C. Titanium. 2nd edition. Springer; 2007.
[23] Kuczmaszewski J. Fundamentals of metal-metal adhesive joint design. Printed by Polish Academy of Sciences, Lublin Branch, Lublin University of Technology, Lublin 2006.
[24] 〈www.loctite-kleje.pl〉 (February 2009).