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STRENGTH OF METAL TO POLYMER ADHESIVE BONDED AND RIVETED JOINTS

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Abstract: *An important problem in the design of modern lightweight structures is the choice of an assembling method adequate to join dissimilar materials: adhesive bonding, mechanical fastening or a hybrid technique.*
Mechanical fasteners tend to be inefficient in the load transfer because of high stress concentrations that occur. Adhesive joints are more convenient because of the continuity of bonding line, more uniform distribution of stresses, superior fatigue life, reduction or elimination of machining operations, diminution of costs.
This paper presents the results of a combined study based on finite element analyses and laboratory tests performed on aluminium or steel sheets assembled by adhesive bonding and riveting with plates made from different plastic materials.
Keywords: *adhesive bonding, bonded and riveted joints*

1. INTRODUCTION

The increasing complexity of modern assembled structures and the diversity of materials used have led to many joining applications that would not be possible with more conventional joining techniques.
Adhesives are substances that are used to join two or more components together through attractive forces acting across the interfaces. Also, adhesives can be used either alone or in combination with traditional fastening methods [1], [2].
For well-designed joints assembled with proper processing procedures, adhesive usage can assure a reduced weight, an improved fatigue and corrosion resistance, a diminution of costs. Adhesives can be used to assemble dissimilar or heat sensitive materials (first of all, plastics), and components which might be damaged by drilling holes for mechanical fasteners (as example, fiber reinforced composites).
Because of their viscoelastic nature, polymeric adhesives are able to dissipate energy, and can significantly reduce vibrations and damages due to the impact loading.
The components being joined are commonly referred to as adherends or substrates, and usually are made of metals, plastics, composite materials, glass, wood and others. There is a large number of adhesive types that may be classified depending on their chemistry (epoxies, polyurethanes, polyimides, cyanoacrilates), their form (e.g. paste, liquid, film), or their load carrying capability (structural, semi-structural, or non-structural).
The glass transition temperature is one of the most important properties of any polymer, and refers to the temperature vicinity in which the amorphous portion of the polymer transits from a hard, glassy material to soft, rubbery material. Structural adhesives are relatively strong materials and are normally used below their glass transition temperature. Such adhesives, first of all epoxies, can carry significant stresses, and increase the stiffness of whole structure.
The major factors determining the integrity of an adhesive bond are selection of the most appropriate adhesive, joint design, preparation of the bonding surfaces, strict quality control in production and monitoring in service.
In order to ensure efficiency, safety and reliability of bonded joints an adequate understanding of their behaviour is necessary. A lot of works concerning the stress analysis, mathematical modelling and experimental study of adhesive bonded joints has been done. The solution of the mathematical model is either analytical or numerical, depending of its complexity. Analytical models have the disadvantage of some simplifications needed to obtain a solution, but the simplified analytical models are very useful for preliminary design, approximate analysis and verification of numerical models.

The majority of the works which imply analytical models of adhesive bonding have focused on the single-lap or double-lap configuration and the most common approach is to treat the adherends as rods in tension or beams in bending and the adhesive layer as a series of elastic or elastic-plastic springs.
Improved theoretical solutions are proposed in paper [3] and the critical parameter related to the adherend shear deformation has been identified. A set of generalized equations for the stress distribution in adhesive joints of dissimilar materials was developed in [4].
In almost all published works only two stress components (shear stress and transverse peel stress) have been considered. The deformation field near the edge of a joint is three-dimensional because the load carrying adherend is restrained from contracting freely and lateral tensile stresses are developed. There are few works in the literature regarding the complete triaxial stress state of the adhesive [5]-[7].
Earlier studies have suggested that the single strap joint configuration is less efficient than the single lap joint.
However, in papers [6]-[10] it was demonstrated that single strapped joint can be effective if it is properly designed. Also, this kind of joint can be a good solution when a face of the structure is necessary to be smooth.
Taking into account the fact that in many composite repair applications the only practical configuration is the single strapped joint, a thoroughgoing study is required.
This work focuses on the evaluation of the load capacity of adhesively bonded single-strapped joints based on finite element analyses. The adhesive layer thickness, the overlap length, the adherent and strap thicknesses were varied as well as the materials properties.

2. EVALUATION OF MATERIAL PROPERTIES

In order to emphasize the strong influence of the joint design on its stress state, many linear elastic finite element analyses were done. As material properties were required the values of elasticity modulus and of Poisson's ratio for all materials that were used: two-component epoxy adhesives, aluminium 2024 T3, steel, and some polymers (PVC – polyvinylchloride, PMMA – polymethylmetacrilate, PP - polypropylene).
The elasticity modulus E_a and the Poisson's ratio ν_a of two epoxy adhesives (an universal adhesive and an adhesive for metals) were determined respecting the ISO 15166-1:1998 procedure. From each adhesive, two tension bulk specimens having the sizes 60×12×2 were carefully prepared in order to avoid the voids apparition.
Two strain gauges, one on the longitudinal and other on the transversal direction, were glued on each specimen. By means of two Wheatstone bridges (Fig. 1) were measured the longitudinal strains ε_l and the transversal strains ε_t , induced in the specimen by a tensile force. For different forces F_i were determined the strains $\varepsilon_{l,i}$ and $\varepsilon_{t,i}$ ($i=1, 2, ..., n$). The stresses σ_i and the elastic parameters of adhesive were calculated by the formulas

$$\sigma_i = F_i / A , \qquad E_{a,i} = \sigma_i / \varepsilon_{l,i} , \qquad \nu_{a,i} = -\varepsilon_{t,i} / \varepsilon_{l,i} , \tag{1}$$

where A is the area of the specimen cross section.
The results show that universal adhesive is more flexible than adhesive for metals. The mean values obtained by strain gauges measurements are the following: for the first adhesive E_a =1560 MPa, ν_a= 0.38 and for the second E_a= 3190 MPa, ν_a= 0.36 . The tensile strength of tested adhesive specimens was between 12 MPa and 17 MPa. There are more resistant structural adhesives. As example, adhesive AV 119 (also known as Araldite® 2007), have the modulus of elasticity E_a = 3050 MPa, the Poisson's ratio ν_a =0.34, the tensile strength σ_r = 70 MPa and the shear strength τ_r = 47 MPa.
Some tensile tests were undertaken on a Zwick Z010 testing machine in order to emphasize the mechanical behaviour of three polymers: PMMA (fig. 2,a), PVC (fig. 2,b) and PP (fig. 2,c). It is to observe that PMMA is a rigid and less resistant material that breaks suddenly. The most resistant of these materials was PVC that plasticizes under a stress of 48 MPa (at the necking point) and have an ultimate strain of about 11.5 %.
Based of some tensile tests, the values of elastic modules were given between 2800 MPa and 3400 MPa for PMMA and PVC and between 1000 and 1250 in case of PP.
Other material properties that were taken into account were the following: E_{Al} = 73000 MPa , ν_{Al} = 0.33 in case of aluminium 2024 T3 and E_{steel} = 210000 MPa , ν_{steel} = 0.3 for steel.

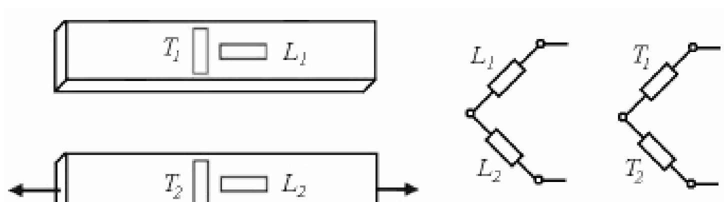
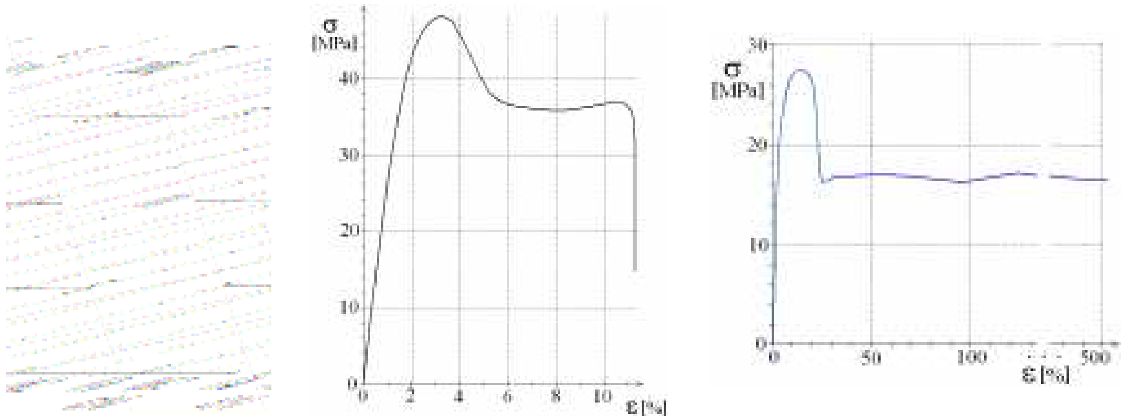


Figure 1: Placement of strain gauges on the adhesive bulk specimens



a *b* *c*

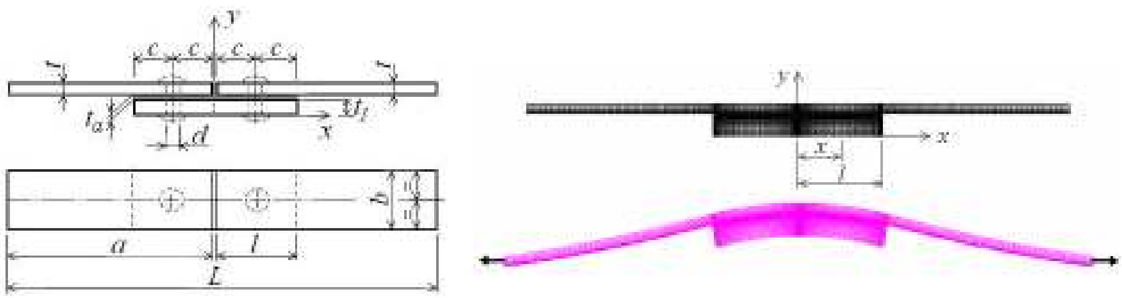
Figure 2: Tensile stress-strain curves for some polymers: a) PMMA, b) PVC, c) PP

3. FINITE ELEMENT ANALYSES AND RESULTS

The configuration shown in figure 3,a was analyzed by means of Finite Element Method (FEM) in two situations: 1) as adhesive joint, 2) as riveted bonded joint. Its typical deformation shape in tension is presented in figure 3,b. The main sizes were t=2 mm, t_a=0.25 mm, a=*120* mm, b=25 mm and the gap between the adherends ends (of 0.4 mm) was filled with adhesive.

The influences of some parameters (overlap length (l), strap thickness to adherend thickness ratio ($k=t_1/t$), elasticity modules of the used materials) on the stress state in the components of the were studied.

For inter-comparative purposes, the equivalent stresses (σ_{eq}), the peel stresses (σ_y), the shear stresses (τ_{xy}) and the tensile stresses (σ_x) were normalized with respect to the nominal tensile stress induced into the adherends $\sigma_n = P/(bt)$.



a *b*

Figure 3: The joint configuration (a) and its deformation shape in tension

The diagram from figure 4 emphasizes, in case of adhesive bonded joint, the strong influence of elastic modules of the adhesive and of the materials used to make the adherends and the straps on the maximum equivalent stresses induced in the components of the joints. It was taken $k = t_1 / t = 2$, $l = 20$ mm and the Young's modulus of the adhesive was varied between 1000 MPa and 3000 MPa. The nominal tensile stress is the same for all analyzed cases because the material of the adherends was the same (PVC) while the straps were considered as made from steel, aluminium or PVC. In the analysis of results from figure 4 it is to take into account that a more resistant strap can support an increased equivalent stress.

It is evident that a convenient situation is when the elastic modules of all involved materials have near values. In such case (C – adherends and strap from PVC) the rigidity of the adhesive has an insignificant influence and the structure behaves as a monobloc piece. If the adherends and the straps are made from dissimilar materials, then the use of flexible adhesives can have a beneficial effect.

By increasing the ratio $k = t_1 / t$ it is possible to reduce the maximum equivalent stresses in straps. The ratio k must be greater than 1, a convenient value being 1.75 . The results from figure 5 were obtained by considering the adherends from PP, the straps from steel or aluminium and the adhesive with E_a=3000 MPa.

The influence of the overlap length (l) is emphasized in figure 6, in case of a single strapped joint with adherends from PVC, strap from aluminium and adhesive with E_a=2000 MPa. It is to observe that by increasing the overlap length a moderate reduction of equivalent stresses in strap and adhesive is possible.

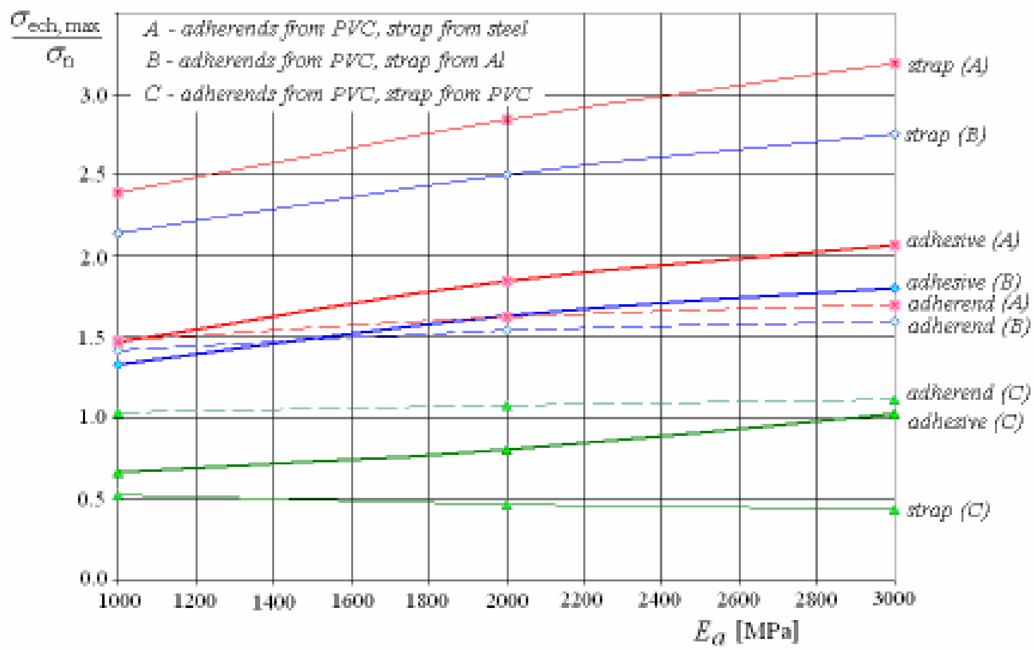


Figure 4: Influence of material combinations on the stress state in the joints

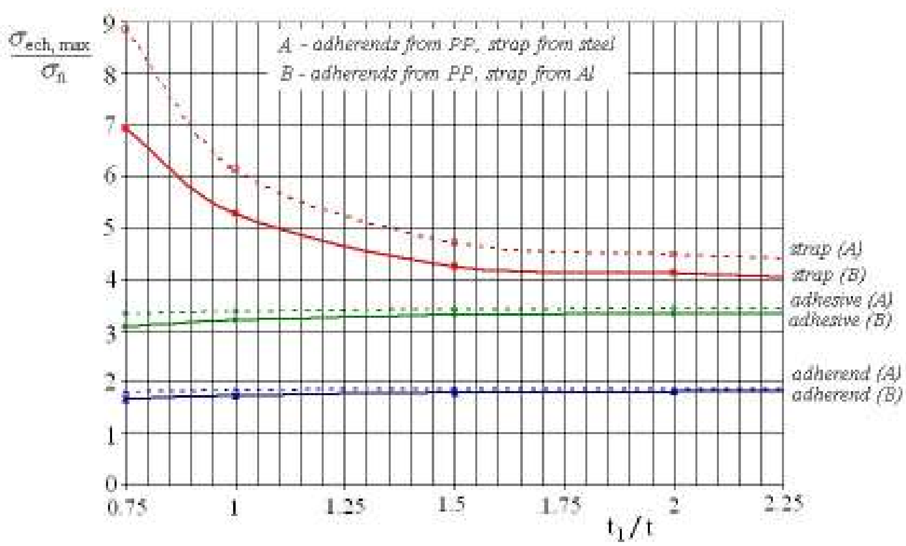


Figure 5: Influence of strap thickness to adherend thickness ratio

The graphs from figure 7 show that all stresses have extreme values at the adhesive layers ends but a large zone in the overlap area is less loaded. It is convenient that peel stresses (σ_y) are negative (compression in direction normal to the adhesive layer plane).

In case of variable loading the safety of the joining can be assured by using rivet bonded assembling. Many specimens having the adherends of PVC, the straps and the rivets from aluminium and the adhesive with the elasticity modulus E_a=3000 MPa were tested up to breaking.

For comparison in figure 8 were drawn two load-time graphs, first one for an adhesive bonded joint and second for a hybrid joint with the same main sizes. The last was damaged in a longer time and had an ultimate load with 27 % greater than the first joint.

Other important advantage is that by means of rivets mounted immediately after bonding it is possible to maintain the correct relative position between the assembled parts until the curing of adhesive is achieved.

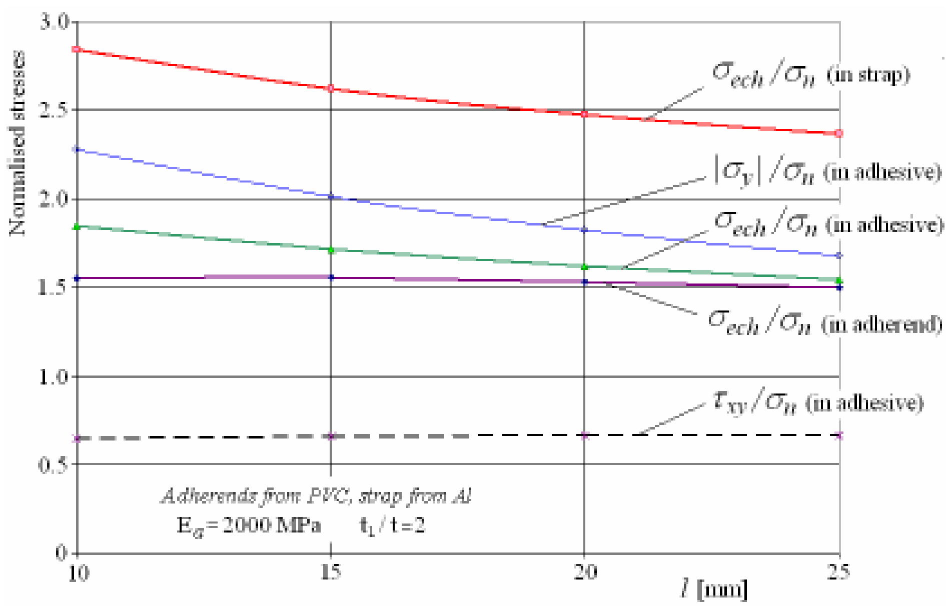


Figure 6: Influence of the overlap length on the stress state in the single-strapped bonded joint

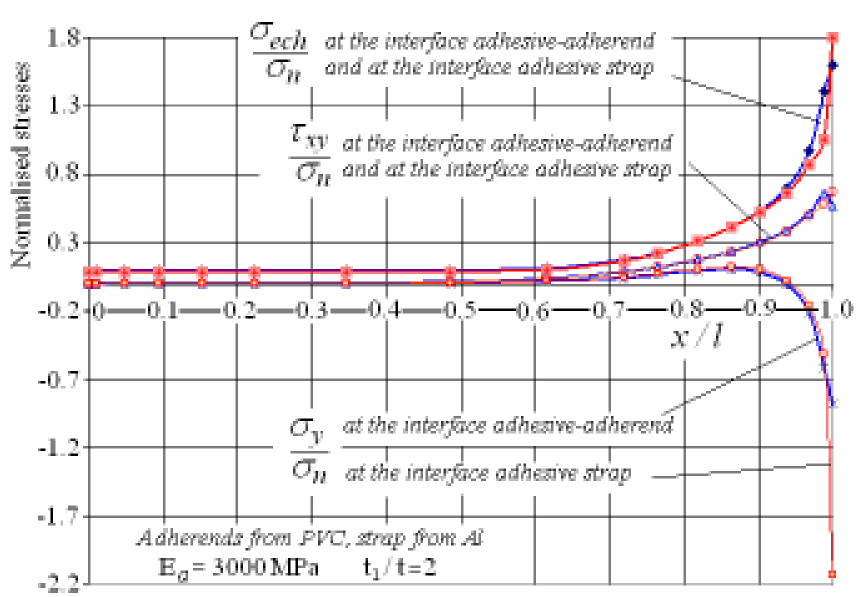


Figure 7: Variation of stress components in adhesive along the overlap length in case of single-strapped adhesive bonded joint

4. CONCLUSIONS

If the adherends and the straps are made from dissimilar materials, then the use of flexible adhesives can have a beneficial effect. By increasing the strap thickness to adherend thickness ratio it is possible to reduce the maximum equivalent stresses in straps.

In case of single-strapped adhesive bonded joint all stresses have extreme values at the adhesive layers ends but a large zone in the overlap area is less loaded. It is convenient that peel stresses are negative (compression in direction normal to the adhesive layer plane).

A comparison between the adhesive bonded joint and the riveted bonded joint with the same main sizes show that the last was damaged in a longer time and had an ultimate load greater than first kind of joint.

Other important advantage is that by means of rivets mounted immediately after bonding it is possible to maintain the correct relative position between the assembled parts until the curing of adhesive is achieved.

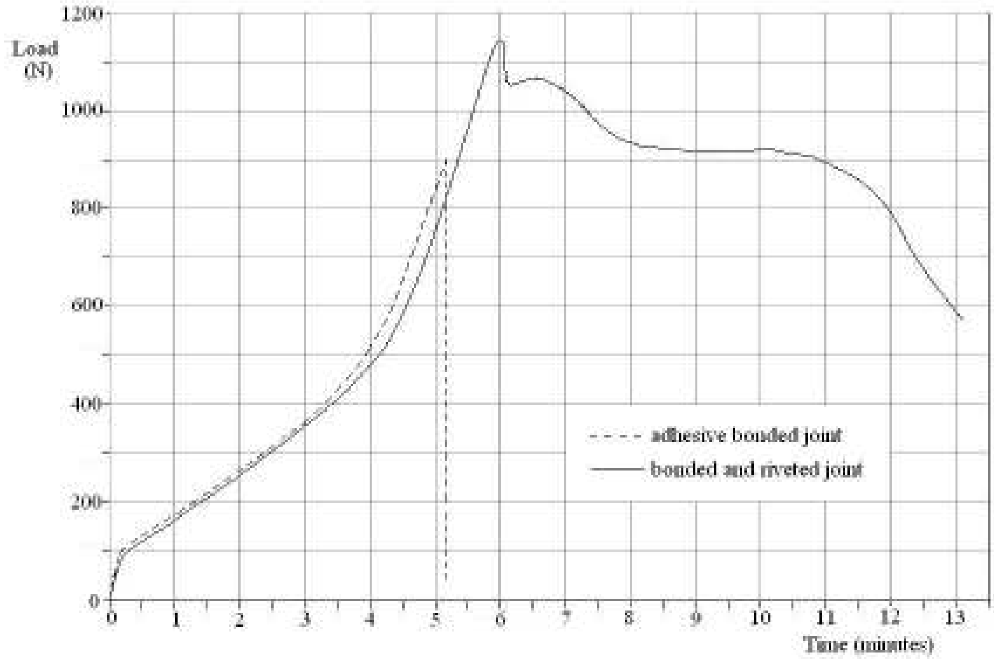


Figure 8: Time-load recordings obtained by tensile tests on adhesive bonded and rivet bonded single-strapped joints

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