FUNCTIONALLY GRADED BOND-LINES FOR METAL/COMPOSITE JOINTS

R. Breto[a*], A. Chiminelli[a], E. Duvivier[a], M. Lizaranzu[a], M.A. Jiménez[a]

[a]*Materials and Components Division, Aragon Institute of Technology, María de Luna 7, 50018, Zaragoza, Spain.*
**rbreto@ita.es*

Keywords: metal/composite, adhesive joint, functionally graded.

Abstract

The failure in adhesive joints is usually driven by the non-uniform distributions of stresses that generally appear along the bond-lines, with peak stresses near the ends of the overlaps and inner zones on which the adhesive practically does not work. For joints of dissimilar materials, the stress fields are also affected by the absence of symmetry. The present work is focused on 'functionally graded adhesive joints' to avoid this phenomenon and to improve the strength of aluminium/composite joints under shear loads. In order to get the most favourable properties grading, a search/optimization procedure has been implemented based on finite element calculations and considering continuous variations of properties within the adhesive layer. After that, a comparative analysis against discrete/'banded' approximations of these continuous distributions has been performed, being configurations more feasible to be manufactured and therefore more suitable for industrialization.

1. Introduction

Bonding clearly constitutes one of the best techniques for joining composites with metals or other dissimilar materials. The failure of bonded joints is generally strongly influenced by the non-uniform distributions of stresses and strains that usually develop in the bond-lines, as it happens in single-lap joints under shear loads (Figure 1). The maximum stresses/strains, commonly located near the ends of the overlaps, determine the rupture of the joints. This phenomenon is especially critical when rigid or semi-rigid adhesives are used, affecting to all the possible failure modes that can operate (cohesive, adhesive or through the substrates).

Several research works have been published focused on the mitigation of this phenomenon by means of variations in the geometry of the overlaps [1-3] (for example, using 'tapering' or 'fillet' configurations). These approaches generally complicate significantly the joints manufacture.

An alternative strategy is to introduce a variation/grading of properties in the adhesive layer or in the adherents along the overlap, solutions usually referenced as 'functionally graded adhesive joints'. The former concept involves the use of more flexible adhesive at the joint boundaries and a rigid one in the centre. Several works have been also reported in this research line in the last years [4-6], especially with focus on the adhesive grading. In this sense, different approaches have been proposed: softening of rigid adhesives through rubber particles, stiffening of flexible adhesives by means of glass micro-spheres, combination of different adhesives, among others.

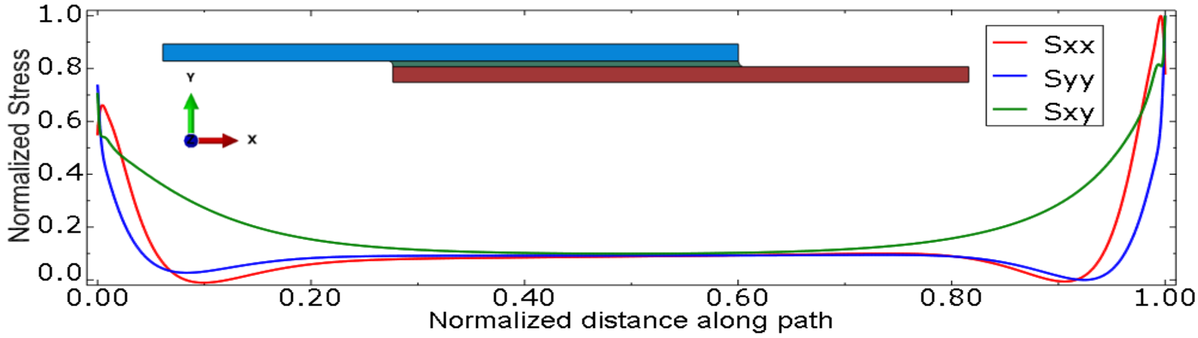

Figure 1. Adhesive stresses distribution on a single lap joint under shear loads.

Regardless of the method used, the control of the fabrication process in order to obtain a certain distribution/variation of properties with enough accuracy is still a pending challenge, even more thinking on the industrial application. For grading solutions based on continuous variations, the complexity from the manufacturing point of view is even higher. Taking into account that, many researchers have attempted to improve the stresses/strains fields simply through bi-adhesive solutions. In this sense, the works of Pires[7], and Da Silva and Adams[8] are worthy of remark. However, the improvements reported in these works are somewhat moderate, partially since two phases are not enough to make the most of the technique and, on the other hand, because they consider configurations that have not been fully optimised in terms of adhesive properties vs. bands widths, as it can be inferred from the work of M.D. Fitton and J.G. Broughton [9].

Despite of what it has been mentioned, nevertheless regarding the manufacturing complexity, the knowledge of the optimum grading to get the maximum joint strength for a given configuration constitutes a result of enormous interest from a mechanical/structural point of view. In a sense, it defines the objective solution that should be approximated as much as possible. The limitations that can arise during the fabrication process will determine how far or close from this ‘best solution’ a joint will be. For joining of dissimilar materials, there is an additional complexity associated to the absence of symmetry in the overlap. This produce stress-strain fields that are also non-symmetric. In these cases, the procedure used to determine the optimum grading should take into account that issue (i.e. should be capable to optimise non-symmetric gradings).

In this line, some of the studies carried out assuming continuous variations of properties, although they propose adjustments base on functions that a-priori allows to approximate the optimum solution adequately, they do not consider the non-linear behaviour that many adhesives present prior to the failure. Then, the accuracy of the predictions that they offer in terms of maximum load capacities is somewhat limited. As examples of these studies, the works of Kumar[5] and Stapletonand, Waas and Arnold[6] can be mentioned. The non-linear responses that present many adhesives generate an evolution of the stress and strain fields along the bond-lines while the load increases. In overlaps with a grading of properties, each material point will follow different non-linear stress-strain curves. In these cases, the stress field usually does not give enough information to determine how far an adhesive layer is from its final rupture, and then more complex failure criteria are required.

The aim of the present work is the determination of the optimum grading of properties in a bond-line to maximise the ultimate loading capacity of a single-lap aluminium/composite joint under shear loads. The study has been performed considering a grading strategy based on mixtures of compatible adhesives with dissimilar characteristics in order to obtain the properties variations. The analysis has been carried out using the finite element method as calculation tool taking into account the non-linear behaviours that present the structural adhesives selected for the study. Finally, the work includes a comparative study with discrete/'banded' approximations of the optimum continuous distribution obtained, being configurations more feasible to be manufactured.

2. Preliminary feasibility analysis

Previous to the optimization study, the viability of the grading technique has been analysed through the experimental characterization of a simple single lap joint, comparing a mono-adhesive and a bi-adhesive (3 bands) configurations. The adhesive layer lengths have been adjusted to ensure a strength improvement through preliminary FE calculations similar to the ones that have been employed lately for the optimisation. The specimen dimensions are shown in Figure 2.The length of both substrates was 150 mm with a grip area of 50 mm. In order to reduce the size of the numerical model this grip length has not been represented. The width of the specimen was 10 mm.

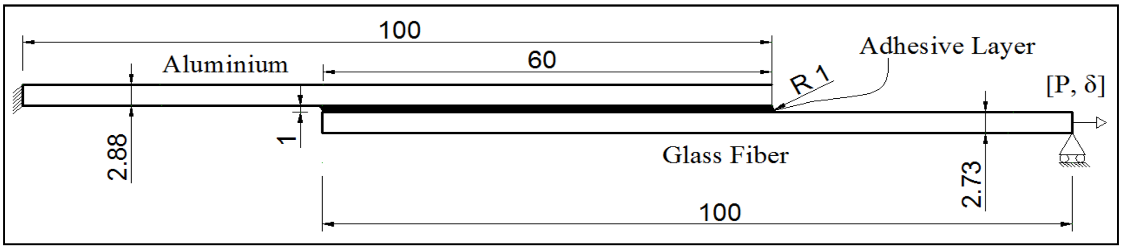

Figure 2. Single lap test specimen geometry analysed.

The main characteristics of the substrates considered in the study are presented in table 1. Both substrates have been treated superficially to improve their adhesion with the adhesives.

Substrate	Young Modulus (GPa)	Poisson	Limits (MPa)
Aluminium 6005A-T6	70	0.25	$\sigma_Y = 210$, $\sigma_{Max} = 310$
Unidirectional glass fibre composite laminate	$E_{11} = 36300$ $E_{22} = 6853.7$ $G_{12} = 3495.5$	$\nu_{12} = 0.34$	$S_{11} = 677$

Table 1. Mechanical properties of the substrates

The 3-banded joints were made with a central band of 35 mm of a rigid structural adhesive and two exterior bands with a more flexible one. This bi-adhesive configuration has been compared with the mono-adhesive solution (with the rigid adhesive, the one that leads the maximum joint strength). More information about the adhesives used is presented in the next section. The results obtained are shown in table 2.

Configuration	Ultimate Load (N/mm)	Failure mode
MonoAdhesive	[5 tests] 420	Adhesive
3 Bands	[5 test] 658	Adhesive, thin layer cohesive

Table 2. Ultimate loads of the preliminary tests.

Despite the fact that the failure mode was not cohesive, there has been a global improvement of about 57% that evidences the potential of the technique. The flexible adhesive in the ends of the overlaps produces less stress concentration in all the adhesive thickness and also in the adhesive-substrate interface.

3. Adhesives selected

The main objective of the work performed is to improve the response of the joint introducing a property grading into the adhesive layer. As it has been previously introduced, the grading strategy considered is based on mixtures of two base structural adhesives: a relatively rigid one (A) and other more flexible (B). In order to obtain intermediate phases with tailored properties, both base adhesives must:

- Be chemically compatible (in this work two epoxy resins with the same chemical base).
- Have enough different mechanical properties.
- Be able to be polymerised with a common curing cycle (both the adhesives and their mixtures).

As first step, tensile tests have been performed in order to characterise the adhesives selected and to analyse the behaviour of the mixtures. The mechanical behaviour obtained in terms of the true stress and true strain for the base adhesives and different mixture ratios are plotted in Figure 3. This plot evidences how the mixture of both adhesives generates materials with intermediate resultant mechanical properties.

Considering the previous curves, the constitutive model chosen for the FE simulations for the adhesives is a tri-linear law suited for finite strains with J2 plasticity and isotropic hardening. A small artificial hardening is added to the rigid adhesive in its final section in order to avoid numerical difficulties. The properties for the numerical definition of the material model are summarized in the Table 3. The stress-strains curves are shown in Figure 4.

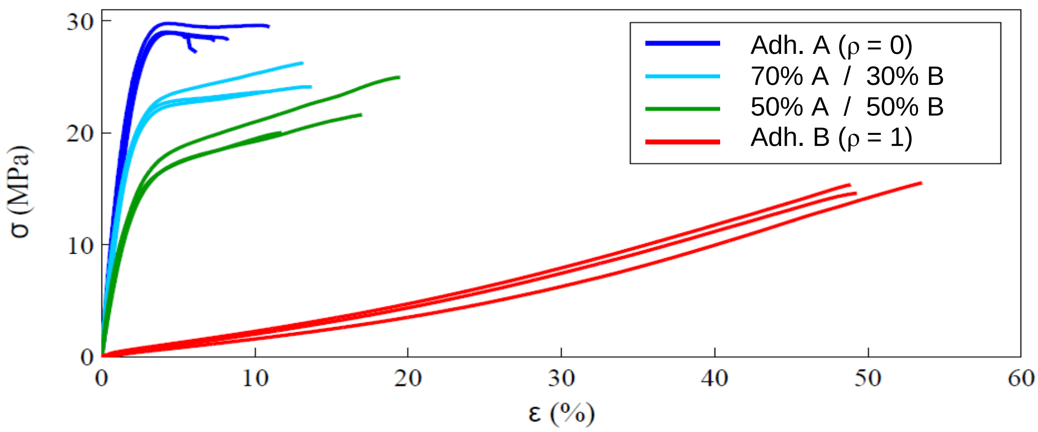

Figure 3. Adhesive adjusted curves with the experimental data.

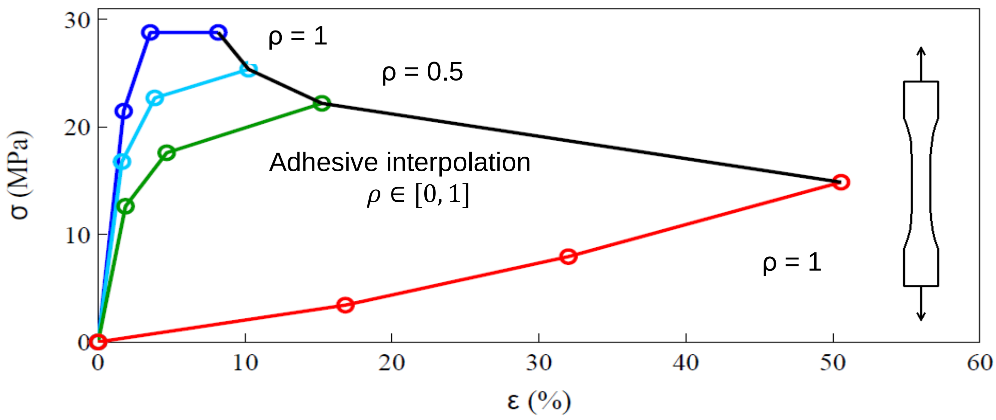

Figure 4. Adhesive adjusted curves with the experimental data.

P	E (MPa)	ν	(σ_1, ε_1)	(σ_2, ε_2)	(σ_{max}, ε_{max})
0 (Adh. Rigid)	1225.6	0.4	(21.5, 0)	(28.8, 0.04)	(28.9, 0.08)
0.3	1026.3	0.4	(16.8, 0)	(22.7, 0.04)	(25.4, 0.12)
0.5	675.7	0.4	(12.6, 0)	(17.6, 0.05)	(22.2, 0.15)
1 (Adh. Flexible)	20.3	0.4	(3.42, 0)	(7.9, 0.32)	(14.9, 0.50)

Table 3. Mechanical properties of the adjusted adhesives and different mixture ratios.

4. Adhesive grading optimization

In order to obtain the best material properties distribution along the bond-line, a finite element model of the single lap joint has been developed under plane strain conditions. The type of element used is CPE4R (4 node lineal element with reduced integration, available in Abaqus Standard). There are at least 12 elements through the adhesive layer thickness and 7 elements in the substrates. All the simulations have been carried out under static considerations and with an imposed displacement. The joint failure criteria considered is the point when the first adhesive element reaches its correspondent maximum plastic strain.

A field variable (ρ) is used to introduce the material properties variation, so the adhesive constitutive model is unique for all the phases. This variable takes a constant value within each element. The law that describes this spatial dependency of the material is a piece-wise function that allows the existence of the non symmetric distributions (Equation 1). The variation that has been taken into account is along the longitudinal coordinate x.

$$\rho(x) = \begin{cases} a_1 \cdot |x|^{b_1} + \rho_0, \;\; b_1 = \ln\left(\frac{\rho_1 - \rho_0}{a_1}\right)\frac{1}{\ln(L/2)}, \;\; (\rho_1 - \rho_0) > a_1, \;\; x \le 0 \\ a_2 \cdot |x|^{b_2} + \rho_0, \;\; b_2 = \ln\left(\frac{\rho_2 - \rho_0}{a_2}\right)\frac{1}{\ln(L/2)}, \;\; (\rho_2 - \rho_0) > a_2, \;\; x > 0 \end{cases} \tag{1}$$

The b_i coefficients have been calculated in a way that the ρ_i in the extremes are input parameters. Consequently, the function is completely defined with 5 parameters. In order to obtain the best adhesive distribution (i.e. the one that gives the maximum ultimate load) a parameter design process has been implemented. A full factorial searching has been performed. The values that have been chosen are:

$a_1 = [\ 10^{-5},\ \ 10^{-7}];\ \ a_2 = [\ 10^{-5},\ \ 10^{-7}];\ \ \rho_0 = [0.0,\ \ 0.2];$
$\rho_1 = [0.0,\ \ 0.2,\ \ 0.4,\ \ 0.6,\ \ 0.8,\ \ 1.0];\ \ \rho_2 = [0.0,\ \ 0.2,\ \ 0.4,\ \ 0.6,\ \ 0.8,\ \ 1.0]$

The maximum load has been obtained for the combination $[10^{-5}, 10^{-7},\ 0.0,\ 0.6,\ 1.0\ ]$. A refinement of the search around this point has been made with the following values:

$a_1 = [10^{-3},\ \ 10^{-5},\ \ 10^{-6}];\ \ a_2 = [\ 10^{-6},\ \ 10^{-7},\ \ 10^{-8}];\ \ \rho_0 = [0.0]$
$\rho_1 = [0.5,\ \ 0.6,\ \ 0.7];\ \rho_2 = [0.8,\ \ 0.9,\ \ 1.0]$

This gave an optimum point of $[10^{-3}, 10^{-7},\ 0.0,\ 0.6,\ 0.9]$ with an ultimate load of 848 N per depth unit, approximately 70 % higher than the mono-adhesive joint (with the rigid adhesive). The function with these parameters is plotted in Figure 7 with dashed line. It is clear that the optimum distribution is non-symmetric since the materials are dissimilar.

In order to determine the substrate influence, the searching process has been carried out considering both plastic behaviour in the aluminium substrate and perfect elastic behaviour. The composite substrate has been defined as linear-elastic in all cases. An important conclusion is that the optimal parameters are the same for both models. This is because the zones where the yield stress is reached are small and, globally, does not affect significantly to the joint response. Figure 5 shows both the load-displacement curves and the fraction of the maximum plastic strain (DUCTCRT) reached in the adhesive.

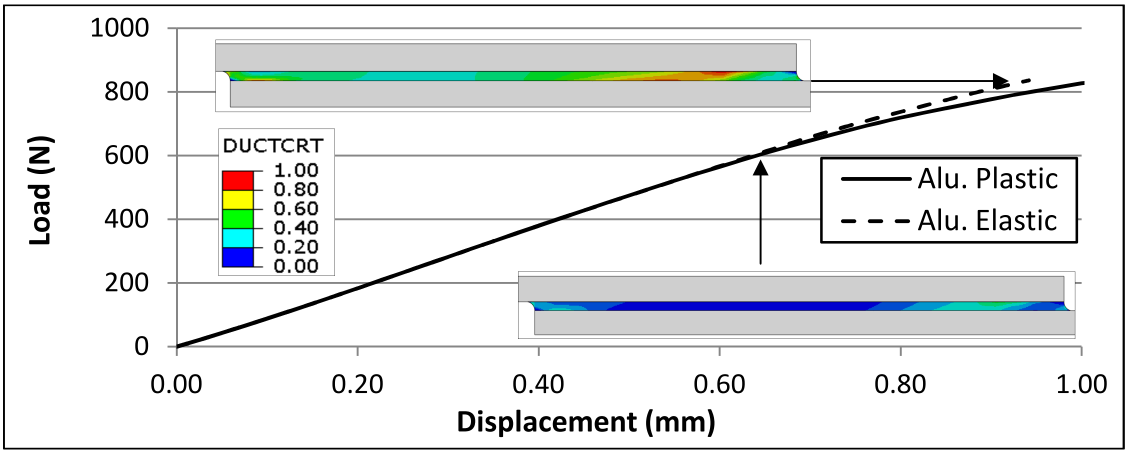

Figure 5. Load – displacement curve from FEM analysis for the SLS joint with and without plasticity in the aluminium.

Taking into account that a continuum grading is quite difficult to manufacture, 'banded' or discrete approaches are usually considered trying to fit the optimum continuum distributions. In this sense, an additional analysis has been carried out in this work for this type of solutions, focused on the evaluation of different ways to approximate the optimum grading previously found. The objective is, given an optimum continuum grading, to obtain the most effective distribution in bands. This approach is convenient because making a searching process for all the parameters that may define a banded grading would require a significant computational effort (with the amount of simulations to be performed increasing with the number of bands).

Due to the properties jump between neighbour elements numerical singularities may arise. The bigger the jump, the higher the singularity order is. One way to avoid this phenomenon is to introduce in the models a thin continuum grading between the bands, as shown in Figure 6.

Through this strategy the results are mesh independent. The width of this transition has been set to a value that do not affect to the global behaviour of the joint, for these adhesives 1 mm.

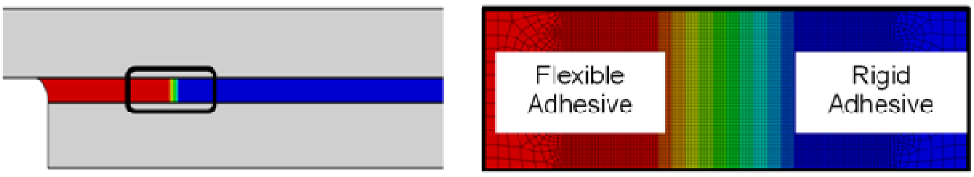

Figure 6. Transition of the mechanical properties between two adhesive bands.

Once the numerical strategy was established, three ways to approximate the continuum grading solution in the adhesive layer have been proposed. In the first and the second cases the adhesive bond line is divided into bands of the same length. For the first discretization proposal the value of the interpolation variable ρ is calculated as the average of the function in each band domain. For the second approach, the values of the continuum function in the band extremes were selected.

In the third method proposed, all the parameters (band widths and their field values) were left free to change within the operational range. An exploration technique for the different parameters has been used. In the Figure 7 these three profiles are shown for the 5 band configuration.

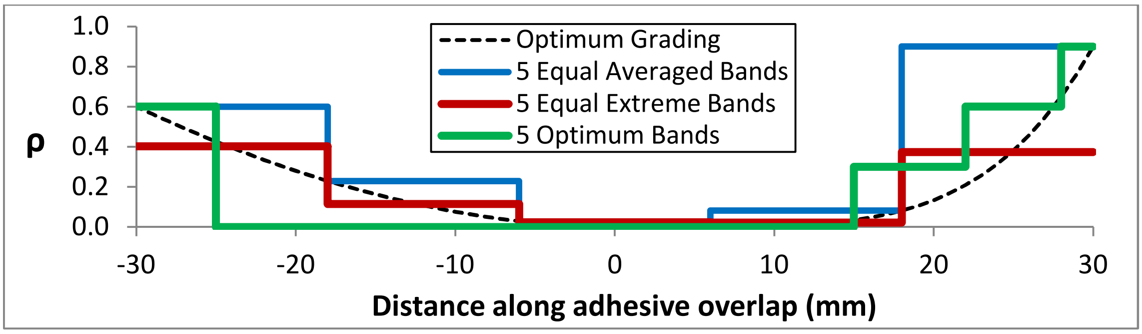

Figure 7. Interpolation variable along the adhesive bond line for the different solutions.

In the Figure 8 the evolution of the maximum load with the number of bands is shown for the three discretization proposals presented. The loads corresponding to the optimal continuum solution and the mono-adhesive solution with the rigid resin are also included.

It is clearly evidenced that the way on which the continuum solution is approximated strongly affects the level of improvement finally reached. Moreover, fixing the sizes of the bands with uniform lengths limits considerably the efficiency of the technique. However, optimizing all the parameters, the discrete solution with 5 bands can provide almost the same performance than the continuum one. It is shown that, for the joint analysed and considering a cohesive failure mode, the ultimate load can be improved around a 70%.

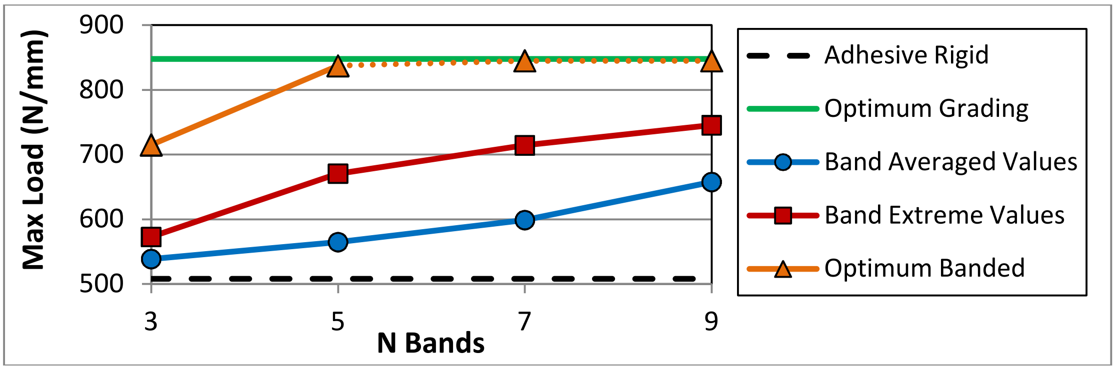

Figure 8. Evolution of the maximum load with the number of adhesive bands for the different solution schemes.

5. Conclusions

From the preliminary test as a proof of concept it is clear that the variation of the adhesive properties along the bond line has a significant potential. Additionally, the characterization of the two base adhesives and some mixtures of them has evidenced the feasibility of the grading strategy based on mixtures of two compatible adhesives with different mechanical properties.

The finite element analysis performed has shown that the joints strength can be considerably increased through continuum variations of properties, reaching approximately a 70 % of improvement. For the geometry analysed, the lack of symmetry of the substrates produces stress states into the adhesive layer with different peaks in the extremes of the overlap. This fact determines the non symmetry of the optimal material distribution. Also, it has been clearly evidenced that the way on which the best continuum grading is approximated by means of bands strongly affects the level of improvement finally reached.

References

[1] Lucas F M da Silva, R D Adams. Techniques to reduce the peel stresses in adhesive joints with composites. *International Journal of Adhesion and Adhesives*, 27 (3):227-235, 2007.

[2] R. Haghani, M. Al-Emrani, R. Kliger. Effects of geometrical modifications on behavior of adhesive joints used to bond CFRP laminates to steel members - experimental investigation. Nordic Steel Construction Conference 2009, Sweden.

[3] Lang TP, Mallick PK. Effect of spew geometry on stresses in single lap adhesive joints. *International Journal of Adhesion and Adhesives*, 8:167–77, 1998.

[4] Boss JN, Ganesh VK, Lim CT. Modulus grading versus geometrical grading of composite adherends in single-lap bonded joints. *Compos. Struct*, 62: 113–21, 2003.

[5] S. Kumar. Analysis of tubular adhesive joints with a functionally modulus graded bondline subjected to axial loads". *International Journal of Adhesion and Adhesives*, 29 (8): 785-795, 2009.

[6] Scott E. Stapleton, Anthony M. Waas, Steven M. Arnold. Functionally graded adhesives for composite joints. *International Journal of Adhesion and Adhesives*, 35:36-49, 2012.

[7] Pires I et al. Performance of bi-adhesive bonded aluminium lap joints. *International Journal of Adhesion and Adhesives*, 23 (8):215-223, 2003.

[8] Lucas F.M. da Silva, R.D. Adams. Adhesive joints at high and low temperatures using similar and dissimilar adherends and dual adhesives. *International Journal of Adhesion and Adhesives*, 27 (3):216-226, 2007.

[9] M.D. Fitton, J.G. Broughton. Variable modulus adhesives: an approach to optimized joint performance. *International Journal of Adhesion & Adhesives*, 25:329–336, 2005.