FEM ANALYSIS OF STRESSES IN ADHESIVE SINGLE-LAP JOINTS WITH NON-LINEAR MATERIALS UNDER THERMO-MECHANICAL LOADING

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Abstract
This study presents comprehensive numerical stress analysis in the adhesive layer of a single-lap joint subjected to various loading scenarios (mechanical and thermal loading). For this purpose numerical model (finite element method) with novel displacement coupling conditions able to correctly represent monoclinic materials (off-axis layers of composite laminates) has been developed. This model includes nonlinear material model and geometrical nonlinearity is also accounted for. The effect of thermal residual stresses (in adhesive) is analysed for various methods of manufacturing of single lap joint. The sequences of application of thermal and mechanical loads for the analysis of the thermal residual stresses in joints are proposed. It is shown that the most common approach used in many studies of linear superposition of thermal and mechanical stresses works well only for linear materials and produces wrong results if material is non-linear. The present study demonstrates suitable method to apply combined thermal and mechanical loads to get accurate stress distributions. Based on the analysis of these stress distributions the conclusions concerning the effect of the thermal residual stresses on peel and shear stress concentrations are made. The comparison between effect of thermal stresses in case of the one-step and two-step joint manufacturing techniques is made.

1. Introduction

Some of the big concerns in the world related to the modern transportation are reduction of the fuel consumption and pollution emissions. These issues may be resolved (at least partially) by reducing the weight of vehicles, e.g. swapping the metal parts by composites. The aerospace and automotive industries are already following this trend [1,2]. The most recent and successful examples are Boeing 787 (uses up to 50wt % composites in structures) and Airbus 380 (uses ~25wt % composites in structures) in aerospace [3] and BMW *i3* [4] in automotive industries. As the percentage of the composite within structures is increasing the joining of composites with similar and dissimilar materials becomes a subject of research and development. One of the most favorable ways to join composites in terms of mechanical performance is adhesive joining. However, manufacturing of composites as well as adhesive joining is usually done at elevated temperatures while the temperature of use of these structures is much lower than at the conditions they were produced. Because of the difference of these temperatures as well as the mismatch of coefficients of thermal expansion between fibers/matrix in the composite and adherends/adhesive in joints, significant thermal residual stresses are generated inside the composite

and in the adhesive. Thus, during the design of adhesive joints these factors have to be considered. This requires an accurate method for stress analysis in joints under thermo-mechanical loading to account for the residual thermal stresses (due to cooling-down after the curing process) and prediction of failure within the composite laminate and the adhesive. There are many studies [5-10] dealing with investigations of various parameters (e.g. material properties, geometry, etc.) responsible for the mechanical performance of adhesive joints with similar and dissimilar adherends under mechanical load. Whereas, there are only few studies [11-13] focused on the experimental as well as numerical investigation of the thermal residual stresses in a single lap joint (SLJ) and a double lap joint. However, most of these studies use linear superposition to obtain stresses caused by thermal and mechanical loads. This approach may work with linear material but it will produce inaccurate results if non-linear material is used.

The current study considers a general case (e.g. independent on material, type of loading, geometry) and demonstrates different scenarios of how thermo-mechanical loads have to be applied depending on the joint manufacturing method to obtain correct stress distributions within the adhesive of the SLJ.

2. Finite element model and material properties

In this investigation, the stress analysis for a SLJ subjected to thermal and mechanical loads was carried out by using the commercial finite element method (FEM) package ANSYS 18.0 (utilizing APDL codes). The same numerical model as presented in the parametric study [14] is considered. The 3D model used in this analysis is represented by the geometry and dimensions shown in Fig. 1, with the following boundary condition: one of the joint ends (at $X=-L_t/2t_a$) is fully clamped while the load (average stress σ_x) is applied on the free end (at $X=L_t/2t_a$) with other displacements fixed ($U_y=U_z=0$). The rest of boundary conditions (BC) will be described further in section 2.1. In order to be more general and to cover a wide range of applications, all geometrical parameters are normalized with respect to the adhesive thickness t_a. The thickness of the upper and the lower adherend are assumed to be equal.
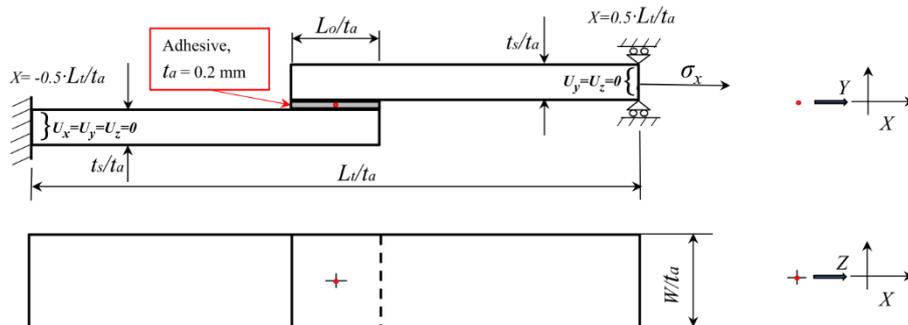

Figure 1. Geometry and dimensions of SLJ [14].

To avoid joint end interaction the overlap region is far from both ends of the joint ($X=\pm L_t/2t_a$), so the end loading conditions do not affect the stress distribution in the adhesive layer. Linear and non-linear material models were used in this analysis. The standard material model implemented in ANSYS (bi-linear isotropic hardening) was employed to simulate a non-linear material. The geometrical non-linearity option in ANSYS is activated in order to improve the accuracy of results [14].

Different types of SLJ are analysed here: a) metal-metal (M-M); b) composite-composite (C-C) (multi-directional as well as unidirectional laminates), two types of composites are used: carbon fiber reinforced polymer (CFRP); glass fiber reinforced polymer (GFRP). In case of composites four stacking sequences of laminate are considered: 1) two unidirectional laminates (UD), $[0_8]_T$ or $[90_8]_T$; 2) two quasi-

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isotropic laminates (QI), [0/45/90/-45]$_S$ or [90/45/0/-45]$_S$. The notations used further in the text and graphs are summarized in Table 1 with material properties given in Table 2.

Table 1. Composite laminates notations.

Material	Stacking sequence	notation	
		graphs	text
CFRP	[0/45/90/-45]$_S$	CF$_1$	CF-QI-0 (0-layer next to the adhesive layer)
CFRP	[90/45/0/-45]$_S$	CF$_2$	CF-QI-90 (90-layer next to the adhesive layer)
GFRP	[0/45/90/-45]$_S$	GF$_1$	GF-QI-0 (0-layer next to the adhesive layer)

Table 2. Mechanical properties of the adhesive and CFRP, GFRP and Aluminum adherends.

Material Type	E_1 (GPa)	E_2, E_3 (GPa)	G_{12}, G_{13} (GPa)	v_{12}, v_{13}	v_{23}	α_1 (10^{-6}/K)	α_2, α_3 (10^{-6}/K)
CFRP (CF) [13]	130	8	4.5	0.28	0.49	-0.9	27
GFRP (GF) [15]	40	8	4	0.25	0.45	6	35
Aluminum_linear (Al) [16]	71	71	-	0.33	0.33	23.1	23.1
Adhesive_linear (A) [16]	2.7	2.7	-	0.4	0.4	63	63
Material Type	E (GPa)	E_T (MPa)	σ_y (MPa)	v	α (10^{-6}/K)	
Aluminum _ non-linear (Al$_N$) [17]	71	500	280	0.33	23.1	
Adhesive _ non-linear (A$_N$) [16]	2.7	465	10.8	0.4	63	

Indexes: 1-fiber direction, 2-transverse to the fibers direction, 3-out-of-plane direction, T-tangential. The material notations used further in the text and graphs are given in brackets.

2.1. Coupling boundary condition

In order to avoid edge effects (at $Z = \pm W/2t_a$) due to the final (finite) width of the joint in the parametric analysis and to separate them from the end effect (at $X = \pm L_o/2t_a$) a special type of BC has been employed. The middle part of the infinite plate is simulated by applying coupling of displacements. These conditions allow to neglect width dimension and use a very narrow model without compromising accuracy of results.
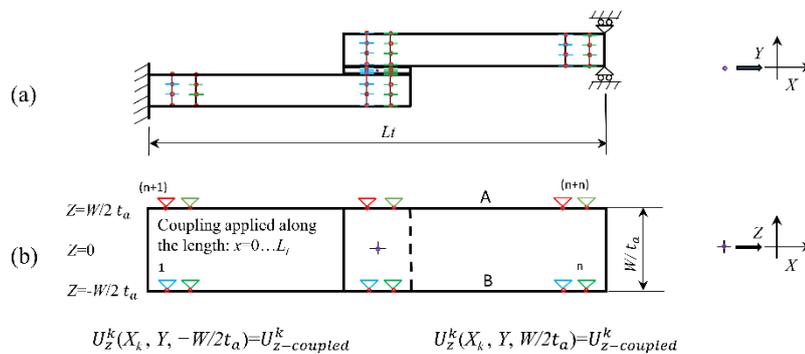

Figure 2. Coupling of displacement U_z applied on the nodes belonging to the vertical lines on the edges with the same X-coordinate.

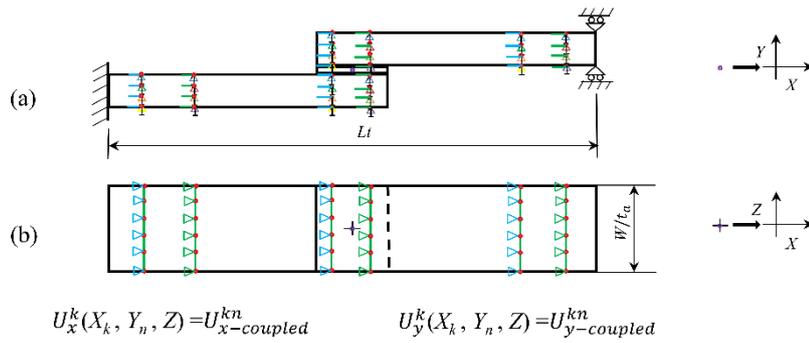Nawres J. Al-Ramahi, Roberts Joffe and Janis Varna

Figure 3. Coupling of displacement U_x and U_y applied on the nodes belonging to the horizontal lines running through the width of the joint with the same X and Y coordinates.

This allows to use only a few elements in the width direction with computation time reduced by ~90%, thus a very fine mesh can be used within the layers and at the interface of the joint. Moreover, the BC presented here are not the typical coupling often used in simulations, conditions used here (see Fig. 2 and Fig. 3) allow to simulate not only isotropic or orthotropic materials but also monoclinic composite layers with off-axis fiber orientations. The BC are separated into two parts: 1) the coupling is applied on the all nodes on one of the vertical lines indicated in Fig. 2 at the edges A and B separately, these nodes are forced to have the same displacement U_z; 2) coupling is applied on the nodes through the width of the sample (from $Z = -W/2t_a$ to $Z = W/2t_a$, at fixed X_k, see Fig. 2 (b)), all nodes located on the horizontal line at fixed X_k and Y_n (see Fig. 3) have the same displacements U_x and U_y. These conditions are not explained here in all details but more information can found in [14].

2.2. Thermo-mechanical loading

Three different ways to apply thermal and mechanical loads are analysed in this study: 1) denoted as "T&M", thermal and mechanical loads are applied together (simultaneously); 2) denoted as "T+M", thermal and mechanical loads are applied in two separated simulations and then the total stress distributions are found as a linear superposition (e.g. see in [12,13]); 3) denoted as "T/M", the simulations are done in two subsequent stages, thermal load is applied first and stresses are calculated, these stresses are re-assigned to nodes as an initial conditions for the second stage (mechanical), and then, the mechanical load is applied and total stresses are obtained. The simulations according to these methods for application of thermo-mechanical loads are performed for isotropic (e.g. metal adherend and polymer adhesive) as well as for anisotropic material (e.g. composites).

In case of "T/M", if at least one adherend is a composite, the simulation is done according to different scenarios (two- or three- stage simulation) depending on the manufacturing sequence of the joint. For example, if the composite adherend and adhesive are cured simultaneously (co-curing), the simulation is done in two stages. But if the composite is made prior to the bonding, the simulation is done in three stages with two thermal stress calculations: first thermal stresses in layers of the laminate are obtained with temperature of cure of the composite and they are used as initial condition for calculation of stresses with respect to the temperature of adhesive curing.

In case of metal-metal joints, only the adhesive has to be cured and therefore, two-stage simulation is performed. According to the datasheet, the curing temperature of the adhesive is equal to 60⁰C. The temperature applied on all components of the joint is the difference between the curing temperature of the adhesive (60⁰C) and temperature of use (room temperature, 25⁰C), so $\Delta T = -35$ºC, since cooling down from the curing temperature to the room temperature is considered. The same approach is used to

simulate the manufacturing of composite-composite or composite-metal joints in 1-step (co-curing: the matrix in the composite and the adhesive are cured at the same time). However, since the curing temperature of the composite is 175^{0}C, the applied temperature difference is ΔT = -150ºC.

In the case of composite-composite joints and the manufacturing in two steps (composite laminates are cured prior to the bonding) a three-stage simulation is carried out. The temperature difference is not the same in each stage of calculation and it is not applied on all members of the joint. The first stage uses ΔT_1 = -115ºC (cooling down from the temperature of curing of the composite 175^{0}C to the curing temperature of the adhesive 60^{0}C). This thermal load is applied only on the composite part and this step generates initial stresses in the plies of the composite laminate. The second stage uses ΔT_2 = -35ºC which is applied to the whole joint, this is according to the assumption that joint is assembled at the curing temperature of the adhesive and then it is cooled down to the room temperature. The third stage is application of mechanical load to calculate the total stresses (the thermal stresses obtained in stage one and two are initial stresses applied on nodes).

In order to demonstrate the validity of this approach, the stress distribution within the composite layers are compared against results from Classical Laminate Theory (CLT) and with load-displacement curves for the joint (data from the literature) [18].

The following notations are used further in the figures: (1S) - thermal load is applied once (curing of the adhesive only or adhesive and composite simultaneously); (2S) - thermal load is applied twice (first calculation for the thermal stresses in the composite and second in the whole joint).

3. Results and discussion

The discussion is focused on the peel and shear stresses within the adhesive layer of the SLJ. The analysis is performed on stress distributions along the overlap length from $(X = -L_o/2t_a)$ to $(X = L_o/2t_a)$ in the middle of the adhesive layer $(Y = 0)$ at the centre line of the joint $(Z = 0)$. The following dimensions of the SLJ are used (all the dimensions are shown as a ratio with respect to the adhesive thickness, $t_a = 0.2\ mm$): adherend thickness $t_s/t_a = 10$; overlap length $L_o/t_a = 200$; total SLJ length $L_t/t_a = 1500$ and width $W/t_a = 5$.

3.1. Different techniques to apply thermal load

In this section the differences between results from three simulation schemes (see section 2.2) "T&M", "T+M" and "T/M" are presented. Linear adherend (aluminum) and adhesive materials are considered for similar SLJ with the mechanical load applied as a strain ($\varepsilon_x = 0.1\%$) and thermal load (ΔT = -35ºC). The results are shown in Fig. 4. As can be seen from these plots the differences of stress distributions in the adhesive layer between "T&M" and other load application schemes are very significant, while only small difference between "T+M" and "T/M" is observed (which is probably due to the numerical error). It should be noted that similar trends with smaller differences were obtained for SLJ with composite adherends (not shown in this paper).

Moreover, the results of the verification of the model [18] show that in case of "T&M", the global response of the joint and local stress distributions are substantially different from the literature data. Similarly, analysis of stresses on the ply level inside the composite laminate show that "T&M" case produces wrong results [18]. On the other hand, the "T+M" and "T/M" schemes show a good agreement between ANSYS, CLT and literature [18]. It has to be mentioned however, that "T&M" scheme works correctly when mechanical load is applied as a force (not strain or displacement). Thus, in order for results to be independent on the type of the applied load it is preferably to use other methods than "T&M" of application of thermo-mechanical loading.
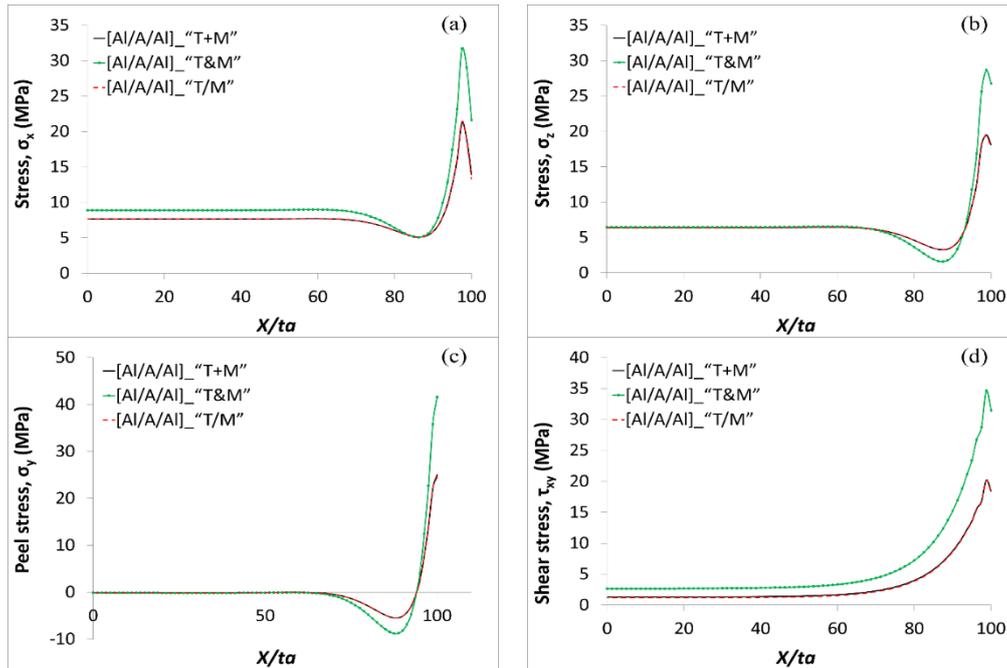
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Figure 4. The stress distributions in the adhesive layer of [Al/A/Al] SLJ for "T&M", "T+M" and "T/M" scheme, $t_a = 0.2\ mm$, $t_s/t_a = 10$ and $L_o/t_a = 200$, 0.1% strain and ΔT= -35°C are applied.

3.2. Effect of material nonlinearity on the stress distributions in the adhesive layer

The linear superposition "T+M" and scheme "T/M" are proved to be in a good agreement with CLT and literature data for linear elastic material. This section analysis validity of these methods for nonlinear materials. Non-linear material model for adherends (Al) and adhesive materials are used for calculations of stresses in a M-M SLJ, the results are presented in Fig. 5. It can be seen that while the peel and shear stresses are almost the same for both calculation schemes, there is a noticeable difference between σ_x and σ_z stresses when the non-linear material model is compared to the linear one. Moreover, it should be pointed out that the material may behave linearly under each of the loading components (thermal and mechanical) separately but when thermal and mechanical loads are applied together (simultaneously or in sequence) the material behavior may be shifted from the linear to the non-linear region. Accordingly, differences observed in Fig. 5 will be even larger as the thermal load or/and the mechanical load are increased.

Thus, in order for the results to be independent on the material model the simulation should be done in a sequence (thermal simulation and then mechanical simulation) and therefore, only the "T/M" scheme is employed further in this paper.
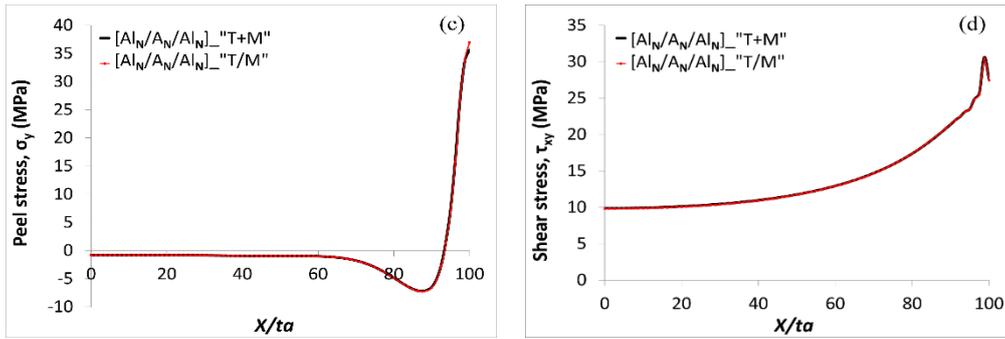

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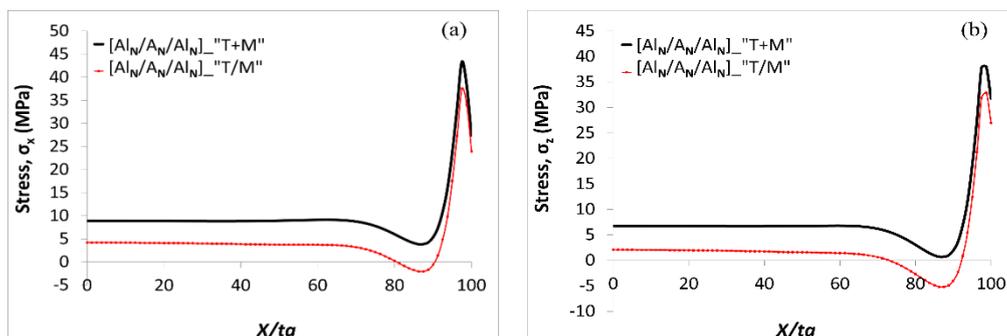
Figure 5. The stress distributions in the adhesive layer of [Al$_N$/A$_N$/Al$_N$] SLJ for "T+M" and "T/M" scheme, $t_a = 0.2 \, mm$, $t_s/t_a = 10$ and $L_o/t_a = 200$, 0.1% strain and ΔT=- 35ºC are applied.

3.3. Effect of curing procedure (1-step vs 2-step) on the stress distributions in the adhesive layer

In order to study the differences of stresses in the SLJ produced by 1-step and 2-step procedures (see description in section 2.2) the joints with CF-QI-90 adherends and linear adhesive are considered. The results of the simulation are presented in Fig. 6 and it is observed that in joints produced by 1-step procedure the peel stress concentration at the ends of the overlap as well as the shear stress level within the plateau region is lower than in case of the SLJ made by 2-step method. However, this effect is caused by the different curing temperatures: the curing temperature (175ºC) in 1-step is higher than the curing temperature (60ºC) in 2-step. In this particular case it may be speculated that the use of adhesive with higher curing temperature may have a positive effect (e.g. reduce the stress concentration in the adhesive layer).
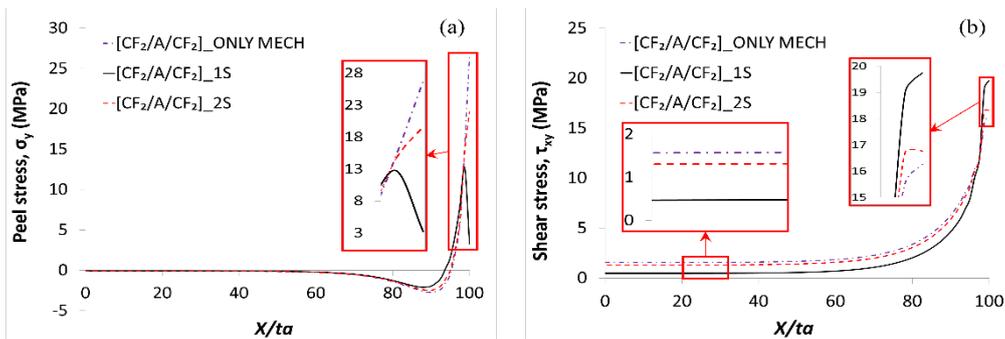

Figure 6. The peel and shear stress distributions in adhesive for SLJ with CF-QI-90 composite adherends for 1-step and 2-step manufacturing methods of joints, with and without residual thermal stresses accounted for. Applied: 60 MPa, ΔT=-150ºC for 1-step and ΔT=-35ºC for 2-step curing.

Conclusion

The simulations of single lap joints with various schemes led to the following conclusion:
- Linear superposition scheme works only for linear elastic material but produces wrong results in case of use non-linear material.
- Thermal simulation and then mechanical simulation with the calculated thermal stress as initial condition is more suitable because results will be valid independently on the material model and type of the applied load (force or displacement).

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- – In some configurations residual thermal stresses may play a positive role and delay the failure by reducing the peel stress concentration at the ends of the overlap as well as the shear stress level within the plateau region.
- – The peel stress concentration at the ends of the overlap as well as the level of the shear stress within the plateau region can be reduced by curing the adhesive and composite in 1-step or by using adhesive which has high curing temperature (this has to be validated for other systems).

Acknowledgments

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