Numerical stress analysis for single-lap adhesive joint under thermo-mechanical load using non-linear material

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Abstract. A comprehensive stress analysis by means of Finite Element Method (FEM) for single-lap joint subjected to thermal and mechanical loads is presented in this paper. Simulation is used to predict the effect of residual thermal stresses (caused by difference of temperature of use and elevated temperature during the assembly of the joint) on stress distribution within adhesive layer. The residual thermal stresses are assigned to joint members as initial condition before the mechanical load is applied. The FEM model employs linear and nonlinear material model and accounts for geometrical nonlinearity. It is confirmed that the difference between the manufacturing and the ambient temperature results in high residual thermal stresses, especially in axial and lateral directions of the joint. The calculation of total stress as superposition of thermal and mechanical stresses works only for linear materials. Moreover, simultaneous application of temperature and mechanical load (applied strain in case of displacement controlled test) in FEM produces inaccurate results, since in real situation the strain is applied to already thermally loaded structure. It is also found that the residual thermal stresses may reduce the peel and shear stress concentration in the adhesive at the ends of overlap and the shear stress within the overlap.

1. Introduction

The fuel consumption and pollution emission are the main concerns for the modern transportation industry. These problems may be mitigated by reducing the weight of the vehicle structure (e.g. using composites in some parts of the structures instead of steel). There is active development within the automotive and aerospace industries towards these objectives [1,2]. For instance, Boeing 787 [3] is one of the successful examples in the aerospace industry (uses up to 50wt % composites in structures), while BMW i3 [4] shows progress in the automotive industry. Considering such hybrid structures the joining of composites with similar and dissimilar materials becomes an important research topic. In case of composite material, the most suitable joining to achieve best mechanical performance is by use of adhesives. The composite manufacturing as well as the adhesive joining is done at an elevated temperature although the temperature of use is typically much lower. This means that the residual thermal stresses are generated inside the composite and the adhesive layer. The knowledge about these stresses is a key factor for design of reliable adhesive joints. To gain understanding about these stresses requires an accurate numerical model for the stress analysis of adhesive joints under thermo-mechanical loading.

This information allows accounting for the residual thermal stresses (due to cooling-down from the manufacturing temperature to temperature of use) as well as prediction of the failure initiation within the adhesive layer and composite laminate. The work on this subject is on-going and there are various numerical and experimental studies [5–10] to investigate the mechanical performance of adhesive
joints under mechanical load by using different joint parameters such as (material properties, geometry, etc.). However, only few of these investigations [11–13] deal with thermal residual stresses in double lap joint and single lap joint (SLJ). One drawback of these studies is use of the linear superposition to obtain the total stresses caused by thermal and mechanical loads because such approach may work well for linear material but it produces incorrect results if non-linear material is considered. The work on the problems associated with residual thermal stresses on the adhesive joint strength is on-going and with more recent publications available [14–17].

The main purpose of this study is to develop a realistic numerical model that can produce accurate data for the analysis of stresses within the joint members under thermos-mechanical loads. As well as demonstrates the possible errors which may be introduced if thermal and mechanical loads are introduced simultaneously in one step. The importance to account the residual stresses is also shown in relation with use of appropriate type of material model (linear vs non-linear). The simulations are performed only on metal-metal SLJ by using a general numerical model (independent on the loading type, geometry as well as material behavior).

2. Finite element geometry and material properties

A commercial FEM package ANSYS 2019 R3 (employing APDL codes) with numerical model described in [18] is used in this study for the stress analysis of SLJ. A 3D solid element (SOLID185) [19] with eight nodes is used to create the mesh. In order to get more accurate results, a refined mesh is used for the adhesive layer (from $X = -0.5 \cdot L_o/t_a$ to $X = 0.5 \cdot L_o/t_a$) as well as at the singularity regions. To accommodate mesh with varying element size, the thickness of adherent plate is divided into three parts. A very fine mesh is used for the adhesive layer and the part of the adherend next to the adhesive layer, while a medium mesh/coarse mesh is applied for the middle and surface respectively. The size of elements is chosen to maintain length ratio between elements in different locations: small/large = 1:20 and the medium/large = 1:4, while the length of large elements to the total length ($L_i$) is 1:300. The convergence of the results was obtained by monitoring the influence of the mesh size on the stress value at the singularity region. The full convergence was achieved at 50000 elements and this number of elements will be used for the calculations.

The geometry and dimensions of the 3D model of SLJ are shown in Figure 1. The following boundary conditions are applied: the load is applied on the free end (at $X=0.5 \cdot L_i/t_a$) with other displacements fixed ($U_y=U_z=0$) while another end ($X=-0.5 \cdot L_i/t_a$) is fully clamped. The following dimensions are used: adhesive thickness $t_a = 0.2$ mm; total length/adhesive thickness ratio $L_i/t_a = 1500$; overlap length/adhesive thickness ratio $L_o/t_a = 200$; width/adhesive thickness ratio $W/t_a = 5$; and adherend/adhesive thickness ratio $t_o/t_a = 10$. The lower and upper adherends are of the same thickness. It should be noted that in order to make the results applicable for a wide range of joint configurations, the adhesive thickness $t_a$ is used to normalize other geometrical parameter. To avoid any interaction between the joint ends (at $X = \pm 0.5 \cdot L_i/t_a$) and the overlap region (at $X = \pm 0.5 \cdot L_o/t_a$), the load is applied far away from the overlap region. Moreover, in order to get more accurate results, the geometrical non-linearity options within ANSYS is activated [18,20,21]. The standard non-linear material model implemented in ANSYS (bi-linear isotropic hardening) is used for simulations. The stress-strain curves for non-linear aluminum and non-linear adhesive are shown in Figure 2 [22].

In order to separate the effect of the overlap ends (at $X = \pm 0.5 \cdot L_o/2t_a$) from the edge effects (at $X = \pm 0.5 \cdot W/t_a$), the infinite plate is modelled by applying special boundary conditions (coupling) (see Section 3 for more details).

The metal-metal [M/A/M] joint with the material properties in Table 1 is considered.
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Figure 1. Geometry and dimensions of SLJ [18].

Table 1. Mechanical properties of the adhesive and Aluminum adherends.

| Material Type                     | $E$  | $E_T$ | $\sigma_T$ | $\nu$ | $\alpha$ (10^{-6}/K) |
|-----------------------------------|------|-------|------------|------|----------------------|
| Aluminum_linear (Al) [23]         | 71   | -     | -          | 0.33 | 23.1                 |
| Adhesive_linear (A) [23]          | 2.7  | -     | -          | 0.4  | 63                   |
| Aluminum_non-linear (Aln) [19]    | 71   | 500   | 280        | 0.33 | 23.1                 |
| Adhesive_non-linear (An) [23]     | 2.7  | 465   | 10.8       | 0.4  | 63                   |

The notations in the brackets are used in the text and graphs to identify materials.

Figure 2. Stress-strain curve for a) non-linear adhesive material (An) and b) non-linear Aluminum (Aln) [22].

2.1. Coupling boundary conditions

As mentioned above, to eliminate the width (edge) effect (at $X = \pm 0.5 \cdot W/t_a$) due to finite width and separate them from the end effect (at $X = \pm 0.5 \cdot L_0/t_a$), special type of boundary conditions are utilised. This allows accurate representation of the middle of an infinite plate by using a very narrow model. By using this type of coupling, a very fine mesh can be used within the layers and at the interface of the joint while reducing computational time by 90%.

The application of the boundary conditions is done by the following procedures: a) at the edges A and B (as shown in Figure 3) the coupling is applied through the thickness (on nodes with the same X-coordinate, those nodes are located on the vertical lines), thus all the selected nodes will have the same displacement $U_z$; b) the nodes having the same X-coordinate and Y-coordinate (placed on the horizontal lines across the width from $(Z = +0.5 \cdot W/t_a)$ to $(Z = -0.5 \cdot W/t_a)$) are coupled together. This coupling imposes the same displacements $U_x$ and $U_y$ (see Figure 4) on the selected nodes. The full details concerning these boundary conditions have been explained in [22].
2.2. Thermo-mechanical loading

There are three different possible ways to apply the thermal and mechanical loads in order to investigate the effect of the residual thermal stresses: 1) apply thermal and mechanical load simultaneously (denoted as “T/M”); 2) apply the thermal and mechanical loads in fully separated simulation and calculate the final stresses as a linear superposition (as presented in [11–13]) (denoted as “T+M”); 3) the thermal and mechanical loads are applied in two successive phases, the stresses induced by thermal loading are calculated first and then applied as an initial condition for the phase with mechanical loading (denoted as “T/M”). The initial stress state for the joint under mechanical load is obtained by applying thermal load only and extracting the stresses generated in each node then these stress values are arranged (MATLAB code used) into ANSYS input file (it is opened prior to application of mechanical load). To clarify the succession of how the thermal and mechanical loads are applied the corresponding flowchart is presented in Figure 5. It should be mentioned to that the third scenario (“T/M”) can be used for any types of joint independently on material behaviour as well as the type of applied load. For the [M/A/M] the adhesive has to be cured prior to tensile test at temperature of 60ºC (according to the adhesive datasheet [23]). The residual stresses are generated within the joint members due to cooling down from the curing temperature (60ºC) to the ambient temperature (25ºC), thus ΔT = -35ºC is applied as thermal load.
3. Results and discussion

The discussion is based on the analysis of the stress distributions along the overlap length at the centre of the adhesive layer from \((X = -0.5 \cdot L_o/t_a)\) to \((X = 0.5 \cdot L_o/t_a)\). Since in case of SLJ these distributions are symmetric with respect to \(X=0\) (middle of the joint), only half of the overlap length is considered (and in figures stress distributions are presented over this distance). The analysis of influence of various parameters on stress distributions is presented here. In order to verify the model, a very simple case study on single composite laminate was performed. A composite laminate with unidirectional and quasi-isotropic layup is simulated to compare stresses in the layers obtained from ANSYS with results from Classical Laminate Theory (CLT). The following cases were checked: 1) only mechanical load is applied; 2) only thermal load is applied; 3) thermal load and then mechanical load are applied in two sequential steps. The comparison shows that results from CLT and FEM are almost identical, thus the suitability of boundary conditions in numerical model is validated.

3.1. Various scenarios for application of thermal load

The effect of application of thermal load is discussed in this section assuming three different scenarios: 1) the thermal and mechanical loads are applied simultaneously; 2) two independent calculations are performed for thermal and mechanical loads, then the resulting stress is obtained by using superposition; 3) the calculation is performed for thermal load to obtain stresses which are used as initial condition for the case with mechanical load only.

The main focus for discussion here is to demonstrate the difference between these three scenarios in case of linear and non-linear material considering displacement controlled tensile test. The simulations are carried out by applying strain \((\varepsilon_x = 0.1\%)\) as a mechanical load.

3.1.1. Linear material model

The results of calculation for abovementioned scenarios with use of linear material model (for adherend and adhesive) are presented in Figure 6. As can be seen from Figure 6 there is no difference between the stress distributions in case of T+M (superposition) and T/M (thermal stresses as initial conditions) but there is a significant difference in case of T&M (simultaneous). This is due to misrepresentation of real test/manufacturing conditions by the assumptions in the T&M: the cooling down occurs while the joint is constrained by applied load, thus in general stress levels obtained from this case are higher. In reality the joint is cooled down unconstrained and then the mechanical load (strain) is applied during the test. This is how T+M and T/M simulations are carried out: the thermal stresses are calculated on the unconstrained model (free boundary condition) and then the mechanical load is applied with some constraints on the joint end. This means that the T&M scenario should be avoided as unrealistic and study should focus only on the T+M and T/M scenarios.
3.1.2. Non-linear material model
The comparison between the T+M and T/M scenario for the non-linear material model (for adherend and adhesive) is discussed in this section. The results of simulations are presented in Figure 7. First of all, it can be noted that thermal residual stresses (or simulation scenario) do not dramatically affect shear stress $\tau_{xy}$, moreover, the peel stress $\sigma_y$ is absolutely unaffected. On the other hand, the in-plane normal stresses ($\sigma_x$ and $\sigma_z$, see Figure 7c and 7d) are affected by the presence of thermal stresses as well as by the scenario of how loads are applied. Besides, this difference will increase as load level (either thermal or mechanical) is increased, since stresses will be shifted to higher level and non-linear region of stress-strain curves of the material will be reached. While the influence of the loading scenario on the shear stress distribution is not very significant in terms of stress levels, there is noticeable change of the shape of the curve, especially if kinking on the curve is observed. This kink represents the transition point between linear and non-linear material model. It can be stated that this transition point is the same for mechanical loading or T+M case, but it is shifted to the left for T/M (as it was observed for the increase of the mechanical load in [18]). This means that for the T+M scenario the material is still behaving the same with respect to linearity/non-linear under each loading component separately, consequently the final result is incorrect because non-linear behaviour is not captured. Therefore it can be stated that T+M scenario cannot be employed in case when material is non-linear.

Figure 6. Comparison of stress components in the adhesive layer of [Al/A/Al] SLJ using T&M, T+M and T/M simulation methods, 0.1% strain and $\Delta T = -35^\circ C$ are applied.
3.2 Evaluation of magnitude of mechanical vs thermal loads

In this section, the effect of increasing the mechanical load is compared against changes caused by the increase of the thermal load (the peel and shear stress distributions are analysed). In order to demonstrate these effects the simulation is done at mechanical load which ensures that the whole material is in the linear-elastic mode (applied strain of $\varepsilon_x = 0.08\%$ corresponding to stress of $\sigma_x = 53\text{MPa}$) and temperature difference of $\Delta T = -35^\circ\text{C}$. Then these parameters are increased by factor of 2 to see changes in stress distribution they cause separately and combined together. As seen from the Figure 8a the increase of temperature does not affect the peel stress distribution. However, the mechanical load has a notable influence on the peak stress next to overlap ends as well as on the maximum peel stress at the overlap ends. This behaviour is likely due to the eccentricity of the load in SLJ that results in intensification of the bending of the joint as applied load is increased which gives rise of the peak and maximum peel stress.

As expected, the increase of applied mechanical load moves the values of shear stress upwards but the shape of the stress distribution is not affected so much. On the other hand, the variation of temperature results in a visible (although local) change of the shape of shear stress distribution (see Figure 8b). The linear/non-linear material transition point (observed at around $X/t_a = 80$ for $\Delta T = -35^\circ\text{C}$) disappears when the temperature difference reaches $-70^\circ\text{C}$. This is because all material within the monitored region starts to behave non-linearly. However, twice as high mechanical load only shifts transition point to the left but it does not completely disappear (some of the material still behaves linearly).

In order to exemplify this phenomenon additional calculations are performed by keeping the same mechanical load and changing only the temperature. The comparison is done by analyzing the shear stress component and the linear/non-linear transition point is monitored. The simulation is done for mechanical load of $0.08\%$ combined with four different temperatures $\Delta T$: $0^\circ\text{C}$ (only mechanical load), $-17.5^\circ\text{C}$, $-35^\circ\text{C}$ and $-40^\circ\text{C}$. The results in Figure 9 show that the increase of temperature leads to shift
of the transition point to the left (to the middle of the joint) and it is almost gone at -40°C. This explains why the transition point disappeared when the temperature difference reaches -70°C in Figure 7b (this temperature is high enough to push material within analyzed region into non-linearity). Based on these observations it is possible to state that the thermal load has an important effect on the stress distribution within the overlap of the SLJ. Furthermore, this effect locally can be more significant (for comparative magnitudes of changes for the load level) than the mechanical load.

![Figure 8](image8.png)

Figure 8. Comparison of peel and shear stress in the adhesive layer of [Aln/An/Aln] SLJ for T/M simulation methods, two different mechanical load level (0.08% and 0.16% strain) and two different temperature (ΔT = -35°C and -70°C) are applied.

![Figure 9](image9.png)

Figure 9. Comparison of shear stress in the adhesive layer of [Aln/An/Aln] SLJ for T/M simulation methods, 0.08% strain and four different temperature (ΔT =0, -17.5 °C, -35°C and -40°C) are applied.

4. Conclusions
It has been demonstrated that in order to obtain accurate and reliable stress distributions in SLJ the thermal and mechanical loads have to be applied in two consecutive steps. Moreover, if the non-linear material is used in the joint the superposition method to combine thermal and mechanical loadings are not applicable and will produce incorrect result. It has been also noted that the increase of temperature will increase level of thermal residual stress and this increase may have more significant effect on local material behaviour (linear vs non-linear) in the adhesive layer of SLJ than variation of mechanical load (at least for the same magnitude of the changes of loads).

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