Numerical stress analysis in adhesively bonded joints under thermo-mechanical loading

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Abstract
The objective of this work is to evaluate the effect of residual thermal stresses, arising after assembling a single-lap joint at elevated temperature, on the inelastic thermo-mechanical stress state in the adhesive layer. The numerical analysis (FEM) employing linear and non-linear material models, with geometrical nonlinearity accounted for, is carried out. Simulating the mechanical response, the calculated thermal stresses are assigned as initial conditions to polymeric, composite and metallic joint members to reflect the loading sequence where the mechanical strain is applied to cooled-down structure. It is shown that the sequence of application matters and simulations with simultaneous application of temperature and strain give different result. Two scenarios for adhesive joints with composites are studied: joining by adhesive curing of already cured composite parts (two-step process) and curing the adhesive and the composite simultaneously in one-step (co-curing). Results show that while in-plane stresses in the adhesive are higher, the peaks of out-of-plane shear stress and peel stress (most responsible for the joint failure) at the end of the overlap are reduced due to thermal effects. In joints containing composite parts, the one-step joining scenario is more favorable than the two-step. The ply stacking sequence in the composite has significant effect on stress concentrations as well as on the plateau value of the shear stress in the adhesive.

Keywords
Composites, single-lap joint, adhesive joints, thermo-mechanical load, residual thermal stresses, similar and dissimilar adherends, co-curing

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Introduction
In order to reduce the weight and fuel consumption in aerospace and automotive applications, composite materials have been widely used in modern manufacturing¹,² instead of metals. For example, fuel consumption in Boeing 787 was reduced by 20% due to decrease of the weight by 50% achieved by use of composites, and in Airbus A380 the energy consumption was reduced by 12% as a result of use of 25% carbon fiber reinforced plastic (CFRP) in weight of the structure.³ These trends to build hybrid structures (metal and composites) will continue and more metal parts will be substituted by composites in the future. Unavoidably, these different materials have to be joined together, so there will be numerous joints within the structure between similar and dissimilar material (e.g. composite-composite and composite-metal). Typically, three types of joints are considered: adhesive joint, mechanical joint or

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The adhesive bonding has unique advantages in comparison to traditional mechanical connection, they are lighter and the joint fatigue life is improved, the stress distribution in the bonding area is more uniform, better resistance to environmental effects like corrosion is achieved. One of the main problems concerning replacement of mechanical joint by adhesive bonding is the residual thermal stresses due to joining process of similar and dissimilar materials at elevated temperatures. The residual thermal stresses arise because of mismatch of thermal expansion coefficients between the adherends and the adhesive. Moreover, the composite laminates are usually produced at elevated temperature which causes residual thermal stresses within the laminate itself (e.g. in plies with different fiber orientation within multi-axial laminate) that may have a significant impact on joint strength. Sometimes these stresses are high enough to cause failure within the laminate layers even before any mechanical load is applied.

There are a number of studies where residual thermal stresses in adhesive joints with composite adherends are accounted for. These studies were carried out on the single-lap joint (SLJ) with similar and dissimilar adherends. Experimental data and results of a numerical model to predict the residual thermal stresses in dissimilar (CFRP/aluminum) adhesively bonded SLJs are presented. As expected, the residual thermal stresses are higher if curing temperature is increased, at the same time the thermal stresses (Von Mises stress) in adherends (aluminum and CFRP) are higher than in the adhesive layer. This results in compressive stress in the CFRP and tensile stresses in the adhesive layer as well as in the aluminum adherend. Distribution of residual thermal stresses in SLJ and double lap joint (DLJ) with similar and dissimilar adherends was studied numerically by using 2D and 3D finite element models. The results show that the 2D finite element analysis and analytical solution are not capable to fully characterize a 3D stress state, and the material and geometric nonlinearity should be incorporated into the models simultaneously to get accurate results. As it turns out, the residual thermal stresses generated in longitudinal/transverse directions and shear for DLJ of CFRP/Al/FM73 have significantly higher levels than for the SLJ. As well as the highest thermal stresses were obtained for dissimilar adherends. Experimental and 2D finite element analysis studies for hybrid SLJ with different adherend thickness and overlap length were presented. The experimental curing process was studied with curing temperature 145°C and under two different pressures (0.1 and 0.5 MPa). The maximum peel and shear stresses are located at the overlap ends and between the adhesive centerline and the adherend/adhesive interfaces with the most critical points on the adherend/adhesive interface along the overlap length.

Residual thermal stresses in joints developed after the co-curing process were also studied. Experimental investigation of shear strength for co-cured hybrid SLJ (composite-steel) under tensile load with different bonding parameters is presented. It has been shown that the increase of the overlap length increased the overall joint load capacity but decreased the lap shear strength. It is also shown that the fiber orientation has a significant effect on the lap shear strength with the maximum value obtained for the \( \{ [\pm 45_S]_6 \} \) laminate. Another case with co-cured SLJ with several joint parameters (e.g. overlap length and stacking sequence) was studied numerically. Residual thermal stresses were calculated and then added to the mechanical stresses in order to find final stress distribution. The results show that the peel and shear stress concentration occur at the ends of the overlap, with decrease of the peel and increase of the shear stress levels as the fiber orientation angle \( \{ [\pm \theta]_6 \} \) in the stacking sequence increases. The effect of surface roughness of the steel adherend and the stacking sequence of the composite adherend on the stress distribution as well as failure of co-cured SLJ and DLJ under static/fatigue loads including residual thermal stresses was studied. It has been demonstrated that in SLJ the residual thermal stresses may play a positive role in delaying failure by reducing opening of the crack at the interface due to reduction of peel stress. However, it is also shown that the residual thermal stress will increase the shear stress concentration.

It seems that the residual thermal stresses and their effect on the performance of adhesively bonded joints are extensively studied, however, the majority of studies deal with the combination of thermal and mechanical stresses by means of superposition. This works for linear elastic materials, while it may produce incorrect results for more complex cases (if non-linear material is included). In this study a comprehensive numerical model with special boundary conditions (developed in previous work) is employed. Simulation is done for joints with inelastic constituents to predict the residual thermal stresses due to cooling down from the curing temperature to room temperature of adhesive and/or composite as well as both of them. However, no temperature or time dependence of material properties is considered in this work.

Suitable application of the thermo-mechanical loading in FEM is proposed and several scenarios of joint assembly are analyzed. The approach is based on solving the thermal problem first and then using obtained stress distribution as an initial condition to solve the problem with only mechanical load applied. Although failure analysis is not performed in this study, the most important achievement of this paper is development of a model that produces realistic and accurate stress distributions within adhesive and adherends under
thermo-mechanical loading. This model can be used further in the analysis of the damage initiation and failure of joints.

**Description of numerical model**

**General considerations**

A commercial FEM package ANSYS 18.0 (utilizing APDL codes) is used to analyze a SLJ subjected to thermal and mechanical load. The 3D model used for simulations is based on the geometry and dimensions shown in Figure 1.

A standard ANSYS 3D solid element (SOLID185)\(^{15}\) with eight nodes (each with three degrees of freedom) are used. The model had been divided into three regions with different elements sizes in order to optimize the mesh with respect to the accuracy and computational time. The following regions through the thickness of the joint are defined:

(a) Coarse mesh with large elements away from the bond line, close to the surface of adherends, \((0.5 \cdot t_a/t_a + 0.5) < Y < (t_s/t_a + 0.5)\) and \((-t_s/t_a - 0.5) < Y < (-0.5 \cdot t_s/t_a - 0.5)\);

(b) Medium mesh closer to the bond line, in the middle of adherends \((0.125 \cdot t_s/t_a + 0.5) < Y < (0.5 \cdot t_s/t_a + 0.5)\) and \((-0.5 \cdot t_s/t_a - 0.5) < Y < (-0.125 \cdot t_s/t_a - 0.5)\);

(c) Fine mesh in the adherends layer adjacent to the adhesive and within the adhesive layer \(0 < Y < (0.125 \cdot t_s/t_a + 0.5)\) and \((-0.125 \cdot t_s/t_a - 0.5) < Y < 0\).

The length of a large element is \(1/300\) of total length \(L_t\), while length ratio of large element to small and medium elements is 20:1 and 4:1 respectively. The mesh optimization (refinement and convergence of solution) and optimization has been performed in previous study.\(^{14}\) The numerical model developed earlier\(^{14}\) is employed with the following dimensions: adhesive thickness \(t_a = 0.2\) mm; adherend/adhesive thickness ratio \(t_s/t_a = 10\); overlap length/adhesive thickness ratio \(L_o/t_a = 200\) and total length/adhesive thickness ratio of the SLJ is \(L_o/t_a = 1500\). In order to simulate infinitely wide plate the same type of boundary conditions (coupling) as in previous work\(^{14}\) is used (see Figure 2), with sample width/adhesive thickness ratio \(W/t_a = 5\).

Perfect bonding between the adhesive and adherends is assumed and the simulations are performed with linear and non-linear material models. The geometrical nonlinearity option is activated in ANSYS in order to improve the accuracy of the results.\(^{9,14,16,17}\) A standard material model (bi-linear isotropic hardening) which is available in ANSYS is employed to represent non-linear material.

**Experimental results supporting the model**

At this point the model has not been fully validated by experiments because the tests required to make direct comparison with the numerical simulation are rather complicated and it is virtually impossible to obtain stress distribution in the middle of the adhesive layer. However, limited number of experiments is performed to verify that the proposed numerical model captures characteristic behavior of SLJ. Since this is only preliminary tests, the experimental part is not presented as a separate section in the paper.

The experimental results presented here are intended only as a qualitative assessment of the numerical model since tests are done on materials with different properties than used in simulations and on SLJ with fixed width. The tests were carried out for SLJ of similar adherend (composite, T700/ET445) with Sika Power 533-MBX as adhesive. The comparison is done on strain distribution within the adhesive layer obtained from the simulation and the experimental strain distribution within the adhesive layer.

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**Figure 1.** Geometry and dimensions of single-lap joint.\(^{14}\)
distribution in the adhesive layer measured from the edge of SLJ by using Digital Image Correlation (DIC). The strain distributions (normalized with respect to the maximum value) are presented in Figure 3 for comparison. As expected, there is significant discrepancy in terms of numerical values between experiment and simulation but the shape of the distribution is captured very well. The dissimilarity in numbers is anticipated due to differences in material properties and boundary conditions (edge effects in case of experimental measurements).

The experimental strain distribution was obtained from the full strain field captured by DIC (see Figure 4(b)–(c)) from the specimen edge within the overlap region (see Figure 4(a)). While the strain distribution from the numerical simulation is presented in Figure 4(d).

**Material properties**

The thermo-mechanical properties (Young’s modulus $E$, shear modulus $G$, Poisson’s ratio $\nu$, coefficient of thermal expansion $\alpha$) of materials are listed in Table 1 (the material notations are given in brackets). Figure 5 shows the stress – strain curves for non-linear aluminum and non-linear adhesive. It should be noted that no time or temperature dependence of the material properties is considered in this study, thus the material properties are assumed to be constant during cooling down and mechanical loading. Similar and dissimilar adherend materials are used to present three different types of SLJ: (1) metal-metal (M-M); (2) composite-composite (C-C) (unidirectional as well as multi-directional laminates); (3) composite-metal (C-M). Four stacking sequences are considered for composite laminates: (a) unidirectional laminate (UD: $[0/90]$ or $[90/0]$); b) quasi-isotropic laminate (QI) with the lay-up $[0/45/90/–45]$ or $[90/45/0/–45]$. The notation presented in Table 2 is used further in the text and graphs.

**Combined thermo-mechanical loading**

The current paper only addresses evaluation of residual thermal stresses due to cooling from the manufacturing to the service temperature. Other parameters affecting material properties (e.g. ambient elevated temperature) or stresses (relaxation due to time-dependence of material properties) are not considered. However, the procedure described here for simulation of thermo-mechanical loading is also applicable at elevated (or cryogenic) temperatures if dependence of material properties on temperature is known.

This investigation showed that it is not always possible simply to apply thermal and mechanical loading on the SLJ as a superposition of these loads. The procedure has to be carried out in multiple stages (mimicking the sequence of cooling down of joint after assembly and further mechanical loading). This section describes a method which allows accounting for the residual thermal stresses developed during the cool-down and combining them with mechanical stresses from tensile loading.

The first verification of correctly applied thermo-mechanical loading was done by considering composite laminate (composite plate) only and then the results obtained from ANSYS were compared with Classical Laminate Theory (CLT). In this case thermo-mechanical load was applied on composite laminate and the local stresses in layers as well as global
### Table 1. CFRP, GFRP and Aluminum adherends and adhesive mechanical properties.14

| Material Type                  | Property          | Value 1                 | Value 2                 | Value 3                   |
|--------------------------------|-------------------|-------------------------|-------------------------|---------------------------|
| CFRP unidirectional lamina (CF) | E<sub>1</sub>     | 130 GPa                 | 12 = 4.5 GPa            | 12 = 0.28                 | α<sub>1</sub> = -0.9 x 10^-6 1/K |
|                                | E<sub>2</sub>     | 8 GPa                   | 13 = 4.5 GPa            | 13 = 0.28                 | α<sub>2</sub> = 27 x 10^-6 1/K  |
|                                | E<sub>3</sub>     | 8 GPa                   |                          | v<sub>12</sub> = -0.9 x 10^-6 1/K |
| GFRP unidirectional lamina (GF)| E<sub>1</sub>     | 40 GPa                  | 12 = 4 GPa              | 12 = 0.25                 | α<sub>1</sub> = 6 x 10^-6 1/K  |
|                                | E<sub>2</sub>     | 8 GPa                   | 13 = 4 GPa              | 13 = 0.25                 | α<sub>2</sub> = 35 x 10^-6 1/K  |
|                                | E<sub>3</sub>     | 8 GPa                   |                          | v<sub>13</sub> = 27 x 10^-6 1/K |
| Aluminum _ linear (Al)         | E<sub>Al</sub>    | 70 GPa                  |                          | v<sub>Al</sub> = 0.33      | α<sub>Al</sub> = 23.1 x 10^-6 1/K |
| Aluminum _ non-linear (Al<sub>N</sub>) | E<sub>Al</sub>    | 71 GPa                  |                          | v<sub>Al</sub> = 0.33      | α<sub>Al</sub> = 23.1 x 10^-6 1/K |
| Adhesive _ linear (A)          | E<sub>ad</sub>    | 2.7 GPa                 |                          | v<sub>ad</sub> = 0.4       | α<sub>ad</sub> = 63 x 10^-6 1/K  |
| Adhesive _ non-linear (A<sub>N</sub>) | E<sub>ad</sub>    | 2.7 GPa                 |                          | v<sub>ad</sub> = 0.4       | α<sub>ad</sub> = 63 x 10^-6 1/K  |
|                                | σ<sub>ad</sub>    | 280 MPa                 | E<sub>ad</sub> = 500 MPa |                          |                           |
|                                | σ<sub>ad,T</sub> | 10.8 MPa                | E<sub>ad,T</sub> = 465 MPa |                          |                           |

Indexes: 1-fibers direction, 2-transverse to the fibers direction, 3-out-of-plane direction, 
T-tangential (see Figure 5). The material notations used further in the text are given in brackets ()

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![Figure 5](image-url)  
**Figure 5.** The stress-strain curve for (a) non-linear adhesive material (A<sub>N</sub>) and (b) non-linear Aluminum (Al<sub>N</sub>).14
response of the laminate were monitored. The results showed that even using CLT the stress in thermomechanical loading depends on the manner of its application. The two scenarios (a) simultaneous application of temperature and strain vs (b) first applying temperature and then strain will give entirely different stress distributions in layers. That is because in case (b) the mechanical load (strain) is applied to thermally shrunk configuration. However, when applying the mechanical load as stress (force) the results coincide within numerical scatter. The same dependence is found from simulation for the complete SLJ: in this case a difference was shown that even using CLT the stress in thermomechanical loading depends on the manner of its application (e.g. force vs displacement) or material type (linear elastic vs inelastic), it is more appropriate to split application of thermal and mechanical loads into separate stages. The first stage is to apply temperature on the joint which is not mechanically constrained and is completely free to expand. This stage generates thermal stresses in the components of the joint. These thermal stresses are then applied as initial stresses for the joint subjected to mechanical loading. Use of this procedure was verified on composite adherends (Footnote: the described scenarios) and then the load-displacement curve was compared with data from the literature. These obvious results were obtained only if the mechanical load is applied as a displacement, which is commonly the case for displacement controlled tensile test.

In order to account for the combination of residual thermal stresses (due to cooling after curing) and mechanical load according to real test sequence to be independent of the loading type (e.g. force vs displacement) or material type (linear elastic vs inelastic), it is more appropriate to split application of thermal and mechanical loads into separate stages. The first stage is to apply temperature on the joint which is not mechanically constrained and is completely free to expand. This stage generates thermal stresses in the components of the joint. These thermal stresses are then applied as initial stresses for the joint subjected to mechanical loading. Use of this procedure was verified on composite laminate by comparing results from ANSYS and CLT.

In case of the composite adherend, the actual procedure of application of thermal and mechanical loads also depends on the way materials have been joined together; (a) two-step assembly: first, composite is manufactured and then parts are bonded to assemble the joint (thermal history may be different); (b) one-step assembly: adhesive and composite adherend are solidified simultaneously at the same temperature. Therefore, two different scenarios for the simulation of the tensile test of SLJ at room temperature are presented: two-stage simulation for metal-metal joint (one-step manufacturing) and two- or three-stage simulation for the joint with at least one composite adherend.

**Metal-Metal joint.** This case is modeled as a two-stage: (1) application of temperature (to obtain residual thermal stresses developed due to joining at elevated temperature); (2) application of mechanical load. The temperature applied on all of the components of the joint in the first stage is equal to the difference between room temperature 25°C and manufacturing temperature of adhesive 60°C. It should be noted that applied temperature difference (ΔT) is negative (cooling from the manufacturing to the room temperature). Stresses produced during this stage are extracted from ANSYS to generate initial stress state for the joint under mechanical load by reapplying stresses to each node of the FEM model (this is done by using MATLAB code to construct ANSYS input file). Then mechanical load is applied and the second stage of the simulation is carried out.

**Composite-Composite or Composite-Metal joints.** In case of one-step joining (co-curing) the adhesive layer and the composite adherend are manufactured simultaneously. After thermal stresses are calculated they are applied as initial stresses and mechanical load is applied to complete the simulation.

For this simulation, it is assumed that temperature for manufacturing of the adhesive and composite is the same. The applied temperature is equal to the difference between manufacturing temperature of composite 175°C and room temperature 25°C, thus ΔT = −150°C. The procedure is the same for metal-metal joint, except for temperature difference ΔT = −35°C.

In case the composite laminates are manufactured prior to the bonding and then adhesive joint is assembled, three-stage simulation is performed. Two
Simulations are carried out to calculate initial stress state in the joint prior to the application of mechanical load. First calculation (due to cooling of composite adherend) generates thermal stresses in layers of the laminate and the second calculation (due to cooling of adhesive) gives the total residual thermal stresses in the adhesive and adherends. The final result is obtained in the third stage when only mechanical load is applied.

The sequence of application of thermal and mechanical loads is shown in the form of flowchart in Figure 6. The notations 1S and 2S are used for one-step and two-step manufacturing, respectively.

**Results and discussion**

The analysis here is focused on peel and shear stresses in the adhesive layer of the SLJ with the future goal to analyze the adhesive failure using different strength based criteria. The stress distributions presented in the graphs are along the overlap length from \(X = -L_o/2t_a\) to \(X = L_i/2t_a\) in the middle of the adhesive layer \((Y = 0)\) at the centerline of the joint \((Z = 0)\). It should be mentioned that when the stress distribution has symmetry with respect to \(X = 0\) only half of the distribution is presented. Calculations are done by using two types of mechanical load (applied at \(X = L_i/2t_a\)): (1) applied displacement corresponding to average strain \(\epsilon_{x} = 0.1\%\) in case of comparing different methods for applying thermal load (in sections “Different schemes to apply thermal load” and “Effect of material non-linearity”); (2) stress \(\sigma_x = 60\,\text{MPa}\) applied for all other simulations. In this section additionally to peel (\(\tau_y\)) and shear stresses (\(\tau_{xy}\)) other stress components (\(\sigma_x\) and \(\sigma_z\)) are also presented for comparison.

**Effect of material model (linear vs non-linear) and method of application of thermal load**

This section describes the effect of residual thermal stresses developed during the cooling process after curing the composite or the adhesive or both of them on stress distribution within the adhesive layer of SLJ. Cases with linear and non-linear material models (for adhesive and adherends (e.g. aluminum)) are presented. Simulations are performed according to the three schemes described in section “Combined thermo-mechanical loading” (1) T&M, thermal and mechanical loads are applied simultaneously; (2) T+M, thermal and mechanical loads are applied separately and the total stress is obtained as superposition of results from these two calculations (similar approach in other studies\(^{12,13}\)); (3) T/M, two-stage simulation with results from the thermal load used as initial conditions for the stage where mechanical load is applied. In order to demonstrate the difference between these three schemes.
in case of a displacement controlled tensile test, the simulations are done by application of strain $\varepsilon_x = 0.1\%$
as a mechanical load.

Different schemes to apply thermal load. This section describes the difference between T&M (simultaneous) and T+M (separate, superposition) application of thermal and mechanical loads. Linear adherend and adhesive materials are used within SLJ with similar adherends. The differences between stress distributions obtained from T&M and T+M simulation methods for [Al/A/Al] and [CF1/A/CF1] are shown in Figures 7 and 8, respectively.

In case of [Al/A/Al] joint (Figure 7) the differences of stress distributions in the adhesive layer are much more significant than in case of a joint with composite adherends (Figure 8). That is expected because the CF joint has almost zero macroscopic thermal shrinkage and therefore there is no noticeable difference in stresses distribution dependent on the way how to apply the mechanical load (before or after the cool-down). The same agreement is obtained for [GF1/A/GF1] as for [Al/A/Al] with a little bit higher difference in case of [GF1/A/GF1] but stress distributions for this material are not presented here due to limited space. If one looks at global response of the joint, rather than local stress distributions the difference between T&M and T+M cases is also obvious. For example, global force acting on joint calculated at the free end of the joint (at $X = L_t/2$) in case of T&M for [Al/A/Al] is 252.8 N and 112.1 N for [CF1/A/CF1], in case of T+M these values are 134.6 N and 95.3 N for [Al/A/Al] and [CF1/A/CF1] respectively (difference of ~50% for Al and ~15% for composite). Moreover, when stresses are analyzed inside the composite laminate on the ply level T&M method may produce false results: the simulation show that application of thermal load and mechanical strain simultaneously T&M produces incorrect results for local stress distributions in the laminate, adhesive as well as for global response of the joint if mechanical load is applied as displacement. This is because the T&M scheme represents the plate cooling down within displacement constrained conditions and this is not
representative for the real case scenario: in reality the plate is freely cool-down first and after that the mechanical load is applied (as a strain).

**Effect of material nonlinearity.** The comparison between T+M (superposition) and T/M (thermal stresses as initial conditions) is shown in Figures 9 and 10 for aluminum-aluminum SLJ with linear and non-linear material model for adherends and adhesive materials. There is a very small difference between stresses obtained from either of the methods (which is likely due to the numerical error) in case of linear material model is considered (see Figure 9).

However, if non-linear material model is used the difference between $\sigma_x$ and $\sigma_z$ stresses is evident as can be seen in Figure 10, although peel and shear stresses do not differ. The difference between $\sigma_x$ and $\sigma_z$ is very significant and cannot be attributed to the accuracy of simulation (numerical error). Moreover, with increase of thermal load or/and mechanical load this difference will grow because the thermal and mechanical stresses together (when applied simultaneously or in sequence) will shift even more material behavior toward non-linear region. However, if the thermal and mechanical loads are applied in two unrelated calculations and then stresses are superimposed, it may happen that the material is still in the linear region under each of the loads separately, thus the final result will be incorrect. Therefore, in the case of non-linear material the in-plane stresses obtained from T/M scheme are always lower than results from the T+M simulation. In order to demonstrate this effect more clearly the simulation is done by applying $e_x = 0.16\%$ (equivalent to $\sigma_x = 110MPa$) as presented in previous work\textsuperscript{14} when only mechanical load is applied.

The comparison between the stress distributions of three cases (only mechanical load vs T+M vs T/M) is presented in Figure 11. The results in Figure 11 show that transition from linear to non-linear behavior occurs at the same location in case of application of mechanical load only or superposition of thermal and mechanical stresses. However, when T/M approach is used (thermal stresses applied as initial
conditions) there is obvious difference – the transition point is shifted to the left (similarly to that observed for the increase of the mechanical load) and it means that the material behavior becomes more non-linear. This supports the statement that simple superposition of stresses in the non-linear region produces results which lack accuracy and the real transition point between the linear and non-linear regions in shear stress distribution cannot be detected. Thus, for more accurate stress calculations and future failure analysis of the joint (as well as for failure of the composite adherend) the T/M method has to be used. According to the previous investigations, the model presented here can handle any type of material at different conditions. To ensure higher accuracy of results the T/M method is used in the remaining parts of this paper.

**Effect of residual thermal stresses on the total stress distribution in a joint with linear material model**

In this section, only linear material model is considered in order to prevent the interaction between non-linear behavior (transition from linear to non-linear behavior within adhesive material) with other effects (e.g. one or two-step assembly, stacking sequence of the composite laminate, etc.).

**Influence of residual thermal stresses on the total stress distribution.** In case of C-C and M-M joints two components of the residual thermal stresses inside the adhesive are rather high: in-plane normal stress components $\sigma_x$ and $\sigma_z$. These stresses will shift the rather low mechanical stresses (for this particular load case) to much higher level, as shown in Figure 12 for SLJ with linear adherends (Al) and linear adhesive.

Although the overall level of $\sigma_x$ and $\sigma_z$ in adhesive is increased by the residual thermal stresses, the peel stress concentration at the ends of the overlap joint as well as level of shear stress within the plateau region, presented in Figure 13, are reduced, which is in agreement with other results. In case of [Al/A/Al] joint this effect is clear in peel stress but it is almost negligible in shear stress (see Figure 13) while for C-C joints in Figure 14 this change is fairly noticeable for peel and shear stress.
shear stresses. As shown in Figure 14 for [CF₁/A₁/CF₁], the concentration of peel stress at the ends of the overlap and shear stress level within the plateau region are reduced by ~2.4 and ~5 times, respectively (similar trend is also obtained for [GF₁/A/GF₁]). This may work favorable with respect to the delayed initiation of local damage and suppress (or at least significantly delay) premature failure of the joint. In order to verify this feature more numerical simulations as well as experimental evidence are required.

Figure 10. The comparison of different stress components in the adhesive layer of [Alₙ/Aₙ/Alₙ] SLJ T+M and T/M simulation methods, t₀ = 0.2mm, tᵢ/tₑ = 10 and Lᵦ/tₑ = 200, 0.1% strain and ΔT = −35°C are applied.

Figure 11. The comparison of different stress components in the adhesive layer of [Alₙ/Aₙ/Alₙ] SLJ for only mechanical load, T+M and T/M simulation methods, t₀ = 0.2mm, tᵢ/tₑ = 10 and Lᵦ/tₑ = 200, 0.16% strain and ΔT = −35°C are applied.
**Influence of processing, one-step versus two-step.** This section discusses the results of the simulations performed for similar (CF$_1$ and GF$_1$ adherends) and dissimilar (Al-C joint with one of the adherends being CF$_1$) joint. The results show that one-step assembly may be more favorable than the two-step joining: the reduction of...

**Figure 12.** The influence of residual thermal stresses developed after the curing on (a) $\sigma_x$ and (b) $\sigma_z$ stress distributions in the adhesive layer of [Al/Al/Al] SLJ, 60 MPa and $\Delta T = -35^\circ$C are applied.

**Figure 13.** The comparison of peel (a) and shear (b) stress distributions in the adhesive layer of [Al/Al/Al] SLJ with and without residual thermal stresses accounted for, 60 MPa and $\Delta T = -35^\circ$C are applied.

**Figure 14.** The comparison of peel (a) and shear (b) stress distributions in adhesive layer for [CF$_1$/A/CF$_1$] SLJ with and without residual thermal stresses accounted for, 60 MPa and $\Delta T = -35^\circ$C are applied (with initial conditions on composite $\Delta T = -115^\circ$C).
the peel stress concentration at the ends of the overlap and the stress level of shear within the plateau region is more significant in joints assembled by one-step method rather than by the two-step procedure. This positive effect in the one-step procedure is likely a result of the curing temperature in one-step being 175°C, whereas the adhesive curing in the second step of the two-step procedure is at 60°C. This means that increasing the curing temperature results in lower peel and shear stress. This is shown in Figure 15 for C-C joints with similar materials (CF1 and GF1 composite adherends). For dissimilar joints the peel stress in one-step case is reduced at X = L_o/2ta (next to aluminum corner) and shifted from tensile to compressive stress at X = L_o/2ta (next to composite corner; see Figure 16(a)). However, the shear stress in joint with dissimilar materials in one-step case will be significantly increased at X = L_o/2ta and swapped from positive to negative values for shear stress at X = L_o/2ta, as shown in Figure 16(b).

Figure 15. The comparison of peel and shear stress distributions in adhesive for SLJ with [CF1/A/CF1] (a, b) and [GF1/A/GF1] (c, d) fiber composite adherends for different manufacturing methods of joints (one-step vs two-step method), with and without residual thermal stresses accounted for, 60 MPa and ΔT = −150°C for one-step curing and ΔT = −35°C (with initial conditions on composite ΔT = −115°C) for two-step curing are applied.

Effect of stacking sequence of the composite laminate. In this section SLJs assembled in one-step with similar materials in adherends are considered. The comparison is made between behavior of UD and QI laminates, as well as between QI laminates with different stacking sequence (fiber orientation in plies adjacent to the adhesive layer is varied: (a) [0/45/90/−45]S; (b) [90/45/0/−45]S).

The highest peel and shear stress concentration with longer plateau region (lower stress perturbation zone) are observed for the [90\Sb] composite. The lowest peel stress concentration is obtained for the QI with the layup [90\Sb/45/0/−45\Sb] (see Figure 17). In the case of the QI laminate, more favorable stress distribution (with lower stress concentration) is obtained when 90-layer is next to the adhesive layer rather than when stiff 0-layer is placed next to the bond line. Swapping 0-layer with 90-layer in the QI laminate results in reduced peel stress concentration at the end of the overlap to ~30% (see Figure 17).
as well as longer plateau region for shear stress is obtained. The thermal effect is apparent when maximum stresses caused by mechanical load\textsuperscript{14} are compared with the result of combination of thermal and mechanical loading (see Figure 17 and Table 3). As follows from this comparison, for CF the stress concentration at the end of the overlap is reduced by 40% to 65% (except for CF2 reduction by \textasciitilde 90%), while for GF the reduction of the stress concentration is by 35% to 50% (except for GF2 reduction by \textasciitilde 70%). Thus results for the thermo-mechanical loading show that drastically lower peel stress concentration for QI can be achieved simply by swapping 0 and 90 plies within the laminate (this will not change the in-plane stiffness of the laminate, although the bending stiffness will be affected).

Adherend stiffness effect on thermal stresses. In this section the effect of the adherend stiffness on stress distribution in the adhesive with applied thermal load only is demonstrated. In order to evaluate this effect, all the parameters of the joint are fixed and only the stiffness of the adherends is varied. M-M joint (isotropic material) is analyzed with the stiffness values of $E = 140, 70$ and $35$ GPa ($\nu = 0.33$ and shear modulus is calculated).

The results of applying thermal load ($\Delta T = -35^\circ C$) are presented in Figure 18. These data show that four times increase of the adherend stiffness results in the decrease of the peel stress at the ends of the overlap by \textasciitilde 10%. Similar trend is observed for the shear stresses but with much higher magnitude (comparison is done for relative, not absolute values). Increase of the stiffness of the adherends four times, results in \textasciitilde 2.5 times decrease of the shear stress at the ends of the overlap. It can be noted from Figure 18 that stresses are rather small, especially the shear stress component. However, the stress values will increase with increase of curing temperature, furthermore these values also depend on the mismatch between thermal expansion coefficients of the joint members. Since the external force is equal

### Table 3. Comparison between the stress concentrations at the end of the overlap for different stacking sequence

| Stacking sequence | GF       | CF       |
|-------------------|----------|----------|
|                   | Peel stress (MPa) | Shear stress (MPa) | Peel stress (MPa) | Shear stress (MPa) |
|                   | Only mech.\textsuperscript{14} & Therm. and mech. | Only mech.\textsuperscript{14} & Therm. and mech. | Only mech.\textsuperscript{14} & Therm. and mech. | Only mech.\textsuperscript{14} & Therm. and mech. |
| $[0/45/90/-45]_s$ | 27.5 & 16.3 | 23.3 & 21.3 | 21.7 & 9.2 | 17.2 & 15.2 |
| $[90/45/0/-45]_s$ | 30.1 & 9.7 | 21.2 & 23.6 | 26.8 & 3.3 | 16.3 & 19.8 |
| $[0_4]_T$         | 26.1 & 13.0 | 18.5 & 17.6 | 20.1 & 7.1 | 13.1 & 11.7 |
| $[90_4]_T$        | 33.3 & 21.9 | 29.5 & 29.1 | 33.5 & 20.1 | 30.2 & 29.7 |

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to zero, the resulting shear stress should be also zero but locally there is very small shear stress concentration at the ends of the overlap.

Summary of the effect of material properties on thermomechanical stress distributions. Finally, the analysis showing the effect of thermal stresses on the total stress

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**Figure 17.** The comparison of the stress distributions in the adhesive layer of C-C SLJ with different stacking sequence of plies in adherends, 60 MPa and \( \Delta T = -150^\circ C \) are applied.

**Figure 18.** The effect of stiffness variation on distributions of peel (a) and shear (b) stress in adhesive for M-M SLJ with linear material model with only thermal load applied \( \Delta T = -35^\circ C \).
distribution within the adhesive layer is done by comparing the result from previous work\textsuperscript{14} with T/M calculations obtained in this paper, see Figure 19. The results show that the maximum value of the peel stress is reduced with the increase of the bending stiffness of the adherend. But the maximum value of the shear stress is reduced with increase of the axial modulus ($E_x$) of the adherend. These trends can be described by power function and it is valid for the behavior of GF and CF composites. The T/M results follow the same trend when only mechanical load is present\textsuperscript{14} but the level of peel stress is significantly lower.

**Conclusions**

A comprehensive methodology to account for residual thermal stresses developed during the cool-down after curing process of adhesive/composite was worked out by comparing different sequences of application of thermal and mechanical loads. The most common approach used in many publications of simple superposition of thermal and mechanical stresses works well only for linear materials. This approach produces inaccurate results if material is non-linear, since uncoupled thermal and mechanical loads when applied separately may not be high enough to bring material into non-linear region. The model and simulation technique presented in the current paper rectifies this issue and accurate stress distributions are obtained. Analysis of stress distributions in different single-lap joints has led to the following conclusions concerning the stress state in the adhesive layer:

- As expected, high processing temperature causes high in-plane normal stresses inside the adhesive layer for composite-composite as well as for metal-metal joints.
- The residual thermal stresses will reduce the peel stress concentration at the ends of the overlap and the shear stress within the plateau region.
- The one-step assembly (the adhesive and the composite are manufactured simultaneously) for composite-composite joint and composite-metal joint will reduce the peel stress concentration at the ends of overlap more than in two-step joining (the composite is manufactured first and the adhesive is cured when the joint is assembled). The level of the shear stress within the plateau region will be also lower for the one-step curing than for the two-step process.
- In case of a joint with quasi-isotropic composite adherends (CFRP and GFRP) more favorable stress distribution is obtained when the 90-layer rather than the 0-layer is the closest to the adhesive layer. Swapping the 0-layer with the 90-layer will reduce the peel stress at the ends of the overlap by approximately 60% to 70%.

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References
1. Khashaba UA, Sallam HEM, Al-Shorbagy AE, et al. Effect of washer size and tightening torque on the performance of bolted joints in composite structures. Compos Struct 2006; 73: 310–317.
2. Kweon J-H, Jung J-W, Kim T-H, et al. Failure of carbon composite-to-aluminum joints with combined mechanical fastening and adhesive bonding. Compos Struct 2006; 75: 192–198.
3. Zhang K, Yang Z and Li Y. A method for predicting the curing residual stress for CFRP/Al adhesive single-lap joints. Int J Adhes Adhes 2013; 46: 7–13.
4. Puchala K, Szymbczyk E and Jachimowicz J. About mechanical joints design in metal-composite structure. J KONES 2012; 19: 381–390.
5. Wahab MMA. Fatigue in adhesively bonded joints: a review. ISRN Mater Sci 2012; 3.
6. Kim K-S, Yi Y-M, Cho G-R, et al. Failure prediction and strength improvement of uni-directional composite single lap bonded joints. Compos Struct 2008; 82: 513–520.
7. Pramanik A, Basak AK, Dong Y, et al. Joining of carbon fibre reinforced polymer (CFRP) composites and aluminium alloys—a review. Compos Part A Appl Sci Manuf 2017; 101: 1–29.
8. Hahn HT. Residual stresses in polymer matrix composite laminates. J Compos Mater 1976; 10: 266–278.
9. Jumbo FS, Ashcroft IA, Crocombe AD, et al. Thermal residual stress analysis of epoxy bi-material laminates and bonded joints. Int J Adhes Adhes 2010; 30: 523–538.
10. Aydin MD, Temiz Ş and Özel A. Effect of curing pressure on the strength of adhesively bonded joints. J Adhes 2007; 83: 553–571.
11. Shin KC, Lee JJ and Lee DG. A study on the lap shear strength of a co-cured single lap joint. J Adhes Technol 2000; 14: 123–139.
12. Shin KC and Lee JJ. Prediction of the tensile load-bearing capacity of a co-cured single lap joint considering residual thermal stresses. J Adhes Technol 2000; 14: 1691–1704.
13. Shin KC and Lee JJ. Effects of thermal residual stresses on failure of co-cured lap joints with steel and carbon fiber–epoxy composite adherends under static and fatigue tensile loads. Compos Part A Appl Sci Manuf 2006; 37: 476–487.
14. Al-Ramahi NJ, Joffe R and Varna J. Investigation of end and edge effects on results of numerical simulation of single lap adhesive joint with non-linear materials. Int J Adhes Adhes 2018; 87: 1–222.
15. ANSYS 16–Structural Analysis Guide, https://ansyshelp.ansys.com (2014–2015).
16. Apalak MK and Gunes R. On non-linear thermal stresses in an adhesively bonded single lap joint. Comput Struct 2002; 80: 85–98.
17. Wahab MA. The mechanics of adhesives in composite and metal joints: finite element analysis with ANSYS. Lancaster: DEStech Publications, Inc, 2014.