DEVELOPMENT OF A COMPUTATIONAL TOOL FOR BONDED JOINT ANALYSIS

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Abstract. The use of bonded joints is one of the most efficient ways of transmitting loads between the parts of a structure. Showing some different advantages when compared to fastener joints, it also allows the bonding of dissimilar materials, as metals and composites. For structural design these joints, it is necessary to know the forces, moments, displacements and stress acting in the joint after load application. In order to help the design process of bonded joints, a computer program which is capable to evaluate single and double lap bonded joint is proposed. The set of differential equations for each part (adherents and adhesive) of the problem geometry are obtained from the constitutive and equilibrium equations. To solve the set of equations of this boundary value problem, a computational tool in Matlab program is used. Two commercial programs are used to validate the program por computational tool implemented. One is the finite element program ABAQUS, and the other one is ESAComp. The comparison between these programs showed a good curve fit for joint displacement field and adhesive stresses for composite joints, as well as for hybrid joints (metal-composite).

Keywords: bonded joints, hybrid joints, composite materials, boundary value problem, analytical methods

1. INTRODUCTION

In the last years, the use of composite materials as a primary structural element have been increased. Some new aircraft design, for example: Airbus A380 and Boeing 787 use composite materials even in primary structural elements such as wing spars and fuselage skins, achieving lighter structures without loss of airworthiness. One way to assembly, these structures consists on using bonded joints which shows some advantages like a better fatigue endurance, joining dissimilar materials, better insulation, smooth surface and lighter weight. Nevertheless, there is no possibility to disassembly the joints, peeling stress should be minimized and the preparation of the surfaces that will be bonded must be done carefully (Mortensen, 1998).

Many researches have been carried out about bonded joints, trying to predict the behavior, failure, and the strength of bonded joints using finite element models, analytical models or experimental tests. Thomsen (1992) showed that an increase in the overlap lenght reduces the stress in the adhesive layer and application of adhesive layer with lower elastic shear and tensile moduli decreases the adhesive stress that is better use identical or nearly identical adherents in bonded joints. Mortensen (1998), in his PhD thesis, presented a development of a computational tool for analysis of bonded joints showing the equations and hypothesis for various type of bonded joints, as well as, the solving process of differential equations using the multi-segment method of integration. Ganesh and Choo (2002) showed the effect of spatial grading of adherent elastic modulus on the peak stress and stress distribution in the single lap joint, which lead to decreasing in the stress peak and a more uniform shear stress distribution.

Belhouari, Bouiadjra, and Kaddouri (2004) showed a comparison between single and double lap joint using a finite element model. In that study, the researchers showed the advantages of using symmetric composite patch for repairing crack, also, that double patch has lower stress when compared with single patch repair. Myeong et. al. (2008) showed that an increase of bonding pressure leads to higher strength bonded joints, an increase in the overlap lenght also leads to higher strength bonded joints and the major failure mode for single lap hybrid composite/aluminum joints is the delamination of the composite adherent. Agnieszka (2009) showed a numerical method, regarding the sensitivity for hydrostatic stress, for prediction of the delamination initiation, which allows to simulate the failure of the joint (overlap region) and composite adherent.

In order to help the design process of bonded joints, it was developed a software called SAJ (System of Analysis for joints), which is capable of analyze a bonded joint behavior in detail, not only for single lap joint, but also, for double lap joint. These joints could be made of composite/composite materials or dissimilar materials i.e. hybrid joints (metal/composite). The software developed can calculate the joints stresses, loads and displacements. Two commercial software were used to perform SAJ validation, a finite element software, ABAQUS, and specific composite analysis software, ESAComp.
2. COMPUTATIONAL TOOL

In order to help the assessment of bonded joints was developed a computational tool that are able to calculate the joint loads, displacements, stress and adhesive/adherents stresses. Only linear elastic results are showed in this paper.

A computational tool was developed to help the analysis of single and double lap bonded joints. This software was programmed in Matlab™ language. In the case of composite adherents, this software is also capable to obtain the stress and strain for each layer. SAJ is also capable to solve composite/composite and metal/composite bonded joints.

SAJ reads an input file within data of adherents, adhesive and joint characteristics. These file contains information such as lay up and layer thickness in case of composite adherents, mechanical properties for adherents and adhesives, joint dimensions of adhesive and adherents, as well as, loads and boundary conditions. For results, SAJ shows the graphics of forces, displacements and adhesive stresses, also these results are given in tabular form.

2.1 Mathematical formulation

SAJ solves a set of differential equations of the multi-domain boundary value problem using Matlab™. In order to obtain the set of differential equations, first a subdivision of the joint in three regions were made, one part with only adherents, other part with the bonded region and the last part again only with adherents. These subdivisions are showed for single lap joint in Fig. 1(a) and for double lap joint in Fig. 1(b). In these figures are also showed the boundary conditions, loads and coordinate system.

For each region, using the equilibrium equations of an infinitesimal element are obtained the set of differential equations as showed in Fig. 2 for single and double lap joint. With Classical Laminate Theory, and assuming the hypothesis that all derivatives in $y$ direction are equal zero, plane stress state, Kirchhoff’s kinematic relations and the equilibrium equations leads to the complete set of differential equations.

For the regions with only adherents (subdivisions 1 and 3 of Fig. 1(a) and (b)), the set of differential equations are showed in Fig. 3(a). Figure 3(b) shows the equations for adherent 1 (subdivision 2 of Fig. 1(b)) for a double lap case inside the overlap region, and Fig. 3(c) shows the equations for adherents 1 and 2 for single lap case and for adherents 2 and 3 for double lap case inside the overlap region (subdivision 2 of Fig. 1(a) and (b)).

Where $t_i$ is the thickness of the $i$ adherent; $t_a$ is the adhesive thickness; $\kappa_x$ is the rotation of the $x$ axis; $u_0$ is the midplane displacement in $u$ direction; $v_0$ is the midplane displacement in $v$ direction.

The adhesive is simulated as tension/compression and shear springs (Mortensen, 1998), Eq. (1) to Eq. (3) shows the equations for the adhesive model.

$$\tau_{ax} = \frac{G_a}{t_a} (u_i^x - \frac{t_i(x)}{2} \kappa_x - u_j^x - \frac{t_j(x)}{2} \kappa_x)$$

$$\tau_{ay} = \frac{G_a}{t_a} (\nu_i^y - \nu_j^y)$$

$$\sigma_{ax} = \frac{E_a}{t_a} (w_i^x - w_j^x)$$

These differential equations system for each subdivision are solved using Matlab™, which can deal with multi-domain boundary values problem.
Figure 2. Free body equilibrium forces for each subdivision part.

\[ \begin{align*}
\delta a_{ix} &= a_{ij} N_{ij} - a_{ij} N_{ij} - b_{j1} M_{ij} = 0 \\
w_{ix} + k_1 = 0 \\
K_{ix} = b_{i1} N_{ij} - b_{i1} N_{ij} - a_{ij} d_{ij} M_{ij} = 0 \\
v_{ix} - a_{ij} d_{ij} N_{ij} - a_{ij} d_{ij} N_{ij} - b_{j2} M_{ij} = 0 \\
N_{ij} = 0 \\
N_{ij} = 0 \\
M_{ij} = 0 \\
Q_{ix} = 0 \\
Q_{ix} = 0
\end{align*} \]

Figure 3. (a) Set of differential equations for bonded joint out of overlap zone for i=1,2,3; (b) Set of differential equations for double lap joint adherent 1; (c) Set of differential equations for adherents in the overlap joint. For single lap, i=1,2 and for double lap, i=2,3.
2.2 Computational Implementation

The analysis starts reading input data from a file that prescribe the joint type (single or double), adherents and adhesives mechanical properties, ply thickness and orientation (in case of composite materials), adhesive thickness and the dimensions, as well as, loads and boundary conditions. With all necessary data, first SAJ, using the classical laminate theory, perform the calculus of the stiffness and the compliance matrix.

After calculus of compliance matrix and knowing the joint type and the boundary conditions, the next step consists on to, solve the boundary value problem using bvp4c Matlab function. Figure 4 presents the SAJ block diagram.

![SAJ block diagram](image)

Figure 4. SAJ block diagram.

2.3 Finite element model

A finite element model for single and double lap joint using a commercial software ABAQUS™ were simulated to compare to the SAJ computational results. The finite element model use a second order element with 20 nodes (C3D20) for adherents and adhesives even for single and double lap joint C3D20 is used also for modeling composite adherents. Figure 5(a) shows the finite element model for single lap bonded joint and Fig. 5(b) shows the finite element model for double lap bonded joint. Notice that these models are simulating the boundaries conditions and loads for each joint as showed in Fig. 1(a) for single lap and Fig. 1(b) for double lap joint.

![Finite element models](image)

(a) Single lap joint
(b) Double lap joint

Figure 5. (a)Single lap joint finite element model, (b) Double lap joint finite element model.

ABAQUS™ constraint function "tie" is used to join the adhesive and adherents in the overlap region. The constraint function tie transfer all degrees of freedom between adherents and adhesive.

2.4 Results

For a first case study a composite/composite joints, using symmetric laminate, were used and the adherents and adhesives mechanical properties, as well as, the characteristics given in Tab.1 (Hexcel T3T-190-F155). The boundary conditions in Fig. 1(a) for single lap joint and Fig. 1(b) for double lap joint. The adherents were carbon fiber reinforced plastics and the adhesive was epoxy (Tab.1). A normal load of 0.015kN/mm were used for single and double lap joint to proceed with this comparison. It is important to notice that this load is small enough do not cause any plasticity even in adherents or in adhesive.

Table 1. Hexcel T3T-190-F155 carbon fiber reinforced plastic, Hysol EA 9321 epoxy adhesive and aluminum 2024-T3 mechanical properties and characteristics.

<table>
<thead>
<tr>
<th></th>
<th>(E_1[kN/mm^2])</th>
<th>(E_2[kN/mm^2])</th>
<th>(G_{12}[kN/mm^2])</th>
<th>(\nu)</th>
<th>Thickness[mm]</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexcel T3T-190-F155</td>
<td>126.0</td>
<td>71.0</td>
<td>4.0</td>
<td>0.30</td>
<td>0.8(0.2mm per ply)</td>
<td>([0/45]_s)</td>
</tr>
<tr>
<td>Epoxy adhesive</td>
<td>1.485</td>
<td>-</td>
<td>-</td>
<td>0.35</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>2024-T3</td>
<td>72.0</td>
<td>-</td>
<td>-</td>
<td>0.33</td>
<td>0.8</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 6. (a) Single lap joint displacement in w direction; (b) Double lap joint displacement in w direction; (c) Single lap joint $\sigma_x$ ans $\tau_{zx}$; (d) Double lap joint $\sigma_x$ and $\tau_{zx}$.

The results in Fig. 6(a) shows the displacement field for single lap joint and in Fig. 6(b) shows the displacement field for double lap joint. Figure 6(c) shows $\sigma_x$ and $\tau_{zx}$ for single lap bonded joint, Fig. 6(d) shows $\sigma_x$ and $\tau_{zx}$ for double lap joint.

Figure 7. (a) Single lap hybrid joint displacement in w direction; (b) Double lap hybrid joint displacement in w direction; (c) Single lap joint $\sigma_x$ and $\tau_{zx}$; (d) Double lap joint $\sigma_x$ and $\tau_{zx}$.
For a second case study, a double and a single lap hybrid bonded joint (metal-composite) was investigated. Aluminum was used for adherent 1 and laminate for adherent 2 (see Fig. 1(a)) for single lap, and for double lap hybrid bonded joint, aluminum was used for adherent 1 and laminate for adherents 2 and 3 (see Fig. 1(b)). The materials properties were showed in Tab. 1.

The results in Fig. 7(a) shows the displacement field for single lap hybrid joint, in this figure ESAComp\textsuperscript{TM} model shows to be more flexible in the composite side and more stiff in the aluminum side, SAJ presents results between ESAComp\textsuperscript{TM} and FEM model, these differences happens due to differences in computational method applied to solve the problem, as well as, little differences between load and boundary conditions applications. Figure 7(b) shows the displacement field for double lap hybrid joint, also some difference, mostly between ESAComp\textsuperscript{TM} and other models occurs, although these differences, when compared with joint dimensions are small. Figure 7(c) shows $\sigma_z$ and $\tau_{zx}$ for single lap hybrid bonded joint, Fig. 7(d) shows $\sigma_z$ and $\tau_{zx}$ for double lap hybrid bonded joint.

Due to $\sigma_z$ and $\tau_{zx}$ possess a more significant role in the failure analysis, the results for $\tau_{zy}$ were suppressed. Other important parameter, results for displacement, are also shown in this work, more details about SAJ validation in Ribeiro (2009) and Tita, Angelico and Ribeiro (2008).

3. CONCLUSIONS

The proposed program, SAJ, had showed to be adequate to perform composite/composite and metal/composite bonded joint analysis for single and double lap joint types.

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5. REFERENCES


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