ANALYSIS OF ADHESIVE BONDED JOINTS

André de Jesus
Instituto Tecnológico de Aeronáutica - ITA
Divisão de Engenharia Mecânica Aeronáutica - IEM

Sergio Frascino Müller de Almeida
Instituto Tecnológico de Aeronáutica - ITA
Divisão de Engenharia Mecânica Aeronáutica - IEM

Abstract. *This paper presents an approach for the analysis of adhesive bonded joints using the commercial finite element package MSC.Nastran. The adherends are modeled as CQUAD4 plate elements and they are considered as generally orthotropic laminates. Consequently asymmetric and unbalanced composite laminates can be included in the analysis as adherends. The adhesive layer is modeled with CHEXA8 solid elements by two ways. The first approach assumes the adhesive layer to be modeled as linear elastic material and the second one takes into account the typical elastic-plastic behavior of many adhesives. Constraints equations (MPC) are used to link the adherends to the adhesive. The results obtained using this approach are displacement field along the joint, peeling and shear stresses in adhesive layer.*

Keywords*. Adhesive bonded joint, MSC.Nastran, laminates, coupling effects, stacking sequence, non-linear.*

1. Introduction

The use of bonded, riveted and bolted joints to assemble components or structural parts is unavoidable in aeronautic industries. With the recent development of new materials and new manufacturing techniques, bonded joints have been increasingly used due to some distinct advantages over traditional riveted and bolted ones, namely: more efficient load transfer, better sealing, better finishing and, most important for aeronautical applications, less weight.

The design of bonded joints is based upon analyses to estimate peeling and shear stresses and the displacement field along the bonded region. Several authors such as Goland (1944), Hart Smith (1973a and 1973b) and Chihdar (1992 and 1993) have investigated the most common types of adhesive bonded joint using different types of approaches. Parametric studies on the performances of these joints have been conducted. However, in the analyses, the adherends have been modeled as isotropic plates or symmetric laminates. The objective of this work is to present a finite element technique to model bonded joints applicable to a general configuration, using this technique to investigate the influence of coupling effects induced by asymmetric and unbalanced laminated adherends, stacking sequence of the plies and non linear effects due an elastic-plastic adhesive material. These studies will be performed for the adhesive bonded single lap joint configuration, since these effects experienced for the other bonded joint are less pronounced for advanced joints types such as double lap joint and scarfed lap joints.

2. Description of finite element model

The single lap joint configuration, composed of two similar or dissimilar generally orthotropic laminates subject to general loading condition, is shown in Fig. (1). The adherends thicknesses are t_1 and t_2 and the thickness of the adhesive layer is t_a.

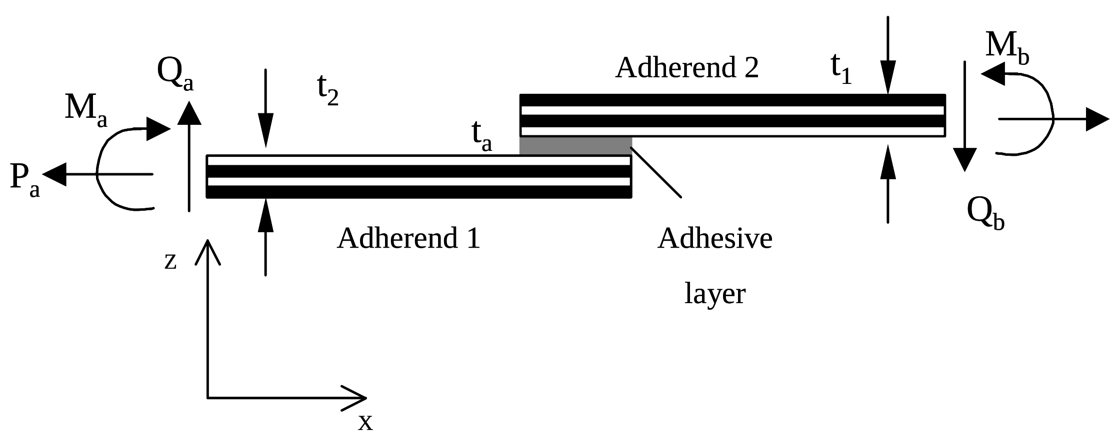

Figure 1. Schematic illustration of adhesive single lap joint subjected to general loading conditions.

The assumptions adopted for the structural modeling are the following:

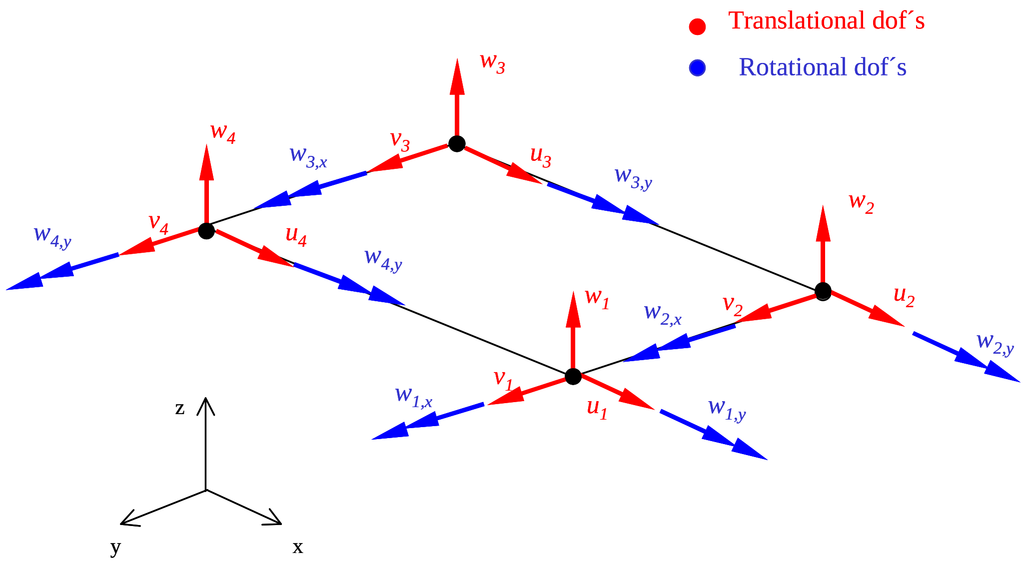

Figure 2. CQUAD4 plate element with corresponding degrees of freedom.

1-The adherends are generally orthotropic laminate modeled with CQUAD4/PCOMP plate elements, (John, 1994). This element has four nodes, each one with five degrees of freedom, three related to translation and two related to rotation as shown in Fig. (2).

2- The laminates (adherends) are assumed to be linear elastic.

3- The strains and rotations are small.

4- Generally orthotropic laminates can be included in the analysis using classical laminate theory (e.g. asymmetric and unbalanced composite can be included in the analysis).

5- The adhesive layer is modeled with CHEXA8/PSOLID solid elements, (John, 1994). This element has eight nodes, each one has three degrees of freedom, all related to translations as shown in Fig. (3).

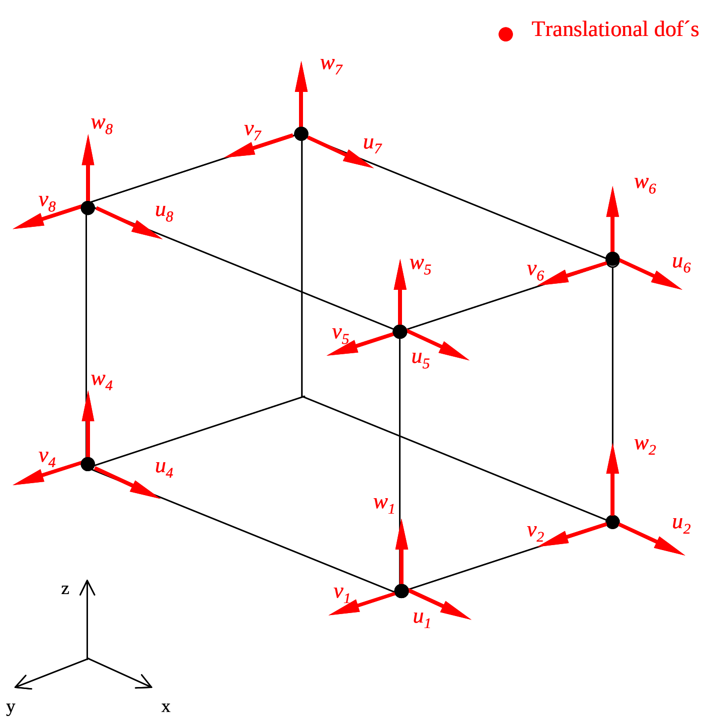

Figure 3. CHEXA8 solid element with corresponding degrees of freedom.

6- Inclusion of non-linear adhesive properties, by using elastic perfectly plastic constitutive model with von Mises yielding function. This is done using the MAT1 (MSC.Nastran isotropic material definition) with MATS1 (non-linear material properties).

7- Load and boundary condition can be chosen arbitrarily.

8- MPC (multi-point constraint) equations are used to link adherends to the adhesive layer. The adherends nodes are defined as MASTER nodes and adhesive nodes as SLAVE nodes, the Fig. (4) shows adherend element linked with adhesive elements, the link is done by using only translational degrees of freedom, because MSC.Nastran solid elements do not have rotational degrees of freedom.

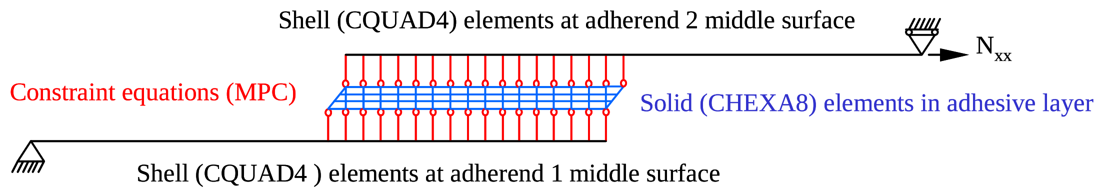

Figure 4. Single lap joint FEM.

The results investigated using this approach are shear and peeling stresses in adhesive layer as shown in Fig. (5) and displacement field along the joint. Due to the eccentricity of load path in single lap joints, high peeling stresses appear at the end of the bonded surface and theses stresses may cause catastrophic failure. Generally, when the adherends are laminated plates, the interlaminar tension strength is so much less than the peel strength of good structural adhesive, that the failure occurs within the laminate at the end of bonded surface, where the peeling stress is high, (Hart Smith, 1973a).

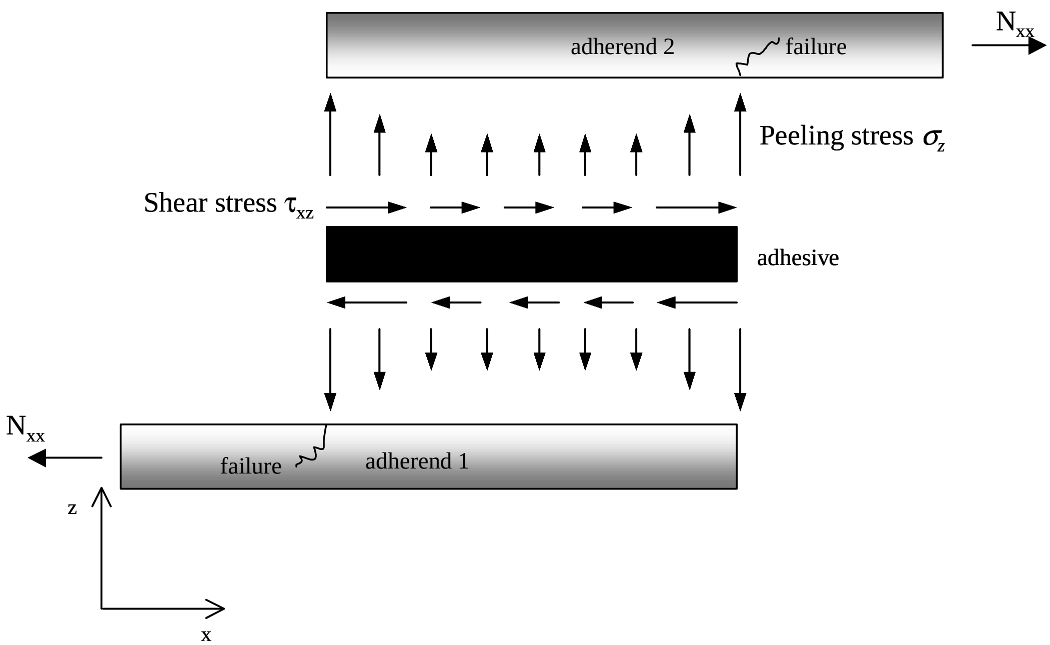

Figure 5. Peeling and shear stresses in single lap joint.

3.0. Examples and Discussions

To demonstrate the applicability of the developed approach, examples of a single lap joint analyses are presented. The adherends used in theses examples are chosen to be unbalanced, and thereby coupling effects appear. This is chosen to demonstrate the capabilities of the present approach. The adherends and adhesive properties assumed in these examples are shown in Tab. (1).

Table 1. Specification of ply and adhesive material properties used for the single lap joint examples.

Plies Graphite/Epoxy	E_1=164GPa	E_2=8.3GPa E_3=8.3GPa	G_{12}=8.3GPa G_{13}=8.3GPa G_{23}=8.3GPa	ν_{12}=0.34 ν_{13}=0.34 ν_{23}=0.34
Adhesive Epoxy AY103	E_a=2.8GPa	σ_Y=27MPa	$G_a= E_a / 2(1+ \nu_a)$	ν_a=0.4

The adhesive used, AY103 from Ciba-Geigy is a plasticized epoxy, which is considered to be a general structural adhesive forming strong semi flexible bonds. Figure (6) shows the joint basic dimensions and laminate coordinate system.

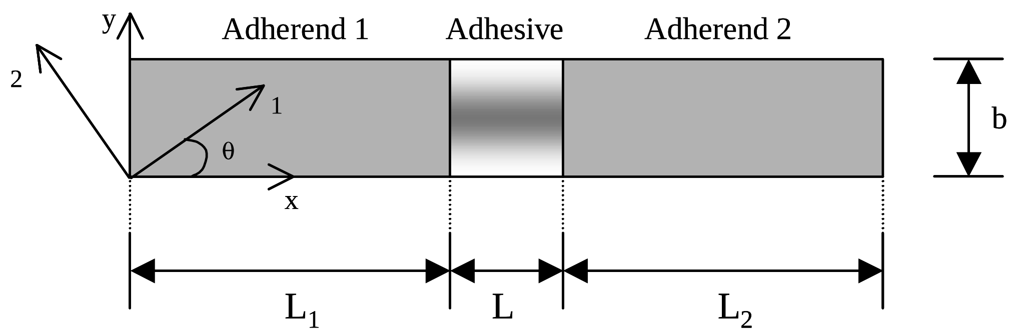

Figure 6. Single lap joint : basic dimensions and laminate coordinate system.

3.1. The influence of coupling effects induced in asymmetric and unbalanced laminated adherends

The influence of coupling affects in the laminate adherends is investigated by using two laminates [θ, 0°] and [0°, θ] as adherend 1 and 2 respectively, where $\theta \in$ [0°,45°]. For $\theta = 0°$ there is no coupling in the laminates, whereas for $\theta = 45^0$ strong coupling effects are induced in the laminates. To show the change of the structural response as a function of increasing coupling affects, the analysis has been performed for different values of the angle θ.

The lay-up of the adherends, the dimensions and the boundary conditions for the bonded single lap joints assumed are shown in Tab. (2).

Table 2. Laminate lay-ups, thickness, lengths and boundary conditions used for investigation of coupling effects.

Adhesive thickness	0.05mm
Ply thickness	0.125mm
Adherend 1	Graphite/epoxy [θ, 0^0], t_1=0.25mm
Adherend 2	Graphite/epoxy [0^0, θ], t_2=0.25mm
lenghts	$L_1= L_2$=30mm, L=20mm
widht	b=1mm
Load and boundary conditions	$x = 0 : u_0 = w = M_{xx}= 0$ $y = b: v_0 = 0$ $x = L+L_1+L_2: w = M_{xx} = 0, N_{xx}$=1N/mm
Number of nodes	26048
Number of solid elements in adhesive layer (CHEXA8)	9180
Number of shell elements in adherends (CQUAD4)	12090
Number of constraint equations (MPC)	6528

In Fig. (7) the maximum vertical displacement w as a function of θ are shown. It can be seen that vertical displacement is tremendously increased for high θ values. Fig. (8) displays the maximum adhesive layer peeling stresses as a function of θ.

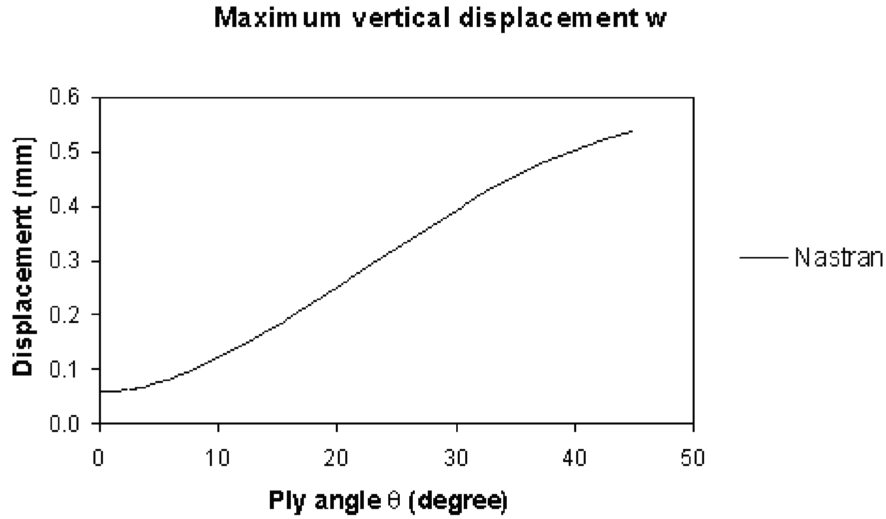

Figure 7. Maximum vertical displacements of adherends as function of ply angle θ.

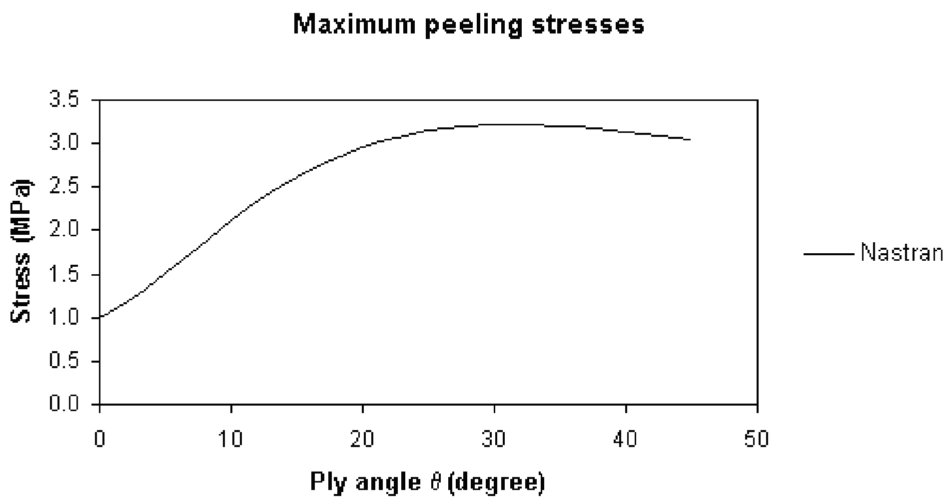

Figure 8. Maximum peeling stresses of adhesive as function of ply angle θ.

It can be concluded from Fig. (8) that the adhesive layer stresses are only significantly affected by the coupling effects for $\theta \in [0^o,20^0]$.

3.2 The stacking sequence of the plies in the laminated adherends

The stiffnesses A_{ij}, A_{ij}^*, B_{ij} and D_{ij} are the constitutive relations between forces and the middle surface strains, defined by

$$\begin{Bmatrix} \{F\} \\ \{M\} \\ \{Q\} \end{Bmatrix} = \begin{bmatrix} [A] & [B] & [0] \\ [B] & [D] & [0] \\ [0] & [0] & [A^*] \end{bmatrix} \begin{Bmatrix} \{\varepsilon\} \\ \{\kappa\} \\ \{\gamma\} \end{Bmatrix} \tag{1}$$

where,

$$\left(A_{ij}, B_{ij}, D_{ij}\right) = \sum_{k=1}^{k} \int_{z_{k-1}}^{z_k} \left[\overline{Q}_{ij}\right]_k \left(1, z, z^2\right) dz \qquad i, j = 1,2,6 \tag{2}$$

and

$$\left(A^*_{ij}\right)=\sum_{k=1}^{k}\int_{z_{k-1}}^{z_k}\left[\overline{Q}_{ij}\right]_k dz \qquad i,j=4,5 \tag{3}$$

where k is the total number of lamina in the laminate and z_{k-1}, z_k, are the bottom and top coordinate of the *k*th layer with respect to the plate middle surface.

Changing the stacking sequence of the plies in a laminate can change the coupling stiffnesses B_{ij} and the bending stiffness D_{ij} of the laminate, (Daniel, 1994). To study the influence of the staking sequence in laminate adherends, two cases have been considered. In the first case, the stacking sequence is changed such that only the coupling stiffnesses B_{ij} are modified, and in the second case, the stacking sequence is changed such that only the bending stiffnesses D_{ij} are modified.

3.2 1 A_{ij} and D_{ij} constant, B_{ij} changed

To investigate the influence of changing the stacking sequence such that only the coupling stiffnesses B_{ij} are modified, two laminates, $[0^o,45^o]$ and $[45^o,0^o]$, are used as adherends 1 and 2, respectively. Then the laminate is changed such that adherend 1 is a $[45^o,0^o]$ laminate and the adherend 2 is a $[0^o,45^o]$ laminate. Thus, in the first case 0^o plies are facing the adhesive layer and in the second case the 45^o plies are facing the adhesive layer. The laminate stiffnesses for these two cases are identical except for the signs of the coupling stiffnesses B_{ij} , which are opposite, (Daniel, 1994). The load and boundary condition are the same as used before. Figure (9) shows the peeling stresses, along the adhesive layer for case 1 and case 2. It can be seen that the adhesive layer peeling stresses increase by approximately 61% when the 45^0 ply is facing the adhesive (case 2) and the adhesive shear stresses τ_{xz} shown in Fig. (10) increase by 42%. The differences in these results are due to the change in coupling stiffnesses B_{ij} for the two laminates and the change in D_{11} for the whole joint. It is observed in Fig. (11) the displacement field *w* along the joint when 45^0 is facing the adhesive, the whole joint has less flexural stiffness than when 0^0 facing is used. This explains why the displacement field is higher for case 2.

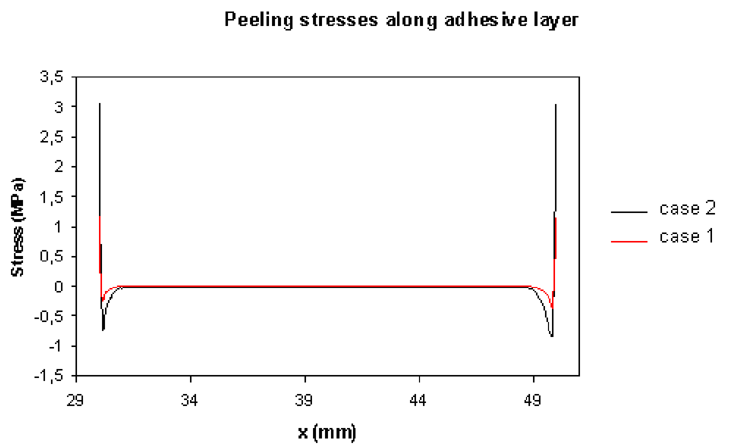

Figure 9. Peeling stresses along adhesive layer for cases 1 and 2 in coupling effect study.

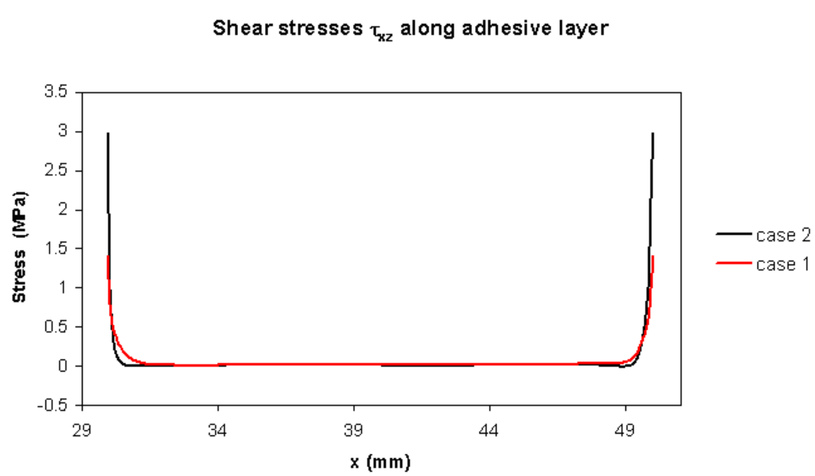

Figure 10. Shear stresses τ_{xz} along adhesive layer for cases 1 and 2 in coupling effect study.

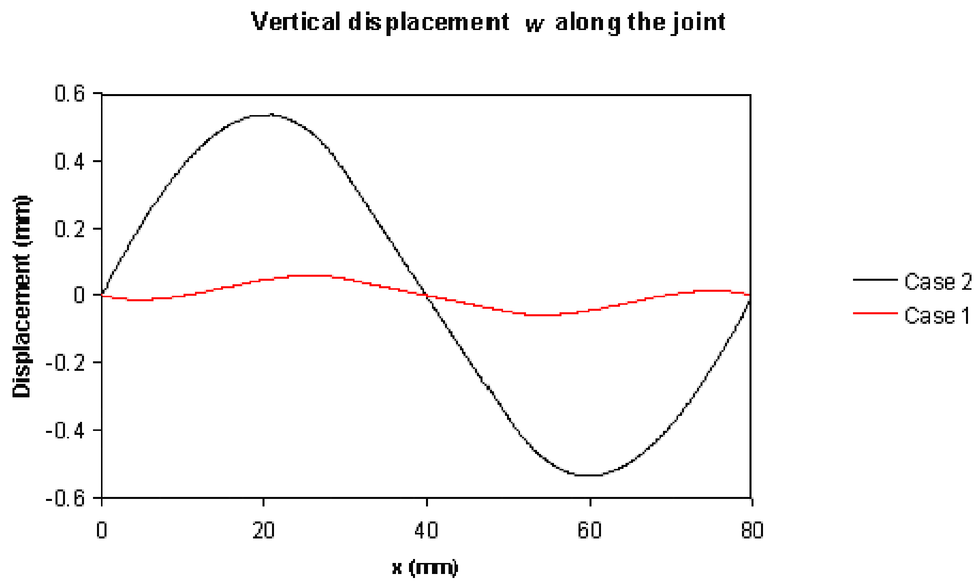

Figure 11. Vertical displacement *w* along the joint for cases 1 and 2 in coupling effect study.

3.2 2 A_{ij} and B_{ij} constant, D_{ij} changed

To investigate the influence of changing the stacking sequence such that only the flexural stiffnesses D_{ij} of each laminate change, two symmetric and identical laminates are assumed for two adherends. The laminates used are in the first case $[0^o, 0^o, 0^o, 90^o, 90^o, 0^o]_s$, and in the second case $[0^o, 90^o, 90^o, 0^o, 0^o, 0^o]_s$. The load and boundary conditions are the same used before. In Fig. (12) the peeling stresses along the adhesive layer are shown for cases 1 and 2. It can be seen from Fig. (12) that the peeling stresses are increased 21% as the 0^o plies are moved towards the midsurface of the laminated adherends. The reason for this is due the decrease in D_{11} for each adherend.

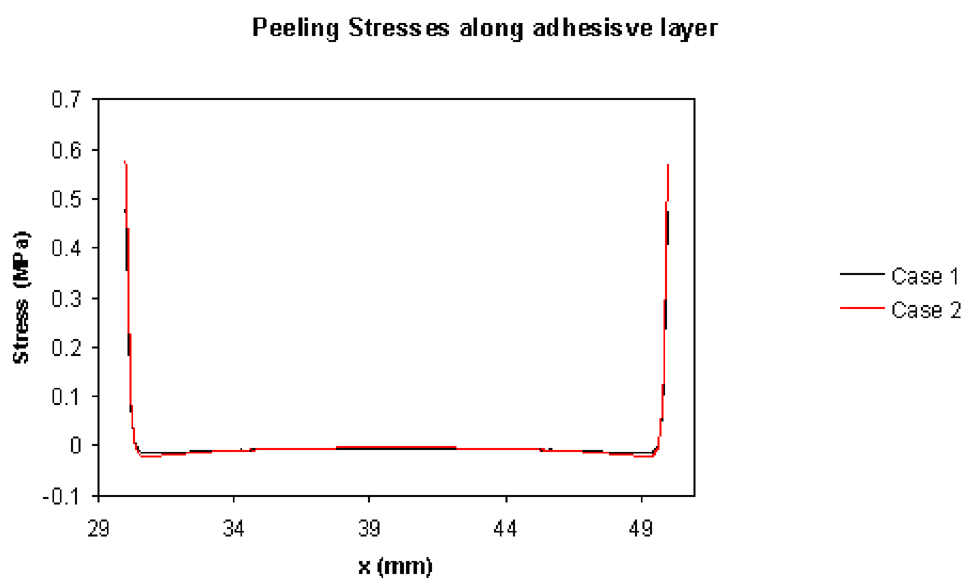

Figure 12. Peeling stresses along adhesive layer for cases 1 and 2 in stacking sequence study.

The adhesive layer shear stresses τ_{xz} are not shown since the shear stresses in the longitudinal direction remain almost unchanged. The reason why the shear stresses τ_{xz} do not change is that they primarily depend on the extensional and coupling stiffnesses that do not change.

3.3 The use of elastic plastic perfectly plastic constitutive model in adhesive layer

The structural modeling described is based on the assumption that the adhesive layer behaves as a linear elastic material. This is a good approximation at low load level, and the approach is useful to predict the stress distribution and location of peek stress values as shown in the previous sections. However, most polymeric structural adhesives exhibit a non-linear behavior and it is common to appear plastic strains at the end of the surface bonded at low levels of external load. This section investigates the non-linear behavior of the joint due to the use of elastic plastic perfectly plastic constitutive model in adhesive and the consideration of large displacement formulation in adherends and adhesive elements. The adherends and adhesive properties assumed in this study are shown in Tab. (1). The lay-up of the adherends, the dimensions and the boundary conditions for the bonded single lap joints assumed are shown in Tab. (3). The finite element model used in this study is presented in Fig. (13).

Table 3. Laminate lay-ups, thickness, lengths and boundary conditions used for investigation of non linear effects.

Adhesive thickness	1.0 mm
Ply thickness	0.2mm
Adherend 1	Graphite/epoxy [0^o, 90^o, 0^o,90^o, 0^o], t_1=1.0 mm
Adherend 2	Graphite/epoxy [0^o, 90^o, 0^o,90^o, 0^o] , t_2=1.0 mm
lenghts	$L_1 = L_2$=20mm, L=40mm
wide	b=20mm
Load and boundary conditions	$x = 0 : u_0 = w = M_{xx} = 0$ $y = b: v_0 = 0$ $x = L+L_1+L_2: w = M_{xx}=0, N_{xx}=500.0$N/mm
Number of nodes	1265
Number of solid elements in adhesive layer (CHEXA8)	400
Number of shell elements in adherends (CQUAD4)	500
Number of constraint equations (MPC)	462

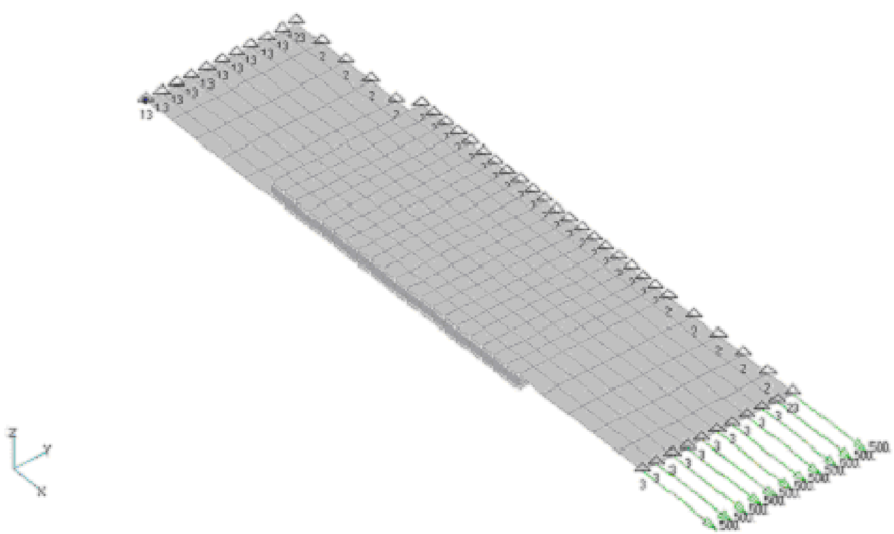

Figure 13. Nastran finite element model used in non-linear study.

The basic difference between the linear and non linear analysis is that the adhesive stresses, at higher levels of loading, are reduced and smoothed out in the regions adjacent to the ends of the bonded surface. In Fig. (14) the peeling stresses at adhesive layer are shown for Nastran and EsaComp. This is a software specific for analysis and design of bonded joints, Mortensen (2000).

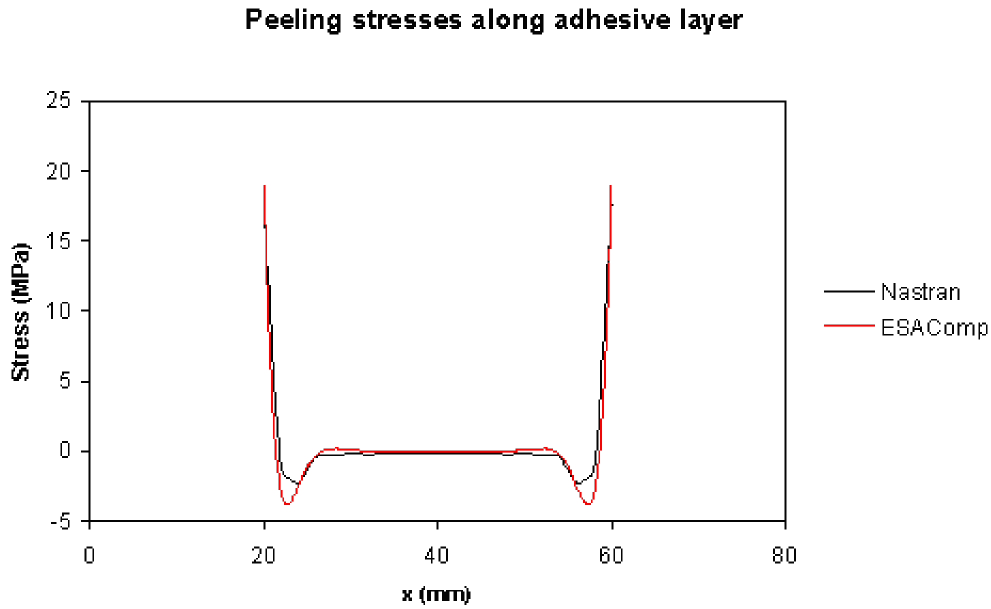

Figure 14. Peeling stress along adhesive layer in non-linear analysis.

Fig. (15) shows the deformed shape and the peeling stress distribution in the adhesive layer; from this figure it is possible to identify the plastic region at the end of the adhesive layer.

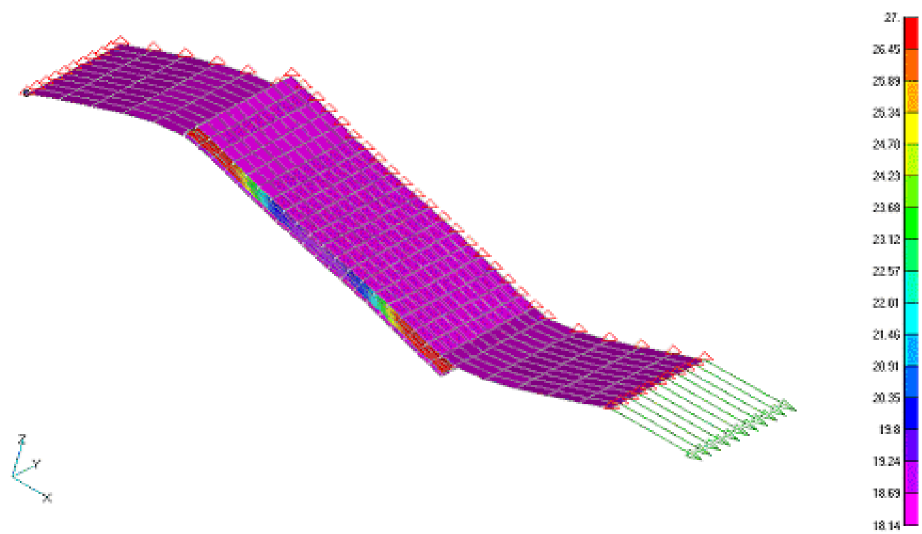

Figure 15. Deformed shape and peeling stress along the adhesive layer in non-linear analysis.

4. Conclusions

A general method using a commercial finite element package MSC.Nastran for the analysis of adhesive bonded joints with composite laminated has been presented. The technique accounts for coupling effects induced by adherends made as asymmetric and unbalanced laminates. The analysis can be carried out with the adherends modeled as plate elements and the adhesive layer is assumed to behave as a linear elastic and elastic plastic perfectly plastic material. The approach for modeling of adhesive bonded joints between composite laminates has been used to perform a parametric study of the laminate adherends influence on the adhesive layer stresses. From this investigation of different parametric effects it is concluded that the coupling effects caused by the use of asymmetric and unbalanced laminates can have a strong influence on the performance of a adhesive bonded joint. The laminate stacking sequence also has a significant influence on the joint performance. From the parametric investigation, the following general design guidelines for adhesive bonded joints with laminated adherends can be specified to maximize the adhesive bonded joint performance:

1-Use symmetric laminates, the use of asymmetric and unbalanced laminates with significant coupling stiffness components B_{ij} should be avoided.
2-Use adherends with high bending stiffness D_{ij} . This minimizes the bending of the adherends and thereby decreases the adhesive layer peeling stresses.
3-Use 0^0 plies adjacent to face the adhesive layers. This will provide the best load transfer from the adhesive to the adherends and reduces the adhesive layer stresses.

These design guidelines should be added to the known design guidelines for adhesive bonded joints derived in other references, (Hart-Smith, 1973a and Hart-Smith, 1973b):
1-Use identical or nearly identical adherends.
2- Use an overlap length of minimum ten times the minimum adherend thickness.

5. References

Chihdar, Y., and Pang, S., 1996,"Stress-Strain Analysis of Single-Lap Composite Joints Under Tension", Journal of Engineering Materials and Technology, Vol. 118, pp. 247-255.

Chihdar, Y., and Pang, S., 1993,"Stress-Strain Analysis of Adhesive-Bonded Single-Lap Composite Joints Under Cylindrical Bending", Composite Engineering, Vol. 8, pp. 1051-1063.

Daniel, I. M., and Ishai, O., 1994, *Engineering Mechanics of Composite Materials*, Oxford University Press, New York.

Goland, M., and Reissner, E., 1944,"The stresses in cemented joints", Journal of Applied Mechanics, Vol. 66, pp. A17-A27.

Hart-Smith, L. J., 1973a, *Adhesive-bonded double lap joints. NASA CR112237*, Douglas Aircraft Company, Long Beach.

Hart-Smith, L. J. , 1973b, *Adhesive-bonded single lap joints. NASA CR 112236*, Douglas Aircraft Company, Long Beach.

John, P. C., and John, M., L., 1994, *MSC/Nastran Linear Static Analysis*, The Macneal-Schwendler, Los Angeles.

Mortensen, F., Thomsen, O. T., and Palanterä, M., 2000, "Facilities in Esacomp for analysis and design of adhesive bonded joints", *ESA/ESTEC*, ESA SP-468.

6. Copyright Notice