European Conference on Spacecraft Structures, Materials and Mechanical Testing
ESA/ESTEC, Noordwijk, The Netherlands, 29 November – 1 December 2000
(ESA SP-468)

FACILITIES IN ESACOMP FOR ANALYSIS AND DESIGN OF ADHESIVE BONDED JOINTS

Flemming Mortensen[1] and Ole Thybo Thomsen

Aalborg University, Institute of Mechanical Engineering
Pontoppidanstraede 101, DK-9220 Aalborg, Denmark
tel. +45 96 35 93 19, fax +45 98 15 14 11, e-mail: ott@ime.auc.dk
[1] Currently at TERMA Industries Grenaa AS, Fabrikvej 1, DK-8500 Grenaa, Denmark
tel. +45 8632 1988, fax +45 8632 1448, e-mail: flemming.mortensen@grenaa.terma.com

Markku Palanterä

Helsinki University of Technology, Laboratory of Lightweight Structures
P.O. Box 4300, FIN-02015 HUT, Finland
Currently at Componeering Inc., Topeliuksenkatu 7, FIN-00250 Helsinki, Finland
tel. +358 9 4342 1550, fax +358 9 4342 1551, e-mail: markku.palantera@componeering.com

ABSTRACT

This paper presents a newly developed analysis and design module for adhesive bonded joints implemented in ESAComp, software for analysis and design of composite laminates and laminated structures. The module includes facilities for the analysis and design of typically used standard and advanced joints. The analysis facilities are based on a newly developed unified approach for the analysis and design of adhesive bonded joints. The adherends are modelled as wide beams or plates in cylindrical bending, and are considered as generally orthotropic laminates by using the classical lamination theory (CLT). Consequently, asymmetric and unbalanced composite laminates can be included in the analysis. The analysis can be performed as load response or failure analysis with linear or non-linear adhesive material properties.

INTRODUCTION

The use of polymeric fibre reinforced composite materials has gained widespread acceptance as an excellent way to obtain stiff, strong and very lightweight structural elements. However, load introduction into composite structural elements through joints, inserts and mechanical fasteners is associated with considerable difficulties. The primary reason for this is the layered structure of composite laminates, which results in poor strength properties with respect to loading by interlaminar shear and transverse normal stresses. Thus, the interaction between composite elements and adjoining parts often proves to be among the most critical areas of a structural assembly.

Joining of composite structures can be achieved through the use of bolted, riveted or adhesive bonded joints. The performances of these joint types are severely influenced by the characteristics of the layered composite materials, but adhesive bonded joints provide a much more efficient load transfer than mechanically fastened joint types. Accurate analysis of adhesive bonded joints, for instance by using the finite element method, is an elaborate and computational demanding task [1,2] and there is a specific need for analysis and design tools that can provide accurate results with little computational efforts involved. Such tools are very useful for preliminary design purposes, i.e. in the stages of design where fast estimates of stress/strain distributions as well as joint strength and margin of safety to failure are needed.

The objective of the present paper is to present a newly developed analysis and design module for adhesive bonded joints implemented in the ESAComp version 2.0. ESAComp, whose development was initiated by the European Space Agency, provides an easy-to-use environment for preliminary evaluation and detailed analysis of plies, laminates and structural elements composed of laminates [3]. The developed analysis tools for adhesive bonded joints are completely integrated into the ESAComp system.

The analysis capabilities implemented in the module are based on a newly developed unified approach for the analysis of adhesive bonded joints. The approach can be used for the analysis of most types of adhesive bonded joints. The implemented joint types in ESAComp 2.0 are:

- Single and double lap
- Single and double strap
- Single and double sided scarfed lap
- Bonded doubler

In the analysis, the adherends are modelled as beams or wide plates in cylindrical bending and are considered as generally orthotropic laminates by using the classical lamination theory (CLT). Consequently, the effects due to asymmetric and unbalanced laminate lay-ups of the adherends are included in the analysis. The adhesive layer is modelled as continuously distributed linear tension/compression and shear springs. As non-linear effects in the form of adhesive plasticity play an important role in the load transfer, the analysis allows inclusion of non-linear adhesive properties. The analysis module provides a set of standard boundary conditions.

The analyses are carried out following the same principal approach for all the bonded joint configurations mentioned above. The approach is based on an explicit formulation of the governing set of differential equations that are solved numerically using a direct integration-scheme known as the "multi-segment" method of integration. The mathematical formulation together with the adopted numerical solution scheme result in short computation times. This makes the bonded joint analysis module well suited for preliminary analysis and design considerations as well as for conducting parametric and feasibility studies on adhesive bonded joints. For a detailed description of the approach used for all the joint types, see [4].

The analysis can be performed as a load response or failure analysis. The output of the load response analysis is the adhesive layer stresses and the fundamental variables for the adherends, i.e. displacements, rotations, stress and moment resultants. The output of the failure analysis includes, in addition, the margin of safety or reserve factor for the cohesive failure of the adhesive and for the first ply failure (FPF) of the adherends. Both load response and failure analyses can be performed with linear or non-linear adhesive behaviour and with the adherends modelled as beams or plates in cylindrical bending.

STRUCTURAL MODELLING

The structural modelling is carried out by adopting a set of basic restrictive assumptions for the behaviour of bonded joints. Based on those the constitutive and kinematic relations for the adherends are derived, and the constitutive relations for the adhesive layers are adopted. Finally, the equilibrium equations for the joints are derived, and by combination of these equations and relations, the set of governing equations describing the system behaviour is obtained. The governing system equations are solved numerically using a method called the "multi-segment method of integration".

As an example, a single lap joint configuration composed of two similar or dissimilar generally orthotropic laminates subjected to general loading conditions is shown in Figure 1.

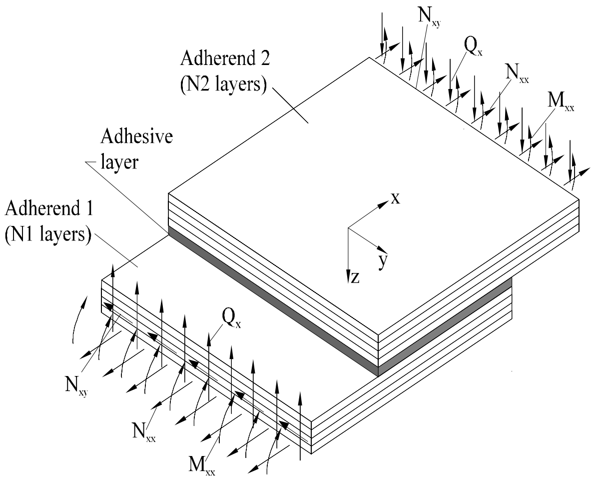


Figure 1: Schematic illustration of an adhesive single lap joint subjected to general loading conditions.

The basic restrictive assumptions adopted for the structural modelling are the following:

Adherends

- Beams or plates in cylindrical bending, which are described by use of ordinary "Kirchhoff" plate theory ("Love-Kirchhoff" assumptions).
- Generally orthotropic laminates using the classical lamination theory (e.g. asymmetric and unbalanced composite laminates can be included in the analysis).
- The laminates are assumed to obey linear elastic constitutive laws.
- The strains are small and the rotations are very small.

Adhesive layer(s)

- Modelled as continuously distributed linear tension/compression and shear springs.
- Inclusion of non-linear adhesive properties by using a secant modulus approach for the non-linear tensile stress-strain relationship in conjunction with a modified von Mises yield criterion.

Load and boundary conditions

- Can be chosen arbitrarily, but are in ESAComp 2.0 restricted to sets of pre-defined boundary conditions.

The system of governing equations is set up for two different cases, i.e. the adherends are modelled as plates in cylindrical bending or as wide beams. In the following, the case where the adherends are modelled as plates in cylindrical bending is considered. The modelling of the adherends as beams can be considered as a reduced case of this.

Modelling of Adherends as Plates in Cylindrical Bending

For the purposes of the present investigation, and with reference to Figure 1, cylindrical bending can be defined as a wide plate (in the *y*-direction), where the displacement field can be described as a function of the longitudinal coordinate only. Consequently, the displacement in the width directions will be uniform, and the constitutive relations for a laminated composite material [5] in cylindrical bending are therefore given by:

$$
\begin{aligned}
N^i_{xx} &= A^i_{11} u^i_{0,x} + A^i_{16} v^i_{0,x} - B^i_{11} w^i_{,xx} \\
N^i_{yy} &= A^i_{12} u^i_{0,x} + A^i_{26} v^i_{0,x} - B^i_{12} w^i_{,xx} \\
N^i_{xy} &= A^i_{16} u^i_{0,x} + A^i_{66} v^i_{0,x} - B^i_{16} w^i_{,xx} \\
M^i_{xx} &= B^i_{11} u^i_{0,x} + B^i_{16} v^i_{0,x} - D^i_{11} w^i_{,xx} \\
M^i_{yy} &= B^i_{12} u^i_{0,x} + B^i_{26} v^i_{0,x} - D^i_{12} w^i_{,xx} \\
M^i_{xy} &= B^i_{16} u^i_{0,x} + B^i_{66} v^i_{0,x} - D^i_{16} w^i_{,xx}
\end{aligned}
\qquad (1)
$$

where A^i_{jk}, B^i_{jk} and D^i_{jk} (j,k = 1,2,6) are the extensional, coupling and the flexural rigidities. N^i_{xx}, N^i_{yy} and N^i_{xy} are the stress resultants and M^i_{xx}, M^i_{yy} and M^i_{xy} are the moment resultants.

Kinematic Relations and Equilibrium Equations

Based on the previously presented assumptions, the kinematic relations for the laminates are derived. The equilibrium equations are derived based on equilibrium elements inside and outside the overlap zone. For details see [4].

Modelling of the Adhesive Layer

The coupling between the two adherends is established through the constitutive relations for the adhesive layer, which as a first approximation is assumed homogeneous, isotropic and linear elastic. The constitutive equations for the adhesive layer are established by a spring model, where the adhesive layer is assumed to be composed of continuously distributed shear and tension/compression springs. The constitutive equations of the adhesive layer are suggested in accordance with [4,6–9].

Modelling of the adhesive layer by spring models has been compared with other known analysis methods such as FEM [1,4] (including the spew fillet) and a high-order theory approach [4,10], and the results show that the overall stress distribution and the predicted values are in very good agreement. For a detailed description of the validity of the approach, see [4,10].

The Governing Equations and Solution Procedure

From the equations derived, it is possible to form the complete set of system equations for the problem by combining the equations. This leads to sets of linear coupled first-order ordinary differential equations. The sets of governing equations, together with the boundary conditions defined for the problem, constitute a multiple-point boundary value problem, which is solved using the “multi-segment method of integration” [4]. This method is based on the transformation of the original “multiple-point” boundary value problem into a series of initial value problems. The principle behind the method is to divide the original problem into a finite number of segments, where the solution within each segment can be accomplished by means of direct integration. For a detailed description of the method, see [4].

The output from the analysis is a set of fundamental variables from each adherend defined as the displacements, rotations, stress and moment resultants.

In addition to the fundamental variables for the adherends, the adhesive layer stresses are determined, i.e. the longitudinal and width direction shear stresses and the transverse normal stresses.

If the adherends are modelled as wide beams instead of plates in cylindrical bending, all the fundamental variables related to the width direction (*y*-direction) are equal to zero.

The structural modelling and solution procedure described in the paper is the same for all the other joint types implemented in the analysis module, see [4].

Non-linear Adhesive Formulation

Most polymeric structural adhesives exhibit inelastic behaviour in the sense that plastic residual strains are induced even at low levels of external loading. Thus, the assumption of linear elasticity of the adhesive is an approximation.

The concept of effective stress/strain is one way of approaching this problem. In this approach, it is assumed that for a ductile material plastic residual strains are large compared to the creep strains at normal loading rates. Therefore, a plastic yield hypothesis can be applied, and the multidirectional state of stress can be related to a simple unidirectional stress state through a function similar to that of von Mises.

However, it is widely accepted that the yield behaviour of polymeric structural adhesives is dependent on both deviatoric and hydrostatic stress components. A consequence of this phenomenon is a difference between the yield stresses in uniaxial tension and compression. This behaviour has been incorporated into the analysis by the application of a modified von Mises criterion suggested by Gali et al. [11].

The non-linear formulation is solved together with an effective stress-strain relationship derived experimentally from tests on adhesive bulk specimens [6,11]. Thus, it is assumed that the bulk and "in-situ" mechanical properties of the structural adhesive are closely correlated [11].

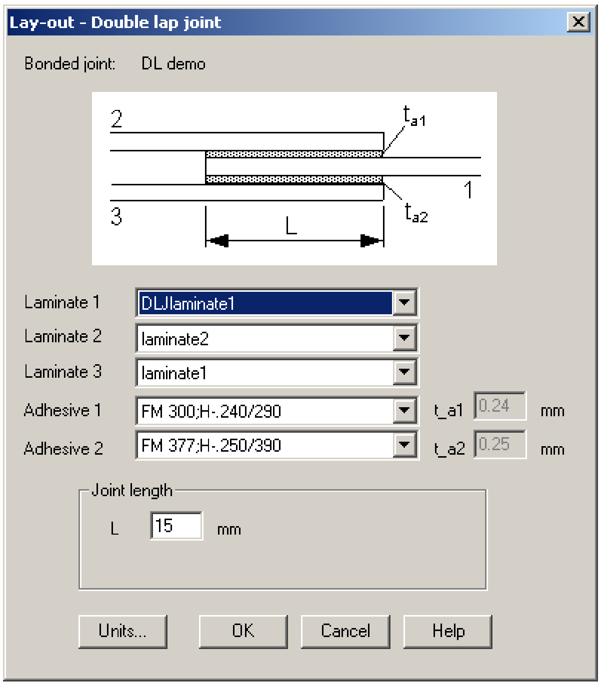
The non-linear solution is obtained based on a tangent modulus approach for the effective stress-strain relationship for the adhesive. For each adhesive point, the effective strain and stress are calculated using the elasto-static solution procedure, and if the stresses *s* are larger than some given proportional limit, the elasticity modulus for this point is reduced. Convergence is usually achieved within a few iterations.

ADHESIVE BONDED JOINT ANALYSIS IN ESACOMP 2.0

The concept of *objects* is essential to the ESAComp system. Fibres, matrix materials, plies, laminates and loads are examples of ESAComp objects. A *case* is a set of related objects that can be stored in the database as a whole. The case in the working area is called the *active case*. Laminates are specified in the active case using the plies of the active case. Structural elements, such as plates and beam cross sections, can further be specified from the laminates of the case. A modification made in the specification data of an object reflects to the dependent objects.

The adhesive bonded joints are realised in ESAComp as objects formed from laminates, the adherends, and the adhesive. Adhesives can be either adhesive plies or matrix materials. For adhesive plies, non-linear stress-strain behaviour can be specified with a bi-linear model independently for tension and compression. Linear behaviour is always assumed for matrix materials. In addition to the selection of the adherends and the adhesive, the joint overlap length is required for the specification of the joint object. Scarfed joints require also additional dimensions defining the geometry. The adhesive thickness need to be specified as well, unless it is part of the adhesive ply specification. An example of the joint specification windows is shown in Figure 2.

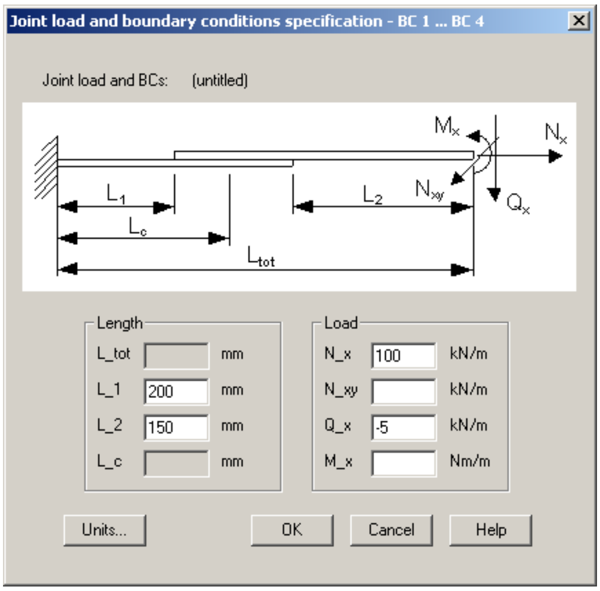
The geometric boundary conditions and the mechanical loads applied to a bonded joint are combined as a single object. The dimensions defining the location of the joint with respect to the end supports are also included in this object. A specification window for the mechanical loads and the model lengths is shown in Figure 3.



Bonded joint: DL demo

Laminate 1: DLJlaminate1
Laminate 2: laminate2
Laminate 3: laminate1
Adhesive 1: FM 300;H-.240/290 t_a1 0.24 mm
Adhesive 2: FM 377;H-.250/390 t_a2 0.25 mm
L 15 mm

Figure 2: ESAComp bonded joint specification window for a double lap joint.



Joint load and BCs: (untitled)

L_tot mm
L_1 200 mm
L_2 150 mm
L_c mm
N_x 100 kN/m
N_xy kN/m
Q_x -5 kN/m
M_x Nm/m

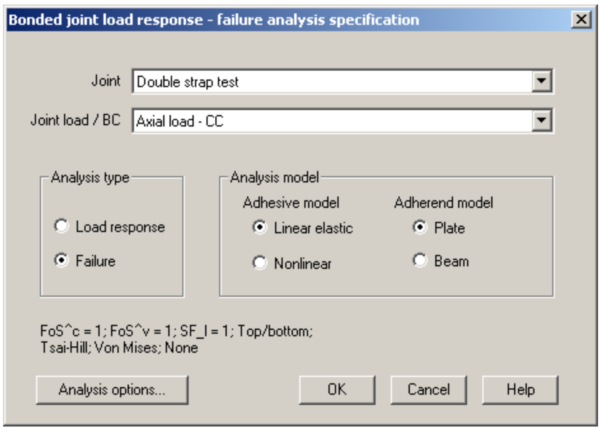
Figure 3: ESAComp Joint load and boundary condition specification window.

In ESAComp 2.0, three predefined boundary condition types are available for bonded joints. These are:

- CC = clamped–clamped, i.e. the joint is clamped at both ends, with the one end fixed and the other end capable of moving in the length and width direction.

- SS = simply supported–simply supported, i.e. the joint is simply supported at both ends, with the one end pinned and the other end capable of moving in length and width directions as well as rotating.
- CF = clamped–free, i.e. the joint is clamped at one end and free at the other end and thus capable of moving and rotating in all directions.

Analyses are performed in ESAComp by first selecting the objects to be analysed and by giving required additional specification data for the analysis. In this case, the additional specification data include selection of the analysis type (load response or failure), adhesive model (linear elastic or non-linear), and adherend model (plate or beam). The *analysis specification window* for the bonded joint analysis is illustrated in Figure 4.



Bonded joint load response - failure analysis specification

Joint: Double strap test
Joint load / BC: Axial load - CC

Analysis type
○ Load response
● Failure

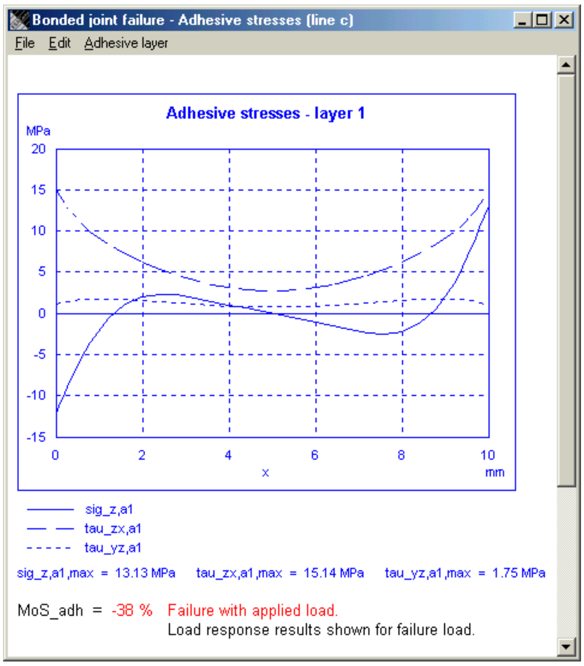
Analysis model
Adhesive model
● Linear elastic
○ Nonlinear
Adherend model
● Plate
○ Beam

FoS^c = 1; FoS^v = 1; SF_l = 1; Top/bottom;
Tsai-Hill; Von Mises; None

Figure 4: ESAComp analysis specification window for Bonded joint Load response / Failure analysis.

The load response analysis gives as output the fundamental variables for the adherends and the adhesive layer stresses (Figures 5 and 6). The failure analysis gives the same output as the load response analysis and, in addition, the reserve factor or margin of safety for the cohesive failure of the adhesive. The failure analysis is performed by iterative use of the load response analysis by incrementing the load until failure is reached. The fundamental variables and the adhesive layer stresses determined in the failure analysis are given for the applied load or for the failure load if the margin of safety is less than zero.

In addition to the cohesive failure of the adhesive, the failure of the adherends due to joint induced bending moments is predicted. The laminate first ply failure (FPF) analysis of ESAComp is used for assessing laminate failure of potentially critical locations in the vicinity of the joint (Figure 7). The in-plane forces and bending moments acting at these locations are obtained from the joint analysis. For comparison, the FPF reserve factors or margins of safety computed away from the joint are also displayed.



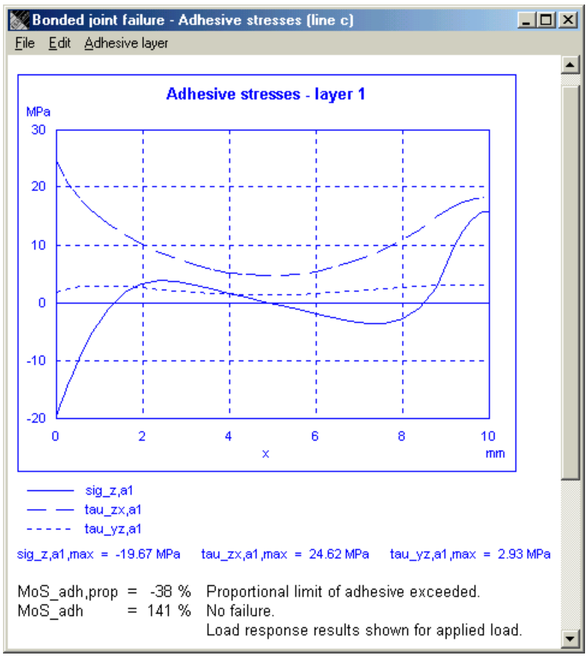
Bonded joint failure - Adhesive stresses (line c)

sig_z,a1
tau_zx,a1
tau_yz,a1

sig_z,a1,max = 13.13 MPa   tau_zx,a1,max = 15.14 MPa   tau_yz,a1,max = 1.75 MPa

MoS_adh = -38 % Failure with applied load.
Load response results shown for failure load.

Figure 5: Adhesive layer stresses of a double lap joint predicted using the linear adhesive model.



Bonded joint failure - Adhesive stresses (line c)

sig_z,a1
tau_zx,a1
tau_yz,a1

sig_z,a1,max = -19.67 MPa   tau_zx,a1,max = 24.62 MPa   tau_yz,a1,max = 2.93 MPa

MoS_adh,prop = -38 % Proportional limit of adhesive exceeded.
MoS_adh = 141 % No failure.
Load response results shown for applied load.

Figure 6: Adhesive layer stresses of a double lap joint predicted using the non-linear adhesive model.

Besides the cohesive failure of the adhesive and the laminate failure due to in-plane and bending loads, there are also other possible failure modes of adhesive bonded joints. The adhesive–adherend interfaces may fail due to high shear and transverse normal stresses. High interlaminar shear stresses may also cause failure in the adherends made of composite materials. In the current system, failure predictions are not given for these two failure modes, but the adhesive stresses computed in the joint analysis can be used as the basis for assessing the criticality of these modes.

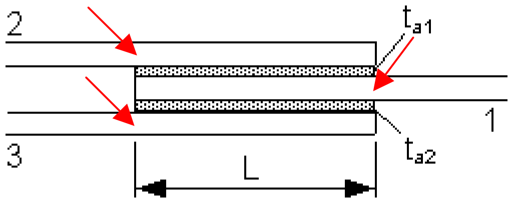


Figure 7: Potentially critical locations of a double lap joint at which laminate FPF analysis is performed.

CONCLUSIONS

A general method for the analysis of adhesive bonded joints between composite laminates has been presented and the implementation into the ESAComp version 2.0 has been illustrated. The analysis accounts for coupling effects induced by adherends having asymmetric and/or unbalanced laminate lay-up. The analysis can be carried out with the adherends modelled as wide beams or as plates in cylindrical bending. The adhesive layers can be modelled as linear or non-linear materials. The analysis can be performed as a load response or failure analysis.

Together with the ESAComp analysis and design system seen as a whole, and with the ESAComp facilities for post processing of results, display of analysis results, as well as export and import to/from FE software, the developed bonded joint module provides a fast, unique and comprehensive tool for preliminary analysis and design of composite structures including adhesive bonded joints.

ACKNOWLEDGEMENTS

The work reported in this paper was co-sponsored by the Danish Technical Research Council's, “Program of Research on Computer-Aided Engineering Design”, and by the Danish Research Council under the “Program of Research Associated with the European Space Agency”. The integration of the analysis code into the ESAComp system performed by HUT has been funded by the European Space Agency (ESA/ESTEC contract no. 9843/92/NL/PP) and by Tekes – the National Technology Agency of Finland.

REFERENCES

1. Crocombe, A. D. and Adams, R. D., An effective stress/strain concept in mechanical characterization of structural adhesive bonding. *Journal of Adhesion*, Vol. 13(2), 1981, pp. 141-155.
2. Harris, J. A. and Adams, R. D., Strength prediction of bonded single lap joints by non-linear finite element methods. *International Journal of Adhesion and Adhesives*, Vol. 4, 1984, pp. 65-78.
3. The official ESAComp web site at www.componeering.com/esacomp
4. Mortensen, F., *Development of Tools for Engineering Analysis and Design of High-Performance FRP-Composite Structural Elements.* Ph.D. thesis, Special Report No. 37, Institute of Mechanical Engineering, Aalborg University, Denmark, August 1998.
5. Whitney, J. M., Structural Analysis of Laminated Anisotropic Plates., *Technomic Publishing Company. Inc., Lancaster*, 1987.
6. Thomsen, O.T., Elasto-static and elasto-plastic stress analysis of adhesive bonded tubular lap joints. *Composite Structures*, Vol. 21, No. 4, 1992, pp. 249-259.
7. Tong, L., Bond strength for adhesive-bonded single-lap joints., *Acta Mechanic, Springer-Verlag*, Vol. 117, 1996, pp. 101-113.
8. Mortensen, F. and Thomsen, O.T., A simple unified approach for the analysis and design of adhesive bonded composite laminates. In *Proc. 11th International Conference on Composite Materials (ICCM-11)*, Gold Coast, Australia, 14-18 July, 1997, Vol. VI, pp. 129-137.
9. Mortensen, F. and Thomsen, O.T., Simplified Linear and non-linear analysis of stepped and scarfed adhesive bonded lap-joints between composite laminates. *Composite Structures*, Vol. 38, No.1-4, 1997, pp. 383-394.
10. Y. Frostig, O. T. Thomsen and F. Mortensen, Analysis of adhesive-bonded joints, square-end and spew-Fillet - high-order theory approach. *Journal of Engineering Mechanics, ASCE Engineering Mechanics Division*, Vol. 125, No. 11, Nov. 1999, pp. 1298-1307.
11. Gali, S., Dolev, G. and Ishai, O., An effective stress/strain concept in mechanical characterization of structural adhesive bonding., *International Journal of Adhesion and Adhesives*, 1981, Vol. 1, pp. 135-140.