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# FATIGUE STRENGTH INVESTIGATION OF BONDED JOINTS

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***Abstract***

*Numerous advantages of the bonded joints result in wide application in the aircraft, motor industry or powertrain components. These types of joints enable joining materials with different mechanical properties (e.g. stiffness) and dimensions without structure change. Proper joint design limits the field of local stress concentrations or even eliminates them. The structural integrity of complete structure depends on the fatigue estimation of the bonded joint. Application of the finite element method to life prediction of the double lap bonded joint metal-composite-metal is presented. Three dimensional numerical models are generated by professional engineering software tools. The contact problem is modelled between the epoxy resin and metal and composite surfaces. A laminated composite consists of the epoxy woven carbon prepreg. Elasto-plastic materials models of the adhesion and metal and orthotropy composite model allowed determining the contact normal stress in the interfaces in each deformation increment which is induced by an external load. MSC.Marc was used to determine the strain and stress distribution in the double lap bonded joint including contact normal stress in the steel/adhesive and laminated composite/adhesive interfaces. Two numerical models of the double lap bonded joint were compared. The use of the presented method is more suitable for structure optimisation than numerical analysis.*

***Keywords:*** *Adhesive bonded joint, Fatigue strength, Non-linear analysis*

## 1. Introduction

Numerous advantages of the bonded joints result in wide application in the aircraft, motor industry or power train components. This type of joint allows connecting materials with different mechanical properties (e.g. stiffness) and dimensioning without structure change and is particularly attractive where fatigue is a problem.

Design requirements, particularly for lightweight structures, often dictate that adhesives must sustain and transfer loads in the structure. But conservative design and engineering practices result in heavier and more costly component [1].

Debonding at an interface is a potential mode of failure in an adhesive joint. The "interfacial" character of a fracture surface is usually detected by visual inspection, but advanced surface characterisation techniques such as spectrophotometry allows identifying the precise location of the crack path in the interphase. The bonding state at interfaces between two laminated plies plays a critical role in determining the mechanical behaviour of a laminated composite. [9].

Metallic fatigue is an approach using some well established concepts as the low cycle fatigue from Coffin and Manson and the megacycle fatigue from Whöler. For composite materials S-N curves are usually in the range between $10^3$ and $10^6$ cycles. Therefore the damage tolerance for a metal-composite joint is difficult to predict. It is difficult to find a way to characterize joint behaviour under mechanical load applied cyclically over a long period of time [10]. Computational simulation methods are becoming increasingly necessary for cost-saving design evaluation of the composite structures. Mathematical approach that is implemented in the Finite Element Method (FEM) software allows solving a wide range of mechanical problems such as structural analysis, failure or damage [6, 11].

A significant advantage of using a life prediction tools in the design process is that the number of experimental tests at the substructure and complete structure can be substantially reduced and experimental testing is more efficient.

The numerical-experimental approach that is undertaken in this paper permits to quantify the strength of adhesively bonded joints from an engineering point of view. Numerical modelling contact problem between the mating components (for example plies in the laminated composite or adhesion surface steel/adhesive) as two sets of nodes is presented. It allows determining the strain and the stress on the contacting surfaces and stressing concentration fields.

## 2. Numerical-Experimental Approach

The steps of the numerical-experimental approach to determine the design life according to the proposed method is following:

- perform the tension tests to determine the mechanical properties of materials for each component of the joint;
- perform the experiments to obtain the S-N curves (stress-number of cycles to failure) for the material of each component of the joint of interest, corresponding to the frequency of the cyclic loading the part may be subjected to;
- generate numerical models of test specimens – choice of an appropriate modelling technique;
- perform the static nonlinear numerical analyses of test specimens, read off stress level – compare the numerical and experimental results;
- prepare a numerical model of the structure with material properties which were obtained from the experimental tests;
- numerical analysis of the structure model to obtain static stress;
- analysis of fatigue strength of the structure.

## 3. Theory Background

MSC.Software tools i.e. Patran, Marc and Fatigue are used for numerical simulation. Pre- and post processor Patran is used to generate the finite element model and to display the analysis results.

The MSC.Marc code is used to perform the non-linear stress analysis. The implementation of equations governing mechanics allowed to solve the non-linear problems due to material behaviour, large deformation and boundary conditions [8].

The contact problem is modelled between steel/adhesive and adhesive/laminated composite. In the contact region the degrees of freedom are transformed to a local coordinate system and constraints are imposed such as:

$$\Delta u_{normal} = v_r \cdot \mathbf{n}\,, \tag{1}$$

$$\Delta u_{tangential} = v_r \cdot \mathbf{t}\,, \tag{2}$$

where: ***n***, ***t*** normal and tangential vector to the contact surface, $v_r$ is relative sliding velocity [8].

Along a contact surface, the material flows in one direction in part of the surface and in the opposite direction in another part of the surface. This flow is defined as a relative sliding velocity vector. Therefore the tangential vector is described as:

$$\mathbf{t} = \frac{v_r}{\left\| v_r \right\|}\,. \tag{3}$$

The penalty method is a procedure used to numerically implement the contact constrains [8]. The governing FEM equation is so0lved by the Newton-Raphson method

$$\mathbf{K}\,\mathbf{u} = \boldsymbol{F}, \tag{4}$$

where:

u - nodal-displacement,
F - external nodal-load vector,
K - tangent-stiffness matrix.

A kinematics' boundary condition is continuously changing because the normal and tangent can change from iteration to iteration. This leads to change of the global stiffness matrix by the stiffness matrix contribution following from:

$$K_{ij} = -\frac{\partial f_{t_i}}{\partial v_{r_k}} \frac{\partial v_{r_k}}{\partial \Delta u_{t_i}}, \tag{5}$$

where $f_{ti}$ is friction force in the iteration *i*.

Therefore, the contact normal and internal forces and stresses are obtained for each load increment.

The normal contact stress must be positive inside of the contact area and zero outside [5]. Therefore a node should separate when the tensile force or the normal stress exceeds the surface tension. Such an approach allowed determining and comparing the forces and stressing distribution on the adhesive and adherend surfaces.

The laminated composite is modelled as composite finite elements with various layer thickness and different orientations. MSC.Marc forms a stress-strain law by performing numerical integration through the thickness. The constitutive law for an orthotropic elastic compressible material is given by the following more general form of Hooke's Law:

$$\begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_{xx}} & -\frac{\gamma_{yx}}{E_{yy}} & -\frac{\gamma_{zx}}{E_{zz}} & 0 & 0 & 0 \\ -\frac{\gamma_{xy}}{E_{xx}} & \frac{1}{E_{yy}} & -\frac{\gamma_{zy}}{E_{zz}} & 0 & 0 & 0 \\ -\frac{\gamma_{xz}}{E_{xx}} & -\frac{\gamma_{yxz}}{E_{yy}} & \frac{1}{E_{zz}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{xy}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{zx}} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{bmatrix}, \tag{6}$$

The fatigue life estimation is obtained by MSC.Fatigue code. MSC.Fatigue using various life estimation tools depending on whether the analysis is for a crack initiation (E-N), a total life (S-N), or a crack growth. Because the basic material data are unavailable the S-N approach must be applied [7].

The S-N analysis being based on the nominal stress-life method using rainflow cycle counting and Palmgren-Miner linear damage summation. A range of analysis parameters may be selected, including Goodman or Gerber mean stress corrections, confidence parameters, manufacturing details (surface finish), and material heat treatments. The analytical procedure used may be summarized as follows:

a) By means of linear static FEA, derive the local stress time history from the load time histories. Ensure that the S-N data applies to the situation being modelled.
b) Extract the fatigue cycle in the local stress time history by means of the rainflow algorithm.
c) Assess the damage contribution of each cycle by referring to the selected damage curve.
d) Linear sum of the damage associated with each cycle by using Miner's rule.

Material properties are updated for each iteration, reflecting any changes resulting from damage.

MSC.Fatigue constructs the S-N curves on the basis of the ultimate tensile strength (UTS) by fixing the stress axis intercept (one cycle) at the value of fracture stress, fixing the stress at 1000 cycles and endurance limit according to the fraction of UTS. The basic equation for the S-N curve is:

$$\Delta S = SRI1\left(N_f\right)^{b1}, \tag{7}$$

which may be written as:

$$\log(\Delta S) = \log(SRI1) + b1\log\left(N_f\right), \tag{8}$$

where:

ΔS is nominal stress range,

SRI1 stress range intercept of the life line, b1 is the slope of the life line.

There are many procedures for accessing the S-N curve. The main differences lie in the treatment of mean stresses and the damage contribution cycle with "small" ranges. The authors use a procedure which was firstly proposed by Goodman:

$$S_a = S_0\left\{1 - \left(\frac{S_m}{S_u}\right)\right\}, \tag{9}$$

where:

$S_a$ is allowable stress amplitude,

$S_0$ - allowable stress amplitude at zero mean stress,

$S_m$ –mean stress, $S_u$ –ultimate tensile stress.

## 4. Laminated Composite

Mechanical properties of the laminated composite have an effect on the strength of the steel/composite joint. The important source of composite failure is technology of manufacturing. Experimental and numerical tension test is performed.

The laminated composite is made of the thirteen layers of pre-impregnated material (prepreg CE8208). The prepreg consists of the carbon fabrics KDL 8003 impregnated with curable resin E201. The prepreg is characterised by weight of fibre per unit area 200 g/m$^2$ and resin content 45%±3% [12].

The specimen overall dimension is shown in Fig. 1.

The specimen is fully supported in one grip region and is loaded in the second one. The uniform pressure which corresponds to the load magnitude of P = 45 000 N is applied to the opposite side of the specimen.

During experimental tension test the Young modulus in the direction 1 is determined. Other material parameters are obtained from other experiments.

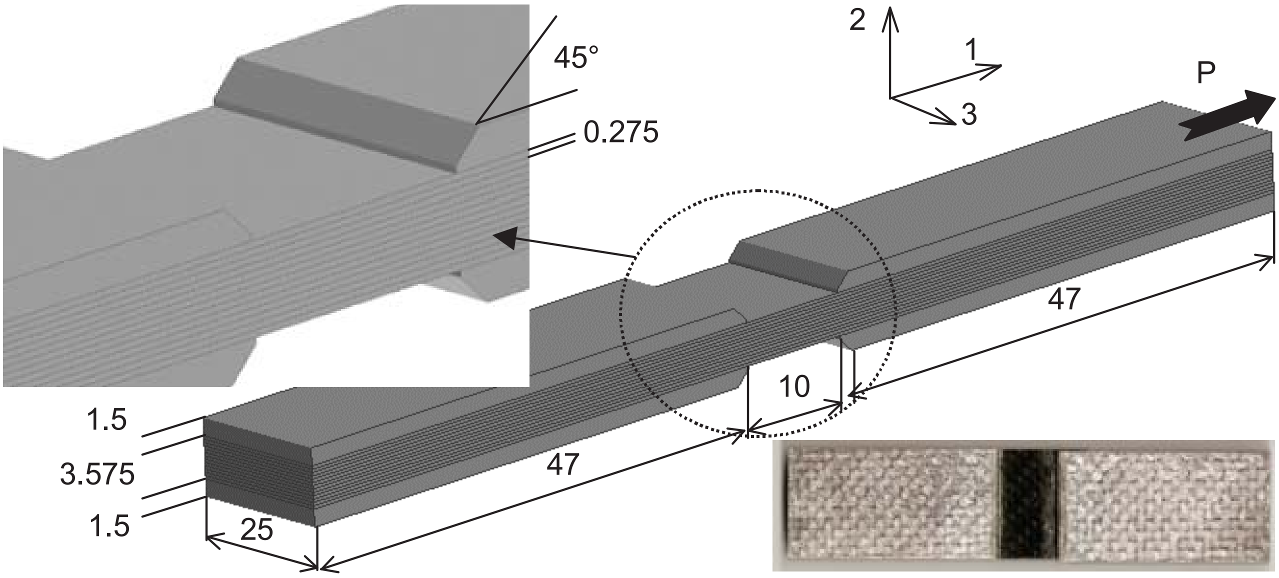


*Fig. 1. Overall dimensions of the laminated prepreg*

The nine constants are specified for laminated composite are shown in Tab. 1.

*Tab.1. Laminated composite properties*

| $E_{11}$ [MPa] | $E_{22}$ [MPa] | $E_{33}$ [MPa] | $G_{12}$ [MPa] | $G_{23}$ [MPa] | $G_{31}$ [MPa] | $\nu_{12}$ | $\nu_{23}$ | $\nu_{31}$ |
|---|---|---|---|---|---|---|---|---|
| 58093 | 58093 | 9759 | 3545 | 2564 | 2564 | 0.0154 | 0.5356 | 0.1575 |

The contact is modelled between each ply of the prepreg [2]. A non-linear static analysis, due to the contact problem, is performed. The experimental and numerical results are compared. The stress versus strain for both tests is shown in Fig. 2.

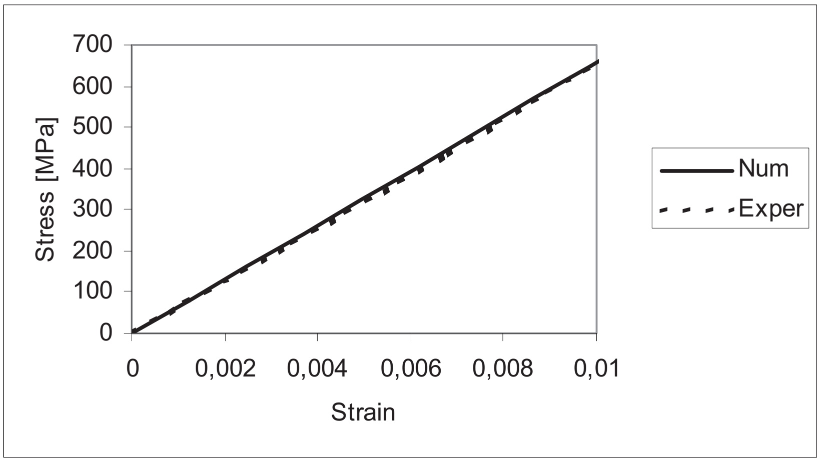


*Fig. 2. Comparison of experimental (Exper) and FEM analysis (Num) results*

Next figure (Fig. 3) presents a picture of the failure specimen during the tension test and distribution of maximum principal stress which is obtained in the FEM analysis.

Value of the contact normal stress for nodes which lie through the laminated composite thickness is shown in Fig. 4. Double contact normal stress values occur because the interface between two prepreg plies is modelled as two sets of nodes.

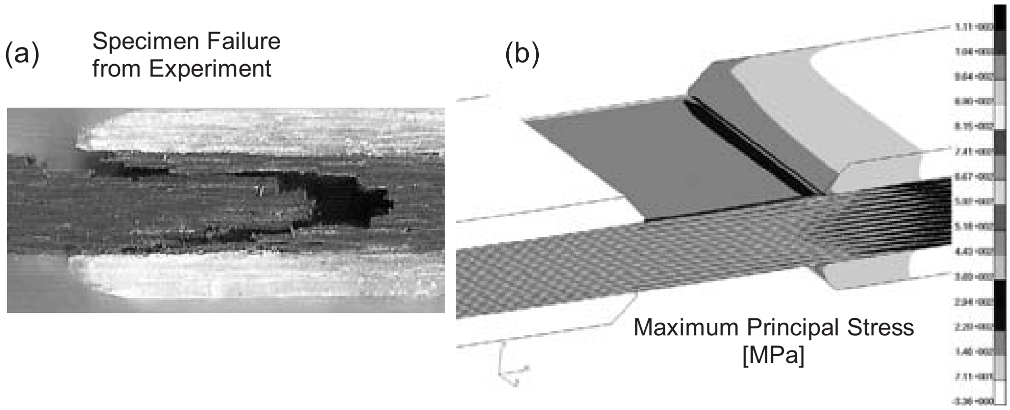


*Fig. 3. Experiment (a) and FEM analysis (b) results*

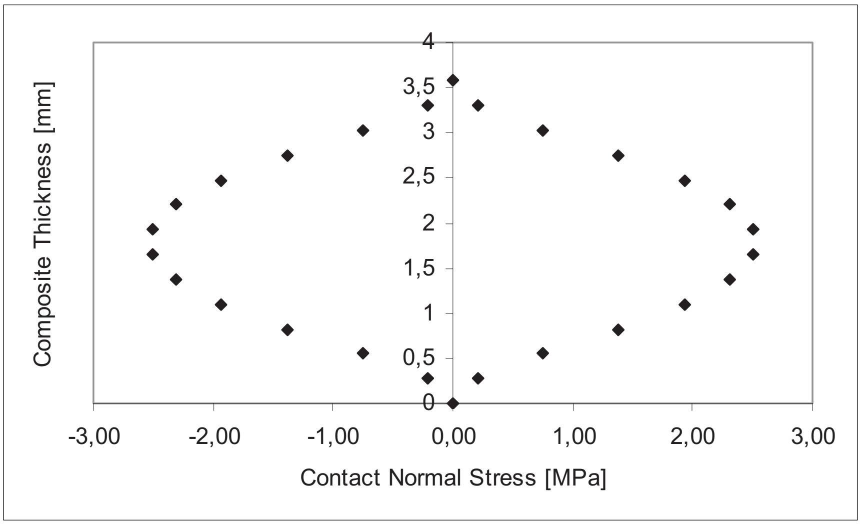


*Fig. 4. Contact normal stress through the laminated composite thickness*

## 5. Double lap joint

Symmetric full-scale double lap joint geometry is chosen for the investigation. This variant of joint allows eliminating the eccentric loading, responsible for bending of the joint. The composite spacer in the grip region (between steel adherends) is used to ensure the symmetrical loading. Two models are generated. Each model consists of two steel sheets lying outside and composite FRP which is manufactured from seven plies of prepreg lying inside. The first model does not include adhesive (epoxy resin Epidian) between the steel and the laminated composite. The second one includes adhesive layers between the steel and the composite. The overall dimensions of the joint with adhesive are shown in Fig. 5. The length of the grip region is 30 mm, and the length of the overlap is 12 mm. 0.02 mm adhesive thickness is assumed. The overall lap joint geometry is critical to the performance.

The discrete model of the investigated double lap bonded joint consists of three solids. Three-dimensional, eight-node elements (HEX8) are used to discretize the complete joint. Authors aim to create cubical elements near the ends of the adhesive. Therefore, the mesh density depended on the number of elements through the thickness of the adhesive.

Contact surfaces are given in discrete form for two sets of nodes. All nodes that create contacting surfaces in the overlap regions are coupled. A multipoint constraint (called tying) is automatically imposed and such constraint expression is formed, so that no relative motion occurred (p. 3).

The contact is modelled between the bonded surfaces, i.e. steel/adhesive and adhesive/composite or steel/composite, depending on the model. The contact is also modelled between the prepreg plies, but a higher friction coefficient is assumed.

One grip region of steel adherends is fully supported. The uniform tensile loading is applied to the second grip region of the composite sheet in the FEA analysis. The uniform pressure which corresponds to the load magnitude of P = 19500 N is applied to the composite sheet (Fig. 5). Pressure value gradually increased until the joint failed due to a large plastic deformation.

A non-linear static finite element analyses are performed for both models.

Mechanical properties of all components are obtained from experiment, mainly tension test performed for the whole strain range [3]. The epoxy properties are determined from a compression test. The compression test is a more useful procedure than tension test for the adhesive [4]. A compression test is performed for the cured adhesive. The cure state of the adhesive in the bonded joint is similar to that of the bulk adhesive specimen.

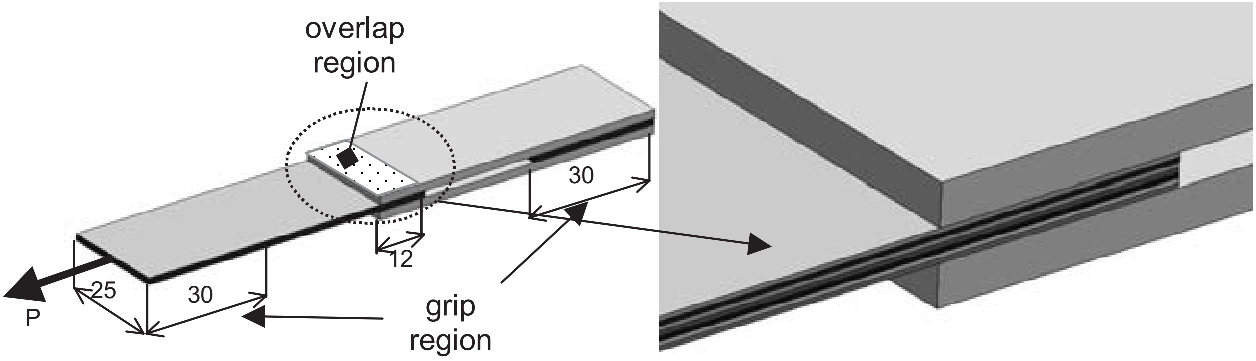
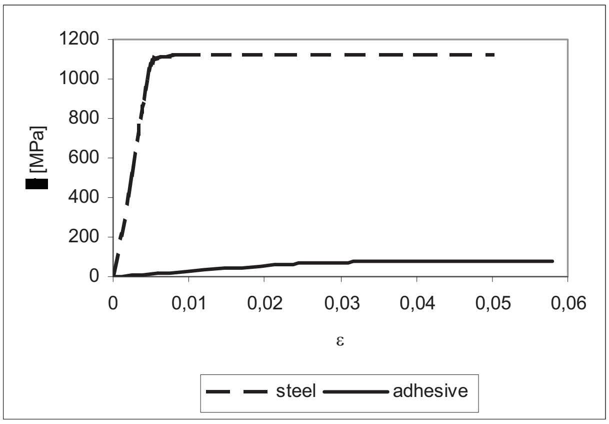


*Fig. 5. Specimen dimensions*

Steel sheets and epoxy adhesive are modelled with elastic-plastic material models with stress-strain curves as shown in Fig. 6. The material for metal sheets is the steel with Young's modulus E = 196 000 MPa and Poisson's ratio ν = 0.29. The material properties of the adhesive are E = 3221 MPa and ν = 0.375.



|  | a<br>Steel | b<br>Adhesive |
|---|---|---|
| E [MPa] | 196000 | 3221 |
| ν | 0,29 | 0,375 |
| Re [MPa] | 412 | 19 |

*Fig. 6. Strain-Stress Curves: a) steel; b) adhesive*

Mechanical properties of the laminated composite, determined during tension test, are described in p. 4.

The selection of a proper model of calculation is made at first step. The maximum principal stresses are compared for models with and without adhesive, because these stresses are decisive in fatigue analysis (Fig. 7).

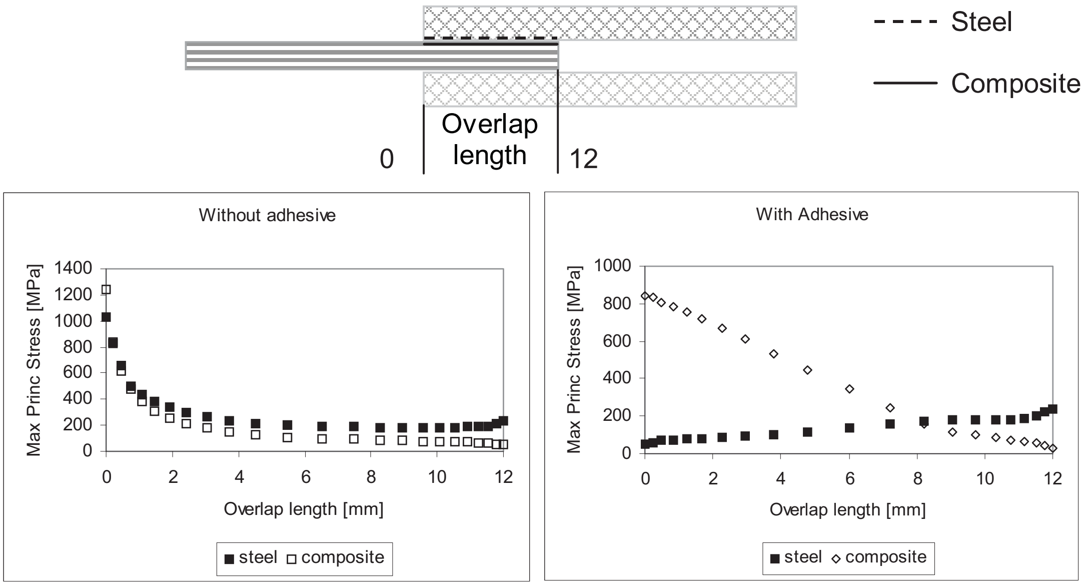


*Fig. 7. Maximal principal stress versus adhesive length for upper steel adherend and composite*

## 5. Lifetime estimation

The S-N method is used for life prediction of a double lap bonded joint. MSC.Fatigue assumes the minimal damage to be 1E-20 [7].

The S-N curves are used to predict the fatigue lives of joint components. By use of statistics, the S-N curves are estimated by MSC.Fatigue according to p.3. These curves are shown in Fig. 8 and the basic parameters are given in Tab. 2.

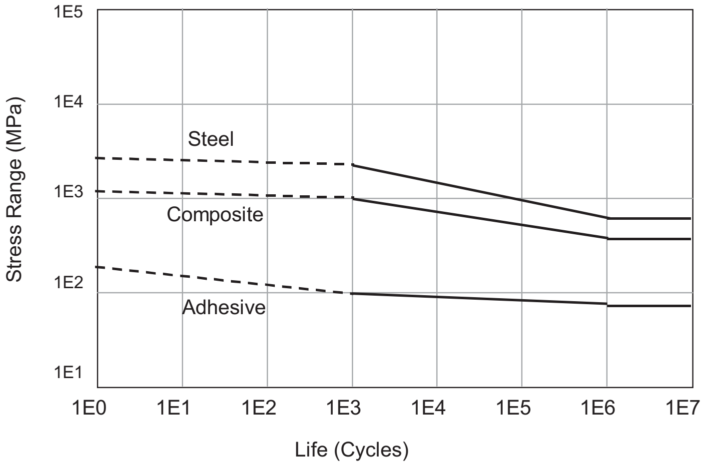


*Fig. 8. S-N curves*

*Tab. 2. Stress-Life Data Parameter*

| Material name | SRI1 [MPa] | b1 |
|---|---|---|
| steel | 5073 | -0.1339 |
| composite | 2518 | -0,1339 |
| adhesive | 453.8 | -0.1339 |

A fully reversed stress cycle with a sinusoidal form is assumed in to the fatigue process.

The most damaged nodes are shown in Fig. 9. It means that these points are the weakest ones in the structure.

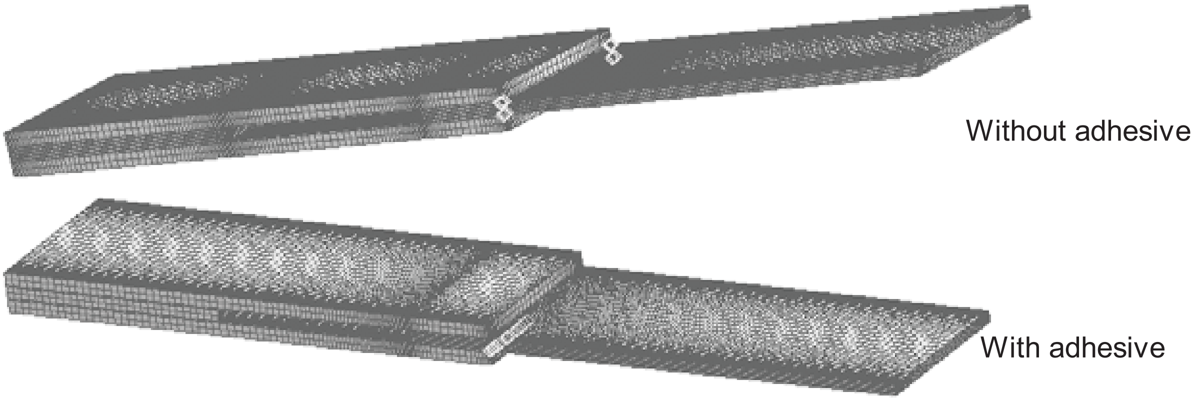


*Fig. 9. The most damage nodes*

The logarithm of damage, in a probabilistic manner according to the Miner's law, for the full loading and 0.4 of the full loading is shown in Fig. 10.

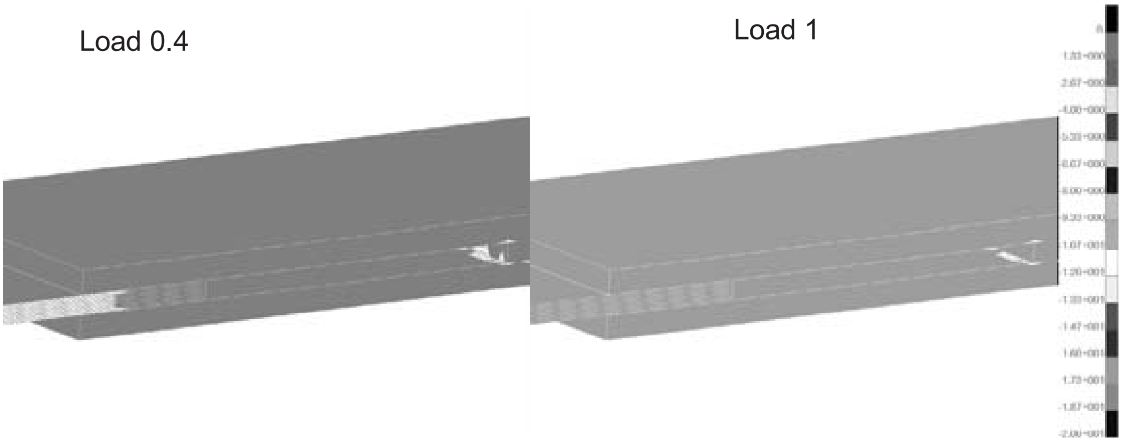


*Fig. 10. Log of damage for a model with adhesive*

## 6. Conclusions

This study intended to show an experimental-numerical approach to predicting the mechanical fatigue. MSC.Marc is used to determine the strain and stress distribution in the double lap bonded joint including contact normal stress in the steel/adhesive and laminated composite/adhesive interfaces.

Modern integrated virtual product development tools are useful to solve even very complicated engineering problems. Experimental verification of the laminated composite model indicates that implementation of actual mathematic solvers of the contact problem and composite mechanics enables a numerical analysis without special interface element. The model contact model is applied between the plies in the composite. It permits to include all phenomena which can find there, for example, initial stress produced during manufacturing process.

Two numerical models of the double lap bonded joint are compared. One of them does not contain the model of the adhesive. Two different maximum principal stress distribution (Fig. 7) indicate that the numerical model should be adequate to the real structure. In the opposite case the fatigue life estimation is incorrect. Failures usually are of brittle character but different failure modes are observed separately for the laminated composite and adhesively bonded joints.

The adhesive stress is determined without taking into account the microstructure and liquid state diffusion bonding mechanism.

In further study, the fatigue behaviour and failure mode will be investigated under various environmental conditions. Next experimental tests are currently under way.

The use of the presented method seems to be more suitable for structure optimisation than numerical analysis only.

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