ALMA MATER STUDIORUM
UNIVERSITY OF BOLOGNA

MaSTeR Lab
Material and Structure Research Laboratory
Via Fontanelle 40, Forlì (FC), Italy

Simulation of Crack Growth in Adhesively Bonded Joints Via Cohesive Zone Models

Nicola ZAVATTA[1], Maria Pia FALASCHETTI[1], Johan BIRNIE HERNÁNDEZ[1], **Enrico TROIANI**[1]*
[1] University of Bologna, Department of Industrial Engineering (DIN), Via Fontanelle 40, 47121 Forlì (FC), Italy
*corresponding author: enrico.troiani@unibo.it

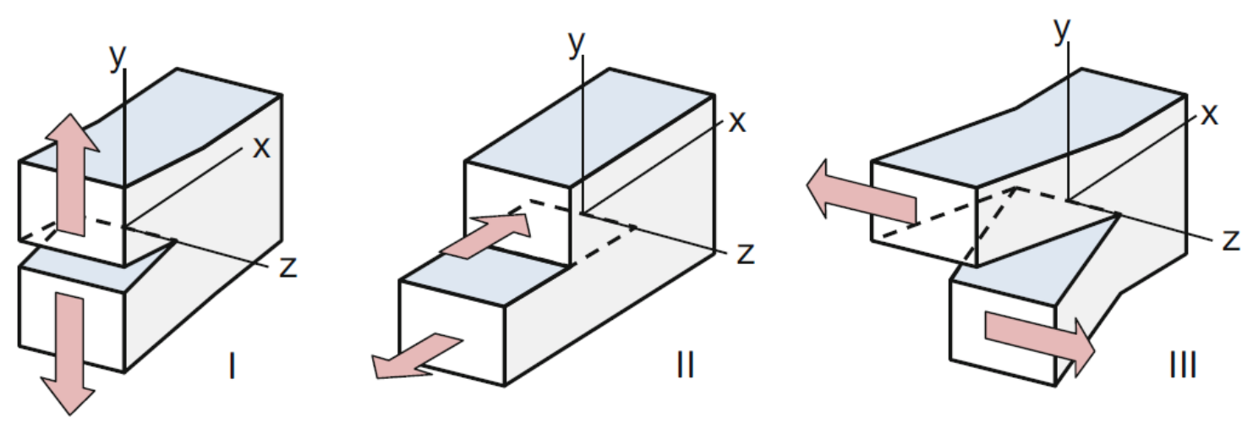
ABSTRACT

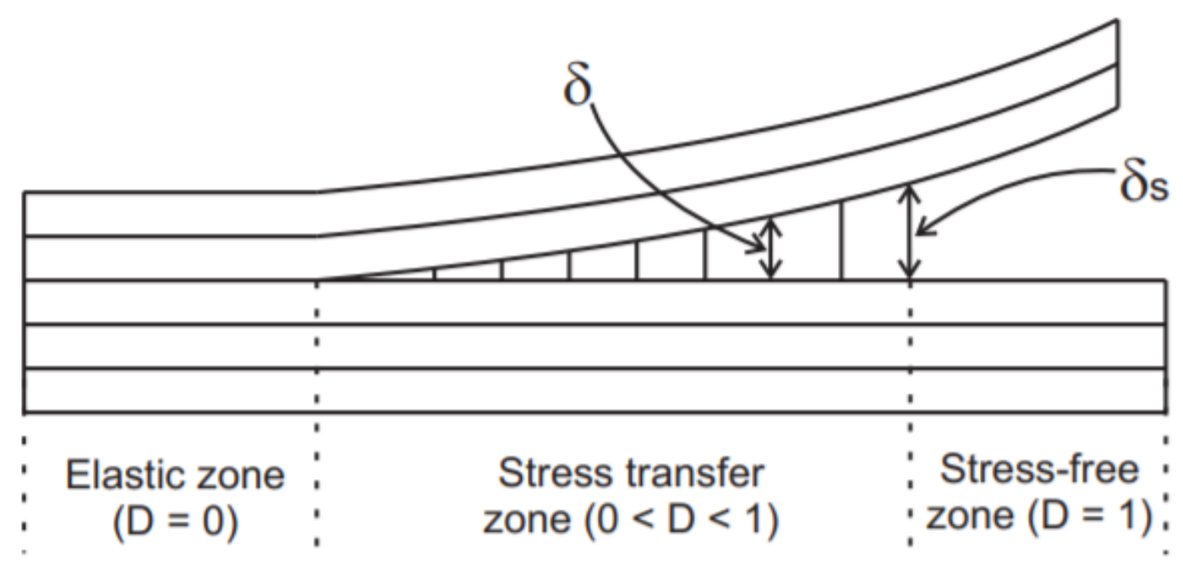
Adhesively bonded joints allow to reduce the overall structural weight and improve the fatigue life characteristics due to reduction of stress concentrations (uniform stress distribution). However, one of the main concerns is their characterization under **fatigue loading**, i.e., a comprehensive study of crack growth which will allow the development of standardized tests and certification in the aerospace sector. Today, their certification for primary structures requires that critical disbond be prevented by proper design. To this end, **Disbond Arrest Features** (DAFs) have been tested as a mean to improve the fatigue resistance of bonded joints. In this work, a numerical model to assess fatigue disbonding under mixed-mode loading has been developed. The model was based on a cohesive zone formulation. Two test cases were simulated: a **Double Cantilever Beam (DCB)** specimen and a modified **Cracked-Lap Shear (CLS)** specimen with a bolted DAF. The results of the simulations were compared with experimental data, showing that the model can reproduce the fatigue disbonding and capture the disbond arrest by the DAF.

THEORETICAL BACKGROUND

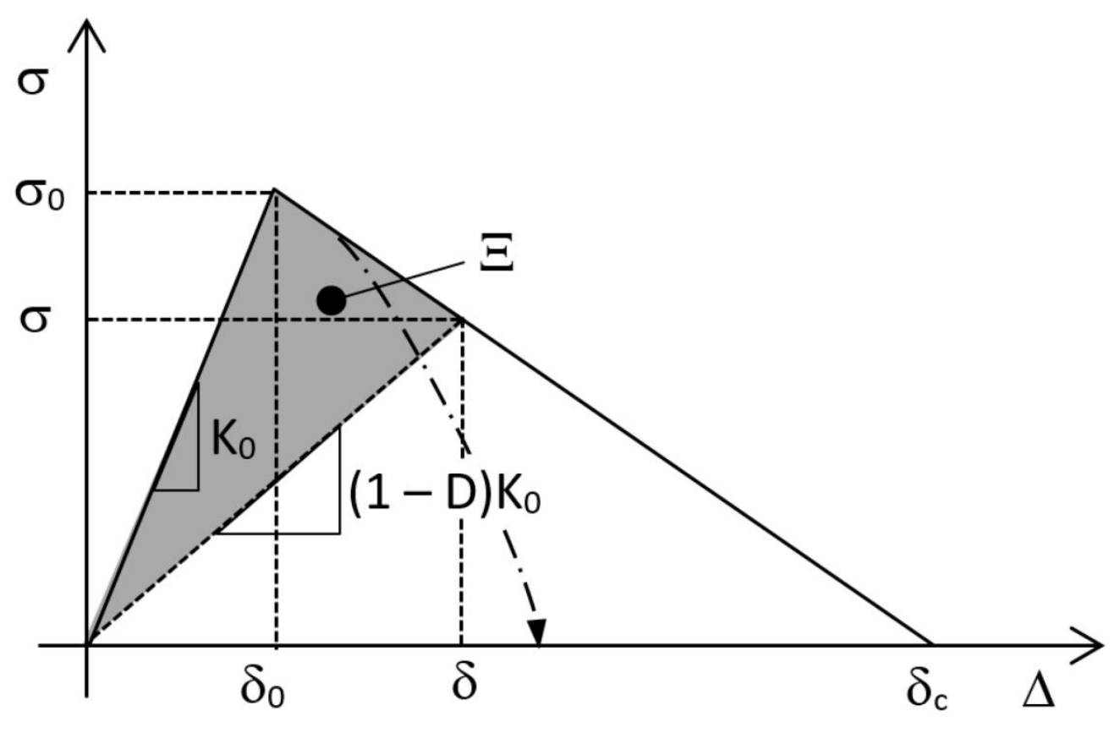
Crack Propagation by Cohesive Zone Modelling

Delamination refers to one of the most common failure modes in laminate fibre reinforced materials. The failure consists in the separation between two plies due to the difference between high interlaminar stresses and low through-thickness strength in the matrix. Interlaminar fractures may be described by the three basic crack opening modes or a combination of these. In most practical applications, a combination of mode I (DCB coupons) and II (ENF coupons) can be found. The Cracked-Lap Shear (CLS) test specimen is of special interest, since it reproduces a shear-dominant mixed-mode ratio like the one seen in aeronautical structures (i.e. stringer-to-skin attachment). This specimen also gives an almost constant mix-mode ratio for different crack lengths, thus facilitating the study of crack-stopping design features.

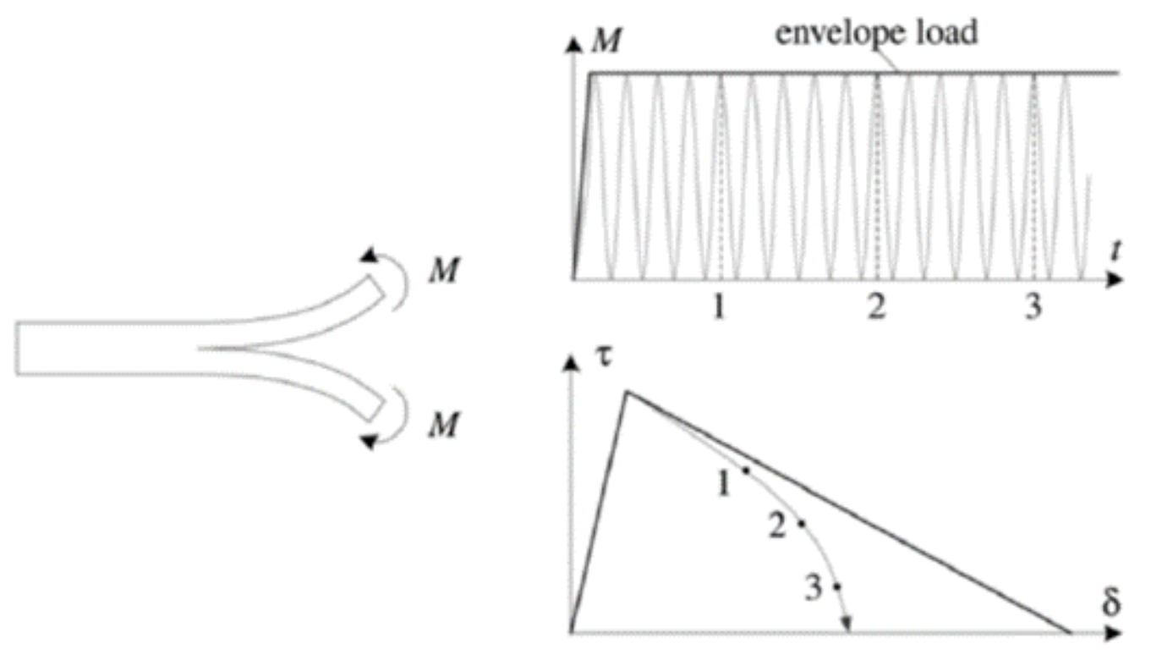




In order to perform disbonding simulations, the **Cohesive Zone Modelling (CZM)** approach is one of the most effective. Cohesive models assume that fracture takes place in a region between two fictitious surfaces (cohesive zone). The model enables progressive deterioration of the material, allowing for decreasing stress transfer as cracking occurs, according to a damage parameter D.



Cohesive Zone Modelling under Fatigue Loads



The cyclic loading can be implemented through the **Envelope Load damage model**. Only the maximum load in the fatigue cycle is modelled and the variation is just considered by means of the load ratio. The load is therefore a continuous time-dependent variable, simplifying how the damage accumulation occurs cycle by cycle. This model is the most used with cohesive elements since it allows to reduce the computational time and complexity.

To evaluate the **damage accumulation** under fatigue loads, the damage is split into quasi-static and fatigue contributions, since the mechanisms of damage are different, and the overall damage is to be considered.

Damage

Calculate current damage

$$d = \frac{\Delta^f(r - \Delta^0)}{r(\Delta^f - \Delta^0)} \qquad r = \frac{\Delta^0\Delta^f}{\Delta^f - d_{-1}(\Delta^f - \Delta^0)}$$

Define Stiffness Matrix

$$D_{ij} = \begin{bmatrix} K_n(1-d) & 0 \\ 0 & K_t(1-d) \end{bmatrix}$$

Define Tangent Stiffness Matrix

$$D_{ij}^{tan} = \begin{bmatrix} D_{11} - K_n H\langle\Delta_3\rangle^2 & -K_n H\Delta_3\Delta_{shear} \\ -K_t H\Delta_{shear}\Delta_3 & D_{22} - K_n H\Delta_{shear}^2 \end{bmatrix}$$

$$H = \frac{\Delta^f\Delta^0}{\Delta^f - \Delta^0}\frac{1}{\lambda^3}$$

Calculate stress tensor

$$\sigma = D_{ij}\Delta_i$$

Fatigue

$$d = d_{static} + d_{fatigue}$$

$$d_{fatigue} = \frac{\partial d}{\partial N}\Delta N$$

$$\frac{\partial d}{\partial N} = \frac{\partial d}{\partial A}\frac{\partial A}{\partial N}$$

Relation damage-damaged area

Crack Growth Rate

Fatigue methods for disbonding are not implemented in commercial software. Standard approaches as Virtual Crack Closure Technique (VCCT) have many limitations.

Therefore, a User Defined subroutine (UMAT) was developed to simulate the cohesive element behaviour in Abaqus. The results from the subroutine have been compared with experimental results for Double Cantilever Beam (DCB) coupons and CLS coupons with and without DAF. Two loading conditions were considered: quasi-static and fatigue loading. The adherends (aluminium for DCB, Glare for CLS) are modelled by solid elements, while the adhesive is modelled as a cohesive layer. For simplicity, a 2D numerical model is used.

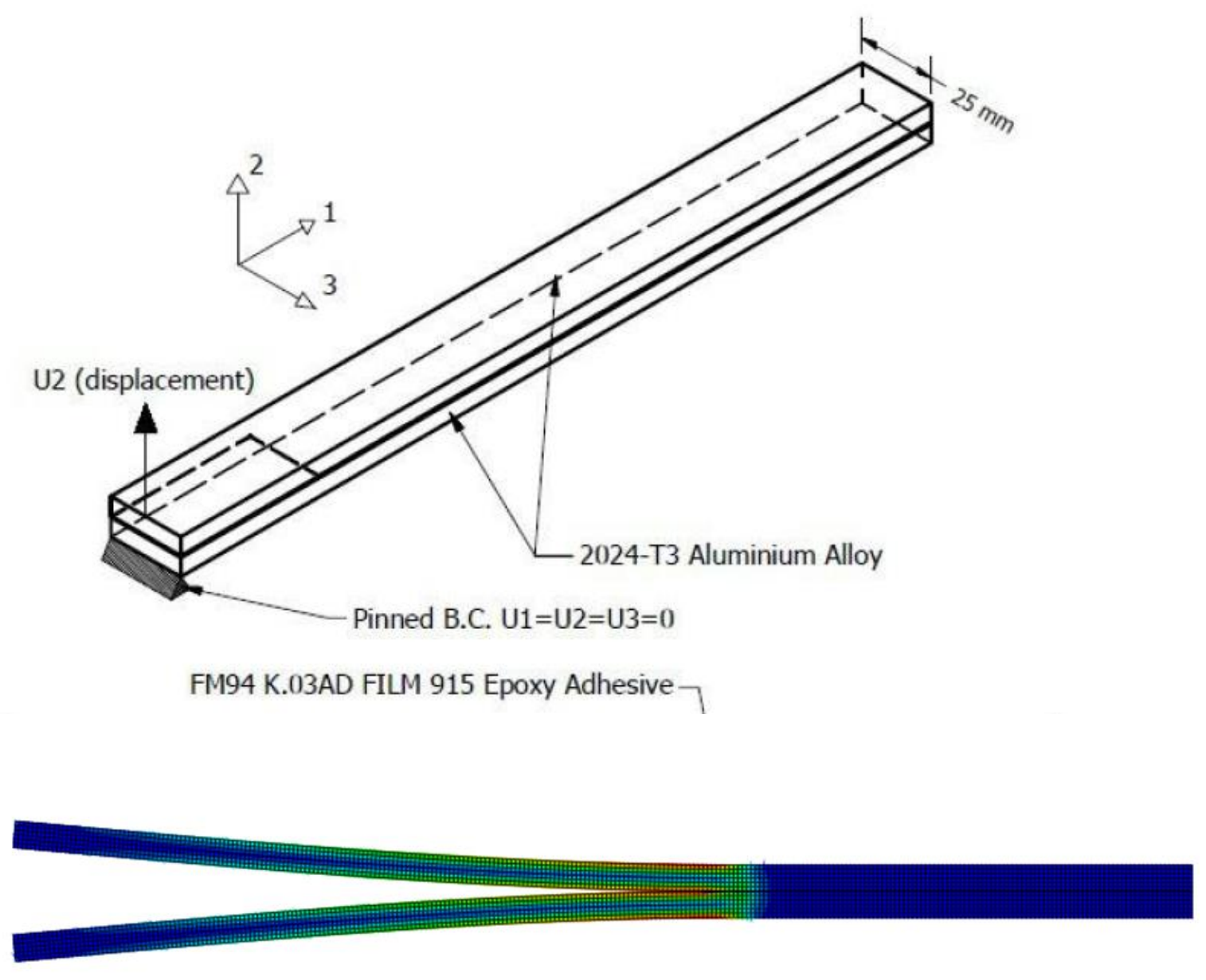
DCB

$$\frac{\partial A}{\partial N} = \begin{cases} C\left(\frac{\Delta G}{G_{Ic}}\right) & if\ G_{th} < G^{max} < G_C \\ 0 & otherwise \end{cases}$$

CLS

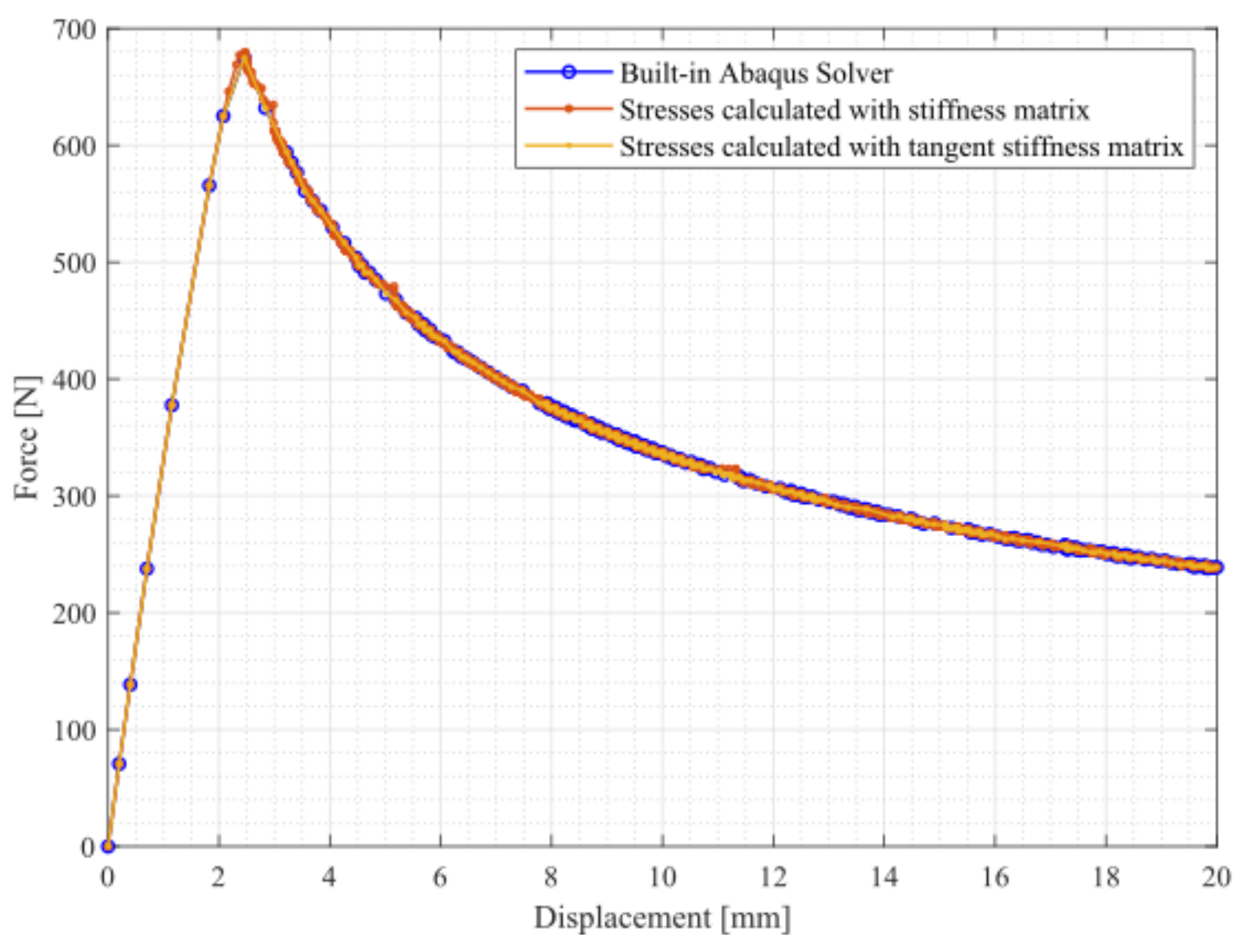
$$\frac{\partial A}{\partial N} = \begin{cases} C\left(\Delta\sqrt{G_{1eq}}\right)^m & if\ \sqrt{G_{theq}} < \sqrt{G_{1eq}^{max}} < \sqrt{G_{Ceq}} \\ 0 & otherwise \end{cases}$$

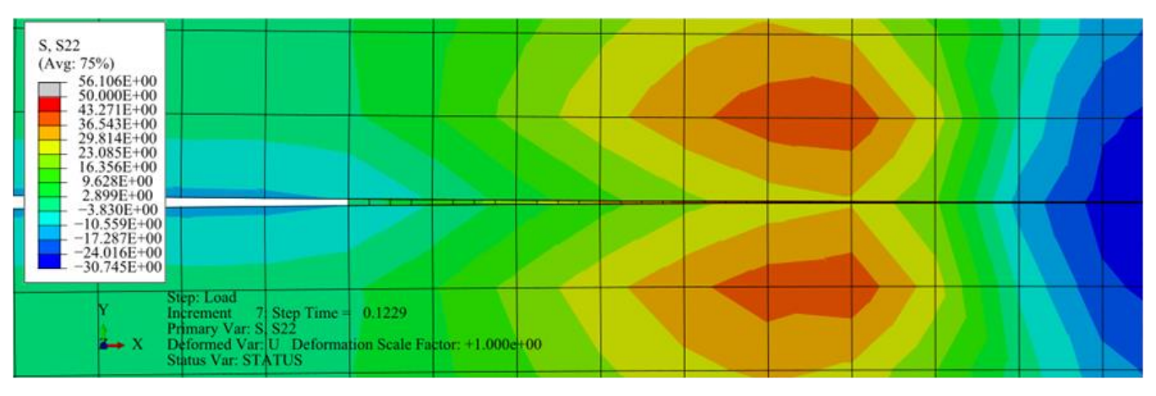
DOUBLE CANTILEVER BEAM (MODE I)



Von Mises stress distribution over the whole specimen

Quasi-static Loading

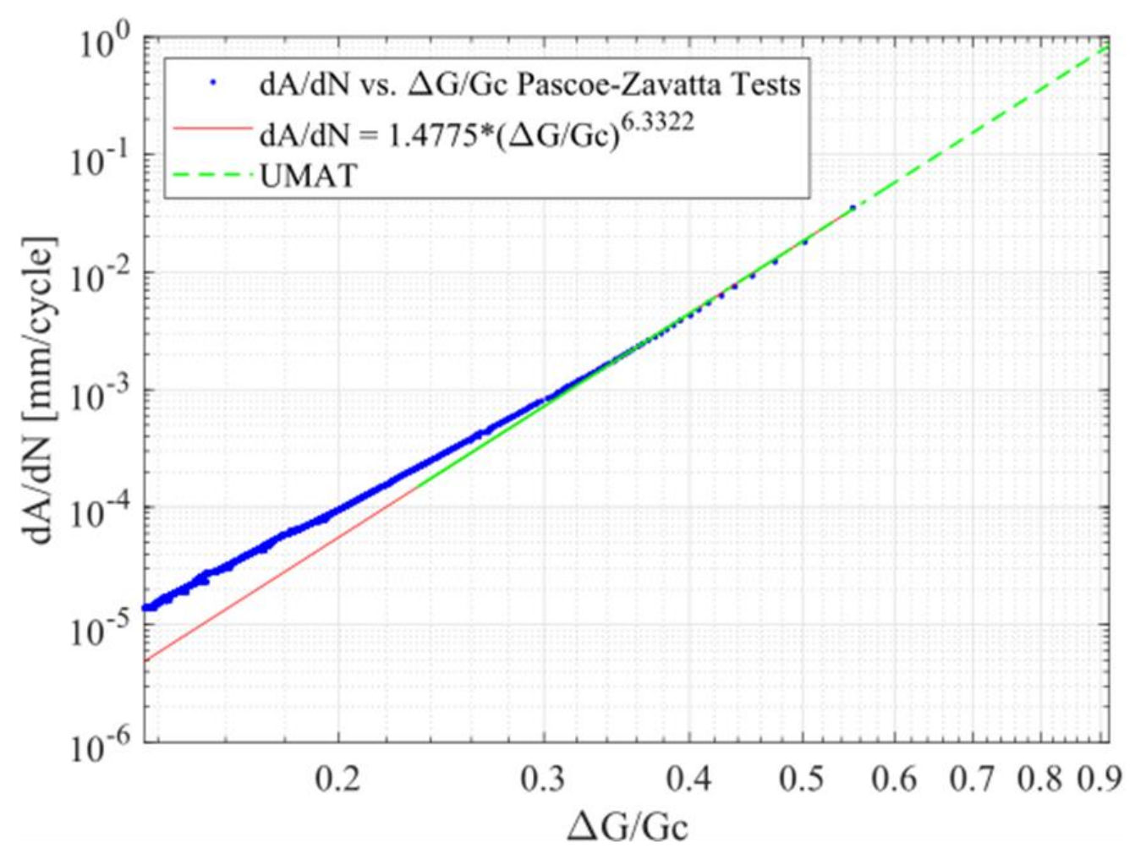


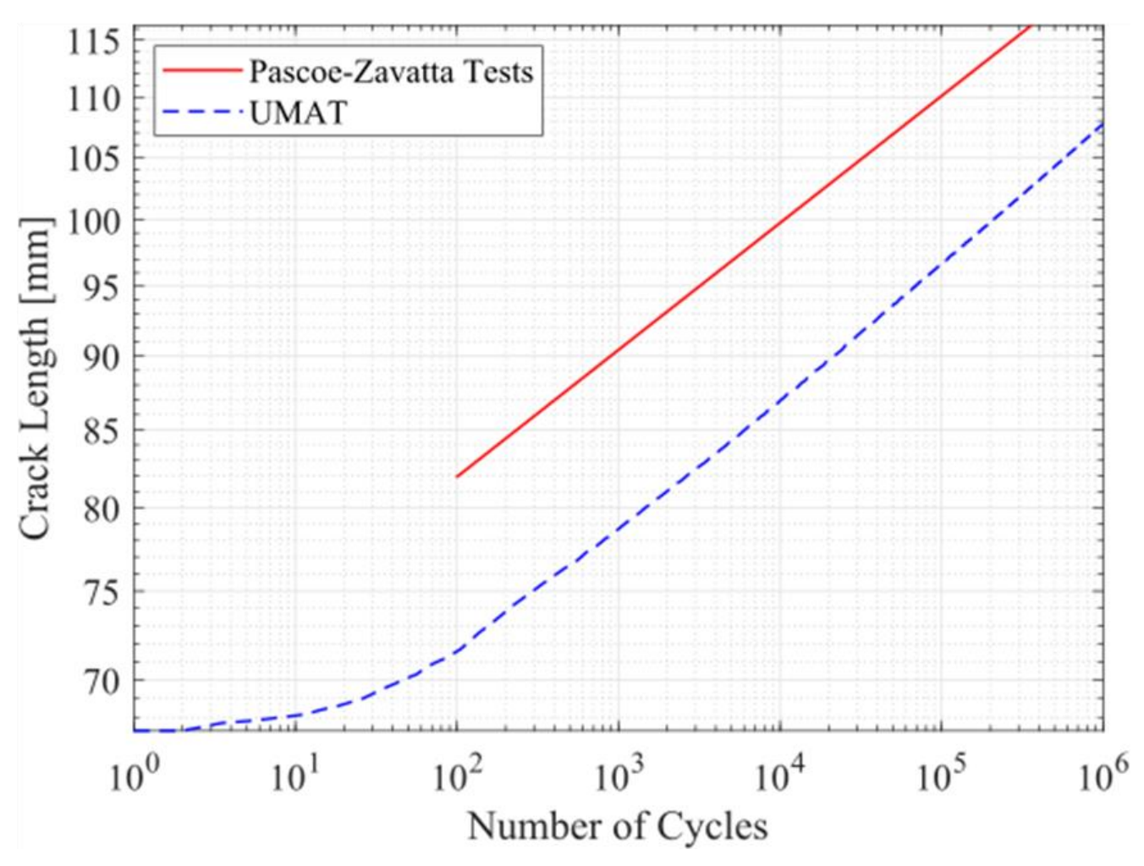


Stress in normal direction around the crack front

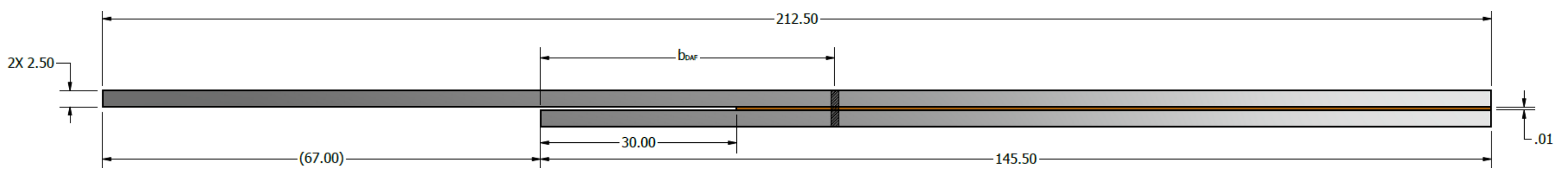
Fatigue Loading

Crack growth rate is almost overlapping. The discrepancy in the crack length is due to pre-cracking in tested specimens.

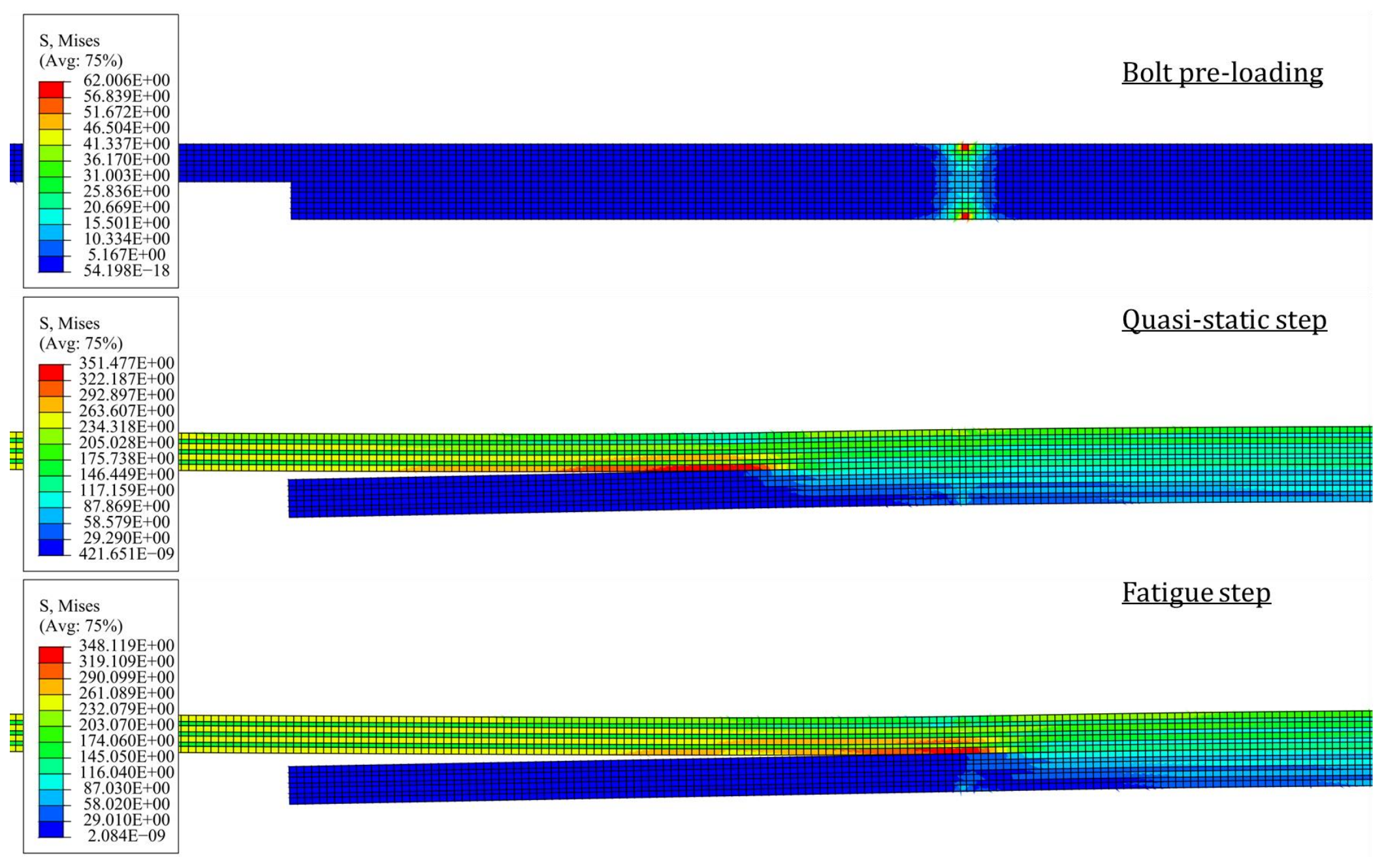




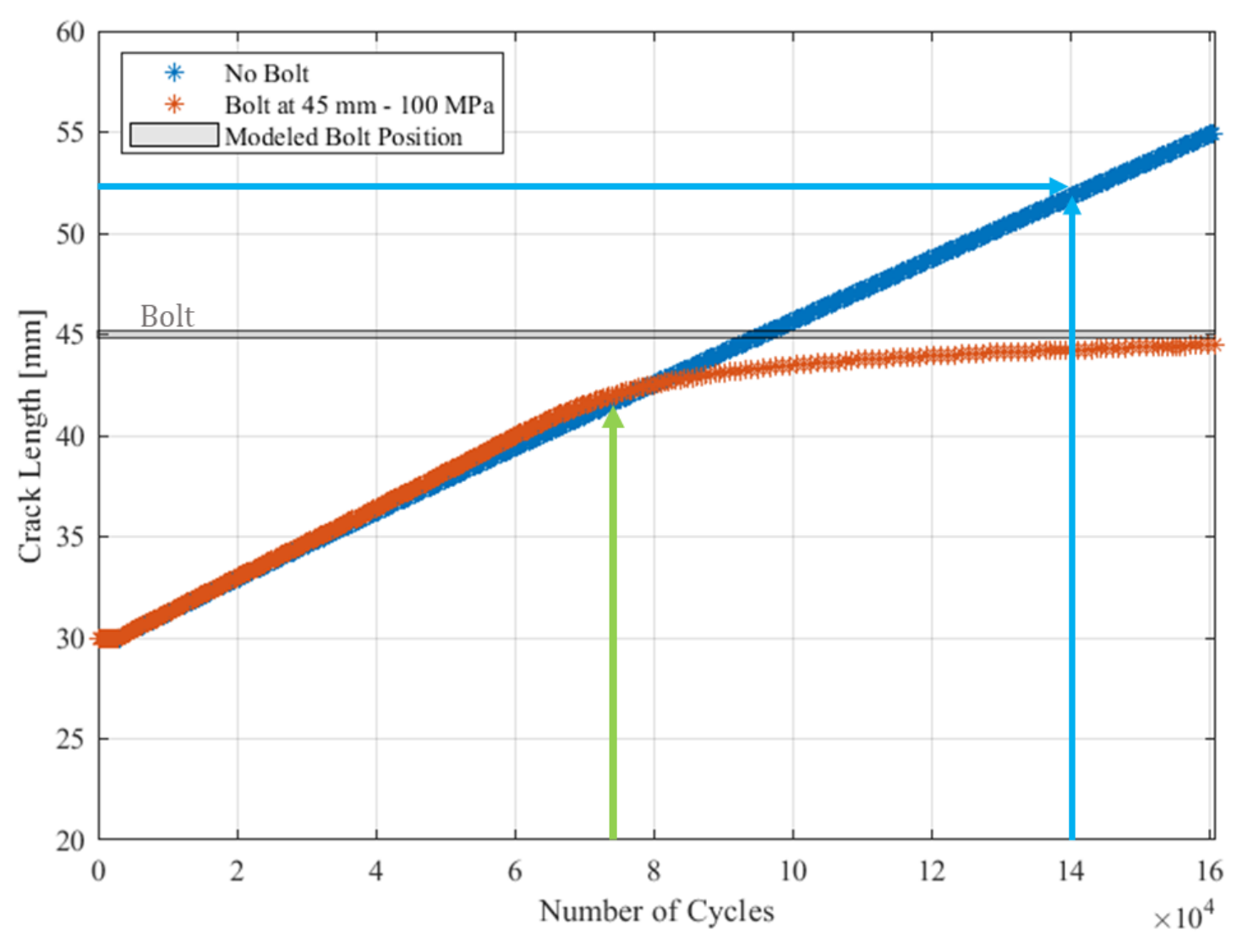
CRACKED-LAP SHEAR (MIXED MODE)



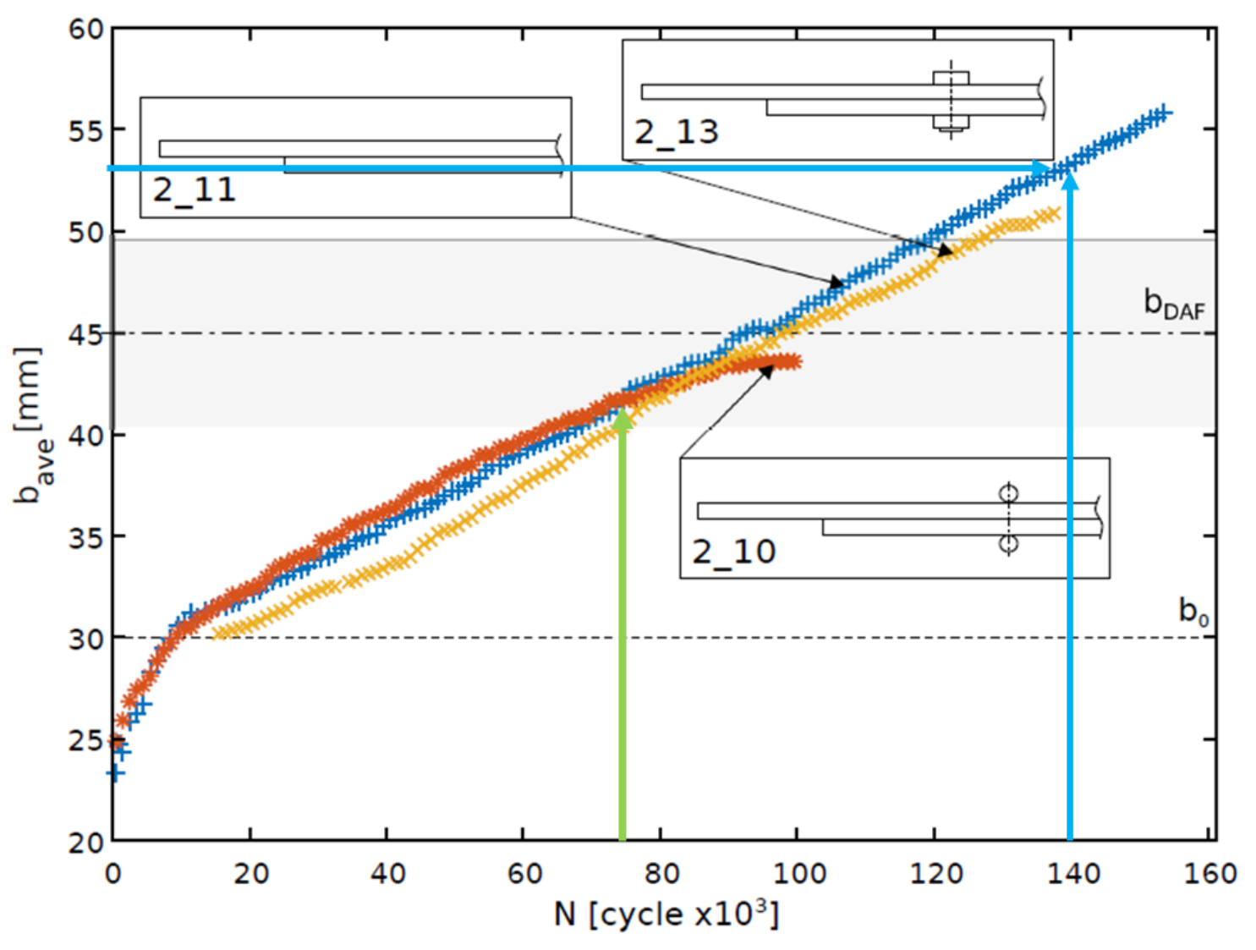
Implementation of Bürger's Model for disbonding: this is an experimental model, with principal stresses to describe disbond growth. Evaluation of the effect of DAFs, to check if crack growth can be stopped.



Simulations



Experimental data



CONCLUSIONS

2D numerical simulations by Cohesive Zone Models of crack growth in adhesively bonded joints under quasi-static and fatigue loading conditions were performed through UMATs.

Results for both DCB and CLS were validated by comparison with experimental results, showing the same crack growth behaviour. For CLS specimen without DAF, the crack opening is always under mixed-mode conditions (due to shear and tension loading), and calculated crack growth followed the Paris' Law. On the other hand, in the presence of the DAF, the mode I opening was suppressed, resulting in a reduction of crack growth and a change of the mixed-mode ratio as the crack front approaches the bolt.

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