Hybrid titanium-CFRP laminates for high-performance bolted joints

Pedro P. Camanho
Department of Mechanical Engineering
University of Porto, Portugal
pcamanho@fe.up.pt

Axel Fink
DLR, German Aerospace Center
Braunschweig
Germany

Cristóvão Cardoso
INEGI, Porto
Portugal

Andreas Obst
European Space Agency – ESTEC
Noordwijk
The Netherlands

Contents

- Introduction.
- Computational models for the analysis of hybrid joints.
    - ⇨ Bearing region.
    - ⇨ Transition region.
- Discussion.
- Conclusions.

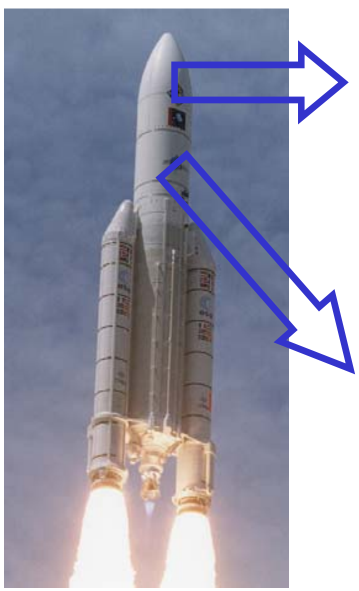
Introduction

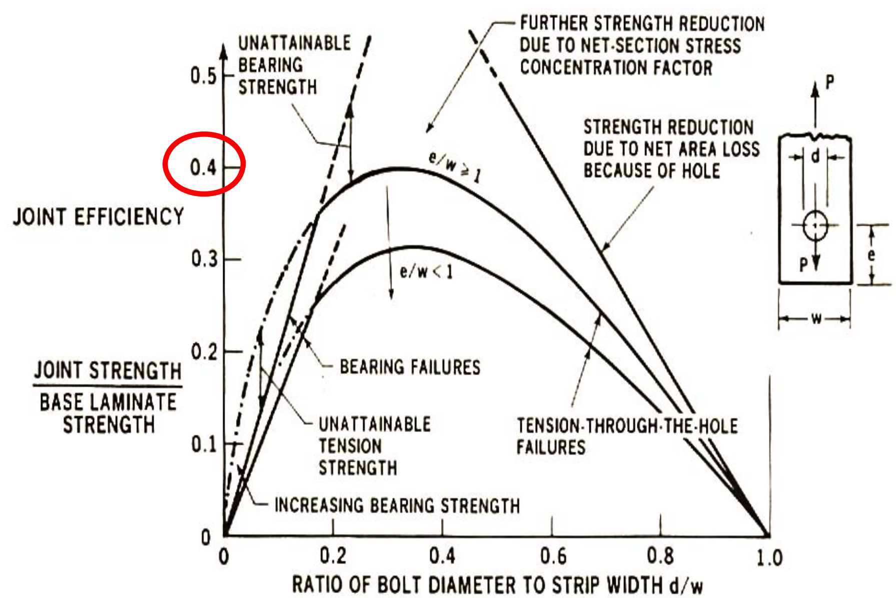
Advantages

- No complex preparation of the parts to be joined.
- Allow component replacement/ inspection.
- Low cost.
- Well suited for thick structures.

Disadvantages

- High stress concentration.
- Low structural efficiency.
- Galvanic corrosion.
- Increased weight.



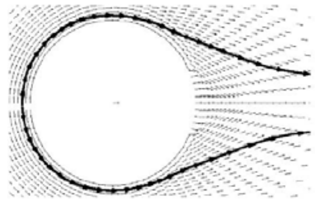


(Hart-Smith, Douglas Report)

Introduction

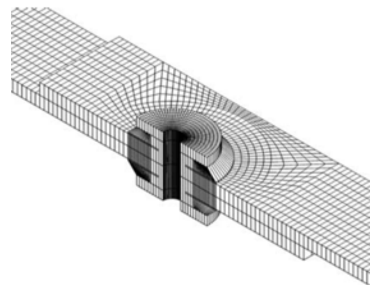
Previously proposed technologies to improve joint efficiency:

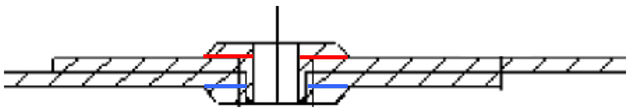
- Fibre steering around holes.



Li et al., Composite Structures, 27, 2002.

- Bonded metallic inserts.

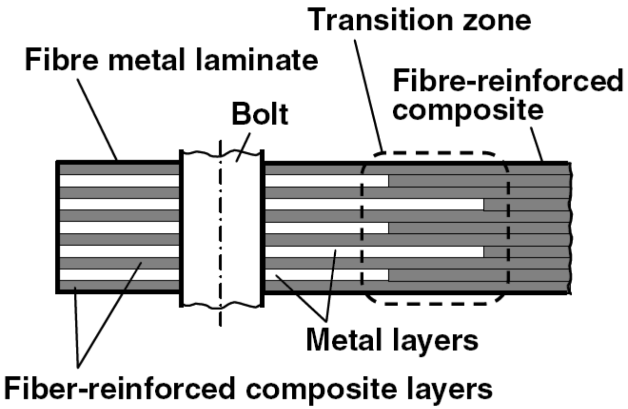




Camanho et at., Composites-B, 36, 2005.

Proposed solution:

- Local reinforcement of the bolted joint using metal layer embedding.



Kolesnikov, Herbeck, Fink, Composite Structures, 83, 2008.

<u>Titanium:</u>

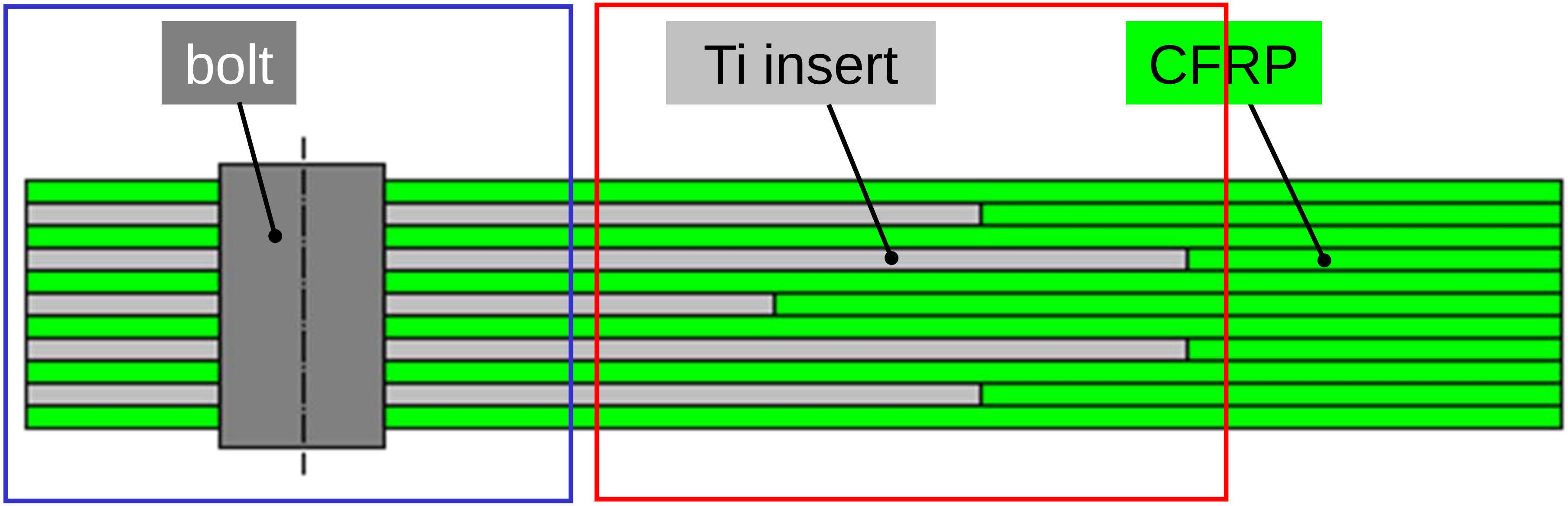
- Relatively low CTE.
- Electrochemical compatibility with carbon.
- High-strength.

Introduction

Objectives:

- To increase the efficiency of highly-loaded composite bolted joints using hybrid CFRP-Titanium laminates.
- To quantify the improvements obtained using hybrid composites.
- To develop and to validate computational methods to support the design of bolted joints based on CFRP-Titanium laminates.

Approach:



FEM/experimental tests: bolt-bearing region

FEM/experimental tests: transition region

Introduction

Material properties

Titanium Ti-15-3-3-3

E (GPa)	$\sigma_{0.2\%}$ (MPa)	σ_r (MPa)
116	1534	1634

$\alpha = 9.2 \times 10^{-6}/°C$

M40J/CYCOM 977-2 CFRP

- Elastic

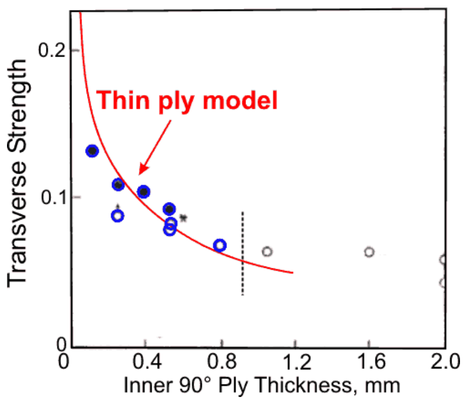
E_1 (MPa)	E_2 (MPa)	G_{12} (MPa)	G_{23} (MPa)	υ_{12}	υ_{23}
211424	6287	3895	2095.7	0.30	0.5

- Strengths

X_T (MPa)	X_C (MPa)	Y_T (MPa)	Y_C (MPa)	S_L (MPa)
2132	994	47	217	67

- Thermal $\alpha_{11} = -0.84 \times 10^{-6}/°C \quad \alpha_{22} = 29.1 \times 10^{-6}/°C$

- Fracture toughness $G_{1+} = 81.5\text{N/mm} \quad G_{1-} = 106.3\text{N/mm}$



Ply	Y_T^{is} (MPa)	S_L^{is} (MPa)
Outer ply, t=0.125mm	71.4	100.4
Outer ply, t=0.25mm	50.5	80.6
Inner ply, t=0.125mm	112.9	123.3
Inner ply, t=0.25mm	79.8	100.4

Introduction

Material properties

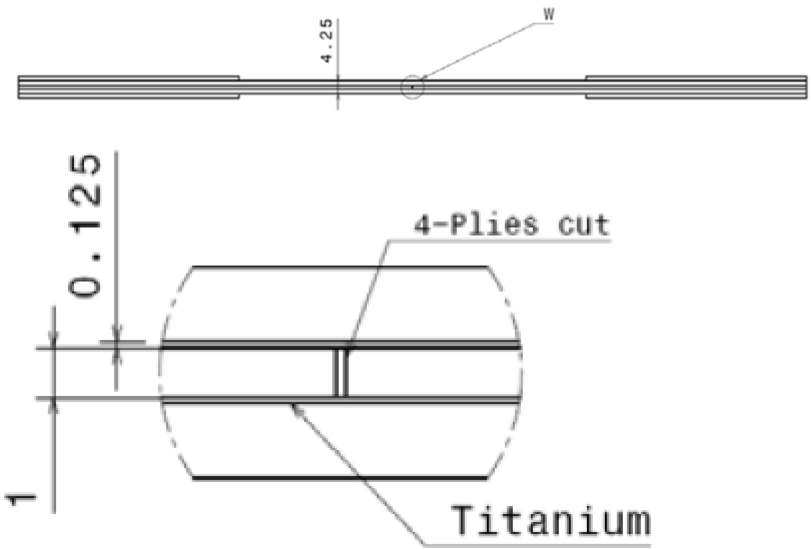
- Fracture toughness

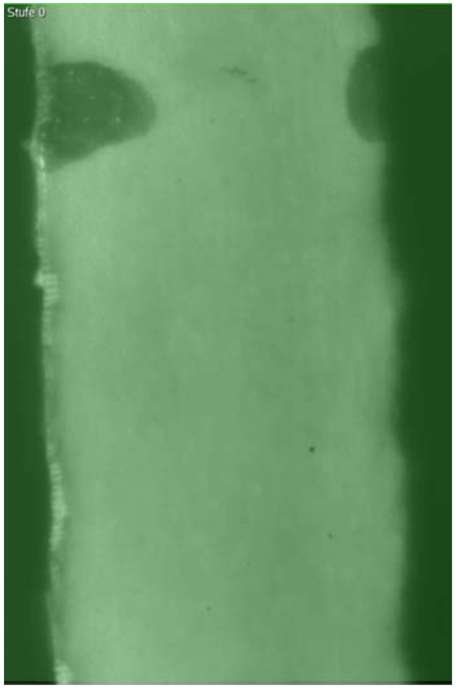
	Titanium-CFRP	CFRP-CFRP
G_{Ic} (N/mm)	0.179	0.199
G_{IIc} (N/mm)	2.784	0.699

DCB test specimen

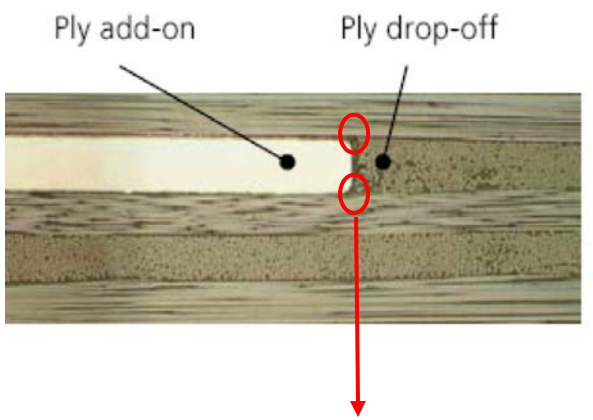
0,25	0	0	A
0,25	Ti	Ti	A
0,25	0	0	A
0,25	0	0	A
0,25	Ti	Ti	A
0,25	0	0	A
0,125	Ti	Ti	A
0,25	0	0	B
0,25	Ti	Ti	B
0,25	0	0	B
0,25	0	0	B
0,25	Ti	Ti	B
0,25	0	0	B

TCT test specimen



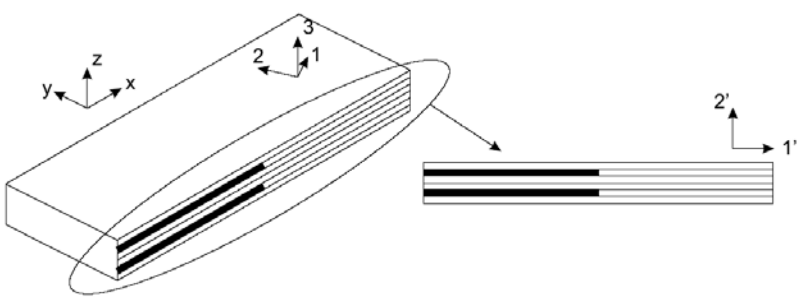


Transition region – modeling strategy



Multi-material corners: singular points

- Plane stress elements (Abaqus CPS4).
- Cohesive elements used to simulate delamination and transverse matrix cracking (Abaqus user subroutine UEL)*.
- Thermal step and subsequent tensile loading.
- Final failure predicted when failure of the 0º plies occurs (average stress criterion used).
- Elasto-plastic model for the titanium plies.

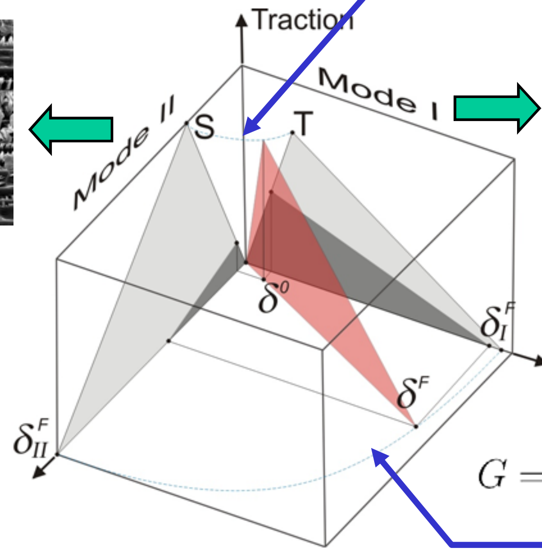


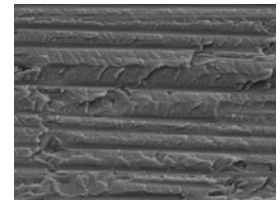
*Turon, Camanho, Dávila, Costa, Mechanics of Materials, 38, 2006.

Computational models

Transition region – modeling strategy

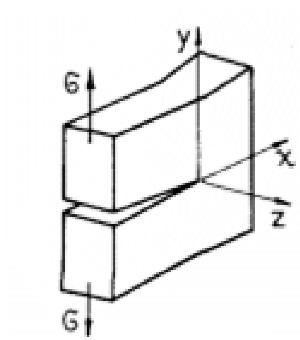
$$\left(\tau^0\right)^2 = \left(\tau_3\right)^2 + \left(\tau_1\right)^2 + \left(\tau_2\right)^2 = \left(\tau_3^o\right)^2 + \left(\left(\tau_{shear}^o\right)^2 - \left(\tau_3^o\right)^2\right)[B]^\eta$$



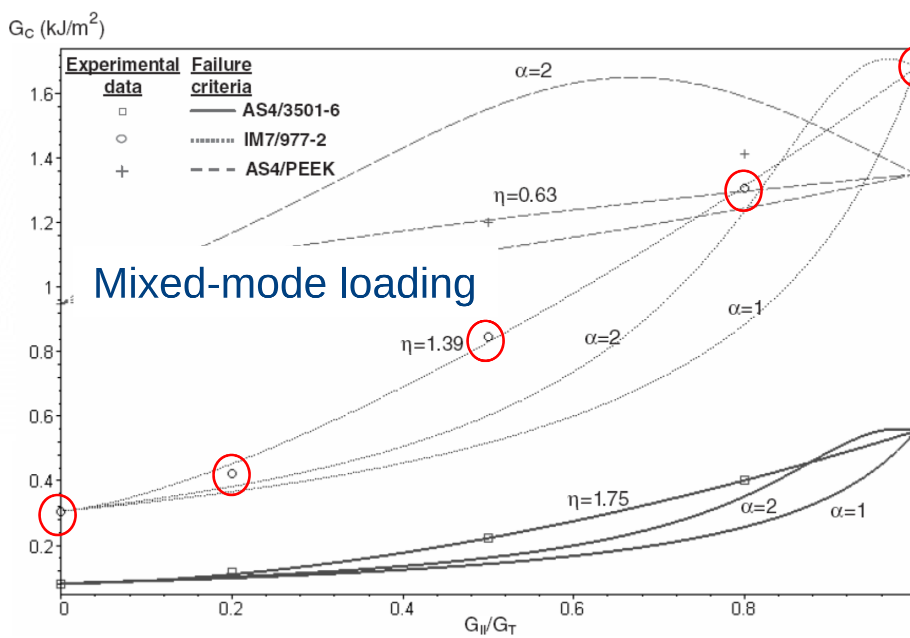


- Traction interaction law maps damage initiation
- Mixed-mode critical G_c maps delamination growth

$$G = G_{Ic} + \left(G_{IIc} - G_{Ic}\right)\left(\frac{G_{shear}}{G_T}\right)^\eta$$

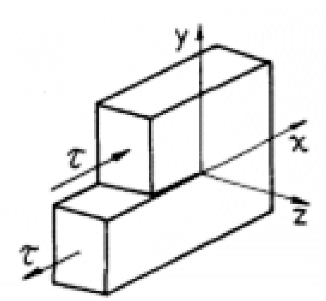


Pure mode I loading



Mixed-mode loading

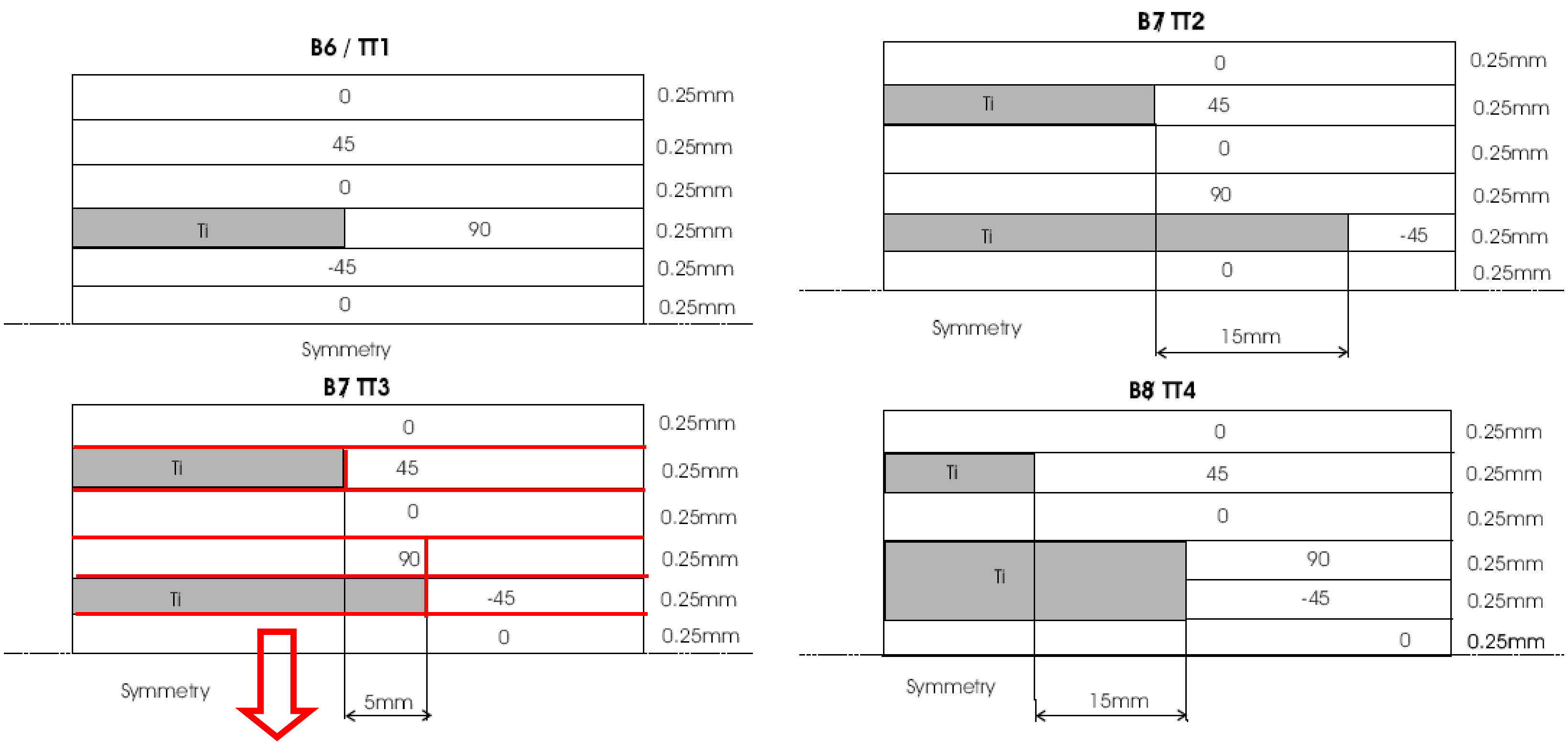
Pure mode II loading



Computational models

Transition region – modeling strategy

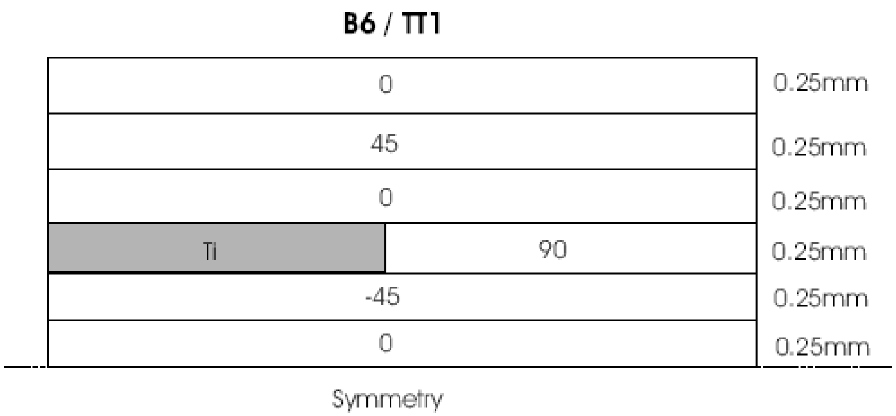
Reference	Stacking sequence
TT1	$[0/+45/0/\mathrm{Ti}\ 90/-45/0]_s$
TT2	$[0/\mathrm{Ti}\ +45/0/90/\mathrm{Ti}\ -45/0]_s$
TT3	$[0/\mathrm{Ti}\ +45/0/90/\mathrm{Ti}\ -45/0]_s$
TT4	$[0/\mathrm{Ti}\ +45/0/\mathrm{Ti}\ 90/\mathrm{Ti}\ -45/0]_s$



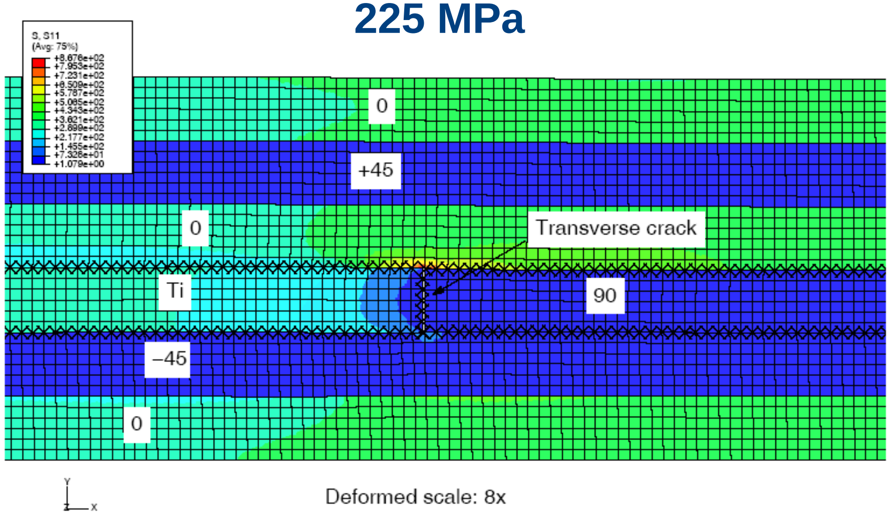
Cohesive elements

Computational models

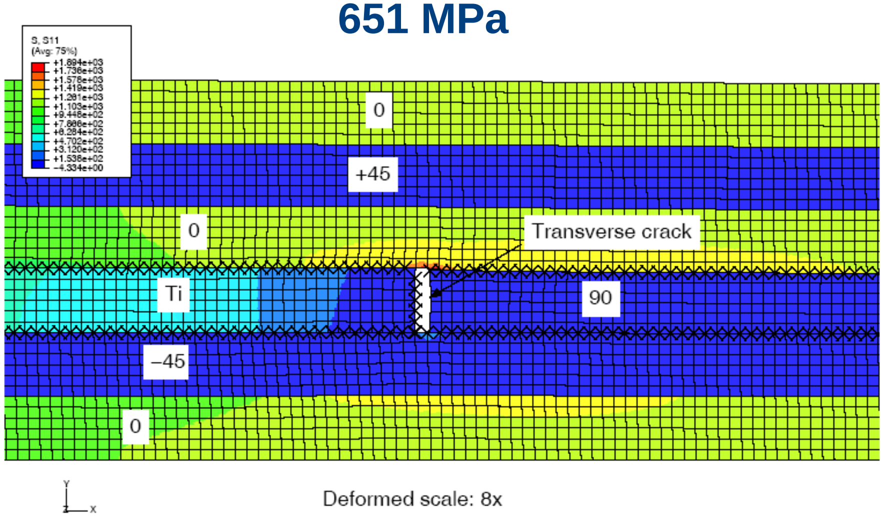
Specimen TT1



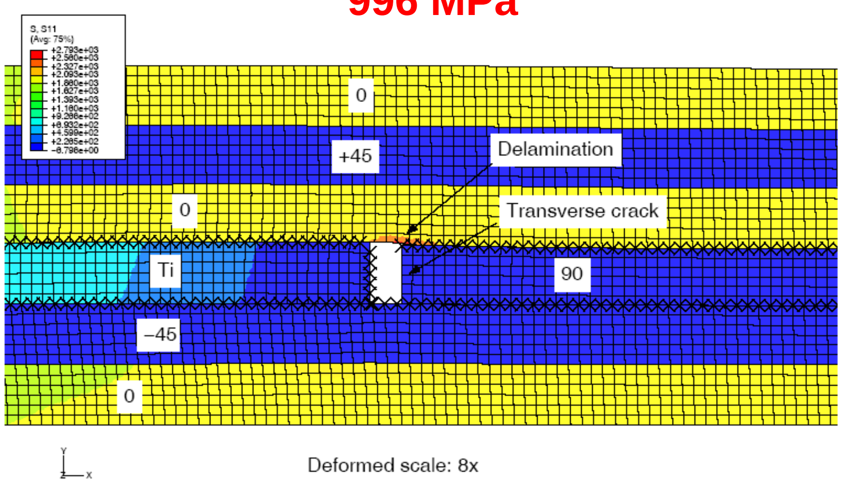
225 MPa



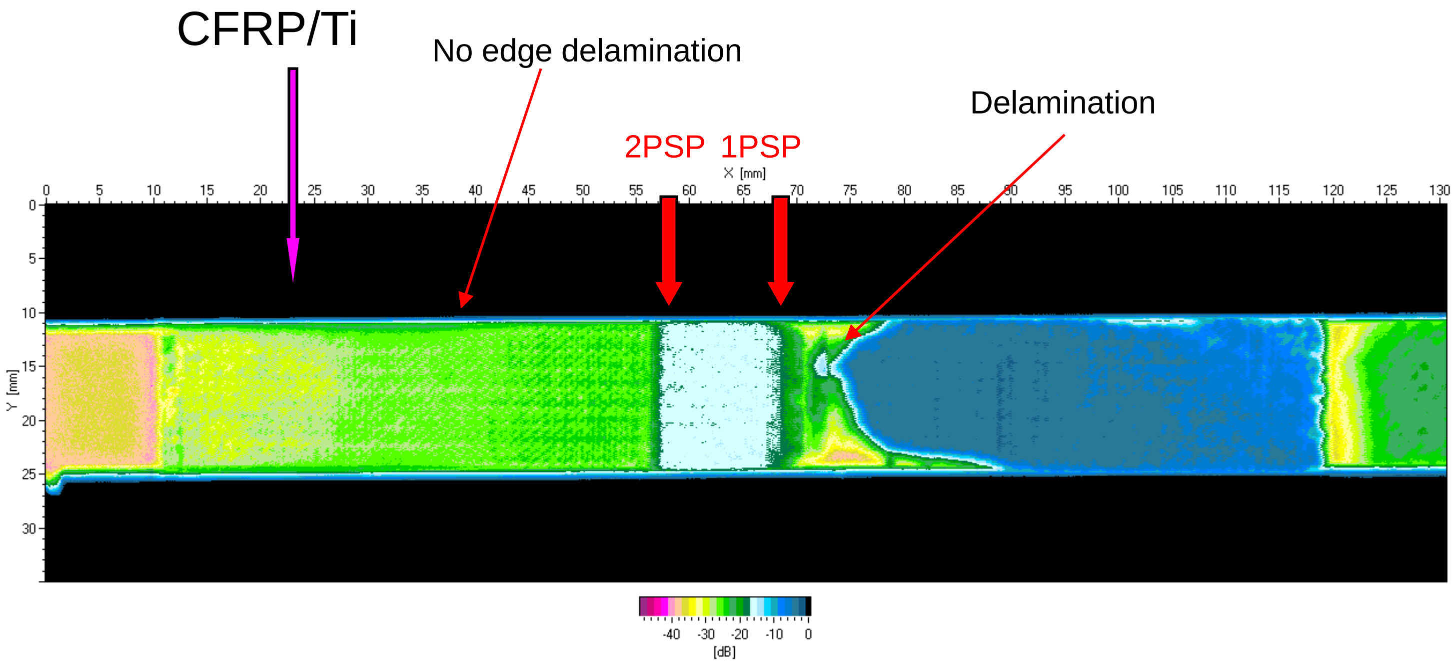
651 MPa



996 MPa

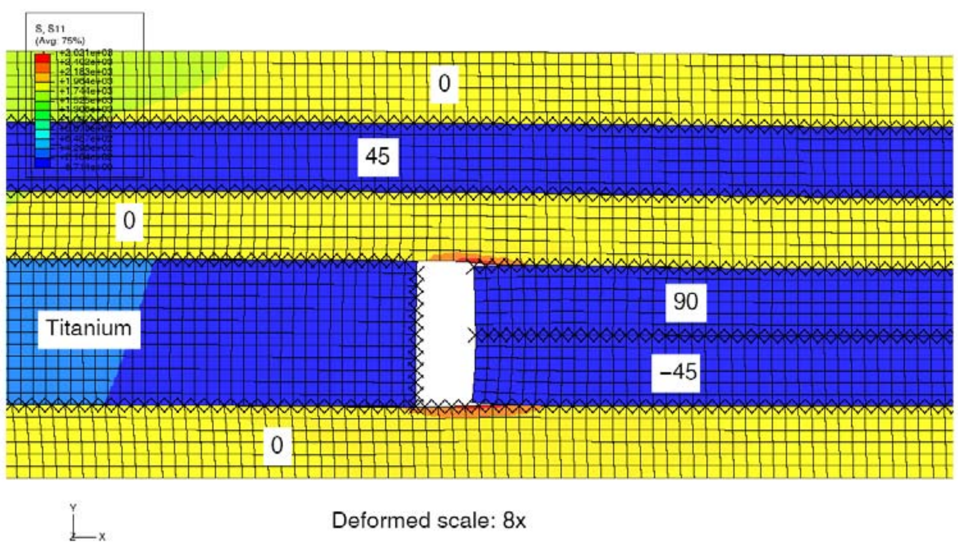


Computational models



TT4

@ 996MPa

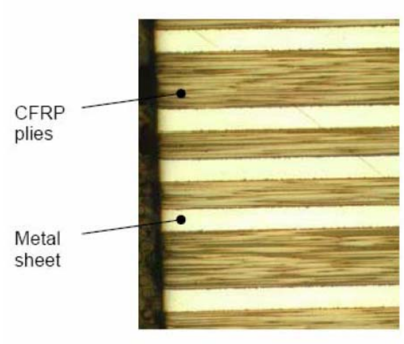


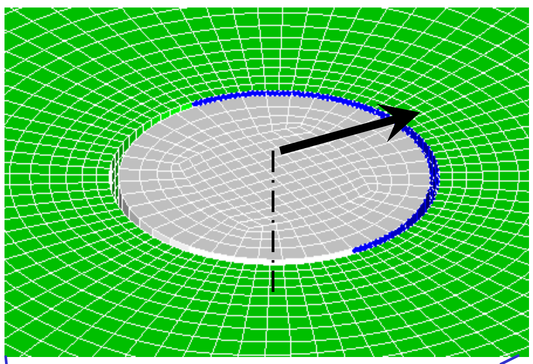
Ref.	$\bar{\sigma}^{\infty}$ (MPa), FE	$\bar{\sigma}^{\infty}$ (MPa), test	Error (%)
TT1	ref.	ref.	n/a
TT2	1007.4	1005.9	+0.1
TT3	1087.2	1024.4	+6.1
TT4	996.5	988.7	+0.8

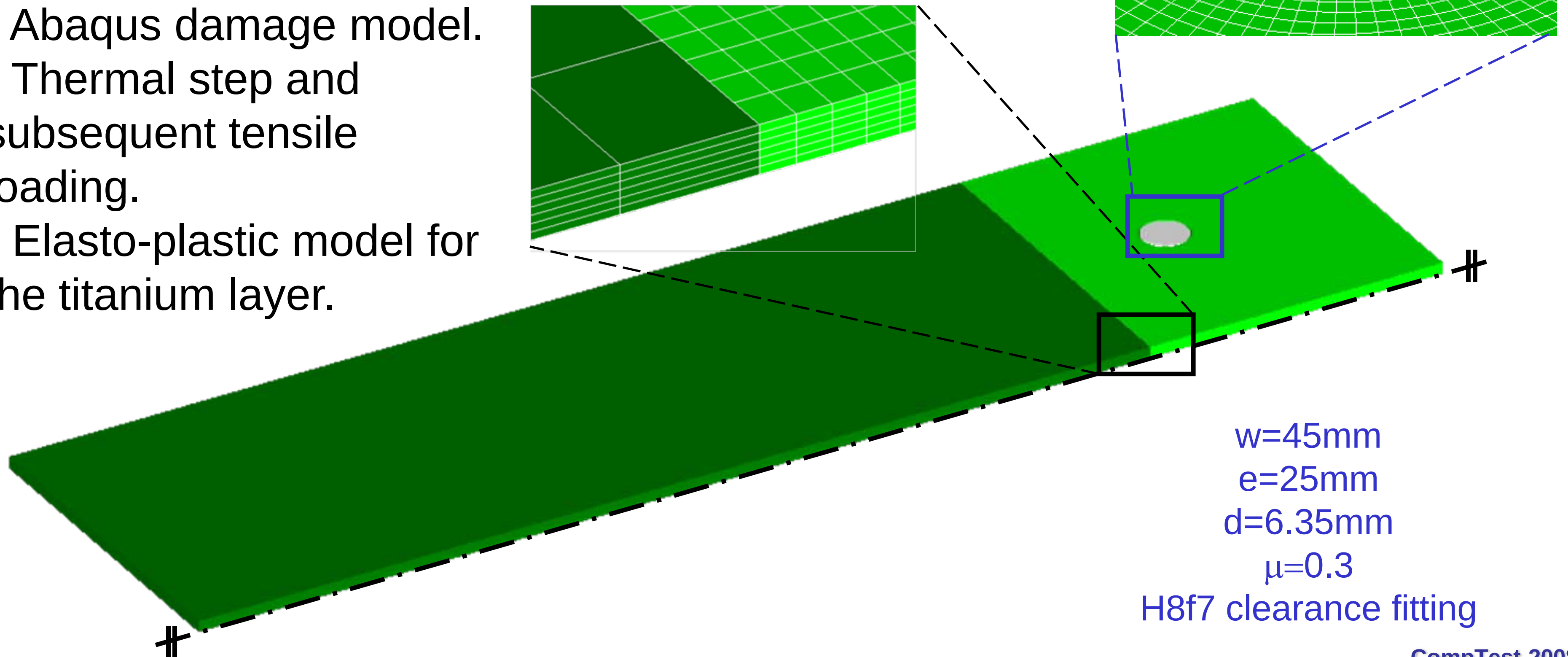
Computational models

Bearing region – modeling strategy

- Three-dimensional model (Abaqus SC8R elements).
- One element per ply thickness.
- Abaqus damage model.
- Thermal step and subsequent tensile loading.
- Elasto-plastic model for the titanium layer.







w=45mm
e=25mm
d=6.35mm
μ=0.3
H8f7 clearance fitting

Computational models

Bearing region – Abaqus damage model

Hashin failure criteria

$$\left(\frac{\tilde{\sigma}_{11}}{X_T}\right)^2 - 1 \leq 0$$

$$\left(\frac{\tilde{\sigma}_{11}}{X_C}\right)^2 - 1 \leq 0$$

$$\left(\frac{\tilde{\sigma}_{22}}{Y_T}\right)^2 + \left(\frac{\tilde{\sigma}_{12}}{S_L}\right)^2 - 1 \leq 0$$

$$\left(\frac{\tilde{\sigma}_{22}}{2S_T}\right)^2 + \left[\left(\frac{Y_C}{2S_T}\right)^2 - 1\right]\frac{\tilde{\sigma}_{22}}{Y_C} + \left(\frac{\tilde{\sigma}_{12}}{S_L}\right)^2 - 1 \leq 0$$

Damage variables

$$d_f = \begin{cases} d_f^t \text{ if } \tilde{\sigma}_{11} \geq 0 \\ d_f^c \text{ if } \tilde{\sigma}_{11} < 0 \end{cases} \qquad d_m = \begin{cases} d_m^t \text{ if } \tilde{\sigma}_{22} \geq 0 \\ d_m^c \text{ if } \tilde{\sigma}_{22} < 0 \end{cases}$$

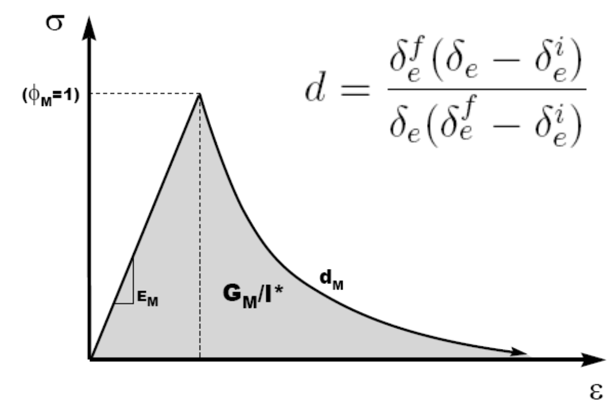
$$d_s = 1 - (1 - d_f^t)(1 - d_f^c)(1 - d_m^t)(1 - d_m^c)$$

Effective stress tensor

$$\tilde{\sigma} = \mathbf{C^0} : \varepsilon \leftarrow \tilde{\sigma} = \mathbf{M} : \sigma \qquad \varepsilon = (\mathbf{C^0})^{-1} : \mathbf{M} : \sigma = \mathbf{H} : \sigma$$

$$\mathrm{M} = \begin{bmatrix} \frac{1}{1-d_f} & 0 & 0 \\ 0 & \frac{1}{1-d_m} & 0 \\ 0 & 0 & \frac{1}{1-d_s} \end{bmatrix} \qquad \mathbf{H} = \begin{bmatrix} \frac{1}{(1-d_f)E_1} & -\frac{\upsilon_{21}}{E_2} & 0 \\ -\frac{\upsilon_{12}}{E_1} & \frac{1}{(1-d_m)E_2} & 0 \\ 0 & 0 & \frac{1}{(1-d_s)G_{12}} \end{bmatrix}$$

Damage evolution

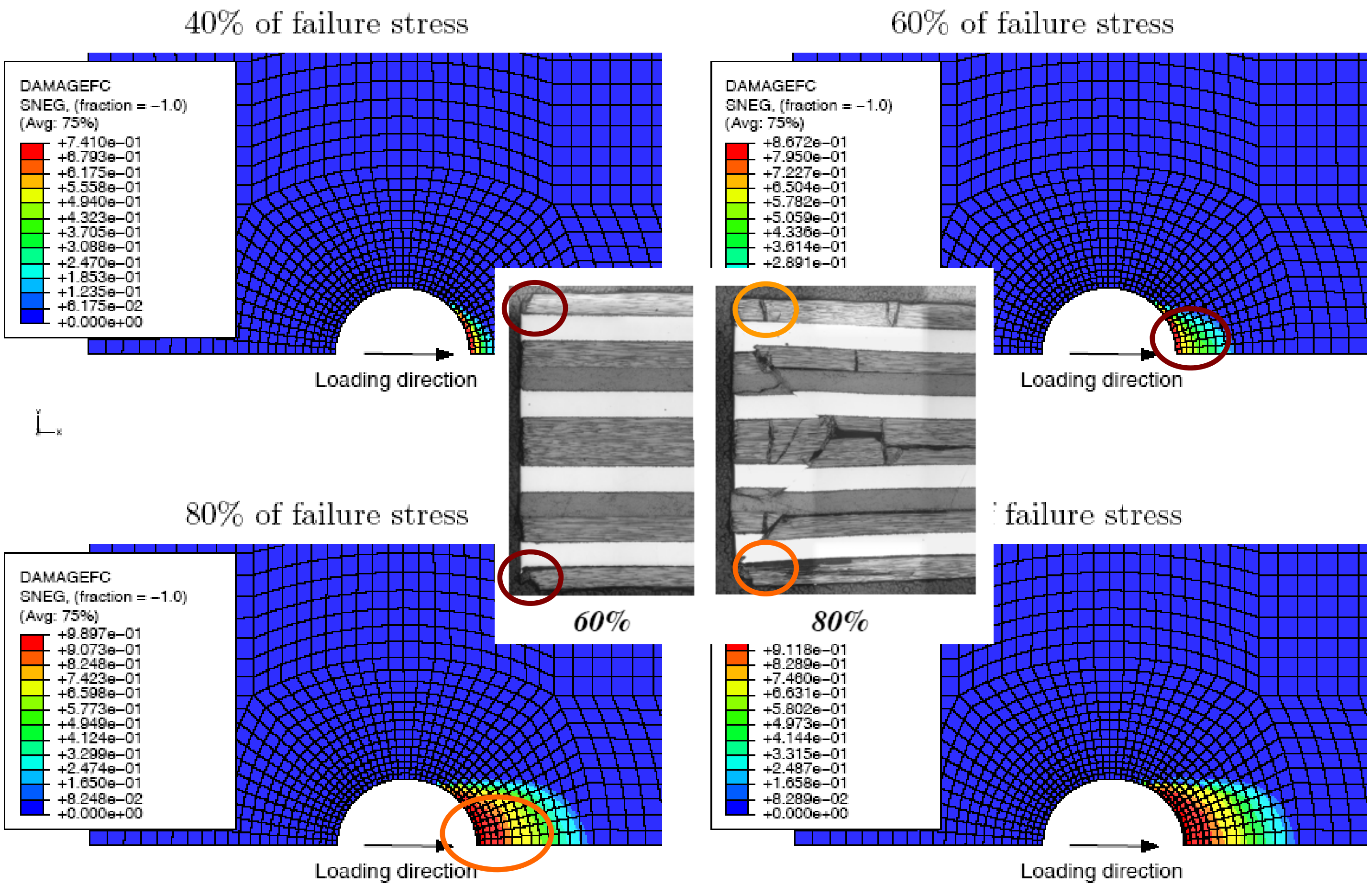


$$d = \frac{\delta_e^f(\delta_e - \delta_e^i)}{\delta_e(\delta_e^f - \delta_e^i)}$$

Computational models

Bearing region – B7

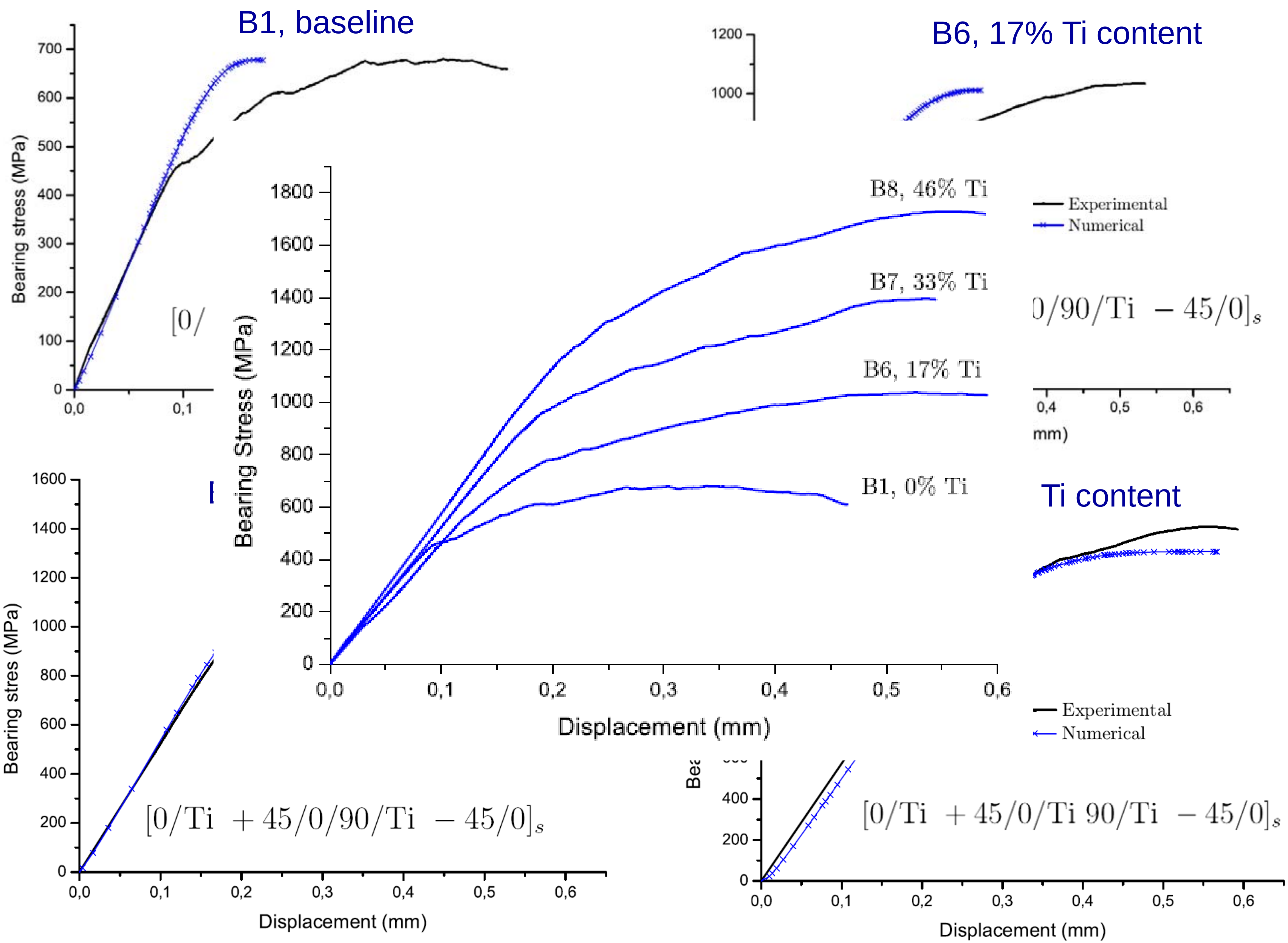
$$[0/\mathrm{Ti}\ +45/0/90/\mathrm{Ti}\ -45/0]_s$$



- Fibre kinking
- Transverse compressive failure.
- Plastic deformation of the titanium layers.

U.PORTO

Computational models



Computational models

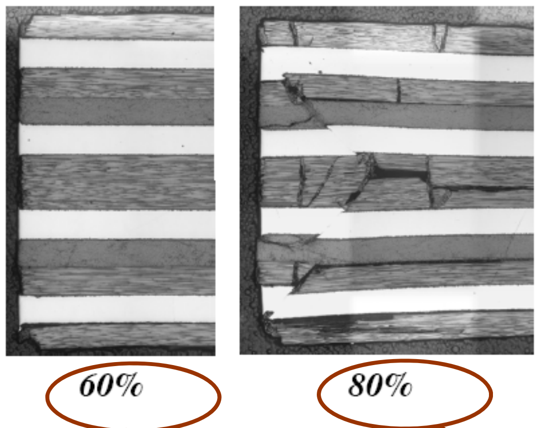
Maximum bearing stress

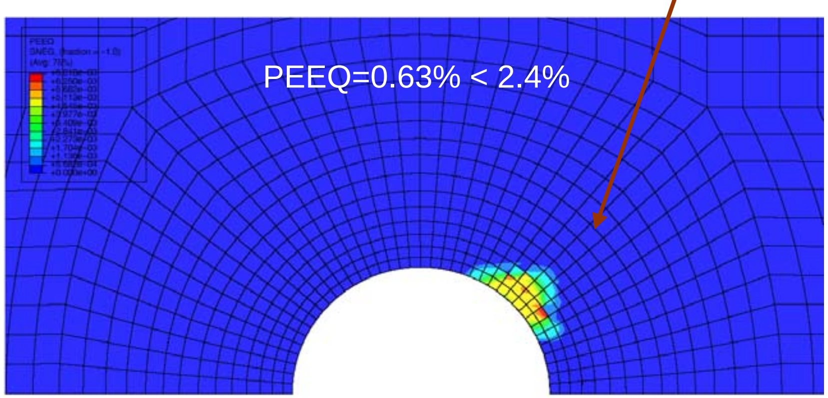
Ref.	$\bar{\sigma}^b$ (MPa)-FE	$\bar{\sigma}^b$ (MPa)-Exp.	Error (%)
B1	678.3	680.6	0.3
B6	1036.2	1012.4	-2.3
B7	1269.1	1395.5	-9.1
B8	1608.7	1729.1	-7.0

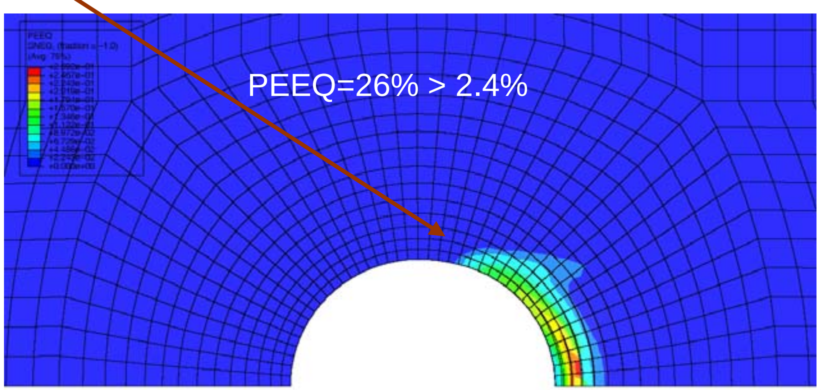
Bearing stress at onset of non-linearity

Ref.	σ_e^b (MPa)-FE	σ_e^b (MPa)-Exp.	Error (%)
B1	500	441.7	+13.2
B6	650	550.1	+18.2
B7	767	758.5	+1.1
B8	1000	933.5	+7.1

B7, 33% Ti content







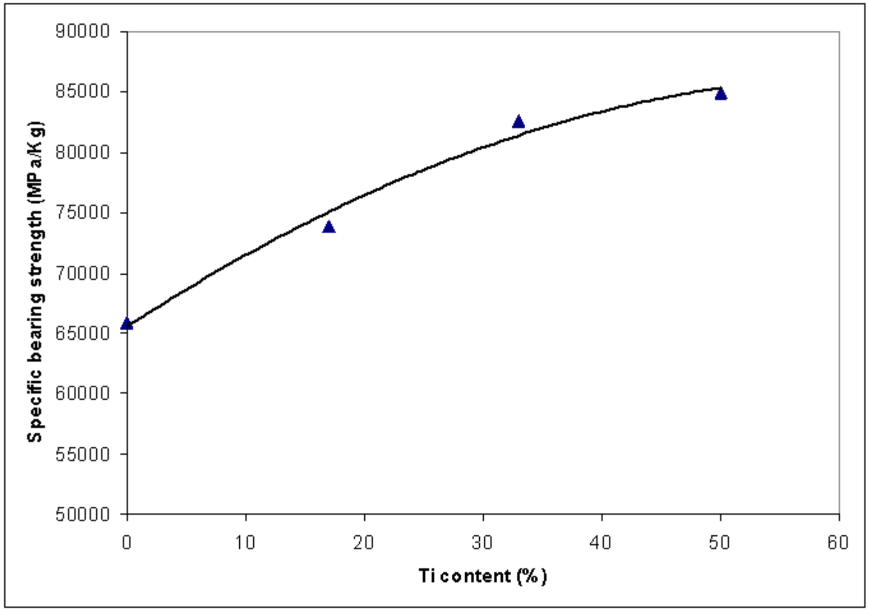
Discussion

Analysis of coupling effectiveness at the transition region

Specimen	Max. bearing stress (MPa)	Remote strength (bearing region) (MPa)	Remote strength (transition region) (MPa)
B6	1012	142	1069
B7	1396	195	1006
B8	1729	242	1024

Analysis of joint efficiency and weight

Specimen	Improvement on bearing strength	Specific bearing strength (MPa/kg)	Joint stiffness (MPa/mm)
B1	Reference	65901	4391
B6	+ 49%	73869	4640
B7	+ 105%	82603	5255
B8	+154%	84957	5777



Conclusions

- The computational models developed are able to predict the response of both the transition region and of the bolt-bearing region.

- For all the configurations investigated, there are no extensive delaminations prior to fibre failure at the transition region.

- Reducing the step distance from 15mm to 5mm does not affect the strength of the transition region.

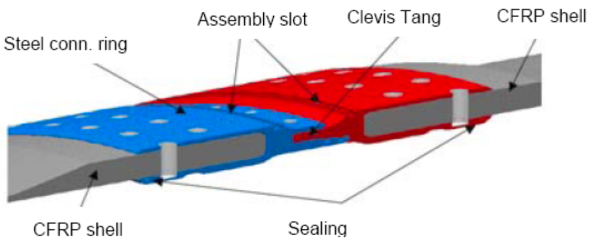
- The hybrid bolted joints fails by bearing, as a result of the accumulation of fibre and matrix compressive failure and plastic deformation and fracture of the titanium plies.

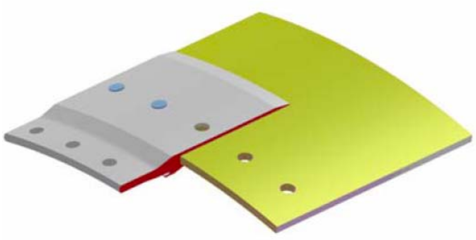
- The predicted strength of the transition region is always higher than the strength of the bolt bearing region – the transition region is not critical.

- The bearing strength and bearing stiffness of the laminate increases with the titanium content (up to 154% for the bearing strength and 32% for the bearing stiffness).

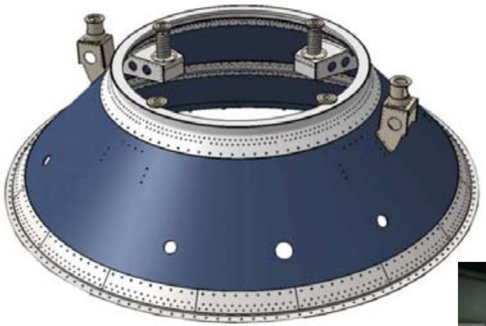
Future/ongoing work

Arianne MT-boosters





Vega payload adapter



Acknowledgements

European Space Agency – ESA – ESTEC

Project BOJO - Increasing Bolted Joint Performance for CFRP