DEVELOPMENT OF A C/C-SIC SANDWICH OPTICAL BENCH

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DLR

Outline

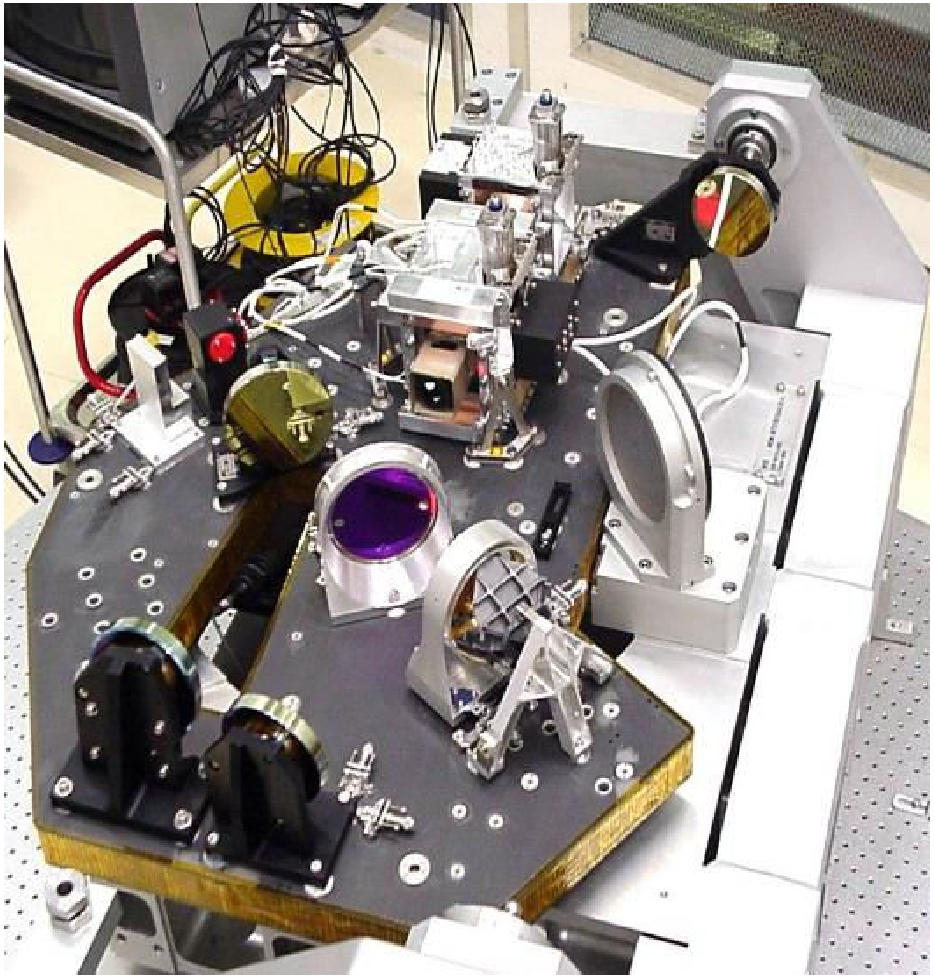
- C/C-SiC for optical benches
- Sandwich manufacture
- Preliminary design and characterization
- Demonstrator design and manufacture
- Summary

Optical Benches (OB)

- Platform for laser systems and optical elements
- Very rigid for minimal deflection
- Stable alignment of optical elements
  - Temperature changes and moisture
  - Vibrations (launch, operation)
  - Long term space environment
  - Typical materials: SiC, Zerodur, CFRP sandwich, C/C sandwich

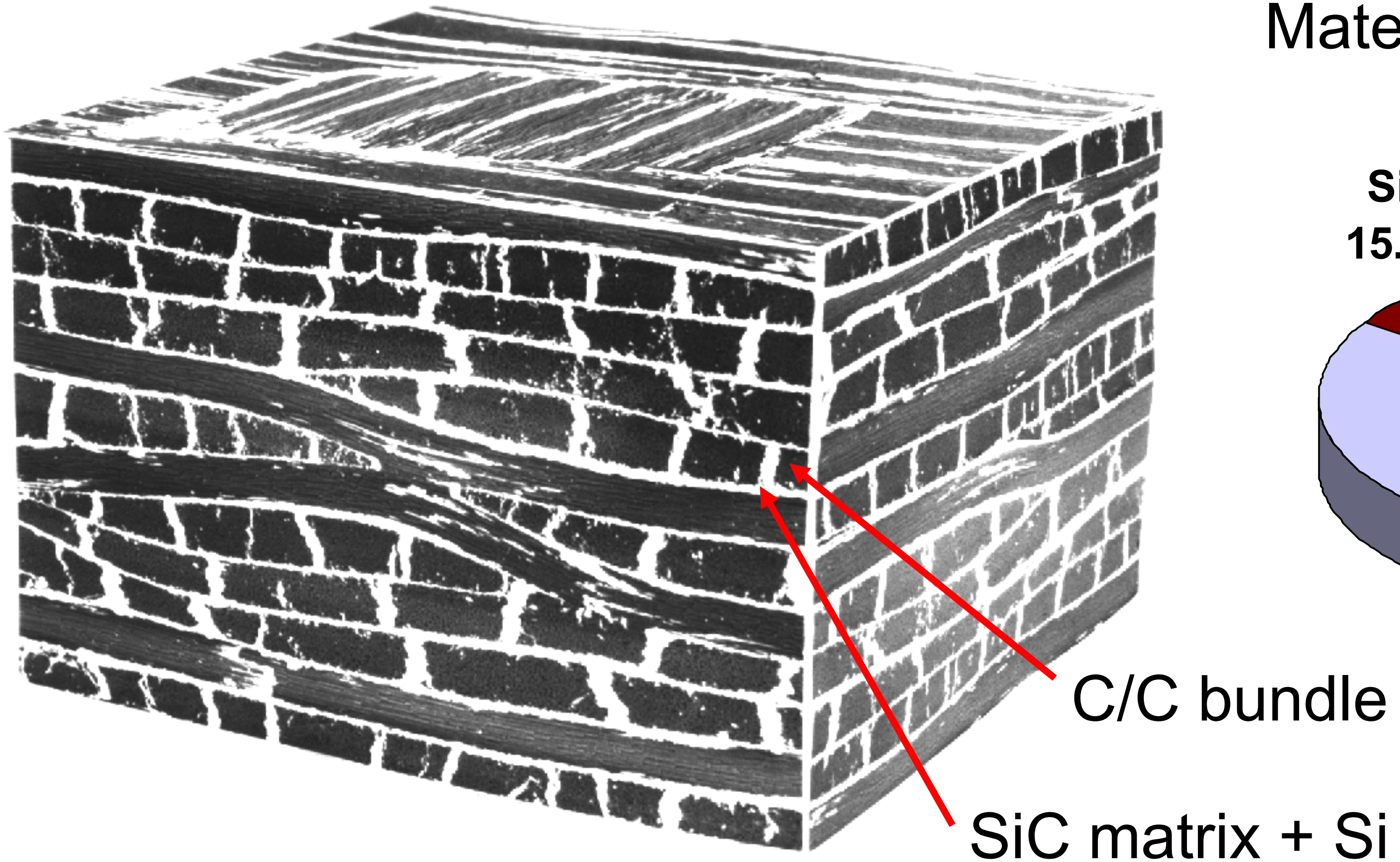
New approach:

Ultrastable OB made of CMC sandwich structures (**C**eramic **M**atrix **C**omposites)

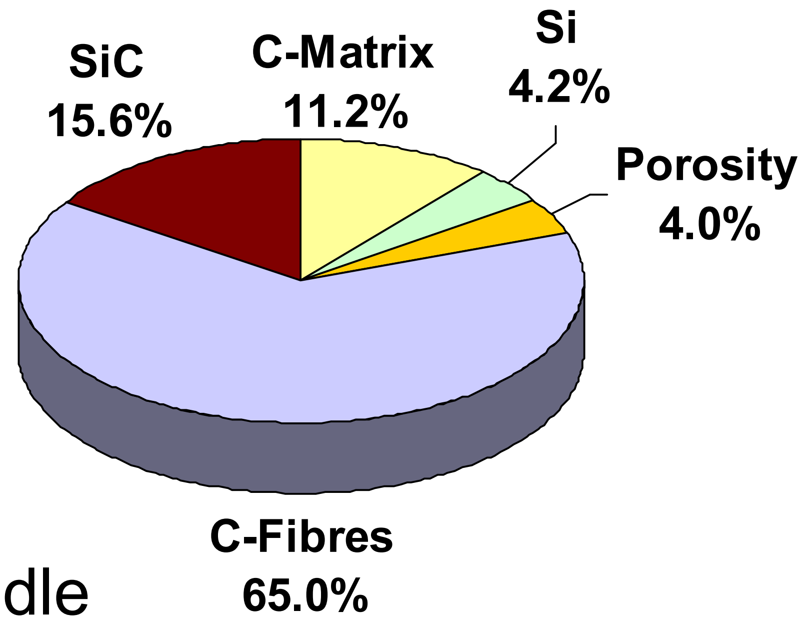


Optical Bench for IASI made of CFRP sandwich (Thales Alenia Space)

C/C-SiC Multiphase Material

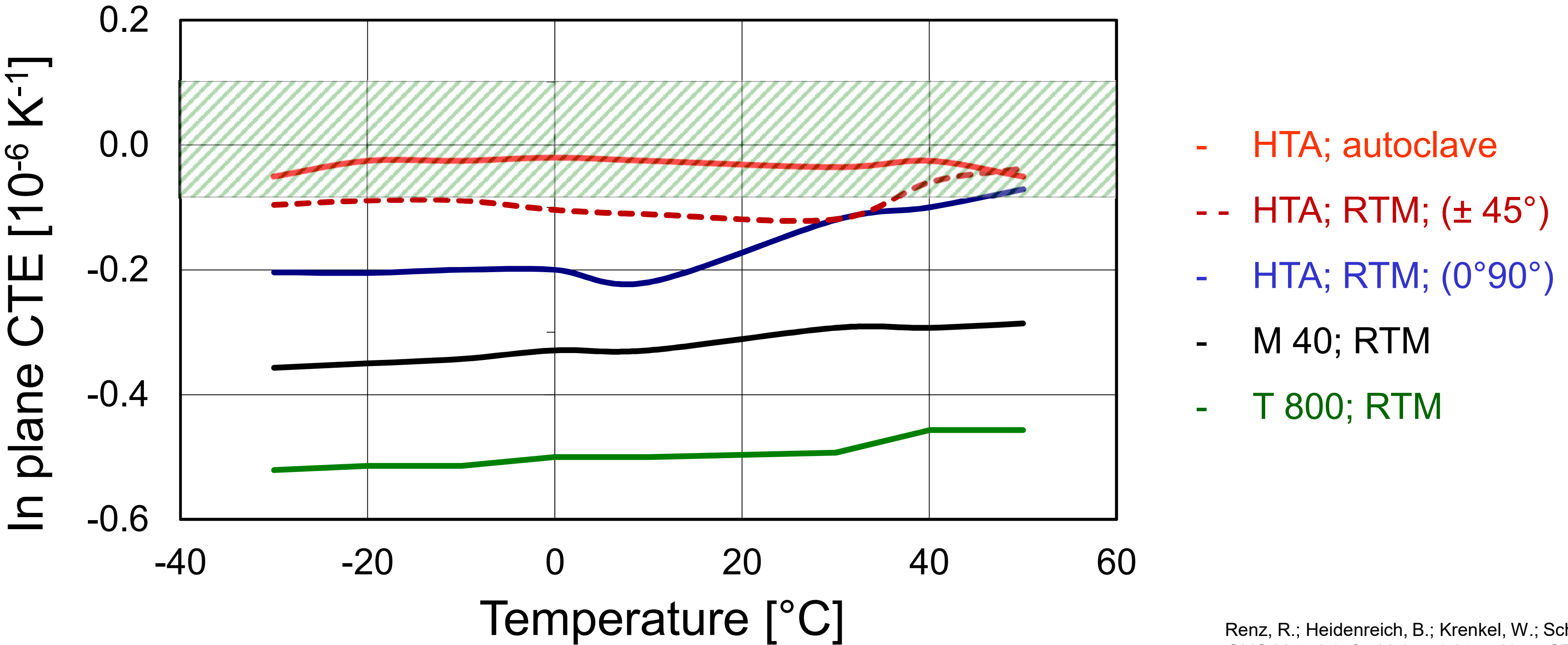


Material composition (HTA)



CTE of C/C-SiC Materials

Fibre		HTA	T 800	M40J
CTE	10^{-6} K^{-1}	-0.1	-0.56	-0.83



DIN 51045-1, DIN EN 821-1 (8 x 3 x 50 mm³)

Renz, R.; Heidenreich, B.; Krenkel, W.; Schöppach, A; Richter, F.: *CMC Materials for Lightweight and Low CTE Applications*, 2001

C/C-SiC Properties

			Zerodur ®	Invar ®	C/C-SiC XB
Structure	–	-	isotropic	isotropic	anisotropic
Density	ρ	[g/cm³]	2.53	8.0	1.90
Young's Modulus	E	[GPa]	90,2	140-150	60
Tensile Strength	σ	[MPa]	< 10	450-590	80
CTE	α	$[10^{-6}\ K^{-1}]$	0 ± 0.02 (1)	1.7-2.0 (2)	0 ± 0.1 (3)
Specific Stiffness	E/ρ	$[GPa\ g^{-1}cm^3]$	35.7	18.7	31.6

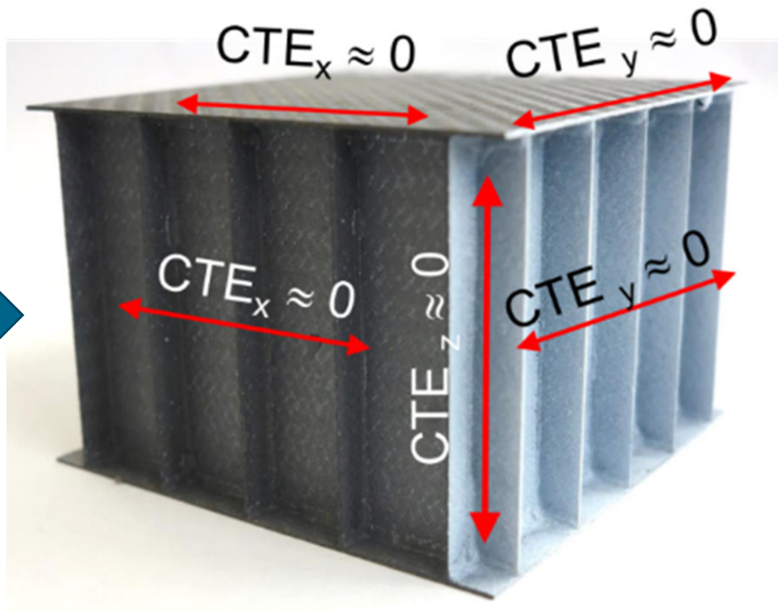
(1) 0 °C to +50 °C; (2) +20 °C to +90 °C; (3) -30 °C to +50 °C (in plane)

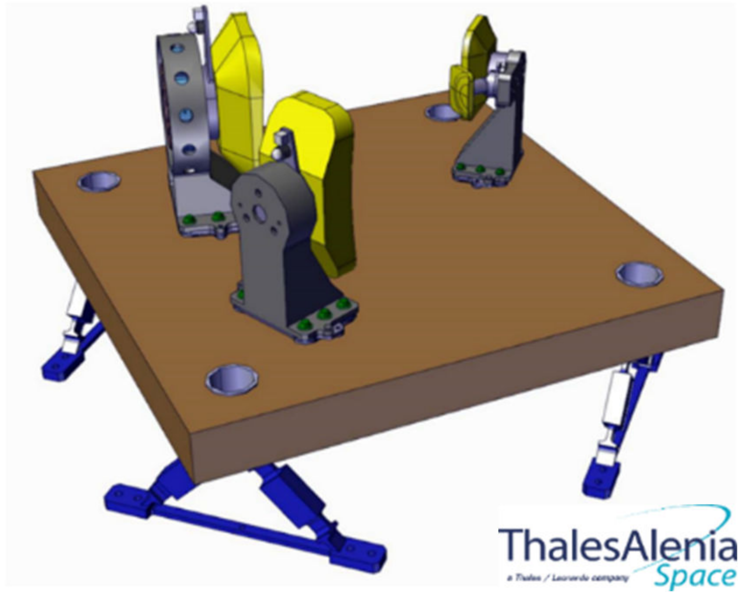
C/C-SiC XB: HTA fibers; 2D fabrics

C/C-SiC Sandwich Structures for Optical Benches

- Lightweight and highly stiff design
- Skin and core structures made of C/C-SiC → Very low thermal expansion in all directions
- Ceramic joining of skins and core (no polymers) → long term stable / no outgassing in space

→ **Ultrastable optical benches for satellites**

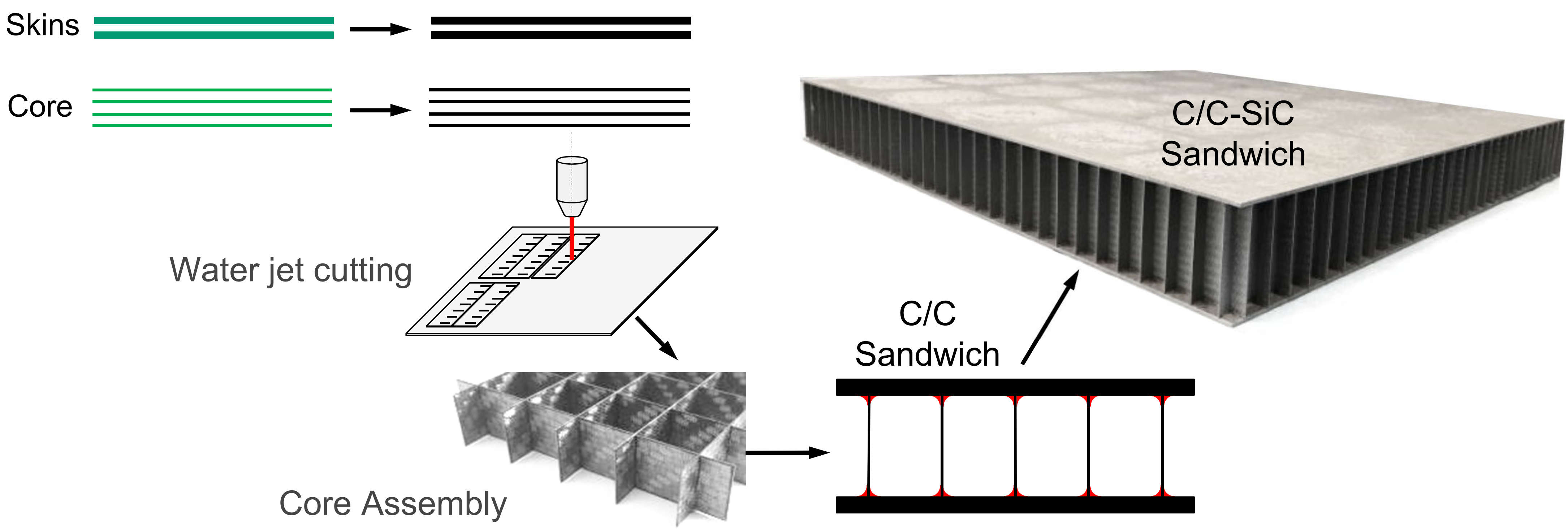




Manufacture of C/C-SiC Sandwich Structures

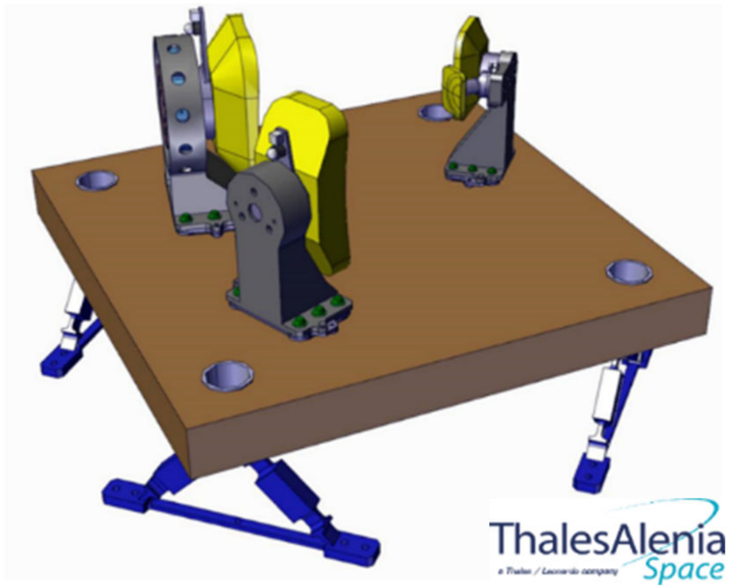
ThalesAlenia Space
a Thales / Leonardo company
DLR

CFRP Manufacture	Pyrolysis	Joining	Siliconization
210 °C / air	1650 °C / N_2	130 °C / air	1650 °C / vacuum
CFRP Preforms	C/C Preforms	C/C Sandwich	C/C-SiC Sandwich

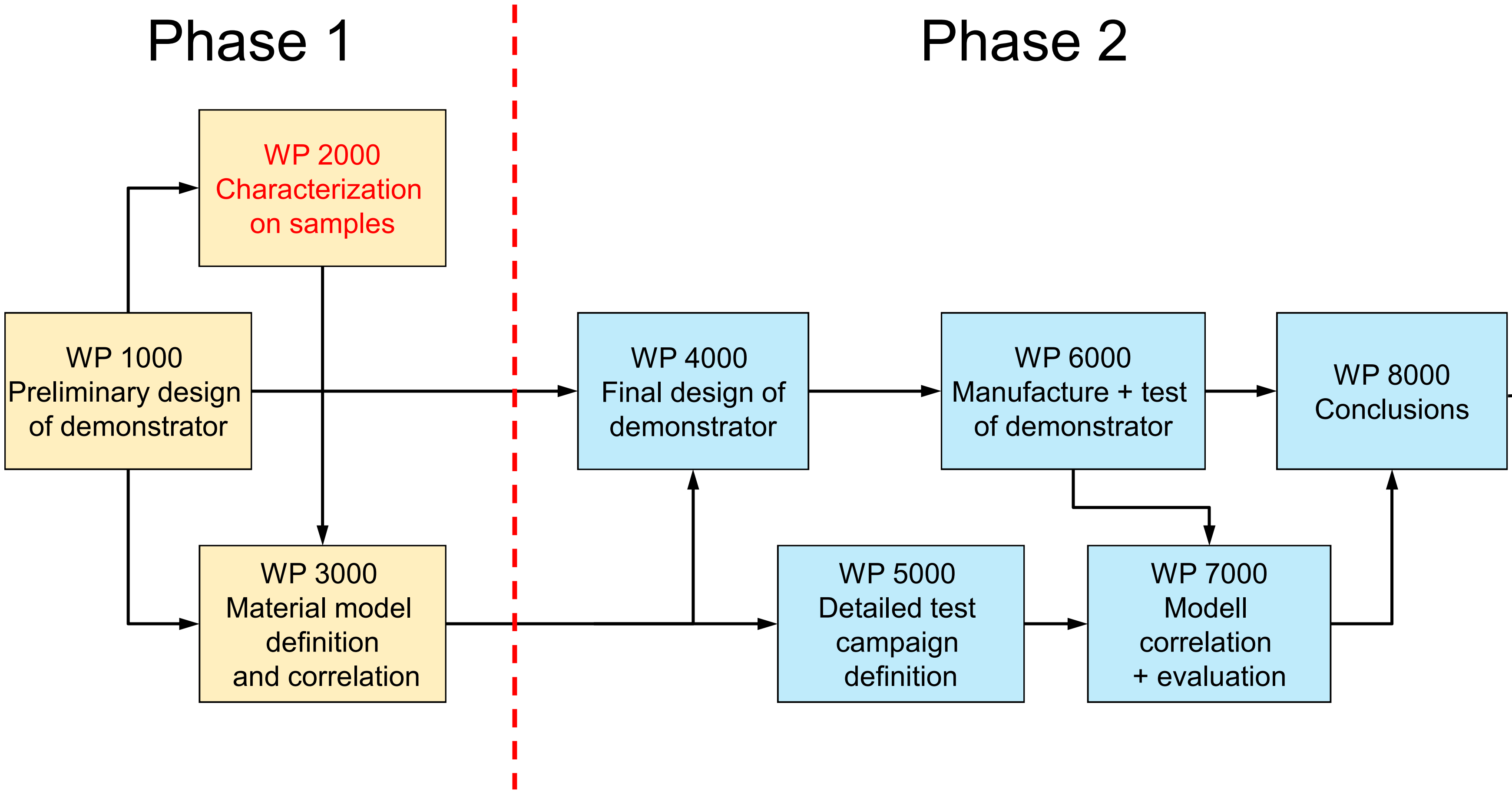


ESA TDE project: Development of a C/C-SiC Optical Bench Demonstrator

- Sandwich structure ≥ 600 x 600 mm²
- Interface concepts
- CTE in all directions < 5 x 10 $^{-6}$ K^{-1}
- Integrity during thermal cycling between -170 °C and 100 °C
- Integrity after sine and random vibration under 20g
- Natural frequency > 140 Hz



ESA TDE project: Development of a C/C-SiC Optical Bench Demonstrator



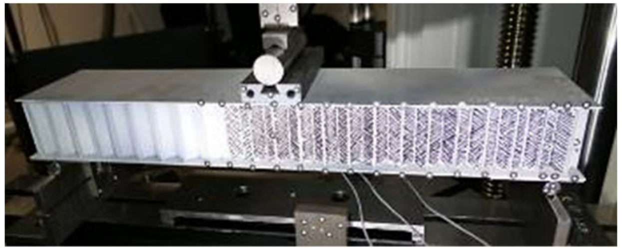
C/C-SiC Sandwich Optical Bench

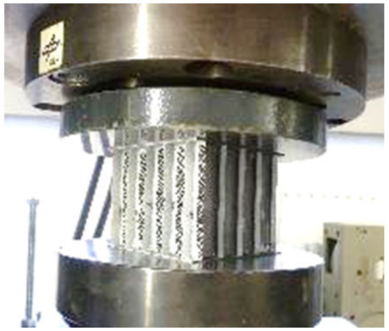
- Low CTE
- Structural integrity under dynamic loads an thermal cycling
- Numerical model

Preliminary Design

Preliminary design based on DLR and TAS heritage

- 600 x 600 x 60 mm³
- Skins: t_{skin} = 2 mm; 0°/90°
- Grid core: t_{core} = 0.6 mm; w = 20 mm; ± 45°



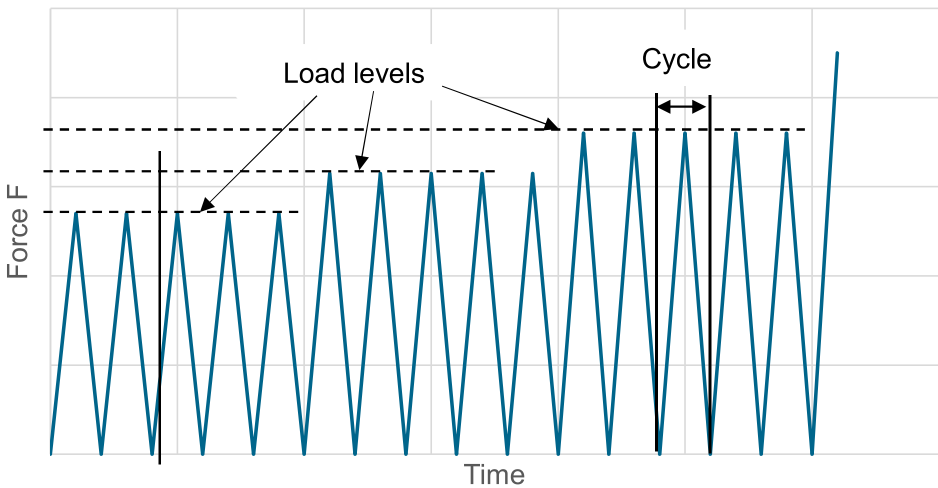


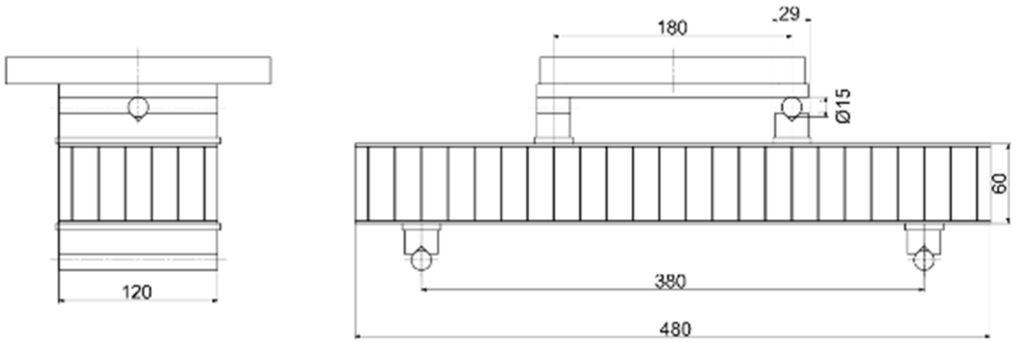
			Skins	Core webs
Wall thickness	t	[mm]	2	0.6
fibre orientation	α_f	[°]	0° / 90°	± 45°
Number of layers		[-]	8	2
Elastic modulus	E_1	[GPa]	60(1)	24(1)
	E_2	[GPa]	60(1)	24(1)
	E_3	[GPa]	20	20
Poisson ratio	$\nu_{12} = \nu_{21}$	[-]	0.01	0.01
	$\nu_{23} = \nu_{32}$	[-]	0.1	0.1
	$\nu_{13} = \nu_{31}$	[-]	0.1	0.1
Shear modulus	$G_{12} = G_{21}$	[GPa]	5	25(1)
	$G_{23} = G_{32}$	[GPa]	6.6	-
	$G_{13} = G_{31}$	[GPa]	6.6	-
Tension strength	σ_t	[Mpa]	60	-
Compression strength	σ_c	[Mpa]	60	-
Shear strength	τ	[Mpa]	-	37.5

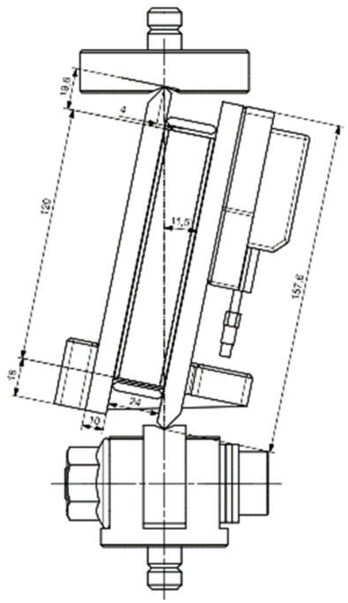
(1) From material tests at ESA

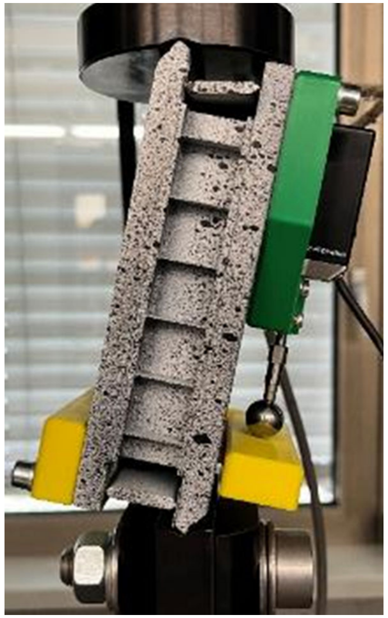
Characterization on Sandwich Samples

- Characterization on sandwich samples:
  - 4-pt. bending
  - In plane shear
  - Out of plane tension
- Quasistatic cyclic testing → mechanical stability



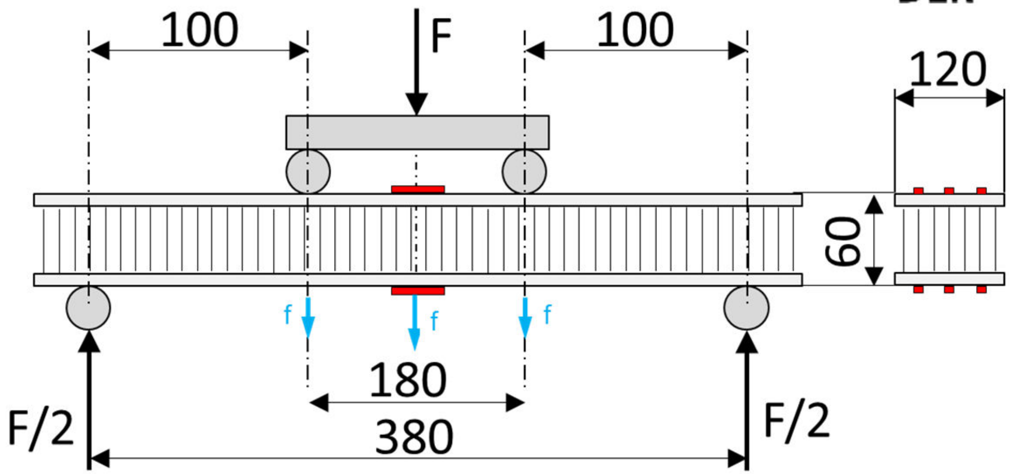


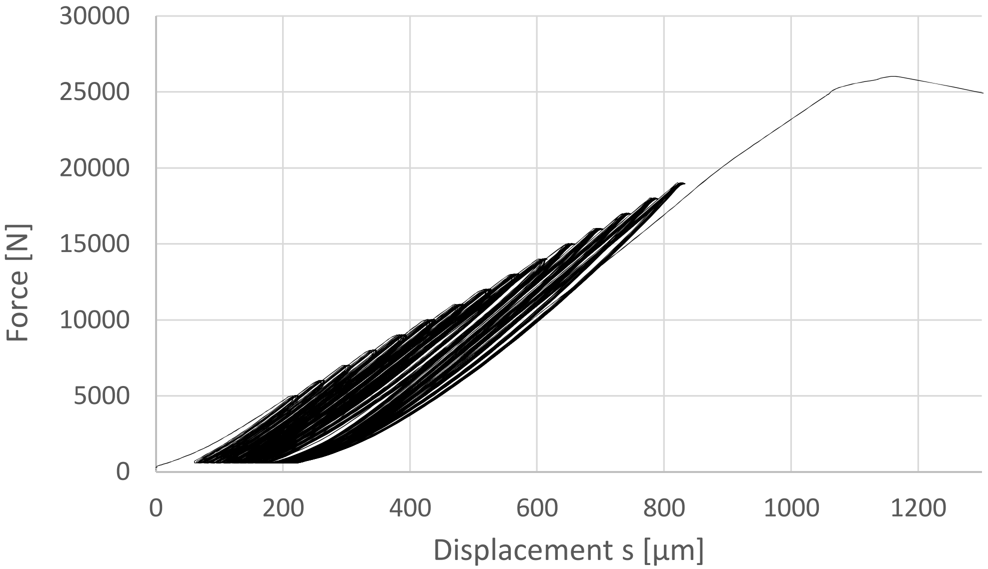


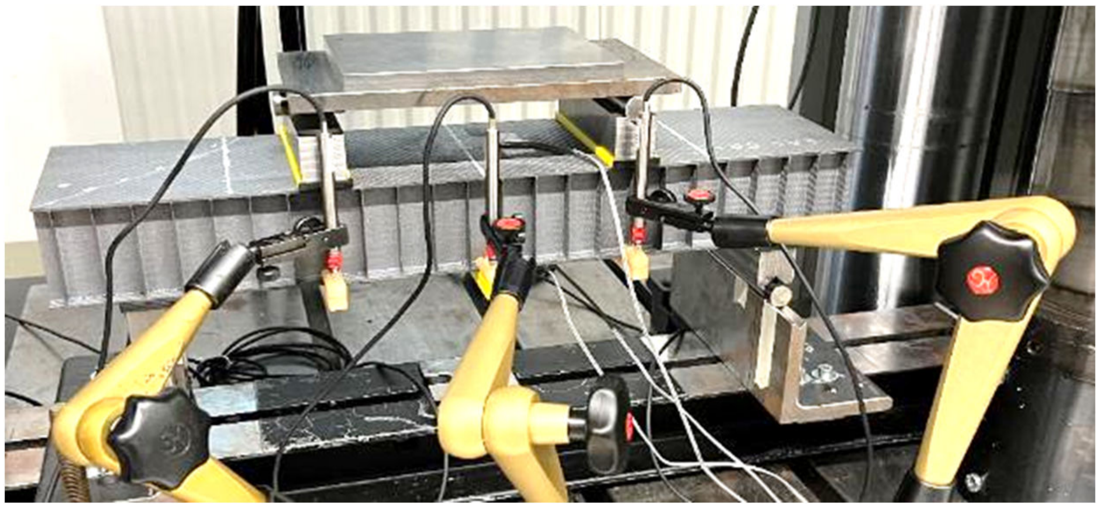


4-Pt.- Bending Test of Sandwich Samples

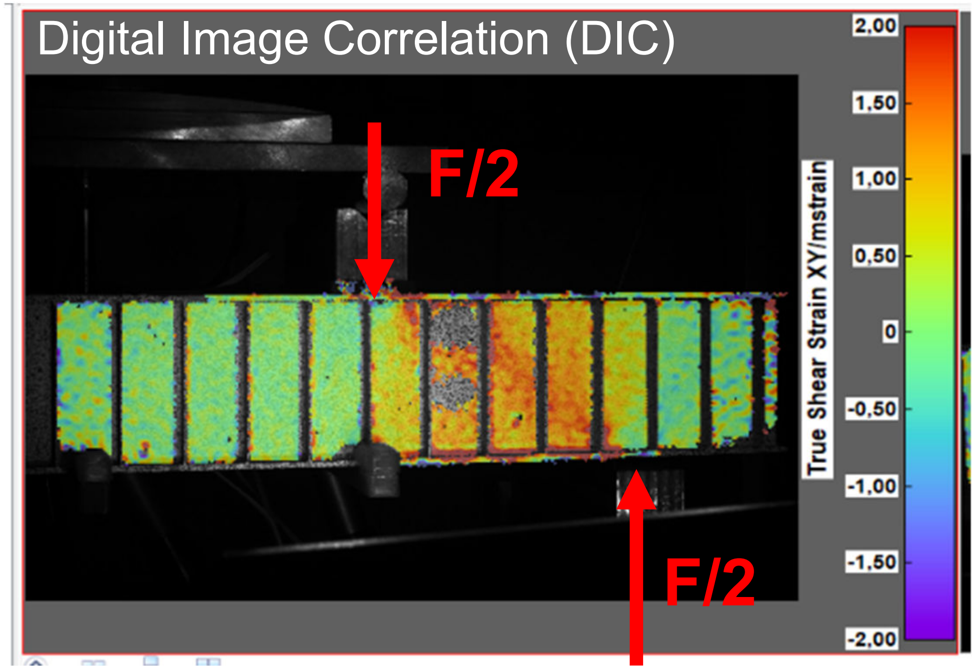
- 4-Pt. Bending according to DIN 53239
- Modelling and FEM simulation for sample geometry definition (480 x 120 x 60 m³)
- Accurate measurement of displacements (LVDT)
- Quasistatic cyclic testing → mechanical stability







Failure Mode



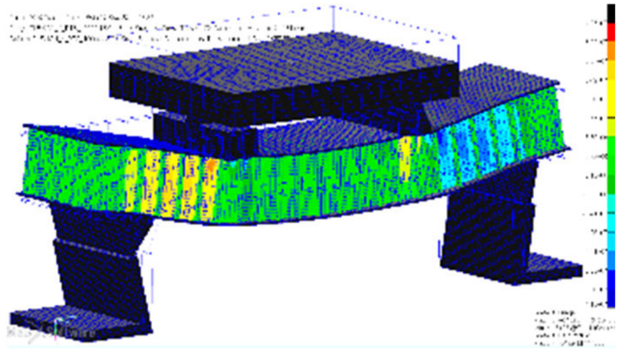
- $F_u = 22.3 \pm 3.1$ kN
- Shear failure of core web in critical load span, followed by local core/skin debonding.

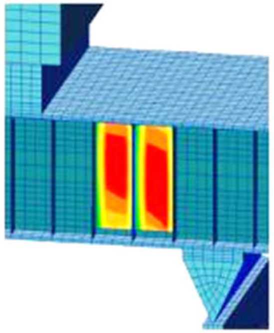
Results

			Theo-retical	Test Mean	Test Deviation	FEM
Failure Load	F_u	[kN]	20.0	22.3	3.1	17.5
Displacement at ultimate load	f_u	[µm]	1 185	940	141	485
Ultimate shear stress in webs	$\tau_{web,u.}$	[MPa]	71.7	82.8	11.4	71.7
Ultimate tension stress in skin	$\sigma_{skin,\ u}$	[MPa]	74.2	68.7	12.5	51.0

Allowable shear stress $\tau_{web,\ allowable}$ = 71.7 Mpa

Allowable tensile stress $\sigma_{skin,\ allowable}$ = 86 MPa

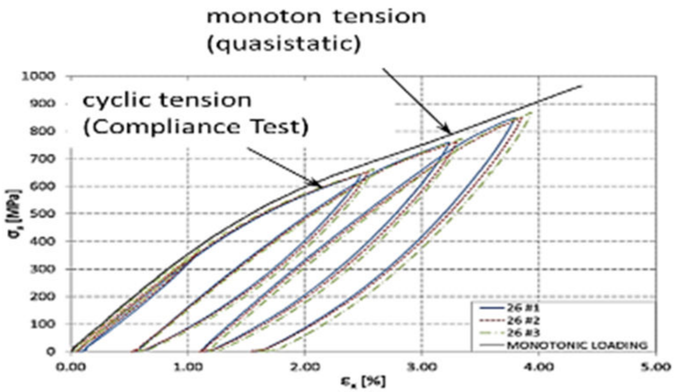




- Maximum stresses in skins and core webs close to material strengths → well-balanced design
- FEM (NASTRAN solver + PATRAN) predicts shear failure, but lower failure load and skin stresses
- Lower displacement due to complex set-up, tilting, linear instead of non-linear calculation

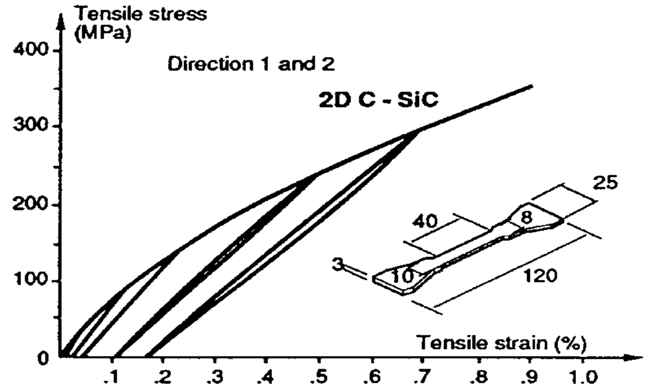
Cyclic Testing of Composites

CFRP



J. D. Fuller, M.R. Wilson, Ductility and pseudo-ductility of thin ply angle-ply CFRP laminates under quasi-static cyclic loading, Composites: Part A 107, pp 31 – 38, 2018]

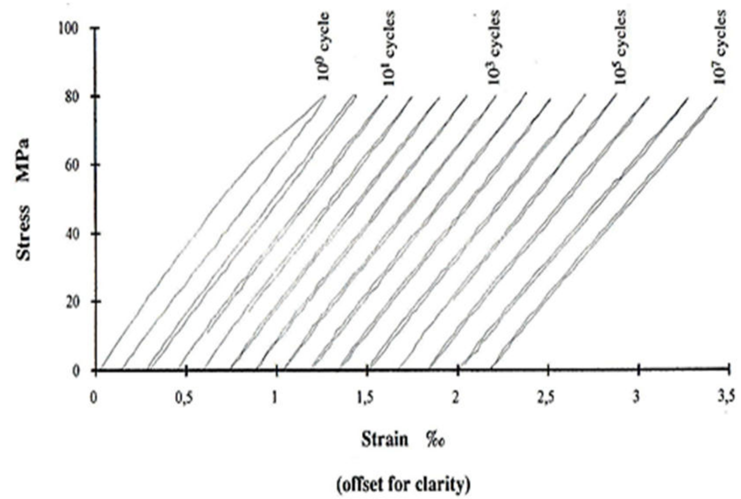
C/SiC



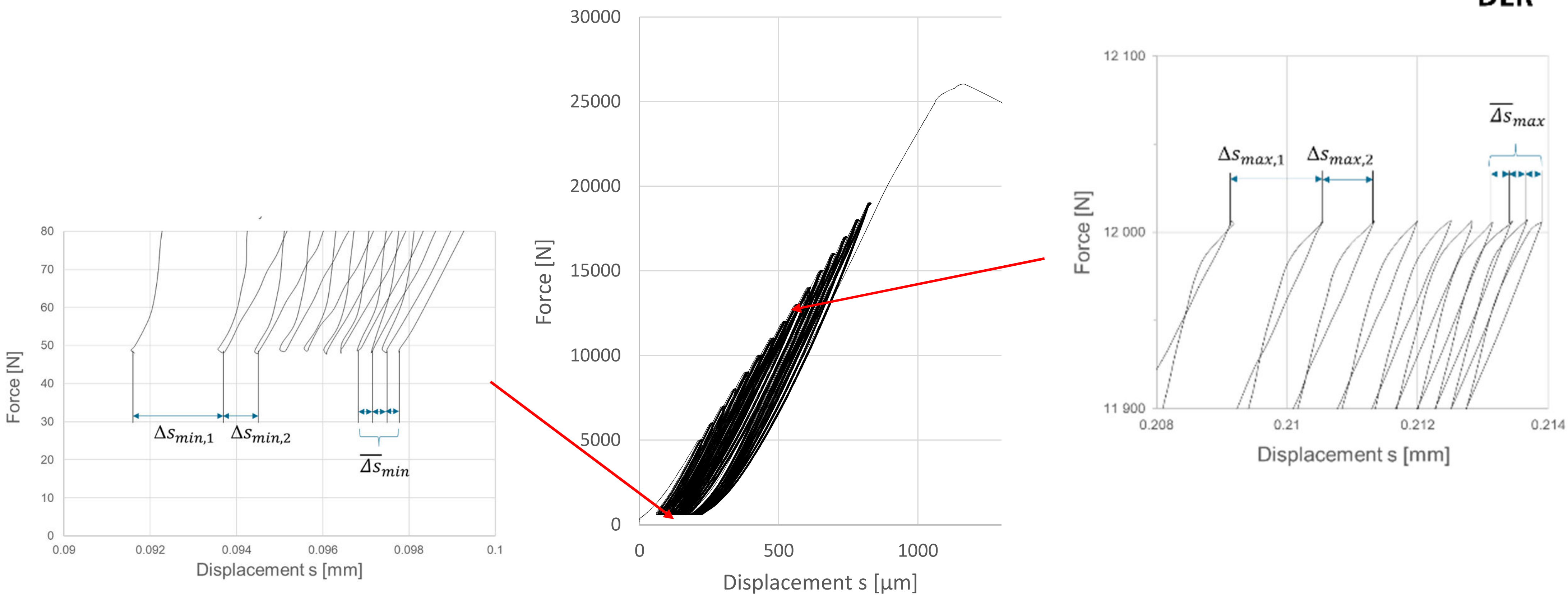
D. Desnoyer, A. Lacombe, J.M. Rouges, *Large Thin Composite Structural Parts*, Proceedings of International Conference Spacecraft Structures and Mechanical Testing, Nordwijk, The Netherlands, 1991]

C/C-SiC

[Kochendörfer, 2000]

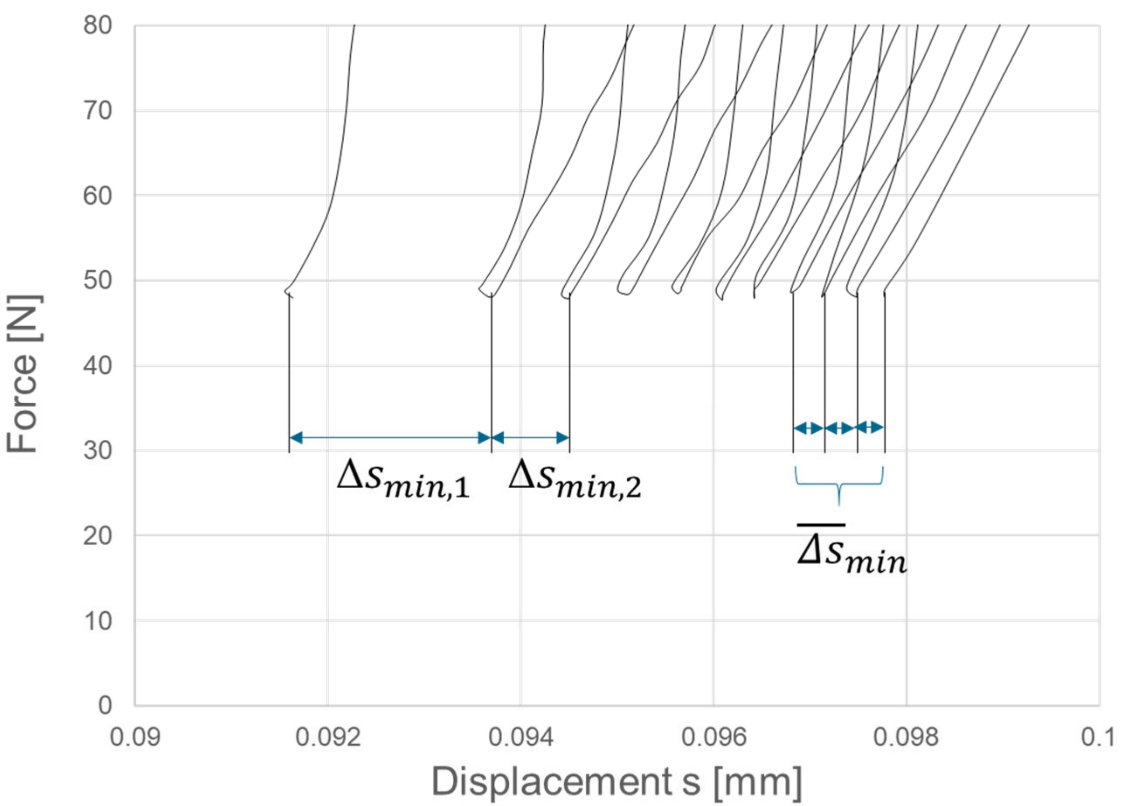


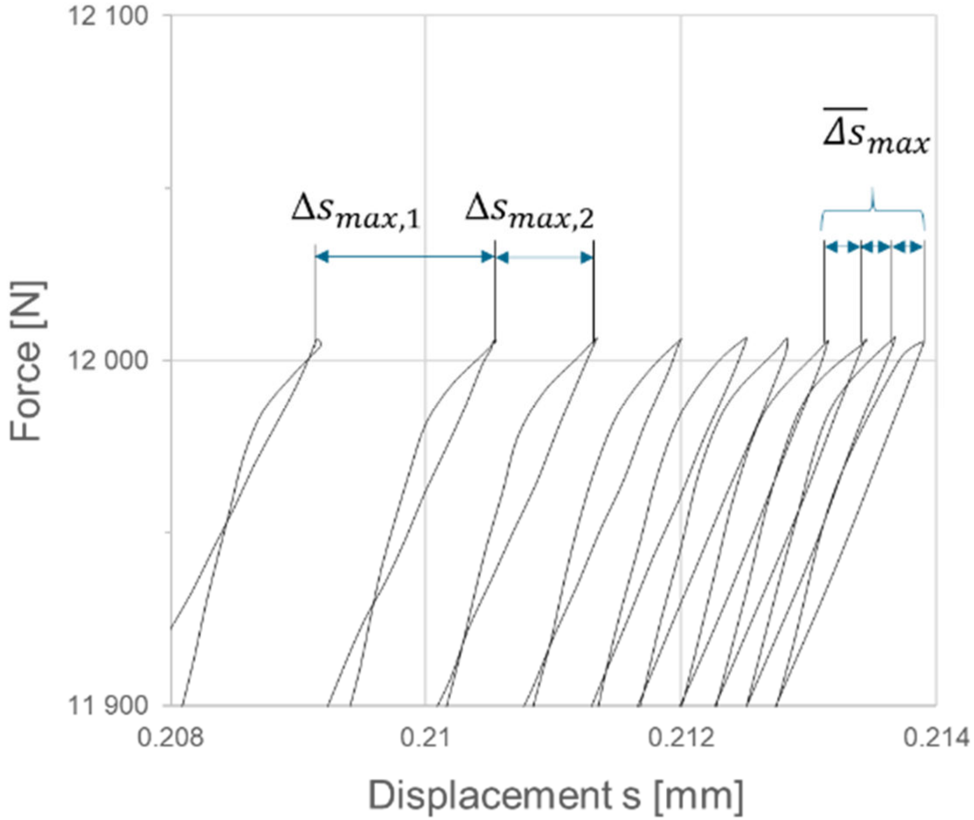
Cyclic Testing of C/C-SiC Sandwich



Cyclic Testing of C/C-SiC Sandwich

4-Pt. Bending

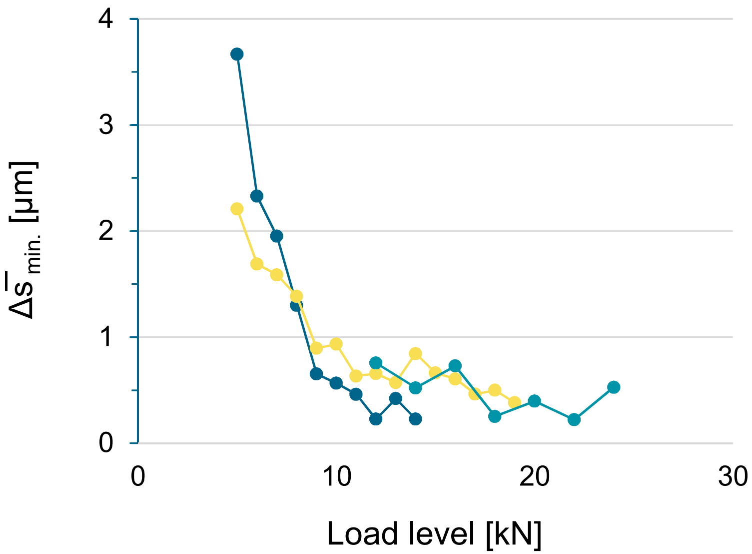


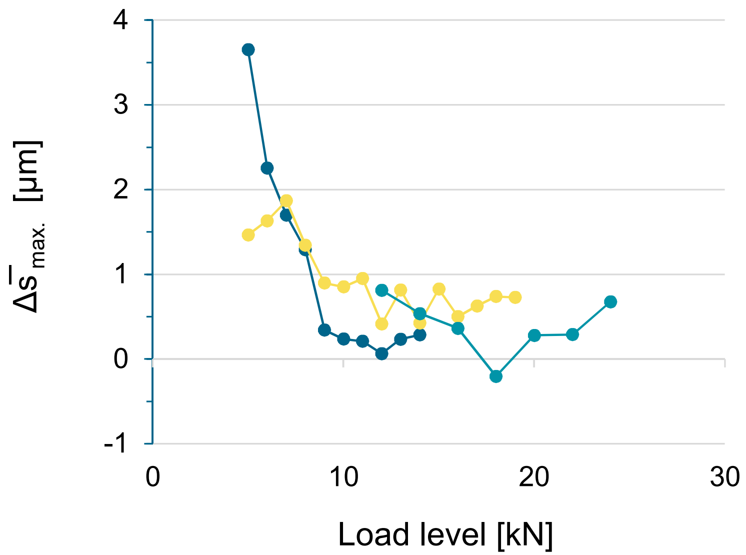


Stable structure <=> s = constant <=> Δ s = 0 ; $\overline{\Delta s} = 0$

Stability of C/C-SiC Sandwich in 4-Pt. Bending

- Lower loads → residual displacements increase slightly (settling effect, due to complex test set-up)
- load levels > 10 kN, the residual displacements are minimal (sensor accuracy)





→ C/C-SiC sandwich is stable after preloading

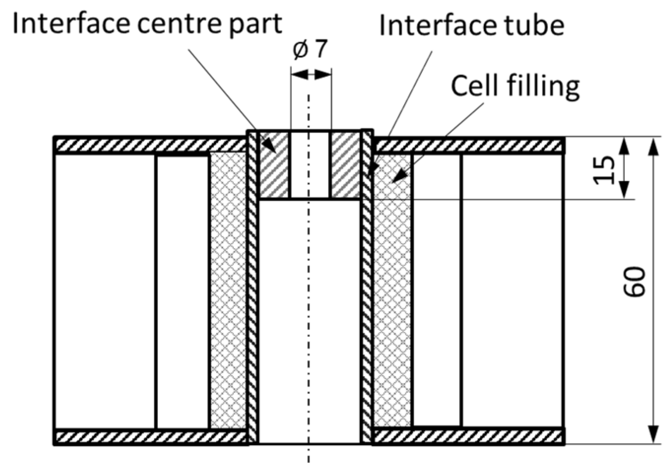
C/C-SiC Interface Concept

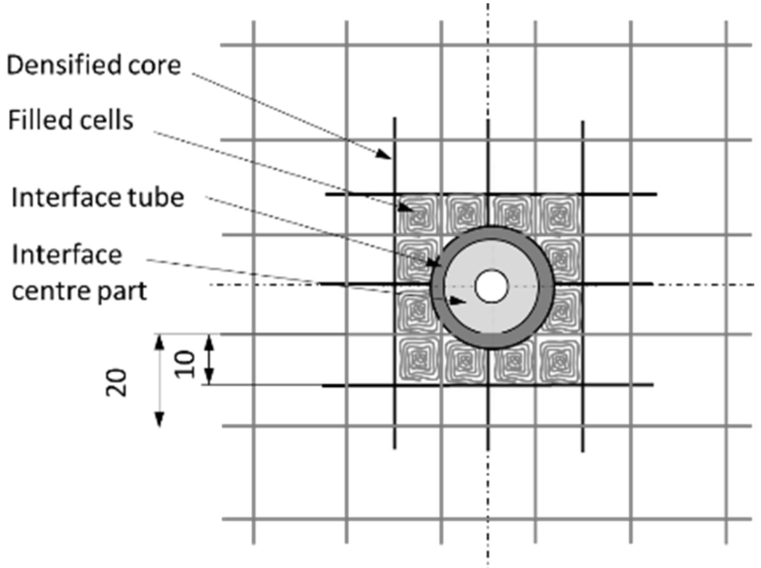
Aim

- Safe load transfer to core structure via shear stresses
- Minimized CTE mismatch between interface components and sandwich structure

Approach

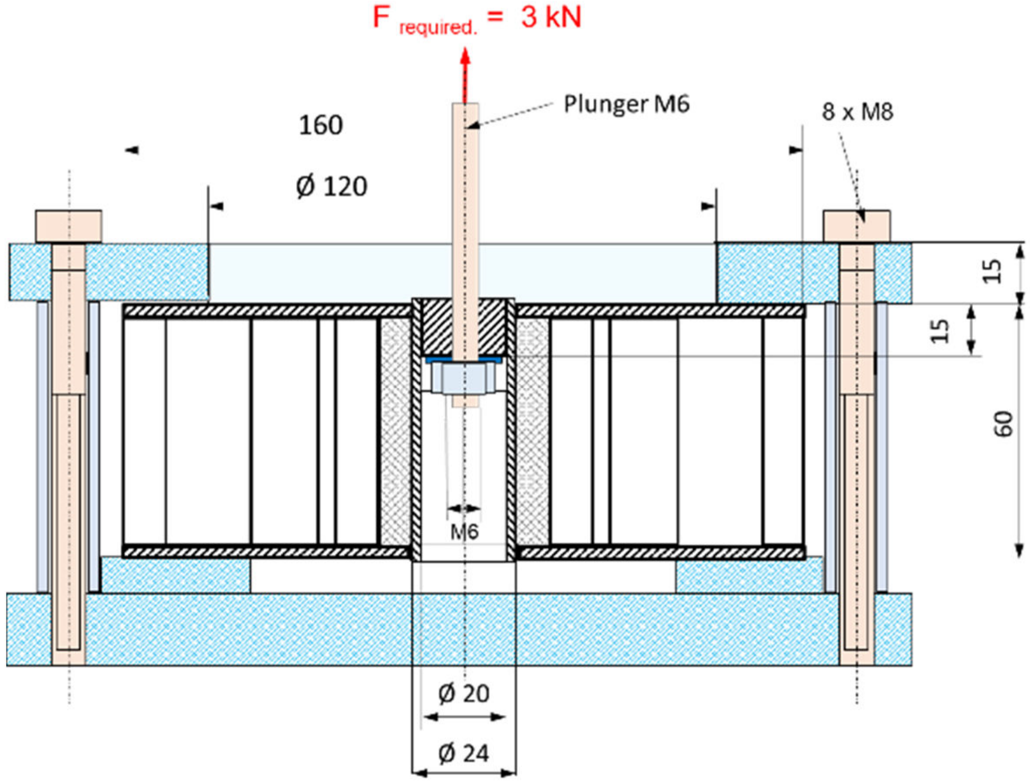
- All C/C-SiC design, no metallic inserts / polymers
- Interface concept based on
  - Ti screws and nuts
  - Massive centre part with boring
  - Interface tube
  - Densified core
  - Filling of core cells



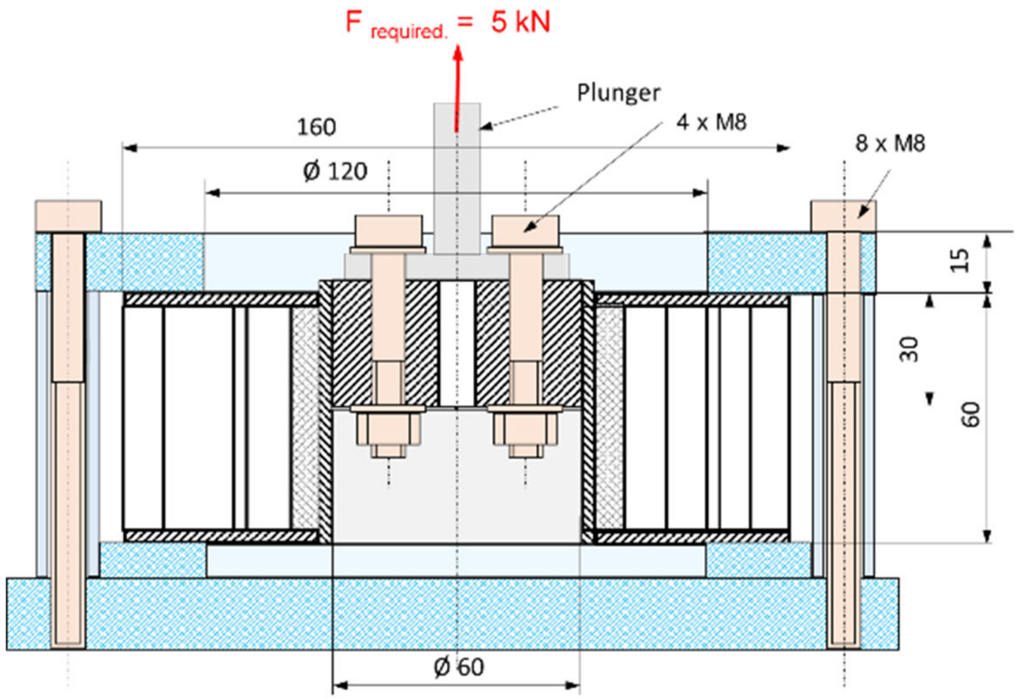


Interface Types

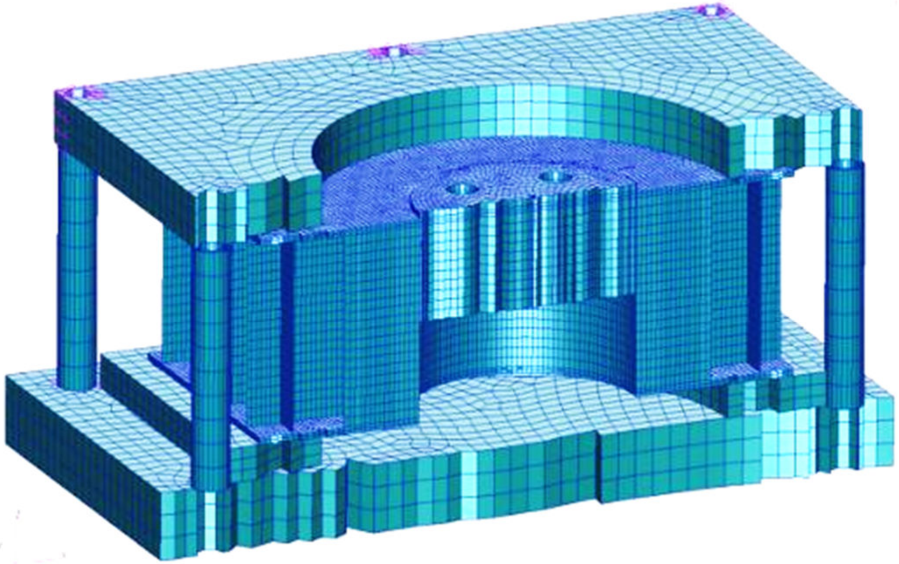
Interface XS
Instrument / OB
(1 x M6)

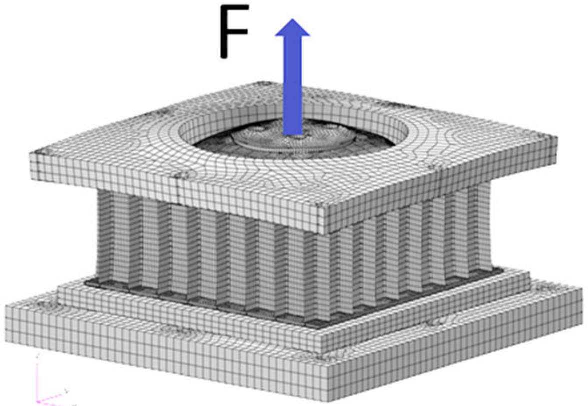


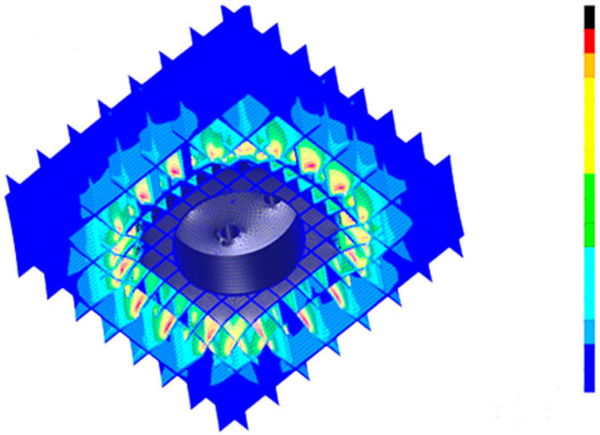
Interface XL
OB / satellite
(4 x M8)

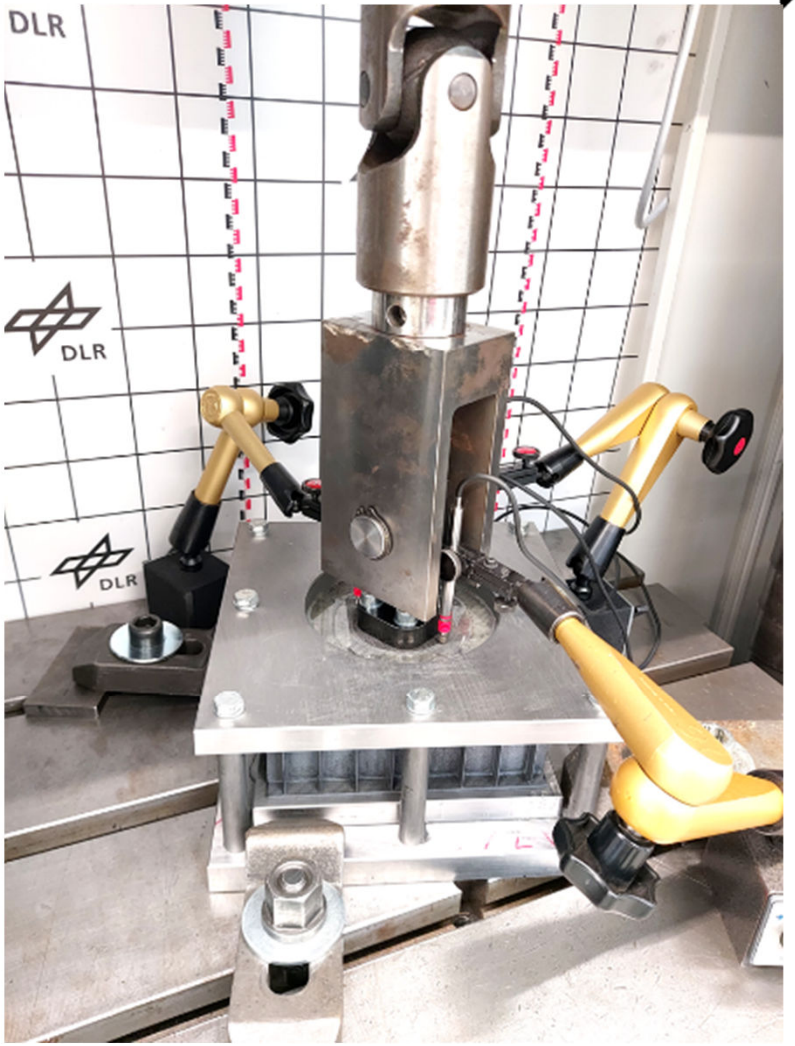


Simulation and Test



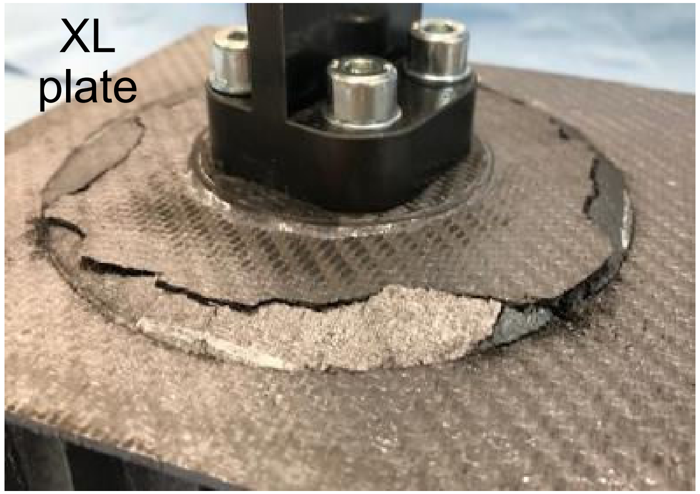




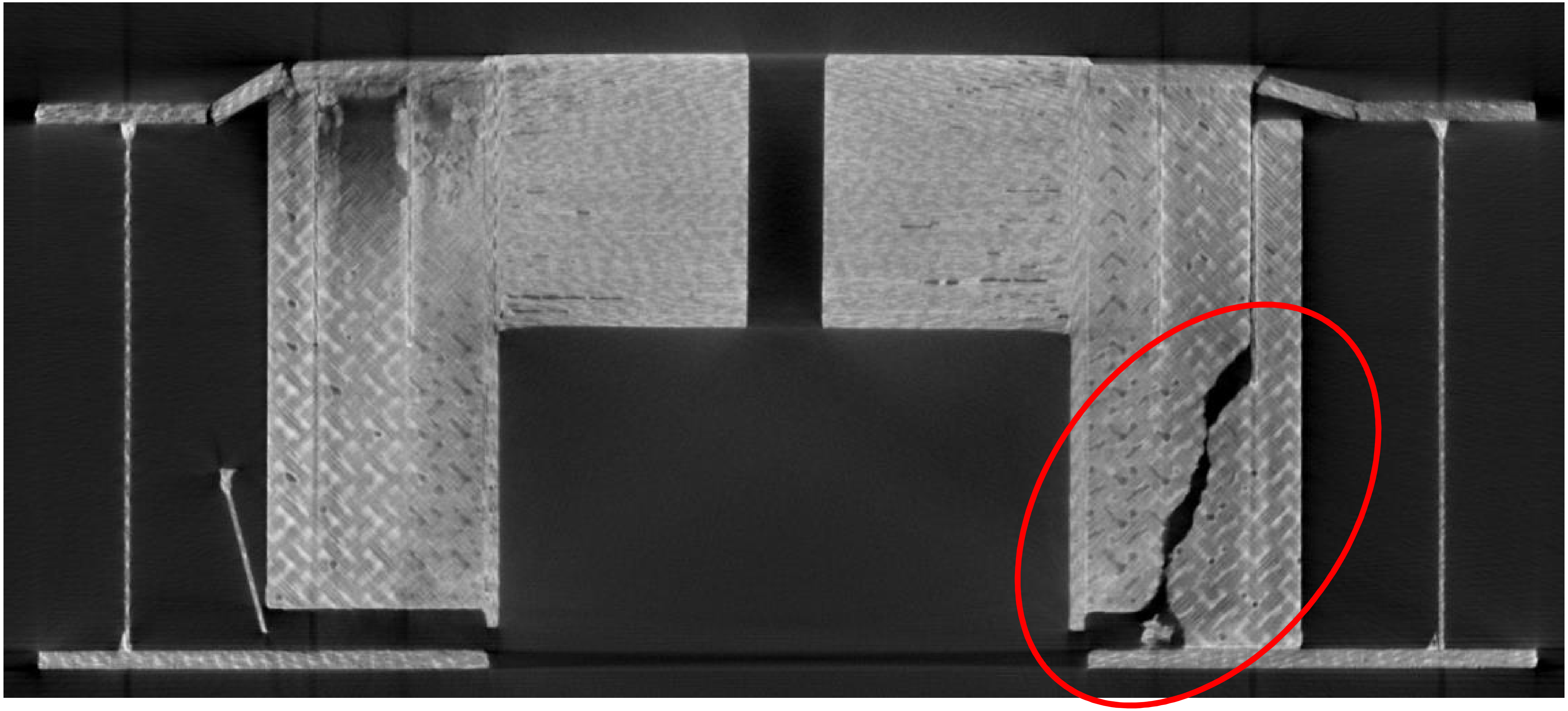


Test Results - Interface Samples

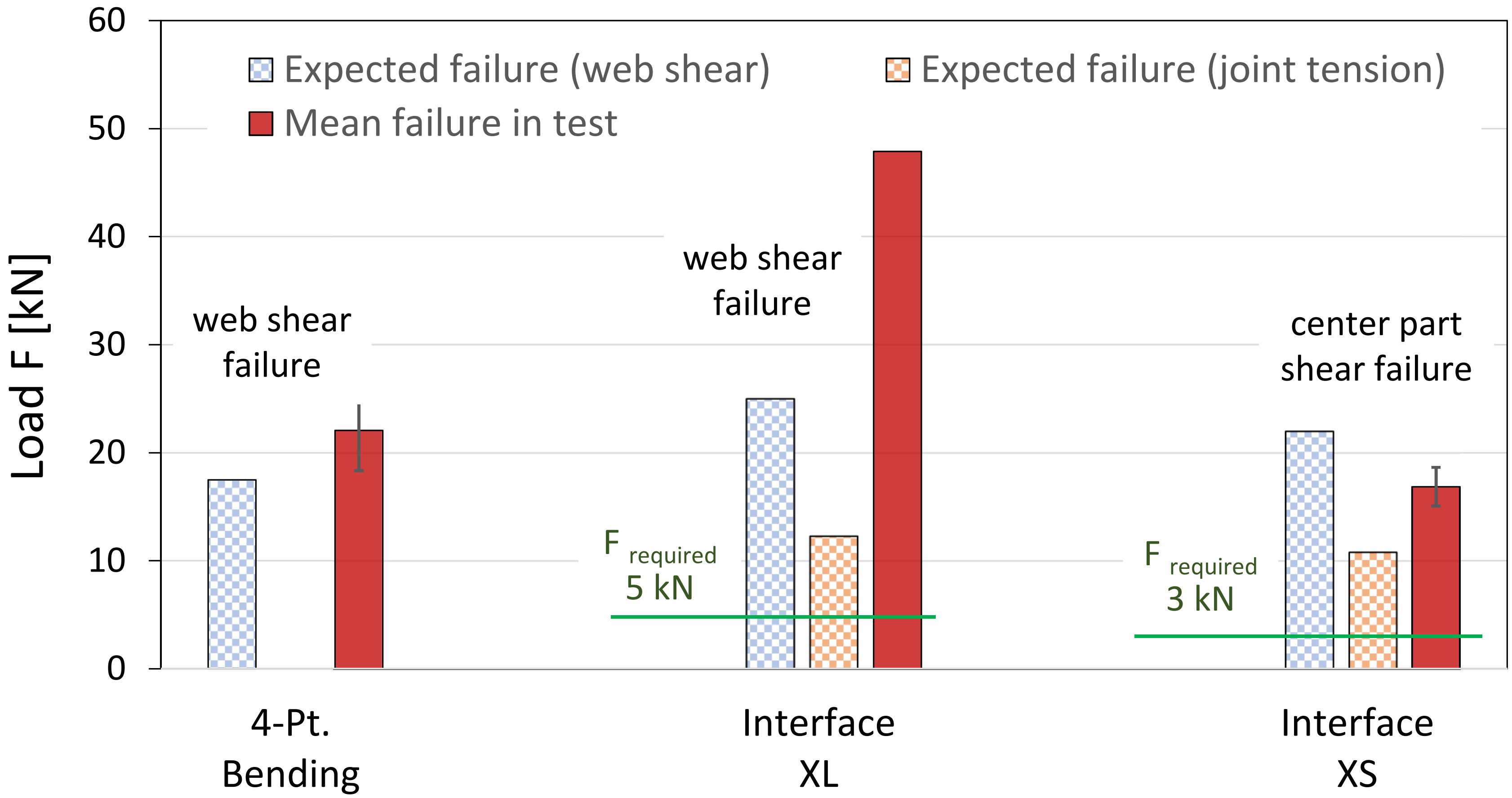
		XS wrapped	XS plate	XL wrapped	XL plate
Fibre orientation in centre part	[°]	ǁ ± 45°	⊥ 0°/90°	ǁ ± 45°	⊥ 0°/90°
Ultimate force	[kN]	18.0 ± 0.7	16.1 ± 2.0	> 24 test stopped	47.9
Displacement at ultimate force	[µm]	133.6 ± 2.1	120.5 ± 11	178.8	280.9



Failure Mode of Interface XL



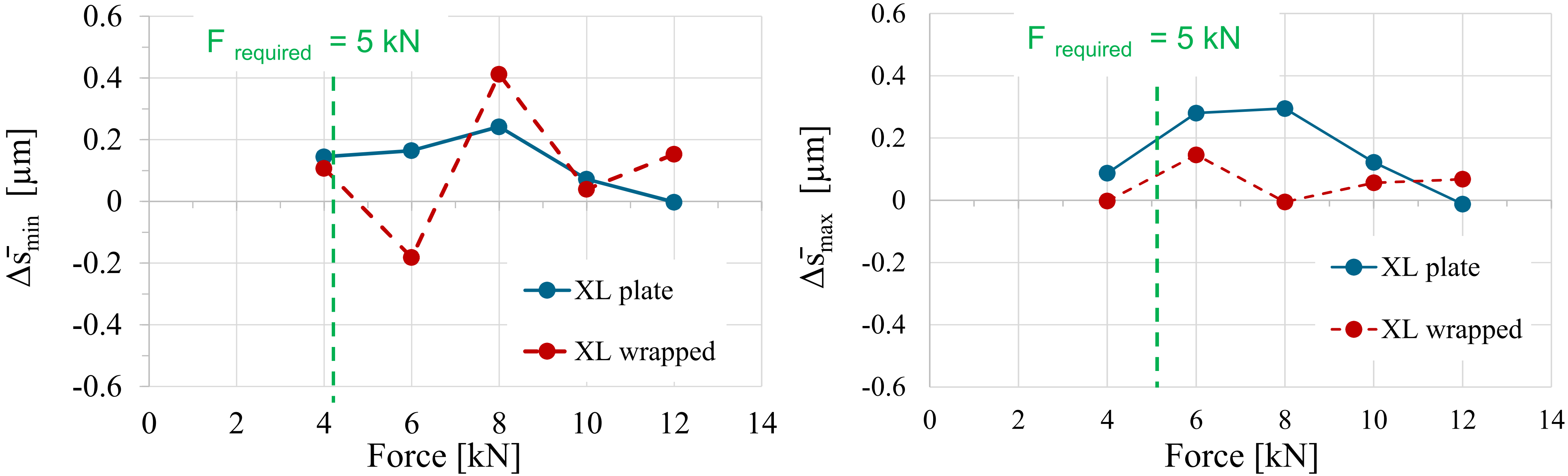
Test Results - Overview



→ High safety margins for interfaces

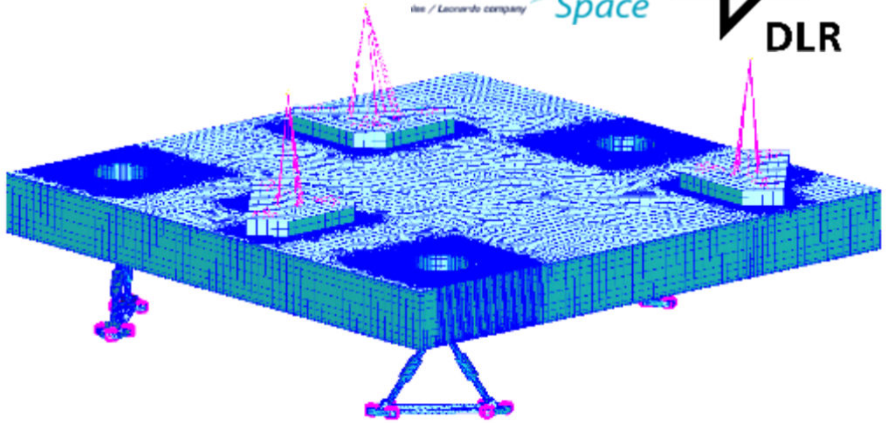
Stability of C/C-SiC Interface Samples

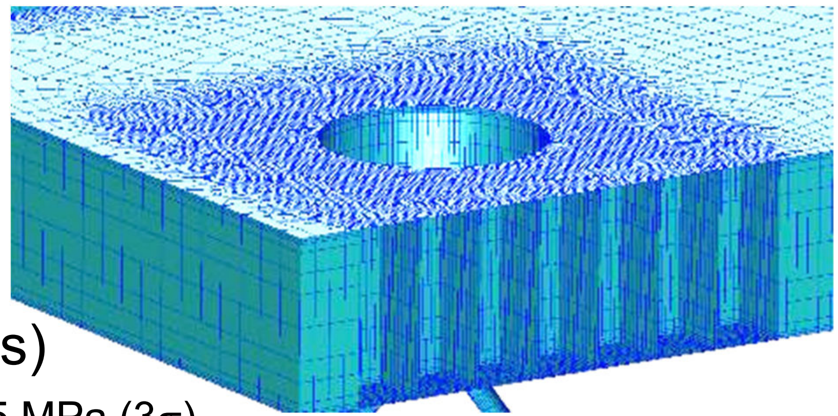
- Residual displacement in the range of sensor accuracy (1 µm).



→ C/C-SiC interface XL is stable after preloading

Demonstrator Design





- 3 Interface XL (bipods) / 9 Interface XS (3 x 7 kg)
- Detailed model around the interfaces, equivalent SOLID elements on the rest
- 1st lateral mode at 106 Hz
- High safety margins under quasistatic and random loads

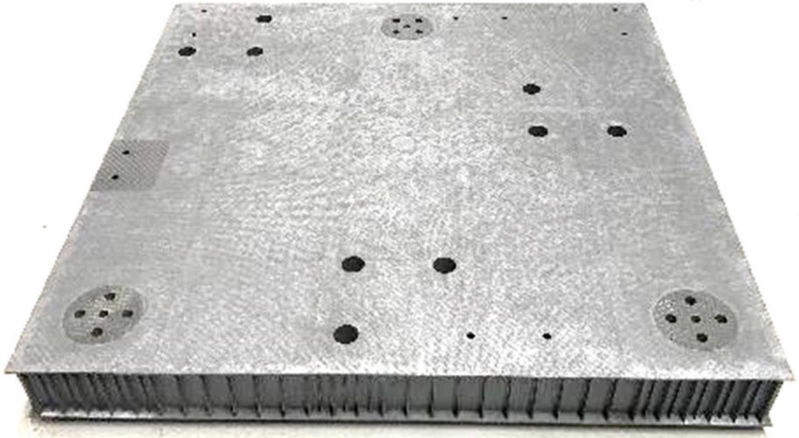
Quasistatic (20 g)

– Skins: 19.6 MPa (σ_f: 60 MPa)
– Core $_{detailed}$: 19.1 MPa (τ_f : 37.5 MPa)
– Core $_{equiv.}$: 0.56 MPa (τ_f : 1.05 MPa)
– F $_{axial,\ XL\ insert}$: 4.83 kN (F_f : 47.9 kN)
– F $_{axial,\ XS\ insert}$: 2.64 kN (F_f : 18 kN)

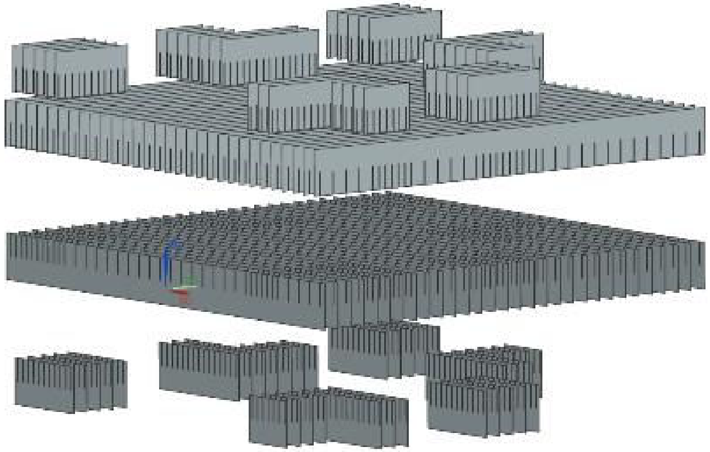
Random (15 grms)

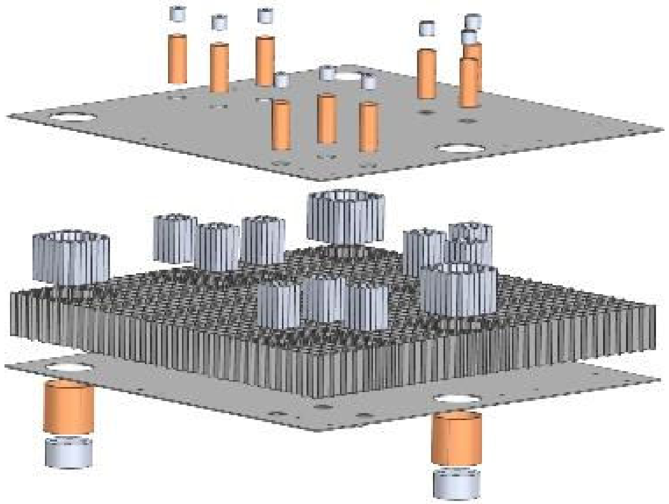
– Skins: 16.5 MPa (3σ)
– Core-detailed: 25.0 MPa (3σ)
– F $_{axial,\ XL\ insert}$: 4.38 kN (3σ)
– F $_{axial,\ XS\ insert}$: 2.85 kN (3σ)

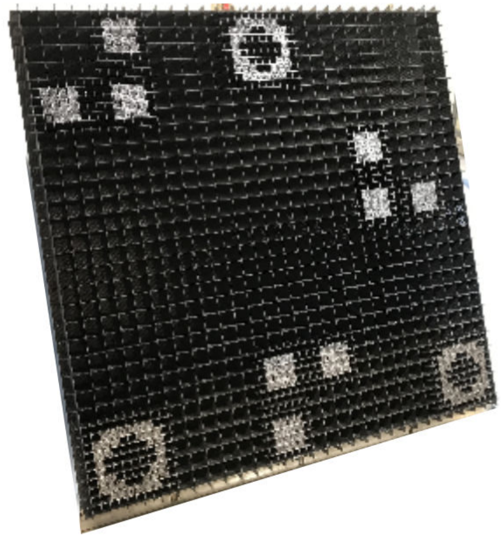
Demonstrator Manufacture



- Sandwich structure with integrated interfaces (3 x XL + 9 x XS).
- Adapting of manufacturing methods developed in sample scale
- Core structure assembled with 123 webs in 20 different geometries



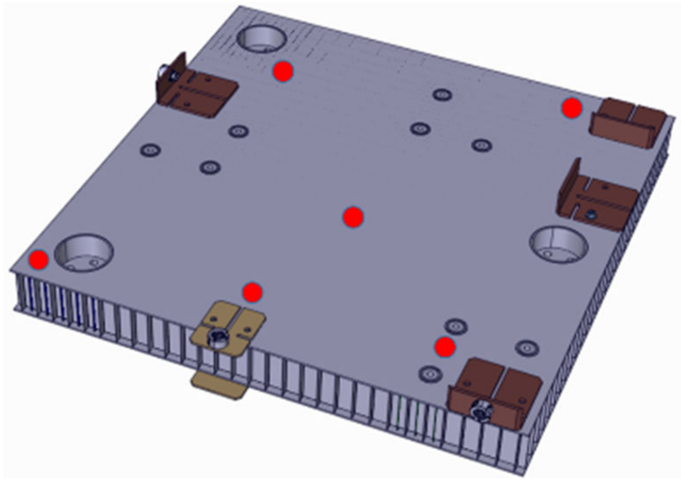


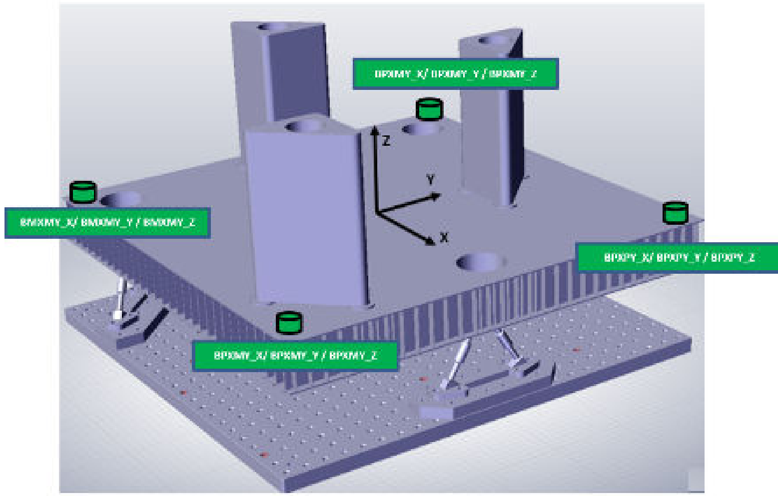


Demonstrator Testing at TAS

- Thermal excursion (-170°C to 100 °C) and photogrammetric measurements ✔
- Interferometric CTE measurements in x, y, z direction (0 °C to 40 °C, Attocube) ✔

- Sine and random mode vibration tests

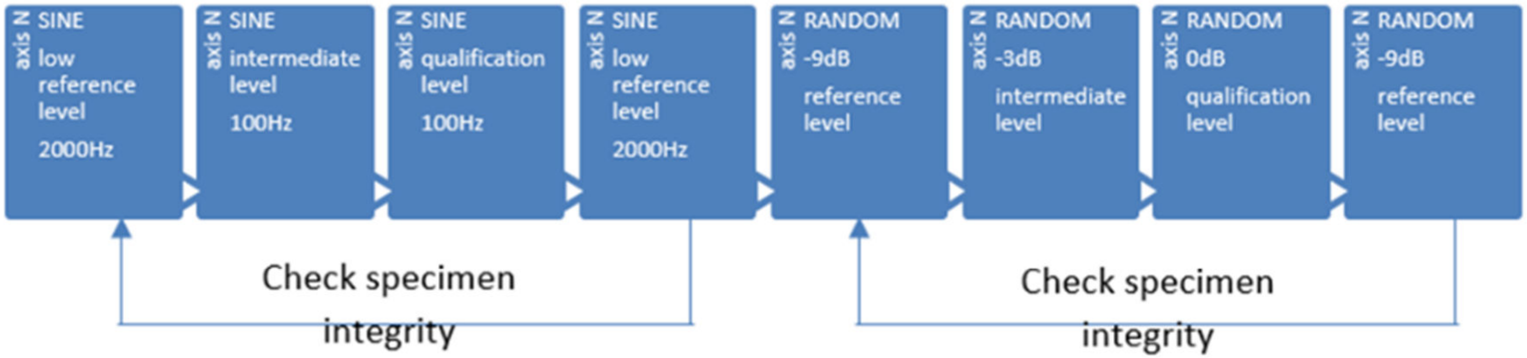




4 tri-axes accelerometers on the bench

Vibration Test Sequences

For each axis X,Y,Z, 8 runs are planned:



1- Sine low level (reference):

Sine X,Y,Z	Low level	Sweep rate (oct/min)
5 – 2000 Hz	0.2g	2

2- Sine intermediate level (Qualif./2):

Sine X,Y,Z	intermediate level	Sweep rate (oct/min)	
5 – 20 Hz	1.5g	2	Primary Notching planned around 100 Hz
20-30 Hz	10g	2	
30-100 Hz	1.5g	2	

3- Sine qualification level:

Sine X,Y,Z	Qualification level	Sweep rate (oct/min)	
5 – 20 Hz	3g	4	Primary Notching planned around 100 Hz
20-30 Hz	20g	4	
30-100 Hz	3g	4	

4- Sine low level (control):

Sine X,Y,Z	Low level	Sweep rate (oct/min)
5 – 2000 Hz	0.2g	2

5- Random (-9db) - reference

6- Random (-3dB) – intermediate level

7- Random qualification level (0dB):

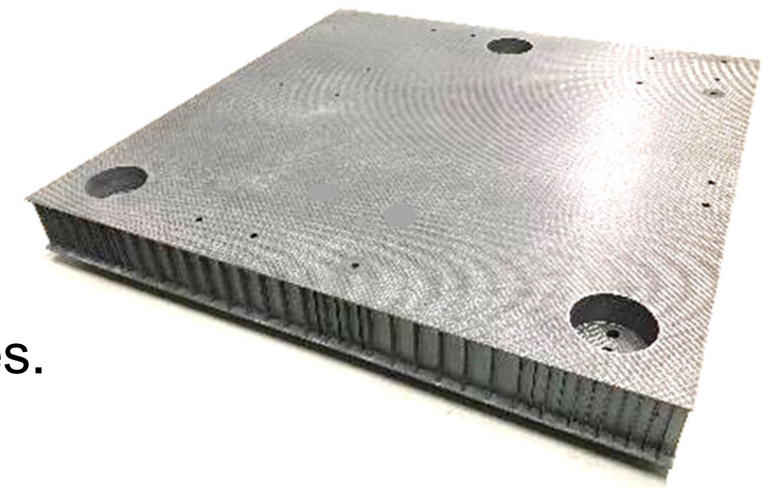
Sine X,Y,Z	Qualification level	
20 Hz	0.0525 g2/Hz	Local notchings planned on optic lests
20-150 Hz	+3 dB/oct	
150-350 Hz	0.4	
350-2000 Hz	-6db/oct	
2000 Hz	0.0125 g2/Hz	
Overall	15.0 grms	

8- Random (-9db) - control

Sucess criterion: no drift on modal frequencies

Summary

- An all C/C-SiC sandwich OB demonstrator, was developed successfully in a close cooperation of DLR and TAS-F.
- Sample tests of the sandwich structure and interface concepts demonstrated:
  - Reproducible manufacturing with a good core to skin bonding
  - Expected mechanical strength (even higher)
  - High stability of sandwich structure and interfaces
  - Material model and simulation close to reality.
    Conservative failure criteria obtained.
- Next step: Vibration test of C/C-SiC
  sandwich demonstrator at TAS-F, Cannes.



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- Teams at TAS-F and DLR

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