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Multi-Scale Analysis and Characterisation of ITER Pre-Compression rings

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2. THE MULTISCALE APPROACH
3. FAILURE CRITERIA
4. MACRO MESO SCALE MODEL ANALYSIS
5. MICRO SCALE MODEL DESCRIPTION, FATIGUE ANALYSIS OF RINGS
6. EXPERIMENTAL TEST MEASUREMENT OF FRACTURE TOUGHNESS AT 4K
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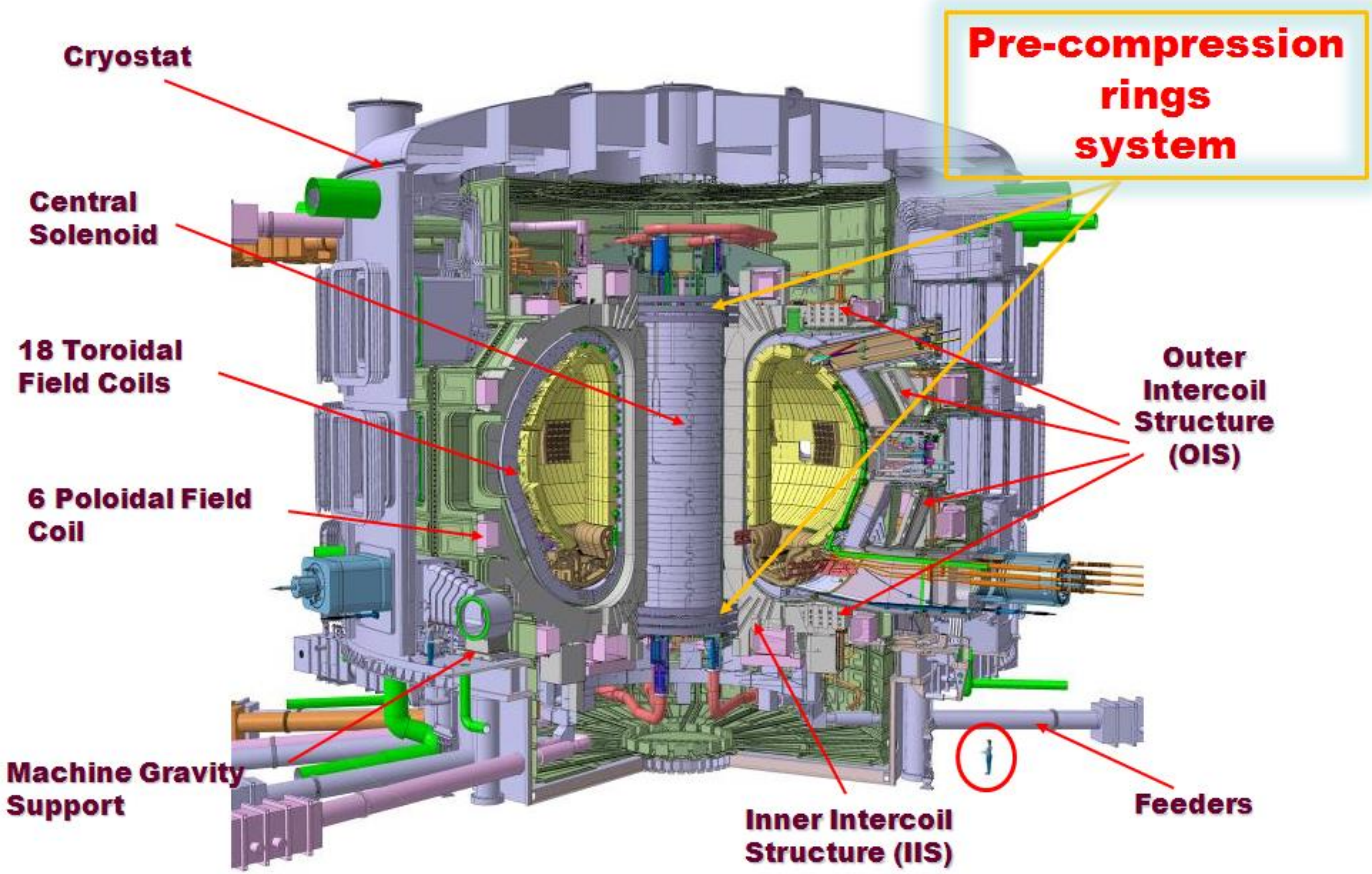
Scope and framework

- Work performed under a ITER development framework contract in collaboration with *SENER Ingeniería y Sistemas SA* to better characterise the behavior of the Composite Pre compression rings in operation and the failure modes. PC-Rings are procured by European Domestic Agency (F4E)

- A multi-scale analysis approach employing various FEM models scales (based on Abaqus package) to assess the response and performance of the Pre Compression rings under mechanical and thermal loads.

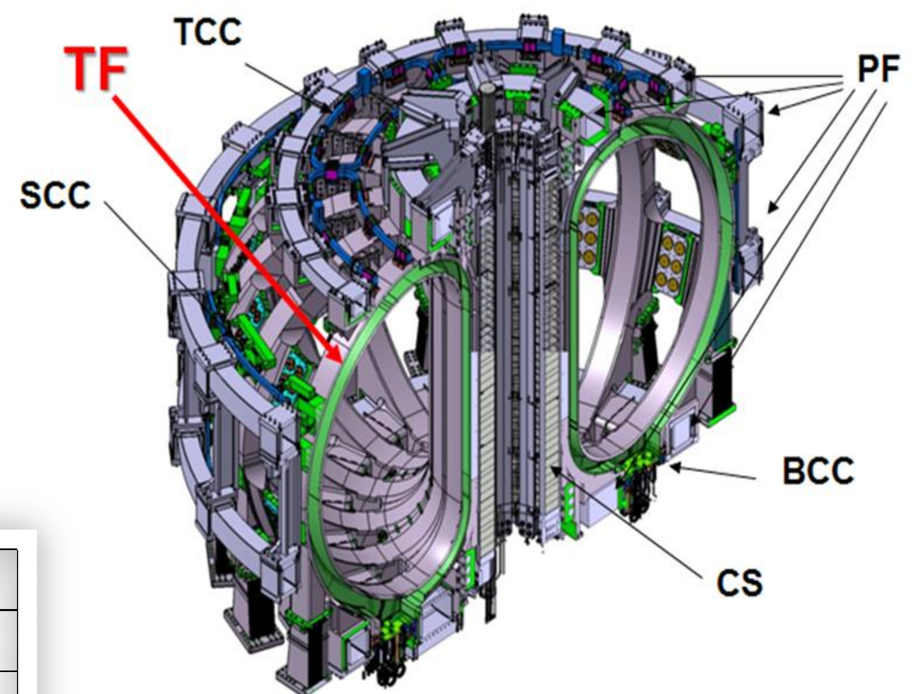
ITER main components



TF coils

- Toroidal Field Coils based on Nb_3Sn CIC Conductor confine the plasma
  - Nominal current of 68KA builds magnetic field of 5.4T in the center of vacuum vessel
- TF stored magnetic energy of 41GJ and released in a controlled way through fast discharge units.
- The TF coils structures as main structural component of ITER,
  - resist the magnetic Lorentz forces generated during operation
  - support all the other 30 SC coils installed (6 PF, 6 CS modules and 18 CC)

Number of TF coils	18
Magnetic energy in TF coils (GJ)	~ 41
Maximum field in TF coils (T)	11.8
Centering force per TF coil (MN)	403
TF discharge time constant (s)	11



Total weight of TF coils system	~6540t
TF cases	~190t
TF WP	~110t
Pre-compression system, keys and bolts	~60 t

PC-Ring LAYOUT

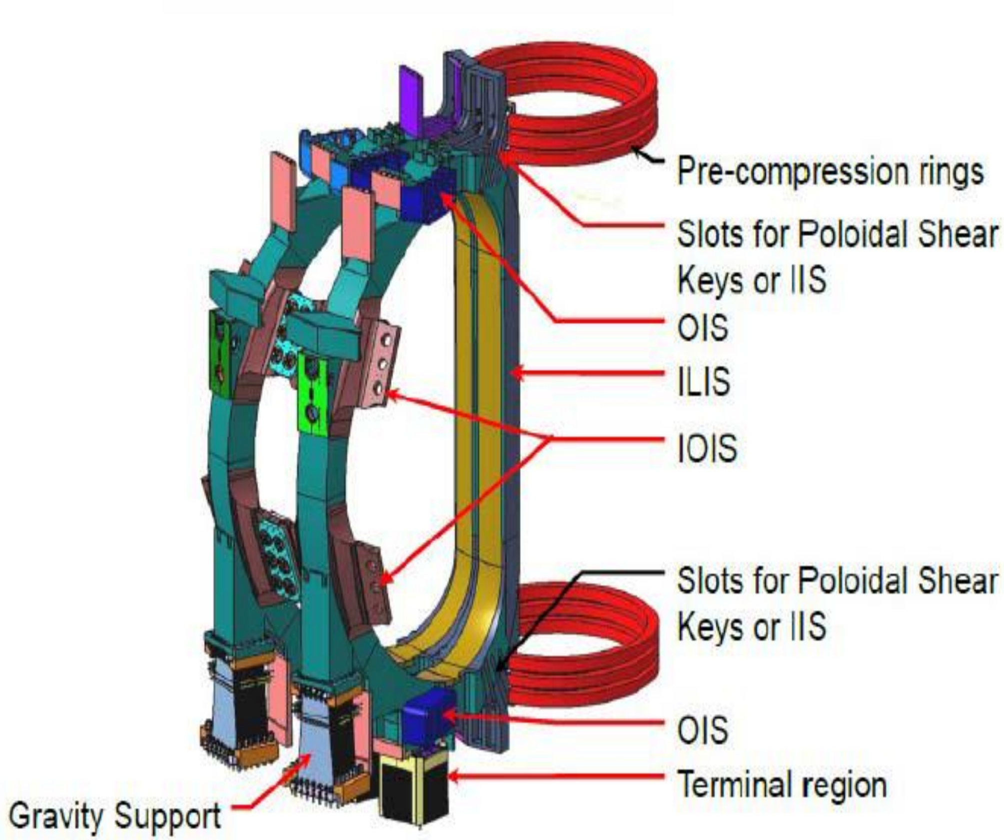


Figure 1: Assembly layout of TF Coils pair

- Three rings at the top and three at the bottom of the 18 D-shaped toroidal field coils (TF)
- each **5 m in diameter and 337 x 288 mm² in cross-section,**
- Manufactured from **S2 fibre-Glass/Epoxy unidirectional composite** based on proposed Advanced Fiber Placement (AFP) method *(see H.Rajainmaki's presentation at ICMC2013).*
- The PC-R system as a keystone of ITER fulfills two main functions:
  - ***Reduction of cyclic stresses in IIS shear keys allowing fatigue life within design criteria***
  - ***Reduction of toroidal stresses in the 4 I-OIS attachment bands***

Boundary Conditions

- **Pre-compression rings pre-loaded** through tightening of the Super-bolts© **at Room Temperature (RT)**
  - 50 MPa radial compression
  - 400 MPa average hoop tension.

- ITER structure as cooled at 4K for the operation, withstands various **thermo mechanical load cycles**

- **Ionizing radiation** in the order of **hundreds kGy** over 20 years of ITER operation life

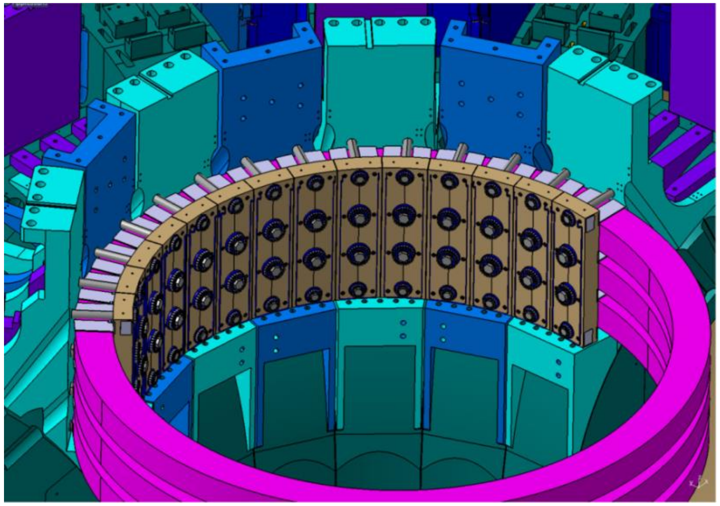
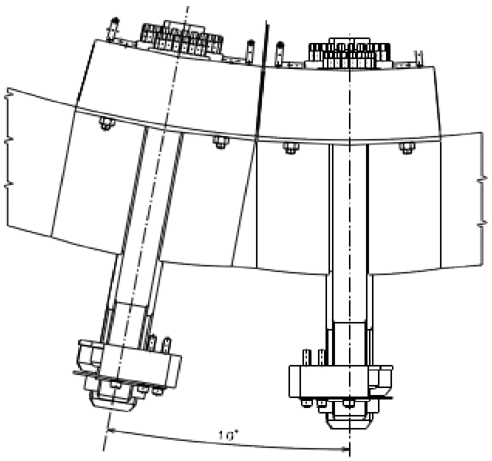


Figure 2: PC rings environment



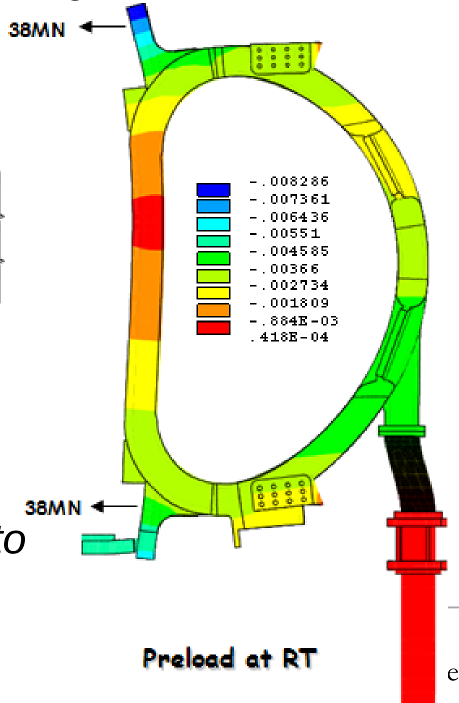


Figure 3: Local deformation due to PC rings preload

Past Material properties tests

- A dedicated test bench scaling down the 18 TF coils layout by ENEA in 2009 (Frascati, Italy)
- Intensive campaign test on more than 10 rings models (1/5 size)
  - Under rupture up to 2201 MPa UTS at RT 2766 Mpa at 77K for VPI.
  - Creep estimate Long term stress relaxation behavior,

$\sigma_{UT\ 4K}$ =1987 * (2766/2201) * (20*365*24)$^{-0.031}$ = **1717 MPa** (20 years at 4K) [Schapery ,12]

Variable	Strength value	Unit	Temp. 289 K (RT)	Temp. 77K	Temp. 4K
S11+	Longitudinal Tension	MPa	2201	**2766**	n/a
S11-	Longitudinal Compression	MPa	-913	-984	-1129
S33+	Radial Tension	MPa	n/a	n/a	n/a
S33-	Radial Compression	MPa	-166	-375	**-492**
S22+	Transverse Tension	MPa	n/a	n/a	n/a
S22-	Transverse Compression	MPa	-172	-452	-354
S12	In-Plane Shear Strength	MPa	49	**78**	n/a
S13	Interlaminar Shear	MPa	60	**127**	n/a

Table 1 - Pre-compression rings material strength properties from measurements (properties at 77K assumed at 4K conservatively)

Ring mock-up testing machine design and manufacture

Detail Design : ENEA
Mechanical structure: Fantini Sud
Hydraulic system (BOSCH REXROTH): Oleodinamica Service, Cedrone Oleodinamica
Assembly: ENEA, Software & DAQ: ENEA
Testing Machine Performances : Max pulling load: 18x57 ton = 1026 ton

Figure 4. Rings mock-ups under test Φ1005 (1/5 scaled from real ring)

Fabricated by VPI process (Φ14 μm diameter S2-glass fibres in yarns of tex 725, impregnated with DGEBA epoxy)

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THE MULTISCALE APPROACH

- **Macro scale model** used as load inputs boundary conditions for sub models (meso and micro scale).
- **Meso-scale FEA model** of the individual layers properties of composite material through the accurate method of Cohesive Zone Model (CZM) elements
  - ✓ to assess mechanically impact of defects like delamination on bonded interface layers.
- **Micro scale model** to assess Matrix and fiber stresses

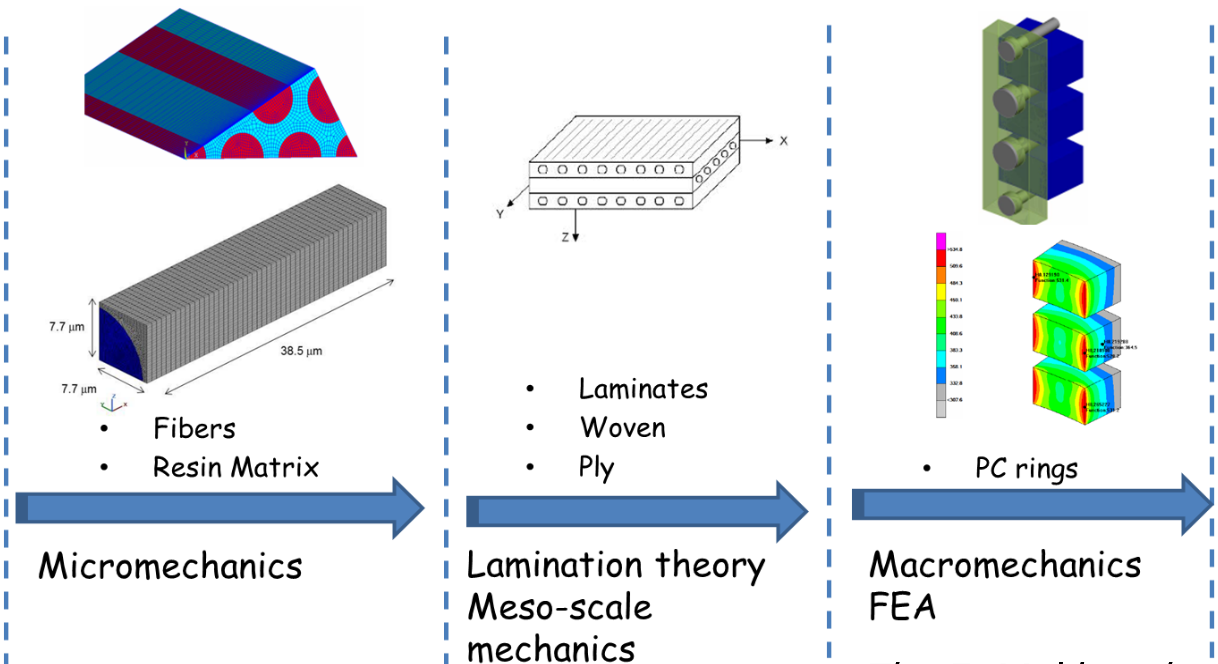

Fig .5 Multi scale step model analysis

Macro scale analysis of the Pre-compression rings

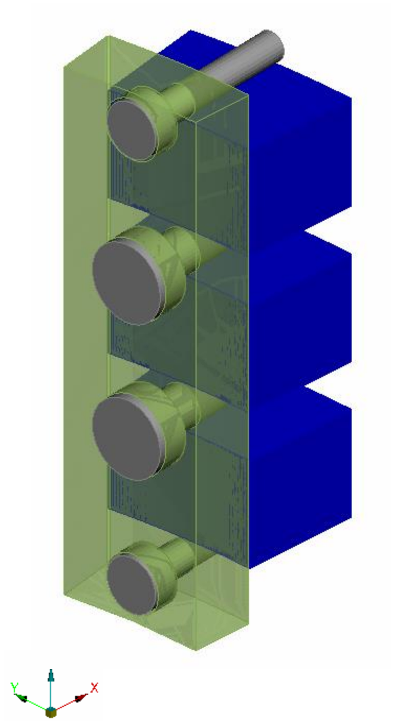

Fig 6. 10 degree segment of Macro scale model of 3 Pre-compression rings (blue), Half PCC flange (green) and associated Superbolts (grey)

- Pre-load applied to the rings through bolt displacements which pass through the Pre Compression Counter Flanges (PCCF's)
- Total centripetal pre-load of 35 MN **per TF coil flange** at Room Temperature.
- Cyclic symmetry boundary conditions applied
- Non linear macro scale Finite Element Model to simulate contact between PCC flange and the ring.
- S2 fiber glass/epoxy composite material properties inputs from ENEA tests used.

Macro scale analysis

- The **applied stress distributions** in the pre compression rings at room temperature (RT) condition are shown below in Fig. 7.

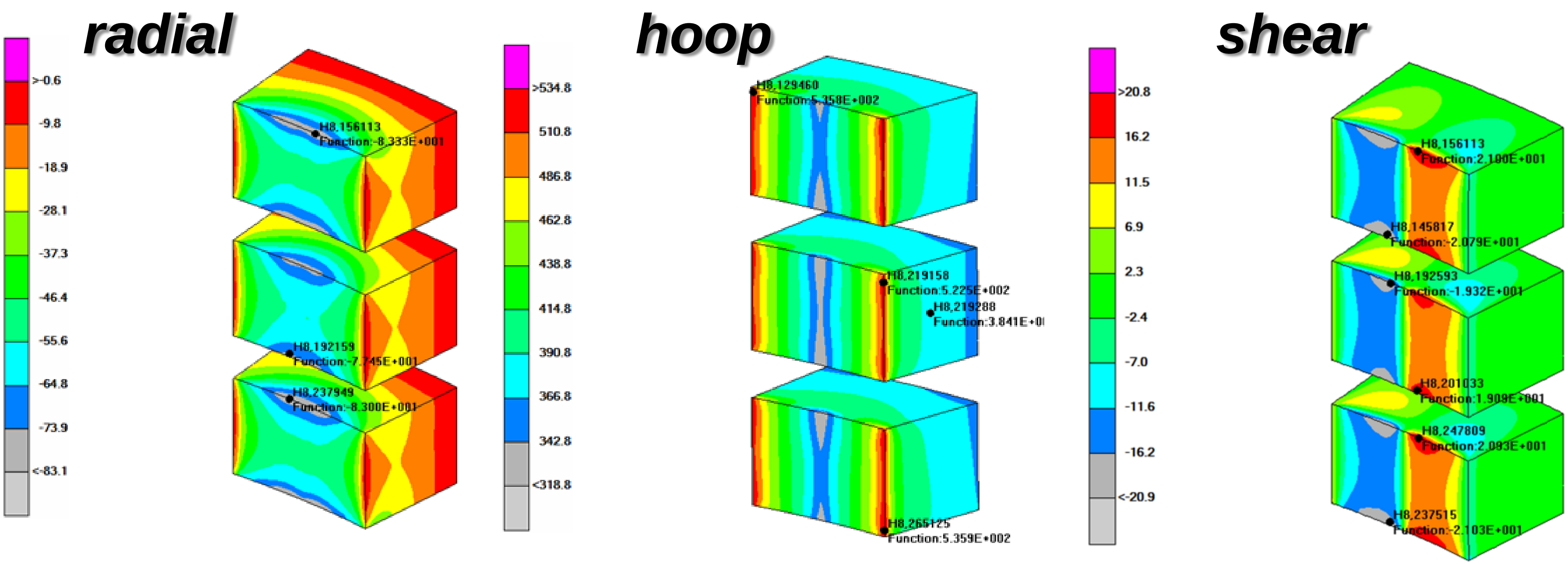

*Fig 7. Macro scale FEM **radial, hoop & shear stress** in pre-compression rings @ RT.*

Macro scale analysis : Strength ratio

- The macro scale applied stresses were compared against S2 fibre glass epoxy composite experimental strength.

- The **ratio of strengths to stresses** given in Table 2 below shows that the pre-compression rings have a **safety factor greater than 2 for all load conditions (RT and 4K).**

Stress Condition	RT (MPa)	4K (MPa)	(4K/RT)·100	SR (RT)	SR(4K)
Peak Hoop Stress	535.9	531.4	99.2%	4,106	5.209
Avg. Hoop Stress	384.1	364.5	94.9%	-	-
Peak Radial compression Stress	-83.3	-78.3	94.0%	**2.000**	6.308
Peak interlaminar Shear Stress	21.0	19.9	94.8%	**2,857**	6.350

Table 2. Macro scale analysis Pre-compression rings stress and Strength ratios (SR).

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Macro scale Failure index: Hashin criteria

- The interaction of the applied stress components in various directions were characterized using Hashin failure criteria [9] based on S2 fiberglass epoxy composite measured material strengths. The results in critical areas at RT are shown in Figures 8a-b below.

Fig 8a. **Hashin and Rotem strength ratio, Fibre tension & shear failure at RT**

$$F_t^+ = \left(\frac{\sigma_{11}}{S_{11}^+}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 \geq 1.0$$

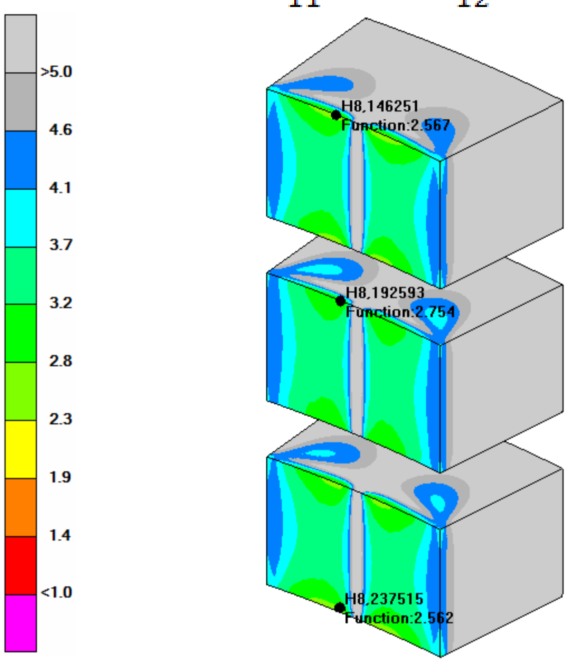
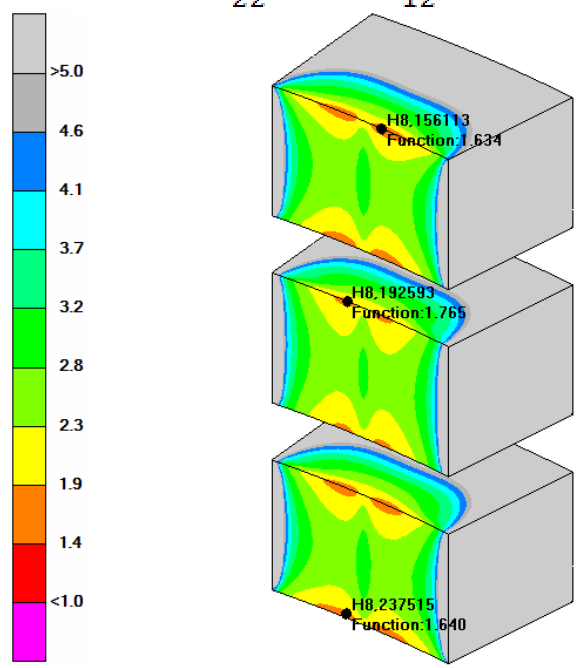


Fig 8b. **Hashin and Rotem strength ratio, Matrix compression & shear failure at RT**

$$F_m^- = \left(\frac{\sigma_{22}}{S_{22}^-}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 \geq 1.0$$



Meso scale analysis: Softening law, Fracture toughness

- Progressive damage-dependent traction–separation softening law in the cohesive zone (yellow) used for fracture assessment.

a)

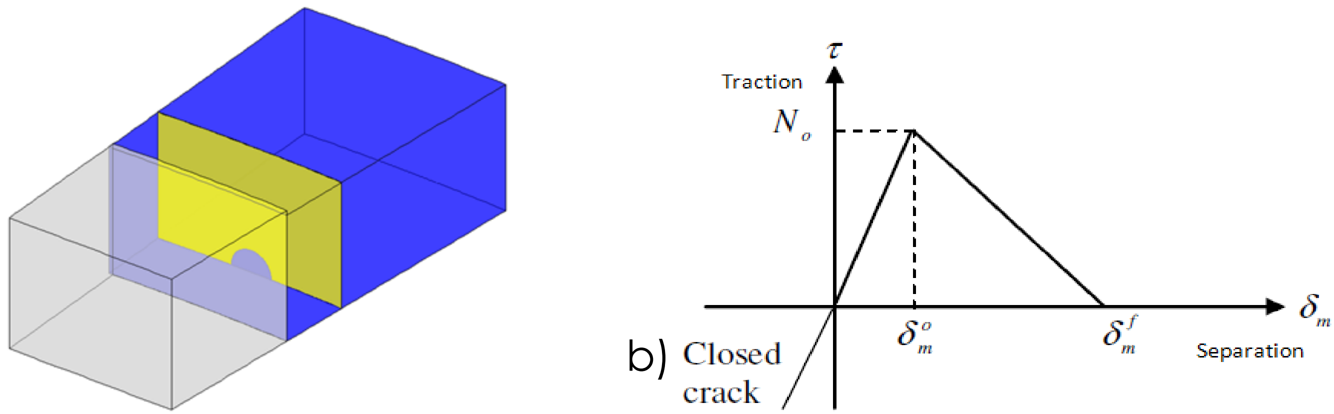


Fig 9 a) Ring sector meso scale model, b) Delamination damage model relationship

Table of Interlaminar and Ply Energy Fracture toughness inputs [10]

GI_{Cint}	GII_{Cint}	$GI_{Cply} = GI_C$	GII_{Cply}
0.088 KJ/m2	0.315 KJ/m2	0.147 KJ/m2	GIcply·GIIcint/GIcint = 0.526 KJ/m2

- Through thickness strengths τ_1^o, τ_2^o and lamina transverse tensile strength τ_3^o respectively calculated to 35 and 65 Mpa. [16]

Meso scale analysis results

- The meso scale analysis results show a shear stress concentration at the edge of the 25 mm radius delamination defect, (see Figure 10).

⇒ The **shear stress and driving mode II energy levels are too low to initiate propagation of the delamination.**

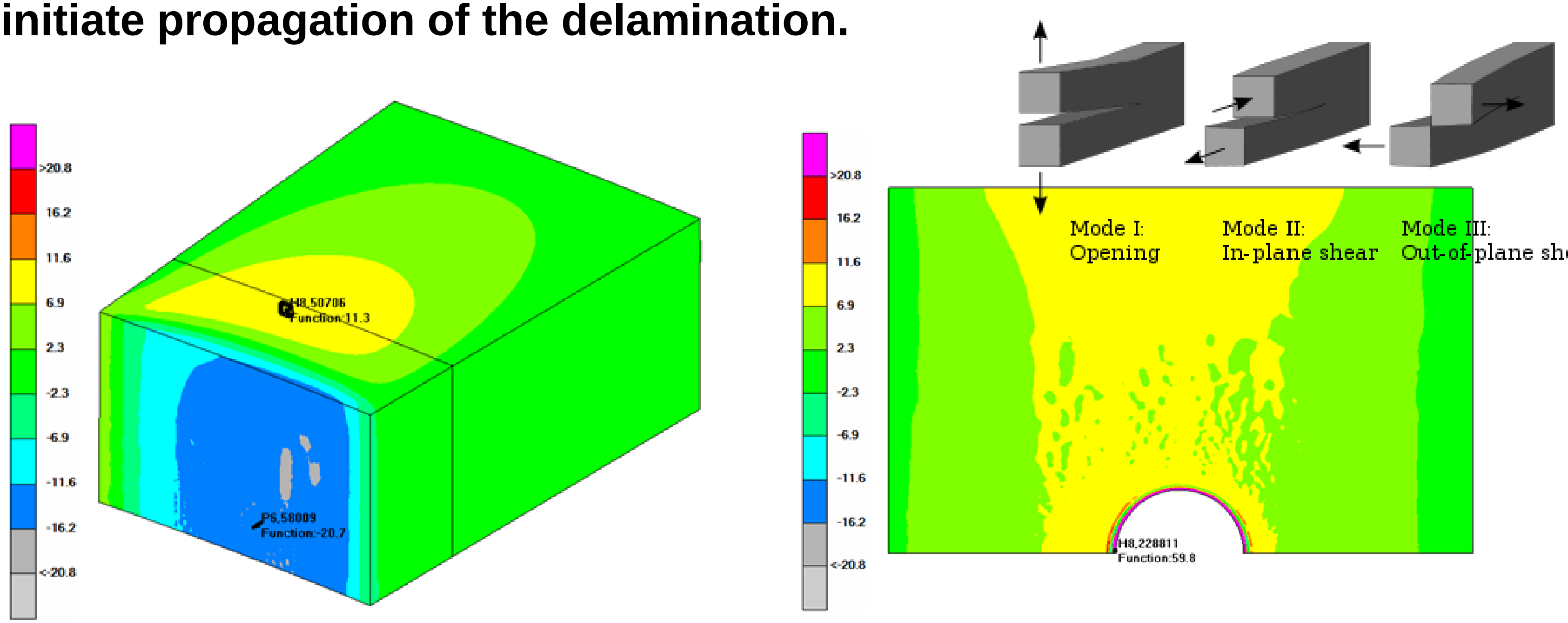


Fig. 10 Meso scale shear stress in ring and cohesive elements

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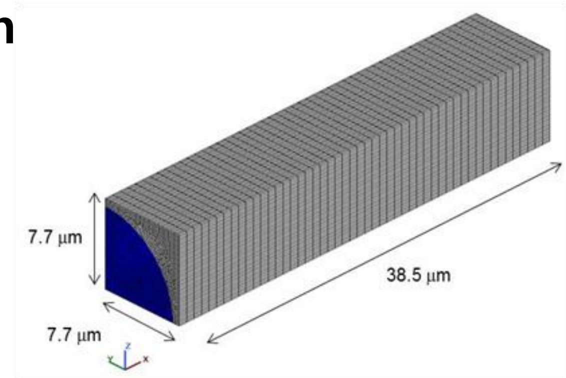
Micro scale analysis results

- The micro scale FE model represents a **volume cell with one fiber filament of radius 7 microns modeled and a volume of matrix** corresponding to a 65% fiber volume.
- Significant matrix stress concentrations from mechanical loads and low temperatures due to the high thermal contraction of the matrix relative to the fiber at 4K,



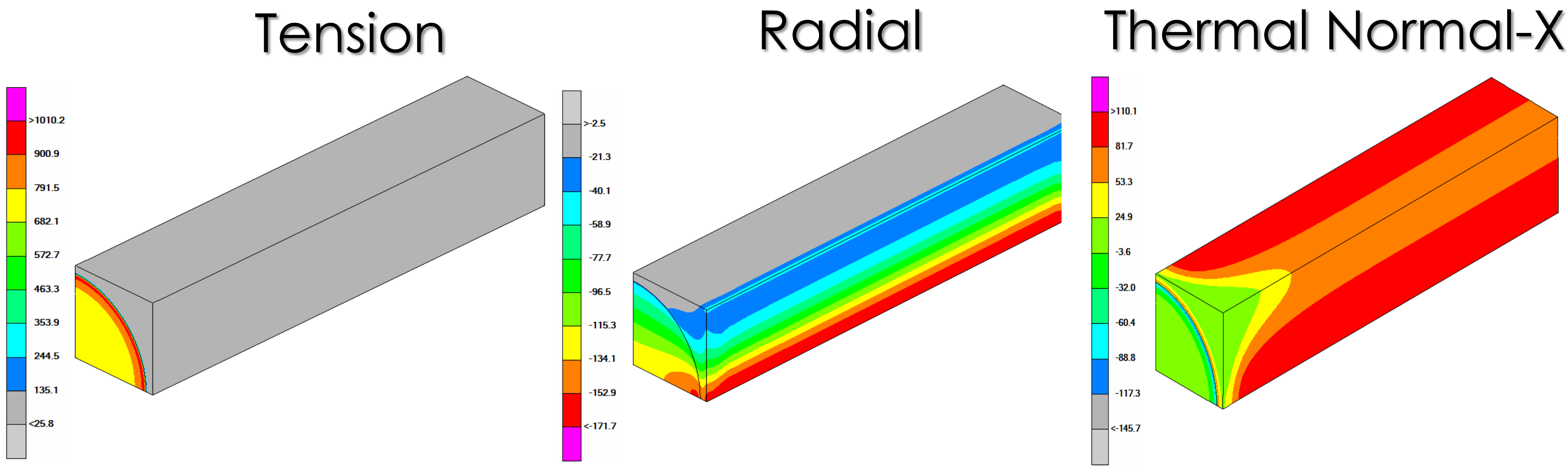


Figure 11: Micro scale tension, radial and thermal Normal-X stresses at 4K

Micro scale analysis

- Applied stresses were compared against both S2 glass fiber and epoxy matrix strengths from ENEA testing at RT and 4K.
- The ratio of strengths to stresses (Table 4) below show the pre-compression rings epoxy matrix material to be the most critical part of the structure at 4K.

Table. 4 Micro scale strength analysis summary at 4K

Stress Condition	Stress MPa	Strength MPa	Strength to Stress Ratio
Fibre Hoop Tension	739	4079	5,522
Matrix Hoop Tension	229	420	1,835
Fibre Radial Comp'n	-154	-966	6,290
Matrix Radial Comp	-155	-970	6,263
Fibre Shear	39	246	6,331
Matrix Shear	39	246	6,331

Further multi scale Fatigue analysis

- Macro scale analysis based on Goodman (figure 12) revealed that the pre-compression ring S2 glass fiber with fatigue stress cycle amplitude of **+/- 27 MPa (around mean stress 530MPa, 78 ksi) gives a fatigue life at the ITER operational load conditions at 4K greater than 10^7 cycles**.

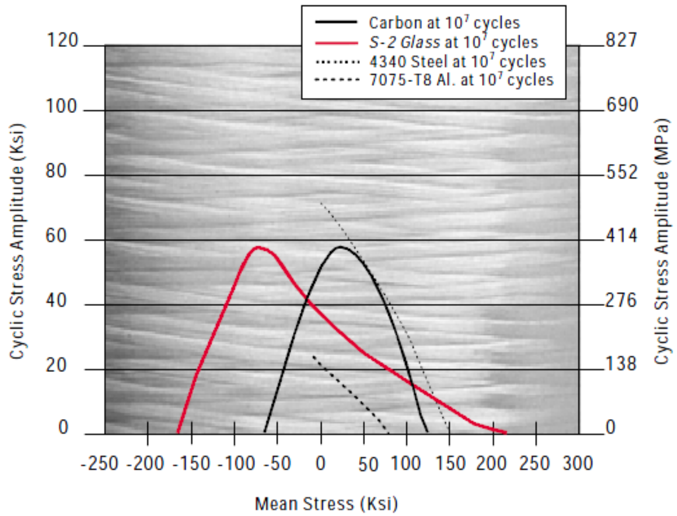


Fig 12. Goodman Diagram of S-2 Glass/Epoxy Fatigue strength data vs. AGY reference

- Micro scale fatigue analysis based on the Zhurkov kinetic theory [5] of fracture revealed that the **pre-compression ring epoxy matrix would have a life of 50 million cycles at the ITER operational load conditions.**

$$\tau = \tau_0 . \exp\left(\frac{U-\gamma\sigma}{kT}\right) \quad [5.1]$$

τ_0 inverse of the frequency of thermal vibrations of atoms

number of cycles to fatigue failure of polymers

$$N_f = 2.f.\left(\frac{h}{kT}\right).\exp\left(\frac{U-\gamma\sigma}{kT}\right) \quad [5.2]$$

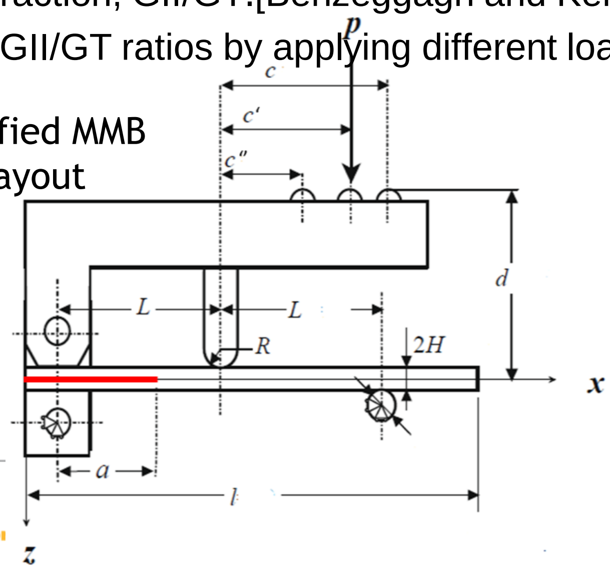
f is the loading frequency, 0.0016 cycles/s
h is the Planck's constant
K is the Boltzmann's constant
fit parameters of U = 140KJ/mol and γ= 8E-04 J/Pa ·mol
σ Is 10% of Von Mises micromechanical stresses in the critical element (max radial stress) of 141 MPa at room temperature

CONTENT

MEASUREMENT OF FRACTURE TOUGHNESS AT 4K

- The measurement of the **three modes fracture toughnesses G_I, G_{II}, G_{III}** will be required to characterize the **resistance of new composite ring material to crack propagation at 4K, (or 77K)**.
- **Most representative mixed loading mode I+II** within the rings through measurement of the interlaminar fracture toughness.
- **Modified Mixed-Mode Bending (MMB) fracture toughness test** (ASTM D 6671)
  - **Critical energy release rate of mixed-mode, GT_c,** at 77 K and 4 K plotted as a function of the Mode II fraction, GII/GT.[Benzeggagh and Kenane, [19]]
  - different GII/GT ratios by applying different loads at different location of the test specimen

Figure 16. Modified MMB test specimen layout



Energy release rates of Mode I (GI) and Mode II (GII), Gt=GI+GII from beam theory:

$$G_I = \frac{(3a^2P^2)}{4B^2H^3L^2E_x}(3c-L)^2 ,$$

$$G_{II} = \frac{(9a^2P^2)}{16B^2H^3L^2E_x}(c+L)^2$$

SUMMARY

- The macro scale analysis indicates that the **ITER pre-compression rings composite structure resists the applied pre-loads at RT and 4K without static, fatigue and Creep rupture.** Minimum strength ratios existing only at local hot spots near the ring contact with the PC rings flange.

- **The meso scale model** constructed with cohesive elements **indicate that the ITER pre-compression rings composite material resists the applied pre-loads at room temperature and 4K with a 50 mm delamination** in the location of the most critical shear stresses

- Micro scale models have been generated to calculate thermo-mechanical stresses in the fibre and matrix of the composite. **The results of the micro scale analysis indicate that the fiber and matrix are capable of resisting the applied preload stresses at 4K.**

- Further assessment correlated with experimental measurement of the three modes fracture toughness at 4K (or 77K) are important to understand behaviour of the crack propagation and visco-elastic epoxy matrix material which could significantly affect the performance by reducing the pre-load of the rings.

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