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ASSESSMENT OF POSSIBLE FAILURE MODES AND NON DESTRUCTIVE EXAMINATION OF THE ITER PRE-COMPRESSION RINGS

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ABSTRACT

The pre-compression rings (PCRs) for the International Thermonuclear Experimental Reactor (ITER) represent one of the largest and most highly stressed composite structures ever designed for long term operation at 4K. Three rings, each 5m in diameter and 337 x 288 mm in cross-section, will be installed at the top and bottom of the eighteen “D” shaped toroidal field (TF) coils to apply a total centripetal load of 70 MN per TF coil. The interaction of the 68 kA conductor current circulating in the coil (for a total of 9.1MA) with the required magnetic field to confine the plasma during operation will result in Lorentz forces that build in-plane and out-of-plane loads. The PCRs are essential to keep the stresses below the acceptable level for the ITER magnets structural materials.

Each PCR will be pre-loaded at RT and cooled to 4K. They are designed to withstand various thermal cycles reaching up to 400 MPa hoop tension and up to 40 MPa radial compression without degradation. The rings will be fabricated (pre-dominantly) by hoop wound S-glass tow to result in a high glass content (>65% in volume) structure [1]. During manufacture emphasis will be placed on obtaining a structure with a low void content (<1.5%) and that it is free from inclusions, faults, cracks and de-laminations. The biaxial loading conditions that exist in the PCRs can lead to complex behaviour patterns while the few existing studies on ring like structures have been limited to testing tubular specimens with axial loading and either internal pressure or a torsion load applied. This paper will study the possible failure modes of the PCRs and consider available non-destructive evaluation techniques that may be applied to the full scale rings after manufacture.

KEYWORDS: ITER, composites, superconducting magnets, glass-fibre, epoxy, TF coils

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INTRODUCTION

The ITER pre-compression rings are possibly the heaviest composite structure ever attempted for operation in a cryogenic environment. Its full description was provided elsewhere [1]. In outline, these rings will be 4975 mm internal diameter and 337 x 288 mm cross section. The ITER magnet system consists of a total of 48 superconducting coils with the 18 Toroidal Field (TF) coils forming the skeleton of the magnet system [2]. These large and heavy superconducting coils are the biggest ever built but are relatively slender subjected to electromagnetic out-of plane forces induced by the operation of the central solenoid and poloidal field coils, which are required to confine the plasma.

Overall there is a resultant over-turning moment about the coil minor radius. The outboard legs of the coil, together with the Intermediate Outer Intercoil Structure bands (IOIS) form a second outboard torsion cylinder which is twisted in the opposite direction to the central vault conformed by the 18 straight sections of the D-shaped TF coils. This becomes the most stressed region of the TF coils where a combination of bending and torsion creates a high cyclic shear stress on the Inconel inner intercoil structures keys (IIS).

The 70 MN inward loads that the pre-compression rings (located at the top and bottom of the coil case inner straight leg (FIGURE 1)) will apply on each TF coil in order to mitigate the cyclic stresses in the IIS and OIS will ensure the 20 years of machine design life without fatigue failure [1].

THE LESSONS LEARNED FROM THE TEN YEARS R&D PHASE AT ENEA

The design of the pre-compression system is the result of 10 years of intense development work in collaboration with ENEA (Frascati). The work was financed along the years by EURATOM and ITER organization. The rings have to overcome strong geometrical and mechanical constraints and eliminate induced currents that originate from the dramatic magnetic flux variations. A purpose designed and built testing device with a scaled down equivalent configuration to that in ITER was installed in ENEA. This machine is based on 18 hydraulic cylinders working at a maximum pressure of 300 bar , which present a maximum pulling capability of 57 ton with a maximum stroke of 70 mm [3]. Each actuator was equipped with a linear position transducer yielding a precision of 0.1 mm.

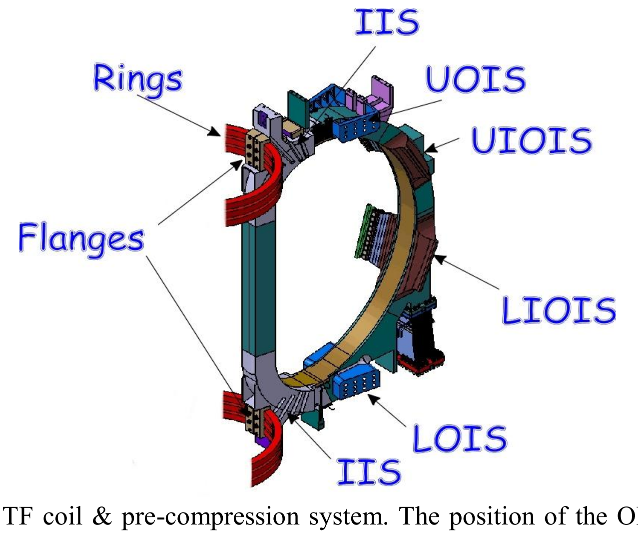

FIGURE 1. Layout of one TF coil & pre-compression system. The position of the OIS, Upper and Lower IOIS and IIS

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Six model rings, 1/5 scale in radius, with >65% volume of glass content were loaded at a rate of 1mm/minute deflection until rupture with an average of 1551 MPa. There was a variety of rupture mechanism, the assessment of which allowed design improvements. Among these are joining fibres from different rolls by adhesive bonding, ring/flange interface to be composite/steel, treated with Molykote® which was found to be better than low friction plastic layers and reinforcement in the radial direction. The Fibre Efficiency Ratio for the model rings as defined by Zhao [4],is the ratio between the actual and theoretical strength of the composites

$$FDR = \frac{\sigma_u}{\sigma_f V_f} \qquad (1)$$

where σ_u is the UTS of the composite, σ_f is the fibre strength measured by the single fibre strength test [5] and V_f is the volume fraction of fibres (0.65) would yield 62%. However, this value might be improved by a custom design sizing on the fibres and by minimizing damage to filaments during the winding / lay-up process.
Full characterization of the mechanical properties in compression at RT and 77K has been performed [6] with specimens extracted from a ring model (see FIGURE 2). In addition, ultimate tensile stress on 5 specimens showed an average of 2201 MPa at RT with 2766 MPa at 77K with 61 GPa of elastic modulus. The work performed has been recently summarized [7].

Creep behaviour of the composite material was also studied in small scale tests with the measurement over a period of 3 years of 12 specimens loaded between 63% and 80% of the measured UTS and this work allowed the determination of the Norton fitting curve [8]. The information retrieved with the 2 long term tests of the rings under constant stress correlates nicely with the creep curve as indicated in FIGURE 5.

The two fabrication process used in the fabrication of the 1/5 scale rings, VPI and filament winding, were successfully qualified and pre-preg type is also perceived as a suitable solution. It is anticipated that it may be difficult to achieve the full cross section in one only curing step and that during the „industrialisation phase" techniques will be developed to manufacture full size rings in sections, if necessary, among the two fabrication routes that must be qualified with 1/5 models before attempting the full scale rings.

TEST (@ENEA)	FIBER Direction	TEMP	TEST Standard	N. Tests	TOTAL average	
Comp hoop	‖	RT	ASTM D695	1	σ [MPa]	913.00
					E_x [GPa]	63.33
					ν_{xy} or ν_{xz}	0.26
Comp hoop	‖	77K	ASTM D695	1	σ [MPa]	984.00
					E_x [GPa]	67.86
					ν_{xy} or ν_{xz}	0.24
Comp rad	⊥	RT	ASTM D695	3	σ [MPa]	166.14
					E_y [GPa]	22.01
					ν_{yz}	0.45
					ν_{yx}	0.12
Comp rad	⊥	77K	ASTM D695	1	σ [MPa]	375.89
					E_y [GPa]	30.65
					ν_{yz}	0.37
					ν_{yx}	0.16
Comp trans	⊥	RT	ASTM D695	3	σ [MPa]	171.51
					E_z [GPa]	20.91
					ν_{zy}	0.36
					ν_{zx}	0.11
Comp trans	⊥	77K	ASTM D695	1	σ [MPa]	451.75
					E_z [GPa]	31.20
					ν_{zy}	0.16
					ν_{zx}	0.16

TEST (@ENEA)	FIBER Direction	TEMP	TEST Standard	N. Tests	TOTAL average	
Shear	⊥	RT	V-notch ASTM D5379	3	τ [MPa]	59.98
					G_{xy} [GPa]	13.70
Shear	⊥	77K	V-notch ASTM D5379	3	τ [MPa]	127.39
					G_{xy} [GPa]	27.23
Shear	‖	RT	V-notch ASTM D5379	3	τ [MPa]	48.94
					G_{yx} [GPa]	10.40
Shear	‖	77K	V-notch ASTM D5379	3	τ [MPa]	78.39
					G_{yx} [GPa]	21.94
Shear		RT	punch tool ASTM D732	3	τ [MPa]	296.78
Shear		77K	punch tool ASTM D732	3	τ [MPa]	456.37

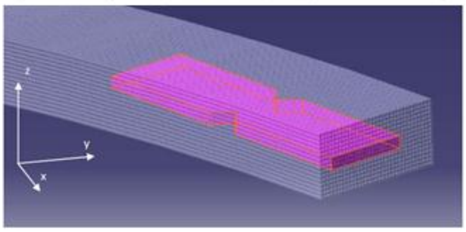

FIGURE 2. Mechanical properties at RT and 77K of the rings composite with specimens extracted from model rings

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An assessment of possible non-destructive evaluation techniques will be carried out with the emphasis placed on methods to cover the full cross section. In the event that full sized rings cannot be realistically evaluated, manufacture in sections represents an alternative solution.

CAN THE PRE-COMPRESSION RINGS BE NON DESTRUCTIVELY EVALUATED SUCCESSFULLY?

The large cross section of the rings makes difficult to achieve a precise 100% volume evaluation of internal defects by Ultrasonic Techniques (UT) or conventional Radiographic Techniques (RT). Computerized tomography with a modulation of the photon energy neutronic radiography may be capable of examining the full volume but the required sensitivity might not be achieved. The possible difficulties of ensuring optimal wetting, compacting and curing of the full cross section with only one fabrication step may lead to sectorization in disc type shapes. This would allow an efficient 100% volume non destructive examination. The size and weight of the rings would have to be considered during the selection of any NDT technique, these rings will be difficult to handle and it is important to avoid any accidental damage during any handling process.

The suitability of a variety of methods to detect particular defects will likely lead to a combination of Visual Techniques; UT suitable to detect delaminations [9] and RT suitable to detect clusters of voids [10] or individual cracks [[11]. A calibration of the techniques in models and test sections with the chosen thickness will be mandatory for efficient implementation.

Performance monitoring during operation to identify possible degradation of the rings will be carried out by Acoustic Emission [REF[12]], which allows the discrimination of the phenomena occurring in the composite thanks to a frequency signature (ranging from around 35 dB for micro-cracking in the matrix, around 50 dB for delaminations and 90 dB if fibre breakage takes place).

WILL THE RINGS WITHSTAND THE REQUIRED OPERATIONAL CONDITIONS?

There are no specific studies on composite structure such as the ITER PCRs with their exacting demands and requirements: a) loaded at about 400 MPa in hoop tension and 40 MPa in compression, b) cyclic loads of about +/-5% in hoop, radial and shear stress and c) over x10 thermal cycles from RT to 4.5K, d) ionizing radiation over 100 kGy and continuously loaded for 20 years. Although replacement is possible, and three spare rings will be in a garage position on the floor of the cryostat, it would become a major operation with a machine shutdown for at least one year to replace a ring. The failure of one ring in service could lead to the catastrophic failure of other rings.

The factors that have an impact on the long term performance of engineered composite materials and the capability of large structures to sustain high stresses without failure has been the subject of decades of research; however the ability to fully understand the behaviour of composites remains restricted [13]. Failure to assign sufficient relevance to technical details across orders of magnitude in size of the components has frequently led to unexpected failures. In particular, the mechanism of damage growth from smaller to larger scale with the related structural changes taking place continuously and also in a cumulative way, is still not completely understood despite the predictions of the modern kinetic theory of fracture. In this section we will assess the rings performance in the light of the existing models of failure of composites.

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The generalization of Von Mises yield criterion for anisotropic materials was developed by Hill14 in 1950. The reduced ductility of fibres led to the adaptation of such theoretical approach by replacing the yield stresses with measured failure stresses, which was first proposed by Tsai15 in 1965 for orthotropic materials and is known widely as the Tsai-Hill failure criterion.

$$\frac{\sigma_1}{\sigma_{1u}}^{2} + \frac{\sigma_2}{\sigma_{2u}}^{2} - \frac{\sigma_1\sigma_2}{\sigma_{1u}^2} + \frac{\tau_{12}}{\tau_{12u}}^{2} < 1 \quad (2)$$

This defines an ellipsoidal envelope in stress space, within which stability of the structure should be guaranteed. A generalization of this approach was carried out in 1971 [16] (although it had been earlier devised in the former Soviet Union in 1961 [17]) overcoming the excessive simplification of EQUATION 2 by pointing out the tensorial nature of the failure surface in the stress space defined by the scalar (and therefore invariant in any coordinate system)

$$f\ \sigma_k\ = F_i\sigma_i + F_{ij}\sigma_i\sigma_j = 1 \quad (3)$$

where $i, j, k = 1, 2, \ldots, 6$ account for principal and shear stresses and F_i and F_{ij} are strength tensors. This tensorial approach meant a breakthrough in the understanding of the composites mechanics allowing a consistent combination of loads and fibre orientation in the analysis and providing an engineering justification on the mathematical assumptions. The tensorial nature permitted the derivation of certain properties from the stability conditions of strength tensors like

$$F_{ii}F_{jj} - F_{ij}^2 \geq 0 \quad (4)$$

that ensures mathematically that a closed ellipsoidal failure surface in stress space will intercept each stress axis.

The (largely) unidirectional winding of the pre-compression rings should ideally become a transverse isotropic structure, a special type of orthotropicity with equal properties in the plane transverse to the winding direction, which yields only 5 independent elastic components. However, fabrication routes will certainly yield a divergence on this theoretical scenario as it has been shown with the full mechanical characterization carried out with specimens extracted from model rings. The inherent symmetries applied to EQUATION 3 for transverse isotropic structures yield EQUATION 2 [16].

Attempts to understand the systematic discrepancies between experiments and real structures led to an approach that differentiated between fibre failure modes and matrix failure modes, taking into account the inherent heterogeneous microstructure of composites [18] with the assumption that fibre and matrix failure are independent events. However, in the range where the pre-compression rings are operating ($\sigma 1>0$ and $\sigma 2<0$) the Tsai-Hill criterion is regarded as conservative [19].

The development of modern computational techniques has allowed the confirmation of a refined criteria taking into account both fibre and matrix failure modes [20] where for the tensile region

$$\frac{\sigma_1}{\sigma_{1u}}^{2} + \frac{\tau_{12}}{\tau_{12u}}^{2} + \frac{\tau_{13}}{\tau_{13u}}^{2} = 1 \quad (5)$$

The presence of compressive loads perpendicular to the fracturing plane would not have

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any impact towards initiating fracture, jeopardizing the shear fracture by shear stresses τ_{12} and τ_{13}. This would give rise to additional resistance to shear fracture;

$$\left(\frac{\tau_{12}}{\tau_{12u}-\rho_{12}\sigma_1}\right)^2+\left(\frac{\tau_{13}}{\tau_{13u}-\rho_{13}\sigma_1}\right)^2=1 \qquad (6)$$

the parameters ρ_{12} and ρ_{13} need to be obtained experimentally.

In addition to fibre or matrix failure, interfacial debonding due to environmental degradation, which in the case of the pre-compression rings could be driven by the over x10 cyclic thermal stresses foreseen during the 20 years of operation, plays a relevant role. Phenomenological observations show that compressive stresses perpendicular to the fibres tend to prevent the formation of inter-fibre fractures, whereas tensile stresses promote this kind of failure [19]. However, high compressive loads can have a severe degrading effect in resin rich areas or dry fibres, which can become crack initiators giving rise to delamination that has been identified as the dominant flaw in reducing the compressive strength. Delaminations follow a log normal statistical distribution [21] tending to be localized at depths between 1/2 and 1/3 of the composite thickness. Damage of this type would have an impact on the pre-compression rings performance. In addition, the ~300 mm thickness would make the detection of faults difficult with the UT, which may not be fully effective at this depth. Delaminations may become critical in the presence of cyclic loads, particularly if oriented in the direction of one of the three known crack growth modes [22], so giving rise to fatigue phenomena.

Fatigue on unidirectional glass-fibre/epoxy composites was successfully studied in 1973 [23] with experimental results matching the theoretical model. Experiments performed under tension with R=0.1 and the endurance limit defined at 1x106 cycles showed a fatigue strength over 700 MPa and over 15 MPa in a matrix driven failure direction. These results were obtained for a composite with σ1u = 1260 MPa, σ2u = 29 MPa and τ12u = 39 MPa. However, fatigue test data with composites is an unreliable source for design because they do not fully capture the range of parameters that real structures undergo. Fatigue characterization is, typically, performed under simplified loading conditions, typically consisting of uniaxial, constant amplitude tensile fatigue loading; however reality is more complex. Studies performed in the last two decades have unambiguously determined that fatigue failure is a matrix-dominated event [24]. This means that the physical behaviour of polymers is the physics-based ingredient needed to predict fatigue. The kinetic theory of fracture, a proven physics based theory for polymer fatigue life, can be applied to the matrix stress in the composite to predict the reduction in strength based on the number of cycles.

The analysis performed on the pre-compression rings at pre-load conditions at RT implementing the mechanical properties reported in a previous section resulted in the plots of FIGURE 3, with the maximum values summarized in TABLE 1.

FIGURE 3. Static stresses during at RT of the lower pre-compression rings

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TABLE 1. Maximum values of stresses in the rings at RT

σ_{1max}	$\sigma_{2\,max}$	τ_{21}
393 MPa	-33 MPa	17 MPa

The presence of vertical fringes with enhancement of hoop stresses, higher compressive stresses and gradient of shear stresses is due to the cylindrical shape of the stainless steel floating flange. The shape of this flange has recently been optimized to eliminate this effect under operating conditions. In addition, a conservative friction coefficient of 0.3 for the stainless steel-composite interface was considered and therefore the real shear stresses are expected to be lower than those shown in Table 1. These values meet the ITER magnets design criteria with a safety factor of 4 following ASME recommendations on stress limits for non-metallic pipes under sustained loads, where the allowable load shall be less than 25% of the minimum value obtained by a proof test.
The general mechanical characterization of composites can often be controversial whereas in-plane and shear moduli can be readily and unambiguously determined. Results from the measurement of in-plane compressive and shear strengths can vary depending on test methodology and a practical engineering approach is necessary when interpreting data for design. This is particularly true on shear strength values. When measured by the V-notch [25] method and compared to through punch tool [26], the latter provides higher values. In the assessment, we use the ones provided by V-notch as a conservative approach.

The application of Tsai-Hill criterion (EQUATION 2) would produce a result of 0.19 and this is mathematically consistent with EQUATION 4 that yields a positive value.

For static assessment the mechanical properties measured at RT are used since the differential thermal expansion between stainless steel (0.3%) and the rings material in the hoop direction (0.083%) results in lower stresses at low temperatures. By using the refined criteria developed in the 90s [20] (EQUATION 5), which includes the matrix driven failure and given the bi-dimensional stress scenario, a value of 0.23 is obtained.

We can conclude that the rings are statically stable with generous margins over the criteria, in particular complying with the 25% safety margin recommended by the ITER magnets design criteria.

For fatigue assessment, the mechanical properties measured at 77K are used, since cyclic loads are of electromagnetic origin and they will only be present during the operation of the superconducting coils. Plots of stresses under operational conditions are shown in FIGURE 4, with a summary of principal and cyclic stress range as indicated in TABLE 2 presenting a stress ratio R > 0.7 in all cases yielding a quasi-static scenario with cyclic values typically in the endurance region of SN curves.

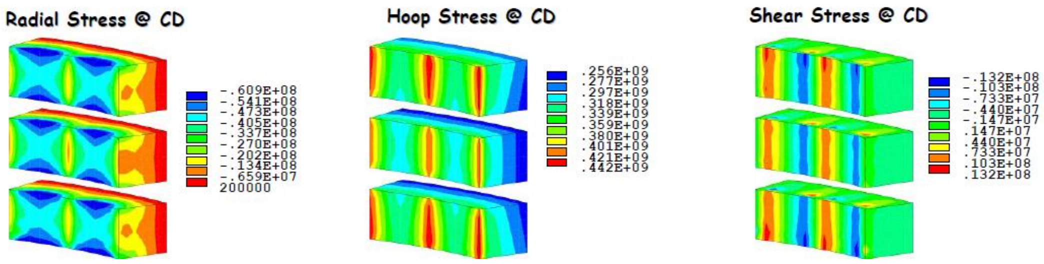

FIGURE 4. Static stresses during at operational conditions of the lower pre-compression rings

TABLE 2. Maximum stress values and stress range in the rings at 4.5 K

σ_{1max}	$\sigma_{2\,max}$	τ_{21}
320 MPa	-27 MPa	13 MPa
33 MPa	8 MPa	3.5

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Creep measurements were performed on specimens at RT and a compliance curve was obtained [1]. Long term tests on model rings have also been performed and a correlation obtained between the creep curve on specimens and the ring performance based on the percentage of ultimate stress of specimens and rings. The behaviour observed can be explained by the successful kinetic fracture theory developed by Zhurkov in 1965 [27], but this is still under study.

Two model rings were fabricated by wet filament winding. One ring was tested to failure with σu = 1437 MPa and the second ring was loaded at a constant hoop stress of 1100 MPa (corresponding to 76.5% of UTS) breaking after 140 hours in the time frame based on measured creep data (see FIGURE 5). Three other rings were creep tested at various percentages of ultimate hoop strength (up to 70%) and monitored daily. In particular, one ring was held for 210 days at 950 MPa with no observable change in appearance or degradation of mechanical properties. These results also correlate with the creep curves since they predict the rupture after many hundreds of years at loads <60% of UTS.

Possible moisture absorption in the rings and the related degradation of the mechanical performance has also been a matter of concern. The rings will be exposed to atmosphere for up to two years during the installation phases, but the assembly hall will be air conditioned and well controlled. However, moisture has little impact on moduli and the margin on measured ultimate stresses is generous. Comparison between dry and moisture saturated glass-fibre/epoxy composite show that moisture presents no impact on tensile strength at 25°C, with about 10% impact on compression strength and basically no impact on shear strength [28].

Nevertheless, scaling up to the full size of ITER pre-compression rings is not straightforward and typically composites studies have focused on understanding performance in optimized structures [29]. All possible failure modes need to be addressed with a positive result. It is unwise to take for granted (unless it has been proven beyond doubt) that an identified failure mechanism is the only one or the dominant one among the others, since things evolve and rapid extrapolation from tests to reality can lead to risky situations. The rings must be continuously loaded without failure for 20 years and, although existing creep curves predict millions of years duration in the secondary steady phase, other observed matrix driven phenomena related with microcracks coalescence may play a role leading to continuum damage mechanics phenomena.

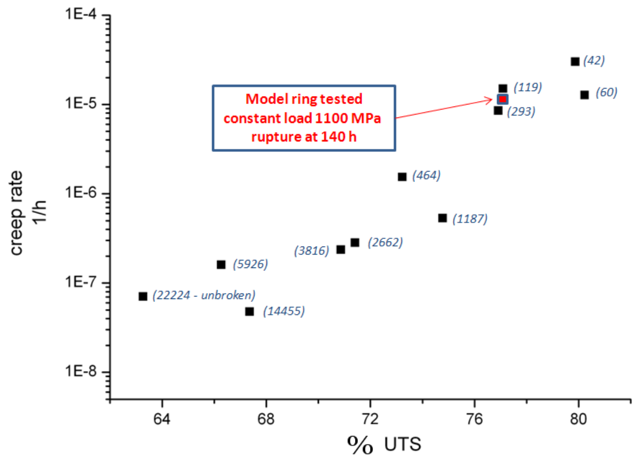

FIGURE 5. Creep behavior of ring material and its correlation with long term tests on model rings. In parentheses is indicated the rupture time.

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As described by Zhurkov (1965) [27], the fracture process at atomic level follows three stages: 1) formation of localized microsites of fracture with strongly overloaded interatomic bonds, which results from non-uniform load distribution, 2) scission of overstressed bonds by thermal fluctuations with subsequent formation of microcraks and 3) coalescence of incipient microcracks into large main cracks, which might lead eventually to a macroscopic loss of stability. A theoretical connection was established between time to rupture of the body under load τ, normal stress σ in the body and absolute temperature T by

$$\tau = \tau_o e^{\frac{U-\gamma\sigma}{kT}} \tag{7}$$

where U_o is the activation energy for a fracture process, τ_o is the inverse of the frequency of thermal vibrations of atoms and γ is related with the atomic volume and the stress level. The coalescence of microcracks into larger cracks is strongly temperature dependent [30], therefore this process will be inhibited during operation at 4.5K. The presence of voids, the level of which depends on the fabrication process chosen by industry, can enhance microcracks coalescence. However the operational hoop stress in the rings is <400 MPa which is less than 30% of the rupture stress and thus unlikely to result in a reduction of ring lifetime, based on the creep data accumulated. Nevertheless, a deeper understanding of rupture and long term tests on more than 10 model rings at the light of the kinetic theory of strength has been undertaken.

CONCLUSIONS

The fabrication of the pre-compression rings is a challenge given their size and their high quality requirements to ensure the successful performance under demanding conditions (permanently loaded at stresses close to 400 MPa for 20 years, thermal cycles from RT to cryogenic conditions, cyclic loads and ionizing radiation of about 100 kGy). Ten years of intense R&D work in collaboration with ENEA has led to a thorough understanding of the requirements necessary to optimise a fabrication processes as well as the composite behaviour. The design margins that can be implemented are known and will guarantee reliable performance.

Full volumetric non destructive examination may be feasible by a combination of UT and RT to detect all possible flaws given that possibly the rings being fabricated in steps to overcome the drawbacks of an inhomogeneous curing of the full cross section in case only one step is implemented.

The full mechanical characterization of the composite of the model rings and the understanding of the stresses during operation allows the application of stability criteria. The Tsai-Hill criterion for orthotropic materials is met with a generous margin. The cyclic loads make the rings perform in a quasi-static mode making irrelevant fatigue degradation.

The determination of the creep curves and their correlation with the model ring long term tests provides several orders of magnitude margin at the stress levels of <30% of the ring UTS. Assessment of possible unexpected long term degradation by applying the continuum damage theory, which takes into account fracture mechanics at microscopic level, will be undertaken.

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