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Recommendations for joint fatigue coefficients for welded P91 junctions at 550 °C

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ABSTRACT

Modified 9Cr1Mo steels are potential candidates as structural materials of GEN-IV nuclear reactors. Since the design of structural components is influenced by the presence of the welds, their mechanical properties are also included in the design codes. In the European code RCC-MRx, a weld is considered as a homogeneous (base metal) component with a margin coefficient, called weld coefficient. Currently no values of joint fatigue coefficients for P91 junctions are given in RCC-MRx. After a recall of the weld design rules contained in the code, this work presents the experimental activities carried out to characterize the fatigue behaviour of TIG welded P91 junctions at high temperatures. Finite elements calculations were performed on the basis of the characterization of the base and weld metal. The results of the tests validate the numerical results. Values of the weld joint fatigue coefficients for P91 are proposed for possible inclusion in RCC-MRx.

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1. Introduction

Modified 9Cr–1Mo steels are being considered as structural material for several components in fourth generation and fusion power plants [1,2] because they present good thermo-physical properties, excellent stability under neutron irradiation and good creep strength up to 550 °C. Design and construction of components for nuclear reactors rely on the use of established Codes and Standards (C&S) in order to meet the mandatory quality and safety requirements. C&S translate the current state of the art in rules to be obeyed for the procurement of materials, construction, joining, design and operation of nuclear components. In Europe, the RCC-MRx code [3], published by the "Association Française pour les règles de conception, de construction et de surveillance en exploitation des matériels des Chaudières Electro Nucléaires" (AFCEN) is selected as reference for the construction of the sodium-cooled Gen-IV prototype reactor ASTRID and the lead-bismuth eutectic experimental reactor MYRRHA. The code is the result of the merging of the previous RCC-MR code, capitalizing the feedback coming from the construction and operation of SuperPhenix, and the RCC-MX code developed by CEA for irradiation rigs. The code includes rules for high temperature operation and irradiated components.

C&S need to evolve in order to satisfy the requirements of new reactor projects. Mechanical properties of 9Cr–1Mo steel and its weldments have to be determined. In the Annex A9 of the RCC-MRx, appropriate coefficients are given to take into account the difference in mechanical properties of welded joints with respect to the base material. Joint coefficients are defined for the following damage modes: monotonic loading, creep and fatigue. Currently no values of joint fatigue coefficients for P91 weldments are given in RCC-MRx. One of the goals of the MATTER project was to investigate experimentally the fatigue behaviour of welded P91 joints and propose appropriate values of the fatigue joint coefficients. In this article, design rules for welded joints in RCC-MRx will be recalled at first and then experimental results will be presented. Finite Element calculations will be performed to evaluate the capability of behavioural models to simulate the experimental results. Finally, joint fatigue coefficients for 9Cr–1Mo steel at 550 °C are proposed and discussed for possible inclusion in RCC-MRx.

2. Design rules for welded joints in RCC-MRx: the joint fatigue coefficient

The RCC-MRx code defines appropriate criteria to guarantee safety with regard to a number of types of damages. General analysis rules for protection against these damages are provided in section RB 3200 and sub-chapters. For welded assemblies, the

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analysis can be performed without considering the presence of the welded joint, using the rules for homogenous materials but modifying the allowable limits by appropriate coefficients that are dependent on the welded joint characteristics (RB 3290).

Fatigue damage takes place in a material subject to a load that is cyclically repeated in time. This phenomenon frequently occurs under imposed displacement or deformation loads such as thermal gradients. Studies of this damage have shown that the variation in strain is the relevant parameter in determining the analysis criterion. In the case of multiaxial loads, the RCC-MR recommends the use of the equivalent strain variation as defined by the Von Mises criterion. Since the analysis is performed assuming elastic behaviour, a correction is made to determine the "real" strain using the procedure detailed in RB3261. The number of cycle to rupture N_f is then calculated starting from the total calculated strain $\Delta\varepsilon_{tot}$ by using the fatigue "design curves" specific to each material and given in Annex A3 of the code as show in Fig. 1. Fatigue design curves are derived from continuous cycling failure tests under imposed uniaxial strain by shifting average experimental curves ("*best fit*" curves) by a factor corresponding to the most severe of the following cases (Fig. 1):

- division of the strain variation by a factor of 2,
- division of the number of cycles by a factor of 20.

These factors are intended to cover effects such as environmental effects, scale effects (between the material and the test piece) and dispersion of the results (due for example to the variability of material characteristics).

The analysis for welded joints implies deducing the fatigue curve for the welded joint from the fatigue curve for the base metal using a characteristic coefficient J_f, refereed as the "fatigue joint coefficient". The coefficient J_f expresses the amplification that has to be applied to the strain variation occurring in a homogeneous structural component (without weld) to obtain the strain amplitude determining the number of cycles to failure *Nr* of the welded component as shown in Fig. 2. For each value of the number of cycles *Nr*, the fatigue joint coefficient $J_f(\geq 1)$ is obtained by dividing the ordinate of the design fatigue curve for the base metal by the ordinate of the design fatigue curve for the welded joint.

3. Experimental testing in support of the definition of the fatigue joint coefficients for 9Cr1Mo weldments

The experimental technique used to determine the fatigue resistance of the welded joint was proposed in Refs. [4,5]. It is based on the assumption that the entire structure imposes the load on the

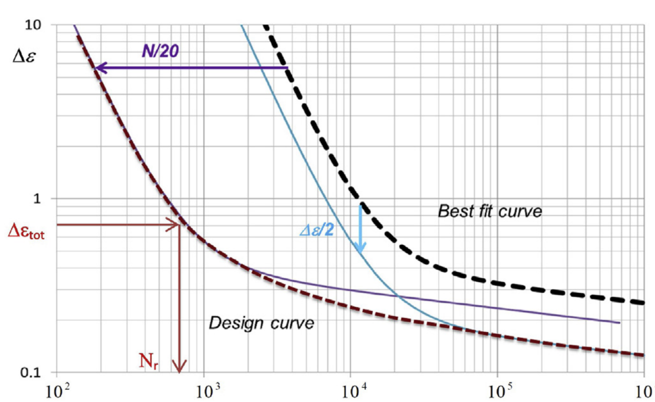

Fig. 1. Construction of the fatigue design curve in RCC-MRx.

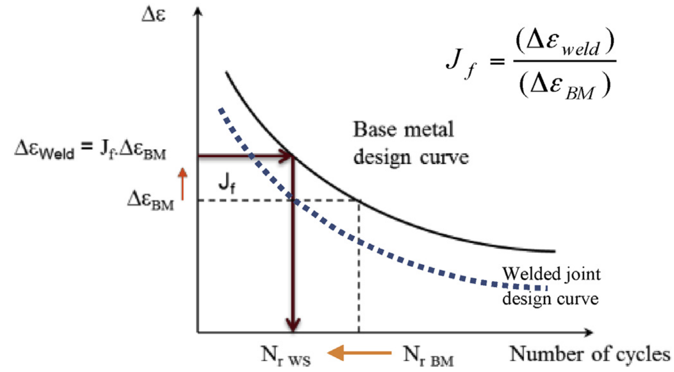

Fig. 2. Joint coefficient J_f for calculation of the number of cycles to failure in fatigue.

welded joint, because the welded joint is only a fraction of the assembly. An experimental approach is adopted that uses the behaviour of the base metal as a reference (control of strain in the base metal – Fig. 3) to study the behaviour of the bi-material junction, in accordance with the analysis in the RCC-MRx that starts by calculating the response of the structure without a welded joint and then applying the joint coefficient.

Fatigue tests have been performed on specimens sampled from a narrow-TIG welded plate joint procured by CEA. The base metal consists of 30 mm thick grade Z10CDVNb9-1 plates procured from FRAMATOME-ANP and the filler metal is the KOBE TGS-9CB wire (pour No. EZ00773) made by KOBE STEEL. Chemical compositions are given in Table 1 and Table 2. The weldments have been made by FRAMATOME-ANP. A tempering and relaxation heat treatment at 740 °C for 10 h 30 min (validated against several tests) was applied to the joint after production.

Additional fatigue tests on homogeneous specimens with only base or weld metal were also performed by the CEA to characterize their mechanical behaviour in view of FE simulations The homogeneous specimens of weld metal were sampled from a specific "wide joint" in the transversal direction. All tests were performed in strain control and a loading ratio R equal to 1 and for a temperature of 550 °C.

Fig. 4 presents the monotonic and the cyclic behaviour of the base metal and the weld metal. Although the monotonic curves are very near, the cyclic curve of the weld metal is above the base metal's one. Indeed the softening of the base metal is larger. The best fit fatigue curve of the weld metal was also determined using a Manson Coffin type adjustment:

$$\Delta\varepsilon_t = C_e.(N_{25})^p + C_p(N_{25})^m \tag{1}$$

with $C_e = 0.02578$, $C_p = 15.1628$, $p = 0.15639$ and $m = -0.51169$.

Fig. 5 presents the results of fatigue tests on the filler metal and welded junctions, and compares them with the best fit fatigue curve of the base metal. One can see that the weld metal and

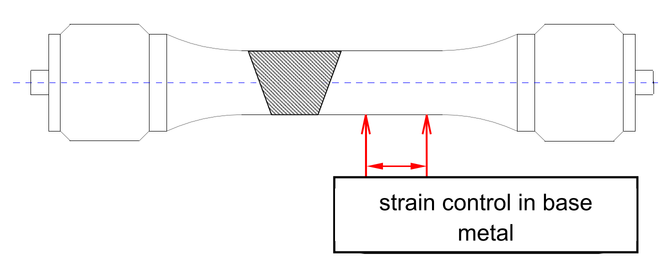

Fig. 3. Control of tests on bi-material specimens.

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