Creep-fatigue damage evaluation for SS-316LN (ORNL Plates): - RCC-MR vs. Experiments

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1 ABSTRACT

In fast breeder reactors (FBRs) due to higher operating temperature creep becomes significant and it is more damaging in the presence of fatigue. Creep-fatigue damage is major failure mode and also it is one of the life limiting factors in FBRs. Studying the creep-fatigue damage in detail, with proper experimental and theoretical background becomes necessity for designing the FBRs. Design code RCC-MR is widely used for design and analysis of fast breeder reactor components. The code gives the robust rule to evaluate creep life of component operating at high temperature. The code also provide rule for multiaxiality and weldments.

In laboratory, experiments for creep-fatigue damage simulation on stainless steel plates (ORNL plate) under highly stressed location were carried out. Axisymmetric finite element analysis of ORNL plate is carried out using CAST3M, for the deformation controlled loads towards evaluating creep-fatigue damage limit as per RCC-MR: 2002 & 2007. All the test results are compared with analytical prediction using numerical investigation plus design code procedure. The major structural material used in Indian FBRs SS-316 LN is used for the experimental investigations on creep-fatigue damage simulation.

2 INTRODUCTION

Engineering materials nowadays are used in severe environmental conditions, which imply that the materials should have sound mechanical behavior in these environments. Creep is one of the principal damage mechanisms for materials operating at elevated temperatures. Larger strain deformation, stress relaxation, and crack initiation & growth are effects of the creep. It can finally cause the material or the structure to fail in different modes like fatigue, rupture, loss of function due to the excessive deformation, etc. For the material under fatigue and creep loading at same time, creep has serious influence on the properties and fatigue life of the material. Strong interaction of bilinear nature makes creep-fatigue interaction more important in deciding the life of a component at elevated temperature.

A series of high temperature experiments are in progress to understand the creep-fatigue damage effects and evaluate any possible conservation in design code. A number of high temperature tests have been completed on components having multiaxiality and weldments. One of them is simulation of creep-fatigue damage in stainless steel 316 LN plate (ORNL plate) at highly stressed location. The high temperature experiment was conducted under deformation controlled loading on ORNL plate.

3 EXPERIMENTAL

3.1 Geometry and material data

The geometrical details of ORNL plate used in the experiments are shown in Fig. 1. The outer diameter of the plate is 380 mm and thickness is 9 mm, other dimensions are shown in figure.

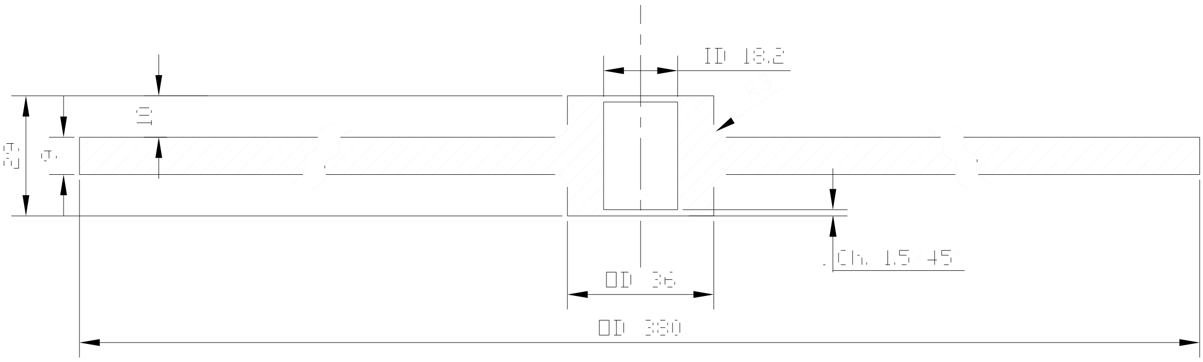

Figure 1. Geometrical details of ORNL plate (All dimensions in mm)

The test material was supplied by M/s Thyseen Ltd., Germany. The composition [1] of the material is given in Table 1. Material properties including creep & fatigue data are taken from RCC-MR [2, 3]

Table 1. Chemical composition of SS-316 LN.

Element	C	Mn	Ni	Cr	Mo	N	S	P	Fe
Amount (Wt %)	0.021	1.75	12	17.0	2.4	0.078	0.002	0.023	Bal

3.2 Experimental set-up

An indigenously developed experimental set up (Fig. 2) used to conduct the experiments consist of 10 ton loading frame, split furnace, actuator operated through motor along with computer and Programme Logic Controller (PLC). There is load cell and LVDT sensors to measure the load applied on the component and its deflection respectively.

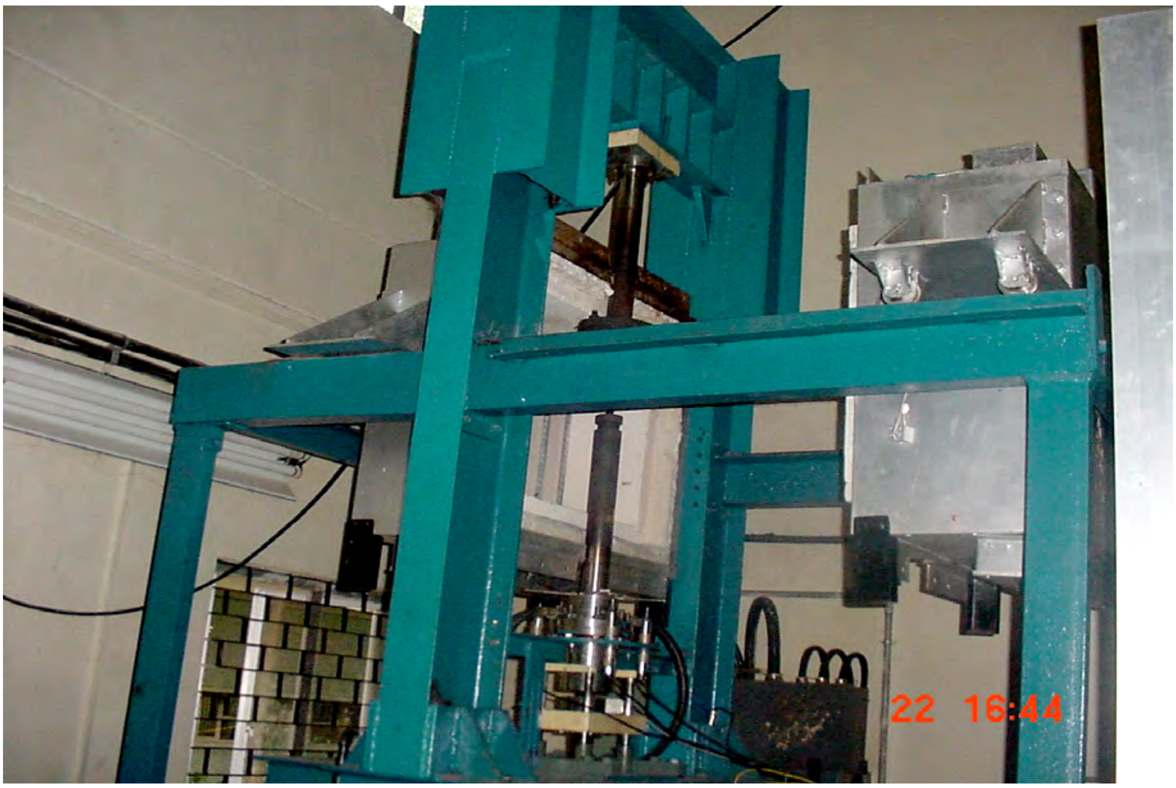

Figure 2. Experimental set-up (IGCAR)

3.3 Experimental conditions

To introduce simulated creep-fatigue damage on the plates these plates are subjected to cyclic deformation controlled loading (± 3 mm deflection at the centre of the plate). Tests has been conducted at 873 K (600 °C) isothermal condition with hold time at both extreme of cyclic loading equal to 1 hour (total hold time 2 hours / cycle). Loading pattern is shown in Fig. 3. The load is applied at centre of the plates with keeping simply supported condition at periphery. The specimens are investigated for the crack at critical location at regular intervals by interrupting the test. However visual inspection was carried through viewing window online.

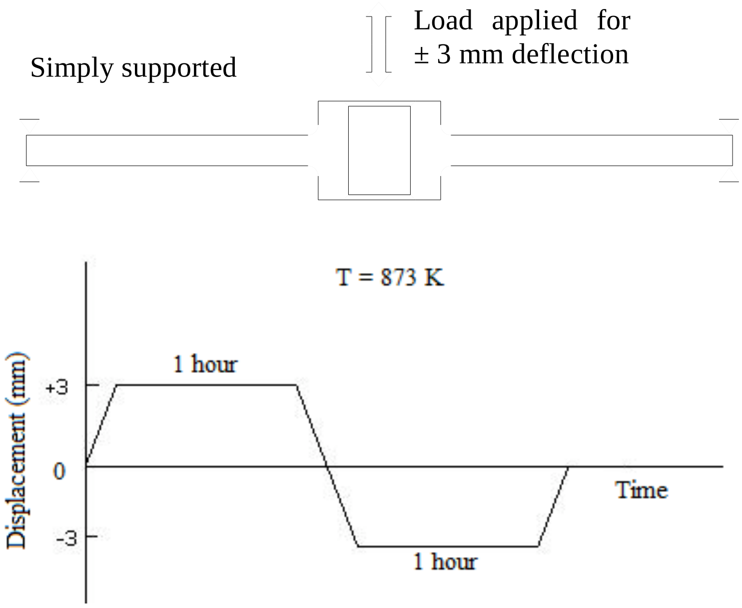

Figure 3. Loading pattern

3.4 Experimental results

Tests are conducted on different plates and their respective load-deflection curve is taken. Number of cycles when the load-deflection curve changes from it's trend or it shifts, is taken as the number of cycles before failure. Typical load-deflection curve of one of the plate is shown in Fig. 4. Average number of cycles for all the tests before failure is ~ 86 cycles (172 hours) because of deformation controlled loading. Tests are allowed to run till crack appears on the plate. Location of crack is at the fillet, at 20.55 mm from centre of the plate and on both side of the plate as shown in Fig. 5. After metallurgical investigation, intergranular creep cracks were seen with fatigue crack which specifies the crack propagation as a mixed mode [4].

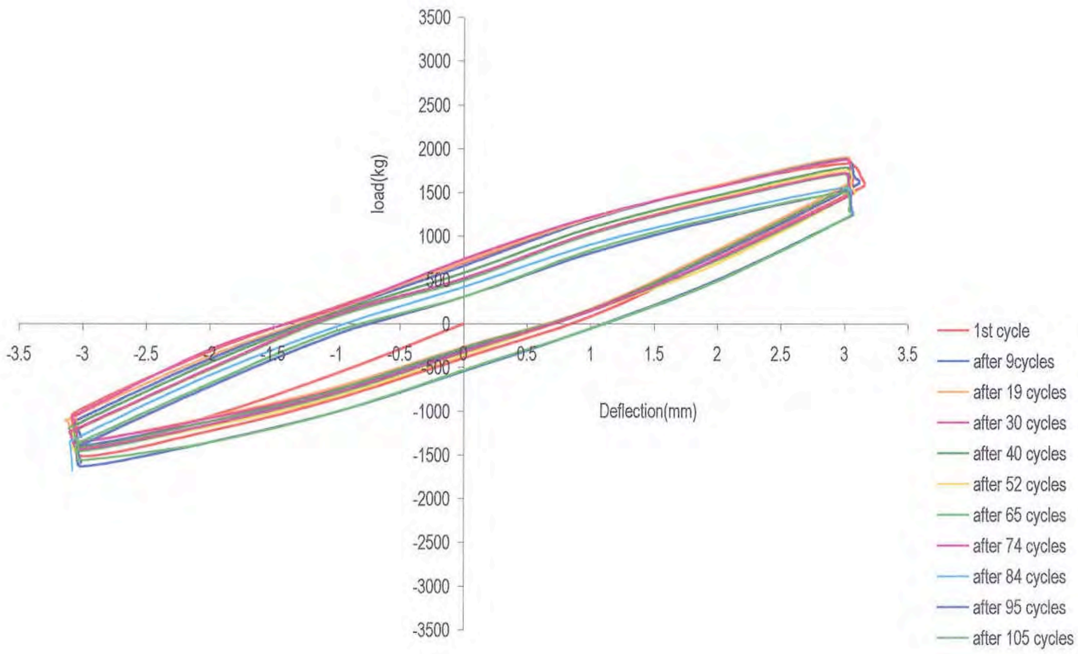

Figure 4. Load vs. deflection (with 1 hour hold time) plot of ORNL plate at 873K

4 ANALYTICAL PREDICTION

ORNL plate is analyzed using CAST3M issued by CEA, France and investigated as per RCC-MR: 2002 and RCC-MR: 2007. The required stresses and strain values are numerically computed using CAST3M with axisymmetric model of QUA4 elements. Finite element model and stress distribution in the same is shown in Fig. 6. Peak stress location from finite element analysis of the plate is at 20.60 mm from centre. For deflection of 3 mm the equivalent stress value (~560 MPa) from finite element analysis is taken for the further calculations.

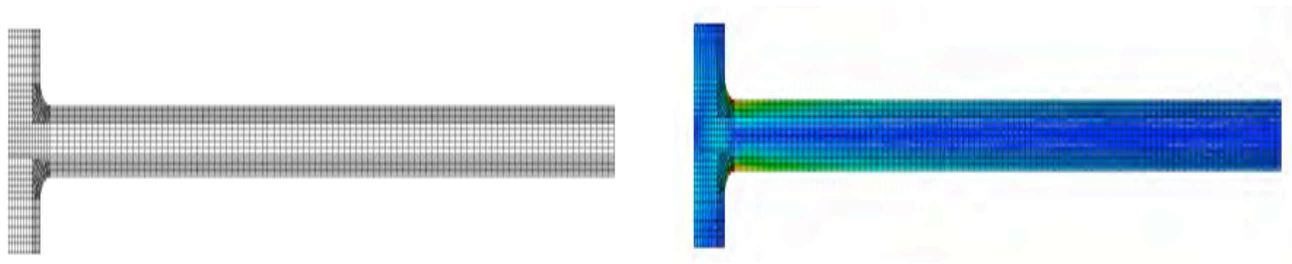

Figure 6. Axisymmetric model and stress distribution of ORNL plate.

4.1 Theoretical calculations

Stresses are classified as per RCC-MR into primary component, secondary component and peak component for calculation of the strain values according to the type of loading. In the case of deformation controlled loading only secondary stress component is present.

RCC-MR procedure for creep-fatigue damage evaluation is followed. As per RCC-MR elastic plastic strain is calculated from elastic stress result. Creep strain per cycle is obtained by considering hold time of 2 hours per cycle. Various strains to be calculated as per RCC-MR are mentioned below:

- Elastic strain $\Delta\varepsilon_1$
- Plastic strain (due to primary stress) $\Delta\varepsilon_2$
- Plastic increase in strain due to strain concentration $\Delta\varepsilon_3$
- Plastic increase in strain due to traixiallity. $\Delta\varepsilon_4$
- Creep strain $\Delta\varepsilon_c$

$\Delta\varepsilon_c$, creep strain developed during the hold time that is associated with the stabilized load cycle can be determined using the procedure of RCC-MR. Values of each of the above are given in Table 2.

Table 2 Strain values as per RCC-MR [2, 3, 5, 6]

Design Code	$\Delta\varepsilon_1$	$\Delta\varepsilon_2$	$\Delta\varepsilon_3$	$\Delta\varepsilon_4$	$\Delta\varepsilon_c$
RCC-MR: 2002	0.6686 %	0 %	0.4908 %	0.1965 %	0.2117 %
RCC-MR: 2007	0.6428 %	0 %	0.4718 %	0.1889 %	0.2053 %

Total strain per cycle as per RCC-MR: 2002 = 1.5678 %
Total strain per cycle as per RCC-MR: 2007 = 1.5089 %

The lower strain value per cycle as per RCC-MR: 2007 as compared to RCC-MR: 2002 is due to overall improved material properties in new version of design code.

4.2 Creep-Fatigue damage

4.2.1 Creep Damage

Creep damage is defined is defined by Robinson's rule as follows:

$$D_c = t / T_d$$

t is total duration of a given stress at maximum temperature.
T_d is allowable time duration determined from stress to rupture curve.

As the creep strain is of plastic in nature, it leads to the relaxation of the secondary stress intensity (as primary stress is for maintaining the equilibrium). The stress relaxes with passage of time because of small scale permanent deformation due to creep strain. The stress relaxation as a function of time is shown in Fig. 7. Total time '*t*' is divided into small time step '*dt*' and corresponding stress value is taken to calculate the creep damage as per RCC-MR for each time step. Since part of the secondary stress intensity not relaxes, RCC-MR recommends a follow up factor 'C_r 'of 3.0. The cumulative creep damage (*W*) is the sum of damage for each time step, assuming that the stress remains constant for that time period.

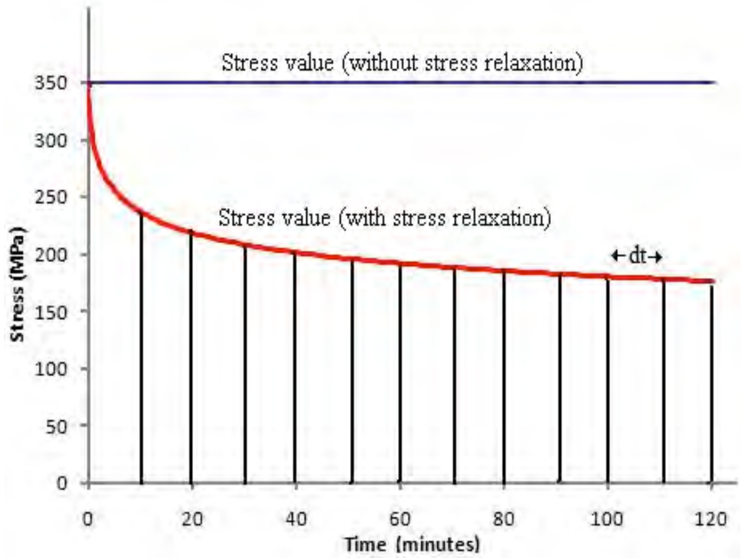

Figure 7. Stress relaxation

The effect of stress relaxation on the creep-fatigue damage evaluation was studied by using the design codes RCC-MR: 2002 and RCC-MR: 2007.

Table 3: Effect of stress relaxation on creep damage evaluation

Creep damage (*W*)	Without stress relaxation	With stress relaxation
RCC-MR: 2002	1.3520	0.01676
RCC-MR: 2007	1.2469	0.01480

If stress relaxation is neglected, the value of creep damage is more than unity which means zero permissible number of cycles as per design code. Neglecting the effect of stress relaxation implies that maximum stress intensity value is taken to calculate the creep damage for the whole time period, but in actual stress intensity value decreases during hold time. Effect of stress relaxation in the presence of significant secondary stress is important and should be considered for doing more realistic analysis.

4.2.2 *Fatigue damage*

Fatigue damage is defined by Miner's rule as follows:

$$D_f = n / N_d$$

Where n is applied number of strain cycles and N_d is permissible number of cycles for given strain range value.

Allowable numbers of cycles corresponding to the total strain value calculated in section 4.1 are taken from fatigue curve given in RCC-MR. Mean fatigue curve should be used to find the allowable number of cycles. The mean experimental curves are offset by factor corresponding to the harshest of 1) division by 2 of the strain range and 2) division by 20 of the number of cycles in RCC-MR for design purpose. Fatigue damage per cycle is calculated from allowable number of cycles as per the design code.

Fatigue Damage 'V' as per RCC-MR: 2002 is 0.00233 per cycle

Fatigue Damage 'V' as per RCC-MR: 2007 is 0.00202 per cycle

4.2.3 *Effective damage (D_{eff})*

When both creep and fatigue damage occurs together, there can be strong interaction which reduces life significantly. As recommended in RCC-MR using bilinear creep-fatigue interaction rule the creep damage 'W' and fatigue damage 'V' values should lie within the safe operating domain (Fig.8). A single parameter called effective creep-fatigue damage (D_{eff}) is derived from the individual values of V and W such that if a particular combination of V and W just lies on the bi-linear curve, then D_{eff} is equal to 1. D_{eff} is derived as shown in Fig. 8.

D_{eff} = 0.0222 ~ 45 cycles or 90 hours as per RCC-MR: 2002.
D_{eff} = 0.0195 ~ 51 cycles or 102 hours as per RCC-MR: 2007.

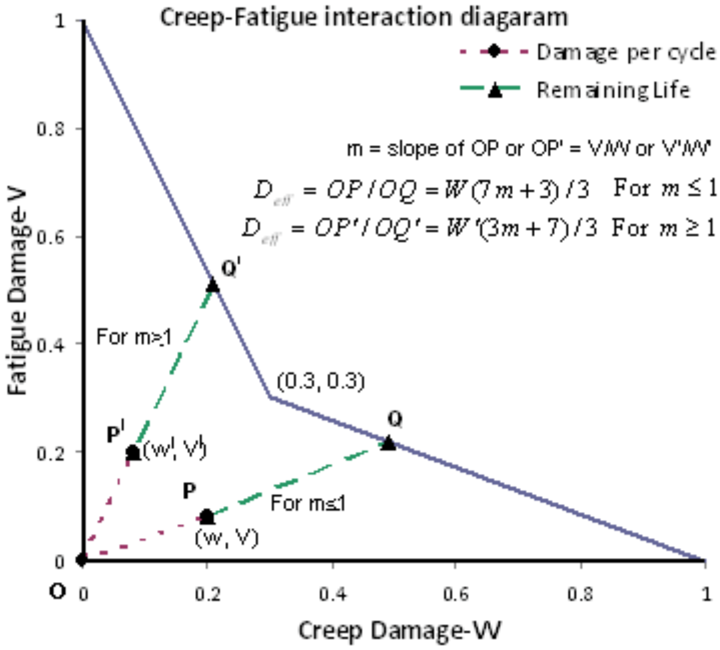

Figure 8. Derivation of effective damage

Life prediction as per RCC-MR: 2002 & RCC-MR 2007 and experimental work is summarized in Table 4.

Table 4: Comparison of life prediction by RCC-MR and experimental results

Life	RCC-MR: 2002	RCC-MR: 2007	Experimental
No: of cycles	45	51	86

5 DISCUSION

The comparison between experimental results and RCC-MR: 2002 & RCC-MR: 2007 creep-fatigue damage evaluation is shown in Table 4. As per RCC-MR: 2007 predicted life is higher as compared to RCC-MR: 2002, this is mainly because of improved properties of material in new version of design code like young's modulus, amplification coefficients. It is to be noted that fatigue curves as per RCC-MR 2007 [3], below 600

°C for SS 316 LN gives less number of permissible cycles as compared to RCC-MR 2002 [2] for same strain value mainly in low cycle fatigue region. Whereas above 600 °C new version of design code gives higher permissible number of cycles for same strain value as compared to RCC-MR 2002 mainly in low cycle fatigue region. The life predicted by RCC-MR as compared to experimental results in this case shows that code is more conservative in case of creep-fatigue damage evaluation.

6 CONCLUSION

Investigations of high temperature tests done on ORNL plate with deformation control loading, under creep-fatigue damage have been presented. The test results with methodology of RCC-MR life prediction under creep-fatigue loading have been assessed. The stress relaxation effect in calculating the life using RCC-MR under creep-fatigue damage is found to be significant in presence of secondary stress. The new version of design code RCC-MR: 2007 is more realistic and gives higher number of cycles (predicts 51 number of cycles) as compared to RCC-MR 2002 (predicts 45 number of cycles) which is demonstrated by the comparison between the experimental work and RCC-MR life prediction. Between RCC-MR and experimental work, design code seems to be more conservative for life prediction due to creep-fatigue damage.

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