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RULES FOR STRUCTURAL DESIGN OF LMFBR CORE SUBASSEMBLIES

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This paper describes how the actual knowledge on austenitic type stainless steel material is used to establish structural design rules for the core subassemblies of the LMFBR-plant SNR-300 presently under construction.

Stress and strain intensity values for primary and secondary stresses under static and cyclic load are defined with reference to standard rules. Mainly those criteria are dealt with, which differ from standard rules due to the essential changes in material behaviour. In particular, this concerns the irradiation induced loss of short-term and long-term ductility and the consequences of irradiation induced creep.

1. Introduction

Austenitic type stainless steel material show significant changes of properties and behaviour under irradiation in a LMFBR core. This concerns the loss of ductility and the creep under irradiation. The material changes require an extension and an adjustment of already existing design rules. The extended design rules shall be deduced from the rules of unirradiated material (see for example ASME-code) and thus be based on the concept of allowable stresses. The allowable stresses are derived from material strength quantities reduced by safety factors, which are justified by experience and plausible considerations as well as by the type of load and failure mechanism.

2. Stress intensity values and allowable stresses

Stress intensity values are determined by reducing material strength quantities by safety factors. Stress intensity values apply to primary membran stresses. An allowable stress is the minimum value among several stress intensity values, which all belong to one type of load. The safety factors are defined with reference to material failure mechanisms and are considered to be independent of irradiation.

Yield strains can be avoided, when the stresses remain within the elastic range of the stress-strain curve. This is confidently achieved by a safety factor of 1.5 against the yield strength $\sigma_{0.2}$. Brittle rupture is secured with a 2-fold safety against the ultimate tensile strength σ_B and the creep rupture with a 2-fold safety in time against the stress-to-rupture $\sigma_{B,t}$. In order to achieve a comparable safety quality in both cases the safety factors are equal. In case of creep rupture this leads on the basis of actual material data to a stress intensity value of $\sigma_{B,t}/1.25$.

In case of an inelastic analysis strain intensity values can be applied directly for the judgement of stresses and strains, i.e. brittle rupture and creep rupture can be avoided by using the uniform elongation ϵ_L^P and the strain-to-rupture ϵ_L^C, respectively, as strain limits.

The stress intensity values given in table I will be used to define the allowable stresses. According to the type of load and failure mechanism, four allowable stresses can be built up from these stress intensity values (table II). The allowable stresses in this table constitute the actual basis of design rules.

3. Material behaviour under irradiation

The influence of irradiation leads to a temperature dependent hardening of material. In the temperature range from 400 to 500 °C yield strength and ultimate tensile strength of irradiated material exceed the corresponding figures of the unirradiated material. By using data of unirradiated material the benefit due to this irradiation induced increase is not taken into account. Above a temperature of about 550 °C cold worked steels show no significant differences of yield strength and ultimate tensile strength between irradiated and unirradiated materials. With increasing neutron fluence the uniform elongation tends to a saturation value. In order to have easy to handle criteria, the limiting value will be defined as the lowest measured uniform elongation.

In addition to the above mentioned loss of ductility the material exhibits a significant creep under irradiation. This irradiation creep is considered to be non-damaging.

4. Design rules for irradiated structures

The loss of ductility under irradiation influences the strain quantities rather than the strength quantities. Since changes of strength quantities are easy to conceive, only those criteria are dealt with in the following subchapters, which are influenced by the reduced uniform elongation.

4.1 Primary short-term bending loads

The consequences of irradiation induced ductility loss can be seen in figure 1 for a beam of rectangular cross section submitted to a bending moment and a normal force. The upper curve refers to a material in ductile condition, the lower one to a material in embrittled condition. The figure shows for both cases, that on the basis of a linear elastic-perfectly plastic material behaviour the elastic limiting moment may be exceeded by a certain factor. For ductile material this factor amounts to 1.5, for embrittled material this factor decreases to 1.3. When replacing the parabolic curves in figure 1 by straight lines, the well-known stress criterion

$$\sigma_{pb}/K_1 + \sigma_{pm} \leq S_{m1} \qquad (1)$$

results, where σ_{pb} stands for primary bending stresses, and σ_{pm} for primary membran stresses. Table III gives a comparison of the factor K_1 for unirradiated (ductile) and irradiated (embrittled) material conditions.

4.2 Secondary short-term loads

According to their strain-controlled character secondary stresses are limited by strains. Since the corresponding stress criterion should be based on an allowable strain, it requires a strain-stress transformation. A possible mode of transformation is shown in figure 2. On the basis of linear elastic-perfectly plastic material behaviour the strain belonging to the secondary stress σ_s is given by

$$\sigma_s/E = \sigma_{0.2}/E + \varepsilon_L^p/2. \tag{2}$$

Inserting actual data into this equation the application of the well-known correlation

$$\sigma_s \leq 3\ S_{m1} \tag{3}$$

is seen to be justified also for embrittled materials. This equation allows to raise a secondary stress to three times the stress S_{m1}.

4.3 Cyclic secondary loads with and without irradiation creep

Allowable strain ranges usually are determined from experiments. However, in order to analyse cyclic strains, if experimental data are lacking, stress criteria are established for secondary loads with and without irradiation creep in such a way, that in each cycle yield strains are not permitted. This requirement leads to the well-known correlation for the allowable secondary stress in the case without creep

$$\Delta\sigma_s \leq 2\ S_{m2}\ , \tag{4}$$

based on linear elastic-perfectly plastic material behaviour. The maximum stress range associated with the two operating conditions (1) and (2) in figure 3 requires certainly an improved presentation, if the corresponding strength quantities have different values

$$\Delta\sigma_s \leq S_{m2}^{(1)} + S_{m2}^{(2)}. \tag{5}$$

To examine the consequences of creep strains on this criterion, the operating condition (1) is defined as condition with creep, while in operating condition (2) creep is not permitted. Under these premises the allowable secondary stress range is reduced in the presence of creep to

$$\Delta\sigma_s \leq S_{m2}^{(2)}, \tag{6}$$

if yield strains are excluded. This relation can be improved, if yield strains are permitted.

Figure 4 shows how an irradiation creep strain $\Delta\varepsilon^c$, originated in condition (1), will be converted into the yield strain $\Delta\varepsilon^p = \Delta\varepsilon^c$ in condition (2). The relevant creep strain $\Delta\varepsilon^c$ results from the highest stress applied, which is given by the secondary stress range $\Delta\sigma_s$ reduced by the allowable stress $S_{m2}^{(2)}$. If this maximum stress is used for the whole residence time, any history of stress relaxation versus number of cycles is covered. The creep strain under irradiation is given by

$$\Delta\varepsilon^{c} = K(\phi t)\cdot(\Delta\sigma_{s}-S_{m2}^{(2)}), \tag{7}$$

where $K(\phi t)$ is a fluence (ϕt) depending function.

The creep strains and yield strains are evaluated via the generalized strain fraction rule

$$\Sigma(\Delta\varepsilon^{p}/\varepsilon_{L}^{p} + \Delta\varepsilon^{c}/\varepsilon_{L}^{c}) \leq 1. \tag{8}$$

$\Delta\varepsilon^{c}$ and $\Delta\varepsilon^{p}$ stand for creep strains and yield strains, respectively, in one time step, and are related to the allowable limiting values of the creep strain ε_{L}^{c} and the yield strain ε_{L}^{p}, respectively. According to experimental findings the irradiation creep is non-damaging, i.e. $\varepsilon_{L}^{c} \gg \varepsilon_{L}^{p}$. Neglecting the yield strain of the first load step, the following secondary stress range results from the generalized strain fraction rule

$$\Delta\sigma_{s} \leq S_{m2}^{(2)}\{1+\varepsilon_{L}^{p}/[K(\phi t)\cdot S_{m2}^{(2)}]\} \tag{9}$$

This relation is presented in figure 5, where the secondary stress range is plotted versus the strain $\varepsilon = K(\phi t)\cdot S_{m2}^{(2)}$. The figure demonstrates the benefit of eq. (9) for short residence times; for typical SNR operating conditions, however, the stress limit is decreased to $S_{m2}^{(2)}$. The reason that despite its non-damaging character irradiation creep leads to a damage of material due to the loss of the yield strain potential.

In conclusion, table IV summarizes shortly the design rules developed above. The table shows exemplary how stress criteria are influenced by irradiation induced loss of ductility.

TABLE I: STRESS INTENSITY VALUES
($\sigma_{0.2}$ = YIELD STRENGTH; σ_B = ULTIMATE TENSILE STRENGTH; $\sigma_{B,t}$ = STRESS-TO-RUPTURE)

TYPE OF LOAD	DESIGN AGAINST	STRESS INTENSITY VALUE	SAFETY FACTOR JUSTIFIED BY
SHORT-TERM	YIELD STRAIN	$\sigma_{0.2}(T)/1.5$	ELASTIC RANGE
	BRITTLE RUPTURE	$\sigma_B(T)/2$	EMBRITTLED MATERIAL
LONG-TERM	CREEP RUPTURE	$\sigma_{B,t}(T)/1.25$	TWOFOLD TIME-TO-RUPTURE

TABLE II: DEFINITION OF ALLOWABLE STRESSES

S_m	$\mathrm{MIN}\{\sigma_{0.2}(T)/1.5;\ \sigma_B(T)/2;\ \sigma_{B,t}(T)/1.25\}$
S_{m1}	$\mathrm{MIN}\{\sigma_{0.2}(T)/1.5;\ \sigma_B(T)/2\}$
S_{m2}	$\sigma_{0.2}(T)/1.5$
S_{mt}	$\sigma_{B,t}(T)/1.25$

TABLE III: STRUCTURAL FACTOR K_1 OF DIVERSE CROSS SECTIONS FOR A MATERIAL IN DUCTILE AND EMBRITTLED CONDITION

STRUCTURAL FACTOR K_1	DUCTILE	EMBRITTLED
RECTANGULAR CROSS SECTION	1.63	1.49
CIRCULAR CROSS SECTION	1.78	1.56
THIN-WALLED TUBE	1.45	1.30

TABLE IV: SUMMARY OF DESIGN CRITERIA INFLUENCED BY LOSS OF DUCTILITY

	PRIMARY	SECONDARY
	MEMBRAN AND BENDING STRESSES	
SHORT-TERM LOAD	$\frac{\sigma_{pb}}{K_1} + \sigma_{pm} \leq S_{m1}$	$\sigma_s \leq 3\ S_{m1}$
CYCLIC LOAD WITHOUT CREEP	-	$\Delta\sigma_s \leq S_{m2}^{(1)} + S_{m2}^{(2)}$
CYCLIC LOAD WITH CREEP	-	$\Delta\sigma_s \leq S_{m2}^{(2)}(1+\frac{\varepsilon_L^p}{K(\phi t)\cdot S_{m2}^{(2)}})$

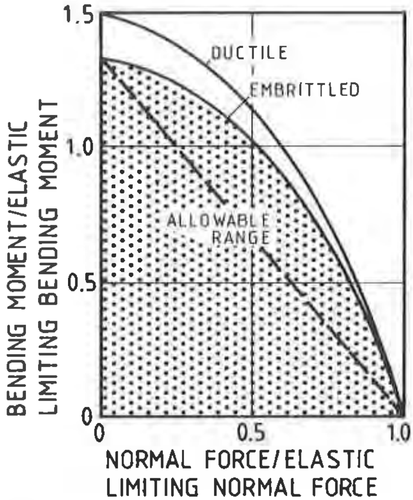

FIG. 1 RELATION BETWEEN THE ALLOWABLE PRIMARY BENDING MOMENT AND NORMAL FORCE FOR DUCTILE AND EMBRITTLED MATERIAL CONDITION

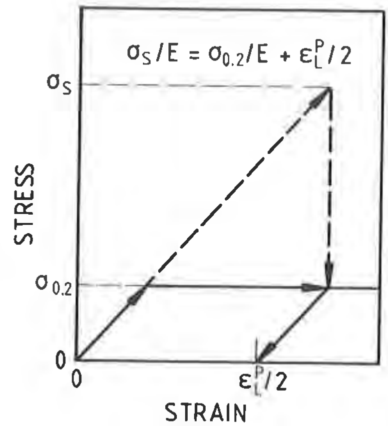

FIG. 2 TRANSFORMATION OF THE ALLOWABLE YIELD STRAIN $\varepsilon_L^P/2$ INTO AN ALLOWABLE SECONDARY STRESS σ_S

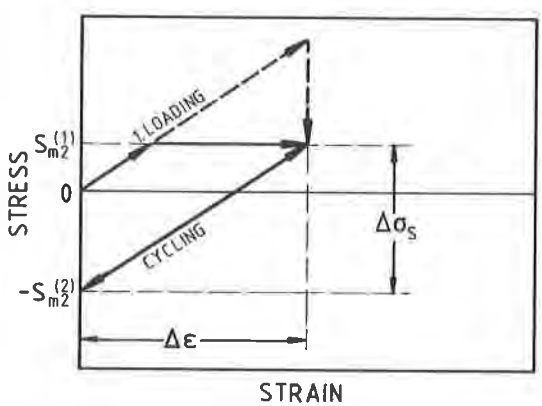

FIG. 3 TRANSFORMATION OF THE STRAIN RANGE $\Delta\varepsilon$ INTO AN ALLOWABLE SECONDARY STRESS RANGE $\Delta\sigma_S$ (S_{m2} SERVES FOR YIELD STRENGTH)

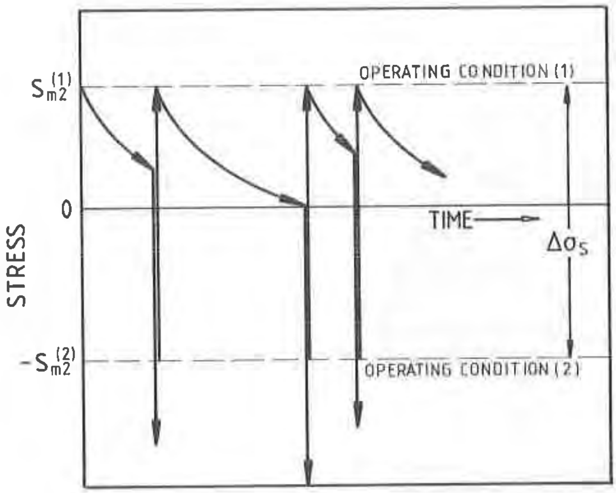

FIG. 4 CONVERTING CREEP STRAINS ORIGINATED IN CONDITION (1) INTO YIELD STRAINS IN OPERATING CONDITION (2) UNDER CYCLIC LOADS

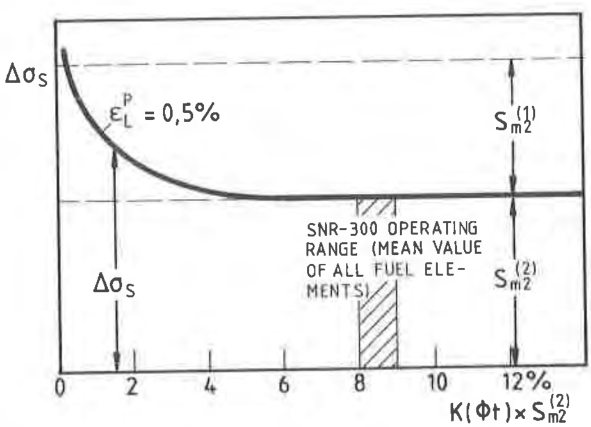

FIG. 5 SECONDARY STRESS RANGE $\Delta\sigma_S$ AS A FUNCTION OF THE CREEP CONSTANT $K(\phi t)$ AND THE ALLOWABLE STRESS $S_{m2}^{(2)}$