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Comparison Between Simplified Predictive Methods of the Ratchetting Phenomenon

Lakhdar Taleb[1], Michel Cousin[1], Marie-Thérèse Cabrillat[2], Odile Gelineau[3] and Nicolas Waeckel[4]

1) I.N.S.A de Lyon URGC Structures, France
2) CEA/DER/SERA/LDM, France
3) FRAMATOME/Novatome, France
4) EDF/SEPTEN, France

ABSTRACT

This paper makes the synthesis of the works performed on the ratchetting phenomenon in the frame of a RCC-MR working group. Some simplified methods for the steady state assessment were taken under consideration. Firstly, the methods were applied considering structures belonging to the European Fast Reactor (EFR). Having no 'experimental results' in this case, the forecasts of the methods were then compared between each other. The objective is to test the applicability of each method to the specific industrial problem taken into account. Secondly, the forecasts of the simplified methods were compared to the test results considering the bitube structure. Some recommendations are given in order to improve the analysis of the progressive deformation by the design code RCC-MR.

INTRODUCTION

The structures related to fast reactors in nuclear industry must be designed taking into account the risk of thermal ratchetting. In France the design code of such structures is the RCC-MR Code [1] (Règles de Conception et de Construction des Matériels et îlots Nucléaires-RNR). It includes two alternative rules which must be verified in order to avoid the ratchetting phenomenon : the efficiency diagram rule and the 3 Sm rule. However some difficulties have appeared to design certain structures like shells subjected to moving free levels of sodium and to predict the results of certain tests [2] by the efficiency diagram rule. In order to improve the latter some works were then carried out in France [3, 4, 5]. In addition to those studies, other simplified methods were proposed especially in Japan [6] and in United Kingdom [7].

This paper summarizes the last works performed by the "progressive deformation group" in the ratchetting analyses using simplified methods. The forecasts of some methods recently proposed are considered in two situations. Firstly, the methods are applied considering structures belonging to the European Fast Reactor (EFR) [8]. In this case, the forecasts of the methods are compared between each other (no experimental results are available). The goal is to test the ability of the methods to describe the behavior of the industrial problem taken under consideration. Secondly, the simplified methods forecasts are compared to some experimental test results.

The first part of this paper is devoted to a short presentation of the principles of the considered simplified methods. In the next part a specific industrial case (theoretical) related to the EFR project is considered. The third part is devoted to the analyses of the simplified methods forecasts in comparison with some test results.

1. CONSIDERED SIMPLIFIED METHODS

The following notations are used :

- σ_p : maximum equivalent stress (Von Mises) due to the prescribed forces,
- σ_Z is the axial stress due to the prescribed forces,
- τ is the torsional stress due to the prescribed forces,
- $\Delta\tau$ is the overload due to the momentarily variation of τ ,
- ΔQ is the maximum range of the thermoelastic stress,
- ε_1^{max} is the maximum equivalent mechanical (elastic + plastic) strain of the first cycle,
- σ_1^{max} is the maximum equivalent stress obtained during the first cycle,
- Q^{max} is the maximum equivalent thermoelastic stress located at the same place as ε_1^{max}.
- σ_{max}, P_{eff} : stress corresponding (on $\sigma - \varepsilon$ curve) to the equivalent mechanical deformation obtained at the steady state,
- $\sigma_{0.2\%}$: conventional yield stress corresponding to a plastic strain equal to 0.2%,
- $\sigma_{1\%}$: stress corresponding to a mechanical strain equal to 1% on the $\sigma - \varepsilon$ curve,
- E : Young modulus.

The main constitutive equations of the considered methods are presented in the following.

1. 1. The Classical Efficiency Rule And The Modification Proposed by Gatt

The efficiency stress (P_{eff}) which corresponds to the maximum equivalent mechanical deformation which would be obtained at the steady state is given by [1] :

$$P_{eff} = \sigma_p \quad if \quad \frac{\Delta Q}{\sigma_p} \le 0.46 \tag{1}$$

$$P_{eff} = \frac{\sigma_p}{1.093 - 0.926\dfrac{(\Delta Q/\sigma_p)^2}{(1+(\Delta Q/\sigma_p))^2}} \quad if\, 0.46 < \frac{\Delta Q}{\sigma_p} < 4 \tag{2}$$

$$P_{eff} = \sigma_p \sqrt{\Delta Q/\sigma_p} \quad if \frac{\Delta Q}{\sigma_p} \ge 4 \tag{3}$$

A modification of the efficiency rule has been proposed by Gatt with two main objectives [3] : make the efficiency rule applicable when there is no controlled force and improve its forecasts when the secondary stress field has a component in the same direction as the primary one. The efficiency stress is given by Eq. 4 where P_G is the 'modified primary' stress given by Eq. 5.

$$P_{eff} = P_G \left[1 + \left[\frac{\Delta Q}{P_G}\right]^2\right]^{\frac{1}{4}} \tag{4}$$

$$P_G = \frac{1}{2}\frac{(\sigma_p+\sigma_1)*\delta\varepsilon^*_{p1}+(\sigma_p+\sigma_2)*\delta\varepsilon^*_{p2}}{\delta\varepsilon^*_{p1}+\delta\varepsilon^*_{p2}} \quad (5)$$

σ_i and $\delta\varepsilon^*_{pi}$ are membrane components deduced from an elastoplastic analysis of the first cycle. Figure 1 specifies schematically those parameters.

An elastic approach has been proposed to evaluate σ_1. In this case P_G is evaluated conservatively as :

$$P_G = \frac{\sigma_p+\sigma_1}{2} \quad (6)$$

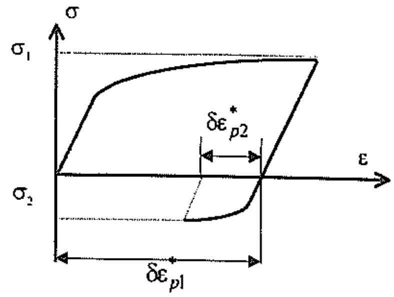

Figure 1

1. 2. The Method Proposed by Igari & al.

The considered version of this method concerns especially the cylindrical thin shell structures subjected to axial thermal gradient which moves axially [6]. The strain increment ($\Delta\varepsilon_r$) at the cycle N is given by:

$$|\Delta\varepsilon_r| = (\varphi+1)\gamma_0^{N-1}(|\sigma_{\theta.el}|-\sigma_{0.2\%})/E \quad (10)$$

$\Delta\varepsilon_r$ expresses the relative variation of the cylinder radius.

N is the number of cycle and $\sigma_{\theta.el}$ is the hoop-membrane stress deduced from an elastic analysis. φ and γ_0 are two parameters depending on the geometry, the material of the cylinder and the moving distance of axial thermal gradient (δ on figure 3).

A creep strain must be added to this ratcheting strain if creep effect exists. The prediction of ratchetting phenomenon included in the "DFBR Design Standard" (DDS) is based on this approach.

1. 3. The Diagrams Proposed by Ponter & al.

Two main 'interaction' diagrams depending on the secondary loading type (membrane or bending or both) have been proposed [7]. The first one (fig. 2a) is similar to the Bree diagram; it concerns the cases where the secondary loading is purely bending. The second one (fig. 2b) is more severe, it concerns the cases where the secondary loading includes a membrane part. These diagrams have two main domains : the allowable one and the one where freedom from ratchetting cannot be demonstrated. A procedure for checking the effects of creep when it is significant is also given [7]. Today the application of these diagrams is limited to the axisymetric and near cylindrical thin shell structures. In figures 2 :

$$C = \frac{\max.\sigma_p}{K_1(\sigma_{0.2\%})_{min}} \quad (7)$$

$$\Delta T = \frac{\max.(\Delta Q)}{K_1(\sigma_{0.2\%})_{min}} \quad (8)$$

C and ΔT are respectively the non-dimensional primary and secondary (range) stresses. K_1 is a factor depending on the temperature and the material. For the 316L stainless steel :

$$K_1 = 0.75 + 0.0026\,(T - 20°\,C) \text{ if } 20°C \leq T \leq 250°C \text{ and } K_1 = 1.35 \text{ if } T \geq 250°C \qquad (9)$$

F is a non-dimensional factor which expresses the role of the membrane component of the secondary stress.

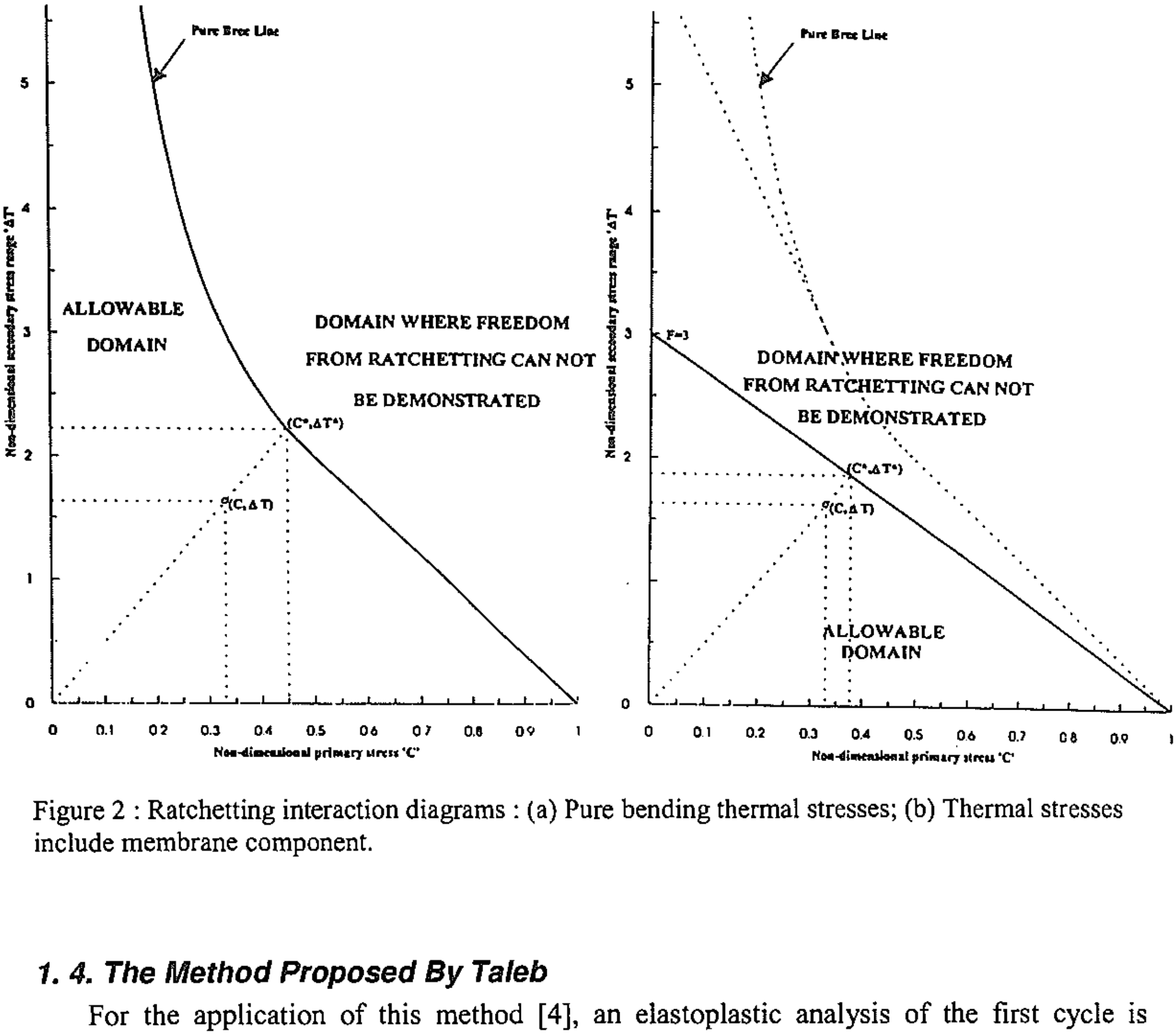

Figure 2 : Ratchetting interaction diagrams : (a) Pure bending thermal stresses; (b) Thermal stresses include membrane component.

1. 4. The Method Proposed By Taleb

For the application of this method [4], an elastoplastic analysis of the first cycle is necessary in order to avoid the problem concerning the classification of the stress into primary and secondary parts. This classification is not always easy especially when the elastic follow-up phenomenon is present and when the 'secondary' loading field has a significant membrane part in the same direction as the primary stress field. When these two phenomena are significant, the elastic analysis cannot generally be reliable [9]. The method enables to have a stress (σ_{max}, Eq. 11) which corresponds (on σ-ε curve) to a conservative forecast of the maximum equivalent mechanical deformation which would be obtained at the steady state.

$$\sigma_{max} = \left(\frac{E \cdot \varepsilon_1^{max}}{P}\right)^{\frac{1}{2} Ln(1+\alpha\cdot\beta\cdot\gamma)} .P \qquad (11)$$

$$\alpha = Ln(1.75 + 2.8\frac{\sigma_{0.2\%}}{E\varepsilon_1^{max}}) \qquad (12)$$

$$\beta = Ln(0.25 + 2.3\frac{\sigma_{0.2\%}}{P}) \qquad (13)$$

$$\gamma = Ln(2.1 + 4.5\frac{\sigma_{1\%} - \sigma_{0.2\%}}{\sigma_{0.2\%}}) \qquad (14)$$

$$P = \sigma_p \text{ if } \sigma_p \neq 0 \text{ and } P = (E \cdot \varepsilon_1^{max} - Q^{max}) \text{ if } \sigma_p = 0 \qquad (15)$$

2. CASE OF A TUBE SUBJECTED TO AXIALLY MOVING THERMAL GRADIENT

This case is taken from the European Fast Reactor and concerns the cylindrical part of the inner vessel. The main features of the problem is presented in figure 3. No force is applied on the cylinder. The structure is only subjected to an axially moving thermal gradient. Two travels of the free level are tested : δ = 130 mm and δ = 60 mm.

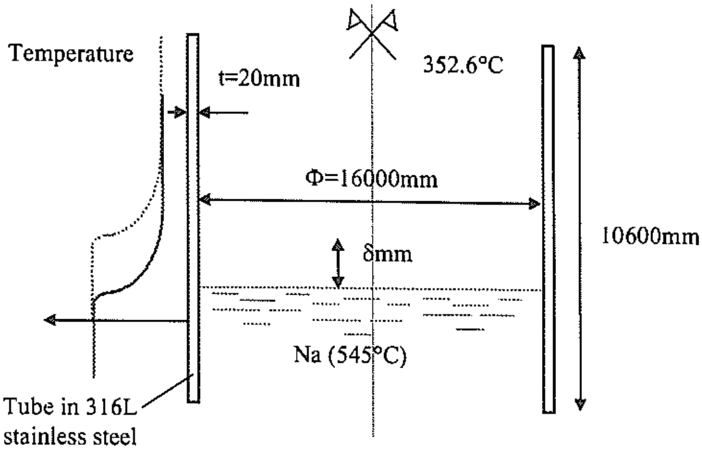

Figure 3 : Tube subjected to axially moving thermal gradient

The methods presented above were used on these examples. The results in term of strain value are given in table 1. In most cases the methods give a result in stress (except the Japanese method). The strain value is derived from the isochronous curve at the maximum temperature by entering the stress given by each method. For the Japanese method, the ratchetting part of the strain is separated from the creep part due to the high level of creep strain found.

Table 1 : results of the different methods tested

Methods	ε_{max}***(δ=130mm)***	ε_{max}***(δ=60mm)***
Efficiency rule	Not applicable	Not applicable
Gatt	3.31%	0.92%
Ponter	>8%	2%
Igari	0.194%, + ∞*	0.173%, +4%*
Taleb	1%	0.45%

(*) : the first value is the ratchetting strain and the second one is the creep strain. The formulation used for the creep strain is taken from the DDS.

3. CASE OF THE BITUBE STRUCTURE

The bitube structure [2] is an assembly of two concentric tubes rigidly fixed at their ends in order to prescribe the same total elongation at any time. The loading is thermo-mechanical : in addition to a prescribed force applied to both tubes, the outer tube is subjected to a cyclic heating while the temperature of the inner one is maintained almost constant. In the "bitube" structure, mechanical and thermal stresses have only a membrane axial component. In most cases, primary stresses have only a membrane axial component, but in a few tests a torsion component (τ) was added. Moreover some tests were conducted with primary overloads.

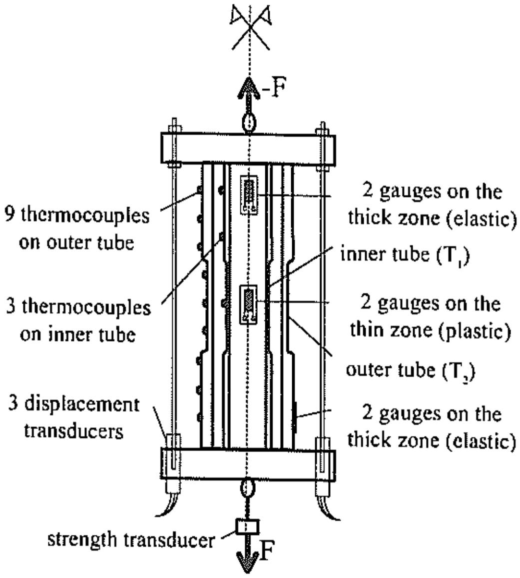

Figure 4 : Bitube structure

Specific developments of the methods have been performed in order to take that into account [4, 9].

The considered experiments concerning this structure has been carried out at the Institut National des Sciences Appliquées (INSA) of Lyon in France.

When thermal stress includes axial membrane component (like bitube structure), the efficiency rule and the method proposed by Ponter & al. recommend to consider this component as primary stress. That choice leads to an excessive conservatism, that is why those methods are not considered here for the bitube structure.

Experimentally it is possible to derive the value of the efficient primary stress $P_{eff\ exp}$ and of the stress $\sigma_{max\ exp}$ corresponding to the maximal total (elastic + plastic) strain at the steady state. The comparison of these experimental values with the corresponding calculated ones gives an idea of the validity of the methods.

Several tests have been analyzed with the elastic version of the modified efficiency rule (Gatt method) and with the method proposed by Taleb. Some results are presented on table 2:

Table 2 : application of Gatt and Taleb methods.

Tests from	σ_p (MPa)		ΔQ (MPa)	Gatt method	Taleb method
	σ_Z	τ		$P_{eff\ calc}/P_{eff\ exp}$	$\sigma_{max\ calc}/\sigma_{max\ exp}$
[2]	100	0	357	1.01	1.08
	100	0	500	1.01	1.11
	150	0	500	1.03	1.15
[3]	80	0	470	1.18	1.09
	80	0	470	1.16	1.21
[11]	46	23	497	1.06	1.09
[11]	66	17 +Δτ =12.4	497	1.06	1.13

We note that the forecasts of the considered methods are in good agreement with the experimental results.

The difference between $\sigma_{max\ exp}$ and $P_{eff\ exp}$ is schematized by figure 5.

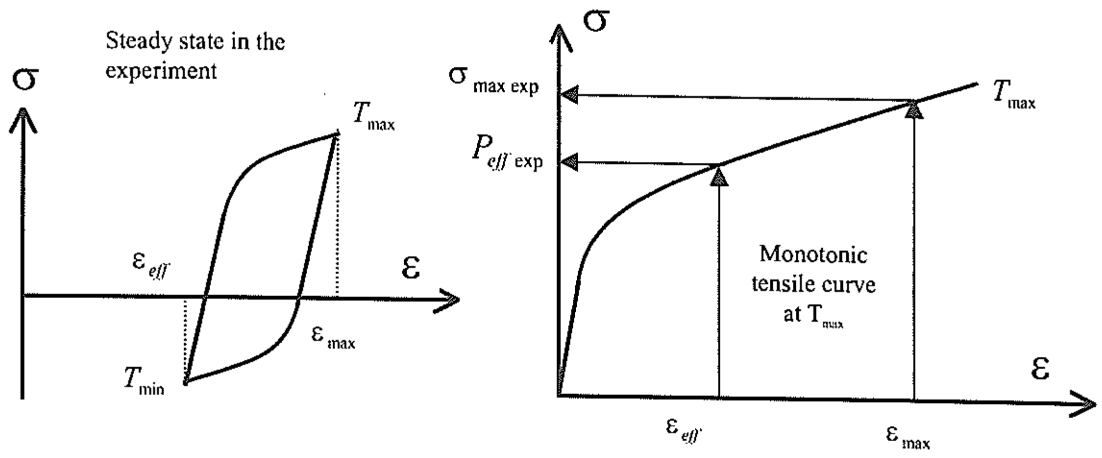

Figure 5 : Determination of $\sigma_{max\ exp}$ and $P_{eff\ exp}$ from the steady state obtained experimentally.

CONCLUSION

In this paper, the available simplified methods for the ratchetting assessment are considered. A comparison of these methods has been performed on two examples of application.

For the sodium free level application it appears that the Japanese method (Igari & al.) provides the less conservative result if only the ratchetting strain is considered. If the creep strain is considered, the forecast becomes too conservative. The method proposed by Taleb gives some interesting results but it necessitates an elastoplastic analysis of the first cycle ! The interaction diagram method (Ponter & al.) gives some results which seem sometimes too conservative. The method proposed by Gatt make the classical efficiency diagram method applicable for the sodium free level case, the obtained forecasts are conservatives.

The second example shows that both Gatt and Taleb methods provide results which are conservative compared to the experiment and similar compared to each other. The interaction diagram method has not been tested on the bitube experiment as this approach is not fitted to deal with problems including thermal axial membrane stresses.

The work performed during these last years has allowed to develop, to test and to validate new simplified methods of ratchetting prediction. In comparison with the methods recommended in the ASME and RCC-MR codes, these methods allow us to deal with a larger number of structures and a larger number of problems. The French methods described here will be included in the next edition of the RCC-MR code and both French and UK methods are the subject of recommendations within a "Design and Construction Rules Committee" report.

The advantages and the drawbacks (for the industrial point of view) of the different ratcheting methods tested are listed on table 3.

Table 3 : advantages and drawbacks (for the industrial point of view) of the tested methods

	Advantages	Drawbacks
Gatt method	• Easy to use • Applicable to any kind of geometry	Sometimes too conservative
Interaction Diagram method	• Very easy to use • Cyclic hardening taken into account	Limited to axisymmetric and near cylindrical thin shells
Japanese Method	• Easy to use	Very conservative when creep strain is considered
Taleb Method	• Partition into primary and secondary stresses no longer necessary • Applicable to any kind of geometry	Needs an elastoplastic calculation of the first cycle

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