Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

F04/6

Thermal ratcheting in biaxial stress state. Effect of primary overloads

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ABSTRACT

In a previous study a coefficient has been proposed in order to take into account the effect of short time primary overloads *(ex: earthquake)* on the steady state of metallic structure under cyclic loadings. That coefficient was validated in the particular case where the overload is applied in the same direction that the one of the primary stress field *(tension)*. In this paper, the validation of that coefficient is performed in a more general case where the overloads are applied in a direction which is different from the primary stress one *(tension+torsion)*.

INTRODUCTION

Design rules, particularly in the nuclear industry, are generally made in order to be moderately conservative. Sometimes, this conservatism is excessive because of the absence of studies of the concerned phenomenon.

For instance, for metallic structures subjected to constant (or variable) primary *(stress due to controlled forces in general)* and cyclic secondary *(stress due to controlled displacement in general)* loadings, the rules dictate to consider the maximum primary load which occurs during the cycle without take the duration of its application into account. In this domain, few years ago, we studied [1-2] the effect of short time primary overloads on a structure under cyclic thermal loading. It was then experimentally demonstrated that the effect of few temporary overloads leads to less progressive deformation in comparison with the case where the overloads are applied in a continuous way. As a result of this study, a coefficient (k) has been proposed [1-2] in order to take this phenomenon into account.

The mentioned study has been carried out considering some primary overloads applied in the same direction that the primary one of the stress field.

The study presented in this paper deals with a more general case where primary overloads are applied in a direction which is different from the primary stress field one. The final objective of the work being to improve the rules in this particular case.

The first part of this paper is devoted to the presentation of the experimental device. In the second part the main results obtained in the previous works are briefly recalled and the effect of primary short time overloads studied in this work is discussed.

1. THE BITUBE STRUCTURE

1.1-Uniaxial primary stress field

A previous study concerning the effect of short time overloads was performed on the bitube structure made up of 316L stainless steel. That structure is composed of two concentric tubes fixed at their ends in order to have the same elongation at any time. The cylinder length is composed of two essential parts: a thin zone, hence liable to undergo plasticity deformation and a thick part which normally remains elastic during the tests.
The deformation measured on the thick part was used to estimate the stress in the tube. The bitube structure used in this study is similar to that presented in figure 1 (with a slight difference in the dimensions of the tubes [1]). The loading was composed of a tension applied on both tubes and a cyclic heating of the outer tube, the inner one is maintained at almost the ambient temperature. The experimental device is presented in figure 2 (where M2 = 0).
The next paragraph is devoted to the presentation of the experimental device modified in order to apply a biaxial primary stress field.

1.2-Biaxial primary stress field

The present work deals with the case where the primary overloads are applied in a direction which is different from the primary stress field one. For that, the experimental device has been slightly modified (figure 1 and 2): in addition to the tension, tubes may be submitted to a torsion force which allows to have a biaxial primary load. That experimental device allows to study three kinds of primary overloads: in tension, torsion or in both directions.

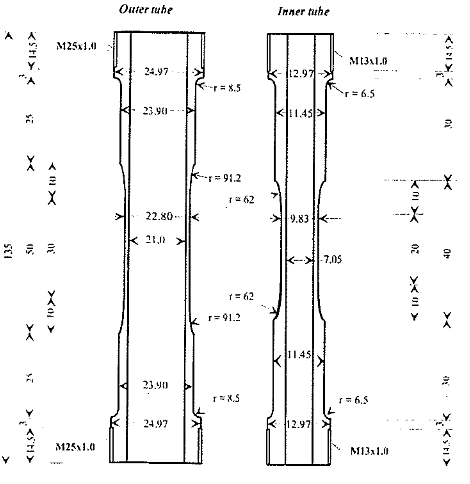

Figure 1: Geometry of the bitube *(in mm)*

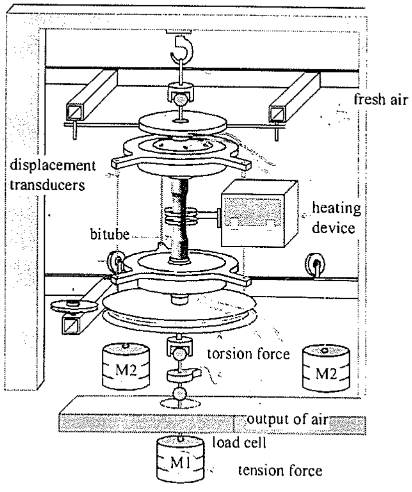

Figure 2: Experimental device

The loading is composed of a tension-torsion applied on both tubes in addition to a cyclic heating *(by induction)* of the outer tube, the inner one is maintained at almost the ambient temperature.

Four types of measurements (figures 3-4) were carried out: temperature *(by 9 thermocouples)*, displacement *(by 3 displacement transducers)* and mechanical force *(by a load cell)*. The deformation was measured by 6 rosettes, principally on the inner tube which remains at almost room temperature. The deformation measured on the thick part (which remains elastic) of the tube was used to estimate the stress in the tube. Figure 3 gives the temperature of both tubes measured by 9 thermocouples during a thermal cycle.

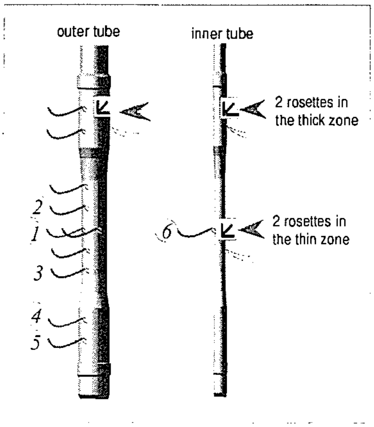

Figure 3: Measurements of temperature and deformation

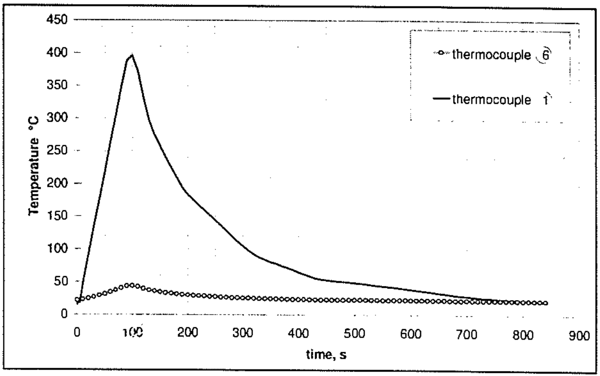

Figure 4: Evolution of the maximum temperature on the tubes during a thermal cycle

2. EFFECT OF PRIMARY SHORT TIME OVERLOADS

2.1- Uniaxial primary stress field

2.1.1- INSA tests [1-2]

Considering the particular case where the primary overloads are applied in the direction of the primary stress field *(tension)*, a previous study was carried out [2] at the I.N.S.A. of Lyon using bitube structure (see section 1.1). The tubes were subjected to a tension *(primary load)* and a cyclic thermal *(secondary load)*. Some short time overloads were applied by varying the tension (figure 5, where torsion $\tau = 0$).

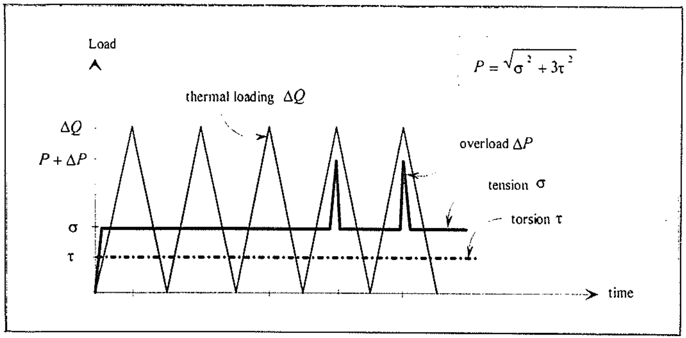

Figure 5: History of the applied loading

Table 1 gives the intensities of the considered loadings.

Test	Primary load P (MPa)	Overload ΔP (MPa)	Secondary load ΔQ (MPa)
1	100	100	357
2	100	100	500
3	150	150	500
3’	150	100	500
4	200	100	500
5	100	190	351

Table 1: Intensities of loadings

The test results leaded to the following conclusions:

- The effect of few temporary overloads leads to less progressive deformation in comparison with the case where the overloads are applied in a continuous way.
- It was shown that the effect of short time overloads could be taken into account by the following coefficient :

$$k = 1 + \frac{P + \Delta P}{2P} \frac{\Delta P}{\Delta Q}$$

Where:

P and ΔP are respectively the variable and the constant parts of the primary load.
ΔQ is the range of the secondary loading deducted from an elastic analysis.

In other words, a primary load P’= k.P (in addition to the secondary loading ΔQ), if maintained constant, would produce at least the same deformation in the steady state compared to that induced by the constant load P (and ΔQ) on which are superposed several momentary overloads of intensity ΔP.

The k coefficient has been validated in two cases : on the tests performed at the Commissariat à l’Energie Atomique (C.E.A.) [3] of Saclay and in a more recent study [4], using also the bitube structure but made up of the modified 9Cr1Mo steel. Both validation cases mentioned above concern the particular case where the primary overloads are applied in the direction of the primary stress field..

2.1.2- Application of k on the CEA tests [3]

The CEA tests were carried out on a tube of 316L stainless steel subjected to tension *(primary load)* and cyclic twisting *(controlled deformation)*. The overload consisted on a momentarily variations of the tension. Two tests (B10, B11) were performed at 350°C and one test (B20) was performed at 650°C (the creep was then significant). Table 2 shows the intensities of loading of these tests.

Test	Primary load P (MPa)	Secondary load ΔQ (MPa)	Overload ΔP (MPa)
B10	35.4	1131	141
B11	40.7	1300	163
B20	31.5	1570	110

Table 2: Intensities of the loadings in the CEA tests

For that tests, it was shown that the k expression gives some conservative forecasts [1-2].

2.1.3. Validation of k forecasts on the bitube structure made up of 9Cr1Mo [4]

The bitube but made up of the modified 9Cr1Mo steel was subjected to a constant primary *(tension)* and a cyclic secondary *(thermal)* loads [4]. That steel presents a cyclic softening behaviour particularly at high temperature. Some overloads *(tension)* was applied during 12 seconds at the maximum temperature *(500°C) (figure 5, where* $\tau = 0$*)*. The thermal cycle *(heating-cooling of the outer tube between 20 and 500°C)* is the same for all tests.

For this objective, two categories of tests were carried out:

- *test 1 and test 3:* In these tests several overloads were applied until the stabilisation *(cessation of increase of deformation and displacement after each cycle)* of the deformation in the structure. The first overload was applied during the third thermal cycle.
- *test 2 and test 4:* In these tests, a constant primary load calculated from the loading applied in the first and the third tests using k expression (P2=k1.P1 and P4=k3.P3, see table 3) was applied until the stabilisation of the deformation in the structure.

The main objective of the tests is to verify experimentally the forecasts of k. For that, the steady state of test 1 and test 3 must be compared respectively to the ones of test 2 and test 4.

Table 3 gives the intensities of the loadings and the obtained deformations at the steady state for each test.

Test	Secondary load ΔQ (MPa)	Coefficient k	Primary load P (MPa)	Overload ΔP (MPa)	Final equivalent strain (%)
1	380	k1=1.111	P1=330	70	0.87
2	380	k2=1.0	P2=k1.P1=365	0	1.00
3	380	k3=1.382	P3=240	170	0.64
4	380	k4=1.0	P4=k3.P3=330	0	0.72

Table 3: Comparison between final deformations

Table 3 shows that the final strain (axial) obtained in test 1 is slightly lesser than the one of test 2 ($\varepsilon_1^{final} < \varepsilon_2^{final}$). The results of the tests 3 and 4 lead to the same conclusion ($\varepsilon_3^{final} < \varepsilon_4^{final}$).

The results of these tests confirm then the good conservatism of the k forecasts in the case when the primary overloads are applied in the direction of the primary stress *(tension)* field.

The next paragraph concerns the bitube structure made up of 316L stainless steel tested in the case where the primary overloads are applied in a direction which is different from that of the primary stress *(tension+torsion)* field.

2.2.- Biaxial primary stress field

2.2.1.- Objective and data of the tests [5]

The final objective of this work and the previous ones [1-2-4] in the short time primary overloads domain is to improve the design rules in this particular case. We particularly try to improve the efficiency rule which is proposed in the 'Règles de Conception et de Construction des Matériels et îlots nucléaires-RNR' (RCC-MR, 1985) [6]. In this work, the bitube structure in 316L stainless (see figure 1) is tested in the case where the primary overloads *(tension)* are applied in a direction which is different from that the primary stress *(tension-torsion)* field (see figure 2).

Table 4 gives the intensities of loadings (figure 5) applied for each phase in the thin part of the inner tube. The thermal cycle *(heating-cooling of the outer tube between 20 and 400°C)* is the same for all phases. These intensities of loadings are defined in order to have a maximal equivalent stress in the thin zone of the outer tube less than the yield stress at 400°C ($\sigma_{elast}^{400°C} \approx 120 MPa$). This test is composed of 4 phases where the thermal cycles are the same:

- phase 1: In this phase, a constant primary load *(tension-torsion, see table 4)* was applied until the stabilisation of the deformation in the structure.
- phase 2: In this phase, several overloads *(tension, see table 4)* were applied until the stabilisation of the deformation in the structure. The first overload was applied during the third thermal cycle at the maximum temperature *(400° C)*.
- phase 3: In this phase, a constant primary load ($P_3 = kP_1$, *see table 4)* was applied until the stabilisation of the deformation in the structure.
- phase 4: In this phase, a constant maximum primary load ($P + \Delta P$) is applied until the stabilisation of the deformation in the structure.

To verify experimentally the forecast of k, the steady state of test 2 must be compared to the one of test 3. To assess the effect of short time overloads compared to a maintained constant primary ($P + \Delta P$), the steady state of test 2 must be compared to the one of test 4.

Phase	Secondary load ΔQ (MPa)	Coefficient k	Primary load (MPa) : $P = \sqrt{\sigma^2 + 3\tau^2}$			Overload ΔP (MPa)
			σ	τ	P	
1	497		46	23	$P_1 = 61$	0
2	497		46	23	$P_2 = 61$	41.4
3	497	k =1.07	51	23	$P_3 = kP_1 = 65$	0
4	497		87.4	23	$P_4 = 96$	0

Table 4: Intensities of loadings

2.2.2- Results and discussion

Figures 6-9 show the evolution of the equivalent strain versus the time *(in the thin part of the inner tube)*. On figures 7 and 8, it can be noticed that the final equivalent strain obtained after phase 2 ($\varepsilon_2^{final} = 0.90\%$) is slightly lesser than the one obtained after phase 3 ($\varepsilon_3^{final} = 0.93\%$, *and* $\varepsilon_2^{final} < \varepsilon_3^{final}$).

This result confirms the validity of the k expression in the studied case.

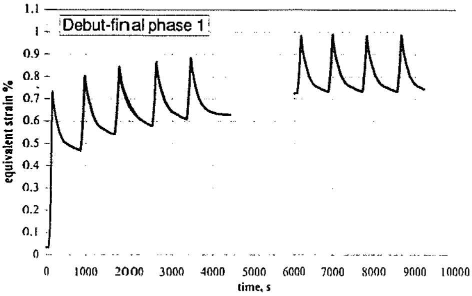

Figure 6: Phase 1

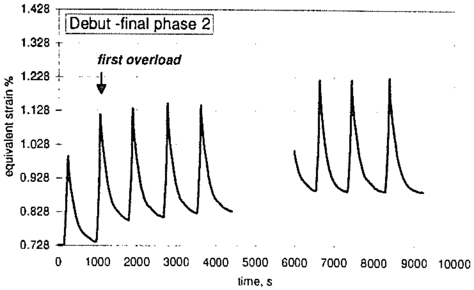

Figure 7: Phase 2

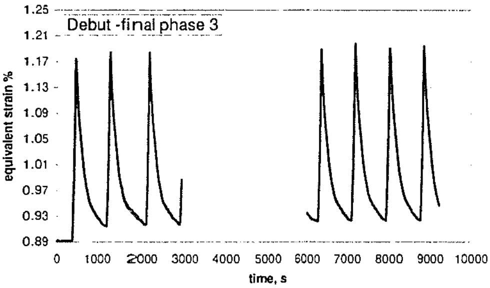

Figure 8: Phase 3

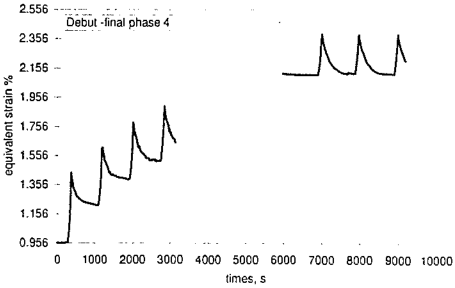

Figure 9: Phase 4

The final equivalent strain obtained after phase 2 ($\varepsilon_4^{final} = 0.9\%$, figure 7) is largely less than the one obtained after phase 4 ($\varepsilon_4^{final} = 2.1\%$, see figure 9):

That result confirms that the effect of few temporary overloads leads to less progressive deformation in comparison with the case where the overloads are applied in a continuous way.

It may be also noticed that the results of this test show the good conservatism of the k forecast in the case when the primary short time overloads are applied in a direction which is different from that the primary stress (tension+torsion) field.

CONCLUSION

The goal of this work concerns the validation of a coefficient proposed in a previous work in order to take into account the effect of short time primary overloads. The validation of that coefficient was already carried out in the particular case where the overloads are applied in the same direction that the primary stress field one.

In this work, the study concerns the case where the primary overloads are applied in a direction which is different from that of the primary stress field one. For that, the experimental device used previously has been slightly modified: in order to be able to apply a biaxial primary load (tension + torsion). Several tests have been carried out where short time overloads were applied in the tension direction. The obtained results show the good forecasts of the proposed coefficient in that case.

In addition, the test results confirm the fact that the effect of few temporary overloads leads to less progressive deformation in comparison with the case where the overloads are applied in a continuous way. It seems then that the conservatism of design rules in this domain is excessive in the case of short time overloads.

To be more general it would be interesting to study also, the particular case where the primary overloads are applied in the other direction (torsion).

REFERENCES

1. Taleb, L. 1991, *Structure métallique sous un chargement thermomécanique cyclique. Effet des surcharges mécaniques de courte durée.* Thèse: Génie civil, structures. Institut National des Sciences Appliqué de LYON. 273p.

2. Taleb, L., Cousin. M. 1994, *Effect of accidental overloads on a structure subjected to periodic loading.* European Journal of Mechanics. A/Solids. VOL.13, N°5, 1994.

3. Cousseran, P., Lebey, J., Tremblais, A. 1982, *Essais de déformation progressive en traction-torsion avec surcharge momentanée de la contrainte primaire*, Note EMT/SMTS/82/88, CEA-CEN, Saclay, 44 p.

4. Taleb, L., Cousin, M. 1995, *Thermomechanical analysis of 9Cr1Mo structure subjected to some overloads. The fifth international symposium on plasticity and its current applications.* PLASTICITY 95. SAKAI, OSAKA PREF., JAPAN, July 17-21.

5. Rakotovelo, M., Taleb, L., Cousin, M., *Déformation progressive des structures métalliques sous contrainte biaxiale, essais et calculs.* Lyon: INSA, 1996.
Rapport EDF/SEPTEN N° INSA/1/928/003.

6. AFCEN, 1985, *Règles de conception et de construction des matériels mécaniques des îlots nucléaires RNR (RCC-MR).* Association Française pour les règles de Conception et de Construction des matériels des chaudières Electro-Nucléaires, Tome 1, Vol.B. p.59-67.