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A new approach for primary overloads allowance in ratchetting evaluation

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ABSTRACT : Seismic loading must be taken into account in ratchetting design analysis. In LMFBR structures it mainly produces primary overloads, which are characterised by severe magnitudes but a generally low number of occurrences. Other cases of severe primary overloads can also observed in pipes during emptying operations for instance.

In the RCC-MR design code rule, the maximum primary stress supported by a structure is considered as permanent. No allowance is made for temporary load.

Experimental ratchetting tests conducted on different structures with and without overloads clearly point out that temporary overloads lead to less ratchetting effect.

A method using the RCC-MR efficiency diagram framework is proposed. A general theoretical approach allows to extend its field of application to various cases of primary loading: constant or null primary loading or overloads.

Experimental results are then used to check the validity of this new approach.

1 RCC-MR ELASTIC DESIGN-RULE

The RCC-MR elastic rule consists in determining an effective primary stress P_{eff} which, if applied alone in the same conditions of time and temperature, would lead to the same cumulated strain as obtained under a constant primary stress P and a cyclic secondary stress range ΔQ. This effective primary stress P_{eff} is evaluated through the efficiency diagram.

If a limited number of cycles with primary stress overloads ΔP is recorded during the studied cycles, the rule must be verified with $Max(P)=P+\Delta P$. This approach generally proves itself very conservative.

2 DEVELOPMENTS BASED ON THE EFFICIENCY DIAGRAM METHOD

Several developments around the efficiency diagram rule have been proposed (ref. 1).

A simplified method was developed starting from a theoretical approach based on energetic considerations. In simple cases, this approach is identical to the method described in the RCC-MR. It can be successfully applied to structures in which primary loading is null, as well as structures characterised by a significant elastic follow up effect or structures submitted to anisothermal loading.

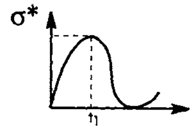
In fact, this method consists in considering the real mean stress involved in ratchetting as the primary stress for the verification of the progressive deformation rule. In order to be conservative, this stress is identified as the effective mean stress obtained during the first cycle.

In simple structure and stress configurations, P can be evaluated on an elastic analysis basis. In the general case, an elastoplastic calculation over one cycle, including primary and secondary stress will be necessary in order to take into account any possible coupling between primary and secondary stresses.

Let $\sigma(t)$ the total stress tensor thus obtained and σ_p the primary stress tensor. $\sigma^*(t)$ represents the equivalent Von Mises stress. It is supposed that limitations on primary stresses are observed.

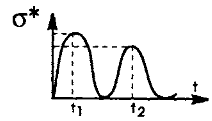
If, at the considered point, yielding only occurs in one part of each cycle, (either loading or unloading) then :

$$P = \frac{1}{2}\left(\sigma_p + \sigma(t1)\right)^*$$



If yielding occurs during loading and unloading :

$$P = \frac{\frac{1}{2}\left(\sigma_p + \sigma(t1)\right)^* \delta\varepsilon^*_{p1} + \frac{1}{2}\left(\sigma_p + \sigma(t2)\right)^* \delta\varepsilon^*_{p2}}{\delta\varepsilon^*_{p1} + \delta\varepsilon^*_{p2}}$$



$\delta\varepsilon^*_{p1}$ and $\delta\varepsilon^*_{p2}$ represent equivalent plastic strain increments obtained during loading and unloading, respectively.

The efficiency diagram method is then applied with the couple (P, ΔQ), ΔQ representing the secondary stress range over one cycle resulting from elastic analysis.

3 INTEGRATION OF OVERLOADS

The existence of primary type overloads, applied during short periods (compared to cycle times) at the most penalizing moment (i.e. : moment where total stress state is maximum for the cycle), is considered.

Let $\Delta\sigma_p^{el}$ the elastic stress range resulting from primary overload, and δt_c it's application time.

There is a restriction concerning the overload value applied: under the effect of all primary stress (overload included) limitations concerning primary stress must always be observed.

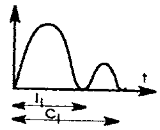
The same formalism as reference 1 is used :

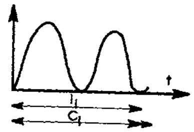
- $\sigma(t)$ represents real stresses at the moment t (taking account of the real behaviour of the material)
- σ_p represents the primary stress tensor in the absence of overloading

secondary elastic stresses are expressed : $\sigma_q^{el} = \sigma_{q0}^{el} + \sigma_{q1}^{el} \sin\omega t$

secondary effective stresses $\sigma_q(t)$ equal : $\sigma(t) - \sigma_p$

Let C_i the i^{th} loading cycle and $I_i \subset C_i$ the time interval over which the structure is in the plastic range. The overload is supposed to be introduced at the maximum of interval I_i in order to be conservative.





Energy dissipated by the structure, over I_i, is expressed :

$$W_{ti} = \int_{VI_i}\int \sigma(t) : \dot{\varepsilon}(t)\, dt dV + \delta W_i$$

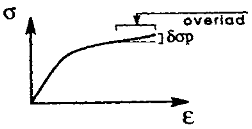
V represents the structure's volume.

δW_i represents the increment of dissipated energy due to the overload.

Overload work in progressive deformation is expressed:

$$\delta W_i = \int_{V\delta tc}\int \delta\sigma_{pi}\,(t) : \dot{\varepsilon}(t)\, dt dV$$

where $\delta\sigma_P$ represents the effective stress increase due to the application of the overload, and not the elastic evaluation. $\delta\sigma_P$ is lower than $\Delta\sigma_p{}^{el}$



Over the time interval corresponding to the application of the overload it can be written :

$\dot{\varepsilon}_p = \delta\dot{\sigma}_P / h$ h : positive constante

and thus : $\delta W_i = \int_V \frac{1}{2}\delta\sigma_{pi} : \delta\varepsilon_{psci}\, dV$ with $\delta\varepsilon_{psci} = \frac{\delta\sigma_{pi}}{h}$

Supposing, as in reference 1, that the effective secondary stress range, over the interval I_i, can be written :

$\sigma_{qi}(t)=\sigma_{q0i}+\sigma_{q1i}\cos(\omega_i t+\phi_i)$

the following is obtained :

$$W_{ti} = \int_{VI_i}\int \underbrace{\sigma_{q1i}\cos(\varpi_i t + \phi_i) : \dot{\varepsilon}(t) dt dV}_{Q_i} + \int_{VI_i}\int \underbrace{(\sigma_{q0i} + \sigma_{Pi}) : \dot{\varepsilon}(t) dt dV}_{W_{pri}} + \delta W_i$$

$$W_{ti} = Q_i + W_{pri} + \delta W_i = Q_i + \int_V P_i . \delta\varepsilon^*_{pri}\, dV$$

with: Q_i = energy dissipated over a closed cycle

W_{pri} = energy dissipated due to ratchetting

δW_i = energy dissipated during the overload

W_{ti} = total energy dissipated over the cycle

P_i is assimilated to the stress working in progressive deformation

By proceeding as in reference 1, the following can be established :

- $W_{pri} = \int_v (\sigma_{q0i} + \sigma_p)^* . \delta\varepsilon^*_{pri}\, dV$ with $\delta\varepsilon^*_{pri} = \int_{Ii} \dot{\varepsilon} dt$ plastic strain increment over the cycle
- $\delta W_i = \int_V \frac{1}{2}\delta\sigma_{Pi} : \delta\varepsilon_{psci} dV = \frac{1}{2}\int_v \delta\sigma^*_{Pi}\, \delta\varepsilon^*_{psci}\, dV$

and thus : $P_i = (\sigma_{q0i} + \sigma_p)^* + \frac{1}{2}\delta\sigma^*_{Pi}\frac{\delta\varepsilon^*_{psci}}{\delta\varepsilon^*_{pri}}$

- $Qi = \int\int_{VI_i} \sigma_{qli} \cos(\varpi_i t + \phi_i) : \dot{\varepsilon}(t) dt dV = \int_V F_i \xi_i \Delta Q_2^{el} dV$

where ξ_i is a function which depends on the position of the studied point, such that :
$\sigma_{qli} = \xi_i \Delta Q_2^{el}$ and : $\Delta Q_2^{el} = 2\sigma_{ql}^{el} + \Delta\sigma_p^{el}$

The resulting simplified design method consists in using the efficiency diagram with the sress couple (P, ΔQ), such that :

$$P = \left(\sigma_{q0} + \sigma_p\right)^* + \frac{1}{2}\delta\sigma_p^* \frac{\delta\varepsilon_{psc}^*}{\delta\varepsilon_{pr}^*} = P_c + \delta P \text{ and} : \Delta Q = \left(2\sigma_{ql}^{el} + \Delta\sigma_p^{el}\right)^*$$

In the absence of overloads, P_c is determined as indicated in Paragraph 2.

The determination of $\delta\sigma_p^*, \delta\varepsilon_{psc}^*, \delta\varepsilon_{pr}^*$ requires, in the general case, a plastic calculation of the first cycle with the introduction of overloading at the maximum of the cycle.

Elastic stresses due to overloading are included in the evaluation of the secondary stress range.

4 APPLICATION

Specific tests intended to study the influence of primary overloading on ratchetting deformation were performed at the INSA in LYON using bitube structures (reference 2).

The mock-ups are comprised of 2 concentric 316SPH steel tubes which are rigidly attached in order to obtain identical axial elongation at all times. The 2 tubes have the same length and section (Figure 1).

The outer tube is heated cyclically whereas the inner tube is maintained at ambient temperature. The assembly is submitted to an axial load. Strain records are made on the cold tube.

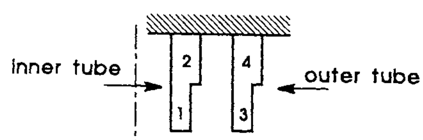
Several tests were conducted with and without overload. Table 1 summarises the different loading conditions (elastic stress values calculated at the centre of the cold tube) and strains reached at stabilisation in each case.

For this type of structure, it is not necessary to use inelastic calculations in order to evaluate $\delta\sigma_p^*, \delta\varepsilon_{psc}^*, \delta\varepsilon_{pr}^*$ values. Indeed, loading is simple, the stress state is uniaxial and only the thin part of the inner tube yields upon loading (heating of the outer tube). This has been verified experimentally.

Using equilibrium stress conditions and displacement compatibility equations along with the material stress-strain behaviour curve, it is possible to determine $\delta\sigma_p^*$ as a function of $\Delta\sigma_p^{el}$ at the centre of the cold tube (area 1 on the diagram).

The following is obtained :

$$\delta\sigma_p = \frac{(1 + E_2/E_1) + (1 + S_1/S_2)}{\left(1 + E_2/E_1'\right) + (1 + E_2/E_1)S_1/S_2} \Delta\sigma_p^{el}$$



with : $1/E'_1 = 1/E_1 + 1/h$
E_1, E'_1 : modulus, cold (inner tube)

E_2 : modulus, hot (outer tube)
and : $\delta\varepsilon_{psc} = \delta\sigma_p/h$

In this case, the value P_c is directly determined using experimental results for the first cycle. Since the cold tube only yields upon loading, the following is applied:

$P_c = \frac{1}{2}\left(\sigma_p + \sigma(t1)\right)$ where $\sigma(t1)$ represents the maximum stress reached at the centre of the inner tube at the end of the outer tube heating sequence.

By applying the method proposed, the couple (P, ΔQ) which will be used to enter the efficiency diagram, is determined. These values are indicated in table 2.

Using the pair (P, ΔQ) and the final strain value reached during the tests, it is possible to place experimental points on the efficiency diagram (Figure 2). It is observed that with this stress evaluation method, all points representative of tests are correctly placed on the diagram.

Furthermore, it is possible to compare efficient primary stress based, firstly on experimental results (P_{eff}exp) and, secondly on the proposed method (P_{eff}calc). These values are also indicated for all tests in Table 2.

In all cases, the value P_{eff}calc is higher than P_{eff}exp. This guarantees the conservatism of the method.

However, it is observed that the calculated value P_{eff} remains very close to the experimental value for all tests, the maximum deviation being approximately 10%. This very good correlation between experimental results and predictions obtained through a simplified elastic method can be explained by the fact that the stress-strain curve of the material as well as the loading conditions were known precisely.

5 CONCLUSION

Developments based on the RCC-MR efficiency diagram method have made it possible to integrate the effect of short primary overloads in ratchetting analysis. In simple structure and stress loading configurations, an elastic analysis is well adapted. In more complex configurations, it is necessary to perform a plastic calculation of the first loading cycle with introduction of the overload at the maximum of the cycle.

The analysis of tests conducted using bitube structures, with and without overloads, provided very satisfactory results. Nevertheless, in order to validate this method, it will be necessary to apply it in other structure and stress loading situations.

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6 REFERENCES

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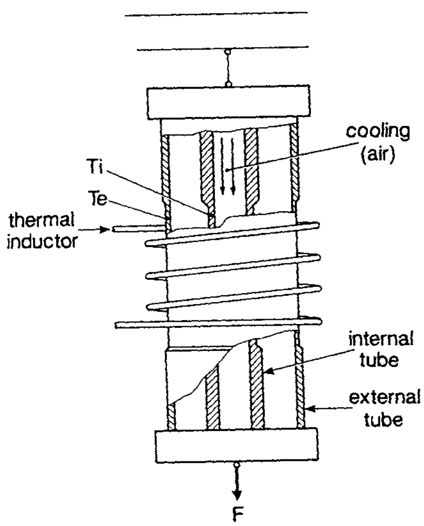
TABLE 1

test	σ_y MPa	$\Delta\sigma_0^{el}$ MPa	ΔQ^{el} MPa	$\Delta\varepsilon$ %
11a	100	0	357	0.27
11b	200	0	357	0.56
12	100	100	357	0.37
21a	100	0	500	0.45
21b	200	0	500	0.97
22	100	100	500	0.63
31a	150	0	506	0.60
31b	300	0	506	3.11
32	150	150	506	1.07
41a	200	0	500	0.84
41b	300	0	500	2.20
42	200	100	500	1.16
51a	100	0	351	0.32
51b	290	0	351	1.25
52	100	190	351	0.76

TABLE 2

test	P MPa	ΔQ MPa	$P_{eff}exp$ MPa	$P_{eff}calc$ MPa
11a	212	357	285	296
11b	289	357	363	364
12	222	457	318	336
21a	233	500	345	358
21b	292	500	395	411
22	235	600	373	389
31a	244	506	338	370
31b	334	506	420	450
32	249	656	375	418
41a	287	500	380	407
41b	343	500	410	456
42	289	600	407	439
51a	198	351	261	283
51b	307	351	375	379
52	217	541	329	356



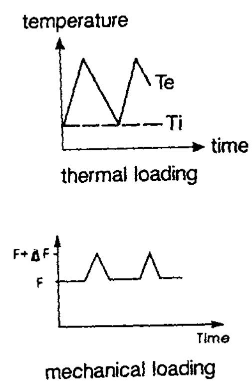


Figure 1

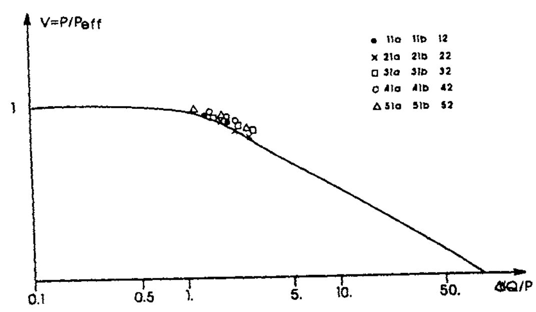


Figure 2 EFFICIENCY DIAGRAM METHOD