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Fatigue analysis of a structure with welds considering metallurgical discontinuities

Cabrillat, M.T., Lejeail, Y.
CEA Cadarache, St. Paul-Lez-Durance, France

ABSTRACT : The behaviour of a welded structure generally differs from that of an identical structure without welds. This is due to geometrical and metallurgical discontinuities.

In classic elastic analyses, geometrical discontinuities are taken into account through stress concentration factors, and metallurgical discontinuities through joint coefficients which describe more precisely the mechanical properties and fatigue resistance differences between the two materials in presence.

In inelastic analyses, material behaviour differences can be directly assessed using stress-strain curves and fatigue resistance properties associated with each material.

Such calculations are used to establish the validity of joint coefficients.

I INTRODUCTION

Within the framework of a creep-fatigue experimental program, called EVASION, thermo-mechanical tests were conducted on two mock-ups, the first one was fully machined and the second one welded and then machined (in order to eliminate geometrical discontinuities, thus only leaving metallurgical discontinuities).

These two mock-ups were submitted to exactly the same loading history.

Plastic analyses with a correct description of mechanical properties and fatigue strength of materials are conducted and compared with experimental results in order to highlight the influence of the weld.

2 TEST DESCRIPTION

This experimental programme was partially described in Reference 1: test facility, mock-ups tested, loading conditions and first experimental results.

The mock-ups form a cylindrical shell (outer diameter: 160 mm, thickness: 8 mm) attached to a 10 mm thick plate. The first mock-up is entirely machined from a solid bar. The second one is made up of a rolled and welded shell which is itself welded to the plate. After welding, the whole mock-up is machined. This second mock-up therefore includes one axial weld in the shell, and one circumferential weld at the plate-shell junction.

These mock-ups are submitted to thermal shocks in sodium. Their temperature is maintained at 600 °C and the thermal shock is created by sending cold sodium inside them during approximately 20 seconds. The plate, which is drilled in order to permit sodium flow, then cools down very rapidly (much faster than the shell). This produces high stress load levels at the junction, i.e. traction inside, compression outside.

After 20 seconds, the mock-up is reheated to 600 °C and maintained at this temperature until the following shock. During this phase, yielding occurs in the opposite direction, i.e. compression inside, traction outside.

The two mock-ups were submitted to exactly the same loading history:

- 1,500 thermal shocks with cold sodium at 350 °C and 6 h hold times at 600°C between two shocks
- 1,000 thermal shocks with cold sodium at 200 °C, with 1 h hold times at 600°C between two shocks.

Metallo-graphical analyses performed at the end of the tests show that fatigue damage is similar on the internal area of each mock-up: transgranular cracks are observed in the two fillet radii (upper and lower) up to 900 μm deep. On the welded mock-up, incipient cracks are observed both in base metal and filler metal.

Non destructive tests performed after the 1,500 first cycles did not evidence defects in the fillet radii. The second loading sequence therefore seems decisive in the fatigue damage process.

On the outer side, an intergranular crack (due to creep) 26 mm long, centred on the plate, was detected on the welded mock-up's longitudinal weld at the end of the tests, whereas no defect was detected in this area after the 1,500 first cycles.

Concerning the machined mock-up, no defect was evidenced on the outer surface at the end of the tests.

Fatigue damage is therefore similar on the inner fillet radius for both mock-ups. On the outer surface, creep-fatigue cracks only occurred on the welded mock-up.

3 INTERPRETATION

Various elastic and inelastic analyses were performed (Ref. 2 and 3) without taking the presence of welds into account.

An inelastic analysis was conducted by modelling the circumferential weld between the shell ring and the plate. This analysis only concerns this weld, which can be axisymmetrically modelled and only involves fatigue behaviour. Preliminary calculations and experimental results showed that creep was insignificant in this area, and also that the second loading sequence (1,000 cycles with cold sodium at 200 °C) was decisive in the occurrence of damage. The analysis is thus limited to the second loading sequence.

Both calculations are conducted in parallel:

- the first one, representing the machined mock-up, with one single material for the whole mock-up: the base metal
- the second one, representing the welded mock-up, taking into account the characteristics of base metal and filler metal.

  An identical mesh will be used for both calculations, considering either one single material or two materials (Figure 1).

3.1 *Material characteristics*

The base metal (316SPH) and the filler metal (OKR3U) behave very differently. Figures 2 and 3 show reduced cyclic and monotonic tensile curves for both materials at 20 °C and 550 °C. Cyclic hardening is a lot higher for base metal than filler metal. The two materials' reduced cyclic curve intersection is located at ε = 1.2 % (20 °C) and at ε = 0.6 % (550 °C).

It can finally be noted that, for the filler metal, the reduced cyclic curve is located below the monotonic curve for low strain levels.

In this analysis, fatigue resistance curves (Figure 4) associated with each material are also taken into account. The deviation between the two curves is relatively small. Indeed, the base metal's fatigue resistance is slightly higher for strain ranges below 1 % and slightly lower beyond.

3.2 *Plastic calculations*

These calculations were conducted using a linear kinematic model identified on reduced cyclic curves of materials at various temperatures between 20 °C and 600 °C. These calculations were performed over two cycles.

The evolution of stresses is similar for both calculations, with however slightly higher values for the calculation involving two materials.

The following table gives maximum values for Von Mises stresses obtained at various points indicated on Figure 1 for both calculations.

Node	B1	B3	B2	W1	W2	J1	B5
Position	base metal near weld			weld		junction weld/base metal	base metal outer skin
(1) σ_{vm} MPa 1 material	461	460	375	317	313	208	268
(2) σ_{vm} MPa 2 materials	471	465	389	353	348	226	267
σ_{vm} (2)-(1) MPa	+10	+5	+14	+36	+35	+18	-1

For both calculations, higher stresses are observed in the base metal area.

Taking two materials into account increases stress values, mainly in the weld area.

For the most heavily loaded points in the two areas, the maximum strain range obtained on one cycle, for both calculation configurations, is evaluated.

Node	B1	B3	B2	B4	W1	W2
Position	base metal				weld	
(1) $\Delta\varepsilon$% 1 material	1.204	1.189	0.864	0.880	0.673	0.643
(2) $\Delta\varepsilon$% 2 materials	1.239	1.201	0.936	0.934	0.536	0.496

It can be observed that, when the presence of the weld is taken into account, base metal strain ranges increase (by approximately 3 % at the most heavily loaded point) and that filler metal strain ranges significantly drop (by approximately 20 %).

For strain range levels obtained ($\simeq$ 0.6 %), the filler metal is more resistant than the base metal. Indeed, an elastic follow up effect is created, which tends to accumulate plastic strain in the base metal.

3.3 *Consequences for fatigue damage*

The most heavily loaded points are located in the base metal. They are therefore analysed with the corresponding fatigue curve.

Points located within the weld area are analysed with the base metal fatigue curve, for the calculation with 1 material, and with the filler metal fatigue curve, for the calculation with two materials.

The following number of pure fatigue initiation cycles is obtained for each calculation:

calculation	base metal B1	weld W1
1 material		
$\Delta\varepsilon\%$	1.204	0.673
N_f	50	220
2 materials		
$\Delta\varepsilon\%$	1.239	0.536
N_f	45	300

It can be observed that considering the filler metal's real characteristics does not significantly modify fatigue analysis results. In both cases, the occurrence of incipient fatigue cracks in the base metal is foreseen at the same point (B1, upper fillet radius) for an equivalent number of cycles. As a consequence, the behaviour of both mock-ups (machined and welded) should be similar in terms of fatigue damage. This apparently correlates experimental results.

4 CONCLUSIONS

The fatigue strength of the EVASION mock-up was assessed considering the filler metal's real plastic behaviour as well as its fatigue resistance. Despite the fairly different local properties of the materials, this approach provides a satisfactory interpretation of experimental results.

For this particular case of structure and loading the fatigue weld coefficient seem to be near 1.1. In the RCC-MR code these coefficients are equal to 1.25.

Influence of creep during hold times was not taken into account. Nevertheless predictions of calculations are conservative. In fact stresses are compressive in this area during hold times and consequently less damageable relatively to creep.

Such calculations should give a correct representation of welded structure behaviour and permit assessment of the influence of welds on fatigue life times.

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5 REFERENCES

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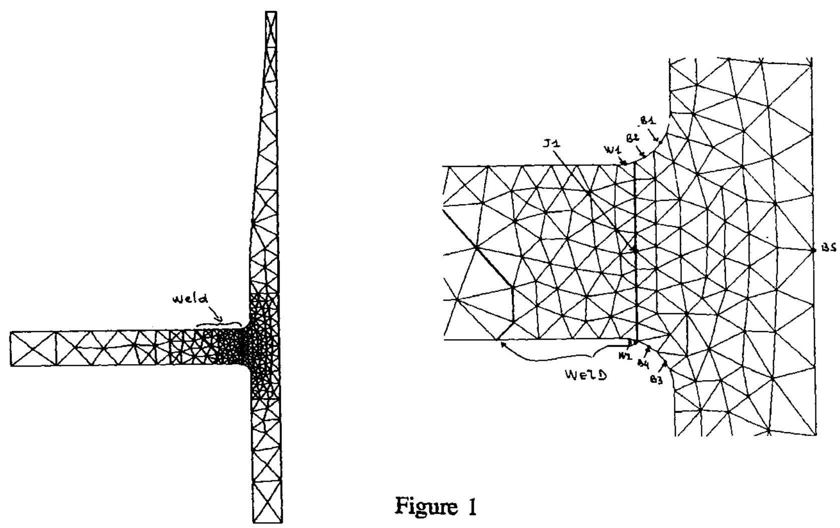

Figure 1

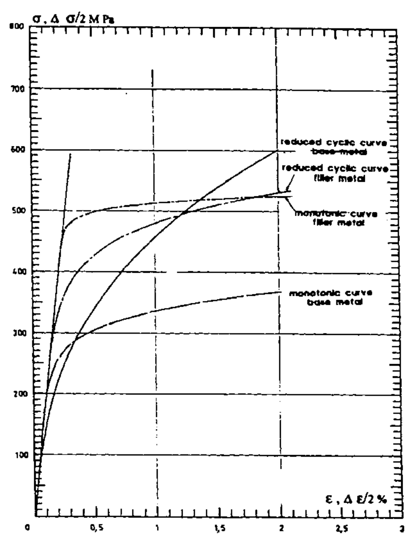

Figure 2 Monotonic and reduced cyclic curve at 20°

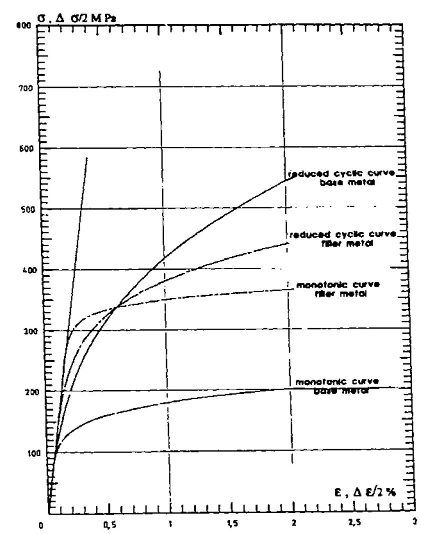

Figure 3 Monotonic and reduced cyclic curve at 550°

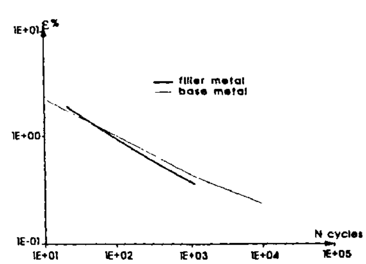

Figure 4 Oligocyclic design fatigue curves