Behavior of surface cracks in aged duplex stainless steel plates submitted to a bending load

Chapuliot S., Moulin D., Mineau V.
CEA, France

ABSTRACT:
This article presents a study on the propagation of surface cracks under monotonic loading in low toughness plates submitted to bending load. The first part of the study is experimental and consists on the determination of the load associated to crack tearing initiation and to a several millimeter stable propagation. The second part of the study is a calculation of $G$ values associated respectively to the load at initiation and to the maximum load imposed during the test (with a non semi-elliptical surface defect observed at the end of the test).

1. INTRODUCTION
As part of a joint project between CEA, EdF and Framatome on the behavior of semi-elliptical surface cracks, a test series named PLAF was done at the CEA/DMT. These tests consist on propagating under a monotonic increasing load, a surface crack in an aged duplex stainless steel plate. Thus, four semi-elliptical cracks with different sizes and shapes, machined in plates, are submitted to bending load and propagated under several millimeters in the thickness and width direction. An analysis of these tests is proposed in this article. It is, in a first time, a study of the experimental results to determine the crack tearing initiation conditions and the associated $J$ values obtained by the simplified method $J_s$. A comparison with material characteristic $J_{0,2}$ can then be made.
In a second time, a numerical study is proposed on a particular test. For that, two defects are modelized: the initial fatigue pre-crack defect, in order to determine more precisely the $J$ values at crack tearing initiation, and the defect at the end of the test, after a stable crack propagation. This last calculation makes the originality of the study and enables us to analyze the behavior of a non semi-elliptical surface crack and then calculate the $J$ values at the end of the test for different crack propagations. All these calculations are validated by a comparison with experimental results measured during the increasing bending moment.

2. MATERIAL DESCRIPTION
The tested material is an aged cast duplex stainless steel. The aging treatment is a thermal treatment at 400°C during about 700 h. During this phase, the degradation of the material is followed by charpy tests. For this particular study, the aging was stopped for a charpy resistance $K_{CV} = 15$ daJ/cm² at room temperature.
2.1 Stress-strain curve

The mean stress-strain curve obtained with eight specimen is shown on fig. 1. Despite the material is an aged cast steel, 15% maximum strain is obtained (more for some specimen). The mean characteristic tensile data are:

\[ E = 180000 \text{ MPa}, \sigma_y = 374 \text{ MPa}, \sigma_u = 802 \text{ MPa}. \]

![Fig. 1: True stress vs true strain](image)

2.2 Ductile tearing

The ductile resistance of the material was determined by the ASTM procedure [1] on 8 CT15 specimen. The mean initiation value of obtained \( J_{0.2} \) is \( J_{0.2} = 34 \text{ kJ/m}^2 \).
3. TEST DESCRIPTION

Tests were done on plates described on fig. 2. The load is a bending load obtained by test device developed and validated by fatigue tests on austenitic steel [2]. The length of the arms to obtain the bending load is 350 mm so that, in the defect section, the ratio of membrane stress on bending stress is \( \sigma_m/\sigma_b = 1.65 \times 10^{-2} \). Tests are made at room temperature.

3.1 Initial and propagated defects

A notch is first machined on the surface of the plate. Then, a pre-fatigue loading is done under elastic conditions (\( R = 0.1 \) and \( K_{\text{max}} < 30 \text{ MPa.m}^{1/2} \)) to obtained a real crack from the notch. This phase is stopped after an approximate 2 mm growth at the deepest point of the crack. The monotonic test is then conducted under slowly increasing load, until a crack propagation is seen on the skin of the plate (the maximum endurable load of the plate is not reached). After thermal marking, the plate is opened and the different defects are observed. Table 1 and fig. 3 give a description of these defects.

<table>
<thead>
<tr>
<th></th>
<th>Notch depth (mm)</th>
<th>Notch width (mm)</th>
<th>Initial crack depth (mm)</th>
<th>Initial crack width (mm)</th>
<th>Final crack depth (mm)</th>
<th>Final crack width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLAF 1</td>
<td>14</td>
<td>56</td>
<td>17</td>
<td>67</td>
<td>18.5</td>
<td>78</td>
</tr>
<tr>
<td>PLAF 2</td>
<td>14</td>
<td>28</td>
<td>15.7</td>
<td>36.8</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>PLAF 3</td>
<td>7</td>
<td>28</td>
<td>9.8</td>
<td>33.2</td>
<td>17</td>
<td>46</td>
</tr>
<tr>
<td>PLAF 4</td>
<td>7</td>
<td>14</td>
<td>7.8</td>
<td>20</td>
<td>11</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 1

![Fig. 3: View of different defects](image)

The first conclusion deduced from the crack shape measurements is that an important ductile crack propagation (between 1.5 to 13 mm) is obtained without instability of the plate.

3.2 Crack tearing initiation load.

Two different methods are used to determine the crack tearing initiation load:

- The first is based on the Electric Drop Potential measurement on the two lips of the defect. The initiation of the defect tearing is determined by the onset of EDP variation.
- The second is an offset technic using the Displacement/Opening angle curve. It is based on the fact that, when the defect starts to propagate, the cinematic relation between the two displacements is modified. Thus, a break can be seen on the curve slope.

Table 2 gives the results determined by the two technics. A good agreement between both
values is obtained.

<table>
<thead>
<tr>
<th></th>
<th>Initial crack depth (mm)</th>
<th>Initial crack width (mm)</th>
<th>F_{initiation} (N) DDP</th>
<th>F_{initiation} (N) offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLAF 1</td>
<td>17</td>
<td>67</td>
<td>5.96 \times 10^4</td>
<td>5.98 \times 10^4</td>
</tr>
<tr>
<td>PLAF 2</td>
<td>15.7</td>
<td>36.8</td>
<td>5.70 \times 10^4</td>
<td>5.71 \times 10^4</td>
</tr>
<tr>
<td>PLAF 3</td>
<td>9.8</td>
<td>33.2</td>
<td>6.64 \times 10^4</td>
<td>6.62 \times 10^4</td>
</tr>
<tr>
<td>PLAF 4</td>
<td>7.8</td>
<td>20</td>
<td>6.43 \times 10^4</td>
<td>6.35 \times 10^4</td>
</tr>
</tbody>
</table>

*Table 2*

3.3 *J* estimation at crack tearing initiation

For each plate *J* is estimated using the crack shape and the load measured during the tests by the A16 simplified method *Js* [3]:

- maximum *K* value over the crack front is calculated with the Raju-Newman formula [4],
- a reference stress, which evaluates the plasticity in the crack section, is calculated:

\[
\sigma_{ref} = \frac{\sigma_{def \cdot b}}{3} + \sqrt{\left(\frac{\sigma_{def \cdot b}}{3}\right)^2 + \sigma_{def \cdot m}^2} \quad \text{with} \quad \sigma_{def \cdot m} = \frac{N}{2 \cdot b \cdot h - \pi \cdot a \cdot c / 2}, \quad \sigma_{def \cdot b} = \frac{6 \cdot M}{2 \cdot b \cdot h^2}
\]

- the associated strain \( \varepsilon_{ref} \) to the \( \sigma_{ref} \) stress is determined on the stress-strain curve,
- finally, the *Js* value is determined by the formula:

\[
Js = \frac{K}{E^*} \left[ \psi_{A16} + \frac{E \cdot \varepsilon_{ref}}{\sigma_{ref}} \right] \quad \text{with} \quad \psi_{A16} = \frac{\sigma_{ref}^2}{2 \left( \sigma_{ref}^2 + \sigma_y^2 \right)} \quad \text{and} \quad E^* = \frac{E}{1 - \nu^2}
\]

Table 3 gives a description of the results obtained for each plates. Despite the approximation made on crack shapes, the agreement between the different values of *J* is rather good.

<table>
<thead>
<tr>
<th></th>
<th>Initial crack depth (mm)</th>
<th>Initial crack width (mm)</th>
<th>F_{initiation} (N)</th>
<th>M_{initiation} (kN.m)</th>
<th>K_{max} (MPa.M)</th>
<th>\sigma_{ref} (MPa)</th>
<th>\varepsilon_{ref} (%)</th>
<th>Js (kJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLAF 1</td>
<td>17</td>
<td>67</td>
<td>5.98 \times 10^4</td>
<td>21.1</td>
<td>81.4</td>
<td>345</td>
<td>0.319</td>
<td>69.7</td>
</tr>
<tr>
<td>PLAF 2</td>
<td>15.7</td>
<td>36.8</td>
<td>5.71 \times 10^4</td>
<td>20.1</td>
<td>71.0</td>
<td>328</td>
<td>0.280</td>
<td>49.2</td>
</tr>
<tr>
<td>PLAF 3</td>
<td>9.8</td>
<td>33.2</td>
<td>6.62 \times 10^4</td>
<td>23.4</td>
<td>67.0</td>
<td>382</td>
<td>0.405</td>
<td>54.1</td>
</tr>
<tr>
<td>PLAF 4</td>
<td>7.8</td>
<td>20</td>
<td>6.35 \times 10^4</td>
<td>21.1</td>
<td>54.4</td>
<td>344</td>
<td>0.318</td>
<td>31.1</td>
</tr>
</tbody>
</table>

*Table 3*

4. FINITE ELEMENT CALCULATION

The numerical study presented here is done on test PLAF 2 with the semi-elliptical fatigue crack defect and the end-of-test defect (fig. 3). The shape of this last one is described by a parametric curve in the plane of the crack.

4.1 Fatigue crack defect

The mesh, constituted by 20 nodes and 15 nodes quadratic elements, represents a quarter of the plate. It is constituted by 1076 elements, which represent approximately 5000 nodes and modelize the constant width part of the plate (200 mm width on 240 mm height, fig. 2) The material law used for this calculation is the true stress-true strain curve, associated to an
isotropic hardening model.

4.1.1 Comparison between tests and calculation

Fig. 4 and fig. 5 give the comparison between the measured and calculated values of strains and crack opening angle. As one can see on these figures, during the elastic phase and as long as the plasticity effect is low, calculation reproduces with a good agreement the experimental measurements, for global data such as $J_2$ and $J_3$ strains or local data such as the COA and $J_1$ strain (at the opposite of the defect - fig. 2). After that, the calculation under-estimates displacements and strains. This is because crack propagation, which appears after a 57 kN load, is not taken into account in this calculation.

This comparison validates the finite element model defined for this calculation.

Fig. 4: Comparison between strains

Fig. 5: Comparison of the opening angles

Fig. 6: $G$ values along the crack front at tearing initiation
4.1.2 \textit{G values along the crack front}

The calculated \textit{G} values corresponding to the crack tearing initiation load are presented along the crack front on fig. 6. We see on this figure that the maximum \textit{G} value is obtained near the plate surface ($2\theta/\pi \approx 0.15$), which agrees with the maximum observed crack propagation. The associated value is $G_{\text{max}} = 26 \text{ kJ/m}^2$, which is in good agreement with the mean $J_{0.2}$ value measured on CT specimens: $J_{0.2} = 34 \text{ kJ/m}^2$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig7}
\caption{Mesh of the final defect}
\end{figure}

4.2 \textit{End of test defect}

The defect modelized in this simulation is an approximation by a parametric curve of the crack obtained at the end of the test by thermal marking (fig. 3). The mesh, which represents a half of the plate and the non semi-elliptical defect, is constituted by 2016 elements and 9593 nodes (fig. 7). The plastic model is the same as the one used for the first calculation.

4.2.1 \textit{Comparison between test and calculation}

Fig. 8 and 9 give a comparison between experiment and calculation for the same global and local transducers. The best agreement between test and calculation is now obtained at the maximum load. This is because we have modelized the final crack. Except the last point, which is not as good as the others because the very large strains on the skin obliged us to use a low precision requirement, the accuracy of the calculation is very good and shows that the history of stresses and strains near the crack tip has a small effect on the local and global behavior.

4.2.2 \textit{G values along the crack front}

Fig. 10 shows the comparison of \textit{G} values at the end of the test. The global distribution of \textit{G} along the crack front is similar to the first presented on fig. 6 because the maximum is still obtained near the surface point of the crack. However, the difference between this point and the deepest point is more pronounced.

A comparison of the \textit{G} and the associated propagation, at the maximum propagation point

412
$(\delta a = 13 \text{ mm})$ and at the deepest point (symmetry plane of the plate - $\delta a = 4.3 \text{ mm}$) can be made on a J-$\Delta a$ diagram (fig. 11).

We see on this figure that the values of J associated to an increasing $\delta a$ can define, as first approximation, an equivalent J-Resistance curve for the semi-elliptical defect in the plate submitted to bending.

**Fig 8 : Comparison between strains**

**Fig 9 : Comparison of the opening angles**

**Fig 10 : $G$ along the crack front at maximum load**
5. CONCLUSIONS

An experimental study on the propagation of surface crack in plates subjected to an increasing bending load was presented in this article. Crack tearing initiation was investigated for semi-elliptical defects and stable growth, over 13 mm, were observed without any instability of the plates.

In addition, a numerical study was coupled to the test campaign to give us values of $J$ corresponding to the initiation load and to the end-of-test load. A good agreement was shown between this first value and the $J_{\infty}$ value measured on CT specimen. The $J$ values calculated with the end-of-test defect, which constitutes the originality of the numerical study with a non semi-elliptical defect, gives, with the initiation point, an equivalent $J$-Resistance curve for the semi-elliptical defect under bending load.

REFERENCES:


Proc. of PVP96, Fatigue and fracture, PVP Vol. 324, July 1996, Montreal - Quebec

Proceedings of ICONE 5, May 1997, Nice - France


ACKNOWLEDGEMENTS:
The authors are grateful to P. Le Delliou from EdF and P. Gilles from Framatome for the follow up of the test campaign.