Fatigue Crack Initiation and Propagation: a complete industrial process compared with experiments on industrial welded structure

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Abstract: This work is part of a global study performed, among a research partnership between three industries and a research laboratory, on the development of a method which allows to better estimate the fatigue life of welded structures (armoured vehicles, ships, Floating Production Storage Off-loading units, wrecking cranes, cars …) submitted to variable loading conditions. The complexity of these structures has lead to adopt a multi-scale approach, based on the use of finite element codes associated to various levels of modelling, going from the global cartography of damaged zones to the local calculation with cracks inserted in the models. The aim of this project is to develop an industrial process, avoiding successive re-meshing, being an efficient and easy tool to apply. It is also open enough to provide tools allowing the engineer to assess crack initiation, propagation until failure. The crack initiation is calculated by the use of a multi-axial fatigue damage criterion based on the local approach. Coupled with an extension of the Line Spring Method, multi-initiation of fatigue cracks in welds and through crack growth are then considered, in order to calculate the stress intensity factors for various loads and geometries. Furthermore, sets of tools were developed to predict crack bifurcation and take into account the influence of the loading history on fatigue crack growth, such as crack growth retardation effect, as a result of overloads. This approach is then applied to an overall aluminium welded structure experiment, which was designed to allow several cracks to initiate and propagate. Local micro-geometries and residual stresses were measured at weld toe, as needed for local stress calculations. Furthermore, a complete instrumentation and test of this welded structure allowed to determine precisely crack initiations and to follow crack propagation. The results are in good agreement with calculations and point out the industrial necessity to measure the local characteristics of welds and to control the quality for fatigue design.

1 \textbf{INTRODUCTION}

The aim of a fatigue analysis on welded complex structures is to evaluate the lifetime to initiate a crack and to propagate it, until the failure of the structure occurs. Those structures as ships, FPSO, armoured vehicles, cars, are submitted to variable amplitude loads, sometimes random, as the wave loads or the haulage on any grounds. The results of such a calculation is to help operators to take decisions for inspection, repair and maintenance process.

In this study, we present a multi-scale approach, based on the use of finite elements from the global cartography of the damaged zones to the local calculation with cracks inserted in the models. The originality of this study is to treat first the crack initiation which expends on a lot of time of the lifetime of those structures and then the crack propagation, avoiding successive re-meshing, until the failure.

Crack initiation can be calculated by several ways. The possibility to define the crack initiation period using S-N curves is available. The other way to take into account the initiation phase of a crack is to perform a calculation using the local approach, taking into account the residual stress fields, notch and plastic corrections. This methodology is then used to take into account multi-initiation of fatigue cracks as damage is accumulated during simulation (where cracks are not initiated). The crack propagation through the thickness of the plate is performed using Fracture Mechanic Theory and those of Line Spring model introduced by Rice and Levy to estimate stress intensity factors for various loads.

All these developments were performed in the software VERICRACK which is efficient and easy to carry out and sufficiently open to provide the engineer tools in order to assess the three phases of initiation, propagation of a crack and failure.
2 MODELLING METHODOLOGY

2.1 Aim of the methodology

The failure of a structural component may be explained by the presence of a crack initiation and propagation under complex and random repeated loads. These loads due to the environment induce fatigue phenomenon which depends on the joint geometry, the material microstructure, and the type and the size of the defects. The aim of the proposed methodology is to forecast crack initiation and crack growth in industrial components until failure. We shall note that, in industrial area, loads are particularly complex. These loads, which can be static or dynamic, can be represented by a combination of unitary loads or modes if the response of the component is linear elastic. But a crack represents a non-linearity and if we want to take into account the effect of the crack on the stiffness of the global structure, the crack must be introduced in a finite element model and propagated, that implies re-meshing. Re-meshing is very time consuming and can be easily used in industry only with 2D models [1]. For part-through crack, the problem is more difficult, because modelling the crack tip requires three-dimensional refined elements. Furthermore, as the crack propagates in complex geometries, under multi-axial loads, analytical solutions can not be used. Considering the component response linear elastic, the use of Line Spring method allows to take into account the stiffness variation during crack propagation without re-meshing.

2.2 Global flow chart

The global flow chart of the method to study the crack from its initiation until the failure occurs is given in Figure 1. Different subroutines using either damage determination or crack growth calculation were combined to define a software called VERICRACK.

![Flow chart of VERICRACK](image)

The first step is to determine the stress field of the component. From the knowledge of the stress field, we are able to forecast where the most damaged zones are located, and to estimate the crack path. A more precise estimation of the crack initiation duration is made. The crack of the maximum length is introduced in the global meshing and all loads are firstly applied on the fully open crack. Structure is then condensed on the crack. From the crack stiffness, we can compute the displacements of the crack nodes for a part-through (Figure 2b) or a through crack (Figure 2c), determining the loads on the crack nodes necessary to close the crack.

During the simulation, after that a crack initiates from the nodes with critical damage (Figure 2a), the Stress Intensity Factors (SIF) are calculated for the crack. Moreover, as the stiffness of the structure evolves when the crack propagates (Figure 2b), stress field is updated (stresses are redistributed) and damage is accumulated for the crack nodes that have not already initiated. This allows to take into account multi-initiation crack phenomenon for welded structures. The various steps of the above flow chart are described in the following.
2.3 Crack initiation by the local approach

The software CALEND [2] is used to evaluate the damage. It is based on a local approach, i.e. the local stresses have to be calculated. For designing welded components, it allows to take into account stress concentration factor $K_t$ to evaluate the stress tensor at the weld toe. Residual stresses can be included too. As the local stresses are often greater than the yield stress, a plastic correction has to be done (using the hardening law of Chaboche [3]). Then a fatigue stress criterion is calculated on different planes of the stress tensor (using Dang Van criterion) and damage is accumulated (using Miner’s rule and Basquin’s law) on extracted cycles (using Rainflow counting). Finally, damage is taken as the maximum damage obtained on all planes of the stress tensor and the crack initiation occurs when damage is over a critical value (for example equal to 1).

For crack location, a light version of CALEND is used without considering $K_t$ and plastic correction. It allows to quickly evaluate the damaged zones on the whole structure. Fine calculations are only carried out in the most damaged zones.

CALEND is fully integrated in VERICRACK and performs damage calculations to determine when a crack could initiate and on which nodes. When the crack propagates, damage is accumulated for all non-initiated nodes.

2.4 Crack path determination

A strong assumption has to be made on the crack path: it must be determined a-priori. Indeed the crack of maximum length has to be introduced in the global model and the SIF are calculated when the crack path is already chosen. To check this hypothesis, SIF in mode I are compared, at each increment, with SIF in mode II and in mode III in VERICRACK. So how is the crack path chosen? Considering that the crack propagates in the direction orthogonal to the maximum principal stresses [3]. This direction is obviously chosen for one load case.
and we have to check that for all load cases, the crack path is approximately the same. Moreover, automatic crack box re-meshing can be used for bi-dimensional elements but, for industrial application, it is avoided.

### 2.5 Crack propagation: part-through surface crack

The Line Spring model was introduced in 1972 by Rice and Levy \[4, 5\] to estimate stress intensity factors due to tension and bending in large plates containing part-through surface cracks. The line-spring model is based on the fact that there is a relationship between local displacements and loads at each point along the crack, noted compliance coefficients. Then, from the point of view of the plate, the surface crack is modelled as a through-crack with a continuous distribution of generalised springs connected across the line of discontinuity: the line springs. It must be noted that the opening displacements of the crack lips are function of the crack depth thanks to Tada coefficients [6].

![Figure 4: Step 1 and step 2 to prepare for VERICRACK simulation](image)

![Figure 5: Definition of neighbour nodes](image)

Two finite element calculations are needed to proceed a VERICRACK simulation (Figure 4). Firstly, the external loads \( F_{ext} \) are applied (Step 1) on the fully-cracked component and we can obtain all displacements of the crack lips \( \delta_i^\infty \), \( i \in N \) (all Nodes). Then, the stiffness \( S_{ij} \) of the cracked component is obtained (Step 2) applying unitary loads on each node \( j \), in all directions, and calculating the displacement at the node \( i \) : \( S_{ij}F_j = \delta_i \).

Then for the desired crack shape, the aim is to find loads \( \{F\} \) and displacements \( \{\delta\} \) to solve:

\[-S_{ij}F_j = \delta_i - \delta_i^\infty \quad (1)\]

One condition has to be added for part-through crack, with Tada coefficients \( A_{ij} \), depending on \( a/h \) (\( a \) : crack depth and \( h \) : plate thickness):

\[-A_{ij}F_j = \delta_i \quad (2)\]

Displacements are calculated not only on the crack nodes but also on the neighbour nodes (Figure 5) which close the crack. Indeed obtaining these displacements allow to precisely determine the stresses at each nodes for damage calculation. So, for node \( I \), stresses are calculated from displacements at neighbour node \( I \) and tip crack node, using interpolation functions of elements \( I \) to 4.

### 2.6 Through crack growth: the crack box technique

It is important to emphasize that SIF calculated with Tada coefficients are available for cracks propagating in the depth of a plate. When the crack front is straight in the depth of the plate, the Line Spring assumption can no longer be used as the crack propagates now in the longitudinal direction (see Figure 2c).
So the idea is to use the technique of sub-modelling: the displacements of nodes at the neighbourhood of the crack are used to drive a 3D sub-model of the structure, including the crack tip which is meshed using fracture mechanic elements. In order to avoid finite element calculations during VERICRACK simulation, the SIF at all the crack tip nodes of the sub-model are previously calculated with unitary displacements applied at its border. Then during VERICRACK simulation, unitary SIF in the crack box are easily combined with the displacements of the neighbour nodes to obtain SIF at each increment. The Figure 6 represents the sub-model with an unitary displacement applied, all the other nodes of the border being clamped.

![Figure 6](image)

The precision of this method depends on the distance between the crack line and the neighbour nodes used to drive the crack box. If we use the first line of neighbour nodes, errors on SIF are between 7 to 13 %, depending of the crack length. But when we use the second line of neighbour nodes, errors on SIF are between 1 to 5 %. Errors can also depend on the sub-model refinement and on the type of elements chosen for the global model (linear or quadratic). In the future, the aim of this technique is to include in the sub-model geometry details (like welds).

2.7 Crack propagation rate

The crack growth is controlled by the Paris law, using the SIF range calculated either from Tada equations or from J-integral calculations in the crack box. It can be corrected using the SIF necessary to open the crack (K_{op}) to determine the effective range of stress intensity factor \( \Delta K_{eff} \). The value of K_{op} can be fixed, or determined by using Elber’s equation or calculated with a Dugdale-Barenblatt model [7].

3 EXPERIMENTAL TESTS

3.1 Description

This approach is applied to an overall aluminium welded component (Figure 7). The plate thickness is equal to 10 mm. A complete set of strain gauges was used to determine precisely the stress field in the component and the time when a crack initiates. The gauges were placed at 10 mm from the weld toes. Furthermore, dye penetrant was used to detect crack initiation. The back floor of the component was bolted on the ground. An hydraulic jack was placed on the sides of the component to load 4 weld beads, allowing so 8 possible cracks at weld toes. The stress ratio of the applied load is R=0.1 and the maximum load is 15000 N.

3.2 Results

Three cracks have initiated: weld toes 3 and 2 on the right side (Figure 8) and weld toe 3 on the left side. The first crack is initiated on weld toe 3 at the left side (between 50000 and 280000 cycles) and then on the right side (between 300000 and 400000 cycles). Later, a crack is initiated on the weld toe 2 at the right side (between 400000 and 550000 cycles). The crack was difficult to observe when its length was less than 100 mm because a multi-initiation phenomenon seems to be the origin of the crack initiation. The case of the left side was different; when the crack was observed at 280000 cycles, its length was about 250 mm, whereas the evolution of gauges seems to give 50000 cycles. This crack did not propagate through the plate thickness at the weld toe, in contrary to other cracks, but it has followed the HAZ. So all calculations on crack growth will be carried out on cracks on the right side.

3.3 Weld toe geometry

The difference between the left side and the right side may be explained considering local parameters (residual stresses and weld toe radius). Residual stresses were measured at the surface and at 100 µm depth by X-ray diffraction. Measurements at 100 µm depth were performed to avoid the superficial residual stresses introduced by wire brushing after welding. Local geometry of the weld toe was measured using CAGEP [7].
Profile recordings were performed thanks to a laser and a CCD camera and were used to obtain the radius distribution along the weld toes (Figure 9). Results for all weld toes are presented in Table 1. The value of transverse stress at 10 mm from the weld toe and the mean radius value can explain why only 3 cracks have initiated. More precise calculations are done in the following.

Figure 7 : Description of the component and experimental boundary conditions (dimensions in mm)

Figure 8 : Picture of crack on weld toes 2 and 3 (right side)

4 NUMERICAL CALCULATIONS

4.1 Crack initiation

In order to determine the crack initiation, it is necessary to calculate the local stress at the weld toe, which depends on the residual stresses and the local radius. The global model used is a shell modelling of the structure, with linear displacement field elements. 3D calculations were performed using either a 3D sub-model or a 2D sub-model in plane strain, driven by the global model displacements (Figure 10). The plane strain assumption can be done so that the crack initiates in the middle of the weld. The 2D modelling was used because it is enough simple to perform calculations for mean radius varying between 0.2 and 1.2 mm. Results are shown in Figure 11 and compared with experimental results. It shows that a good prediction is given considering the residual stresses at 100 µm depth and the mean radius of the weld toe.
Table 1: Transverse stress at 10 mm from the weld toe and weld toe mean radius

<table>
<thead>
<tr>
<th>Side</th>
<th>Weld toe</th>
<th>Transverse stress at 10 mm (MPa) (FEM)</th>
<th>Mean radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>weld toe 1</td>
<td>82</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>weld toe 2</td>
<td>78</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>weld toe 3</td>
<td>95</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>weld toe 4</td>
<td>50</td>
<td>1.23</td>
</tr>
<tr>
<td>Right</td>
<td>weld toe 1</td>
<td>82</td>
<td>1.26</td>
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<td></td>
<td>weld toe 2</td>
<td>78</td>
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<tr>
<td></td>
<td>weld toe 4</td>
<td>50</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Figure 9: weld profile measurement (left) and radius distribution for weld toe 1 on the right side (right)

4.2 Crack growth

Crack initiation and growth are then simulated in VERICRACK, for the right side of the component. For crack initiation, the calculations are based on experimental material data and local approach with mean radius. For crack growth, experimental crack growth of MIG welded joints is used.

Different hypothesis were done for the simulation with VERICRACK:

- a crack initiates when the damage accumulation is equal to 1;
- when the damage accumulation is equal to 1 at a node, a crack of 1 mm depth is introduced;
- when the stress in the ligament is greater than the Yield Stress at a node: the crack is supposed to have fully grown in the thickness of the plate;
- when the crack front is almost straight, the crack can propagate thanks to the crack box;
- there is a competition between crack growth using fracture mechanics and using damage accumulation at nodes;
- the radius of the weld toe 2 is the minimum value of radii instead of mean radius.

Results are shown in Figure 12 where the crack shape is presented during simulation. Simulations are compared with experimental results for crack 3 (weld toe 3) and crack 2 (weld toe 2). With the assumption made, the agreement seems to be good but many sensitivity tests have to be carried out.
5 CONCLUSION

In this paper, a global methodology was introduced to forecast crack initiation and propagation without re-meshing. As the behaviour is globally linear, the principle of superposition has been used. So all calculations are made using unitary loads (for static response) or modes (for dynamic response) that are combined in the VERICRACK code. Furthermore, this principle is also used to drive a three-dimensional sub-model of the component including the crack tip in order to determine the SIF for through crack, as the Line Spring method can only be used for part-through surface cracks. So this program can determine crack initiation in welds and make part-through and through crack grow in a 3D shell structure. This method was applied on an aluminium welded structure designed to make various crack initiate. Results of crack initiation life are in good agreement with experiments if we consider the local geometry of the weld toes (radius) and the residual stress at 100 μm depth. Results of crack growth simulation are close to experiments, considering different hypothesis, knowing that it is very sensitive to parameters like the size of the initial flaw and the Paris law parameters. The aim of such experiments is to determine the appropriate parameters to predict the lifetime of a component until it fails.

6 ACKNOWLEDGMENTS

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7 REFERENCES

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