Crack Box Technique for Fatigue Design of Welded Structures

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Abstract :. In this paper we introduce a methodology and results obtained thanks a research partnership between Bureau Veritas (Paris La Défense, France), CETIM (Senlis, France), NEXTER System and LaMI. In this collaboration, we have developed a complete multi-scale tool called VERICRACK allowing to calculate crack initiation and crack propagation in industrial welded structures submitted to complex loading environment. In this context, we will present the use of a Crack Box Technique to calculate the Stress Intensity Factor (SIF) and the crack path in linear elasticity for an overall aluminium welded structure test. This test has been designed to allow several cracks to initiate and propagate. A phenomenon of crack growth deceleration and arrest has been observed and explained thanks to simulations. So, 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, the importance to take into account the flexibility of the overall structure due to cracks in order to calculate the crack growth. In fact, the propagation of cracks modifies the global stress field and finally, the necessity to couple local and global approaches to simulate crack propagation.

1 INTRODUCTION

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 on the type and size of the defects. The aim of the proposed methodology is to forecast crack initiation and crack growth in industrial components until failure.

This work is the continuation of the study introduced in fatigue design conference 2005 [1]. This study is part of a global work 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 that will be first introduced. In this paper we present the methodology used to take into account variable loads and to particularly focus on the crack box technique, which has been extended in VERICRACK program. This program is used to calculate an aluminium welded structure test already introduced in the former paper [1] but extended here. This work will be considered as a validation of our methodology.

2 A MULTI-SCALE APPROACH FOR FATIGUE CRACK INITIATION

The approach developed to design the welded structures, taking into account the fatigue life, is based on a multi-scale approach, as the fatigue phenomenon is very local, whereas the phenomenon generating it is global. For fatigue calculation purposes, it is necessary to determine the stresses in the entire structure (global stresses) before modelling local geometries to obtain the local stresses, which is the major parameter to calculate the fatigue damage.

2.1 Determination of global stresses

The load spectrum due to the use of the vehicle or the ships has to be known. As an example, for a vehicle, it is defined by the various grounds on which it has to move on, the speed and the number of kilometers per year which are associated to them. Loads are determined thanks to global dynamic system modelling. As an example, a rigid body representing the vehicle with its mass and inertia whereas suspension components are precisely modelled. The interaction between the wheels and the ground are taken into account so that it is possible to obtain the internal loads on the structure (the frame). To simulate the behaviour of the structure, the variable loads are then used in static or dynamic analysis on finite element representation of the structure. An example of this methodology is illustrated in Figure 1.

Driving process induces no-proportional multi-axial random loads on the structure. Those loads give either a quasi-static or dynamic response of the chassis. So a complete calculation method has been developed allowing to take into account the real response of the structure. The equation below gives the expression of stress versus time [2]:

$$\{\sigma(\mathrm{t})\} = \lfloor Q_{qs}^{\sigma} \rfloor \{f(t)\} + \lfloor Q_{dyn}^{\sigma} \rfloor \{q(t) - q(t;static)\} \tag{1}$$

$$\text{with : } m.\ddot{q}(t)+2.\xi.\sqrt{k.m}.\dot{q}(t)+k.q(t)=\Phi_{dyn}^{U}.f(t) \tag{2}$$

The first term $\lfloor Q_{qs}^{\sigma} \rfloor \{f(t)\}$ represents the quasi-static part of the stress with $\lfloor Q_{qs}^{\sigma} \rfloor$ the matrix of quasi-static modes of the structure, calculated by finite element model of the structure by a series of unit loads calculation; the vector $\{f(t)\}$ represents the history of the various components of the load, coming from dynamic simulation of the vehicle. The second term $\lfloor Q_{dyn}^{\sigma} \rfloor \{q(t)-q(t;static)\}$ represents the dynamic part of the stress; $\lfloor Q_{dyn}^{\sigma} \rfloor$ represents the matrix of dynamic modes of the structure calculated on finite element model by modal analysis; the term $q(t)$ represents the response of each mode whereas $q(t;static)$ represents the quasi-static part of the response of each mode; it allows to fit the dynamic response from the quasi-static part already took into account in the quasi-static response of the structure. Those two terms are calculated by numerical integration of the modal dynamic equation (2). Then the global response can be calculated at each node of the structure.

2.2 Looking for hot spots

In order to determine the region where there is likelihood to have a crack initiation, a damage criterion, based on the local approach is then calculated at each finite element node. This damage criterion will be introduced in the next paragraph. It allows to obtain a cartography of damage on the entire structure so that the engineer can focus on the region of hot spots. Then, a precise modelling of the local stresses and the local damage is carried out.

2.3 Determination of local stresses and damage

To determine the local stresses, it is necessary to determine the local geometry of the welded structure and to represent it in another model which is a sub-model of the global model. Several degrees of sub-modelling may be necessary to obtain the stresses where the crack can initiate, generally at the weld toe (see Figure 3). The displacements of the global model are then used to drive the displacements of the nodes at the border between the global and the local models. The software CALEND [8] is used to evaluate the damage. For welded components design, it allows to take into account stress concentration factor K_t to evaluate the stress tensor at the weld toe. Residual stresses have to 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 [8]). Then a fatigue stress criterion is calculated on different planes of the stress tensor (using Dang Van criterion [8]) and damage is accumulated (using Miner's rule and Basquin's law [1]) on extracted cycles (using Rainflow counting [8]). Finally, the damage is taken as the maximum damage obtained on all planes of the stress tensor and the crack initiation occurs when damage is greater than a critical value.

2.4 Experimental results

Former results [1] have shown that in the overall aluminium welded component presented in Figure 3, the weld toe quality (i.e. the radius) has to be measured precisely, thanks to a laser and a CCD camera [7], in order to explain why the different cracks have initiated or not on joints submitted to the same loads. A good correlation was observed between calculations and experiments. This is necessary because crack propagation depends on damage cumulation all along the weld bead as it will be developed in the next chapter.

3 A MULTI-SCALE APPROACH FOR FATIGUE CRACK GROWTH

The global flow chart of the methodology developed to take into account crack propagation in welded structure until failure is illustrated in Figure 2. All steps are explained in the followings. This methodology is applicable for global shell finite element modelling.

3.1 Determination of crack path

The crack path must be determined *a-priori.* Indeed we will see in the next paragraph that we only insert the crack of maximum length in the global model and the Stress Intensity Factors (SIF) have to be calculated when the crack path is already chosen. Globally, we have observed in our structure, and it is generally admitted, that crack propagates in the direction orthogonal to the maximum principal stresses. To check this assumption, SIF in mode I, are compared, at each increment, with SIF in mode II and in mode III obtained by VERICRACK program. When this is not the case, particularly when the crack length is very important and influences widely the stiffness of the whole structure, it may be necessary to use automatic crack box re-meshing techniques.

3.2 Insertion of crack in a structure

A crack represents a non-linearity in a structure and the complexity of considering crack growth comes from the difficulty to define where the structure is not affected by the crack. Generally, we consider the crack to be either under constrained stress field (load) or under constrained displacement field. But in a complex structure, it’s a high degree of hypothesis to consider being in one of the both cases. So, calculating crack propagation in a structure might be done by taking into account the effect of this crack on the stiffness of the global structure. But we consider that loads are not affected in the presence of the crack. Generally, the crack is inserted in a finite element model and the crack growth implies re-meshing. Re-meshing is very time consuming and can be easily used in industrial structures only with 2D models [3]. For part-through crack, the problem is more difficult, because modelling the crack tip requires three-dimensional refined elements and these elements have to be connected to the whole structure submitted to a complex environnement. Furthermore, as the crack propagates in complex geometries, under multi-axial loads, analytical solutions can not be used. Considering the component response as linear elastic, the use of Line Spring method allows to take into account the stiffness variation during crack propagation without re-meshing.

3.3 Crack growth calculation

As for damage calculation where submodel are needed, it is necessary for crack growth assessment to create submodels. Moreover, some calculations are needed to prepare the VERICRACK simulation and the response of the structure has to be computed on the fully cracked structure.

3.3.1 Calculation needed before simulation

To perform a VERICRACK simulation, the crack is inserted in the global model, according to the determined crack path. Then two calculations are done:

- Unitary loads are applied on each node of the structure and displacement of all nodes needed are recorded. No external load is applied. That allows to determine the flexibility of the crack. The nodes which are used may the nodes of the crack (A), the nodes in the vicinity of the crack (B) and the nodes around a virtual gauge (C).

- Displacement of each quasi-static and dynamic modes of the fully cracked structure are recorded on nodes A, B and C. Cautiousness is necessary when considering dynamic analyses as dynamic response depends on the flexibility due to the crack (it tends to decrease the frequency of the modes).

It is to be noted that various loads can be applied in VERICRACK, from sinusoidal constant amplitude loads to sequences of blocs and temporal loads. The response of the structure is calculated from the combination of the response of all loads. Use of unitary loads or modes is particularly interesting because it allows to limit the amount of data necessary to describe the loads and afterwards it will allow to obtain the stress intensity factors by combination.

3.3.2 First step : close the crack

The first step of a VERICRACK simulation consists in calculating the loads to be applied on each node of the crack to close it and to obtain the response of the uncracked structure. It has to be noted that this approach is completely linear so that it is not possible to take into account non-linear response of the structure when the crack is large. Under static conditions, we obtain the deformation of the whole structure without crack under each external static load. In mode-based dynamic consideration, not only the modes are modified, but also the response of each mode. And the response for the fully cracked structure may be very different from the response of the uncracked structure. But in some case, the calculation can be performed, particularly for spectrum loads and when the crack shifts the frequency of the modes by only a few percent. The error made in the mode-based dynamic response of the uncracked structure depends on the gap of frequencies between the uncracked and the fully cracked structure. When this gap is large, a modal analysis must be performed with and without the crack. When the assumption that the mode-based response of the structure is not widely affected by the crack growth can't be made, it is necessary to perform multiple modal analysis (and mode-based response calculation) for different crack length. Another way that deserve to be studied is the use of substructuring techniques, considering a substructure of the mesh zone around the crack.

3.3.3 Second step : calculate the crack initiation lifetime

The crack initiation lifetime is calculated thanks to software CALEND [8]. As the global model is far from being enough refined to estimate the local stresses, a K_t , stress concentration factor is applied on the global model to obtain the local stresses. So at each node of the global model, a K_t is considered. It has to be noted that residual stresses can be included too. When a crack has initiated, we consider an initial defect in the depth of the plate.

3.3.4 Third step : calculate the stress intensity factors

Three steps or phenomena of crack growth can be observed in experiments (see Figure 5a) in welded structures as shown in the followings. These three phenomena need a multi-scale approach to better estimate the Stress Intensity Factors of cracks. In fact, displacements of nodes (B) in the vicinity of the crack are used to drive the border nodes of sub-models. This is illustrated in the Figure 7. The three steps are:

- Multi-initiation at the weld toe : the damage cumulation is calculated at each node of the crack during crack growth simulation. To obtain the local stresses, either a stress concentration factor is used, or a submodel (which can be in 2D or 3D media) is driven by the global nodes affected by the flexibility induced by the crack,
- Crack growth in the depth of shells – i.e. part-through cracks. We use the Line Spring model which 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 Tada coefficients [6] allow us to calculate the stress intensity factors in the global model but SIF are affected by the joint geometry, especially when the crack length is small. In this case it is either possible to use 3D sub modelling of cracks driven by border nodes (with crack box shown in Figure 6-1a) or to determine a stress factor correction in 2D analysis (with crack box shown in Figure 6-4). In the latter case, Figure 5d illustrates this correction factor named K_G in a T-joint of the aluminium experiment component. This factor tends to one when the crack depth increases.
- Large crack growth or crack propagation in base metal – i.e. through cracks. The Tada coefficients can no longer be used and it is necessary to consider the use of Crack Box Technique (as shown in Figure 6-1b,c and Figure 6-2). An automatic crack box generation tool has been developed and allows to mesh part-through cracks and particularly through cracks in welded joints (with modelling of the weld bead). Either very local nodes can drive the submodel and in this case it represents a part of the weld bead. But in some case we have to use farther border nodes and a whole bead modelling has to be done. In this case, automatic mesh done by extrusion and tie of different generated meshes allows to calculate SIF in complex geometries.

In order to limit calculations on the submodel, information of the SIF are condensed on the border nodes of the local model by the determination of a SIF matrix for unitary displacements imposed on the border nodes (B) - $\left[K_{local}\right]^{u_{B,dof}}$, in each degree of freedom (dof) as written in equation (3). Hence, stress intensity factors for each unitary static or dynamic mode can be obtained by combination of this matrix and displacement of nodes (B) : $\left[Q^K_{load}\right]$. Finally, by combining $\left[Q^K_{load}\right]$ with the static or dynamic loads, we obtain the SIF $\left\{K_i(\mathrm{t})\right\}$ for the mode $i \in \{1,2,3\}$ as a function of time (see equation (4)) :

$$\left[Q^K_{load}\right] = \sum_{dof} \left[Q^u_{load}\right]_{u_{B,dof}} . \left[K_{local}\right]^{u_{B,dof}} \quad (3)$$

$$\left\{K_i(\mathrm{t})\right\} = \sum_{static\_modes} \left[Q^K_{qs}\right]\left\{f(t)\right\} + \sum_{dynamic\_modes} \left[Q^K_{dyn}\right]\left\{q(t) - q(t;static)\right\} \quad (4)$$

3.4 Results on an industrial structure

The aluminium component is used to point out the necessity to consider the flexibility induced by the crack length. It has been observed in the test that the crack had a lot of difficulty to go through the plate thickness even when the crack length was greater than 500 mm whereas the plate thickness is only 10 mm. Thanks to VERICRACK, we have performed a crack growth simulation and results indicate that the crack will remain a part-through crack until failure. In Figure 4a, the displacement of the fully crack specimen is calculated. two cracks have been inserted in the model (crack A and crack B). After having calculated the stiffness of the fully cracked structure, the crack simulation results are shown in Figure 4b. As observed in the test, crack A initiates before crack B.

Multi-initiation phenomenon is governing the crack growth along the weld bead. But through the plate, SIF are calculated. Results are shown in Figure 5b. What we could see is that there is obviously a delay between crack B and crack A. Moreover the SIF in mode I decreases when the depth of the crack increases. A phenomenon of crack growth deceleration and arrest at about 90% of the plate thickness which has been observed is explained thanks to these simulations. Generally, the crack is considered to be either under imposed displacement field or under imposed stress field. But in a real structure, when the crack length is particularly wide in comparison with the size of the structure, such an assumption can't be done.

Figure 5c compares results obtained by two dimensional automatic re-meshing calculations with or without taking into account the weld bead, under imposed stress and displacement fields. Those results are also compared with a VERICRACK simulation. Considering imposed stress is very penalizing because the crack would have quickly gone through the plate thickness and that is not the case because the overall structure can retain the crack zone. Results of VERICRACK simulation are under results obtained with the two assumptions and that points out the necessity to determine crack growth along the weld bead. Lastly, the use of crack box technique with or without weld bead has allowed to determine the K_G (Figure 5d) factor which can be used by VERICRACK to better estimate the propagation of non deep crack.

4 CONCLUSION

The global methodology developed is based on multi-scale approaches to determine crack initiation and crack propagation in industrial welded structures. Results on an aluminium structure are in good agreement with experiments and the whole study points out :

- the industrial necessity to measure the local characteristics of welds and to control the quality for fatigue design.
- the importance to take into account the flexibility due to cracks in order to calculate the crack growth. In fact, the propagation of cracks modifies the global stress field.
- and finally, the necessity to couple local and global approaches to simulate crack propagation.

5 ACKNOWLEDGMENTS

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7 FIGURES AND TABLES

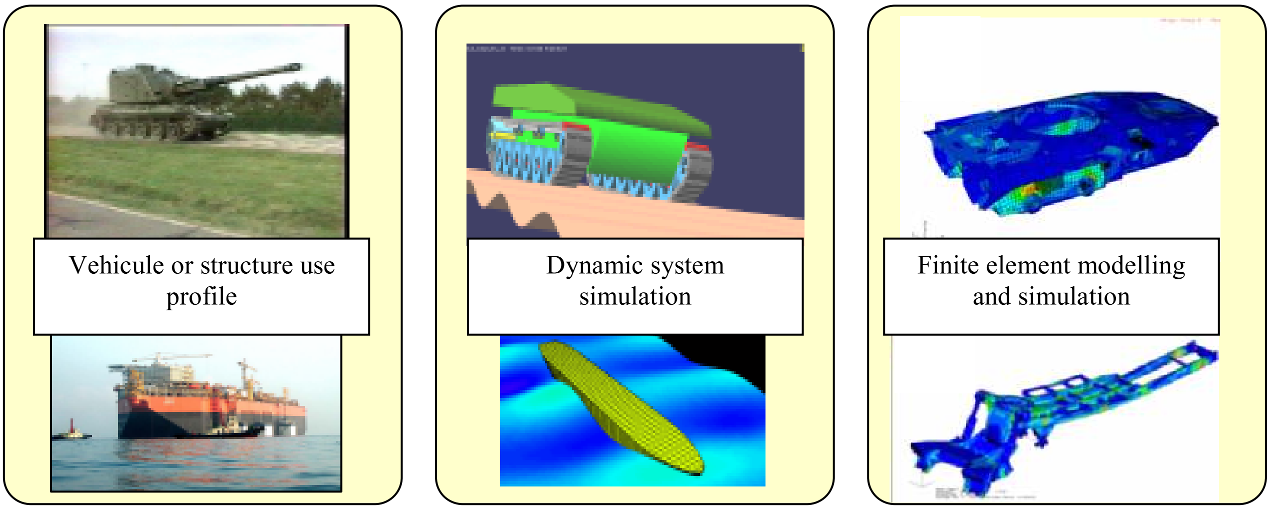

Figure 1 : data and simulation needed before damage and crack propagation calculations

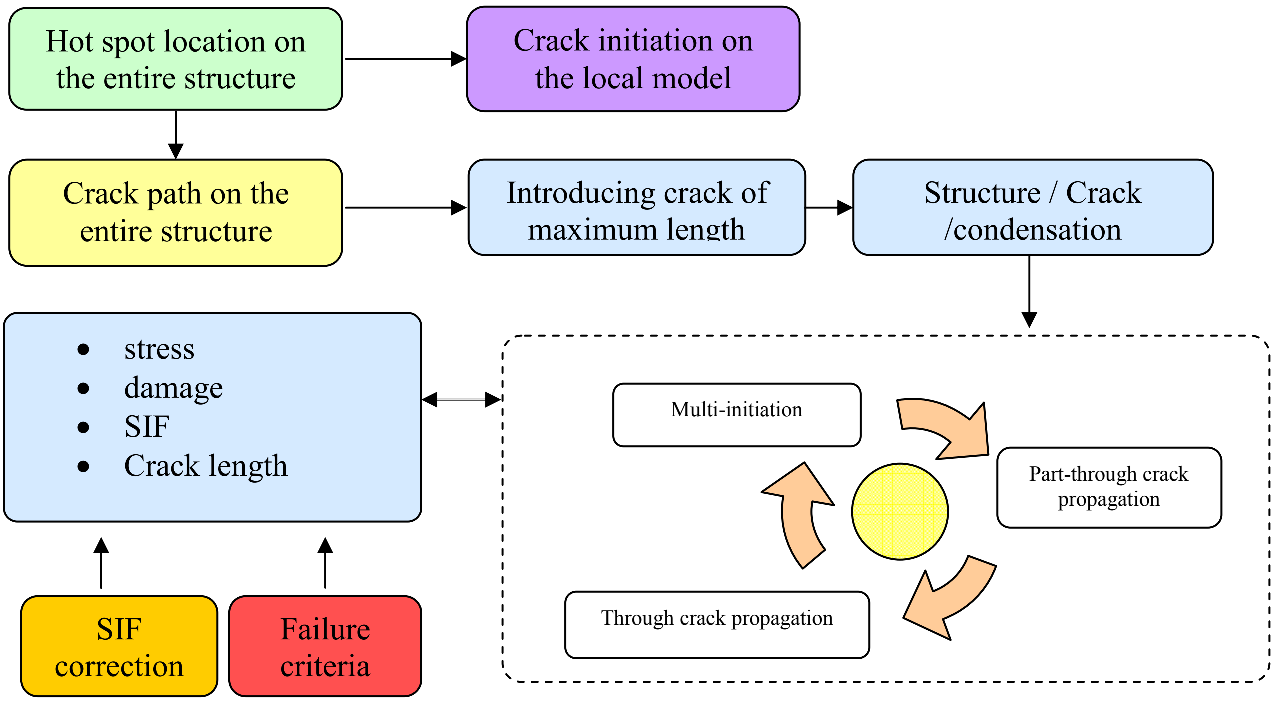

Figure 2 : flow chart of the entire methodology

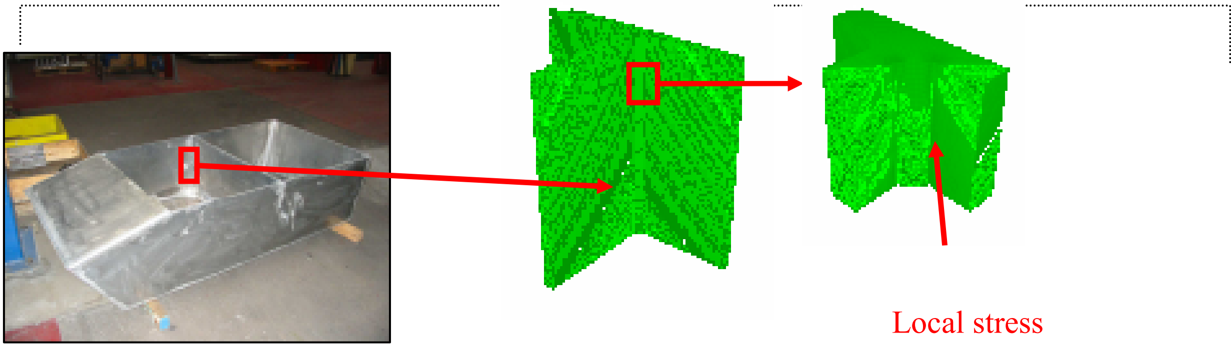

Figure 3 : mesh of refined local zone to estimate local stresses and damage

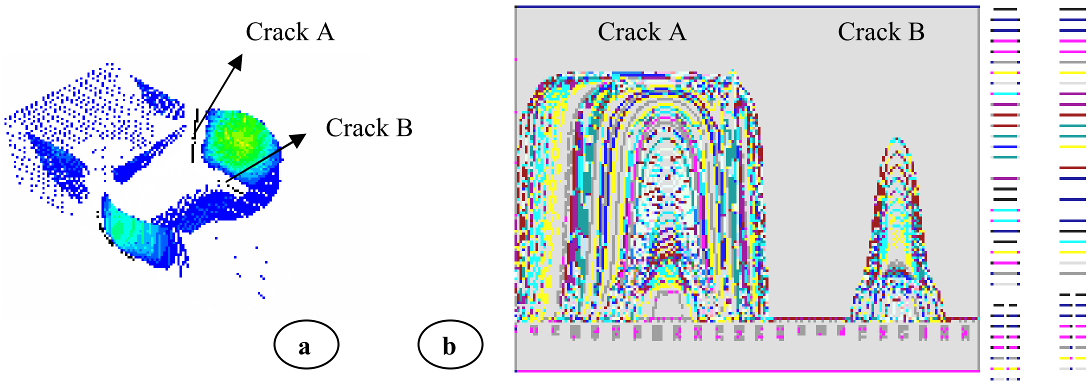

Figure 4 : a : structure displacement when fully cracked, b : crack growth in the aluminum welded structure (numerical results)

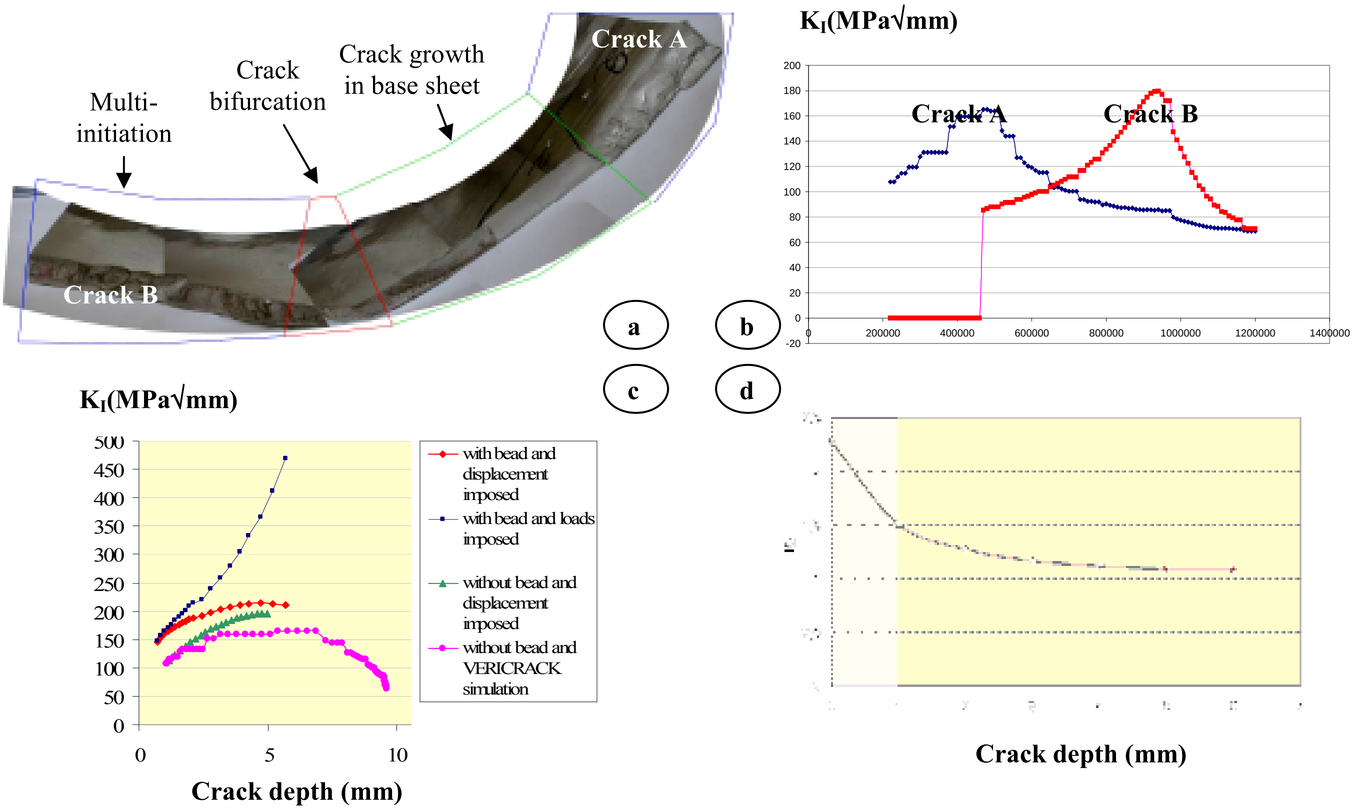

Figure 5 : crack growth in the aluminium welded structure (a. experimental results, b. K_I at the center of each crack, c. influence of weld bead and comparison between VERICRACK and imposed displacement or stress fields, d. SIF correction to take into account weld bead)

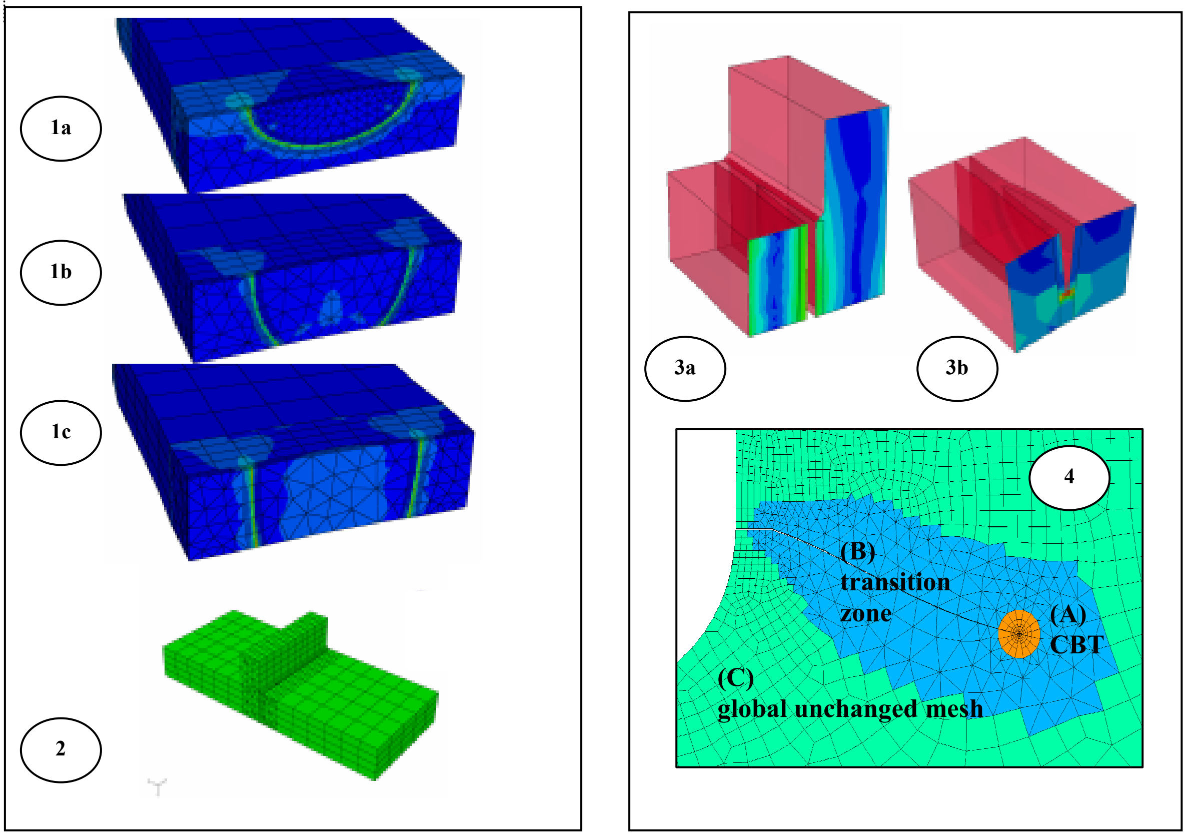

Figure 6 : automatic 2D-3D Crack Box Technique (CBT)

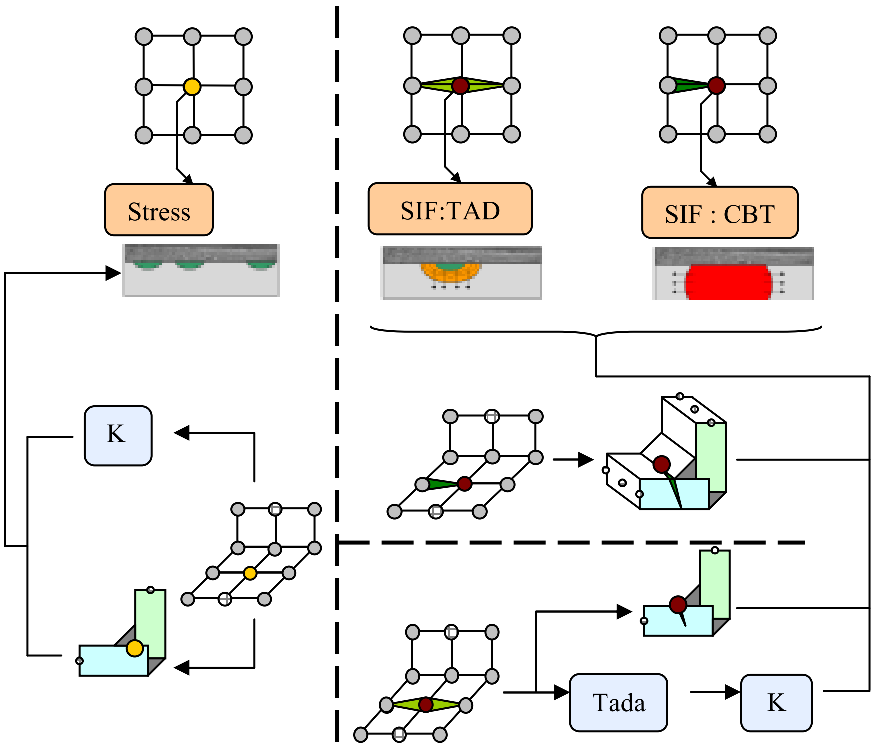

Figure 7 : local stress and SIF calculation from global displacement data