Application of the structural stress method for fatigue design of welded structures

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Abstract A structural stress multiaxial computing method for the fatigue assessment of welded structures is presented. This approach is based on the use of a local equivalent stress, or design stress, derived from the shear stress and the concomitant hydrostatic pressure previously proposed by Dang Van. Associated with a specific shell finite element meshing methodology, the method is successfully used to assess the fatigue resistance of welded structures of complex geometry and with multiaxial loading. The approach also allows the role of the welding process upon the fatigue behaviour to be addressed either by a better description of the influence of the local residual stress state.

1 INTRODUCTION

Although extensive work has already been done, the prediction of the fatigue strength of welded structures is still a widely open subject. Engineers in design offices do not dispose of reliable and accurate methods to evaluate the fatigue life of such structures, with regard to the results provided by the modern structural calculation methods (Finite Element Method). If some propositions exist, they are most of the time inapplicable so that, in practice, engineers use simplified methods of poor accuracy. For example, for the calculation of metallic bridges, a design stress S is evaluated from the nominal stress derived from a beam calculation; then the fatigue life is estimated from S-N curves given by the EUROCODE III established experimentally by class of structural details. One can imagine that if there are a few changes in the geometry or the loading mode of these details, one can be out of the limits covered by the fatigue tests and therefore have erroneous predictions.

Beside the global approaches as the EUROCODE III, several proposals called « local approaches » exist [1]. Among them, one can distinguish those which study the crack initiation and those which consider that microcracks are already formed and only take into account their propagation. The latter uses the Paris law, or derivative laws, which appears to be well founded on the recognised concepts of the Fracture Mechanics, but are nevertheless not so easy to apply on actual structures. As noted recently by D.L. Mc Dowell [2], the first cracks initiated in fatigue cannot be reduced to plane cracks simply characterised by their length a, submitted to simple loading in mode I in a regime coming under the linear elasticity. This makes the calculation of the parameters which are supposed to govern the propagation extremely difficult. The transcription of some parameters which are justified in Fracture Mechanics to fatigue is still poorly founded and therefore ambiguous for a structure. It is the case for instance of the J parameter and the J derived parameter usually invoked to correlate fatigue testing results on specimens. For all these reasons the local approaches based on crack initiation are still preferred by engineers.

As for welded structures, the structural method developed for the offshore industry in the 70' and the 80's (AWS and API codes) and particularly following Radenkovic's proposals [3], is without any doubt the one which allows the most interesting industrial calculations. In this method, the welded connection is characterised by a design stress S, more or less clearly defined, and which better describes the local stress at the «Hot Spot». The latter is obtained either by the extrapolation of strain values measured by strain gauges close to the Hot Spot of the structure or by a thin shell finite element calculation. S is a «geometrical» stress which can be deduced from the nominal stress using a Stress Concentration Factor obtained by experiment and parametric formula. This stress is used to predict the fatigue tests on welded tubular nodes submitted to various service loading by means of a unique S-N line.

It is this idea which is considered in the following, giving a clearer interpretation of the design stress based on the Dang Van classical fatigue criterion.

2 DANG VAN FATIGUE CRITERION

This model is presented in detail in [4]; at the same time, different structural applications are given. In this model the *material is considered as a heterogeneous structure* submitted to cyclic loading, and that fatigue corresponds to limit of possibility of elastic shakedown. Thanks to this assumption, local stabilised stress state σ(t) can be calculated (see [4]). Local shear τ(t) and hydrostatic tension p(t), derived from σ(t) were chosen as pertinent parameters; the fatigue criterion is a linear relation between these quantities:

$$F(\sigma) \equiv \tau + a.p - b \geq 0$$

where a and b are material constants that can be determined by two simple types of fatigue experiments; b for instance corresponds to the fatigue limit in simple shear.

General application of this criterion requires the consideration of the plane on which the set (τ(t),p(t)) is a «maximum» relative to the criterion. This computation can be done as following: the maximum local shear at any time t is given by

$$\tau(t) = Tresca(\sigma(t)) = \underset{I,J}{Max}\left|\sigma_I(t) - \sigma_J(t)\right|$$

The stresses σ_I (t), σ_J (t) are the principal stresses at time t. The quantity that quantifies the risk of fatigue occurrence is defined by the parameter *d* is calculated over a period such that:

$$d = \underset{t}{Max} \frac{\tau(t)}{b - a.p(t)}$$

It is also frequent in some applications to use *the concept of local equivalent stress* for a life duration N_i defined by

$$\tau_{0,i} = \tau + a_i.p$$

It is observed however that for high cycle fatigue ($N > 2.10^5$) a_i depends weakly on N_i so that, taking $a_i \approx a$, we define the local equivalent stress by

$$\tau_0 = \tau + a.p$$

As a final remark, it must be noticed that the local stress in the stabilized state is chosen in preference to plastic strain or dissipative energy, which is also contained in the elastic shakedown hypothesis. The main reasons are that these latter quantities are not easy to evaluate since, in high cycle fatigue, plastic deformations are heterogeneous and occur only in some misoriented grains. Moreover, the increases per cycle of theses quantities are so tiny that such ways of estimating them lead to big errors and great uncertainties in predicting the fatigue resistance.

3 FATIGUE ASSESSMENT OF WELDED STRUCTURES

3.1 A structural approach

Current practice in welded structure design is based on the use S-N curves, hot spot stress or structural stress. These approaches are useful to industrial applications in many cases. However, they are difficult to handle in order to take into account multiaxial loadings, which strongly influence the fatigue strength of welded structures. To overcome this difficulty, we come back to the structural approach with a clear definition of the design stress which can be transposed to multiaxial structural problems.

The classical introduction of the design stress is based on the extrapolation of far field stresses with unclear rules. In order to clarify the description of this design stress we propose an approach deriving from an analogy with the concepts which are at the origin of the Fracture Mechanics. Actually, it is known that the mechanical state in the highly damaged crack tip zone, called the process zone, is inaccessible by the usual mechanics of solids. In this zone, the material is neither really continuous nor homogeneous and the local strains are not small. Nevertheless, the stress solution obtained from linear homogeneous and isotropic elasticity in small strains allows the correct description of the mechanical state outside the process zone. Although it is erroneous at the vicinity of the crack tip, it makes sense in terms of an asymptotic solution which allows the correct control and the interpretation of the phenomena produced in the process zone. Likewise, we will look for a way to build the asymptotic solution which allows the correct control and interpretation of the phenomena produced in the critical zone of the weld. For that purpose we adopt an approach *which combines testing and calculations* with meshing rules taking into account the local rigidity due to the weld instead of the local geometry of the weld itself (as it is the case in Fracture Mechanics, where the actual geometry of the crack tip is not taken into account) which is a very hazardous data. Therefore, the fatigue design can be based on a structural stress calculation from a finite element analysis. On this basis we can establish design rules for welded structures [5, 7] with a structural approach and a unique S-N curve where S is a local equivalent stress defined from τ and p at the Hot Spot as described in the next paragraph.

3.2 Computing procedure and applications

Some computational methods applicable to the prediction of fatigue strength have been proposed by different researchers [1, 6]. In the automotive industry, J.L. Fayard et al. [5] developed with PSA Peugeot Citroen an efficient numerical tool to evaluate the asymptotic mechanical field which defines precisely the design stress state and allows the prediction of the fatigue strength of continuous arc-welded structures. In most of the cases, components are usually made of metal sheets of approximately 2 to 5 mm thick joined by automatic metal active gas (MAG) welding. Thus, the thin shell theory was considered to be the most appropriate calculation method to solve the fatigue life prediction problem of automotive welded structures.

However, in a thin shell finite element model, sheets are described by their mean surfaces. The outstanding difficulty in using such meshes lies in the modeling of the mean surface intersection. In fact, this zone exhibits 3D behavior, whereas a thin shell model only produces biaxial stresses. Moreover, at the intersection of thin shells, where hot spots commonly appear, the stress gradient can be rather steep, so that stress calculations are very sensitive to the mesh size. It is therefore necessary to define a meshing methodology which can be systematically applied to any welded connection. On this basis, a design rule was established [5, 7, 8] as shown in Fig. 1.

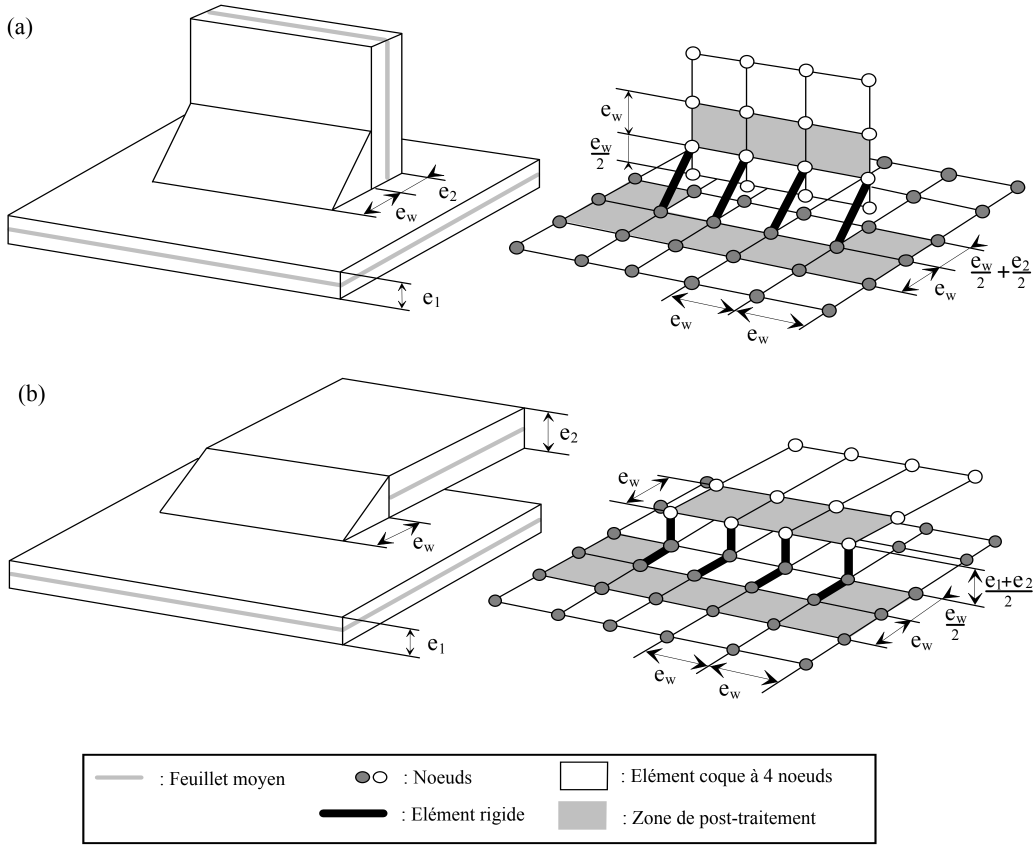

Fig. 1. Meshing rules for arc-welded joints. The geometry on the left hand side is associated to the thin shell modeling on the right hand side : (a) for fillet weld; (b) for overlap welded joint.

The first idea was to reproduce as precisely as possible the local rigidity induced by /eld to the joint, which modifies the local stress distribution. The other principal idea that supports the meshing strategy was to simulate the stress flow from one sheet to another throughout the weld. For that purpose, rigid body elements were used to link the two shells. The «good rule», associated with a design stress representing faithfully the fatigue phenomenon and an appropriated failure criterion, is the one that allows the interpretation of all the experimental results with the minimum scatter. Thus, the size of the elements at the intersection area has been particularly defined such that the geometrical stress is calculated at the weld toe and the weld root, precisely where cracks commonly appear, without interpolation at nodes.

Note that the proposed computational method differs from Dong's method [9] based on equivalent structural stress approach in order to reduce the element size influence.

Actually, the <u>failure criterion N</u> has been defined very carefully in order to be transposable to any situation, being independent of the geometry of the structure and of the loading mode. More precisely, the critical crack <u>size is defined as the size from which the crack leaves the influence of the local effects</u>, which are at the origin of crack nucleation. This size is characterized by a significant increase in the crack growth rate. It was observed that the crack critical size for the tested specimens corresponds roughly to a crack depth of 0.5e (e is the thickness of the sheet) and to a 30% decrease of the signal of a strain gauge situated in the vicinity of the hot spot.

Concerning the calculations, in order to take into account the multiaxiality of the stress, the parameter τ_0 derived from Dang Van's proposal was used. In this case, one obtains the following relationship at 10^6 cycles for steels:

$$\tau_0 = \tau + 0.33.p$$

as shown in Fig. 2. Each point of the figure represents the mean value of the fatigue strength at 10^6 cycles. Figure 3 shows the τ_0-N design curve obtained from more than 200 fatigue tests on elementary structures with different geometry, different materials and different loading modes inducing the multiaxial state at the hot spots. This unique fatigue design curve is limited in its upper part by the plastic yield limit of the material.

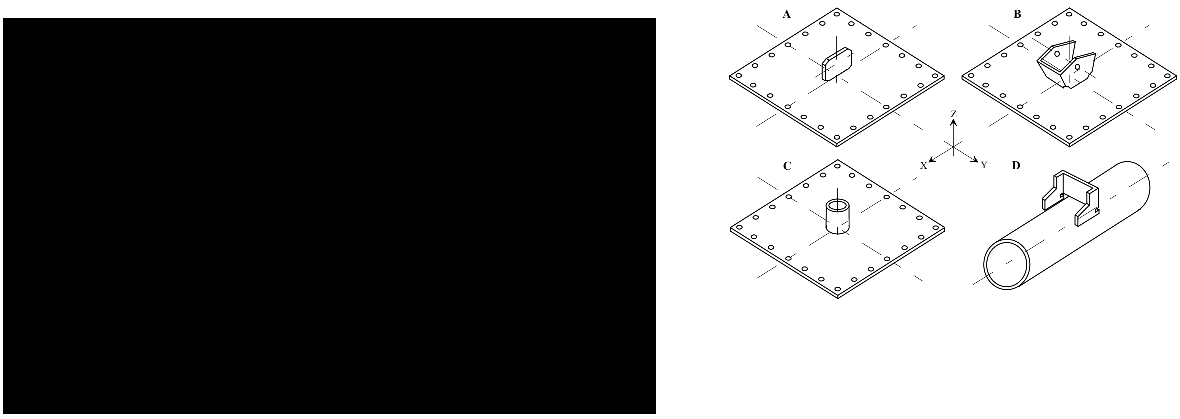

Fig. 2. Mean fatigue strength at 10^6 cycles obtained on elementary arc-welded structures.

Fig. 3. S-N line for continuous arc-welded steel structures where S = τ_0. The highest curve corresponds to high strength steel (σ_y = 450 MPa), the lower curve to low strength steel (σ_y = 170 MPa).

An application to industrial structures was carried out to predict fatigue resistance. For instance, Fig. 4 summarizes the application of the local approach to predict the fatigue resistance of an engine sub-frame made of a metal sheets joined by continuous welds submitted to out of phase multiaxial loading. For an easier interpretation by the design office, the calculated value of the criterion displayed graphically is the quantity Cd=τ-(τ_0-αp)/ τ_0-αp, negative values are in the safe side. The failure happens exactly at the predicted locus and fatigue limit can be evaluated.

As the metal sheets are thin, the engineering residual stresses (i.e. the mean value of residual stresses on a representative volume element whose dimension is of the order of the sheet thickness) can be neglected in most of the considered welded thin sheet structures like in the example above.

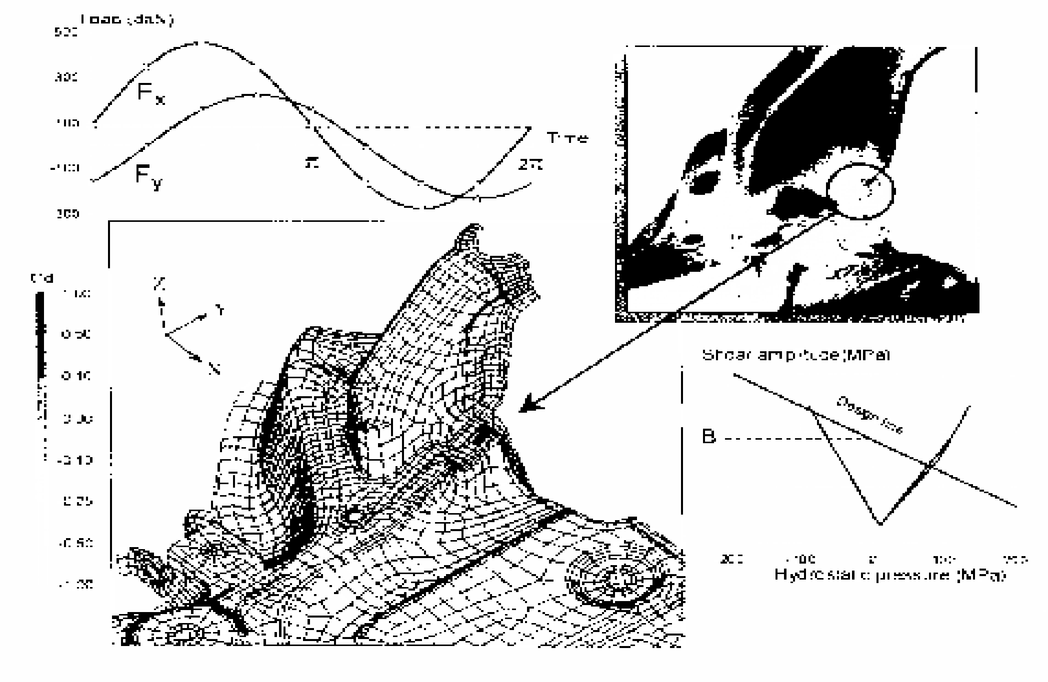

Fig. 4. Application of the local multiaxial approach to assess fatigue resistance of an engine sub-frame undergoing multiaxial out of phase loading. (Courtesy of PSA)

There are however exceptions: for example, some structures are very rigid, which favors the onset of «long range» residual stresses. More precisely, the characteristic dimension of the volume where these stresses are important is much greater than the thickness of the metal sheet. In that case, the proposed methodology gives more accurate prediction if residual stresses are taken into account as it will be shown in the next paragraph.

4 OPTIMISATION OF THE WELDING PROCESS

When thick sheets are welded, one can expect high remaining residual stresses as well as a large scatter in local geometry. The proposed structural approach allows the study of the influence of these parameters using the fatigue law determined by PSA.

Researchers of Institut de Soudure (I.S.) have used Dang Van's fatigue approach to interpret fatigue tests done on fillet welds in order to characterise the quality of the weld (which can be described by the smoothness of the weld toe) and the influence of residual stresses on the fatigue resistance, as the classical existing approaches give only a poor description of these factors. It is not possible for instance to correlate quantitatively in an intrinsic way the local geometry and the residual stresses distribution to the fatigue behaviour. The use of a local approach allows better physical interpretation [10].

In order to be able to take into account the effect of residual stresses and the weld geometry, a systematic research program was undertaken by the I.S. Fillet welds obtained by one pass or by three passes were simulated for S355 steel with a bainitic transformation at cooling. Two sides one-pass fillet welds were first considered and tested. Numerical simulations to evaluate the corresponding residual stress distributions were performed by using the SYSWELD software. Experimental X-ray measurements were carried out to verify the validity (near the surface only) of the prediction. One-side fillet welds carried out in three passes were also examined. The welded pieces were 20mm thick and were free of any clamping.

Figure 5 shows all the experimental and calculation fatigue results in the Dang Van's diagram. Each point corresponds to the fatigue limit loading defined as 2.10^6 cycles without failure with a probability of 50%. PSA's fatigue criterion at 1 million cycles is also plotted. One can observe that the experiments of the I.S. can be interpreted with a very good accuracy using this fatigue criterion if and only if the residual stresses are taken into account in the simulation, Fig. 5.

In spite of the complexity of the physical phenomena, the application of a local approach, which takes into account the calculated residual stresses as well as the quality of the weld, allows the prediction of the fatigue resistance with quite a good accuracy using PSA fatigue criterion. Thus, the optimisation of the welding process can be investigated efficiently.

(a)

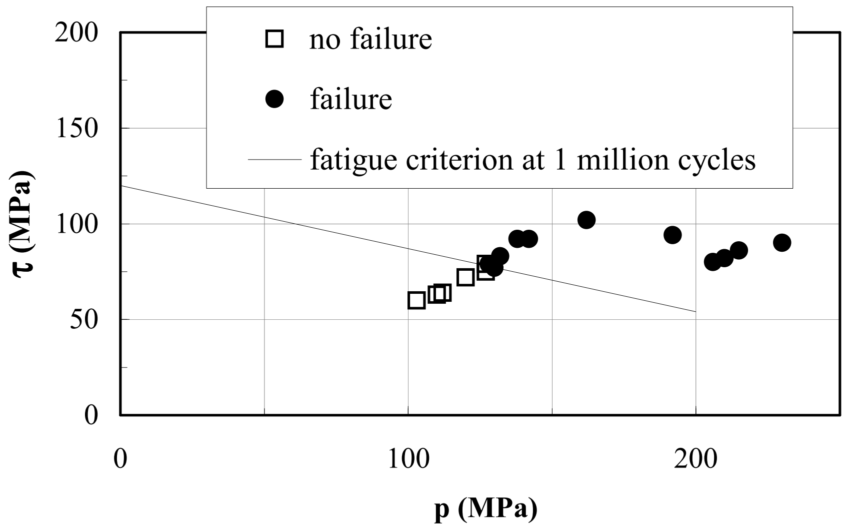

Fig. 5. I.S. test results in the Dang Van's diagram with calculated residual stresses compared to PSA's fatigue limits

5 CONCLUSION

Nowadays, fatigue assessments of welded structures are based on the use of S-N curves, S defined from the nominal or the geometrical stress. These methods are in reality only applicable when the geometry or the loading are simple. Many mechanical structures usually have complex shapes and they have to undergo complex multiaxial loading. This is particularly true for automotive welded structures and fatigue assessment of such specimens is easier using multiaxial approaches. It is the reason which motivated the research which was carried out in order to propose another type of fatigue computational method. The proposed structural approach presented in this paper is based on the use of a mutiaxial parameter derived from Dang van's fatigue criterion. The use of this design parameter allows a very good prediction of complex automotive thin sheet welded structures. The method was also successfully applied to thicker welded structures encountered in railways industries. Furthermore, experiments done by the Institut de Soudure in order to quantify the quality of the weld and the influence of the residual stresses which have a great importance on the fatigue resistance, have been predicted with quite a good accuracy. The application of the method for predicting the fatigue resistance of a great number of mechanical components and structures, which present big differences in geometry and loaded by different ways, is very encouraging for the development of a general methodology for the fatigue assessment of welded structures.

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