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Assessment of welded structures by a local multiaxial fatigue approach

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A new local multiaxial computing method for the fatigue assessment of welded structures is presented. This approach is based on the use of an equivalent stress derived from the multiaxial fatigue criterion proposed by Dang Van for plain machined specimens. Application to fillet welds allows a better description of the influence of local geometries and residual stress states. These factors are related to the weld process and the quality of the weld. This approach, associated with definite shell finite element meshing rules in order to take account of the increase of local rigidity introduced by the weld, is also successfully used to assess the fatigue resistance of welded automotive structures.

Keywords fatigue of welded structures; multiaxial computing methods.

$V(M)$ = representative volume element surrounding a point M

$\Sigma(M)$ = macroscopic stress tensor at point M

$\sigma(m)$ = mesoscopic stress tensor at a point m belonging to $V(M)$

$\rho(m)$ = local residual stress characterizing the local stress in $V(M)$

$\tau(t)$ = maximum mesoscopic shear at time t

$p(t)$ = hydrostatic tension at time t

d = danger of fatigue failure

C_d = normalized coefficient of danger of fatigue failure

$\tau_{0,i}$ = local equivalent stress for a life duration N_i

τ_0 = local equivalent stress

R = loading ratio in fatigue

s = standard deviation

INTRODUCTION

The fatigue strength assessment of welded structures is in general based on the nominal stress concept associated with $S-N$ design curves obtained from uniaxial tests. These curves are valid for a particular geometry corresponding to a design category. The other popular concepts are the hot spot stress and the structural stress used in association with the corresponding design curves. All these concepts are easily applicable when the structure is from the same shape and category and supports the same kind of loading as the test specimen that was used to derive the $S-N$ curves. If it is not the case, for instance if the loading is not uniaxial, one must be very

careful. This situation is in fact very often encountered on welded structures so that the study of loadings which may generate locally varying multiaxial stress and strain states is of primary importance for industrial applications. Curiously however, little research is carried out in this field, probably because of the difficulties that must be overcome in testing as well as in stress or strain computations.

As fatigue is a local phenomenon, it is tempting to try a local approach for studying the fatigue of welded structures, as is done in the classical fatigue of plain machined specimens. A good review of strength assessment of non-welded and welded structures based on local parameters is presented by D. Radaj.¹ These parameters, which are generally derived from uniaxial approaches, are not easy to use in real applications for predicting quantitative fatigue behaviour of industrial

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structures. Variable multiaxial stress states are often encountered. Then, in principle, the use of a multiaxial criterion is more adequate even if the external loading is uniaxial. This situation finds its origin in the presence of residual stresses induced by the welding process, which are difficult to evaluate. Nowadays efficient computational methods or sophisticated test techniques exist which allow confident estimation of the residual stress state. The onset of these stresses is strongly dependent on the welding process, the thickness of the metal sheets to be joined, the clamping conditions, etc. In general, if the sheets to be joined are thin, the level of residual stresses is considered to be low, and they are often neglected. On the contrary, if a panel is welded on a thick sheet, one can expect important residual stresses in the vicinity of the weld toe due to the rigidity of the sheet, which hinders the deformation induced by the high temperature gradients. These local residual stresses are tri-dimensional by nature; if they are superposed to a uniaxial varying stress one obtains a varying tri-dimensional stress state with varying principal directions. Amongst others, this fact could be at the origin of the observed scatter in nominal $S-N$ curves in relation to the previous parameters: the uniaxial treatment alone is *a priori* not sufficient, as one has to take account of the real local multiaxial stress state which is dependent on these previous factors.

If the welded structure is made of thin metal sheets, the residual stress is usually neglected (for the reasons explained later) in practical applications shown hereafter, and the multiaxial stress state is in most cases induced by the service loadings (see for instance the example of a car subframe presented at the end). In that case we have also to use a multiaxial criterion for predicting its fatigue resistance.

These two situations will be discussed in what follows.

LOCAL MULTIAXIAL FATIGUE CRITERION: APPLICATION TO WELDED STRUCTURES

Current practice in weld design (see for instance Radaj¹) is based on the use of concepts such as $S-N$ curves, hot spot stress and structural stress. These approaches are useful to industrial applications in many cases. However they are difficult to handle in order to take account of multiaxial loadings or of local geometries which strongly influence the life duration of welded structures. Engineers in design offices do not dispose at the present time of reliable and sufficiently accurate methods for predicting the fatigue life, with regard to the fitness of the results obtained by modern finite element methods. Moreover, as was mentioned previously, in many cases the residual stress pattern in the weld toe has a great influence on the fatigue resistance by inducing three-

dimensional effects which cannot be described in an intrinsic way with a uniaxial criterion. By intrinsic, we mean that this way of calculating must be transposable to other situations, geometries or residual stress distributions.

For some years now important work has been carried out in France to promote new approaches. The Institut de Soudure for instance has undertaken research to assess a local approach which takes account of a multiaxial stress field induced by the presence of residual stresses due to the welding process. This approach is based on the use of a multiaxial fatigue computation method, recalled hereafter, and which has stood the test of experience on plain structures (Dang Van criterion²). It is widely used in automotive industries in France to evaluate the fatigue resistance of plain structures such as a crankshaft, wheels, springs, and others.

The assessment of this method by Institut de Soudure³ necessitates:

- 1 The evaluation of the residual stress induced by the welding process. This was carried out in two ways, first by using the Sysweld software for simulating the welding process, and second, by an experimental approach to confirm the computational prediction at the surface. Let us recall that computation gives the whole field of residual stress when X-ray measurements only give confident results near the surface.
- 2 Performance of fatigue experiments on structures.
- 3 Interpretation of the obtained results with the help of the new local approach.

Automotive industries are also very much interested in developing a computational method for evaluating the fatigue resistance of continuous welded structures, which are very extensively used in cars. In order to be as general as possible, it is necessary to be able to take account of multiaxial service loadings. A new method was thus developed by J. L. Fayard *et al.*,⁴⁻⁶ which has already proved its efficiency on structural applications. As in the previous approach proposed by the Institut de Soudure, this method is based on the use of a local equivalent stress derived from Dang Van's multiaxial criterion.

DANG VAN CLASSICAL FATIGUE CRITERION

This model is presented in detail in Dang Van;² at the same time, different structural applications are given.

The theoretical foundation of this model is based on an elastic shakedown hypothesis at scales of material description near the fatigue limit which corresponds classically to 10^6-10^7 life duration. In particular, two main scales are introduced as represented in Fig. 1: the macroscopic scale of the order of millimetres (meshing

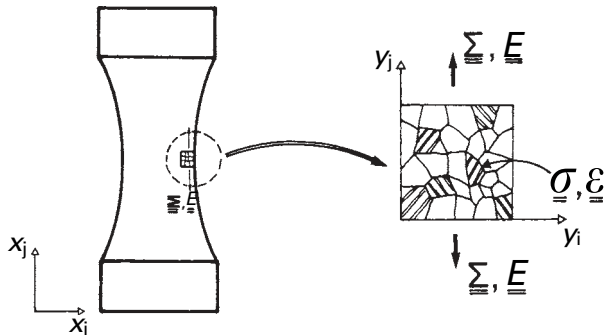


Fig. 1 The macroscopic and the local scale of material description.

size in finite element model calculations or typical size of a strain gauge) which corresponds to the usual scale of engineers (scale 1); a local scale (scale 2) which is a subdivision of the former (for instance the grain size).

The material is supposed to be homogeneous at scale 1, but it is not at scale 2, so that the macroscopic stress $\underline{\Sigma}(M)$ in the representative volume element (RVE) $V(M)$ surrounding M differs from the local stress $\underline{\sigma}(m)$ at any point m of $V(M)$.

The general relation between these quantities at any time t of the loading cycle is:

$$\underline{\sigma}(m, t) = \underline{\Sigma}(M, t) + \underline{\rho}(m, t) \quad (1)$$

where $\underline{\rho}(m, t)$, is the local residual stress tensor which characterizes the local stress in $V(M)$. The tensor $\underline{\rho}$ corresponds to the local fluctuation at the point m of the stress tensor in comparison to mean value $\underline{\Sigma}$ in $V(M)$ induced by inhomogeneous inelastic deformation. If the imposed loading is low (i.e. near the fatigue limit), it is reasonable to suppose that elastic shakedown should occur. This hypothesis means that after a certain number of loading cycles, $\underline{\rho}(m)$ becomes independent of t (Melan's theorem and its extension by Mandel *et al.* as recalled in Ref. [2] and that the local plasticity criterion is then no longer violated; the whole stabilized stress path $\underline{\sigma}(m, t)$ is then contained in the local limit elastic domain represented by a hypersurface in the stress space. If von Mises yield function is chosen, this surface is a hypersphere S centred on $\underline{\rho}(m)$ in the deviatoric stress space. This property provides a way to estimate the local stress cycle in the parts which may suffer fatigue without knowing precisely the local constitutive equation. We observe that the maximum modulus of the local shear corresponds to a point situation on a hypersurface. Another important consequence of this model, in particular for welding applications presented hereafter, is that $\underline{\rho}(m)$ does not depend on the deviatoric part of the macroscopic residual stress; only the hydrostatic part corresponding to its trace intervenes.

Once the local stress cycle in the critical locus is

characterized, one has to choose a criterion. Local shear $\tau(t)$ and hydrostatic tension $p(t)$ were chosen as pertinent parameters; the fatigue criterion is a linear relation between these quantities;

$$F(\sigma) \equiv \tau + ap - b \geq 0 \quad (2)$$

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 one to consider the plane on which the set $(\tau(t), p(t))$ 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

$$\tau(t) = \text{Tresca}(\underline{\sigma}(t)) = \text{Max}_{I, J} |\sigma_I(t) - \sigma_J(t)| \quad (3)$$

The stresses $\sigma_I(t)$, $\sigma_J(t)$ are the principal stresses at time t . The parameter that quantifies the danger of fatigue occurrence is defined by:

$$d = \text{Max}_t \frac{\tau(t)}{b - ap(t)} \quad (4)$$

where d is calculated over a period, and the maximum is to be taken over the cycle.

It is also frequent in the applications carried out later to use the 'concept of local equivalent stress' for a life duration N_i defined by

$$\tau_{0,i} = \tau + a_i p \quad (5)$$

For the fatigue limit $\tau_{0,i}$ corresponds to material constant b , but is different from b in general because $\tau_{0,i}$ and a_i depend on N_i . It is observed however, that a_i (the slope of the fatigue line in the τ - p diagram) depends weakly on N_i so that, taking $a_i = a$, we define the local equivalent stress by

$$\tau_0 = \tau + ap \quad (6)$$

Very often τ and p are maximum at the same time, so that is sufficient in some applications presented hereafter to plot τ_{\max} versus p_{\max} .

APPLICATION OF THE LOCAL MULTIAXIAL APPROACH TO FILLET WELDS

The previous local approach was used by researchers at the Institut de Soudure³ to interpret fatigue tests carried out on fillet welds. It is well known that the quality of the weld (which can be characterized by the smoothness of the weld toe) and the residual stress state have a great influence on the fatigue resistance. The classical existing approaches give only a poor description of these factors as it is not possible to correlate quantitatively in an intrinsic way the local geometry and the residual stress

distribution to the fatigue behaviour. The use of a local approach allows better physical interpretation.

The first applications were done without taking account of residual stresses.

The tested structures were submitted to transversal in-plane loading. In order to determine the fatigue limit by the local approach, it was necessary to evaluate the local stress cycles at every hot spot by numerical simulation, taking account of the characteristics of the welded structure, of the quality of the weld (characterized by the radius of the weld toe), and the nominal loading. For these calculations, homogeneous elastic behaviour was assumed (a weld region can show some heterogeneity, on inelastic properties, but few relative discrepancies in elastic properties). Let us recall that depending on the type of loading, these hot spots are situated at different loci, which should be predicted by the local criterion.

It was then necessary to determine experimentally the fatigue resistance of tested structures on which no stress relaxation treatment was carried out. It was observed that at each time, the critical crack initiated precisely at the region predicted by the local criterion. The results of these tests are represented in Fig. 2. One can observe that the separation line between black points (fracture) and white points (corresponding to no rupture) can be approximated by a straight line as predicted by the proposed local criterion. The maximum discrepancy occurs for the tests corresponding to $R = 0.5$.

However, if residual stresses are taken into account, a supplementary residual hydrostatic term intervenes so that the previous result is only approximate. Complementary work was carried out in order to estimate the correct fatigue limit line by testing specimens on which a stress relaxation treatment had been carried out. The results obtained correspond roughly to a translation of the previous fatigue limit line of 50 MPa in the direction of hydrostatic tension.

In order to be able to take account of residual stress induced by the welding process, a systematic research program was undertaken by the Institut de Soudure. Some results have already been presented in Ref. [3]. Fillet welds obtained by one pass or by three passes were simulated for a S355 steel with a bainitic transformation at cooling.

Two sides of 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. The residual stress distribution obtained is not symmetric as the thermal history is not the same on both sides: the weld is carried out first on one side, then on the other side. The joining radius of the weld, which is related to the

quality of welding, is about 0.5 mm. The thickness of the two pieces to be joined are: 10 mm for the web vertical member and 20 mm for the flange horizontal member. The pieces were welded without any clamping. The fatigue tests consisted of four-point bending ($R = 0.1$) and transverse bending ($R = -1$). Let us notice that in these two cases the hot spot loci are different and correspond to the points A (respectively the first weld), A' (second weld) for $R = 0.1$ and B (first weld), B' (second weld) for $R = -1$ (see Fig. 3). At these points, the residual hydrostatic tension $p = \text{trace}(\sigma_{\text{residual}})/3$ are different at the different locations; at A this value is 100 MPa; at A' it is 66 MPa; the corresponding value at B and B' are around 83 and 33 MPa. The asymmetry observed on the side where the first main crack is initiated corresponds to the asymmetry of the hydrostatic residual stress distribution.

One-sided fillet welds carried out in three passes were also examined. The welded pieces were 20 mm thick and were free of any clamping.

The results of the tests are shown in Fig. 4. In these figures fatigue limit loading defined as 2×10^6 cycles without failure with a probability of 50% is interpreted in the $(\tau-p)$ diagram. In Fig. 4, all experimental fatigue results of fillet welds are plotted, taking account of the geometric qualities of the tested zones as well as the residual stress state induced by the different welding processes. One can draw a very clear line defining the fatigue limit (which is similar to the fatigue limit resulting from test results of specimens in which a stress relaxation treatment was carried out as discussed previously), in contrast to Fig. 5 where the same tests are examined without taking account of the residual stresses.

Thus, in spite of the complexity of the physical phenomena, if one takes account of the residual stress in the local multiaxial criterion, 95% of the tested specimens are situated on the correct side of the fatigue limit in the $\tau-p$ diagram: The locus of failure as well as the fatigue limit can be predicted.

APPLICATION OF THE MULTIAXIAL FATIGUE CRITERION IN THE AUTOMOTIVE INDUSTRY

Welding is one of the most important manufacturing processes in the automotive industries: spot welding is very much used for assembling body panels whereas continuous welds are used for different car parts such as the suspension arm, engine subframe, suspension under structure and cross-member.

Computational methods to predict fatigue resistance of such structures have been proposed by different researchers; in particular in France J. L. Fayard *et al.* have developed a new efficient tool for analysing automotive structures obtained by continuous welding.⁴⁻⁶

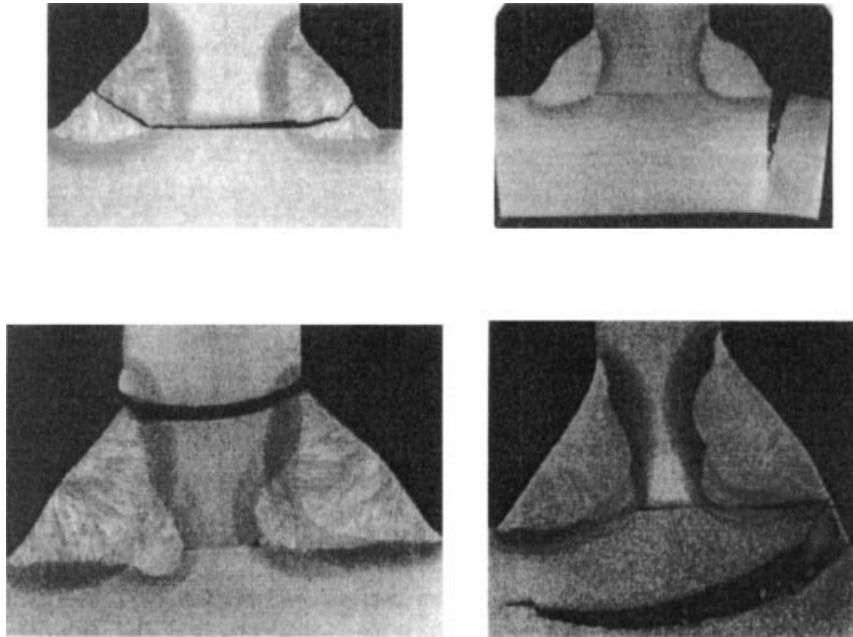
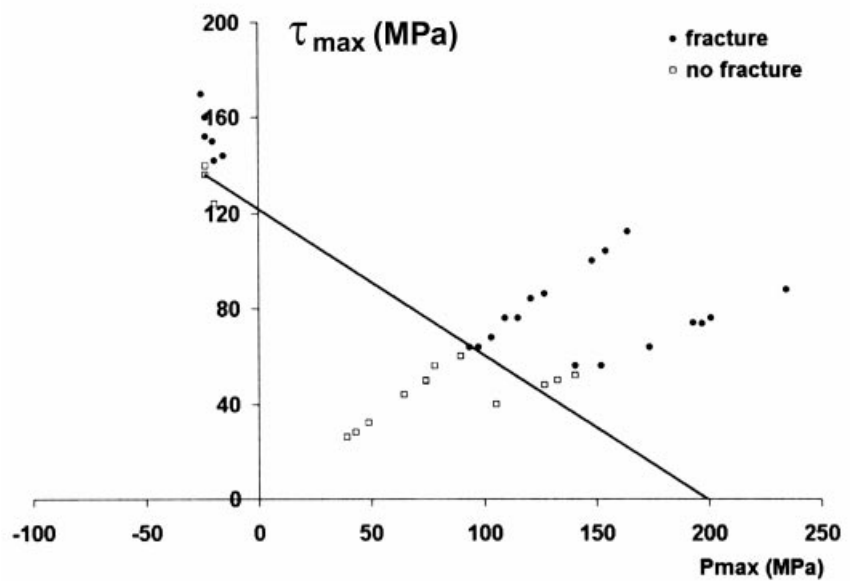


Fig. 2 Macrographs of the cracking initiation locus of fillet welds corresponding to different loading conditions and application of multiaxial criterion.



This method is based on a structural approach combining testing and shell finite element model calculations with defined meshing rules (detailed for instance in Ref. [5] that take into account the increase of local rigidity induced by the weld. In this way, no special consideration is given to the local geometry (in contrast to the previous section); the main assumption is that continuous welds are of the same type, and thus of the same quality, from one component to another and therefore induce comparable local effects. This hypothesis is

justified since, in an industrial context, the welding procedures are strictly defined in order to guarantee the quality of the weld. Therefore, fatigue design can be based on a stress calculation using a shell model because the metal sheets are thin. For the same reason engineering residual stress (i.e. the mean value of residual stress on a representative volume element whose dimension is of the order of the thickness of the sheet) is not taken into account since it is negligible by definition. The structural stress is the stress at the node situated at

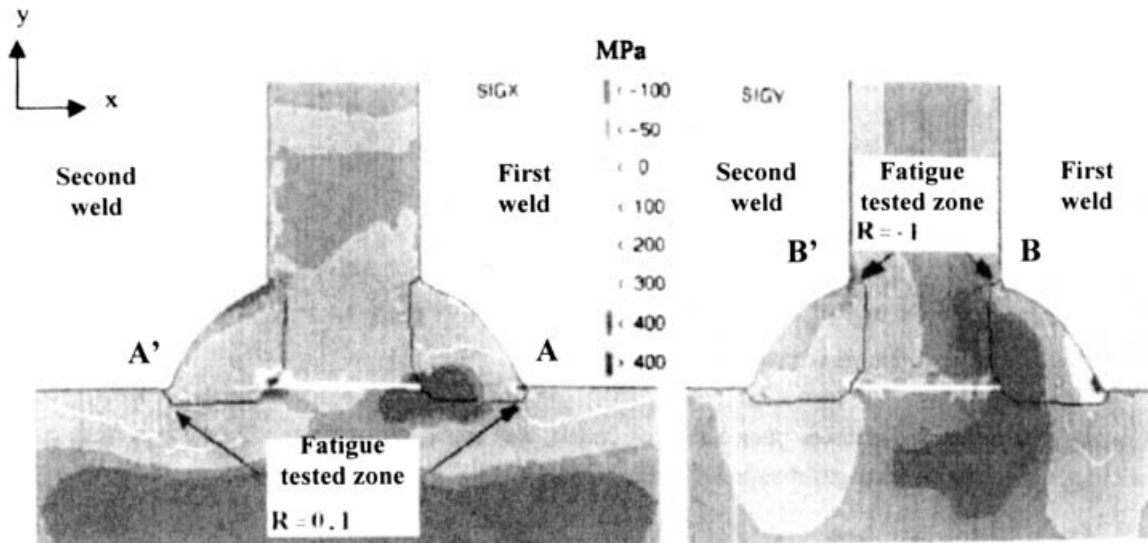


Fig. 3 Residual stress distribution induced by the welding process (symmetric welds).

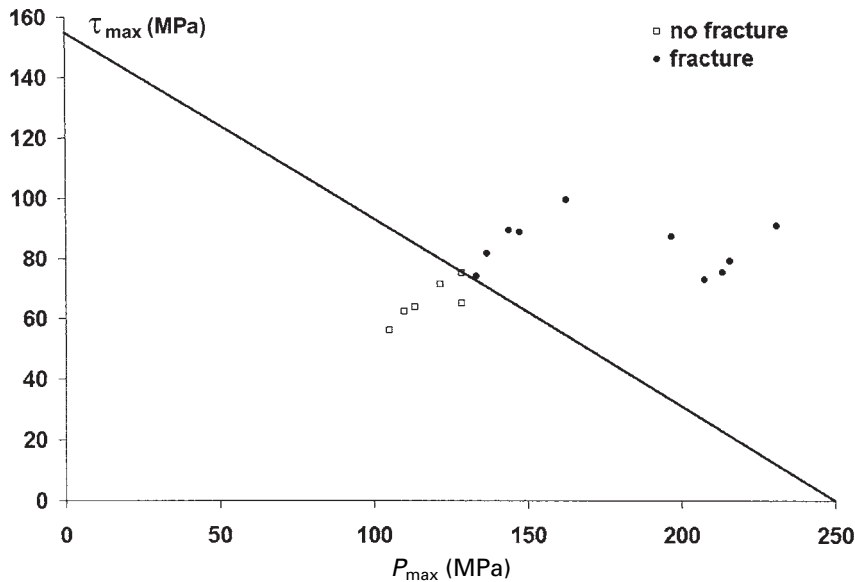


Fig. 4 Application of the multiaxial fatigue criterion for fillet welds, taking account of the influence of local residual stresses.

the weld toe. The 'good' rule is the one that allows the interpretation of all the experimental results with the minimum scatter. On this basis, a design rule for welded components used in the automotive industry was established, see Fayard *et al.*^{4,5} These components are generally made by joining metal sheets of approximately 2 mm thickness by automatic Metal Active Gaz (MAG) welding. The meshing rules which must reproduce as accurately as possible the local rigidity induced by the weld which modifies the local stress distribution are given in Refs [4,5]. The fatigue tests were performed at different loading conditions on the elementary structures made from low and high strength steel sheets shown in Fig. 6.

Various situations including continuous weld zones and weld ends with different multiaxial states were studied. Many of these test results can be interpreted using the principal stress amplitude analysis calculated by the recommended procedure. They correspond to loading situations which generate essentially bending or tension at the critical point. When the load state is of a different nature (torsion for instance) the principal stress amplitude is no longer a pertinent parameter, since the value of the corresponding critical principal stress is then completely different. To overcome this difficulty, the parameter τ_0 deriving from Dang Van's proposal was used. Figure 7 shows the S-N line for more than 200

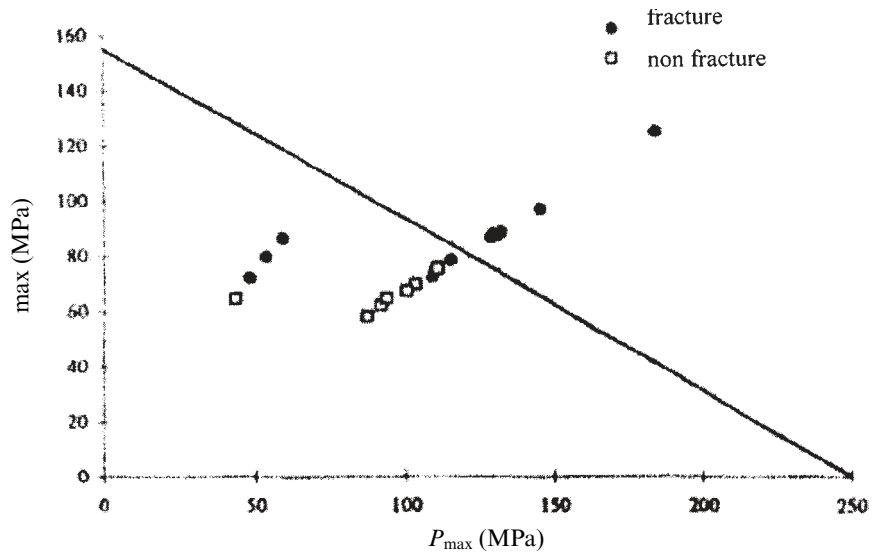


Fig. 5 Application of the multiaxial fatigue criterion for fillet welds, without taking account of local residual stresses.

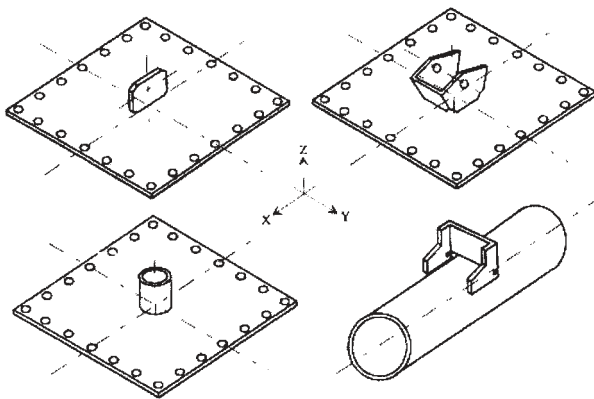


Fig. 6 Typical elementary structures tested with continuous welds.

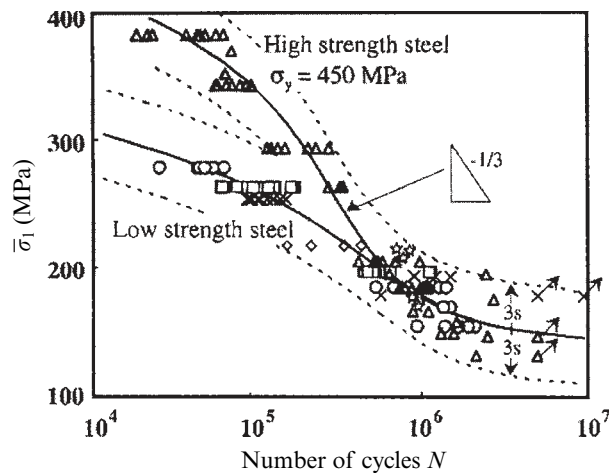


Fig. 7 S-N line for welded steel structures. The highest curve corresponds to high strength steel, the lower curve to low strength steel.

fatigue tests on elementary structures with different geometries and loading modes inducing multiaxial stress states at the hot spot.

An application to industrial structures was carried out to predict fatigue resistance. For instance, Fig. 8 summarizes the application of the local approach to predict the fatigue resistance of a car subframe made of a metal sheet joined by continuous welding that was subjected to out-of-phase multiaxial loadings. For an easier interpretation by the design office, the calculated value of the criterion displayed graphically in Fig. 8 is the quantity $C_d = (\tau_a + ap - b)/(b - ap)$. The failure happens at the predicted locus and the fatigue limit can be evaluated.

CONCLUSIONS

Mechanical structures usually have complex geometries and they have to operate under complex loading. This is particularly true for automotive welded structures and fatigue assessment of such specimens is easier using multiaxial approaches. In the case of industries employing simpler structures such as beams made of fillet welds, the need of such methods is not so evident, because the loadings are also simpler. However, if one wants to take account of the quality of the welds or of the residual stresses, then the local multiaxial approach is very helpful. The use of the equivalent stress derived from the multiaxial approach proposed previously seems to be promising.

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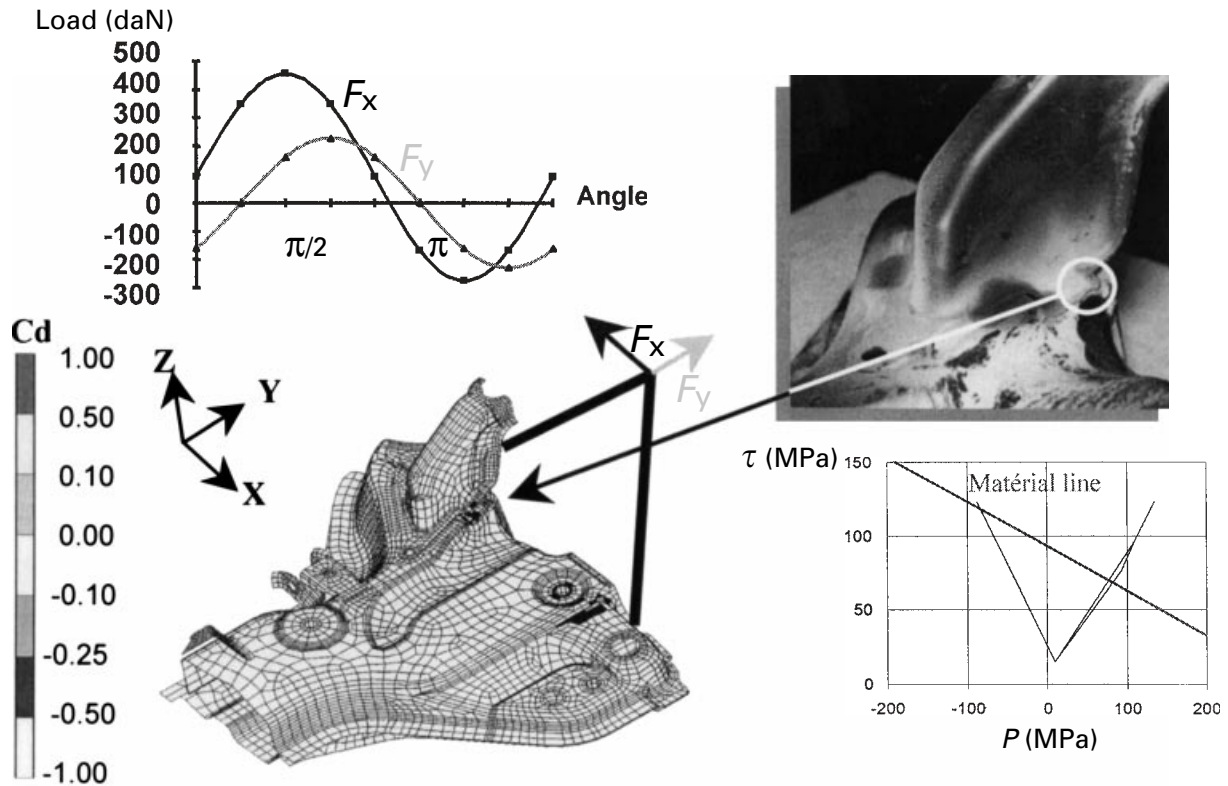


Fig. 8 Applications of the local multiaxial approach to assess fatigue resistance of an automotive welded structure undergoing multiaxial out-of-phase loading.

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