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FATIGUE DESIGN CRITERION FOR WELDED STRUCTURES

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Abstract—For continuously welded structures subjected to cyclic loading, the highly stressed zones where cracks initiate and lead to failure are usually located at weld toes. At these critical points, called hot-spots, the very local stress states are difficult to determine so that standard fatigue criteria are very difficult to apply for fatigue life prediction.

This work presents a fatigue design criterion for continuously welded thin sheet structures, based on a unique $S-N$ curve. The approach, which refers to the hot-spot stress concept, defines the design stress S as the geometrical stress amplitude at the hot-spot.

In practice, the geometrical stress state is calculated by means of the finite element method (FEM) using thin shell theory. Meshing rules for the welded connection, which can be applied methodically to any welding situation, allow the hot-spot location, and therefore the design stress of any structure, to be determined.

Experimental data and FEM calculations show that a unique $S-N$ curve can be obtained whatever the geometry of the welded structure and the loading mode.

Keywords—Design criteria; Welded structures; Hot-spot stresses; Thin shell theory; FE Method

NOMENCLATURE

- e_a, e_p = thickness of the attachment, and thickness of the plate.
 $e_w^{(a)}, e_w^{(p)}$ = weld leg length on the attachment side, and on the plate side.
 $E_i^{(a)}, E_i^{(p)}$ = shell element number i , perpendicular to the intersection curve of the shell element mean surfaces, on the attachment side, and on the plate side.
 F_i = load in the O_i direction.
 F_{\max}, F_{\min} = maximum load and minimum load.
 $n_i^{(a)}, n_i^{(p)}$ = node number i , on the attachment side and on the plate side.
 N = number of cycles to fatigue failure.
 R = load ratio. $= F_{\min}/F_{\max}$
 S = design stress.
 σ_{HS} = geometrical stress at the hot spot.
 $\Delta\sigma_{HS}$ = σ_{HS} range.
 σ_L = actual stress at the hot spot (or local stress).

INTRODUCTION

Nowadays, numerous multiaxial fatigue criteria are applied to structures for fatigue life prediction. However, for welded structures in particular, fatigue cracks occur in the weld zones where the stress state is difficult to determine so that existing fatigue criteria cannot be applied.

The fatigue design of welded structures is usually based on $S-N$ curves, which relate a design stress S to the number of cycles N characterising failure. This approach is used for large welded metallic structures in offshore and civil engineering industries. Design rules are available for steel

structures made of thick plates, usually between 20 mm and 150 mm. Two main types of fatigue design approach are widely used:

- (1) Codes for bridges such as the EUROCODE3 [1] which uses as input the far field stresses on long beams and refers to several $S-N$ lines corresponding to a number of selected welded details.
- (2) Codes for offshore steel structures such as the AWS [2] or UK DOE guidance notes [3] based on the hot spot stress concept [4–5], which give a unique $S-N$ line but are specific to large tubular connections.

Unfortunately, these codes are inadequate for lighter structures because they are based on thick plate testing and refer to particular geometrical situations which are not necessarily representative of common mechanical welded components. Nevertheless, the hot spot stress concept appears to be transposable to other structural situations.

In mechanical construction, arc welded components can be of complex shape. The stress distribution in these components is also generally complex and does not allow the definition of a “Nominal Stress” as is the case for bridge constructions made of long beam assemblies. Consequently, “Nominal Stress” type Design Codes cannot be used.

Therefore, using the hot spot approach, this work presents a fatigue design criterion for continuously welded thin sheet structures submitted to periodic loading with constant amplitude. In the first part of this paper, the hot spot stress concept is presented where the design stress is defined so that a unique $S-N$ curve is obtained whatever the geometry of the welded structure. In the second part, a numerical analysis using the finite element method (FEM) to calculate the design stress is explained. Finally, the experimental data used to define the design $S-N$ curve are presented.

HOT SPOT STRESS CONCEPT AND DESIGN STRESS

For continuously welded sheet assemblies submitted to cyclic loading, the highly stressed zones where cracks initiate and lead to failure are usually located at weld toes. Therefore, the design stress must be defined at these critical points, called hot spots.

In Fig. 1, the case of a welded joint submitted to cyclic loading is typically represented by a tube welded onto a plate. According to Radenkovic [6], the stress state in the vicinity of the intersection area where the hot spot appears can be described; see Figure 1.

- (1) either by the *actual stress* which drastically increases at the weld toe to a value σ_L , due to the local effects. These local effects are created by the weld profile, the shape of the weld toe and the very local notch effects induced by welding defects and undercuts, randomly distributed along the weld toe,
- (2) or by the *geometrical stress* which is due to the geometry of the structure but does not include local effects and reaches a value σ_{HS} at the weld toe.

The actual stress at the hot spot, σ_L , partly governs the fatigue life of welded structures and particularly the crack initiation period. However, the determination of σ_L , either experimentally or by calculation, is too difficult because of its random nature. This led Radenkovic to define the design stress as the geometrical stress at the hot spot σ_{HS} .

This paper is based on Radenkovic’s hot spot stress definition and also assumes that, within industries which use arc welding processes (railway, civil engineering, offshore, heavy construction, automotive), continuous welds are of the same type from one component to another and therefore

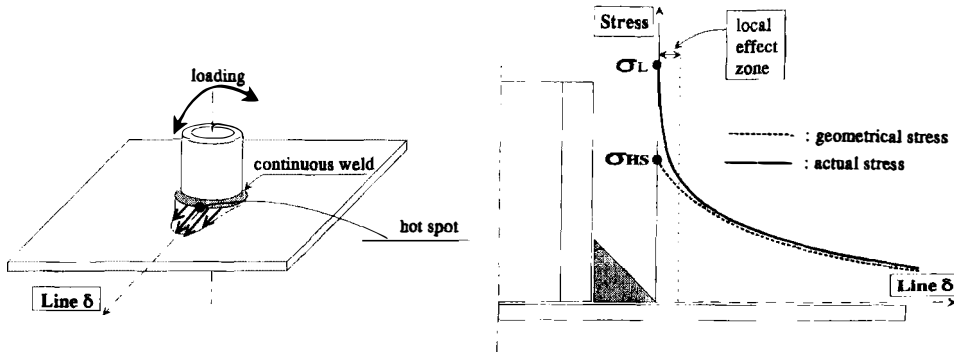


Fig. 1. Illustration of the hot spot stress concept for a tube welded onto an embedded plate and subjected to alternated loading. The following points are as indicated namely:- a hot spot location and an actual and geometrical stress distribution approaching the weld toe (the weld profile is ideally represented, without any penetration).

induce comparable local effects. In this way, σ_{HS} is related to the stress state which leads to fatigue failure of any continuously welded structure.

The design stress S is consequently defined as the geometrical stress amplitude at the hot spot, $\Delta\sigma_{HS}/2$. In the following section, the FEM used to determine S is presented.

NUMERICAL ANALYSIS AND MESHING RULES

Procedure for the numerical analysis

Amongst the numerical analysis methods available for structural calculations, the FEM is the most widely used. It is worth noting that such a method allows a fast and clear analysis of the desired results to be provided, which are location of the hot spots and design stress level. In practice, two kinds of elements can be used to calculate thin sheet structures by FEM (i) solid elements (three-dimensional elements or 3-D elements) and (ii) thin shell elements.

With a 3-D model of the welded connection, only an illusive value of the local stress σ_L at the weld toe can be obtained. This is because σ_L cannot include the real local effect which is random by nature. A numerical approach based on thin shell theory cannot calculate the local stress σ_L but allows the geometrical stress state to be determined. Therefore, within the framework of the hot spot stress concept, thin shell element calculation is the recommended method to calculate the expected design stress [7,8] noting that 3-D modelling does not provide more accurate information.

In a thin shell finite element mesh, elements represent the mean surfaces so that the intersection of two elements, defined by common nodes, is situated inside the material which exhibits 3-D behaviour. Interpolated stresses at the intersection nodes are calculated at a fictitious position and can therefore be inaccurate. Thus, in order to avoid hazardous interpolations, the geometrical stress must be calculated at points corresponding to the centre of gravity of each thin shell finite element.

For sheet structures submitted to fatigue, the maximum principal stress is considered as a significant value responsible for crack propagation. Therefore, the design stress is defined as the maximum principal stress amplitude and is determined by a static-elastic FEM calculation.

Meshing rules

At the intersection of thin shells, where hot spots commonly appear, the stress gradient can be very steep so that stress calculations are very sensitive to the mesh size. Therefore, a simple and logical meshing methodology which can be systematically applied to any welded connection has been developed. By using these meshing rules, the design stress of any continuously welded structure can be calculated.

The meshing rules are presented using the example of an attachment welded onto a plate (Fig. 2 and Fig. 3). They have been chosen for the following reasons

- (1) The first two elements $E1$ and $E2$, perpendicular to the intersection curve, have sizes approximately equal to the weld leg length which provides sufficient accuracy and which is also representative of the engineering scale.
- (2) For continuously welded thin sheets, the weld induces a local rigidity to the structure. This physical aspect is introduced by means of rigid elements which link the two shells together. These rigid elements are defined by pairs of nodes located along the whole weld length. One of the nodes is situated at $n_1^{(p)}$ on the plate mesh, and the other is located on the attachment mesh, each one at the mid-point of the weld leg length. It should be noted that $n_1^{(p)}$ and $n_1^{(a)}$ are not linked.

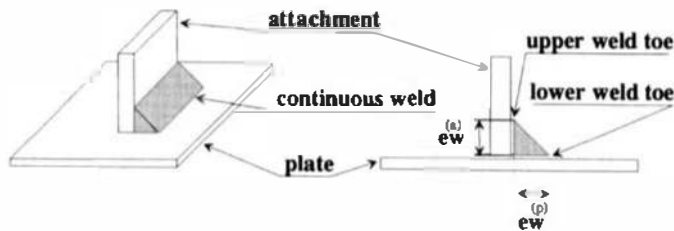


Fig. 2. Attachment welded onto a plate.

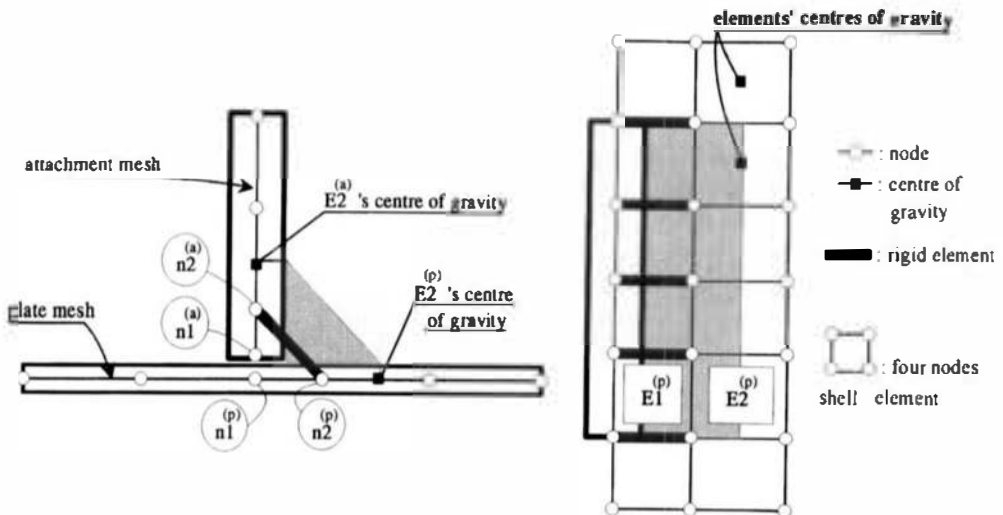


Fig. 3. Meshing rules using thin shell elements at the intersection of an attachment welded onto a plate.

- (3) The highest stress value approaching the intersection line is found at the centre of gravity of $E2$ which is located at the weld toe. It is noticeable that the longer the weld leg length, the larger the rigid element size.

Concerning the mesh elements near to the intersection zone, their dimension must increase gradually as the distance from this zone increases.

EXPERIMENTAL DATA

Introduction

The experimental study has been performed in the context of the automotive industry where numerous continuously welded thin sheet assemblies are used for mechanical components (suspension arms, engine subframes ...). The continuous welds are of the same type from one component to another and this is in agreement with the assumption of comparable local effects presented in previously.

Three different structures, called *elementary structures*, have been defined in order to provide representative geometries and welding configurations of actual car components (Fig. 4). They are made of commonly used serial brackets welded onto 2 mm thick low strength steel sheets ($\sigma_{YS}=170$ MPa; UTS=280 MPa). Among these geometries, two major welding situations can be distinguished

- (1) continuous welds which have no extremities such as a weld around a tube attached to a plate,
- (2) continuous welds with extremities, like the attachment or the *U* shape bracket welded onto a plate.

Welding parameters

Previously we have considered that the weld geometry is almost always the same so that local effects due to the weld shape are comparable from one component to another. However, in order to ensure that this assumption holds true, and to avoid the risk of premature cracking due to poor

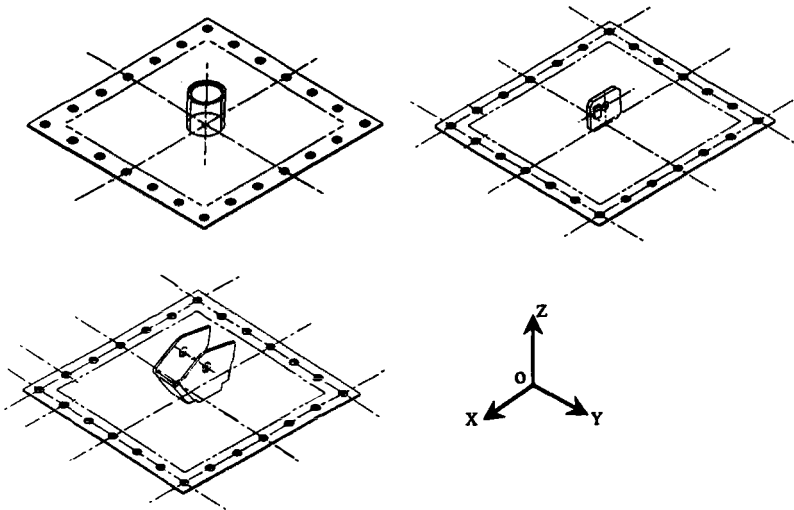


Fig. 4. Elementary structures defined for the fatigue tests: (1) Tube welded onto a plate. (2) Attachment welded onto a plate. (3) U shape bracket welded onto a plate.

weld geometry, welding procedures were rigorously applied. Therefore, the Metal Active Gas process that was used exactly corresponds to the automotive production procedures.

After the welding process, elementary structures were heat treated (550°C/1 h under inert gas) in order to eliminate residual stresses and plate distortion, and also to simplify test result evaluation.

Boundary conditions

For the fatigue tests, each elementary structure is clamped to a testing rig. Infra-red thermo-elasticity and FEM calculation results were compared for each of these structures and for several load cases in order to obtain the same boundary conditions between experimental work and the FEM modelling.

Failure criterion

Whenever $S-N$ curves are used, N always needs to be defined precisely. Therefore, a fatigue crack monitoring system was performed with strain gauges at the hot spots.

Then, different definitions of the number of cycles to failure could be proposed:

- (i) N_1 = first visible crack.
- (ii) N_2 = crack depth equal to half of the sheet thickness.
- (iii) N_3 = through crack.
- (iv) N_4 = end of test (displacement limitation).

For all testing, the number of cycles N_2 was used to define the failure criterion.

Fatigue experiment results

Fatigue tests with fully reversed loading ($R = -1$) in different directions were performed on each elementary structure. For each loading mode, two load levels were applied with a frequency of 30 Hz, in such a way that they caused failure after 10^5 and 10^6 cycles. Between 10 and 15 elementary structures were tested for each load level. On the same basis, several tests were performed to study

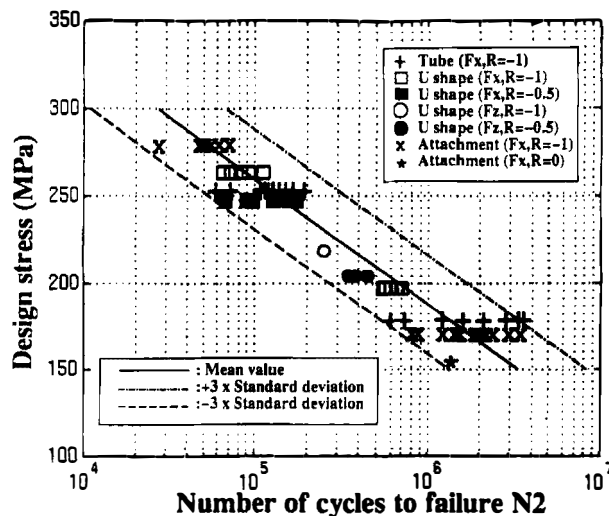


Fig. 5. Endurance ($S-N$) design curve giving the design stress S versus the number of cycles to failure N_2 for continuously welded low strength steel structures.

the effect of a mean load ($R = -0.5$ and $R = 0$). It appears that the mean load effect is of little importance.

Each test shows that cracks which lead to failure, initiate at the weld toe where the hot spot appears. In the case of the attachment and the U shape bracket, they are more particularly located at the extremities of the weld whereas, for the tube, they are situated along the weld.

Results are shown in a $S-N$ diagram (Fig. 5) where the design stress S is calculated by the numerical analysis procedure presented in part 2, and N is the N_2 failure criterion. Under these conditions, all the experimental data fall within the same scatter band around a unique $S-N$ curve. At this stage of our investigations, this curve appears independent of the geometrical effects and the loading modes.

CONCLUSIONS

The hot spot stress approach has been applied successfully to the case of continuously welded thin steel sheet structures. The fatigue strength of continuously welded mechanical structures can be estimated through a unique design curve whatever the geometry of the structure and the applied loading mode. The design stress, defined as the hot spot maximum principal stress amplitude, is obtained easily from a finite element calculation following a recommended meshing methodology which can be applied to any welded connection.

The approach proposed here has been validated for low strength steel but is also transposable to other metallic materials.

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