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On the use of hot-spot stresses, effective notch stresses and the Point Method to estimate lifetime of inclined welds subjected to uniaxial fatigue loading

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ABSTRACT

The present paper addresses the problem of estimating fatigue strength of welded joints when the weld seams are inclined with respect to the direction of the applied cyclic force. From a fatigue design point of view, the main complexity lies in the fact that, with this particular welded geometries, although the applied loading is uniaxial, accurate fatigue assessment can be performed provided that the degree of multiaxiality of the nominal/structural/local stress states at the weld toes/roots is modelled effectively. To this end, in the present investigation the Modified Wöhler Curve Method (MWCM) is attempted to be used to assess the fatigue strength of steel joints with inclined welds by using this multiaxial fatigue criterion in conjunction with nominal stresses, hot-spot stresses, effective notch stresses, and the Theory of Critical Distances (TCD). A large number of experimental results taken from the literature and generated by testing inclined fillet welds was used to check the accuracy and reliability of the MWCM applied along with these different ways of determining the relevant stress states. The results obtained from this validation exercise demonstrate that the MWCM returns satisfactory estimates when it is used to assess fatigue strength in the presence of inclined welds, with this holding true independently of the specific stress analysis strategy being adopted.

1. Introduction

Failure of metals caused by cyclic loading is a very complex problem that has been investigated extensively since the second half of the 19th century. Damage due to fatigue is accumulated cycle by cycle until, after a certain number of cycles, materials fail suddenly without any visible warning [1–3]. In this general context, a considerable amount of research work has been carried out since the beginning of the last century to investigate the effect of welding processes on the overall fatigue behaviour of structural components. These studies indicate that the fatigue strength of welded components is considerably lower than the one of un-welded structural details, with this holding true even though they are made of the same material [1]. This is a consequence of the fact that residual stresses, defects, imperfections and distortions are introduced during welding, with this resulting in an intrinsic reduction of the overall fatigue strength of welded connections [2,4,5]. Further, localised stress concentration phenomena resulting in severe stress/strain gradients always occur at the weld toes as well as at the weld roots [6]. This is the reason why fatigue cracks in welded joints usually initiate in the vicinity of the weld seams rather than in the parent material [2]. This already complex situation is further complicated also by the fact that in the heat affected zone the filler material alters the metallurgical morphology of the parent material, with this leading to a change in the material microstructural features in the vicinity of the welds themselves [2].

Owing to the key role that is played by weldments in applications of industrial interest (such as, for instance, automotive, offshore structures and railway industry), a considerable amount of experimental/theoretical work has been done to formalise and validate specific design techniques suitable for performing fatigue assessment of structural welded components [7–9]. As a result, the available Standards and Codes of Practice suggest different design strategies that include the nominal stress approach, the hot-spot stress approach, and those methods making use of local stresses [9–11]. In this context, certainly, the nominal stress approach is the most widely used in situations of practical interest. In particular, according to this methodology, fatigue strength is directly estimated from *ad hoc* S-N curves that are provided, for specific welded geometries, by the pertinent Standard Codes. To perform fatigue assessment according to this approach the stress analysis is done according to the simple principles of continuum mechanics [9–12]. Even if it is very effective, the main limitation characterising the nominal stress approach is that it cannot be used either when there is no univocal nominal cross-section or when a reference design curve is not available for the specific welded geometry being designed [13].

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Nomenclature

a, b, α, β	fatigue constants for the MWCM's calibration curves
k	negative inverse slope of the uniaxial fatigue curve
k_0	negative inverse slope of the torsional fatigue curve
k_τ	negative inverse slope of the modified Wöhler curve
P_S	probability of survival
$\Delta\sigma_x$	stress range normal to the weld seam
$\Delta\sigma_{nom}$	axial nominal stress range
$\Delta\sigma_n$	stress range perpendicular to the critical plane
$\Delta\sigma_A$	stress range of the uniaxial design curve extrapolated at a reference number of cycles to failure
$\Delta\sigma_{0.4t}$	normal superficial stress range at a distance from the weld toe equal to 0.4 t
$\Delta\sigma_t$	superficial normal stress range at a distance from the weld toe equal to t
$\Delta\sigma_{R,d}$, $\Delta\tau_{R,d}$	design resistance stress range for a specific number of cycles and appropriate FAT class
$\Delta\tau_{xy}$	shear stress range parallel to the weld seam
$\Delta\tau$	shear stress range relative to the critical plane
$\Delta\tau_{0.4t}$	superficial shear stress range at a distance from the weld toe equal to 0.4 t
$\Delta\tau_t$	superficial shear stress range at a distance from the weld toe equal to t
$\Delta\tau_A$	stress range of the torsional design curve extrapolated at a reference number of cycles to failure
ρ_w	critical plane stress ratio
$\Delta\tau_{Ref}$	reference shear stress range extrapolated at N_{Ref} cycles to failure
N_{Ref}	reference number of cycles to failure
N_f	number of cycles to failure
r_{Ref}	reference radius
θ	inclination angle with respect to the applied cyclic loading
R	load ratio

When the nominal stress approach is not directly applicable, either hot-spot stresses or local stresses have to be employed to design against fatigue complex/non-standard welded geometries.

The hot-spot stress approach works by taking into account the stress raising effect by extrapolating a reference stress quantity at the weld toes, with the stress gradient effect being accounted for via *ad hoc* design curves [13,14].

Even if hot-spot stresses have proven to be very effective, examination of the state of the art shows that the most advanced design approaches available to date are those making use of local linear-elastic stresses. In this context, the so-called effective notch stress approach [14–18] is the most advanced fatigue design method being recommended by the International Institute of Welding (IIW) [9]. According to this approach, design stresses are determined by rounding weld toes/roots with a fictitious notch radius equal to either 1 mm (when the thickness, t, is larger than 5 mm) or to 0.05 mm (for t < 5 mm) [16–18].

More recently, attention has been focused on extending the use of the Theory of Critical Distance (TCD) [19] also to the fatigue assessment of weldments [20]. The TCD takes as a starting point the idea that fatigue damage in the presence of stress concentrators of all kinds can be estimated by using an effective stress that is representative of the entire linear-elastic stress field acting on the material in the vicinity of the assumed crack initiation locations [21]. Thanks to its unique

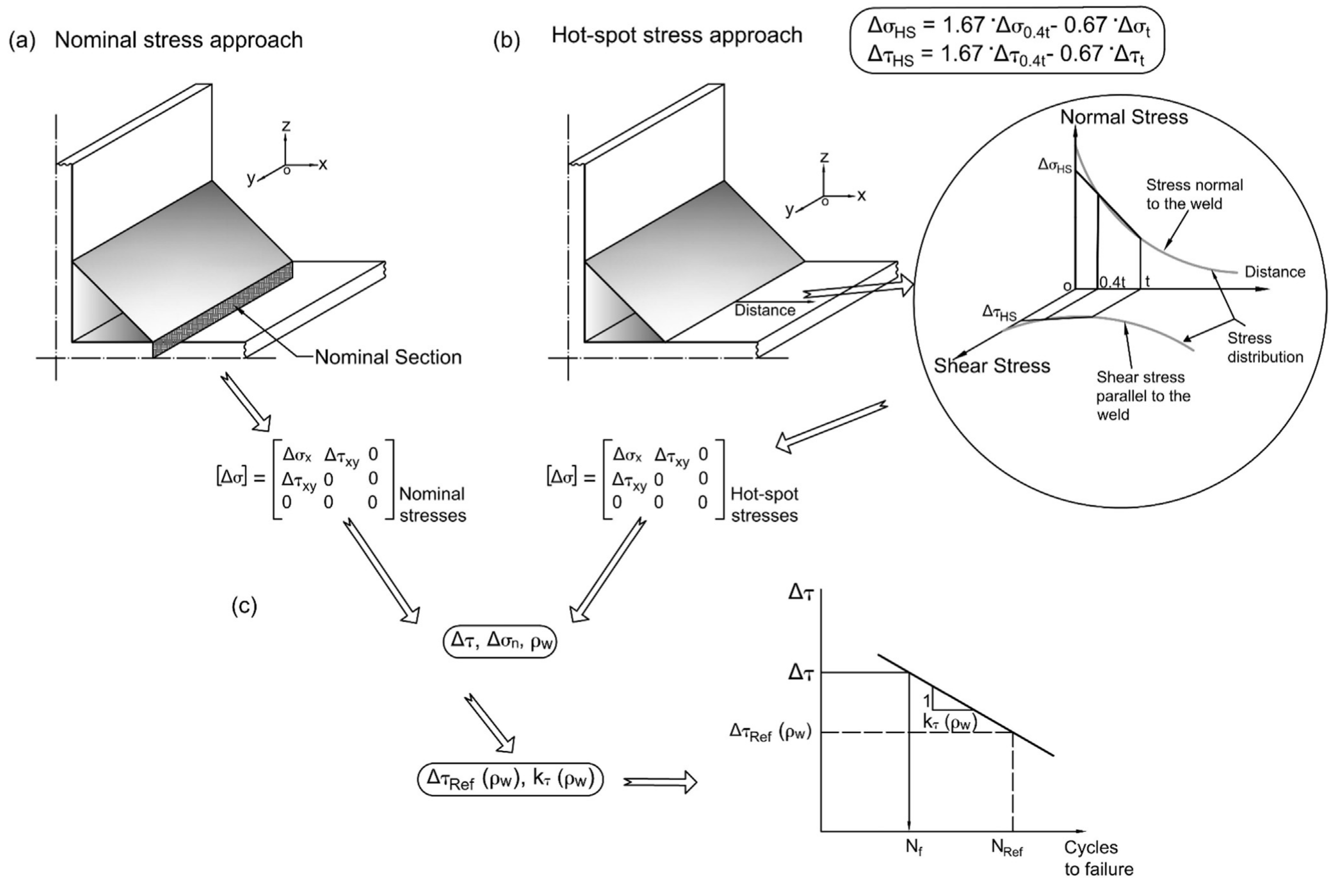

Fig. 1. The MWCM applied in terms of nominal and hot-spot stresses.