Correlation between experiments and Strip Yield model results on fatigue crack growth in a structural steel

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ABSTRACT: *Plasticity induced crack closure is a leading mechanism to control main aspects of fatigue crack growth (e.g. stress ratio and load interaction effects) in metallic materials. The so-called Strip Yield model has proved to be the most versatile and powerful tool for estimating closure levels but its application to structural steels is not straightforward. This paper addresses the Strip Yield model applicability to a low strength structural steel. First, crack growth tests coupled with closure measurements by the compliance method have been carried out. It has been found that only the local compliance technique yields an adequate evaluation of closure, provided that the processing of the load-strain data accounts for compliance variations for the fully open crack. Subsequently, cyclic deformations near the crack tip have been simulated employing the Strip Yield model in conjunction with a novel method based on Westergaard's complex potential. The analyses show that several conceptions of a constraint on yielding of the strip elements can be suitable in terms of the closure estimation but the local cyclic deformations are, in general, inadequately described.*

INTRODUCTION

Fatigue crack closure (CC) is a leading mechanism to explain the influence of different factors on fatigue crack growth in metallic materials, e.g. stress ratio (R) effects and load interaction phenomena typically occurring under variable amplitude loading. Among many existing analytical models to account for these effects, the so called Strip Yield (SY) model, first developed by Newman [1], is the most flexible and powerful tool since it allows to compute crack opening levels (P_{op}) under arbitrary load histories [2].

For the SY models, the key point is adopting the amount of constraint on yielding at the crack tip, quantified by the so called constraint factor (α) which depends on the cracked element geometry and material. The α factor estimate is usually done based on crack growth tests performed at several R-ratios during which CC is measured: the correct α value is the one matching the SY model predictions with the experimental data on CC and crack growth. Recent results by the present authors [3] show that to correctly evaluate CC in structural steels, local compliance measurements should be performed.

The scope of this paper is to study experimentally and simulate, using a SY model developed by Skorupa et al. [2], fatigue crack growth in a structural steel. First, crack growth tests coupled with closure measurements by the local and remote compliance method have been conducted. The measured local compliance data transformed to the load-differential strain (P-ε_{diff}) loops were then used to determine the crack opening levels (P_{op}) [3]. Next, the P-ε_{diff} loops have been simulated employing the SY model [2] in conjunction with a novel method based on Westergaard's complex potential [4]. With this approach, it is possible to obtain the P-ε_{diff} curve assuming any constraint factor value on tensile and compressive yielding (α_t and α_c respectively). The analyses show that constraint concepts developed for Al alloys [1,5,6] can be suitable in terms of the P_{op} estimates, but the cyclic deformations near the crack tip which are crucial to the crack growth behaviour are, in general, inadequately described.

EXPERIMENTS AND RESULTS

The material considered is a Fe430D structural steel having the following mechanical properties [7]: ultimate strength σ_u=475 MPa, monotonic yield stress σ_y=320 MPa, cyclic yield stress σ_{yc}=240 MPa and fatigue limit under rotating bending (R=-1) σ_b=225 MPa.

Crack growth experiments have been carried out on 6 mm thick and 9 mm thick M(T) specimens having width of 80 mm and the starter notch length of 12 mm. Two testing machines with a capacity of 250 kN, namely a SCHENCK Hydropuls located at Politecnico di Milano (machine A) and a DARTEC located at AGH (machine B) have been utilized. For the 6 mm thick specimens, an overload (OL) test (OL ratio =2, baseline load ratio R=0.1) and the constant amplitude (CA) tests at R=-1, 0.5 and 0.7 were conducted. The CA tests on 9 mm thick specimens involved R=0.1, 0.3, 0.5 and 0.7.The operating frequency was in the range of 15-30 Hz, depending on the load conditions.

Crack growth tests

The crack growth tests have been executed following the ASTM E647-95a standard [8]. For the tests carried out on machine A, crack length has been determined by the method of polymeric replicas [9] observed by an optical microscope (100x) while a travelling microscope coupled with a digital camera was employed during the tests on machine B.

The crack growth rates (da/dN) were determined by the polynomial method [8]. The crack growth data (da/dN vs. ΔK), where ΔK is the stress intensity factor range, are provided in Figure 1.

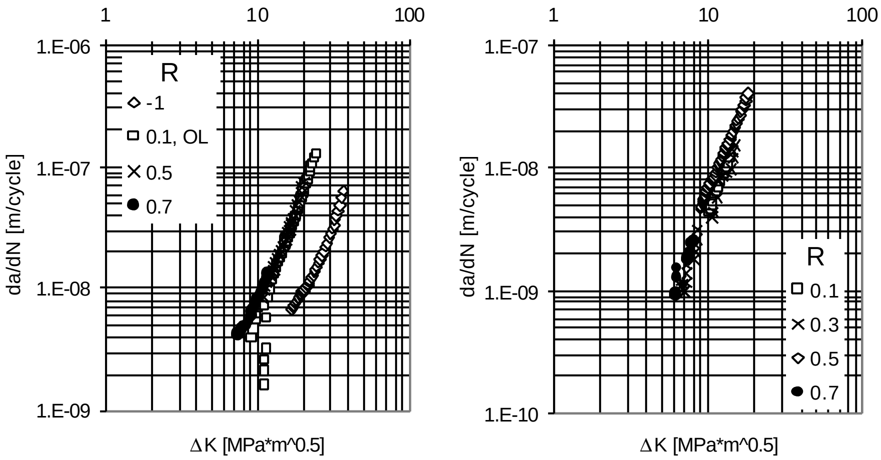


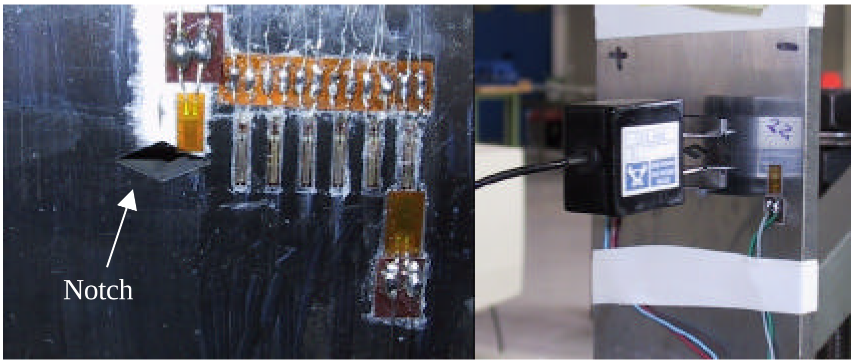
Figure 1: Crack propagation test results for: (a) 6 mm thick specimens; (b) 9 mm thick specimens.

Closure measurements

Most CC measurements have been made using the local compliance technique. The corresponding load-strain (P-ε) data have been recorded employing a series of strain gages ahead of the crack tip. During some tests, the load-displacement (P-v) data were also recorded using a clip gage. Figures 2a and b show the typical locations of the transducers.

The data obtained from the clip gage measurements were analysed using the ASTM compliance offset method [8] for which the opening load corresponds to a 1, 2% or 4% variation of the compliance calculated on unloading from maximum load (when the crack is supposed to be fully open). Processing the data from the CC measurements was carried out in two different ways, namely by the ASTM method [8] and using an approach proposed by Toyosada and Niwa [10] according to which the open crack compliance is assumed to vary. With the latter concept, a P-ε loop is first transformed into the differential loop, P-ε_{diff}. Then, the P_{op} level is found based on slope analyses of the P-ε_{diff} curve for the loading and unloading part of a fatigue cycle. This method has been implemented using the algorithm [3] which includes a special smoothing procedure optimised for this type measurement data.

The difference between the two approaches for CC measurements can be clearly seen when the corresponding P-ε_{diff} diagrams are compared. Note in Figure 3 that for the local data acquisition technique, the loading branch and the unloading branch are distinct, while for the clip-gage and a strain gauge remote from the tip, both the branches overlap.



(a) **FRONT** **BACK** **(b)**

Figure 2: Closure measurements: (a) strain gages for the local evaluation of closure; (b) extensometer for the remote compliance acquisitions.

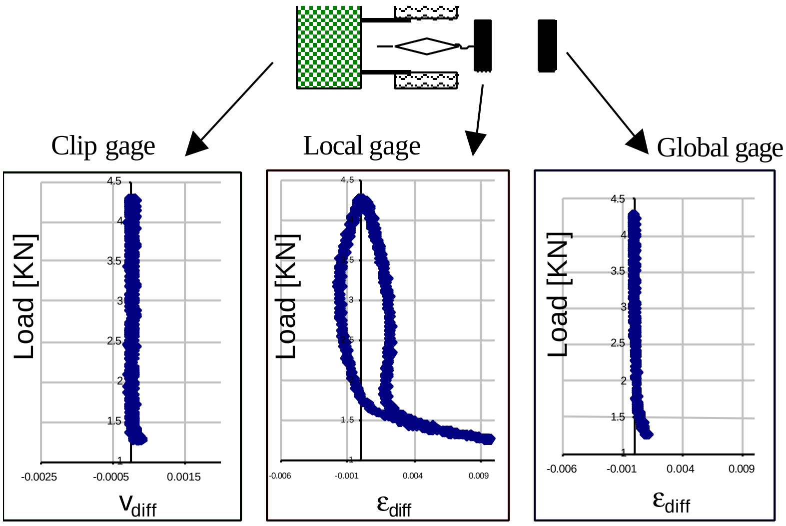


Figure 3: Load-differential strain loops from the local and remote data acquisitions for the R=0.3 test on a 9 mm thick specimen.

Figures 4a and b reveal differences between the ASTM method [8] results based on the remote and local data acquisitions, respectively. Even if the average P_{op}/P_{max} values are very close, the scatter for the remote compliance measurements is much higher than for the local measurements. Comparing the local measurements (Figures 4b,c), it can be noted that the algorithm [3] results tend to be less dispersed than ASTM method results.

da/dN versus DK_{eff} data

P_{op} load estimates obtained from the local CC measurements were then used to obtain the da/dN-ΔK_{eff} data, where $\Delta K_{eff}=K_{max}-K_{op}$ is the effective stress intensity factor range. As seen in Figure 5, the consolidation of the data for different R-ratios and for the OL test is much better if ΔK_{eff} values are based on the P_{op} data obtained via the algorithm [3]. Particularly, the CC levels estimated according to the ASTM procedure are not capable of fully correlating the post-OL crack growth rates.

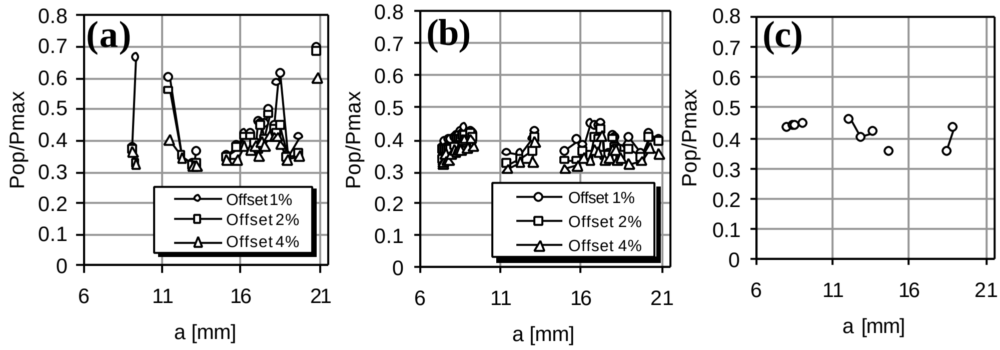


Figure 4: Comparison of closure results for the R=0.3 test on a 9 mm thick specimen from: (a) clip-gage data & ASTM method [8]; (b) strain gage data & ASTM method [8]; (c) strain gage data & algorithm [3].

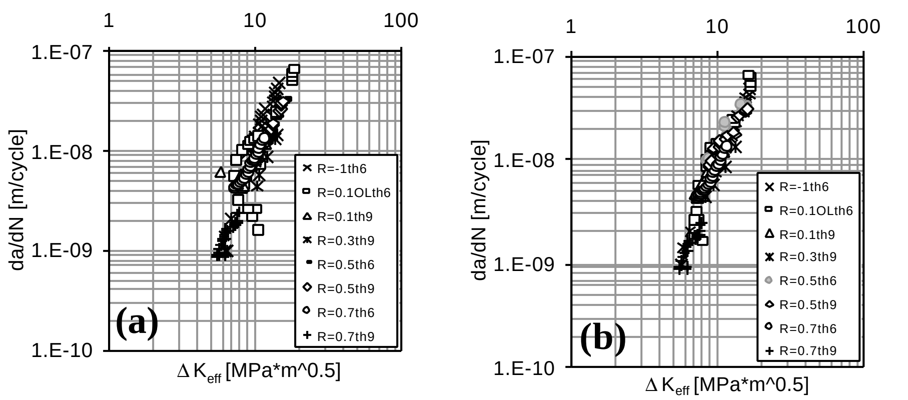


Figure 5: Comparison of the da/dN vs. ΔK_{eff} data based on: (a) the ASTM method [8]; (b) the algorithm [3].

CORRELATION BETWEEN THE EXPERIMENTS AND THE STRIP YIELD MODEL RESULTS

The SY model is a semi-analytical method for predicting P_{op} in which the cyclic deformations at the crack tip and the formation of the plastic wake is simulated by using the Dugdale concept of plasticity at the crack tip. As said afore, imposing a constraint on local yielding enables to account for the stress state at the crack tip. With his respect, several approaches have been proposed in the literature, e.g. original Newman's concept [1] (yielding in tension: $\alpha\sigma_y$, yielding in compression: $-\sigma_y$), the NLR concept (tension: $\alpha_t\sigma_y$; compression: $-\alpha_c\sigma_y$) [5] and others, more complex [6]. Because definite rules for finding correct constraint factors are lacking, their values should be chosen so as to make the predicted P_{op} levels close to the experimental results.

An improved correlation of the SY model results with the observed values can be achieved through a method by Beretta and Carboni [4] based on Westeergard's complex potential. With their approach, the displacements at a given point ahead of the crack tip can be computed from stress solutions obtained via the SY model at different instants of a load cycle, Figure 6.

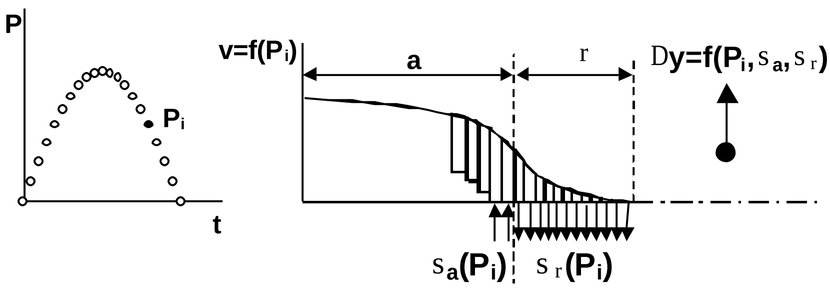


Figure 6: Scheme of the simulation of P-ε_{diff} loops at the crack tip [4].

This analytical tool enabled to simulate the P-ε_{diff} curves obtained from the measurements. The constraint factor concepts according to Newman [1] and the NLR model [5] have been considered with this respect. It has been found that the α factors according to [1] needed to match the CC behaviour measured during the R>0 tests (Figures 7a, b) are inconsistent with the FEM results by Newman [11]. Skorupa et al [12] have shown that for the R=-1 test, the concept [1] prevents a correlation with the observed P_{op} values. Such a correlation could only be achieved if a constraint on compressive yielding was also imposed. Figures 7b,c indicate that although the SY model predictions correlate the observed CC behaviour, the computed P-ε_{diff} diagrams can be very different from the measured P-ε_{diff} data. Compared to Newman’s approach [1], the NLR concept seems to better describe the cyclic strain behaviour for the tests at R>0.

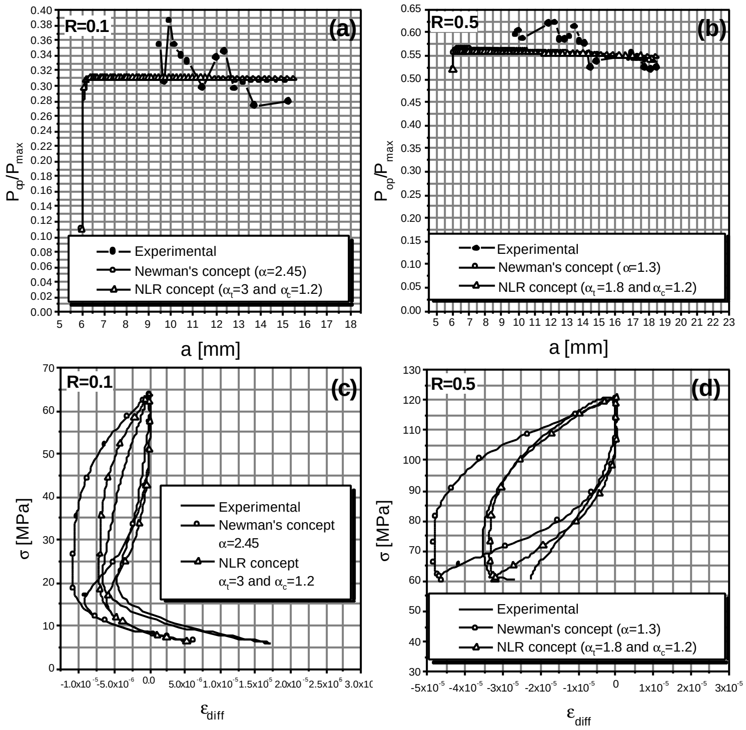


Figure 7: Comparisons between the SY model and experimental results on: (a) and (b) P_{op} at R=0.1 and R=0.5 respectively; (c) and (d) the corresponding P-ε_{diff} data.

SUMMARY AND CONCLUSIONS

Fatigue crack growth tests coupled with crack closure measurements by the compliance technique on M(T) specimens of two different thicknesses in a mild structural steel were conducted. Constant amplitude loading at several stress ratio values and a single overload applied among smaller amplitude cycles were considered. Compared to the remote compliance measurements, the local measurements were found to produce more precise closure estimates. The closure behaviour evaluated from the local compliance data using the algorithm proposed by the authors adequately correlated the observed crack growth behaviour.

A novel method based on Westergaard's complex potential enabled simulations of the cyclic strain behaviour ahead of the crack tip using the Strip Yield model. If a concept of the constraint on tensile yielding at the crack tip, originally developed for Al alloys, was incorporated in the model, a correlation of the observed closure behaviour was only achieved for positive stress ratio values. An agreement between the observed and predicted by the model closure levels did not imply a similarly good correlation for the cyclic strain behaviour at the crack tip. Applying constraint factors on both tensile and compressive yielding enabled a better description of the local cyclic deformations compared to the case when a constraint on tensile yielding only was involved.

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