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CALIBRATION OF THE STRIP YIELD MODEL FOR FATIGUE CRACK GROWTH PREDICTIONS IN STRUCTURAL STEEL

SUMMARY

The paper is focused on the calibration of the strip yield (Dugdale) model for crack growth predictions for structural steel. This is achieved by imposing appropriate constraints on yielding the strip elements. To avoid a fortuitous, i.e. physically unjustified choice of the constraint factors, a novel concept for their selection is proposed, namely matching the experimentally observed and predicted by the model cyclic stress-strain behaviour at the crack tip. The approach is shown to yield satisfactory prediction results on crack growth under constant amplitude loading and after application of an overload cycle.

Keywords: *Fatigue crack growth, prediction models, variable amplitude loading, structural steel*

KALIBRACJA MODELU PASMOWEGO PŁYNIĘCIA
DO PROGNOZOWANIA ROZWOJU PĘKNIĘĆ ZMĘCZENIOWYCH W STALI KONSTRUKCYJNEJ

W artykule skupiono się na kalibracji modelu pasmowego płynięcia do prognozowania rozwoju pęknięć zmęczeniowych w stali konstrukcyjnej, stosując odpowiednie współczynniki skrępowania. W oparciu o wcześniejsze analizy stwierdzono, że w przypadku tego materiału adekwatne przewidywanie trendów eksperymentalnych we wzroście pęknięć zmęczeniowych wymaga zastosowania trzech niezależnych współczynników skrępowania modyfikujących granice plastyczności odpowiednio dla rozciąganych i ściskanych elementów pasma plastycznego przed frontem pęknięcia, oraz ściskanych elementów za jego frontem. W takim przypadku jednak, wymagany poziom otwarcia pęknięcia możliwy jest do osiągnięcia przy wielu kombinacjach tych współczynników. Zaproponowano więc, by dodatkowym kryterium ich doboru była zgodność między wyznaczoną eksperymentalnie a symulowaną przy użyciu modelu lokalną cykliczną odpowiedzią materiału. Pokazano, że tak skalibrowany model dobrze opisuje w sensie ilościowym trendy eksperymentalne we wzroście pęknięć zmęczeniowych w stali konstrukcyjnej przy obciążeniu stałoamplitudowym oraz po pojedynczym przeciążeniu.

Słowa kluczowe: *model pasmowego płynięcia, przewidywanie wzrostu pęknięć zmęczeniowych, badania zmęczeniowe, stal konstrukcyjna*

1. INTRODUCTION

Among non-linear concepts that have been proposed for fatigue crack growth predictions, the so-called strip yield (SY) model based on the Dugdale conception of crack tip plasticity, but modified to allow for the plasticity induced crack closure (PICC) mechanism, remains a particularly versatile predictive tool convenient to use in the case of mode I fatigue crack growth under arbitrary variable amplitude loading histories. The basic material input for the SY model are the fatigue crack growth rate vs. the effective stress intensity factor range ($da/dN–\Delta K_{eff}$) data. To account for the 3D nature of PICC, appropriate constraints on yielding the plastic strip elements should be imposed. As elucidated in more detail by Skorupa and Skorupa (2005), an equally important role of the constraint factors is to calibrate the SY model for a given material in order to account for processes which can affect crack growth but cannot be modelled in a rigorous way.

The predictive capabilities of a well known and most widely used SY model implementation included in the NASGRO software have been systematically evaluated by the present authors under a variety of fatigue loading conditions for both aluminium alloys (Skorupa *et al*. 2007a) and structural steel (Skorupa *et al*. 2005). It has been concluded that altogether unsatisfactory prediction quality stems from an inadequate conception of the constraint factors incorporated in the NASGRO models.

2. CALIBRATION OF THE STRIP YIELD MODEL AND PREDICTION RESULTS

The present paper is focused on the SY model calibration for structural steel. A previous work (Skorupa *et al*. 2002) has revealed that in order that the observed stress ratio (R) effect on crack growth for this metal type be covered by the SY model predictions, three independent constraint factors are required, namely on tensile yielding (α_t) and on compressive yielding ahead and behind the crack tip (α_c and α_w respectively). Because, however, the required value of the crack opening stress (S_{op}) can be obtained for many combinations of the three independent α-values, an additional criterion for their selection is adopted, namely matching the experimentally observed and predicted by the model local cyclic

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stress-strain behaviour. The observed cyclic stress-strain response of the material is represented by the stress vs. offset strain (S–ε_{offset}) diagrams derived from compliance measurements using the strain gauges positioned ahead of the crack tip, centrally on expected crack path. The gage length was from 2 mm to 6 mm, depending on the crack length (longer gage located at larger crack length) and the gage width was as narrow as available (up to 1 mm). More details about experimental procedure are given elsewhere (Machniewicz 2003). The predicted S–ε_{offset} loop at the gage location was obtained by using Beretta and Carboni (2005) approach which allows analytically determine the cyclic strain variations measured by a strain gauge, based on the SY model solution on the strip element stresses for assumed constraint factors values. An exemplary comparison between the observed and computed S–ε_{offset} data for various combinations of the three constraint factors is shown on Figure 1 (Skorupa and Skorupa 2005). It is assumed that both type loops are similar if the loop widths (a measure of the cyclic plasticity) and the total offset strain ranges (reflecting the overall shape of the S–ε data) are approximately the same. Matching the predicted and observed loops automatically yields a matching between the predicted and observed S_{op} levels.

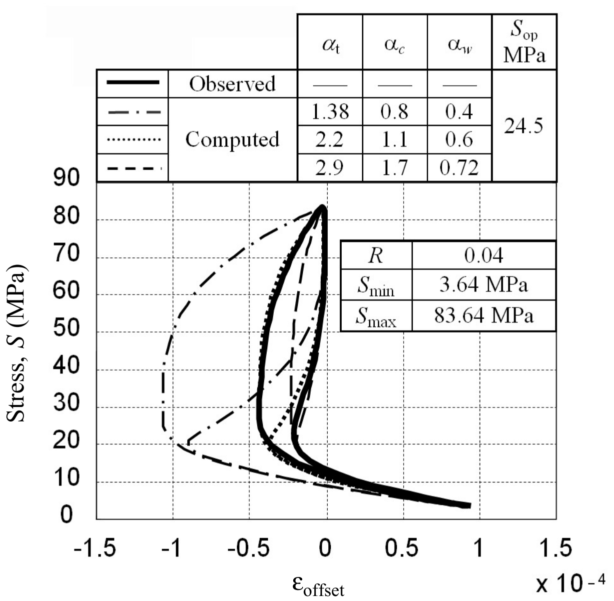

Fig. 1. Exemplary comparison between the observed and computed S–e_{offset} data for various combinations of the three constraint factors

The above concept is applied in the SY model implementation by the present authors to extract variations of the three α-values required to correlate by the model fatigue crack growth results observed under constant amplitude (CA) loading at a range of the R-ratio values. The CA fatigue tests coupled with CC measurements were performed on M(T) specimens in a low carbon structural steel (18G2A, acc. PN-EN 10028) with the yield stress of 398 MPa and the ultimate strength of 540 MPa. The chosen α-factors can be approximated as:

$$\alpha_t = 2.0 \tag{1a}$$

$$\alpha_c = \begin{cases} 0.98 & \text{for } R \le 0 \\ 0.57978 \cdot R + 0.98 & \text{for } R > 0 \end{cases} \tag{1b}$$

$$\alpha_w = \begin{cases} 0.2689 \cdot R + 0.523 & \text{for } R \le 0 \\ 1.224 \cdot R + 0.523 & \text{for } R > 0 \end{cases} \tag{1c}$$

Because the specimen thickness (t) was found to not affect CA crack growth (Skorupa and Skorupa 2005), Eq. (1) is valid within at least the range of thicknesses (4–18 mm) considered in the present tests.

Experiments by Skorupa *et al.* (2007b) have shown that the observed da/dN values following a single overload (OL) cycle or a block of OLs systematically exceeded the rates inferred from the measured S_{op} levels. These discrepancies have been attributed to the discontinuous CC phenomenon which, however, cannot be reproduced by the SY model. Under such conditions, choosing the α-factors based on the similarity between the predicted and observed S–ε_{offset} data would yield overestimated post-OL S_{op} stresses and, consequently, overly low predicted da/dN values. Considering that, the concept of the constraint factors in the OL affected zone has been based on the FE results by Pommier and Bompard (1999). These indicate that material hardening within the OL plastic zone leads to an intensification of the compressive residual stresses ahead of the crack tip. At the same time, the OL promotes a shift of the plastic zone behind the crack tip, which yields enhanced contact stresses. In an attempt to model both above trends, the post-OL α_c and α_w factors have been elevated compared to the CA values, as shown in Figure 2. The concept enables to predict the retarded crack growth increment after the OL (Δa_{OL}) over the distance exceeding the OL plastic zone (r_{plOL}), as typically observed for structural steel (Skorupa and Skorupa 2005). Note that modelling the $\Delta a_{OL} > r_{plOL}$ effect is unfeasible using the NASGRO code (Skorupa *et al.* 2005). In Figure 2, the α-variations are fully defined by two parameters, namely $d\alpha_w/da$ considered to be a material constant (0.4 mm^{-1} for 18G2A) and α_{OL} given by

$$\alpha_{OL} = \max \begin{cases} \alpha_{wCA} \\ \alpha_{wCA} \cdot (3.5 - 2.8 \cdot R - 0.0867 \cdot t) \end{cases} \tag{2}$$

Figure 3 and Table 1, where the results obtained from the SY model incorporating the constraint factors according to Eq. (1) are compared with the CA test results for 18G2A (t = 4 mm), demonstrate that the model correctly describes both the R-ratio and the stress level effect on crack growth.

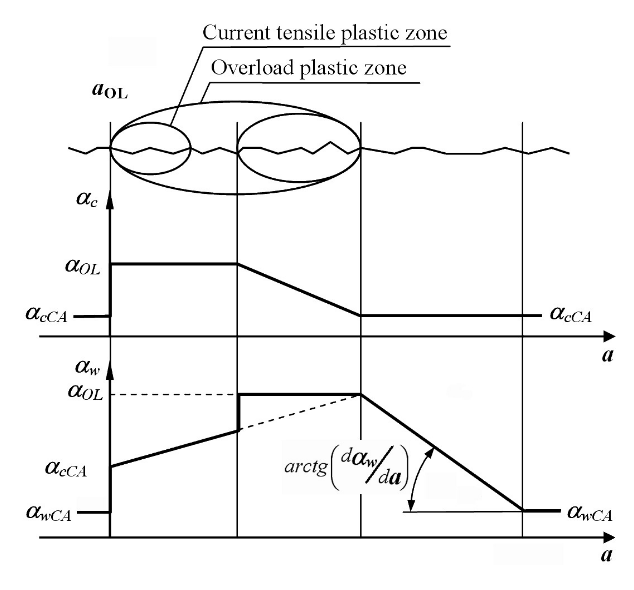

Fig. 2. Modification of the α_c and α_w factors after the OL

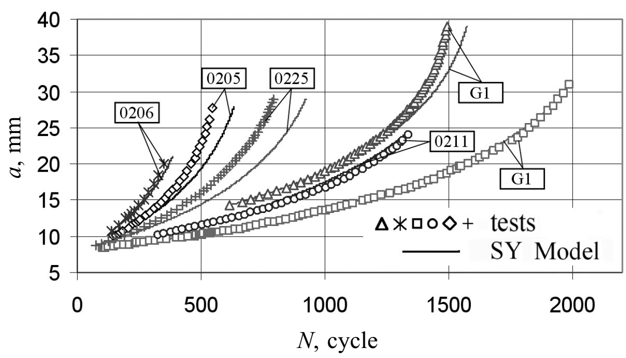

Fig. 3. Comparison between the observed and predicted crack growth curves for several CA tests

Table 1

Comparison between the predicted (N_{SY}) and observed (N_{EXP}) crack growth lives for CA loading

Test No.	Stress ratio R	Stress levels, MPa		N_{SY}/N_{EXP}
		S_{min}	S_{max}	
0225	–1	–55	55	1.150
0227	–0.5	–25	50	1.091
0230	–0.5	–42.15	84.3	0.917
0205	0.05	4.3	84.3	1.217
G1	0.15	9.12	59.52	1.002
0220	0.15	14.1	94.1	1.159
0228–1	0.15	11.5	76.5	0.960
0228–2	0.5	65	130	1.066
0206	0.5	80	160	1.112
G3	0.5	52	102	0.825
0221	0.5	80	160	1.142
0211	0.7	116.8	166.8	0.982

As shown in Figure 4, the constraint factor concept according to Figure 1 and Eq. (2) enables a good correlation of the observed influence of R and t on the post-OL transient da/dN behaviour. The discrepancies between the predicted and observed da/dN values which occur for the thicker specimens when the crack grows outside the OL-affected zone stem from the crack growth acceleration in that region observed in the fatigue tests. This phenomenon is difficult to understand in terms of CC and, for that reason, cannot be predicted by the model.

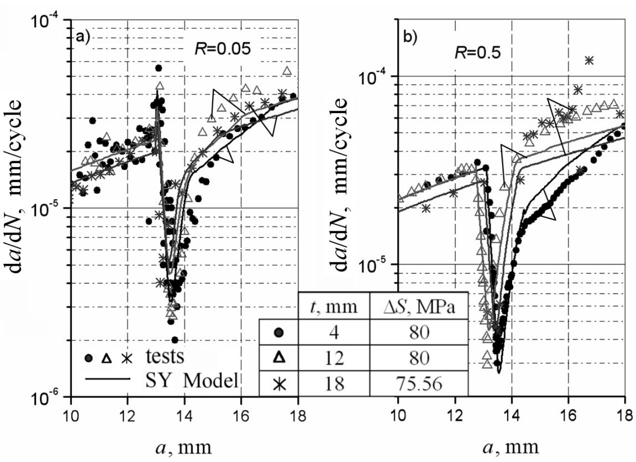

Fig. 4. Comparison between the observed and predicted crack growth rates for the OL tests: a) $R = 0.05$; b) $R = 0.5$

3. CONCLUSIONS

1) The strip yield model requires the calibration for a given material, which can be made by using the suitable constraint factors. To correlate the experimental trends in fatigue crack growth for structural steel, the strip yield model must incorporate three independent constraint factors, namely on tensile and compressive yielding ahead of the crack tip and on compressive yielding in the crack wake.
2) Since the required value of the crack opening stress level can be obtained for many combinations of the three constraint factors, an additional criterion of choosing these factors has been adopted, based on similarity between measured during the tests and predicted by the model local cyclic stress-strain behaviour. This concept enables favourable prediction results for structural steel under constant amplitude loading conditions.
3) For retarded crack growth following a single overload cycle selecting the constraint factors in the same way as for the constant amplitude loading yields overly high crack opening stress values. In view of that the agreement between the observed and predicted fatigue crack growth rate is the only basis available for choosing the proper constraint factors values.
4) The strip yield model calibrated according to above concept correctly covers experimental trends observed in the fatigue crack growth tests on structural steel under constant amplitude loading and after single overloads.

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