APPLICATION OF THE STRIP-YIELD CRACK CLOSURE MODEL TO CRACK GROWTH PREDICTIONS FOR STRUCTURAL STEEL

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ABSTRACT

Though the strip yield (SY) type models for crack growth predictions are currently a widely used tool to simulate fatigue crack growth in aircraft materials, their adequacy for structural steel remains unknown. In this paper, the SY model ability to simulate crack growth observed in fatigue tests on a structural steel is explored. It is shown first that the predictions from the SY model included in the NASGRO software do not reproduce the effects of the stress ratio and the applied stress level observed under constant amplitude loading. Also, they do not correctly account for crack growth retardation after a single overload cycle. Next, a SY model developed by the present authors, which incorporates three independent constraint factors on yielding at the crack tip, is applied. The model calibration for the structural steel is implemented through choosing the constraint factors to match the experimentally observed and predicted by the model the cyclic stress-strain behaviour at the crack tip. The proposed calibration concept enables the model predictions to quantitatively cover all trends in crack growth observed in the present tests.

1 INTRODUCTION

Since Elber's discovery of plasticity-induced crack closure (CC) this mechanism has become an integral component of most theoretical concepts for fatigue crack growth predictions. An example may be the so called strip yield (SY) model based on the Dugdale theory of crack tip plasticity modified to leave the plastically stretched material on the fatigue crack surfaces. A most widely used model of this type, mainly intended for applications to aircraft alloys, is included in the NASGRO software, currently commercially available. Reported verification work on the NASGRO SY model, limited predominantly to Al-alloys, reveals either satisfactory (e.g. [1]) or poor (e.g. [2]) prediction results on crack growth, depending on the material type, load history and specimen geometry.

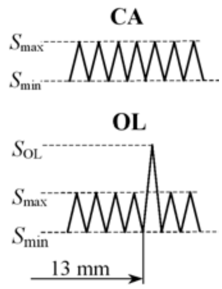
In this paper, the NASGRO SY model performance for structural steel is examined first. With this purpose, the model was used to simulate fatigue crack growth observed in a series of fatigue tests carried out on 18G2A steel. It was found that the NASGRO predictions failed to cover the observed trends, namely the stress ratio (R) effect under constant amplitude (CA) loading and retardation in crack growth due to a single overload (OL). In view of that, a SY model developed by the present authors [3] is applied to extract equations for the constraint factors which enable a better agreement between the predicted and observed results.

2 EXPERIMENTAL PROCEDURE

A low carbon structural steel 18G2A (PN-EN 10028) was used for which 0.2% monotonic yield stress = 398 MPa, cyclic yield stress = 336 MPa, ultimate tensile strength = 540 MPa, elongation to failure = 25%. Fatigue crack growth tests coupled with CC measurements using the local compliance technique were performed under load control on 4 mm thick M(T) specimens 100 mm in width in agreement with the ASTM E647 standard, the loading conditions being specified in Table 1. Fatigue threshold values required by the NASGRO model were derived at the R-ratios of –1 and 0 from the K–decreasing tests (ASTM E647-95A) under pure bending on SE(B) specimens (ASTM E399-83). Details associated with the CC measurements and processing the compliance records to estimate the crack opening stresses (S_{op}) from are provided elsewhere [4,5].

Table 1: Design of the fatigue crack growth tests

Test No.	Stress ratio R	Stress levels, MPa			Test type
		S_{min}	S_{max}	S_{OL}	
0225	-1	-55	55	——	CA
0205	0.05	4.3	84.3	——	
G1	0.15	9.12	59.52		
0220	0.15	14.1	94.1	——	
G3	0.5	52	102	——	
0221	0.5	80	160	——	
0211	0.7	116.8	166.8	——	
0210	0.05	4.3	84.3	164.3	OL
G4	0.07	3.64	53.72	102.6	
0209	0.5	80	160	240	



3 NASGRO SY MODEL PREDICTIONS

The NASGRO SY model calibration for a new material requires specifying its monotonic properties and declaring a number of material parameters. The latter are derived based on the crack growth rate (da/dN) vs. stress intensity factor range (ΔK) data produced in CA tests performed at several R-ratio values and from threshold tests, as shown in Fig. 1. The fatigue crack growth simulations can be carried out using a "constant constraint" or a "variable constraint" option.

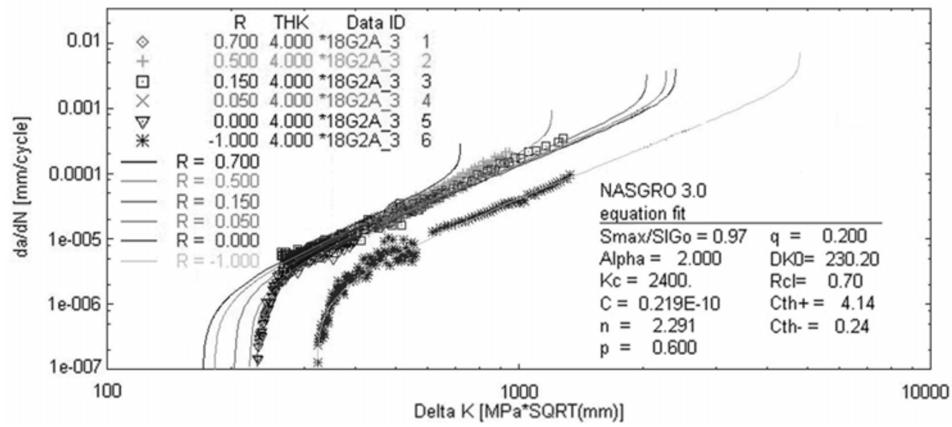


Figure 1: da/dN versus ΔK data from the CA tests and the corresponding material parameters used in the NASGRO SY model

As seen in Fig. 1, the chosen material parameters enable a good correlation of the experimental data by the NASGRO crack growth equation [6]. Fig. 2a demonstrates, however, that the predicted crack growth curves do not agree with the experimental results generated in the CA tests. Surprisingly enough, it is also the case for the data used to calibrate the model (compare Fig. 1) except those for R=0.7 and R=0.5 (Specimens 0211 and 0221 respectively). The conformance between the predicted and experimental curves at the both highest R-values stems from declaring R_{cl}=0.7 in the input data set (compare Fig. 1) which implies that the R=0.7 results are closure-free. Hence, at R=0.7 the CC model is never exercised and the crack growth increments are computed directly from the NASGRO crack growth equation. As shown in Fig. 2a, the lower the R-ratio, i.e. the more active the CC mechanism, the more significant discrepancies between the simulated and observed results. Fig. 2b demonstrates that the model underestimates the beneficial effect of an OL on crack growth, as the predicted OL-affected zones are systematically shorter than the observed values. In Fig. 2b, the differences between the observed and computed crack growth rates on the OL application exhibited for Specimen 0209, 0210 and G4 stem from the poor predictions of crack growth under to the preceding CA baseline loading (compare Fig. 2a).

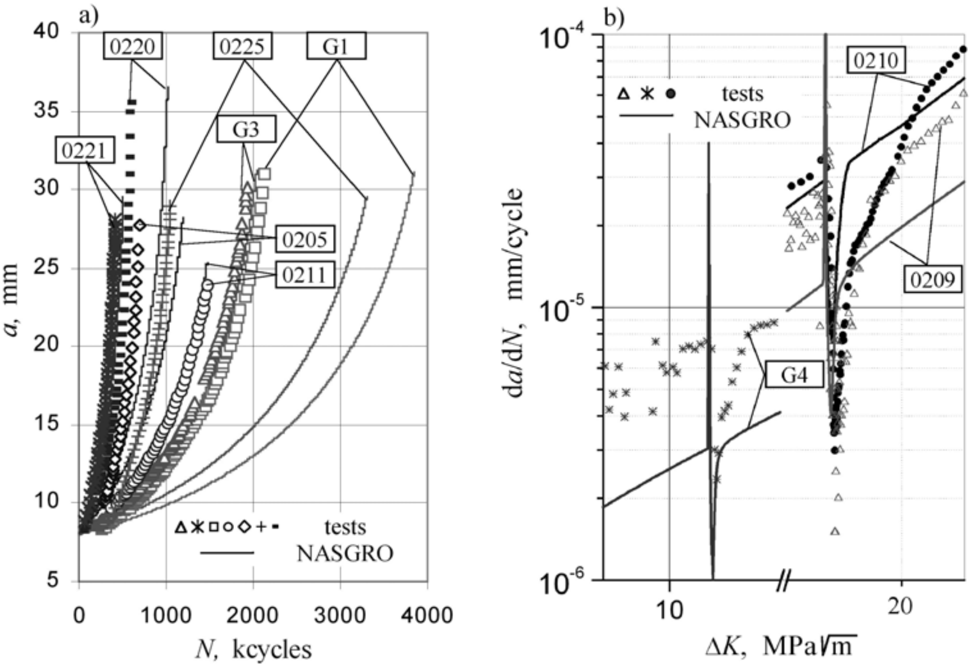


Figure 2: Comparisons between the experimental results and the NASGRO model predictions: (a) CA tests; (b) OL tests

Though the predictions presented above have been obtained from the “constant constraint” option, the “variable constraint” option has also been checked leading to equally inadequate results for CA loading and still worse for the OLs.

Fig. 2a indicates that the NASGRO simulations tend to exaggerate the *R*-ratio effect. For materials which, like the structural steel, show a small influence of *R*, a “bypass” track is recommended in the NASGRO program [6] which yields the constraint factor (alpha) of 5.845 and the S_{max}/SIG_O parameter of 1 (compare Fig.1). Because the load interaction is totally ignored with the latter option, its application to structural steel, which exhibits significant load interaction effects, would be unfounded. Moreover, for the considered material, the “bypass” option has been still found to overestimate the *R*-ratio effect under CA loading. A general conclusion from all the analyses can be that the NASGRO SY model shows an unsatisfactory performance for structural steel.

4 CALIBRATION OF THE SY MODEL

With the purpose of calibrating the SY model for structural steel, its implementation according to the present authors is applied [3]. As distinct from the NASGRO algorithm, the present model requires to declare in the input file Elber’s law based on CC measurements. A previous work [7] has revealed that the *R*-ratio influence on crack growth in structural steel cannot be covered by SY model predictions when a constraint factor is imposed only on tensile yielding, as proposed by Newman [8]. Hence, the present model is tuned using three independent constraint factors on tensile and compressive yielding ahead of the crack tip (α_t and α_c respectively) and on yielding in the crack wake (α_w). Facing that a measured level of

S_{op} can be matched by the model for more than one combination of the three α-values, an additional criterion for their selection is proposed, namely achieving an agreement between the observed and predicted by the model cyclic stress-strain behaviour at the crack tip, as illustrated in Fig. 3. Here, the local cyclic stress-strain response of the material is represented by the observed and predicted stress-offset strain (S-ε_{offset}) loops derived from the local compliance records [4,5] and through employing Westergaard's complex potential [9] respectively. Noteworthy, matching the predicted and observed loops automatically yields matching the predicted and observed S_{op} levels. The similarity criteria for the observed and predicted loops are discussed elsewhere [10].

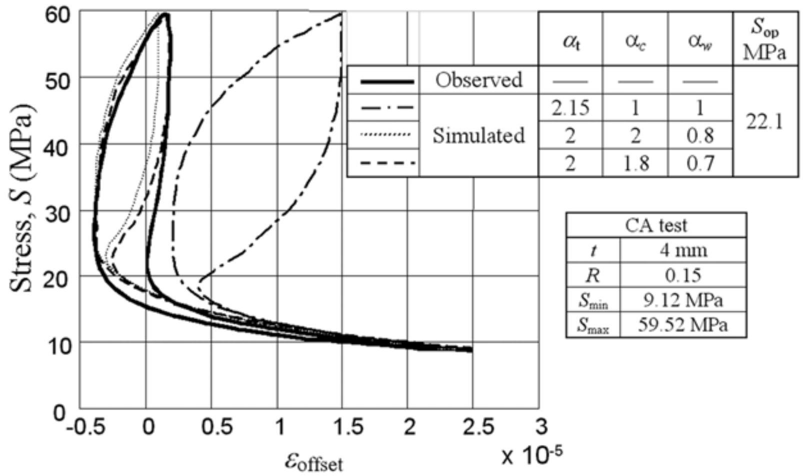


Figure 3: Exemplary comparisons between the observed and simulated P-ε_{offset} loops for various combinations of the calibration coefficients

The above approach was applied to extract the calibration coefficients required to correlate the CA test results. The corresponding variations in α-factors with R can be fitted by the following equations:

$$\alpha_t = 1.041749 \cdot R + 2.643910 \quad (1)$$

$$\alpha_c = \begin{cases} 1.3; & \text{for } R \le 0 \\ -0.3463 \cdot R^3 + 0.7013 \cdot R^2 + 0.03593 \cdot R + 1.3; & \text{for } R > 0 \end{cases} \quad (2)$$

$$\alpha_w = 0.4941 \cdot R^2 + 0.969 \cdot R + 0.8233 \quad (3)$$

Against the trend observed in the present tests and elsewhere [11], the NASGRO SY model is not capable of predicting the retarded crack growth increment after a single OL (Δa_{OL}) over a distance exceeding the OL plastic zone (r_{pOL}). FEM analyses [12] indicate that the $\Delta a_{OL} > r_{pOL}$ effect stems from hardening the material within the OL plastic zone and does not appear if, like in the SY model, a perfectly plastic material is assumed. The material hardening due to the OL 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. To reproduce the above behaviour in the SY model, the α_c and α_w factors are elevated within the OL plastic zone, according to the rules provided in Fig. 4. Here α_c^{CA} and α_w^{CA} are derived from the CA tests and given through Eqs. 2 and 3 respectively, whilst PPZ and SPZ denote the range of the primary (i.e. generated in the material that has not been

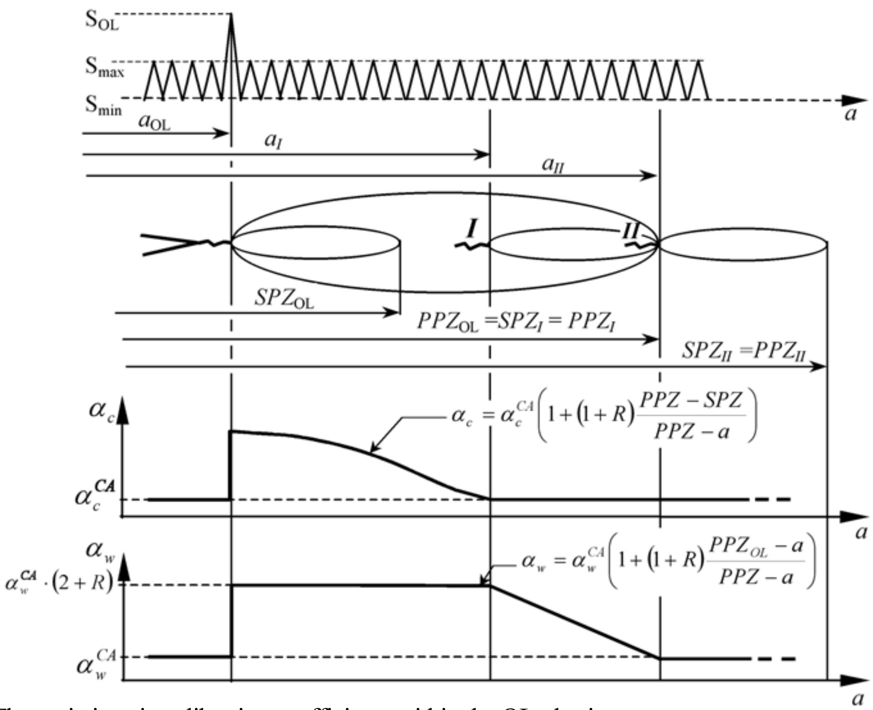


Figure 4: The variations in calibration coefficients within the OL plastic zone

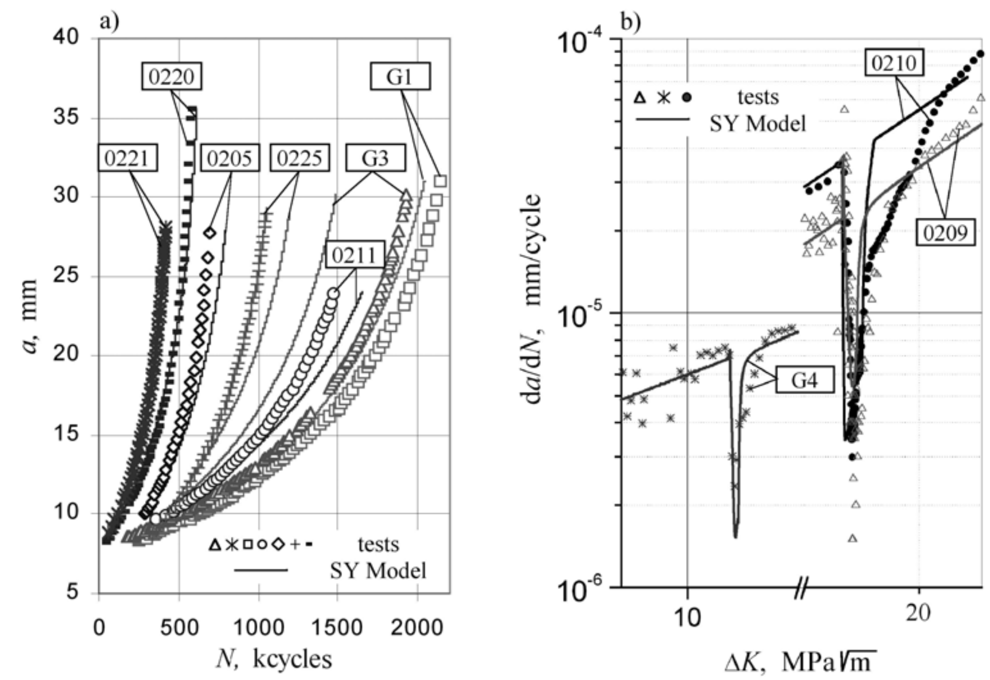


Figure 5: Comparisons between the experimental results and predictions from the SY model according to the present authors: (a) CA tests; (b) OL tests

plastically deformed before) and secondary (i.e. generated inside PPZ) plastic zone. In terms of the Dugdale concept of crack tip plasticity, PPZ is identical with the current fictitious crack length.

The results obtained from the present SY model incorporating the constraint factors according to Eqs. (1-3) and Fig. 4 are plotted together with the experimental data in Fig. 5. Compared to the NASGRO model predictions, a considerable improvement is achieved in the correlation of the *R*-ratio and cyclic stress level effects under CA loading (Fig. 5a) and of the OL influence (Fig. 5b) though the retardation effect of the largest OL (Specimen 0210) still remains underestimated. The ongoing work aims at covering by the model the effect of specimen thickness and the trends observed under periodic single and block OLs.

5 CONCLUSIONS

1. Compared to the crack growth behaviour observed in fatigue tests on a structural steel, the NASGRO strip yield (SY) model predictions using either constant or variable constraint factors were found to exaggerate the effects of stress ratio under constant amplitude loading and underestimate the influence of overloads.
2. To correlate the observed trends in crack growth, the SY model must incorporate three independent constraint factors, namely on tensile and compressive yielding ahead of the crack tip and on yielding in the crack wake.
3. A procedure proposed for selecting the constraint factors offers the means to calibrate the SY model for structural steel based on a physical foundation, namely to match the measured and observed cyclic stress-strain behaviour at the crack tip.
4. The SY model by the present authors coupled with constraint factors extracted using the aforementioned procedure correctly covers the stress ratio and cyclic load level effects on the crack growth response under constant amplitude loading and, compared to the NASGRO model, produces improved predictions of the overload-induced retardation in crack growth.

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