Evaluation of Fatigue Crack Closure from Local Compliance Measurements in Structural Steel

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ABSTRACT: *Two procedures developed by the present authors are applied to evaluate crack closure for structural steel. One of these (the A method) involves operations on electric signals from the load and local strain transducers, whilst the other (the D method) applies processing of the digitized compliance data. The closure levels are identified based on comparisons between the open crack compliance variations upon loading and unloading. Specially designed fatigue tests were conducted to generate fatigue crack growth data and compliance data necessary to check the performance of both methods. Parameters of the compliance data acquisition were found to significantly affect the closure levels according to the D method. For a properly chosen combination of these parameters, the D method results compare well with those from the A method obtained using a different measurement system and assumed to represent the true closure levels. The adequacy of both methods is proved by the ability of the resulting effective stress intensity factor range to correlate the observed effects of stress ratio on fatigue crack growth and to account for the post-overload transient crack growth behaviour.*

INTRODUCTION

Literature evidence indicates that the effective stress intensity factor range (ΔK_{eff}) derived from crack closure (CC) measurements can be not fully capable of correlating the observed crack growth behaviour for structural steel (e.g. [1,2]). Here $\Delta K_{\mathrm{eff}}=K_{\max}-K_{\mathrm{op}}$, where the stress intensity factors $K_{\max}$ and K_{op} correspond to the maximum load of a fatigue cycle and to the crack opening load (P_{op}) which is a lowest load level at which the contact stresses vanish upon loading. In works [1,2] the P_{op} values were estimated from the load-local strain (P-ε) data under the assumption that a P-ε plot is linear for the fully open crack. The condition of a constant compliance value above the P_{op} level is inherent in most methods for the evaluation of CC from load-deformation records (e.g. [3,4]).

Toyosada and Niwa [5] have proposed that because of the presence of glissile dislocations at the crack tip due to the previous cyclic loading, no part of the P-ε plot can be linear. They assume a similar compliance behaviour in two portions of a fatigue cycle when fully elastic conditions prevail ahead of the crack tip, namely just after the crack has fully open on loading (region AB, Fig. 1a) and just below the maximum load on unloading (region CD, Fig. 1a). Points B and D correspond to the onset of tensile yielding and compressive yielding respectively. Typically, not only regions AB and CD but also the total plot of the raw P-ε data look linear. However, provided that sufficiently sensitive measurement instrumentation has been used, compliance changes in these regions can be revealed after an appropriate conversion of the P-ε data into the P-$\varepsilon_{\mathrm{offset}}$ loop, where $\varepsilon_{\mathrm{offset}}$ is the offset strain (Fig. 1b). Then the P_{op} level can be found as the lower bound of the load range within which the original P-$\varepsilon_{\mathrm{offset}}$ loop (full line in Fig. 1c) and the loop rotated by 180° and shifted in the P-axis direction (dashed line in Fig. 1c) overlap. The load range between points C and D is always larger than that between points A and B because in either phase of the fatigue cycle the crack tip acuity is different.

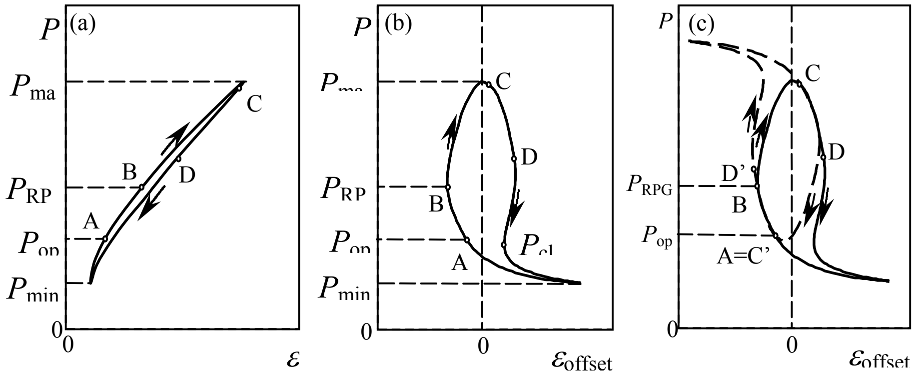

Figure 1: Principle of the crack opening load determination according to Ref. [5]: (a) P-ε plot; (b) P-$\varepsilon_{\mathrm{offset}}$ loop; (c) determination of P_{op}.

Evaluating CC according to the above conception can be done either by operations on the P and ε electrical signals using an electronic circuit developed by Toyosada and Niwa [5] or numerically, as proposed by Skorupa et al [6]. In the present paper, both methods of the P-ε data processing are applied to estimate P_{op} levels in structural steel. The results are considered adequate if the corresponding ΔK_{eff} parameter correlates the effects of stress ratio (R) on fatigue crack growth rates (da/dN) and accounts for crack growth retardation after an overload (OL) cycle.

EXPERIMENTAL PROCEDURES

The material used is low carbon structural steel (18G2A according to PN-EN 10028), yield stress = 392 to 402 MPa, tensile strength = 536 to 544 MPa, and elongation to failure = 22 to 28%. 4 mm thick and 100 mm wide M(T) specimens were machined from an 8 mm thick plate with the specimen axis in the rolling direction. The fatigue crack growth tests were performed under load control until the specimen failure. During each test, CC measurements were made using the local compliance technique. Prior to precracking a series of strain gauges (length 2 to 6 mm, width 0.7 to 1 mm) straddling the expected crack path was bonded on each specimen at various crack length positions. Two test series, further termed A and D because of the analogue [5] and digital [6] processing respectively of the collected P-ε data to estimate P_{op}, were realised.

The Series A tests were carried out utilizing a 50 kN Shimadzu fatigue machine at a loading frequency of 10 Hz. The loading conditions for two constant amplitude (CA) tests and for a test with a single overload (OL) of the P_{OL} level applied at the crack length a=13 mm are specified in Table 1. For the OL test, P_{max} and P_{min} are the baseline load levels prior to and after the OL. The electric signals from the load cell, strain gauges and the subtraction circuit [5] were converted into digital signals of a 12 bit resolution using the simultaneous sampling A/D converter.

TABLE 1: Loading conditions for the Series A tests

Test type	Stress ratio R	Load levels (kN)		
		P_{min}	P_{max}	P_{OL}
CA	0.15	3.66	23.86	
	0.51	20.81	40.83	
OL	0.07	1.46	21.47	41.02

The series D tests were conducted using a 250 kN Dartec fatigue machine and comprised a CA test and an OL test. In first of these, the crack was grown up to a=16.8 mm under the same CA loading as in the Series A, R=0.15 test. Then, loading as in the Series A, R=0.51 test was applied. With the OL test, the load pattern was identical as that in the Series A, OL test until the post-OL retardation in crack growth vanished. Next, at the crack length of 15.2 mm, P_{max} was increased to 33.47 kN which implied the new baseline loading R-ratio of 0.04. When the stable crack growth was achieved, another OL cycle of P_{OL}=57.46 MPa was applied at a=17 mm and the pre-OL baseline loading was recommenced. The load frequency was typically 15 Hz except when CC measurements were taken, as explained later.

A five channel data acquisition system incorporated in the fatigue machine controller was used to store the compliance records. The electric signals from the load cell and 3 strain gauges closest to the crack tip were phase-matched and converted into digital signals of a 19 bit resolution at a sampling rate of maximum 2000 Hz per channel. Analyses of the P-ε data using the algorithm [6] revealed that the resulting P_{op} values were strongly affected by the electrical signal gain, the data sampling frequency (f_S) and the loading frequency (f_L). To optimise the data acquisition the P-ε records were collected using several combinations of the above parameters. Two different values of signal gain were applied and the considered frequency ranges were: f_L= 0.07 to 10 Hz and f_S=25 to 2000 Hz.

RESULTS

The P-ε data processing outlined in Ref. [5] and referred to further as the A method was applied to estimate CC for the Series A tests. The resulting P_{op} variations are shown in Figure 2 by the open symbols. The corresponding da/dN vs. ΔK_{eff} data provided in Figure 3 are independent of the loading conditions which indicates that CC can fully account for the influence of the R-ratio and of the OL on crack growth.

The primary version of the algorithm (further referred to as the D method) used to estimate P_{op} for the series D tests has been described in Ref. [6]. In the currently used procedure, modifications in filtering the measurement data and in identifying the overlapping sections of the P-ε_{offset} loops (compare Fig. 1c) have been introduced in order to improve the computational efficiency and to reduce the scatter in the results.

To chose the optimal combination of the data acquisition parameters for the CC measurement system used in the Series D tests, it was assumed that the results derived via the A method represented the "true" P_{op} values. The results from both methods were found to compare most favourably for the P-ε data collected at f_L=10 Hz, f_S=2 kHz and the strain gauge signal gain of 2660 times. The corresponding P_{op} variations according to the D method are presented in Figure 2 as the closed symbols. A larger scatter exhibited by the D method results compared to those from the A method is mainly due to a user-independent noise of an almost constant amplitude and a frequency of 50 Hz generated inside the fatigue machine controller. The P signal

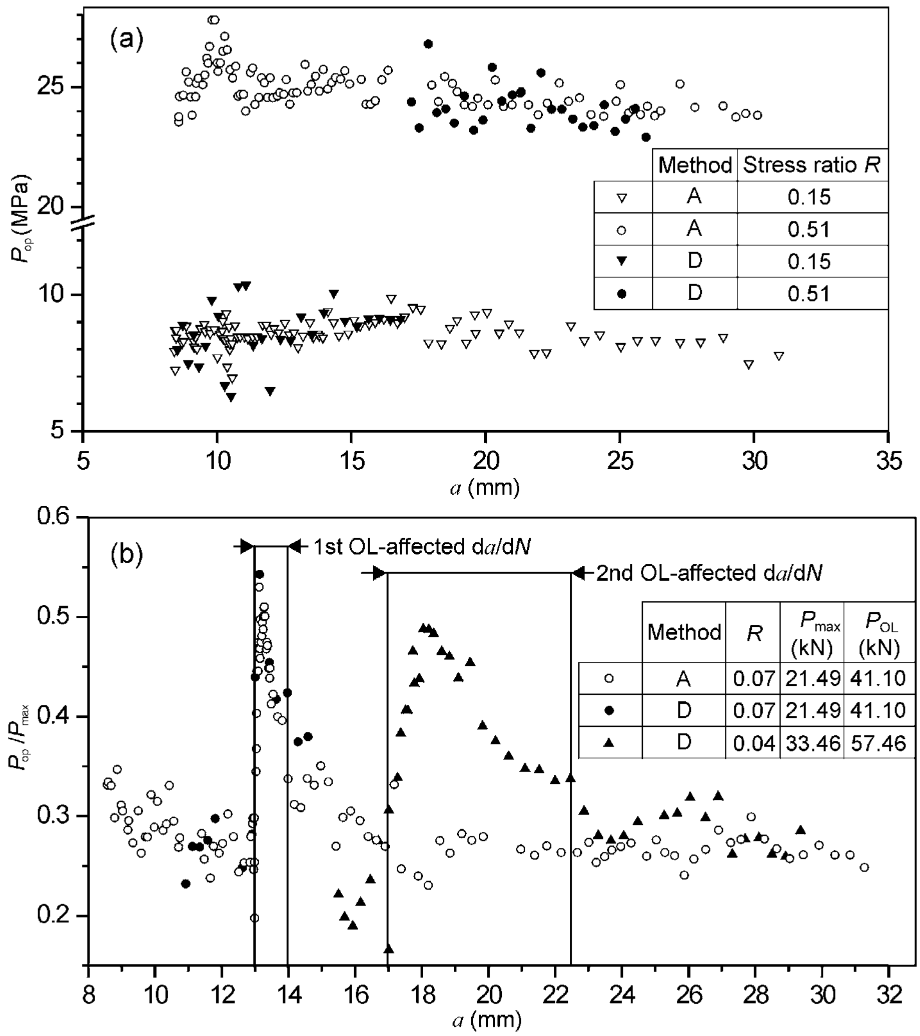

Figure 2: P_{op} variations from the A method and from the D method: (a) CA tests; (b) OL tests.

suffered from noise of 0.1 kN in range which implied 0.5% the lowest load range applied in the Series D tests. The noise on the ε signal was of magnitude 0.98% and 0.14% that of the strain range at the beginning and at the end of the tests respectively. Apparently, the noise levels were not excessive. However, because the P-ε_{offset} loop widths were only from 0.06% to 4% the strain range, the noise-to-signal ratio for the ε_{offset} signal was typically from as much as 15 at the beginning of a test to 0.04 at its end. The present analyses of the P-ε data suggested that valid results on P_{op} could not be obtained if the noise-to-signal ratio exceeded 0.72.

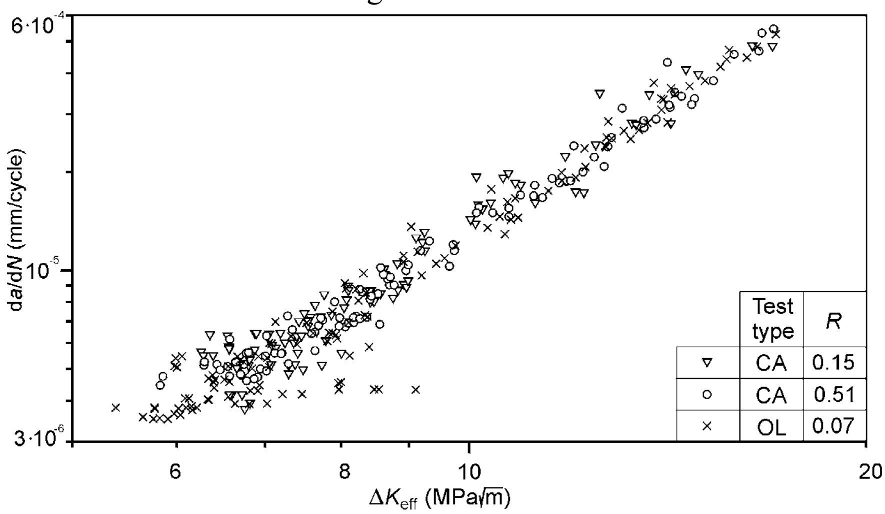

Figure 3: da/dN vs. ΔK_{eff} data for the Series A tests based on the A method.

Because of a premature strain gauge failure, only few measurement data sets have been captured prior to the 1st OL cycle, Figure 2b. The normalised P_{op} levels from the D method after the 1st OL application compare well with those according to the A method. For both methods, however, the distance over which the elevated P_{op} levels occur after the 1st OL exceeds the observed OL-affected zone. The P_{op} values just after the step-up in S_{max} (closed triangles, Fig. 2b) imply a transient acceleration in crack growth as they fall below the stationary level indicated by the results from the A method. A drop in P_{op} detected just after unloading from the 2nd OL suggests a short-termed acceleration in crack growth. The subsequent P_{op} behaviour is typical for the OL-induced delayed retardation in crack growth. The distance over which the CC transients caused by the 2nd OL have been detected equals the observed zone of the transient da/dN behaviour. The normalised stationary P_{op} levels eventually attained after the 2nd OL match those provided by the A method at the similar, near zero R-ratio.

The da/dN vs. ΔK_{eff} data for the Series D tests are shown in Figure 4 together with the scatter bands corresponding to the Series A test data from Figure 3. It is evident in Figure 4 that the ΔK_{eff} parameter based on CC estimates from the D method reconciles the results obtained under various loading conditions although, due to a more excessive measurement noise, the scatter is somewhat larger than in the case of the Series A results. Noteworthy, the data points corresponding to the lowest crack growth rates observed after the 1st OL fall along the regression line for the Series D, CA test data also plotted in Figure 4.

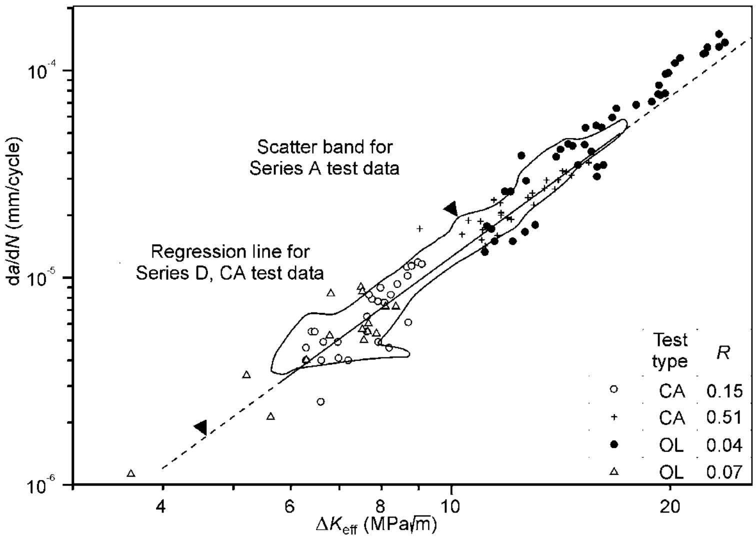

Figure 4: da/dN vs. ΔK_{eff} data for the Series D tests based on the D method.

The correct CC estimates in the Series D tests are further confirmed in Figure 5. Here, the predicted da/dN values for the test with the two OL

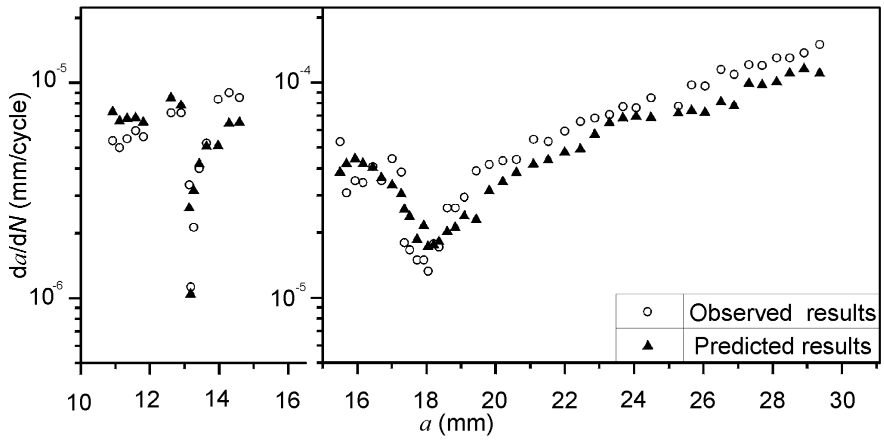

Figure 5: Comparison between observed and predicted from crack closure measurements crack growth rates in the Series D, OL test.

cycles have been computed using the master da/dN=f(ΔK_{eff}) relationship (i.e. the equation of the regression line for the CA results, see Fig. 4) with the ΔK_{eff} values determined from the CC measurements. Though very low strain range values during the 1st part of the test resulted in high levels of the noise-to-signal ratio, the predicted crack growth rates compare well with the observed data.

SUMMARY AND CONCLUSIONS

Literature evidence and results obtained by some of the present authors indicate disparities between the observed crack growth behaviour for structural steel and the closure behaviour estimated from compliance measurements under the assumption of a constant compliance value for the fully open crack. With the two methods presented in this paper, the crack opening levels for a structural steel were determined based on comparisons between the open crack compliance variations on loading and unloading. The analogue (the A method) and digital (the D method) processing of the local compliance data collected during the fatigue tests was applied. Though closure levels from the D method were affected by parameters of the compliance data acquisition, it was possible to select a combination of these parameters for which a conformance of the D method results and the reference values from the A method was achieved. The effective stress intensity factor range based on closure estimates from either method reconciled the crack growth rates measured in the tests under various fatigue loading conditions. It was concluded that the closure behaviour evaluated from both methods adequately accounted for the observed effects of stress ratio and overload cycles on fatigue crack growth.

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