LOAD BEARING CAPACITY OF CRACKED ROLLERS CONTAINING RESIDUAL STRESSESES

H.J. Schindler and U. Morf *

Residual stresses that have been determined experimentally as well as a high Mode II component were identified to be primarily responsible for the forming of cracks that were detected in steel rollers of bridge supports. However, according to a fracture mechanics analysis and comparison with experiments, both of the mentioned load components seem to have - compared with the Mode I stress intensity factor resulting from the service load - only little effect on the remaining limit load of the cracked rollers. In fact, the fracture load of cracked rollers is even higher than the one obtained by linear elastic fracture mechanics analysis. This beneficial behaviour is attributed to nonlinear crack closure effects.

INTRODUCTION

In rollers of high strength steel that are used to support bridges in order to allow for movements caused by dilatation of the bridge, several cracks, some of them reaching as deep as to the centre of the roller, have been detected after some years of service. These cracks appeared to be rather unexplicable, since there are only minor tensile stresses present, and the concentrated compressive stresses in the region of Hertzian contact stay below the limits given by the corresponding design standards. In [1] it is shown, that a Mode II crack loading component is present that is high enough to cause crack growth. However, the hypothesis of a mode-II-driven crack still leaves some features of the cracks unexplained, indicating that there must be further reasons for their growth. Recently, it was found that the residual stresses that are produced by the heat treatment [2] play a dominant role. Although their magnitude is not very high in comparison with the strength of the material, they result in a stress intensity factor (SIF) that exceeds the fracture toughness of the material and makes possible crack spreading as well as their subsequent arrest [3].

*Swiss Federal Lab. for Materials Testing and Research (EMPA), Ueberlandstrasse 129, CH-8600 Dübendorf, Switzerland

From a practical viewpoint, the question of the structural safety of rollers containing undetected cracks arose. Considering the high crack load due to the residual stresses and the linear superposition principle of linear elastic fracture mechanics, one might guess that there is not much load bearing capacity left for the service loads. However, test performed on such naturally cracked rollers showed a surprisingly high critical load, which was about the same as if there were no residual stresses. It is the topic of the present paper to show by theoretical considerations how the Mode I and II crack load components as well as the residual stresses component act together in combination.

EXPERIMENTAL RESULTS

Critical Load of Cracked Rollers

The rollers are made of high chromium quenched and tempered tool steel of a nearly homogeneous hardness of about 47 HRC and a fracture toughness of about 1300 $N/mm^{3/2}$. The diameter is 140 mm and the axial length about 500 mm. For test specimens, disks of 20 mm thickness were sliced from a cracked roller. The initial length of the natural crack was a=70 mm. The representative (i.e. most unfavourable) orientations of the crack with respect to the loading line are those shown in Fig. 1, load cases (a) and (b). The fracture behaviour was brittle, exhibiting an essentially linear force-displacement diagram up to the point of fracture, where an unstable crack growth was initiated. Fig. 2 shows the disk loaded by a one-sided force (Fig. 1, load case (b) after the test. In case of symmetrical loading (Fig. 1, load case (a)), a straight crack path was obtained. The experimentally obtained critical loads F_{cr} were as follows:

- Load case (a): F_{cr} = 25'900 N/mm
- Load case (b): F_{cr} = 21'700 N/mm

For comparison: The design load (allowable load) of this type of rollers is 7960 N/mm. Thus, the cracked rollers seem to be still able to carry the service load.

Stress Intensity Factor due to Residual stresses

The residual stresses and the resulting stress intensity factor for radial cracks were determined by the so called crack compliance method. Thereby, the residual stresses is determined from the strain change at a certain location during progressive cutting. A detailed description of the method is given in [4]. The application to residual stresses measurement in a roller or a circular disk is reported in [2]. The circumferential residual stresses is found to be approximately parabolically distributed, with the maximum tensile stress of about 200 N/mm^2 on the surface. In [3] a technique is developed which enables one to directly obtain the stress intensity factor (SIF) due to the residual stresses. The corresponding experimental results are shown in Fig. 3.

Comparing these experimental values with the fracture toughness of the material (see above) - and taking into account that the effective SIF in the roller is increased due to plane strain condition by a factor of about 1.43 - shows that the SIF exceeds the fracture toughness in a certain range of crack depths. Thus, the SIF due to the residual stresses explains why there is crack growth and subsequent arrest.

STRESS INTENSITY FACTORS DUE TO SERVICE LOAD

Consider load case (b) in Fig. 1, which is the most unfavourable load case of a cracked roller. This system (A in Fig. 4) can be decomposed into an antisymmetrical part B, which is loaded in mode II only, and a symmetrical part C, which is loaded in mode I only (Fig. 4). (The horizontal force H will be discussed later on.) According to [1], the SIF of System B is approximately

$$K_{II} = \frac{F}{\sqrt{D}} \cdot \frac{(1.30 - 0.65A + 0.37A^2 + 0.28A^3)}{\sqrt{\pi \cdot A}(1-A)} \tag{1}$$

where A=a/D is the nondimensional crack length. Eq. (1) is essentially the solution given in [5] for a surface crack in a rectangular plate under a pair of forces acting at the crack mouth. It can be shown that, concerning the resulting SIF, this system corresponds to system B to a high degree. Graphically, eq. (1) is shown in Fig. 5. It exhibits a singularity at A=0, which is due to the perfectly concentrated load. Accounting for the actual distribution of the Hertzian contact stress results in the thinner lines of $K_{II}(A)$ in the region of small A in Fig. 5 (Because of the nonlinear character of the Hertzian contact stress field, the SIF of different load levels are different in the nondimensional representation of Fig. 5; see [6] for more details).

The symmetrical system C in Fig. 4 is special insofar as the vertical forces F/2 tend to close the crack mouth, which results in horizontal contact forces H acting at the crack surfaces near the crack mouth. These forces play an important role in the SIF solution, and adds a nonlinear component to the problem. In [6] it is shown how the SIF for this system C can be obtained by calculating H from the condition of zero crack opening displacement and superimposing the two basic solutions given by Gregory [7]. Therewith, a remarkably simple closed form solution is obtained which is valid for the whole range 0<A<1 (see [6]):

$$K_I = 1.2656 \frac{F}{\sqrt{D}} \left[\sqrt{\frac{A}{(1-A)^3}} - \frac{2.5935 + 4.4533 \cdot A}{\sqrt{A(1-A)^3}} \cdot Z \right] \tag{2}$$

where

$$Z = \frac{2.5935 \cdot I_1 + 4.4533 \cdot I_2}{23.0993 \cdot I_1 + 19.8319 \cdot I_2 + 6.7262 \cdot I_3} \tag{3}$$

with

$$I_1 = \frac{1-(1-A)^2}{2(1-A)^2}, \quad I_2 = \frac{A^2}{2(1-A)^2}, \quad I_3 = \ln\frac{A}{A_0(1-A)} + \frac{2A}{1-A} + \frac{A^2}{2(1-A)^2}$$

$A_0=a_0/D$, where a_0 denotes the width of the contact area of the crack faces near the crack mouth. a_0 can be assumed to be approximately the width of the Hertzian contact area. K_I according to (2) is shown in Fig. 5. In the present case we assume $A_0=0.02$. The contact force H as a function of the crack length is given by

$$H = (\frac{1}{\pi} - 2.2432 \cdot Z) \cdot F \tag{4}$$

[6]. H(A) shows a maximum of about 0.3F (depending on A_0) near $A=A_0$ and decreases approximately linear to zero at A=1. For A=0.5, e.g., H is about 0.17F.

SUPERPOSITION OF SERVICE LOAD AND RESIDUAL STRESSES EFFECT

According to the foregoing two sections, each of the three major components of the crack loading - Mode I, Mode II and residual stresses - is nearly high enough to cause crack extension by itself. Nevertheless, the loading tests performed on specimens containing the residual stresses showed surprisingly high SIFs at maximum force. Inserting the experimentally determined critical forces F_{cr} A=0.5 in the equations (1) and (2) results in the following maximum SIFs:

	K_I [N/mm$^{3/2}$]	K_{II} [N/mm$^{3/2}$]
Loading according to Fig. 1(a)	1738	0
Loading according to Fig. 1(b)	1450	2270

Thus the SIFs due to F_{cr} are even higher than K_{Ic} although there is, in addition, the SIF due to the residual stresses as shown in Fig. 3. Obviously, the residual stresses does not affect the load bearing capacity of cracked rollers significantly. The key to this surprising behaviour is the nonlinear effect due to the crack face contact as discussed above for system C in Fig. 4. The effect of the contact force H, which is given in Eq. (4), is twofold:

- It generates frictinal forces between the crack faces, which reduces the Mode II effect. Assuming a friction coefficient of 1, the reduction of K_{II} is about 40%.
- It cancels the effect of the residual stresses to essentially zero, since the crack-mouth, which is opened by the residual stresses, is re-closed by the vertical compressive forces F/2 of system C in Fig. 4.

CONCLUSION

Although the residual stresses plays a dominant role in the process of crack initiation, spreading, and arrest, it has practically no influence on the load bearing capacity of cracked rollers. The reason for this beneficial behaviour is first of all the nonlinear superposition of the two load cases because of crack closure effects. The SIFs due to the fracture load in both mode I and mode II even exceed the fracture toughness. This aspect needs further clarification. A possible reason could be the extraordinarily high second (constant) term in the near-tip stress field [8]

REFERENCES

[1] H.J. Schindler, in: Proc. of 8th European Conf. on Fracture, Torino 1990, Vol. 3, (Ed. D. Firrao), 1990, EMAS, pp. 1621-1626

[2] H.J. Schindler, W. Cheng, I. Finnie, accepted for publication in: Proc. of 4th Int Conf. on Residual stresses, Baltimore, USA

[3] H.J. Schindler, W. Cheng, I. Finnie, submitted to Int. J. Exp. Mechanics

[4] W. Cheng, I. Finnie, Welding in the World, Vol. 28, 103-110, 1990

[5] H. Tada, et al., "The Stress Analysis of Cracks Handbook", Del research Corp., Hellertown, 1973

[6] H.J. Schindler, to be published

[7] R.D. Gregory, Int. J. Fracture, Vol. 41, 1989, pp. 39-50

[8] M. Wernli, H.J. Schindler, in: Localized Damage, Comp. Mechanics Publication, Southampton, 1992

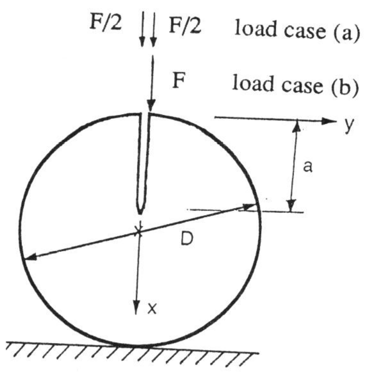

Fig. 1: Cracked roller loaded by compressive radial force

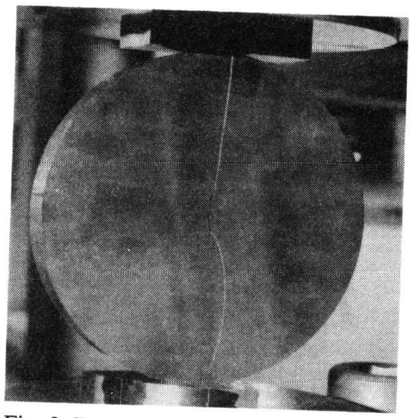

Fig. 2: Test specimen after failure under load case (b) as defined in Fig. 1

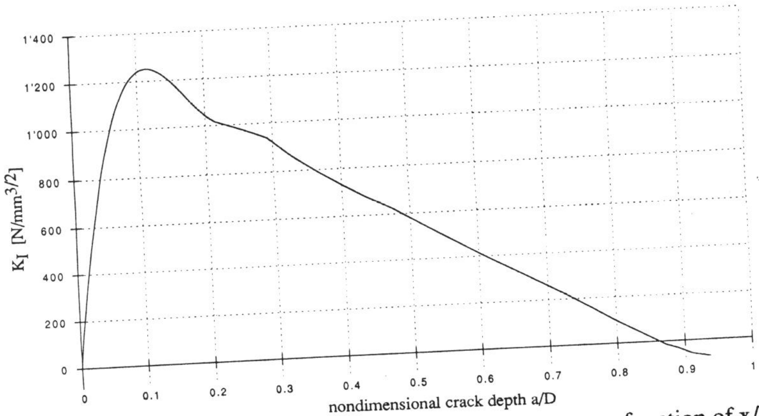

Fig. 3: Experimentally determined SIF due to residual stresses as a function of x/D

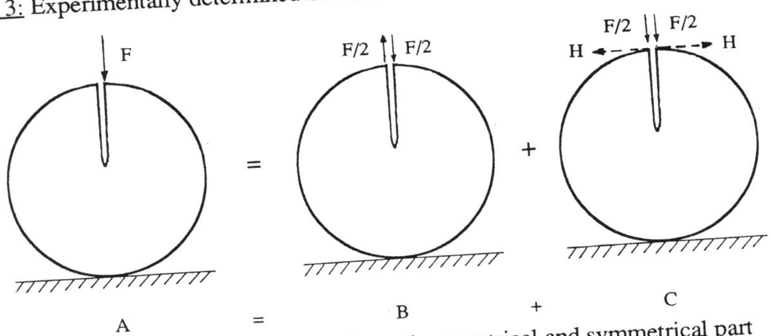

Fig. 4: Decomposition of Fig.1(b) in its antisymmetrical and symmetrical part

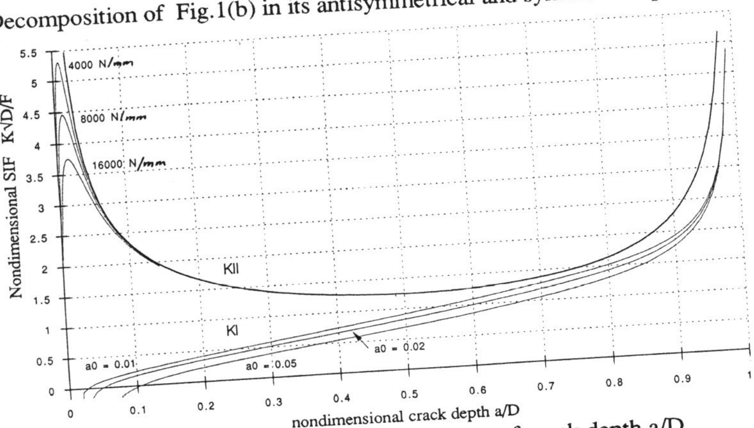

Fig. 5: SIF K_I and K_{II} of system Fig. 1(b) as a function of crack depth a/D