EXPERIMENTAL DETERMINATION OF K_I, K_{II}, K_{III} OF INTERNAL CRACKS UNDER ROLLING CONTACT LOADING

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ABSTRACT

The ever increasing research of performances and lightness leads engineers and manufacturers toward the development of heavily loaded components, made of materials with improved surface mechanical properties, subjected to multiaxial fatigue loads.
In these cases it is not rare the development of internal cracks, whose propagation involves mixed-mode conditions; an accurate prediction of the growth rate and of the crack path requires the knowledge of the stress intensity factors concerning mode I, II and III.
In this paper an original method for the experimental determination of these quantities is described. It is based on the photoelastic technique and allows to obtain internal cracks with regular shape without using any cutting device.

1 INTRODUCTION

In recent years, due to the increasing demand for reliability, lightness and performances, contact analyses have gained more and more attention in many transportation systems. This topic is of particular interest in railway transportation, where the introduction of new trains can result in higher contact pressures and dynamic forces between the wheel and the rail.
The direct consequence of these severe working conditions is that some types of damage, once rare, are now more frequent, causing accidents or undesirable noise and vibrations. In particular, one of the most typical damage mechanisms of train wheels is called "shelling" and consists in the propagation of a fatigue crack originated by an internal pre-existing or fatigue initiated defect. The direction of propagation is about parallel to the free surface of the wheel till the crack approaches the free surface itself. A section of the wheel tread may then separate from the rim, making the wheel unserviceable.
Wheels and rails are periodically subjected to non-destructive tests NDTs) with the aim of detecting any such defects, but it is also necessary to have a tool for evaluating the criticality of any defects found. Since the defects can be modelled as cracks, the problem can be solved by knowing the stress intensity factor variation in a contact cycle and by comparing it with the threshold value of the material. Due to the fact that it is not possible to find an analytical solution of the cracked wheel, the first step is to define an approach to accurately calculate the stress intensity factors of a three dimensional internal crack under contact loads. Notwithstanding the great attention paid to develop numerical method able to accurately analyze the stress field in cracked wheels that is to say able to calculate the stress intensity factor under normal working load), the problem of evaluating the reliability of the solution is still of interest: in fact the problem is really complex, due to the non linearity of the contact condition, the difficulty in evaluating the friction coefficient between the crack faces and the complexity of the stress field near the cracked zone. From this point of view, it should be useful to have an experimental method that could be used to verify the goodness of the numerical results.

Among the experimental methods, the transmission-photoelastic technique can be conveniently used to determine the stress intensity factor concerning different geometrical and loading situations [1]. This technique consists in constructing a model of the analysed element, made of epoxy resin able to show a temporary double refraction when mechanically loaded. If, under the action of the load, the model is observed with a plane or a circular polarized light, it is possible to relate the isochromatic or isocline fringe patterns with the values of the principal stresses in the model by using the stress-optic law.
This experimental technique is well established in plane stress states and allows for the determination of the stress concentration factor for a great variety of geometry.
As regards mixed-mode fracture mechanics problems, it is possible to experimentally determine the modes I, II and III stress intensity factors by using different methods, i.e. [2-4]. In these cases a real problem is how to obtain a crack; that is to say how we can obtain a crack that present a negligible radius at its tip. In fact, only if the stress field is not strongly altered by the fillet radius in the close neighborhood of the crack tip, the values of $K_{I,\ II,\ III}$ will be reliable. This problem, most of time, is solved by using a fine saw, that allows to obtain an adequate sharp notch, with a negligible difference with respect of the crack induced stress field very close the crack tip. However, the case considered in this paper is rather different from the cases treated in literature. In fact, the crack is an internal one and the problem is how to obtain it, since its configuration prevents the use of an appropriate tool.
In this paper it is described an original photoelastic method to determine the stress intensity factors of internal, curvilinear cracks under a general load. The crack is naturally obtained in the model by thermal shock, by heating the specimen above the glass transition temperature of the resin and then by properly cooling it: the result is a surprisingly regular crack front, whose geometry, nearly circular or elliptical, can be varied by changing the cooling parameters. The cracked specimen is loaded in a oven to use the stress-freezing technique; after the cooling some slides normal to a principal stress have been cut by the specimens and the photoelastic fringes are analyzed.
The problems encountered in developing and calibrating the method are critically described and the photoelastic signals are elaborated by using the methods described in [1] and [5]. Particular effort is dedicated to the determination of K_{III}: this is due to the lack of well established methods with this aim. In this light some preliminary tests were executed on analytically solved case: a cylindrical bar including a circular centered crack, loaded with torque. These experiments are presented here and show good agreement with the analytical solution. So it was possible to use the method for the case of an internal crack under Hertz contact load. The dimensions of the specimens are similar to the ones of railway wheels, being the aim to determine the stress intensity factors along a circular or elliptical crack included in a shelling damaged wheel. At this time experiments are on course and the results will be included in the final presentation.

2 EXPERIMENTAL TESTS: PHOTOELASTIC ANALYSIS

The photoelastic technique consists in constructing a model of the analysed element, made of epoxy resin Araldite®), able to show a temporary double refraction when loaded with a mechanical device. If the loaded model is observed with a plane or a circular polarised light, it is possible to put into relation the isochromatic or isocline fringe patterns with the values of the principal stresses in the model by using the stress-optic law [1].

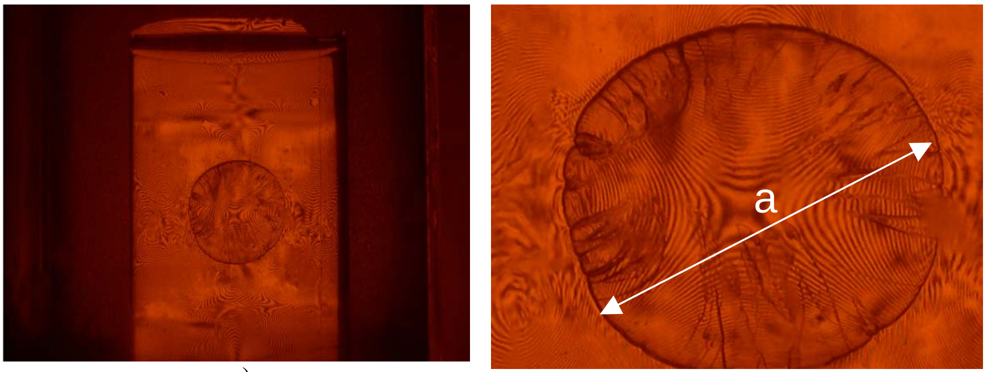
With the aim to evaluate the stress intensity factors related to internal cracks similar the ones found in the wheel internally cracked models have to be realized.
The internal cracks in the photoelastic material have been realized by means of a new method based on the strong variation of the mechanical characteristics of the photoelastic materials with temperature.
The material considered is an epoxy resin (araldite), which has a glass transition temperature equal about to 120°C. The mechanical characteristics are shown in Table 1.

Mechanical Characteristics	**T≈20°C**	**T>120°C**	**Mechanical characteristics**	**T≈20°C**	**T>120°C**
E [MPa] Elastic modulus	3,500	16	ε_R [m/m] Ultimate strain	0.05	0.15
ν Poisson coefficient	0.35	0.47	K_{Ic} [MPa $\sqrt{mm}$] Toughness	24.4	0.23
σ_R [MPa] Ultimate tensile strength	80	2.3			

Table 1: Mechanical characteristics of the araldite

If the specimen is heated to T>120° and then its external surface is quickly cooled till T<120°C, the different mechanical behaviour of the internal and the external material makes possible the formation of a natural internal crack, that does not present the typical problems of the artificially induced ones.
Some cylinders (dimensions: diameter d=50mm and length l=80mm) of araldite were realized. A resistance wire is wound round the central zone of the cylinders in order to heat this zone till a temperature greater than the transition one (T_t=120°C). A thermocouple allows to know the internal material temperature, when the transition temperature is reached in correspondence of a distance from the cylinder axle equal to the value of the desired crack dimension *a*, the heating is stopped and the araldite cylinder is suddenly cooled.
During the cooling the crack initiates and propagates to the desired dimension. In Fig.1 a crack obtained by this method is shown. In this figure is evident the planarity of the crack. Several cracks with a diameter range *a*=4-20mm were obtained by this method and were used to determine the stress intensity factors.
As regards fracture mechanic problems, it is proven that the transmission-photoelastic technique can be used to determine the stress intensity factors concerning different geometrical and loading situations [1-4].
The cracked specimen described in the previous section is included in mould and, by melting fuse Araldite in it, it was possible to include the crack in the model of interest.
Then, after having slowly cooled the system, it was possible to heat it to remove eventual thermal stresses at the interface between the cracked prism and the rest of the cylinder.
Due to three-dimensional nature of the case tested in this work, the photoelastic signal was analysed by using the stress freezing method. The observation of the photoelastic slides was executed by using a diffuse-light polariscope with a monochromatic green light source, and two polarisers and two quarter-wave plates to produce circularly polarised light. The isochromatic fringe data were used to determine the stress intensity factor according to the

method drawn by Dally and Riley [1], as regards the K_{II} and the method described in [5] as regards K_{III}.



a) b)

Fig.1 Crack obtained by means of the thermal method: a) araldite cylinder and crack positioned in a longitudinal plane, b) particular of the circular crack

The rail-wheel case is schematized as two cylinders in contact. In Fig.2 a) the scheme considered is shown: the cracked cylinder representing the wheel is loaded by the hertzian pressure distribution resulting from the contact with the other cylinder. The crack is at a given depth *d* and the photoelastic analysis considered different values of the eccentricity *e* of the load with respect of the crack axis. Two tests were performed: details about them are reported in Table 2.

In Fig.2b and 2c the photoelastic fringes at the crack front point A point A is nearer to the pressure distribution than point B) is shown: the pictures refers to the II test, and, by looking at its trend it is possible to deduce the dominant presence of K_{II}.

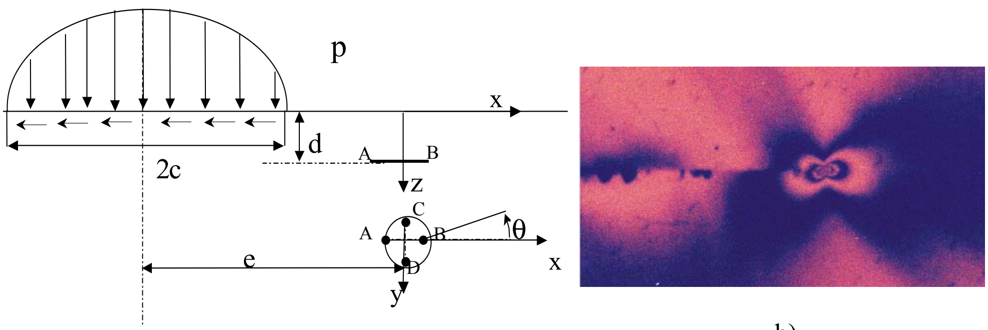
In the Table 2 the results obtained by using an analytical-numerical approach are shown: due to the lacking of data about the friction coefficient between the crack faces these values were imposed according the procedure described in [6], that is to say that it was imposed a friction value that makes equal the experimental and numerical values of K_{II} in A and the comparison is performed by the values of K_{II} in B.

In the points C and D the predominant failure mode is the III one and in previous works [6] it has been determined that this mode is larger than the II one in the points A and B if the defect is elliptical as it is shown in Fig. 3a, where the trend of K_{II} and K_{III} values, with respect of the ratio *r* between the minor and the greater ellipse axis, is reported.

The experimental complexity of the photo-elastic evaluation of the K_{III} in C and D in the case of the two cylinders in contact suggests to apply the technique first to a simpler case: a cylinder R=30mm, h=90mm) internally cracked a=9mm), as shown in Fig. 4, realized by means of the thermal method and loaded in by a torque T. After the stress freezing method was applied, by following the method reported in [5], a tangential slide to the crack border is cut to determine K_{III} at one crack front point. In the plane of the slice see Fig. 4) only tangential stresses are present, and with the applied load case, it is possible to relate the tangential stress pattern with the fringe number [4, 5]. The experimental tests resulted very complex due to the difficult to cut thin tangential slides and to examine a weak fringe pattern.

Test parameters	**I test**	**II test**	**Results [MPa $\sqrt{mm}$]**	**I test**	**II test**
Applied load [N]	650	460	K_{II} experimental A)	0.193	0.150
Crack depth d [mm]	14,5	23	K_{II} numerical A)	0.193	0.150
Eccentricity e [mm]	20	30,9	K_{II} experimental B)	0.096	0.125
Crack dimension [mm]	23 x 18	23 x 18	K_{II} numerical B)	0.100	0.125
Cracked cylinder radius [mm]	800	928			
Uncracked cylinder radius [mm]	540	622			

Table 2: Photoelastic test and comparison between the experimental and numerical results.



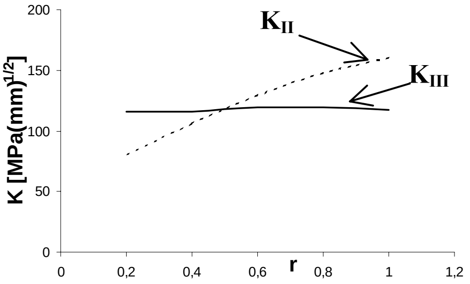
a) b)

Fig.2 In-contact cracked cylinders: a) scheme of the test and most significant parameters; b) photoelastic fringes at crack front point A.

The white light photograph of the tangential slide is shown in Fig.5. The signal is weak but it is possible to find a fringe number N≈0.5, which is similar to the one that could be analytically determined by the theory reported in [7, 8]. These experimental results are preliminary, in fact it is necessary to improve the method by applying a greater torque value in order to have a more intense fringe pattern. The results are, however, encouraging.

CONCLUSIONS

An experimental method, based on photoelasticity, was presented, being the aim the experimental determination of the stress intensity factors of internal cracks loaded under mixed-mode condition. An original method to obtain a internal cracks with regular front in a photoelastic model was developed and enabled to study different geometry and different load cases. The practical cases presented gave promising results; however, further analyses are necessary to tests the applicability and the eventual limitation of the method in the cases in which K_{III} is dominant.



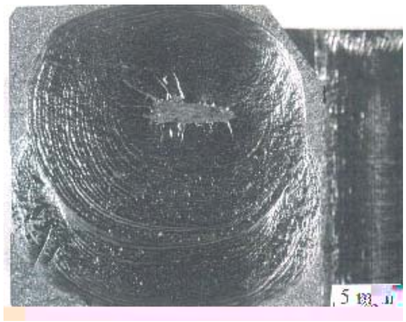


Fig.3a K_{II} and K_{III} trend versus the crack shape r=minor ellipse axis/mayor ellipse axis).

Fig.3b Photograph of a crack detected in a wheel: is evident the initial elliptical shape of the crack that becomes circular.

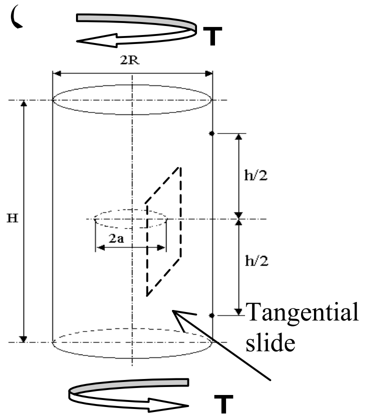


Fig.4 Scheme of the cracked cylinder used for the photoelastic tests

Fig.5 White light photograph of the tangential slide

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