

## DETERMINATION OF STRESS INTENSITY FACTORS DUE TO THERMAL STRESSES USING ISOCHROMATIC FRINGE PATTERS

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**Abstract.** *Transmission photoelasticity was used to obtain an experimental solution for stress intensity factors,  $K_I$ , due to thermal loads in photoelastic models. In a photoelastic plate, a slot to simulate a crack was introduced. Also, a tube to circulate a coolant was fixed in one of the edges of the plate. The photoelastic model was putted on a photoelastic oven and kept at 60 °C. Then, methyl alcohol at -15 °C circulated through the cooling tube. The thermal shock in the plate caused stress on it and, as a consequence, transient photoelastic fringe patterns appeared and were captured by an image acquisition system.*

*For each captured photoelastic fringe pattern, the stress intensity factor  $K_I$  was determined using a dedicated software, specially developed to do it, based on the Dally overdeterministic method. This results are compared with numerical analyses.*

*Based on the obtained results, some conclusions and recommendations on the experimental techniques used were addressed.*

*The paper present a alternative experimental methodology for evaluation of stress intensity factors due thermal loads. The construction of the models can be very simple, the used equipments can be of easy acquisition or manufacture. In this aspect, it should be noticed that in spite of the polariscope used in this work is quite sophisticated, it is necessary a rudimentary polariscope to conduct these type of experiments, just constituted of a light source and plane polarizers plutes easily found.*

**Keywords** stress intensity factor, thermal stress, photoelasticity

### 1. Introduction

When structures or components have discontinuities, such as cracks, the stress fields in the crack tips present singularities. For these materials conditions, the theory of the elasticity is not enough to predict the structural behavior under any loading condition, from the point of view of determining the structure failure. The difficulty in doing such assessment is mainly due to the crack tip geometry with very small curvature radius driving the stresses to very large values. With these singular local stresses, the materials yielding or ultimate stress limits are exceeded even under small loads; in this condition the usual approaches to predict collapse loads based on conventional failure theories are no longer applicable. So it is necessary to use tools from Fracture Mechanics replacing the theory of elasticity to consider the singular stress state at the crack tip (Irwin and De Wit, 1993).

Fracture Mechanics proposes, then, the use of some parameters as the stress intensity factor  $K$ , that takes into account the loads applied to the structure and the crack dimensions. Based on this parameter one can be made decisions regarding the safety of the structure, comparing the value of the applied  $K$  with the value of the material fracture toughness  $K_C$ . For materials of low toughness, the mechanism that governs the structure failure is it is the fragile fracture, and, in this case, the failure critical stress varies in a linear way with the toughness. This problem is dealt with the Linear Elastic Fracture Mechanics that is the base for the methodology presented here. Depending how the loads are applied there are three fracture modes denominated I, II and III, in the literature and corresponding, respectively, to opening mode (associated to stress intensity factor  $K_I$ ), shearing mode ( $K_{II}$ ) and tearing mode ( $K_{III}$ ). The opening mode ( $K_I$ ) is, in general, the more critical and the more common mode in practical situations.

For simple structures geometry, cracks geometry and loading conditions,  $K_I$  can be found in tables or handbooks or be determined using analytical methods. For more complex situations numerical and experimental methods shall be used (Dally and Riley, 1991). Photoelasticity is one of the most used experimental techniques to assess the stress intensity factors.

On the other hand, when thermal gradients in the body cause loads in the structures that are called thermal loads. When the thermal loads act in a discontinuity, the difficulties to determine the stress intensity factors become even greater due to materials non-linearities and due to the uncertainties on the values of the thermal loads.

This work proposal is to present a methodology to determine the stress intensity factor due to transient thermal loads using the experimental technique of the transmission photoelasticity.

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## 2. Adopted methodology

### 2.1. Photoelastic Experiments

To conduct the photoelastic experiments to assess the stress intensity factors due to transient thermal loads a model was built using polycarbonate PSM-1 as its material. This material was selected because its excellent qualities for photothermoelasticity with a highlight on the figure of merit showed in (Miskioglu et al, 1981). The model is a photoelastic plate with a slot to simulate a crack and its schematic drawing is shown in Fig. 1. Also, a plastic tube to circulate a coolant was fixed in one of the edges of the plate with a thermocouple to measure the plate edge temperature during the tests. To measure the model temperatures several electrical temperature strain gages, specially used as temperature sensors, were putted on different locations to obtain the temperature distributions during the tests.

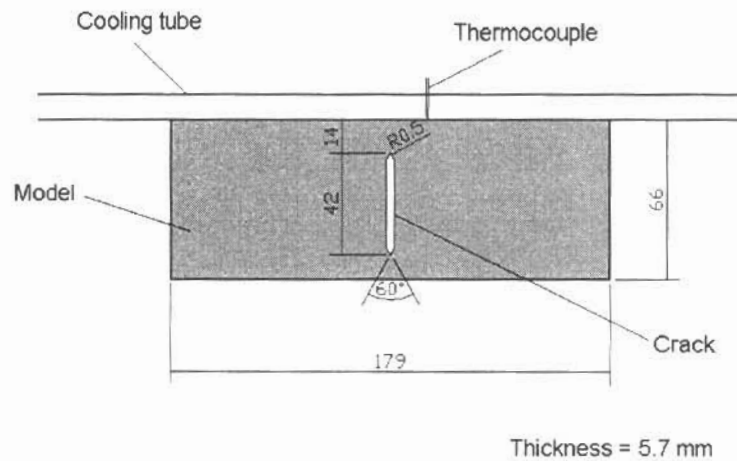


Figure 1 – The photoelastic model – Dimensions in mm

Figure 2 shows the model inside a photoelastic oven. This oven was set up in a transmission polariscope that had an image acquisition system. Figure 3 shows a scheme of this test rig.

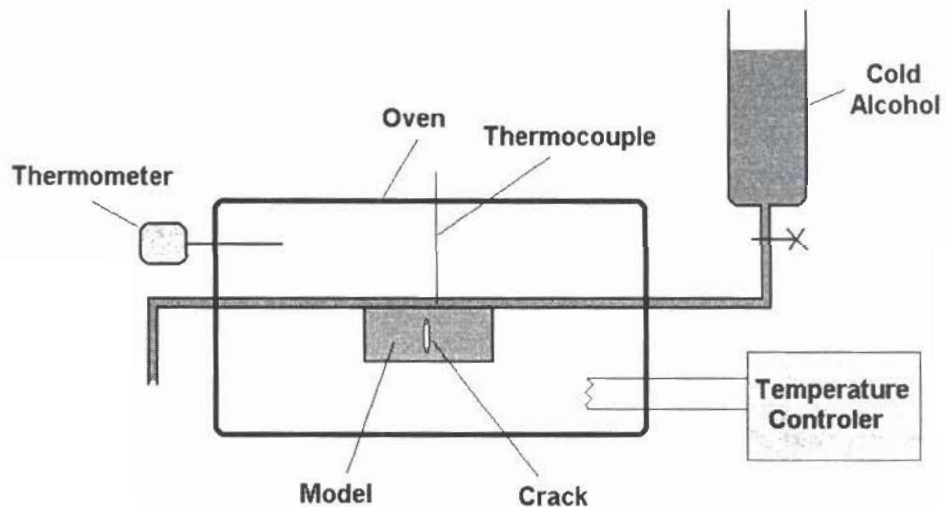


Figure 2 - Schematic diagram of the oven

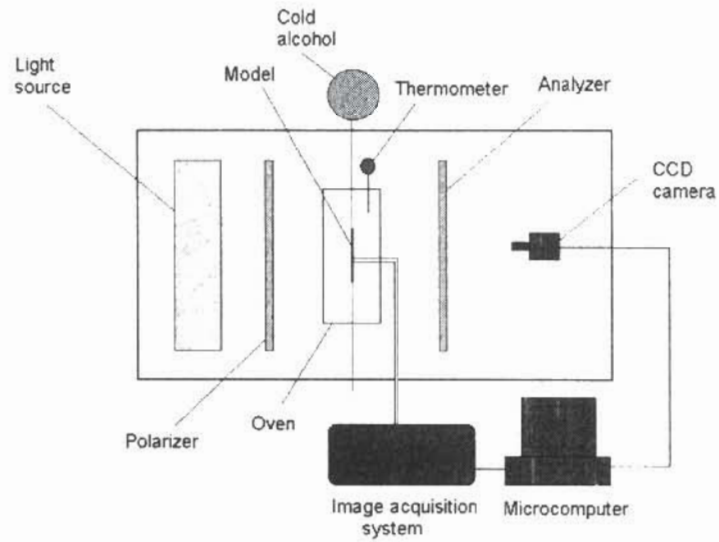
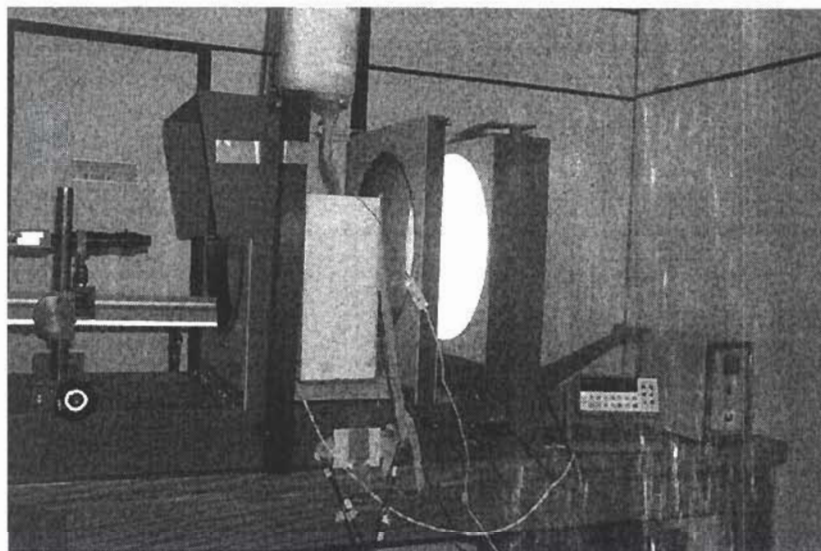
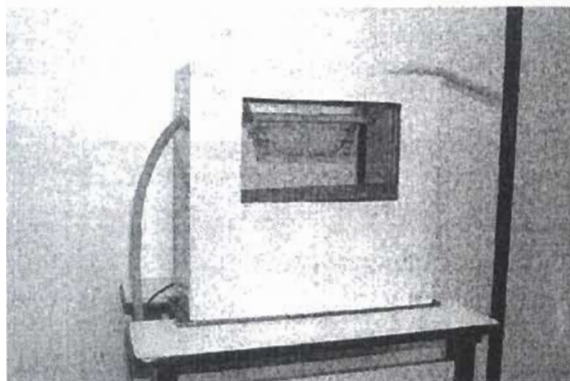


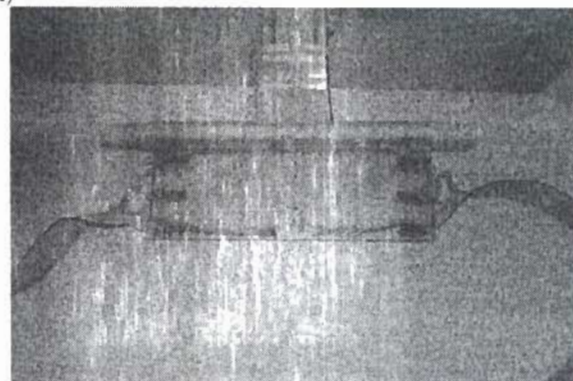
Figure 3 – Schematic diagram of the test rig with the stove set up in a polariscope with an image acquisition system



(a)



(b)



(c)

Figure 4 – (a) General view of the test rig; (b) Photoelastic oven; (c) Photoelastic model.

Figure 4 shows the test rig pictures with details of the photoelastic oven and of the photoelastic model.



The model was kept inside the oven at 60 °C during three hours for temperature stabilization and homogenization. Then, methyl alcohol at -15 °C circulated through the cooling tube during 287 seconds. The resulting thermal shock in the plate caused stress on it and, as a consequence, varying in time photoelastic fringes (isocromatics) appeared. The transient photoelastic fringes patterns were captured by the image acquisition system in 0.7 s intervals during the 287 s of the test, resulting in a total of 410 captured images.

The precision of the measured temperatures was assured by calibrating the thermocouple and the temperature strain gages with a platinum temperature standard (Pt-100) in the complete range of the tests.

## 2.2. Photoelastic images treatment and $K_I$ determination

The captured images by the image acquisition system were processed by two softwares developed by Soares (1997): FOTOFRAN and FOTOVER. The software FOTOFRAN treats the obtained images (to modify contrast, shine, to apply filters, etc.). Also it skeletonizes, tunes and labels the isocromatic fringes and prepares the data for the stress intensity factor determination that is performed by the software FOTOVER. The used calculation method to obtain the stress intensity factors was the Dally overdeterministic method (Soares, 1997; Dally and Riley, 1991).

The stress intensity factors were determined for several times, from  $t = 70$  s, where the images became more clear, to  $t = 287$  s, time of the test end.

The isocromatic fringes pattern, corresponding to time  $t = 210$  s, is showed Fig. 5. It is used to exemplify the above described processing.

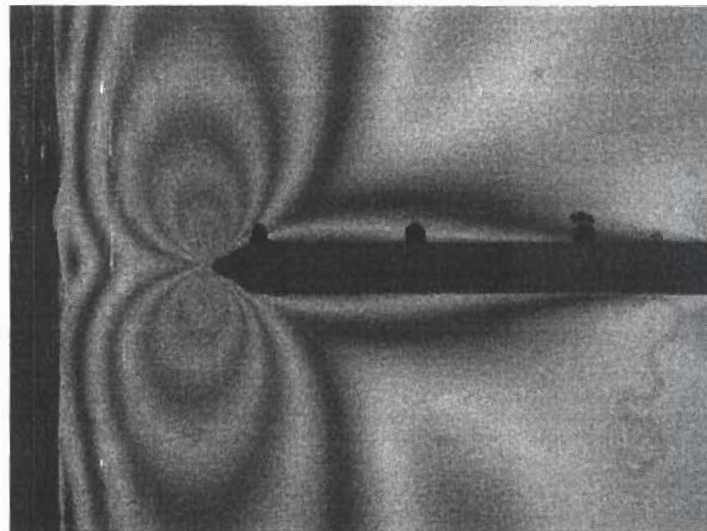


Figure 5 – Isocromatic fringes pattern at time  $t = 280$  s

This image, after the application of some filters to improve its quality, was skeletonized by the software FOTOFRAN. The result of this skeletonization is presented in Fig. 6 (a). Still using the software FOTOFRAN, the image was tuned, resulting in the image of Fig. 6(b). Fig. 6(c) shows the photoelastic image already labeled, that is, a color was linked to each fringe corresponding to its order. At this point, the software FOTOFRAN generates a file to the software FOTOVER calculates the value of the stress intensity,  $K_I$ .

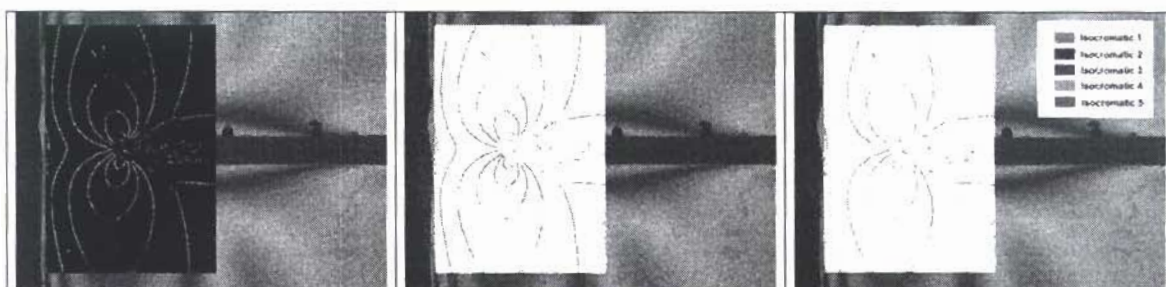


Figure 6 – (a) Result from the skeletonization operation. (b) Result of the tuning operation. (c) Labeling of the isocromatic fringes

### 2.3. Numerical analysis

The finite elements analysis method was used as a tool for the evaluation of the studied cases experimentally. The software ANSYS® version 7.1 was used to perform these analyses. At the first time, a transient type thermal analysis was carried out, in which had been imposed in the superior face of the model, the temperatures measured during the test. To take account of the existing singularity in the stress and strains in the crack tip, the following recommendations had been adopted in the numerical model construction: the elements around of the crack tip should be quadratic and the midside nodes placed at the quarter points. To assist the numerical model construction, in view of these recommendations, command KSCON was used. On Fig. 7 it is shown the elements mesh used in the carried out analyses; in detail, the elements around the crack tip. The mesh was constituted by 500 elements and 1,515 nodes. The used element was the PLANE77.

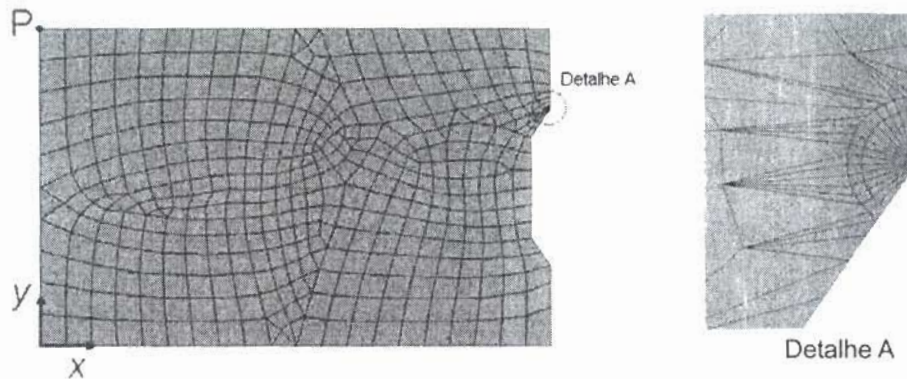


Figure 7 - Elements mesh.

The carried out thermal analyses provide the temperature distributions in model, for each instant of time, and in the case of the ANSYS, each one of these instants is called as substep. Being overcome for base the temperature distribution in each substep, was carried out a stationary type structural analysis. Software ANSYS, when of the beginning of the structural analysis it chooses, automatically, the element of analysis PLANE82, that is compatible with element PLANE77, used in the thermal analyses. It was adopted, still, for point P, a displacement restriction in y direction (Fig. 7). Next, for each analyzed substep, was calculated the value of  $K_I$ , using ANSYS command KCALC.

## 3. Results

### 3.1. Thermal load

The model top edge temperatures were measured during the tests. Fig. 8 shows these temperatures varying in time

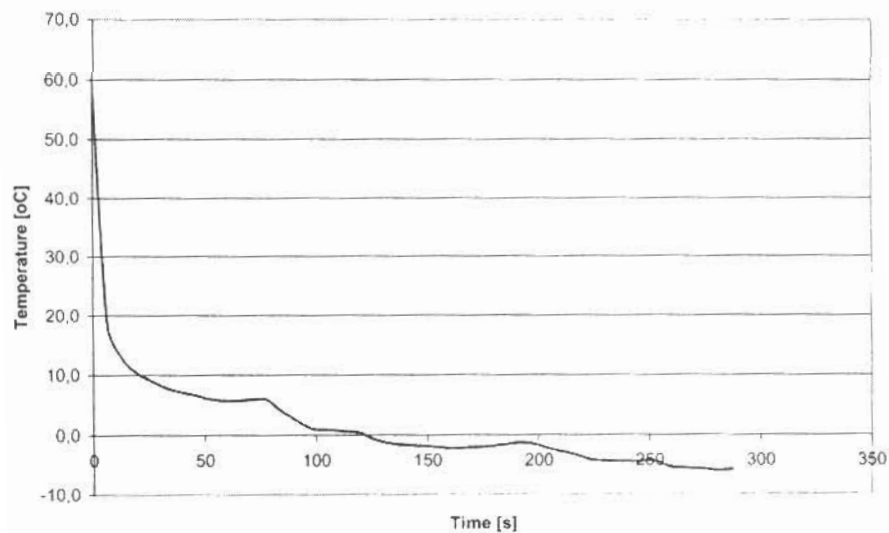


Figure 8 – Model top edge temperature versus time



### 3.1. Photoelastic images and $K_I$ calculations

Figure 9 shows the photoelastic images sequence from  $t = 7$  s to  $t = 287$  s.

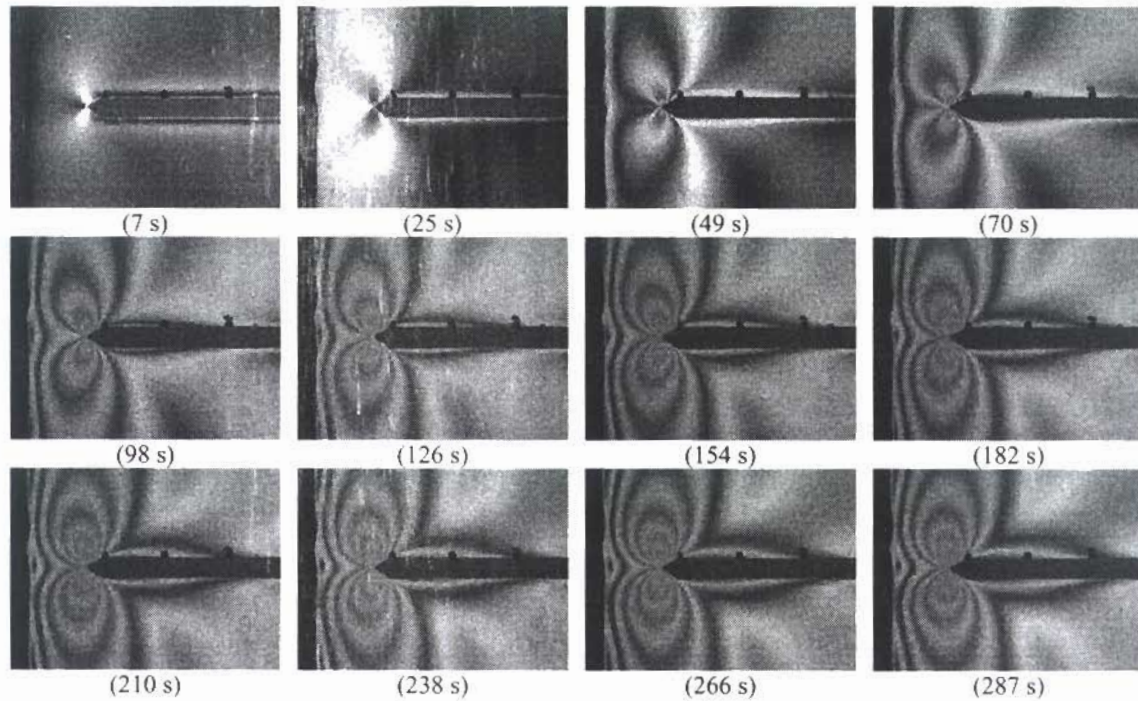


Figure 9 - The photoelastic images sequence from  $t = 7$  s to  $t = 287$  s

Using the methodology previously described, the  $K_I$  calculations were performed for several times, from  $t = 70$  s to  $t = 287$  s. For each time, the calculation procedure was done five times, resulting in five values of  $K_I$ .

Table 1 presents the results of  $K_I$  from photoelasticity and from numerical analysis. Figure 10 compare this results.

Table 1. Experimental and numerical results for  $K_I$ .

Time [s]	$K_I$ [MPa.m <sup>1/2</sup> ]	
	Photoelasticity	Numerical
70	0,310	0,45090
77	0,363	0,46474
84	0,385	0,47745
91	0,392	0,48895
98	0,418	0,50023
105	0,482	0,51055
112	0,502	0,52017
119	0,532	0,52962
126	0,557	0,53912
133	0,562	0,54870
140	0,569	0,55803
147	0,594	0,56691
154	0,601	0,57481
161	0,626	0,58194
168	0,625	0,58844
175	0,646	0,59470
182	0,632	0,59970
189	0,669	0,60421
196	0,675	0,60838
203	0,662	0,61265
210	0,678	0,61616
217	0,694	0,61895
224	0,710	0,62156
231	0,691	0,62377
238	0,710	0,62528
245	0,705	0,62633
252	0,728	0,62698
259	0,724	0,62770
266	0,727	0,62799
273	0,746	0,62811
280	0,739	0,62798
287	0,747	0,62720

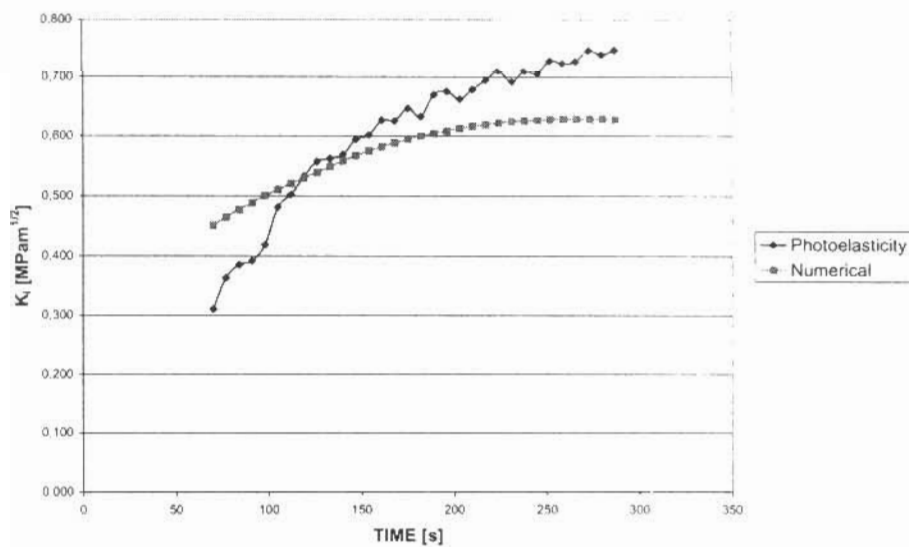


Figure 10 – Photoelastic and numerical graphics for  $K_I$  versus time

#### 4. Conclusions and discussion of the results

The calculated transient stress intensity factors  $K_I$  shows good agreement with the thermal load caused the transient model top edge temperatures. One can see on Figures 7 and 8 that the transient  $K_I$  and the transient model top edge temperatures have almost the same variation on time.

It can be observed that for the test beginning, when the value of  $K_I$  is low, the values gotten for the ANSYS are significantly higher, arriving to be, in the time of test of 70 s, about 45% superior to the gotten one for the photoelasticity. However, for test time near to zero (when the value of  $K_I$  would have to be zero), the ANSYS shows a  $K_I$  value of about  $0,18 \text{ MPa}\cdot\text{m}^{1/2}$ , what it indicates that the used algorithm possess a certain difficulty in carrying out the calculations for small values of  $K_I$ . For the times next to the test end, the differences are about 16%, what it can be considered acceptable. This discrepancy can be related with differences between the values of some material properties used in the finite elements analyses and its real values.

Once the studies accomplished by means of the photoelasticity are developed in models, it becomes necessary that the obtained results can be extrapolated to prototypes. The relationship between model and prototype is established by the so-called Models Theory and by the Dimensional Analysis (Kobayashi, 1993). These relationships model/prototype are well developed in the literature and Monch (1964) describes the Similarity and Models Theory applied to the photoelasticity in a very including way, otherwise Burger (1972) specializes this analysis the thermal modeling using photoelasticity.

When of the definition of the photoelastic experiment, special attention should be giving to the model sizing, including the crack dimensions, and the thermal load range. Another concern of great importance is the choice of the photoelastic material, whose properties should have compatible behavior with the prototype. The polycarbonate PSM-1, used in the experiment, is very appropriate when one wants to establish correlation with metals, in a general way. The most relevant properties, such as modulus of elasticity, Poisson's ratio, coefficient of thermal expansion and thermal conductivity, present a very similar behavior to the metals.

The proposed methodology comes as an interesting experimental alternative for the determination of the stress intensity factors due to thermal loads. The construction of the models can be very simple, the used equipments can be of easy acquisition or manufacture. In this aspect, it should be noticed that in spite of the polariscope used in this work is quite sophisticated, it is necessary a rudimentary polariscope to conduct these type of experiments, just constituted of a light source and plane polarizers plates easily found.

On the other hand, for the fact of being an unpublished methodology, it presents countless possibilities of future works. For example it can be mentioned the determination of the stress intensity factor in three-dimensional models, using the sandwich technique. In this method, the model is built of plastic, translucent and non photoelastic material, usually the Plexiglas. During the construction of the model, a thin slice of photoelastic material is included, in the section of interest. Several loads can be applied but the stress fields will be known only in the section of the photoelastic slice. However, in spite of promising, this methodology still lacks of a larger technological development, especially in how to bond the photoelastic slice to the other parts of the model.

One also believes that the experimental determination of  $K_I$  will be useful to validate  $K_I$  obtained from numerical analyses. One believes, also, that the two methodologies, numerical and experimental analyses, can be used together to obtain more reliable and practical results in the structural integrity assessment of cracked structures under thermal loadings.

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#### 6. Responsibility notice

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