

STRESS INTENSITY FACTORS EVALUATION DUE TO THERMAL STRESSES USING PHOTOELASTICITY

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ABSTRACT

Transmission photoelasticity was used to obtain an experimental solution for stress intensity factors 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.

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

Keywords: photoelasticity, thermal stress, stress intensity factor, fracture mechanics.

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loads; in this condition the usual approaches to predict collapse loads based on conventional failure theories are no longer applicable.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

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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.

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 Figure 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.

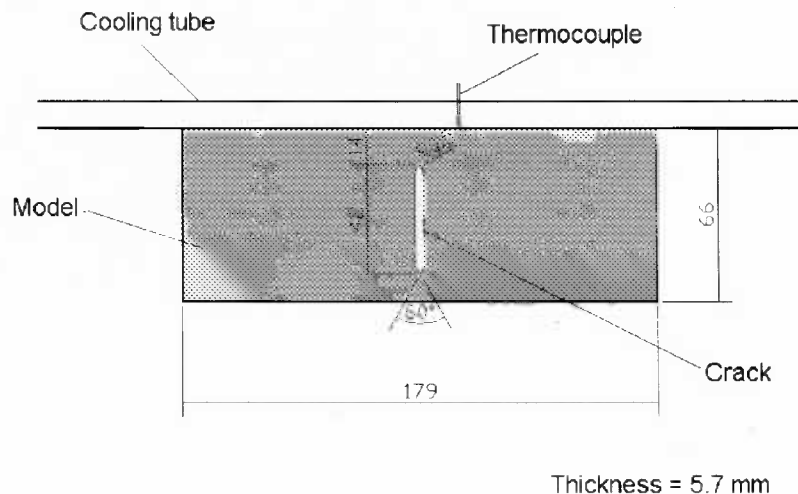


Figure 1 – The photoelastic model – Dimensions in mm.

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.

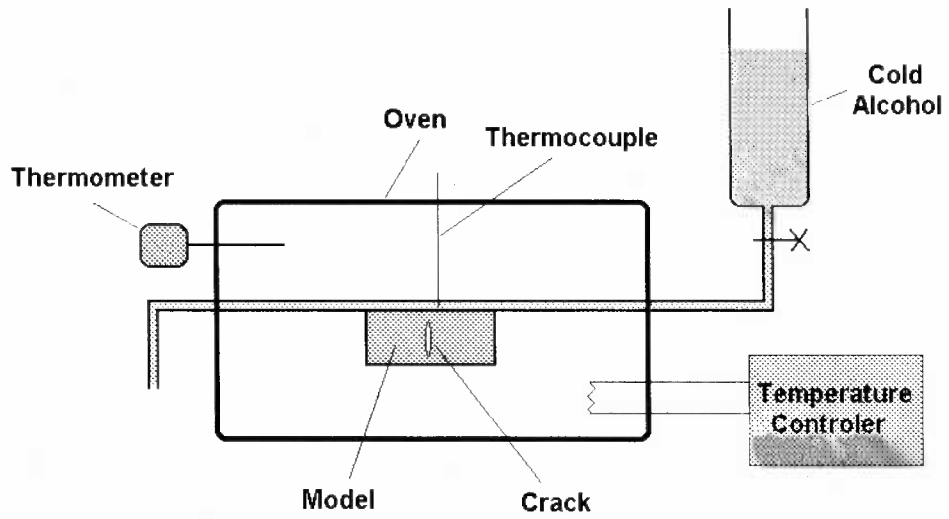


Figure 2 - Schematic diagram of the oven.

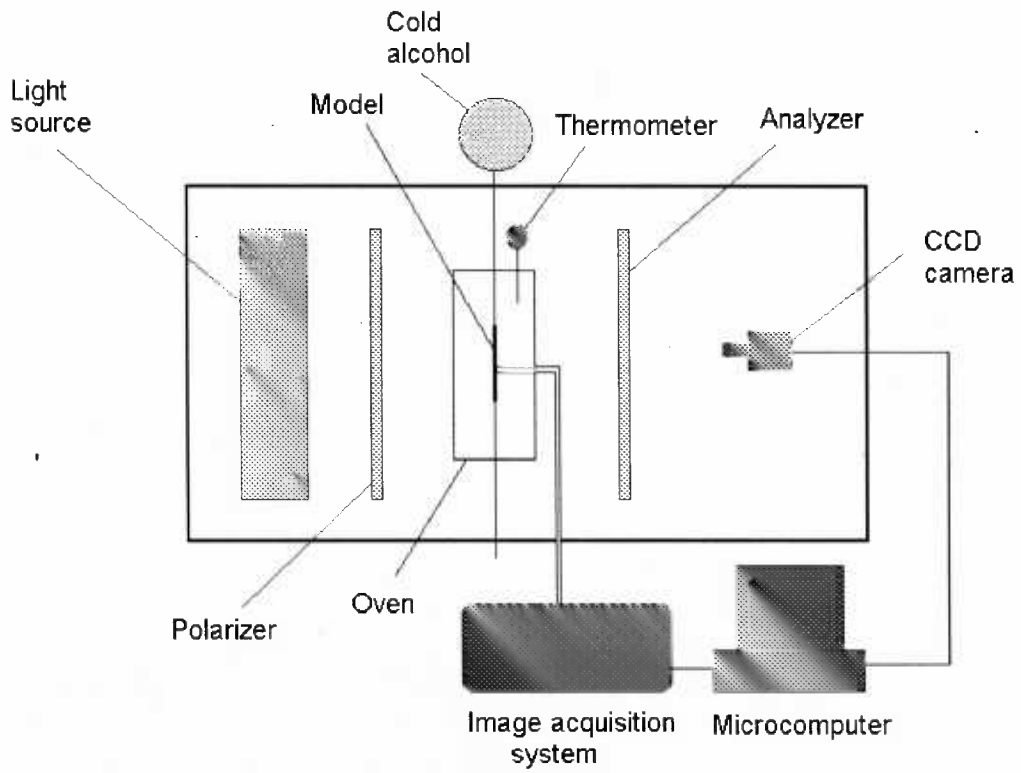


Figure 3 – Schematic diagram of the test rig with the stove set up in a polariscope with an image acquisition system.

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 294 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 294 s of the test, resulting in a total of 420 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.

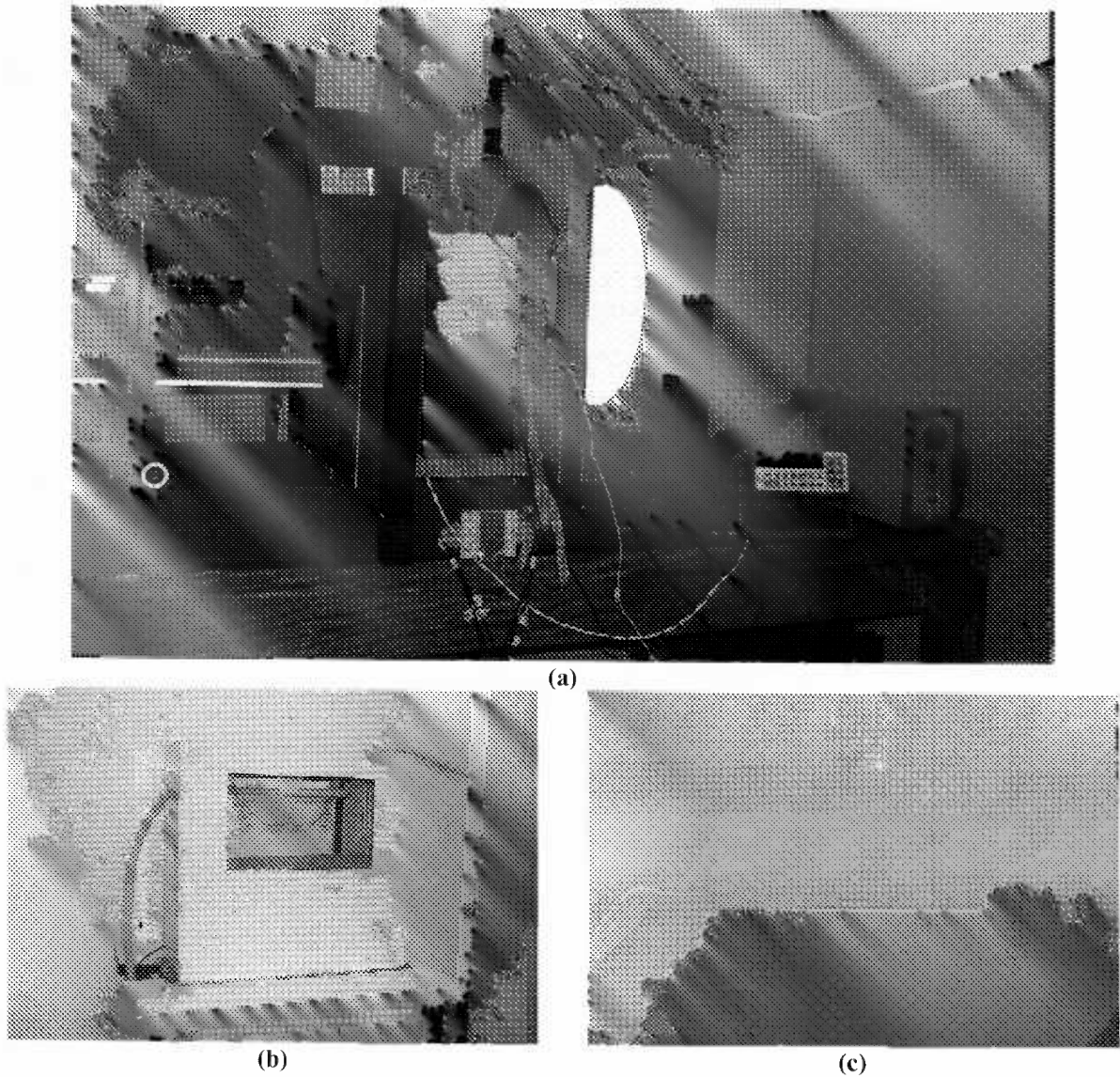


Figure 4 – (a) General view of the test rig; (b) Photoelastic oven; (c) Photoelastic model.

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 $t = 294$ s, time of the test end.

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

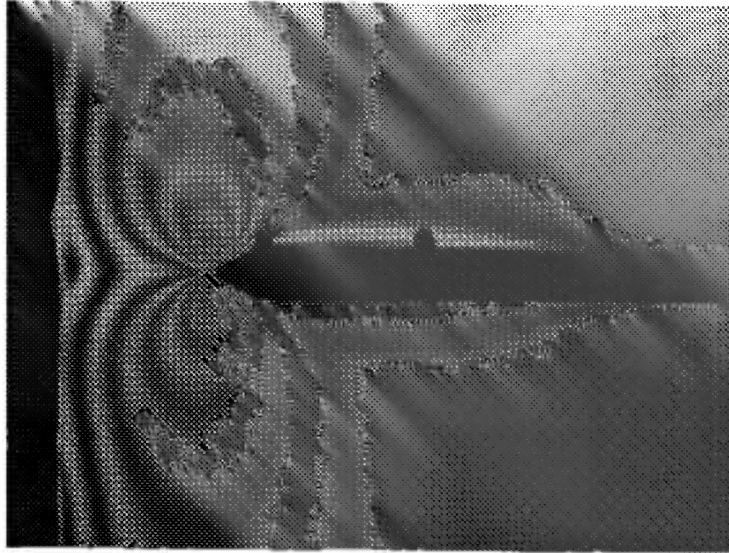


Figure 5 – Isochromatic fringes pattern at time $t = 280$ s.

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 Figure 6 (a). Still using the software FOTOFRAN, the image was tuned, resulting in the image of Figure 6(b). Figure 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 .

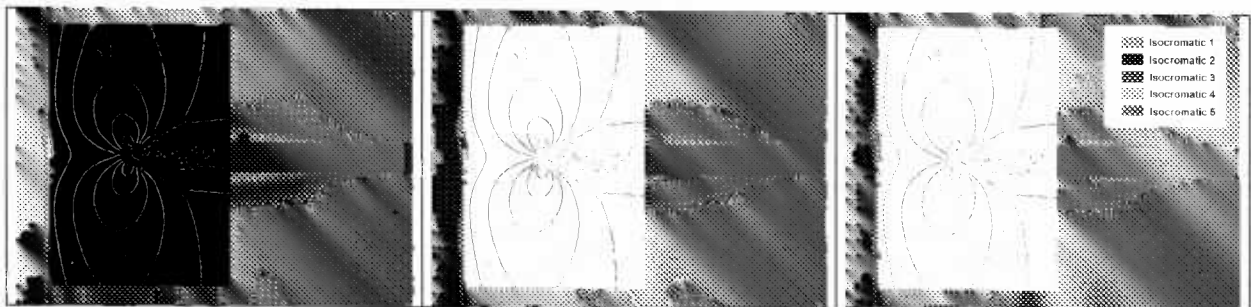


Figure 6 – (a) Result from the skeletonization operation. (b) Result of the tuning operation. (c) Labeling of the isochromatic fringes.

3. RESULTS

3.1 Thermal Load

The model top edge temperatures were measured during the tests. Figure 7 shows these temperatures varying in time

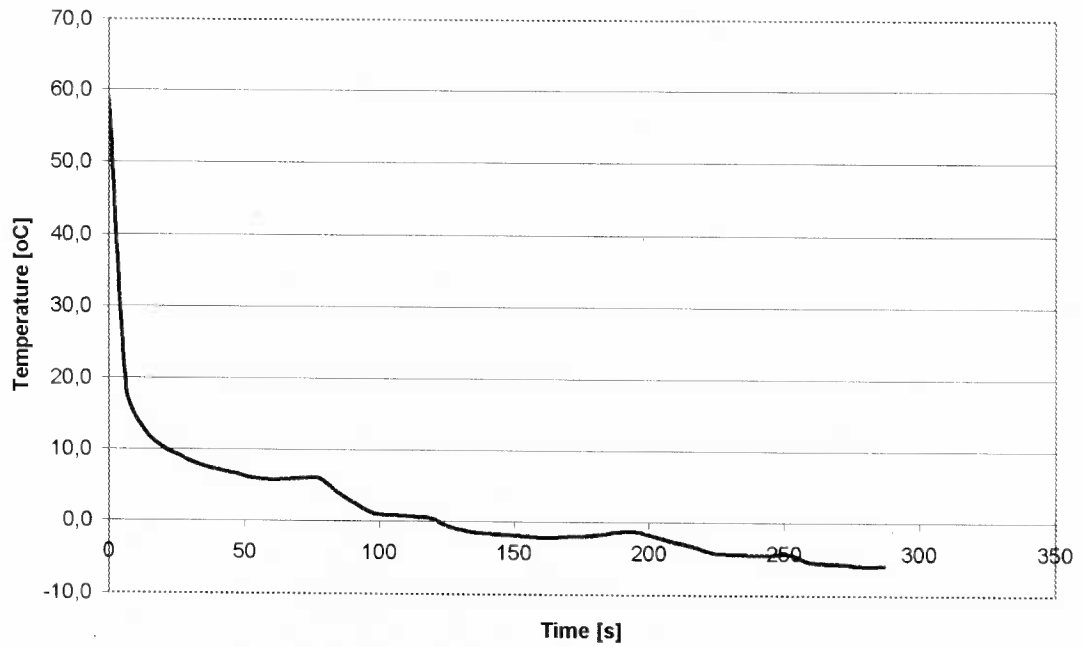


Figure 7 – Model top edge temperature versus time.

3.2 Photoelastic images and K_I calculations

Figure 8 shows the photoelastic images sequence from $t = 7$ s to $t = 294$ s.

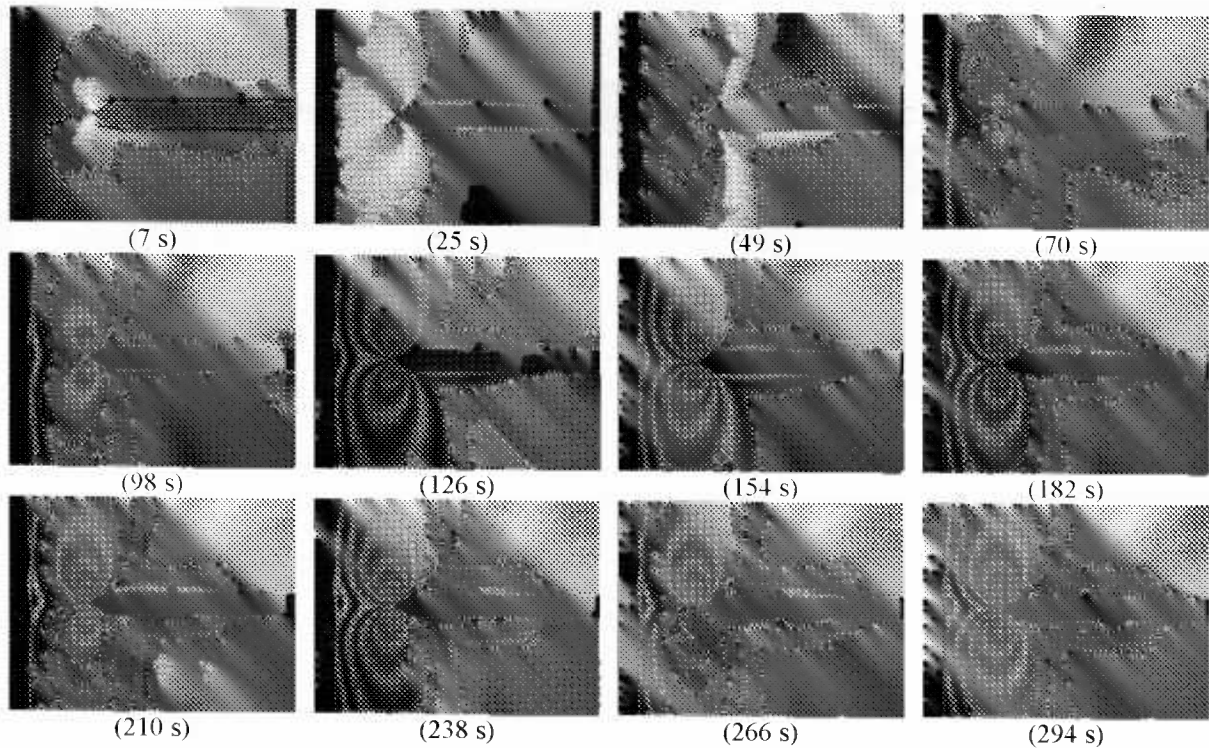


Figure 8 - The photoelastic images sequence from $t = 7$ s to $t = 294$ s.

Using the methodology previously described, the K_I calculations were performed for several times, from $t = 70$ s to $t = 294$ s. For each time, the calculation procedure was done five times, resulting in five values of K_I .

Table 1 presents the results of these calculations and Figure 9 shows the average values of K_I as a function of time.

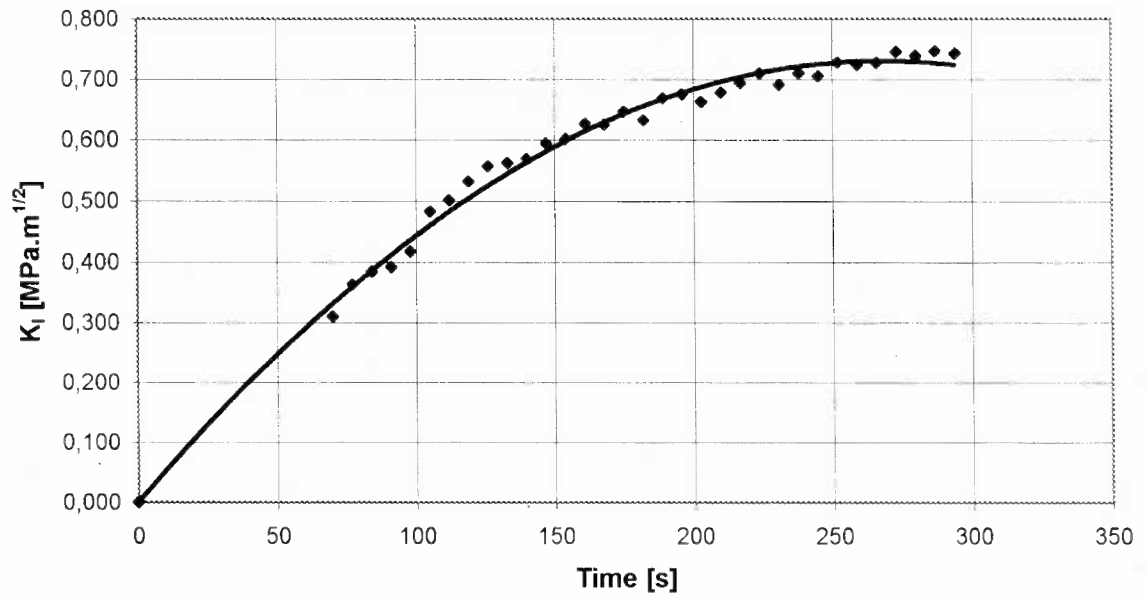


Figure 9 – K_I versus time.

Table 1 – Calculated K_I values for several times.

Time [s]	K_I [MPa.m ^{1/2}]					Mean	Standard deviation
	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5		
0	---	---	---	---	---	0,000	---
70	0,331	0,318	0,291	0,324	0,286	0,310	0,020
77	0,362	0,361	0,362	0,374	0,358	0,363	0,006
84	0,345	0,363	0,391	0,440	0,385	0,385	0,036
91	0,387	0,403	0,394	0,383	0,393	0,392	0,008
98	0,411	0,414	0,425	0,402	0,438	0,418	0,014
105	0,488	0,476	0,500	0,459	0,489	0,482	0,016
112	0,496	0,509	0,518	0,492	0,493	0,502	0,011
119	0,523	0,533	0,522	0,537	0,546	0,532	0,010
126	0,562	0,566	0,539	0,547	0,572	0,557	0,014
133	0,546	0,564	0,563	0,559	0,580	0,562	0,012
140	0,554	0,572	0,572	0,578	0,569	0,569	0,009
147	0,571	0,610	0,575	0,609	0,605	0,594	0,019
154	0,616	0,607	0,624	0,587	0,572	0,601	0,021
161	0,605	0,619	0,638	0,667	0,602	0,626	0,027
168	0,624	0,635	0,622	0,619	0,627	0,625	0,006
175	0,614	0,655	0,679	0,640	0,644	0,646	0,024
182	0,634	0,641	0,615	0,619	0,649	0,632	0,014
189	0,620	0,665	0,674	0,692	0,692	0,669	0,030
196	0,667	0,668	0,676	0,689	0,696	0,675	0,010
203	0,662	0,659	0,666	0,679	0,645	0,662	0,004
210	0,670	0,682	0,679	0,664	0,697	0,678	0,013
217	0,706	0,705	0,690	0,695	0,675	0,694	0,013
224	0,698	0,701	0,714	0,720	0,717	0,710	0,010
231	0,715	0,690	0,706	0,668	0,678	0,691	0,019
238	0,691	0,703	0,736	0,694	0,725	0,710	0,020
245	0,680	0,720	0,725	0,709	0,693	0,705	0,019
252	0,723	0,715	0,733	0,720	0,749	0,728	0,013
259	0,724	0,729	0,725	0,724	0,718	0,724	0,004
266	0,726	0,733	0,722	0,721	0,735	0,727	0,006
273	0,743	0,743	0,727	0,752	0,764	0,746	0,014
280	0,721	0,735	0,760	0,737	0,740	0,739	0,014
287	0,749	0,733	0,762	0,743	0,746	0,747	0,011
294	0,742	0,732	0,772	0,743	0,724	0,743	0,018

4. CONCLUSIONS AND DISCUSSION OF THE RESULTS

The equipment and used softwares are well adequate to perform the proposed test. Although the used digital camera had a relatively low resolution (0.9 MPixel), the used optic system provided images with resolution adapted to proposed job. Using a digital camera with higher resolution better images certainly can be obtained, what would improve the accomplishment of several types of tests in this area.

The photoelastic oven, with electronic control of temperature, demonstrated a temperature stability much better than the necessary for the developed test (stability better than 0,01 °C). So, it opens the possibility of its use in more refined and complex tests.

The developed model also showed a performance adequate to the test purposes. It can be noticed that a large variety of models to accomplish several purposes should be built and tested in the developed test rig.

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.

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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