THE NON-AXISYMMETRIC BEHAVIOUR OF A THERMALLY LOADED MODEL TUBESHEET

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SUMMARY

The analysis of tubesheet assemblies is presently almost exclusively carried out by neglecting the effect of the solid separation (s) between the different perforated zones (e.g. diametral lane). The problem is thus transformed into an axisymmetric one and equivalent elastic constants are used for the perforated zone.

The above approximation is not necessarily conservative since it does not take into account the following two possible effects:

(1) increased local rigidity due to the presence of a lane of unperforated material with resulting high levels of local stresses;

(2) non-axisymmetric displacements of the tubesheet periphery which may induce local loss of contact at the gasket and result in a leaky joint.

The purpose of the paper is to report on an experimental investigation carried out with an epoxy resin model of a tubesheet with two passes and a wide diametral lane. The model tubesheet is 16″ (406 mm) in diameter and 2.5″ (64 mm) thick. 182 holes, 0.5″ (12.6 mm) in diameter were drilled and reamed on a 60° triangular pattern with a 0.75″ (19 mm) pitch. The diametral lane is 4.7″ (119 mm) wide.

Various thermal loading configurations both symmetric and non-symmetric have been applied and, in addition, the effect of rate of temperature increase has been studied. A time similarity ratio of 100 is achieved with epoxy resin as compared to steel so that transients are analyzed in a quasi-static fashion. For example, with the epoxy model, steady state is attained in 6 minutes in the perforated zone and in 150 minutes in the solid diametral lane, the corresponding values for a steel specimen of the same dimension are 3.5 seconds and 85 seconds respectively.

For the measurement of the temperature distribution, 94 thermocouples were used, 77 of which were embedded at various points within the model thickness. 10 specially developed strain gage displacement transducers and 5 precision dial gages were also utilized. Most of the instrumentation was located at or near the diametral lane.

A first series of experimental results for temperatures and displacements have been compared with those of plane and axisymmetric finite element programmes, with the following immediate conclusions:

— The temperature distribution through the thickness of the tubesheet in the ligament region agrees with the results of the numerical computations. As the rate of change of temperature increases, a point is reached where important temperature gradients appear not only on the originally cold end but at both ends of ligaments.

— The temperature distribution in the diametral lane corresponds to that of a wide beam thermally loaded on three sides.

— The diametral lane has an important influence on the overall displacement of the tubesheet during the transient conditions. As steady state conditions are reached however, the results tend to agree with those of the axisymmetric all-perforated geometry.

1. Introduction

The behaviour of a uniformly perforated tubesheet subjected to axisymmetric loadings (mechanical or thermal) is well determined and its structural analysis fairly straightforward [1],[2]. For more complex geometries and loadings however, little information is, to our knowledge, available in the literature. The method of solution therefore involves simplifying assumptions which may or may not be conservative. For example, the presence of an unperforated diametral lane in a tubesheet may cause non-axisymmetric deflections and overall warping of the plate. This may result in higher stresses in the ligaments, it may also affect the sealing capacity of the gasket. Transient non-uniform thermal loadings may further enhance these effects.

An experimental investigation is presently being carried out by the authors for the purpose of clarifying some of the above points. It has involved the construction of an epoxy resin model of dimensions proportional to those of a typical U-Bend heat exchanger tubesheet. Thermal loading of the model was achieved by a combination of two independent hot-air circuits.

The purpose of this paper is to report on a first series of tests for which a wide diametral lane was left unperforated in the model. The results concern the temperature distribution through the thickness of the plate in both the ligament and the diametral lane regions in addition to the overall displacements of the plate for various loading conditions. Conversion of the results from model to prototype is shown to be readily carried out using thermo-elasticity similarity rules.

2. The Model and Thermal Loading

The model blank was cast of epoxy resin (Araldite 6060 + 30% by weight hardener 901) it was then precision machined into its final shape (Fig. 1) (see [3] for the description of casting and machining procedures). A total of 192-1/2" dia. (12.7 mm) holes were drilled and reamed. One end of each hole was countersunk to allow the positioning and cementing of a short length of a pre-machined epoxy tube of the same inside diameter as the hole. Extensions made of Flexible P.V.C. tubing were then fitted as shown in Fig. 2. The channel and shell sides of a typical tubesheet were thus modeled.

The following properties were measured on samples cast together with the model blank (practically constant in the range of temperatures applied to the model):

- Modulus of elasticity = 500300 psi (3450 MPa)
- Poisson's ratio = 0.35
- Linear coefficient of thermal expansion = 3.27×10^{-5} in/in/^{o}F (5.88×10^{-5} m/m/^{o}C)
- Thermal diffusivity = 1.39×10^{-6} ft^2/s (0.12×10^{-6} m^2/s) [4]

The thermal loading of the model was achieved using two independent hot air circuits connected to one or more of the three model zones as shown in Fig. 2. The rate of increase or decrease of temperature in each of the two circuits was controlled so as to create the required transient conditions. A total of four groups of tests were performed as follows (refer to Fig. 2).

- Test No. 1: Zones 1 and 2 on channel side subjected simultaneously to a quasi-instantaneous thermal shock (50^{o}F/min, 28^{o}C/min). Zone 3 maintained at constant low-temperature.

- Test No. 2: Same as No. 1 but with slow ramp (1.3^{o}F/min, 0.7^{o}C/min).

- Test No. 3: Slow ramp applied to Zone 1 on channel side and full shell side (Zone 3) simultaneously. Zone 2 maintained at constant low temperature.

- Test No. 4: Only Zone 1 on channel side subjected to slow ramp. Zones 2 and 3 maintained at constant low temperature.

Superposition of the above thermal loading conditions may be used to simulate any other required configuration. As will be shown from the similarity relations, the above thermal loadings are quite severe when expressed in terms of a steel prototype.

3. Measurements

3.1 Temperature

Ninety-four iron-constantan thermocouples made from 0.005 in. wire were utilized to determine the temperature distribution throughout the model as indicated in Fig. 1. Seventy-seven of the thermocouples were embedded through the thickness as illustrated in Fig. 3. The thermocouples were cemented inside transverse slots cut in short epoxy resin bars. The thermocouple bars were then inserted in specially drilled holes in the model. Epoxy resin cement was used to fill the gaps and hold the thermocouples in position.

3.2 Displacements

Ten specially constructed displacement transducers (0.00005", 1.3 μm resolution) were used to measure the axial movement of the model during the tests. As illustrated in Fig. 4, although the measurement tip of these transducers may move in all directions, the combination of the strain gages in the wheatstone bridge circuits isolates the axial movement. An additional five dial gages (0.0001", 2.5 μm resolution) were used to increase the number of measurement points. The position of all measurement points is shown in Fig. 1.

4. Test Procedure

A typical test cycle was carried out as follows:

1. Start all air circulation fans (room temperature + $10^{o}F$) and instrumentation and allow to stabilize for approximately 2 hours.
2. Apply required temperature ramp.
3. Stabilize at upper temperature for 2 hours.
4. Cool down at same rate as 2.
5. Stabilize for a final 2 hours.

Because of the low thermal diffusivity of epoxy resin very long time intervals are necessary to run a test. In spite of the initial stabilization it was not possible to achieve uniform temperature throughout the model. Its distribution was, instead, that of an initial steady state condition.

An automatic data acquisition system, scanning at the rate of 2 readings per second, was used to record the test data (Thermocouples plus strain gages from displacement transducers). During the first few minutes of a cycles, a full set of readings was recorded at 90-second intervals. Five- then fifteen-minute intervals were used in the more stable part of the thermal cycle.

5. Results

5.1 Similarity coefficients

The various similarity relations are listed in Table I and were obtained from [5]. In order to facilitate the interpretation of the results the following sample case was assumed:

1. Prototype and model are of identical geometry (i.e. $\lambda = 1$).

2. The thermal shock applied to the prototype is of the same configuration as that of the model but ten times more important (i.e. $\delta = 10$).

With these assumptions, and using the physical properties of a steel prototype and the epoxy resin model, the numbers in the last column of Table I are obtained.

5.2 Temperature distribution

Typical results are shown in Figs. 5, 6 and 7* and the following remarks may be made, some of which confirm generally accepted behaviours and hypotheses:

1. A thin superficial layer in the ligament region on the shell side is subjected to nearly the full applied thermal gradient. In steady state conditions this layer is approximately ten percent of the total thickness of the plate (Fig. 5).

2. For the temperature distribution through the thickness of the tubesheet in the ligament region, a comparison of the results for a suddenly applied thermal shock (test 1, Fig. 5(a))and those for the slower thermal ramp (test 2, Fig. 5(b)) shows that, in the first case, an additional thermal gradient appears on the channel side during the transient.

3. The temperature distribution through the thickness of the tubesheet was observed to be very similar for all ligaments measured even for those ligaments adjoining the diametral lane.

4. The central region of the diametral lane behaves in a manner similar to that of a thick plate subjected to a temperature gradient through its thickness (Fig. 6). Under transient conditions, only the thin surface layers are subjected to a sharp temperature gradient; as steady state is reached, however, the temperature profile becomes nearly linear (note that Fig. 6 represents the cooling portion of the cycle).

5. The same observation cannot be made for the region of the diametral lane which is near the ligaments. Fig. 7 presents the temperature profiles at mid-thickness of the tubesheet in the diametral lane for tests 1, 3 and 4 and shows a sharp influence of the adjoining tubes. It may be observed from the results of tests Nos. 1 and 4 (Fig. 7(a) and (c)), in which the shell side of the model was maintained at constant low temperature, that the central portion of the diametral lane remains at a lower temperature than the region adjoining the tubes. The central region has a width approx. 1/4 that of the diametral lane.

6. The steady-state linear temperature distribution sometimes assumed to exist accross a diametral lane [6] was observed only for test No. 3 (Fig. 7(b)) in which both zones 1 and 3 of the model were heated simultaneously: a condition remote from true thermal loading situations.

7. Steady-state is reached almost at the end of the heating ramp in the ligament region (e.g. 4 min. in Fig. 5(a)) but requires more than 120 min. in the diametral lane (Fig. 6).

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*Note: Some temperature overshoot occured at the end of the thermal ramp particularly for test No. 1. It is for this reason that the steady-state temperature curves (120 min) do not envelope the transient curves in Figs. 5, 6 and 7.

5.3 Displacements

Fig. 8 shows a typical transient relative axial plate displacement pattern. In Fig. 9, only the displacements of line AB of Fig. 8 have been plotted. The following remarks may be made:

1. The diametral lane has an important effect on the overall deformation of the model particularly so during the temperature transient (Figs. 8 and 9(a)). The center of the tubesheet deforms with principal radii of curvature of opposite signs (in the shape of a saddle). The same behaviour was observed for all tests.

2. In view of the observed deformations, it is expected that the maximum stresses will occur on the channel side in the ligaments adjoining the diametral lane. For the case of a slow ramp (test no. 2, Fig. 9(a)) it is expected that the maximum stresses will occur when the ligament temperature distribution has stabilized (20 min.).

3. As steady-state is approached, even though not always fully attained, the effect of the diametral lane tends to dissipate and the plate deformation becomes similar to that of a uniformally perforated plate (120 min. in Fig. 9).

4. With regards to the deformation of the outer ring, some local warping is observed (Fig. 9) which may be attributed to an uneven temperature distribution during the tests and the fact that the model was not attached on its outer periphery. Such local warping would probably not exist in a bolted flange connection because of the relatively small bending rigidity of the outer tubesheet ring. Further tests presently being carried out will help clarify this behaviour.

6. Some Comparisons With Numerical Results

In view of the qualitative nature of the results obtained so far, no attempt has been made to obtain three-dimensional numerical solutions for comparison purposes. Instead comparisons are made with the results of two in-house finite-element computer programs [7, 8].

The first comparison is shown in Fig. 10 for the steady-state temperature distribution through the thickness of the tubesheet in a ligament. The experimental results are those of Fig. 5(b) (120 min) and the numerical results were computed [7] on the basis of the experimental temperatures at the surfaces of the plate. Good agreement is observed except for one experimental point which, as seen in Fig. 5, systematically indicated a lower temperature.

The second comparison is for the relative axial plate displacement. For the axisymmetric finite element solution [8] the experimentally determined temperatures were imposed at the nodes. No diametral lane was assumed to exist in the numerical model. The comparison is shown in Fig. 11 for test No. 1 (fast transient). It is of interest to note that, for steady-state (Fig. 11b) the displacements of the model tubesheet are in good agreement with those of the axisymmetric numerical tubesheet. This is not the case however for transient conditions (Fig. 11a) where reversed curvature is observed experimentally in the diametral lane region. The same verification was carried out for test No. 2 (slow transient) with similar observations.

7. Future work

Additional work is presently being carried out in order to:

- confirm some of the results obtained
- check the effect of a narrower diametral lane

- verify whether the warping of the outer tubesheet ring is a significant factor
- assess the stresses at critical locations in the tubesheet

For this purpose the width of the diametral lane has been reduced by drilling one additional row of holes on each side. Also a number of strain gage rosettes have been attached to the model at critical locations.

8. Conclusions

The series of tests reported has permitted the qualitative study of the behaviour of a model tubesheet under loading conditions which are close to those encountered in a true heat exchanger.

Experimentally the work reported has contributed to the development of special techniques which are presently being applied for persuing additional work on this model as well as for other thermal stress investigations using epoxy resin models.

The following practical conclusions may be drawn from the results obtained so far:

1. The presence of the diametral lane and/or the non-axisymmetric thermal loading have no effect on the local temperature distribution through the thickness of the tubesheet at the ligaments. They do however have a definite effect on the time required to reach steady-state conditions and on the overall deformation of the tubesheet.

2. From the examination of the displacements and temperature distributions it may be deduced that the maximum stresses will occur in the ligaments adjoining the diametral lane (this is based also on the conclusions of [9]). In addition, for the case of non-axisymmetric loading, it is expected that the stresses in these particular ligaments will actually be higher than in the case of a uniform thermal loading.

3. Under steady-state axisymmetric thermal loading conditions the behaviour of the model is, for all practical purposes, adequately predicted by an axisymmetric numerical solution in which the diametral lane is neglected.

ACKNOWLEDGEMENT

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[8] ASFENT - Program, Available at Ecole Polytechnique of Montreal, Section of Applied Mechanics; Axisymmetric Finite Elements Program with 3 DOF/Temperature and 6 DOF/Displacements.

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TABLE I

SIMILARITY COEFFICIENTS IN THERMO-ELASTICITY

PARAMETER	MODEL	PROTOTYPE	SAMPLE CASE
Temperature	T_m	$T = \delta T_m$	$\delta = 10$
Geometry	X_m	$X = \lambda X_m$	$X = 1$
Time	t_m	$t = \frac{k_m}{k} \lambda^2 t_m$	$t = 0.0094\ t_m$
Displacement*	u_i^m	$u_i = \frac{(1+\nu)(1-\nu_m)}{(1-\nu)(1+\nu_m)} \frac{\alpha}{\alpha_m} \delta\lambda u_i^m$	$u = 1.7\ u_m$
Stress*	σ_{ij}^m	$\sigma_{ij} = \frac{E}{E_m} \frac{(1-\nu_m)}{(1-\nu)} \frac{\alpha}{\alpha_m} \delta\sigma_{ij}^m$	$\sigma_{ij} = 99.4\ \sigma_{ij}^m$

* State of plane strain

TABLE II

CHARACTERISTIC RESULTS

PARAMETER	MODEL	SAMPLE PROTOTYPE
Applied temperature increase		
- Test No. 1	17.5°F (9.7°C)	175°F (97°C)
- Test No. 2, 3, 4	19.4°F (10.8°C)	194°F (108°C)
Applied rate of heating or cooling		
- Test No. 1	50°F/min (27.8°C/min)	90°F/s (50°C/s)
- Test No. 2, 3, 4	1.3°F/min (0.7°C/min)	2.3°F/s (1.28°C/s)
Observed duration of transient in perforated area		
- Test No. 1	6 min.	3.4s
- Test No. 2, 3, 4	18 min.	10.2s
Observed duration of transient in diametral lane		
- Test No. 1	150 min.	85s
- Test No. 2, 3, 4	180 min.	102s
Steady state displacement of plate center		
- Test No. 1	0.0039" (99 μm)	0.0066" (168 μm)
- Test No. 2	0.0044" (112 μm)	0.0075" (190 μm)

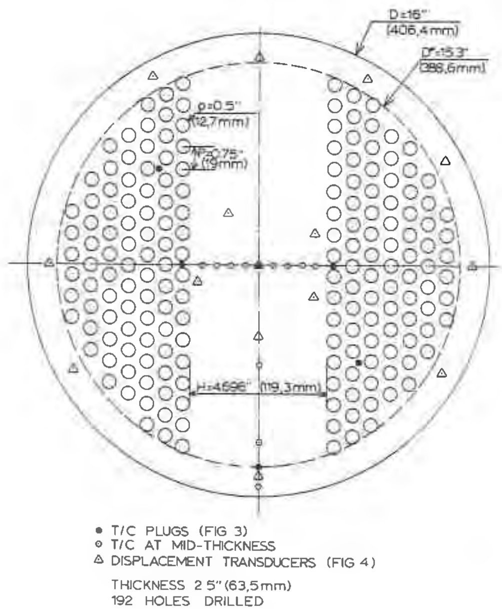


Fig. 1 Model geometry with location of measurement points

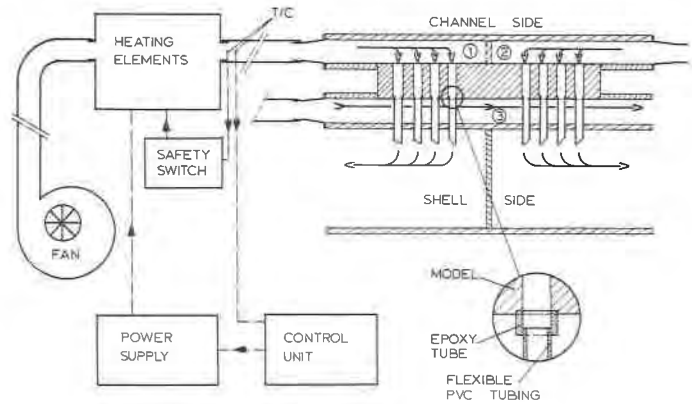


Fig. 2 Test set-up showing the three heating zones on the model with a typical control circuit

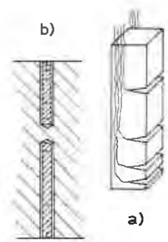


Fig. 3 The thermocouple plug
a) Location of thermocouple junctions along 1/8" x 1/8" epoxy bar
b) Two plugs are typically used for the full plate thickness
(Total of 11 thermocouples).

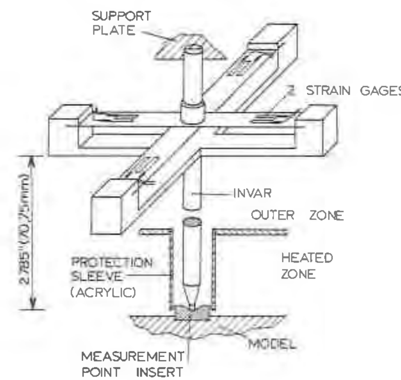


Fig. 4 The displacement transducer (eight strain gages are connected so as to respond only to vertical motion).

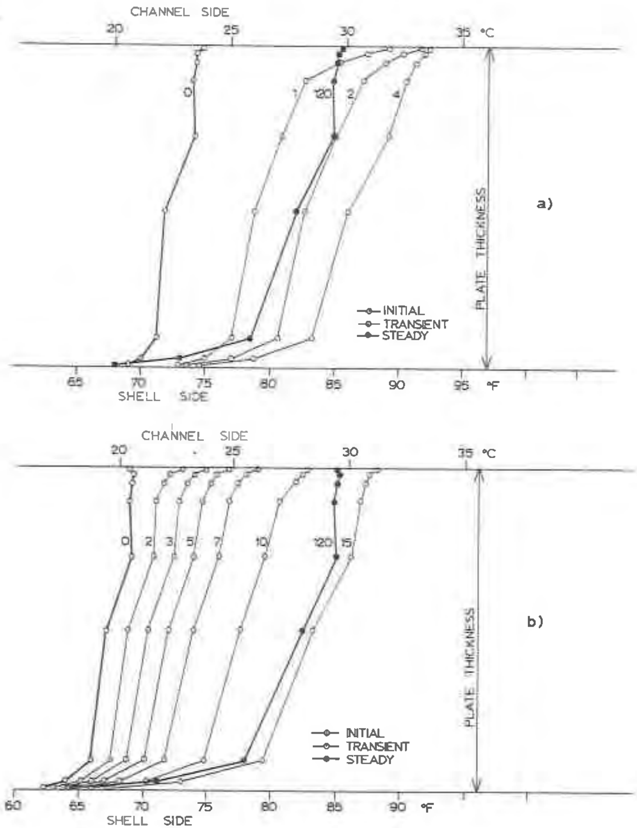


Fig. 5 Temperature distribution through plate thickness in ligament zone as a function of time (in minutes) from an initial steady state at 0 minutes.
a) Test No. 1: sudden heating
b) Test No. 2: slow heating

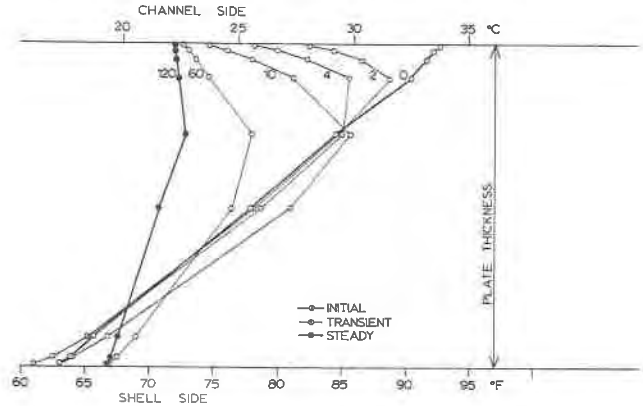
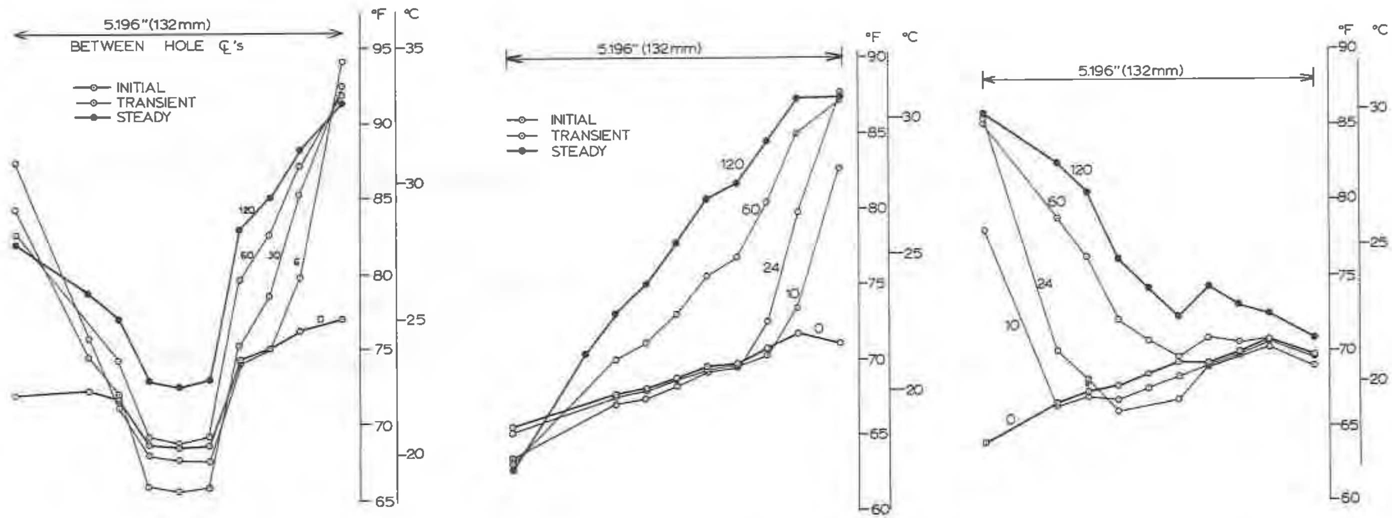
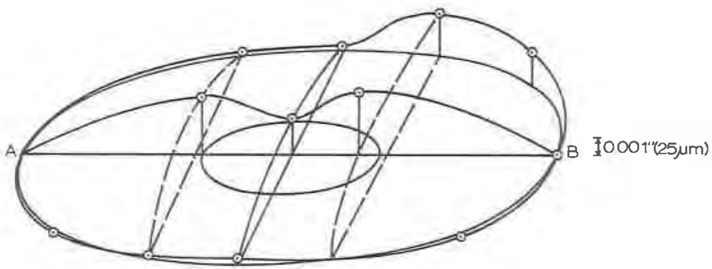


Fig. 6 Temperature distribution through plate thickness at center of diametral lane. Test No. 1: sudden cooling.

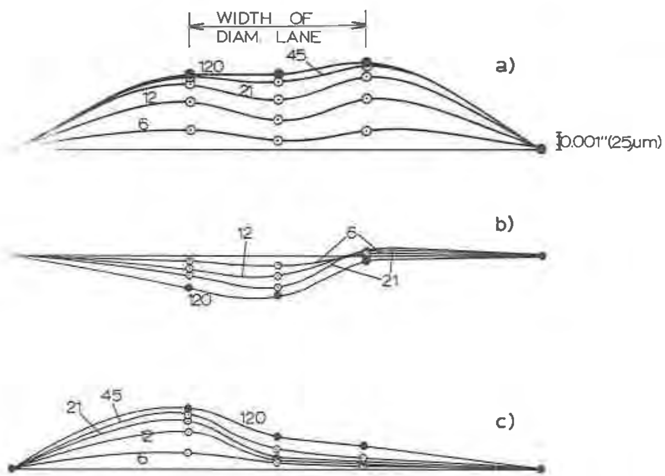


a) b) c)

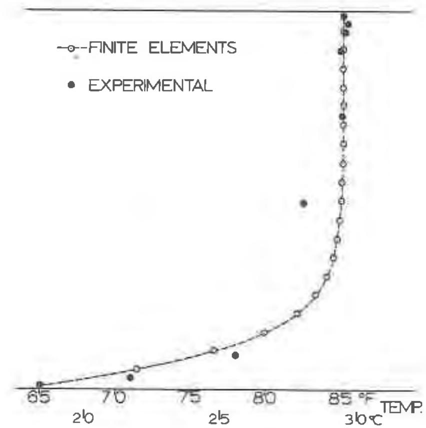
Fig. 7 Temperature distribution at mid-thickness across diametral lane as a function of time (in minutes) from an initial steady state at 0 minutes.
a) Test No. 1 b) Test No. 3 c) Test No. 4



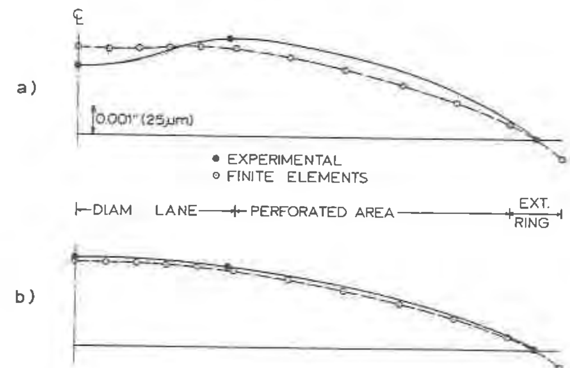
<u>Fig. 8</u> Relative displacements of plate for test No. 1 after 10 minutes.



<u>Fig. 9</u> Influence of diametral lane on plate displacements along line AB (see Fig. 8) at different times (in minutes).
a) Test No. 2 b) Test No. 3 c) Test No. 4



<u>Fig. 10</u> Measured and computed steady state temperatures distribution through plate thickness in ligament region.



<u>Fig. 11</u> Measured and computed plate displacements (Test No. 1)
a) at 20 minutes (transient)
b) at 120 minutes (steady state)