HIGH RESOLUTION MOIRE PHOTOGRAPHY

by

C Forno

Division of Mechanical and Optical Metrology
National Physical Laboratory, Teddington, Middx TW11 0LW

Introduction

The process of masking the aperture of an imaging lens offers a means of improving its optical performance for specific applications. This principle is used at NPL in two photographic metrological techniques.

One of these is currently under development and employs a new metric camera, the Centrax which has been designed and built for high precision photogrammetry.

The other, High Resolution Moire Photography(1) is well-established in the field of deformation measurement and has been used for several years on studies involving a variety of engineering structures.

I. High resolution moire photography

In conventional moire photography, for the study of deformation measurement, an array of stripes is first applied to the surface of the structure. A camera is then arranged to record this pattern at different states during the deformation process. By a comparison of two photographs, taken before and after a deformation has occurred, a moire fringe pattern is obtained which maps out the component of the deformation perpendicular to the stripes. The fringe interval on these maps corresponds to an apparent displacement of one stripe-spacing in the object pattern.

The moire grid technique is singularly free from restrictions to its use. The total displacement or local strain being measured can be very large - as high as 10% - without introducing loss of contrast or ambiguity of the fringe pattern. On the other hand, the requirement that the surface be labelled with some kind of grid pattern is an inconvenience. A second more fundamental limitation is that, if high sensitivity is required, the pattern needs to be so fine that it becomes almost impossible to obtain from the recording camera an adequate resolution together with an adequate depth of focus to cover a wide and possibly deep structure.

Good resolution combined with a large depth of focus has been achieved by modifying the lens of a standard 35 mm camera. The modification, which consists of a 4-slotted mask located close to the iris (Figure 1), "tunes" the lens to resolve 300 lines per mm over the whole field of the image plane in both horizontal and vertical directions. In addition, the image remains sharp over a depth of focus that is approximately three times that achieved with the conventional circular aperture.

The camera is used in conjunction with a fine grain film, Agfa Gevaert 10E56, to record a fine pattern applied to the engineering structure. In some cases this may be random but more usually it is a regular pattern of dots or stripes running horizontally and vertically across the surface. When the camera is set at a predetermined distance the demagnified image of the pattern will appear as 300 resolved elements per mm in the image. Then, using electronic flash illumination, double exposure photographs are made on the same film frame before and after the object is deformed.

After the film has been processed, the fine pattern detail in the image behaves as two orthogonal diffraction gratings. A beam of light directed onto the negative will be diffracted into four first-order directions. By viewing the negative in one of these diffracted beams, using a simple optical system(1), a moire fringe pattern, or displacement map, is seen showing dark fringes corresponding to movements of odd multiples of one half a pitch in the object pattern. From the one negative two such displacement maps are generated representing either the vertical or horizontal displacements, depending on whether a vertically diffracted beam or a horizontally diffracted beam is examined. It is from these maps that the various features of material behaviour, such as cracking and slipping, are identified. An interpretation of the fringe values at different positions on the maps provides the information that leads to strain data by local differencing between adjacent points.

Camera modification

After extensive testing of different camera lenses, we have found that the objective most suitable for aperture-masking is the 55 mm f/2 Super Takumar, fitted to the screw-threaded Pentax camera. It is our experience from testing currently available camera lenses that the degree of correction for primary astigmatism is not always as complete as with the Takumar, resulting in a loss of resolution towards the edges of the field. If this lens cannot be obtained, then the masking of an alternative lens should not be carried out until a check has been made for astigmatism.

The four-slotted aperture, with a separation of 5.9 mm corresponding to a centre-tuned frequency of 300 lines/mm, is constructed from thin paper sprayed matt black. Slots can be cut simultaneously in pairs by means of two pairs of knife blades bonded together and separated by a spacer. With the Takumar lens there is little difficulty in obtaining access to the iris diaphragm. By unscrewing the rear elements as one unit the iris is exposed. The mask can then be lightly attached to the shoulder of the iris mount with a minimal quantity of adhesive.

In addition to the lens modification, the focal plane area is also adapted so as to keep the film stationary during the recording of a deformation study. Our method for improving the mechanical stability of the film uses a transparent 1 mm thick registration plate mounted in the image frame onto which the film is clamped. The spring-loaded pressure plate, fitted to the back of the camera body is made retractable, so that the film can be unclamped only during winding-on.

Photographic records

As well as recording double exposure photographs it is possible to record each increment of the deformation process on a separate film frame. After the film is developed and bleached the negatives are cut up and examined in pairs. The optical reconstructing system is similar to that used for the double exposure and a special jig for holding the negatives in close contact facilitates adjustment of their relative position and orientation.

Although the use of separate exposures may entail some loss of accuracy, because of dimensional changes in the negatives, it does offer important advantages. This technique not only generates deformation data that would normally not be available, unless many cameras are installed each recording a different double exposure event, but the direction of movement of the fringes during alignment defines unambiguously the direction of the deformation. In addition, this facility can be used to record a deformation sequence of an indefinite length, which might include the removal of the camera and its replacement at a later stage. If a permanent stable reference surface is included somewhere in the field of view of the camera then, in general, errors in the repositioning of the camera only introduce straight fringes, due to changes in the demagnification factor of the lens, and from the fringes appearing on the reference surface a simple compensation can be applied during the analysis stage.

Another virtue of single exposure comparison is that it provides a very sensitive means of detecting the presence of cracks when the fringes are slowly manoeuvered across the field of view. The cracks are conspicuous as small phase discontinuities, or jumps along the direction of individual fringes.

Industrial applications

The different structure that have been examined during the course of the development of the technique fall into three categories.

Large scale structures-the brick arch

One of the best examples of a large structure examined by moire photography was a brick arch, 3.6 m x 1.9 m, which was constructed by John Laing R & D Ltd in order to assess a new type of lightweight lintel.

The unprepared surface of the bricks was ideally suited for the application of a halftone dot pattern on paper. This was manufactured by contact copying a master halftone negative onto photographic document paper. For the arch, a pattern having 65 dots to the linear inch was chosen, as it provided the maximum sensitivity that could be achieved with an efficient use of the film format. After a liberal application of wallpaper adhesive to the back, the paper was affixed to the untreated brickwork in the usual paperhanging fashion.

The central vertical girder that supported the hydraulic rams used during the loading tests was also partly covered with the paper. This provided the reference surface which could be assumed to remain substantially unchanged during the tests. A view of the completely covered brickwork together with the rams and load-spreading blocks at the top is shown in Fig 2. The illumination was provided by the two 2000 joule electronic flash units situated on either side of the wall. Two cameras can be seen stationed at the optimum distance of 6.15 m from the wall. The left-hand camera only was set to record as a double exposure both the unloaded state and a heavily loaded state. The other camera was set to record the incrementally loaded conditions, each on a single frame, with double exposures of the incremental steps on alternate frames.

During the two hours of the experiment the wall was progressively loaded until it reached an unstable condition with prominent cracking in the middle of the span and in the right-hand pier. A total of 36 events were recorded without interruption of the loading sequence. The films were processed, and preliminary results from the double exposures were obtained during the afternoon of the same day.

Figure 3 shows the horizontal and vertical displacement fringe maps generated by the 0-30 kN load change. Some of the features of the deformation that can be recognized in the maps are:

1) A vertical crack running through the centre of the span appearing as a horizontally opening crack with little vertical shear;
2) shearing of the piers with respect to the main span;
3) wedge-shaped cracks extending into the span from both sides;
4) compression of the mortar between bricks at the top of the span.

Many of the small defects are apparent as fringe discontinuities of less than 0.1 fringe, indicating an equivalent object displacement of less than 40 m. Such defects could not easily have been observed on the untreated brickwork.

From the sequence of single exposures, one pair revealed the initiation of the central crack at an early stage in the loading sequence. Another pair was chosen as an example for a comparatively detailed study. They represented the difference between the unloaded state and the half-way stage. By dividing the horizontal and vertical displacement fringe maps into a square grid array, an estimation of the fringe value related to a chosen datum point was obtained at 319 points on the main span and

44 points on the piers. The two fringe values for each grid point defined the coordinates of the point at its new deformed position. When the coordinates were plotted for all the points, the figure produced was an exaggerated view of the deformed state of the wall as seen by the camera (Fig 4). Such a plot is a useful aid in visualizing the deformation processes.

Other studies involving large structures have included the monitoring of the collapse of a 9m wide Victorian bridge, a study of deformation in a vierendeel structure in the Hongkong and Shanghai Bank(2) and recently, measurements on the subsidence of the complete facade of a pair of houses.

Small structures at high temperatures-welded joints

Moire photography has been applied to high temperature studies following the development of a heat resistant pattern that can be conveniently applied in situ(3). The pattern is produced by stencilling with titanium dioxide pigment, with a retouching airbrush, through a very fine mesh. When the mesh is carefully lifted away the grid pattern is revealed as white blocks of pigment in relief against the polished surface. This will remain intact if it is not touched and will withstand a temperature of at least 600°C for long periods.

In general, stencils with 1000 holes per inch are the most appropriate where high sensitivity and good resolution coverage are required. The optimum camera distance for this stencil frequency is approximately 0.5 m, which is still within the designed focusing range of the lens.

To preserve the 300 lines/mm tuned response at this close-range the lens mask has slightly wider separated slots to allow for the increase in image conjugate. Apart from this, however, recording and reconstructing processes are as described previously.

The high temperature moire facility has been applied under contract to several problems involving welded structures, including a welded joint in a pipe of 2.25% Cr, 1%Mo and AISI 316 steel(4). A section was cut from the pipe containing a weld interface. After preparing the polished surface with the dot pattern, photographic records were made of the section at different hot and cold states. One double exposure record was made of the specimen at temperatures of 20°C and 560°C. From this negative the x and y expansion fringe maps were generated (Fig 5). The presence of the weld interface can be identified where there is a slope discontinuity to the fringes. Values for the total strain were derived from measurements of fringe spacing and slope. From each map the x or y strain, $_x$, $_y$, is given approximately by

$$\epsilon_x = \frac{u}{x} = \frac{p}{d_x}$$

and

$$\epsilon_y = \frac{v}{y} = \frac{p}{d_y}$$

Where p is the pattern pitch and d is the moire fringe spacing measured parallel to the displacement direction. Values for the total strain, which is made up of thermal and mechanical strains, were calculated at different positions across the specimen and are shown in Fig 6. Close to the weld interface there is a sufficient difference between the two strains to indicate the likelihood of plastic flow in the material.

The high temperature facility has also been applied to the measurement of cracking in welds, creep in small bore welded pipes(5) and tensile test specimens of jet engine turbine blade material.

Small and medium structures

The preparation of the surface for this class depends on the stiffness of the object and the environment in which it is tested. Printed paper patterns are adopted, provided that the mechanical properties of the object will not be affected and provided also that adequate sensitivity will be obtained with a line frequency of 500 lines/in or less.

An example of a particularly suitable material for such a pattern fequency is timber, where the strain levels are usually high and the anisotropy of the grain can produce dramatic effects. Figure 5 illustrates a study carried out on a timber beam and support structure and indicates that a wealth of information, in the form of strain distribution and material behaviour can be obtained by the use of such techniques.

Stencilled paterns, however, are recommended in situations, for example, with plastic materials(6), where the presence of a continuous coating may produce some unknown increase in stiffness of the object. Because the individual elements in the stencilled pattern are isolated, no added strengthening is introduced. In addition, the pattern will not wrinkle or degrade under conditions of high strain.

As the original intention was for high temperature work, there was often no need for protecting the dot pattern. For room temperature applications, however, abrasion resistant versions of the pattern have been developed and have been used in studies on carbon fibre composite structures as well as in explosive environments.

For all the industrial studies so far carried out, it has been practicable to apply regular patterns of one form or another. There is a version of this technique, however, that uses random patterns under circumstances where it is impossible to provide a regular one, for example, with spherical surfaces.

White light speckle photography

For this approach the prepared surface should appear as a random array of bright points. This is most conveniently achieved with a retro-reflective paint coating in conjunction with electronic flash illumination from a position close to the camera viewpoint.

The light distribution reflected from the paint returns in a narrow cone back to the source and camera where the lens-mask combination resolves each bright point as a central spot surrounded by subsidiary "ringing" spots in a cross formation. As a result the total integrated image behaves as two somewhat irregular orthogonal diffraction gratings which can be interrogated in the same spatial filtering system that is used for the regular pattern process. The fringe contrast, however, is not as high as with as the regular pattern process but is similar to the reconstructions from a double exposure laser speckle photograph, although some improvement is obtained when narrow slots are used.

Studies of the vibration modes in a car door have been undertaken using white light speckle and a simple variation can produce absolute shape information in the form of contour fringes(7).

Conclusion

Although the original emphasis for this work was on large civil engineering structures, the technique has lent itself to a variety of measurement problems at realistic levels of deformation and sometimes in hostile environments. The recording equipment required is cheap and portable, and the requirement of applying a surface pattern to the structure is no more inconvenient than the surface preparation needed for more conventional approaches, such as the use of strain gauges. Strain gauging methods of examining deformation are inherently more sensitive but are localized in coverage. Moire photography, by virtue of its examination of large areas, allows critical points of stress and deformation to be located - a necessary preliminary if the advantages of strain gauging are to be fully exploited. Our experience suggests, therefore, that moire photography should be used not as an alternative to strain gauging but rather to complement it.

Aknowledgement

The practical application of High Resolution Moire Photography would not have been possible without the originality and inventiveness of my now retired colleague Dr J M Burch.

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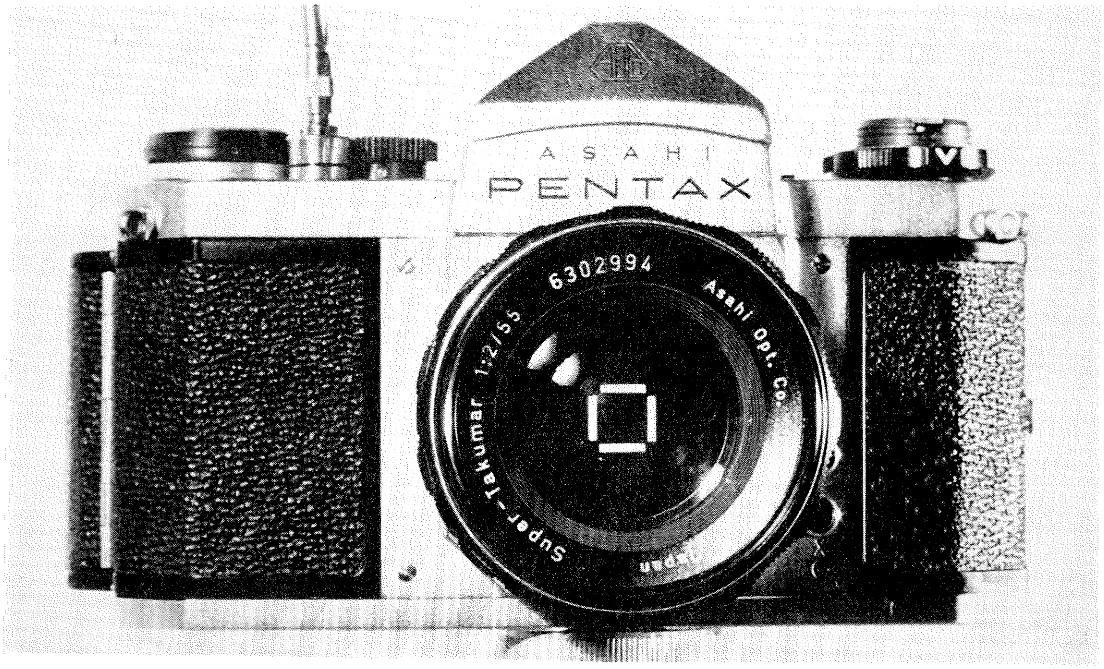


Fig.1 The modified Pentax camera

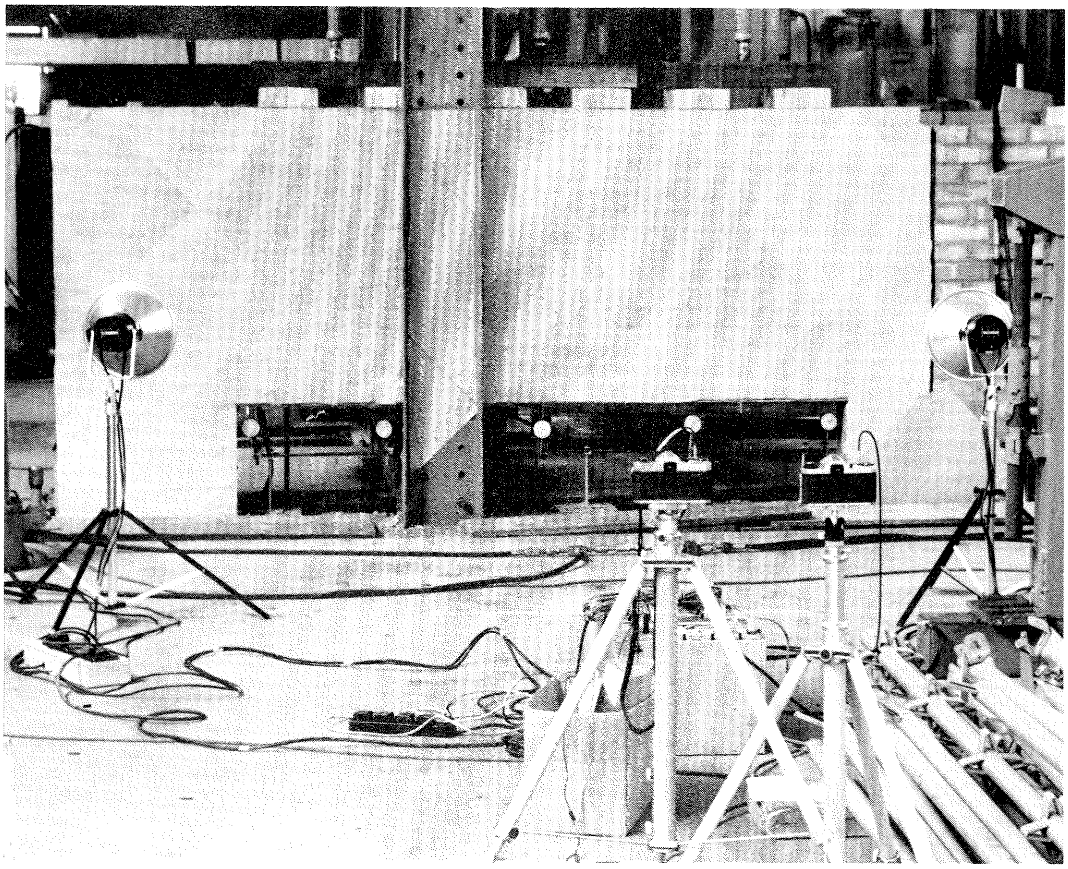
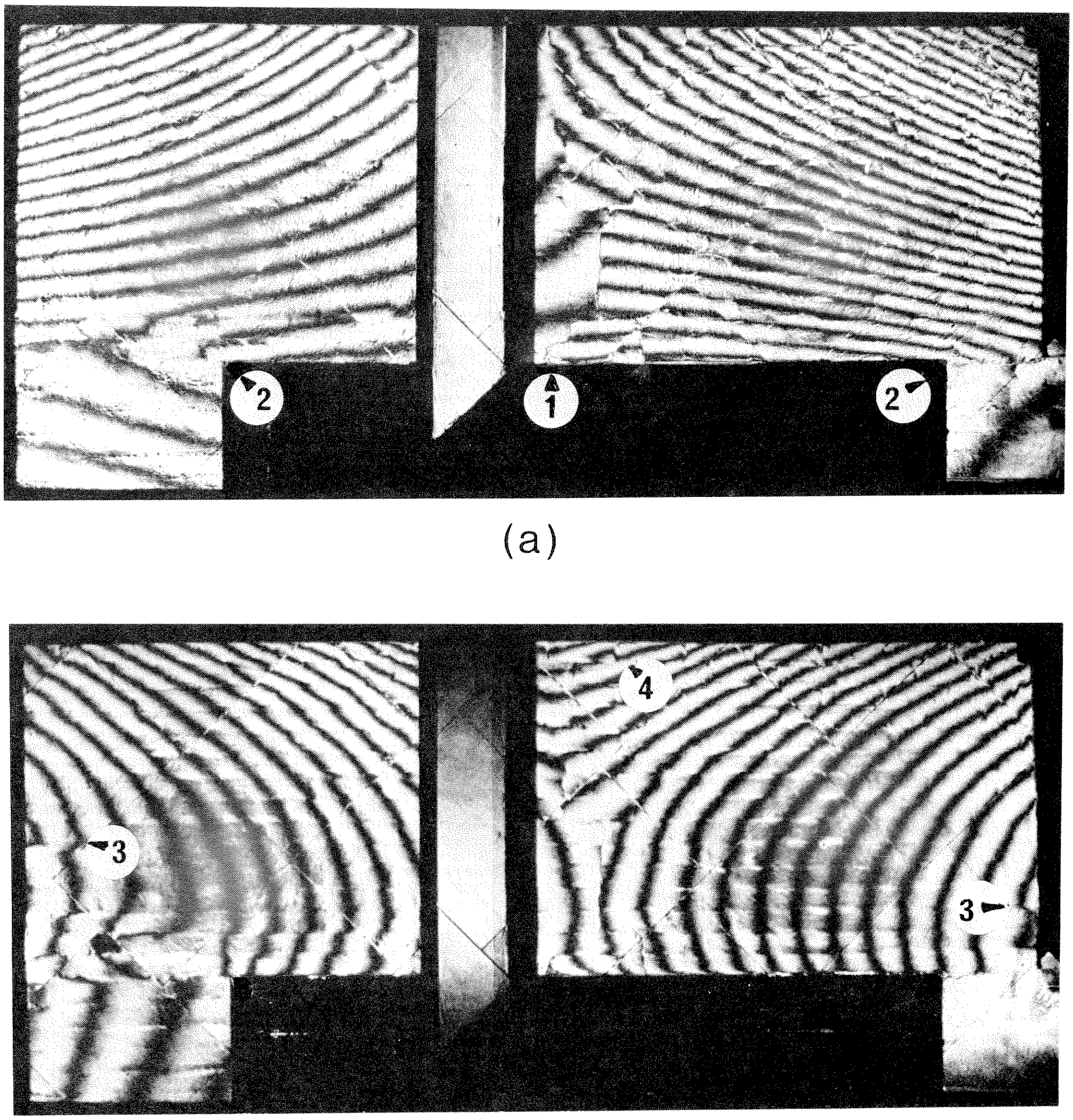


Fig.2 The 3.6m wide brick arch



(a)

(b)

Fig.3 Displacement maps of the arch
(a) horizontal (b) vertical

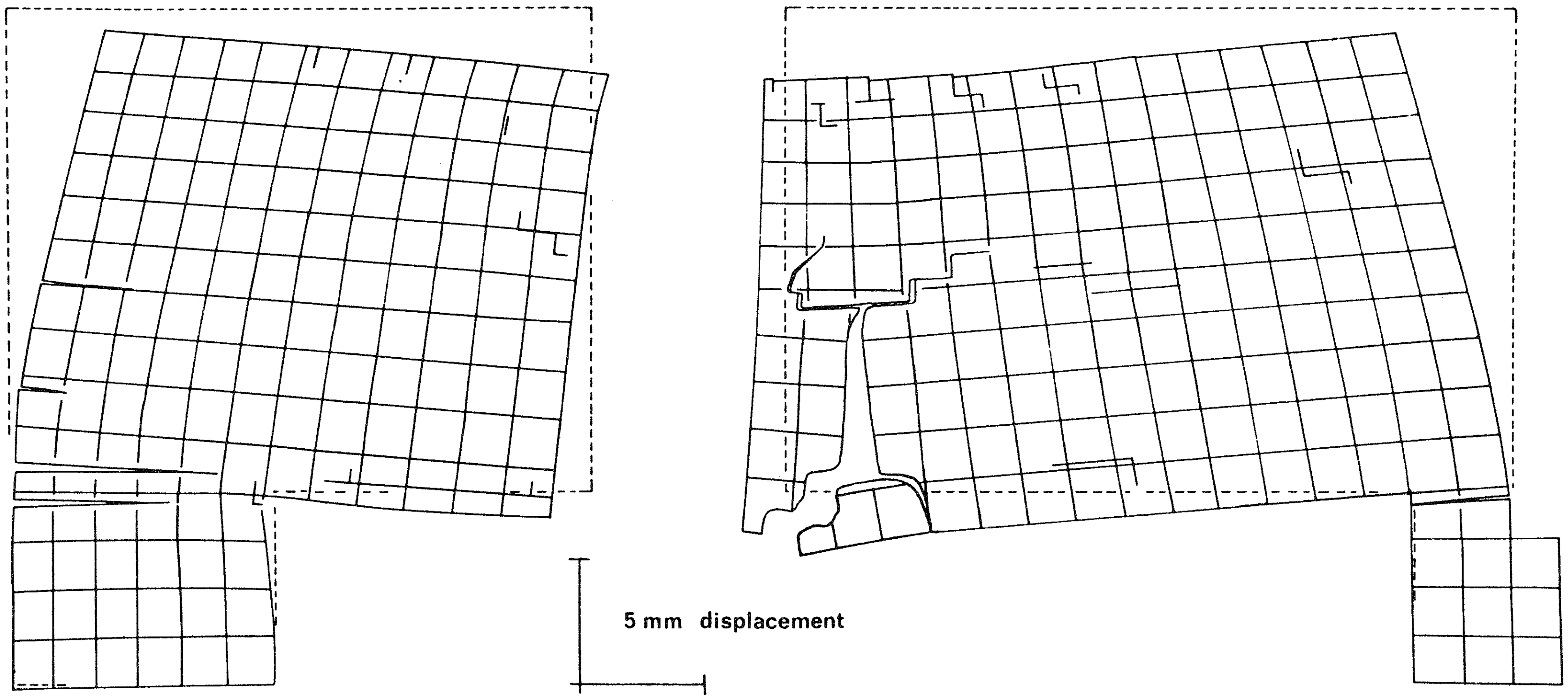


Fig.4 Deformation of the arch at 6000lb/in^2, 50 x Exaggeration

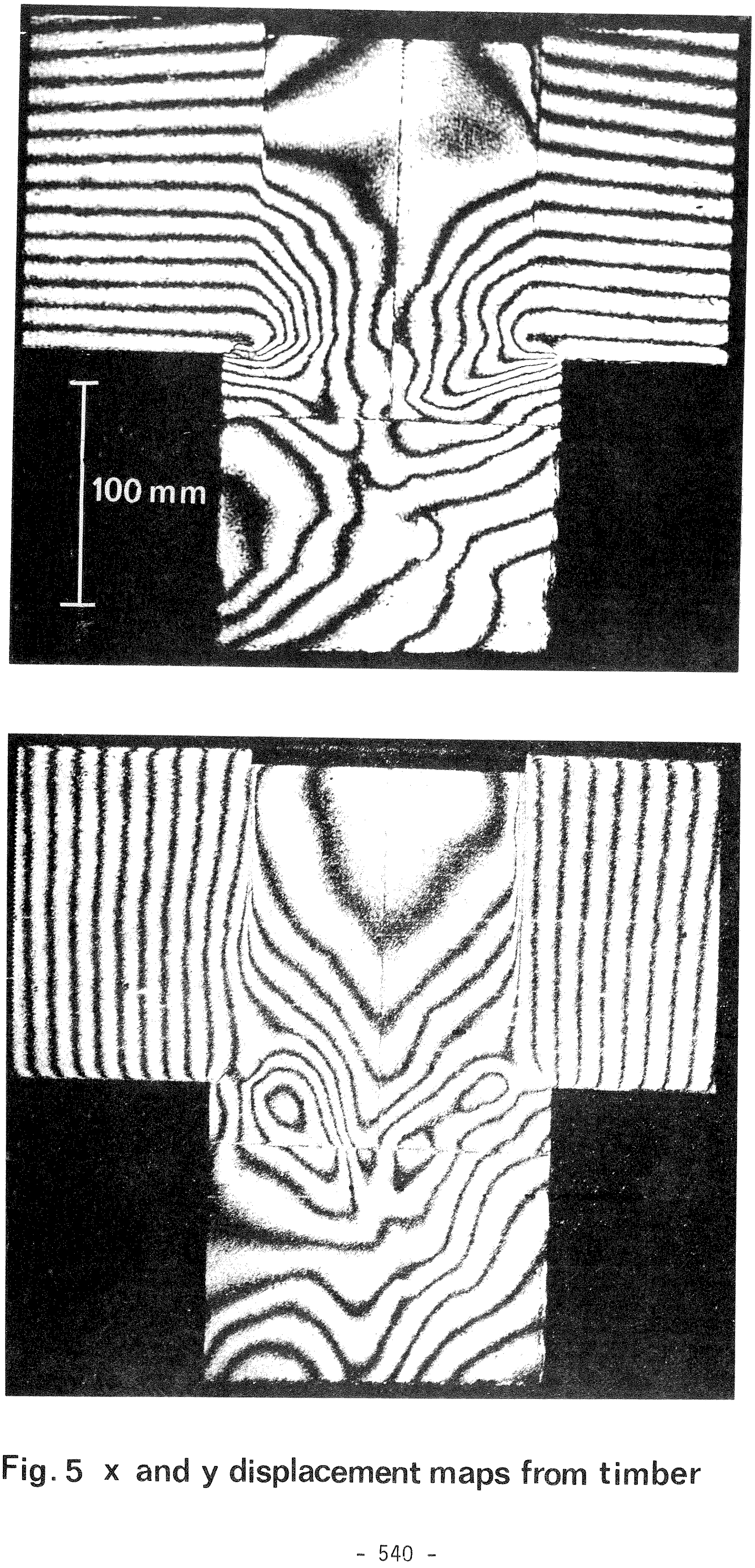


Fig. 5 x and y displacement maps from timber