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The use of photoelasticity to identify surface shear stresses during running

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Abstract

Shear stresses arising between the surface and a studded outsole during running were identified by the use of photoelasticity. A bespoke experimental set-up was designed to capture the dynamic maximum shear stress fringes occurring when a studded outsole came into contact with the photoelastic surface. Image processing methods were used to clearly identify the fringes. Examples of analysis techniques were outlined; focussing on the use of the greyscale intensity of the photoelastic fringes to calculate the subsequent shear stresses.

Keywords: Photoelasticity; Experimental design; Shear stress; Running; Studded footwear

1. Introduction

The analysis of the interaction between the foot and the surface during running is a widely investigated area; a successful outsole aims to improve performance yet limit the risk of injury. Two interaction parameters commonly measured during a foot-strike are pressure and traction force. Ground reaction forces and pressure patterns are typically identified through the use of force-plates and pressure mats [1-4]. The traction force is often measured by use of mechanical testing [5-9]; studded plates or full shoe outsoles are moved across the surface and the horizontal resistive force (traction) determined. The limitation of these approaches is that little is known about the surface shear stresses; in particular the location and magnitude during realistic movements. Few attempts have been made to measure local shear stresses [10]. The purpose of the study was to develop a method to use photoelasticity to identify the shear stresses between an outsole and the surface. This paper outlines the photoelastic set-up and provides examples of analysis techniques that can be used to identify the shear stresses between the outsole and the surface during running.

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2. Background

Plantar foot pressure is often measured by optical techniques as an alternative to the use of force plates and pressure mats. This is most commonly seen in the medical industry where optical methods are used to identify high pressure areas in the foot plantar surface of diabetic patients. The Pedobarograph was a major development in the field of optical foot pressure sensing [10,11]. A Pedobarograph uses the principle of critical light reflection along a glass plate. When pressure is applied to the surface, the critical angle alters and light is transmitted out of the glass. As such, when viewed from below, a pressure profile whereby the pressure is proportional to the intensity of light can be observed [11]. An alternative optical method used is photoelasticity. The theory of photoelasticity has been comprehensively covered by many texts [12-14]; an outline is provided below.

Photoelasticity is a stress analysis technique and inherently shows the maximum shear stresses in the material by utilising the optical phenomenon of birefringence (double refraction). Birefringence occurs naturally in optically anisotropic materials such as non-cubic crystals but can also be seen in some transparent materials when under stress. As the material deforms, the material-light interaction changes and the material becomes optically anisotropic. When a light ray is incident on a photoelastic material it splits into two rays. The resultant rays emerge with a phase difference dependent on the material properties and the wavelength of the incident light; in essence, the material has two refractive indices.

The change in the indices of refraction of a photoelastic material under stress is linearly proportional to the loads and thus related to stresses and strains [15]. This gives rise to the stress-optic law. For plane-stress situations, relating the change in refractive indices to fringe order, this can be expressed as:

$$\tau_{max} = \tfrac{1}{2}(\sigma_1 - \sigma_2) = Nf_\sigma / 2h \tag{1}$$

where τ_{max} is the maximum shear stress, $\sigma_{1,2}$ are the principal stresses, N is the fringe order, f_σ is the material stress fringe coefficient and h is the material thickness. Hence, the maximum shear stress can be simply obtained from measuring the fringe order determined in the resulting fringe pattern.

By polarising the incident and resultant light, two fringe patterns can be seen; isoclinic and isochromatic fringes. Isoclinic fringe patterns appear as dark lines on the image and are used to determine the direction of the principal stress. The isochromatic fringes indicate the lines along which the principal stress difference is equal to a constant and are of main significance in this study. The colour or intensity of the isochromatic fringe is indicative of the shear stresses present in the material at that location. By counting the reoccurrence of a particular colour or intensity the fringe order can be determined; this can be used with the stress optic law to calculate the shear stress.

If the top surface of the material is reflective, a single polariser can be used; this is known as reflective photoelasticity and allows the stress pattern to be viewed from the same side as the incident light. The use of reflective photoelasticity to measure foot pressure was first proposed by Arcan and Brull in 1976 [16]. A similar device was later used by Rhodes *et al.* [17] to determine ground foot reaction forces and by Nishizawa *et al.* [18] investigating the contact pressure distribution in Down syndrome infants. The set-up used by Arcan and Brull [16] consisted of a sheet of photoelastic material on a rigid transparent support. A flexible sheet with contact points was on top of the photoelastic surface, upon which pressure was applied. When illuminated from below stress fringes were visible in the photoelastic material. The outer fringe of each contact point was calibrated against the applied pressure. In essence, a relationship was derived between the outer fringe diameter and the pressure; the higher the pressure, the greater the diameter of the fringe. Rhodes *et al.* [17] indicated that the photoelastic set-up produced high resolution results with a good accuracy.

Although photoelasticity has the potential to measure shear stresses, its use has so far been limited to identifying the internal stresses of two and three dimensional models [19], particularly in the design of mechanical components [12]. The extraction of load information, both shear and vertical, was investigated by Dubey *et al.* [20-22]. Neural networks were employed to interpret a photoelastic foot print image but it was deduced that considerable manual analysis would also be required to evaluate the image [21]. Mechanical methods of measuring shear stresses have more recently been investigated. Davis *et al.* [23] designed a device to simultaneously measure the vertical pressure and the shearing forces in the anterior-posterior and medial-lateral directions under the plantar surface of the foot. The results were able to identify areas of maximum shear and maximum pressure within the forefoot and validated well against force-plate measurements. However, the device had a relatively low sampling frequency and a small test area; the combination of which restricts the range of movements that can be performed on the device.

A photoelasticity system similar to that proposed by Arcan and Brull [16] will be used to produce dynamic photoelastic images enabling the shear stresses between an outsole and the surface to be identified.

3. Methods

3.1. Experimental set-up

In order to analyse the shear stresses using reflective photoelasticity, a bespoke experimental rig was designed to capture the dynamic photoelastic fringe pattern. The system comprised of a sheet of photoelastic material with a reflective top surface. A circular polariser was placed between the photoelastic material and a rigid transparent support. The support used was an elevated glass force-plate; this allowed force-plate data to be recorded alongside the photoelastic images. The force-plate was activated by a falling edge trigger on impact and sampled at 1000 Hz. The surface was illuminated from below and the photoelastic images recorded using a Photron (APX-RS) high-speed video camera focussed on the underside of the material. A VDS Vosskühler (HCC-1000) high-speed camera was used to capture the side-view of the foot-strike. A light-gate was used as the remote trigger for both high-speed cameras. Photoelastic images were sampled at 50 fps and the side-view images at 200 fps.

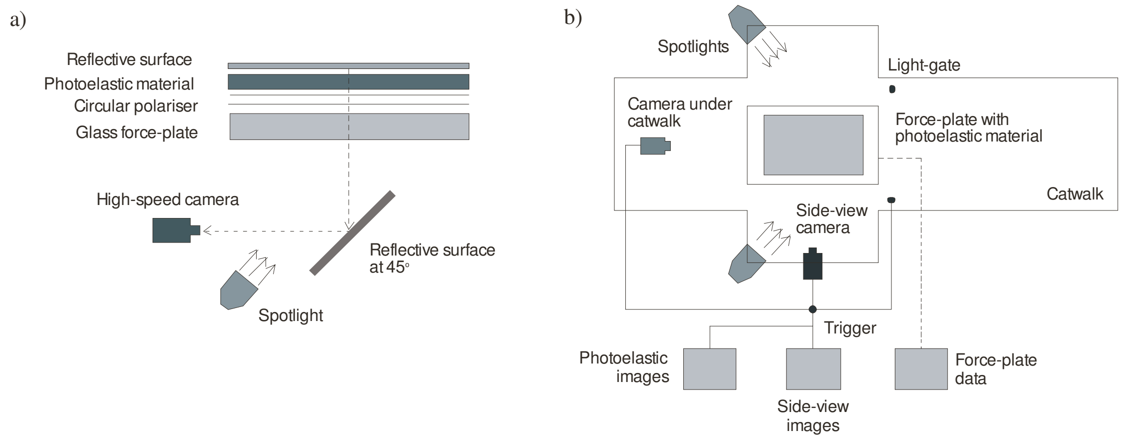


Figure 1 - Schematic of equipment set-up a) Side-view b) Plan view A high-speed camera sampling at 50 fps was focussed on the underside of the photoelastic material via a mirror positioned at 45°.

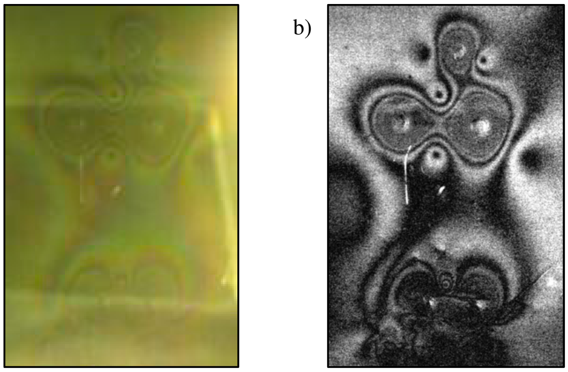
Participants wearing studded footwear were asked to run across the photoelastic material, with the heel-strike landing in the centre of the image. Shear stresses were produced in the material when the outsole came in contact. Studded outsoles (4 studs in the forefoot and 2 studs in the heel) were used to localise the shear stress and minimise the interference from out-of-plane stresses. Each foot-strike had a ground contact time of approximately 0.5 s, producing 25 photoelastic images. The start and end of contact was defined visually through the side-view images and validated against the force-plate results.

3.2. Image processing

Dynamic images were recorded and saved as individual jpeg files using the Photron software. This allowed post-processing of the images to be carried out. The aim of the post-processing was to convert the images into a form from which the fringes could be easily counted, and the movement or growth of a fringe tracked. The images were initially converted into greyscale (0 - 255) and the background removed by the calculation of the absolute difference between the stressed image and a non-stressed image. Figure 2 shows the original and processed image captured at

t = 0.2 s during the foot-strike. The two heel studs and three of the forefoot studs were in contact; i.e. the foot was in transition between heel-strike and forefoot push-off. Figure 2a displays the isochromatic fringes (loci of constant maximum shear stress); when viewed in colour, the repetitions of green and red bands are the most prominent. When converting to greyscale (Figure 2b) the maximum shear stress loci are now visible as bands of constant greyscale intensity. The green and red bands form the lightest and darkest fringes respectively and it is their reoccurrence that can be used to identify the fringe order (N). Due to the set-up and processing, the background of the images appeared dark (N = 0), as such the first fringe detected was a light fringe (N = 1/2) and the next a dark fringe (N = 1). The processed results were then used to evaluate the subsequent maximum shear stresses.

a) b)



c)

Figure 2 - Image processing a) Original b) Processed c) Side-view The images were converted to greyscale and the background removed by calculation of the absolute difference method. The image properties were adjusted to produce a clearer image (t = 0.20 s).

4. Results

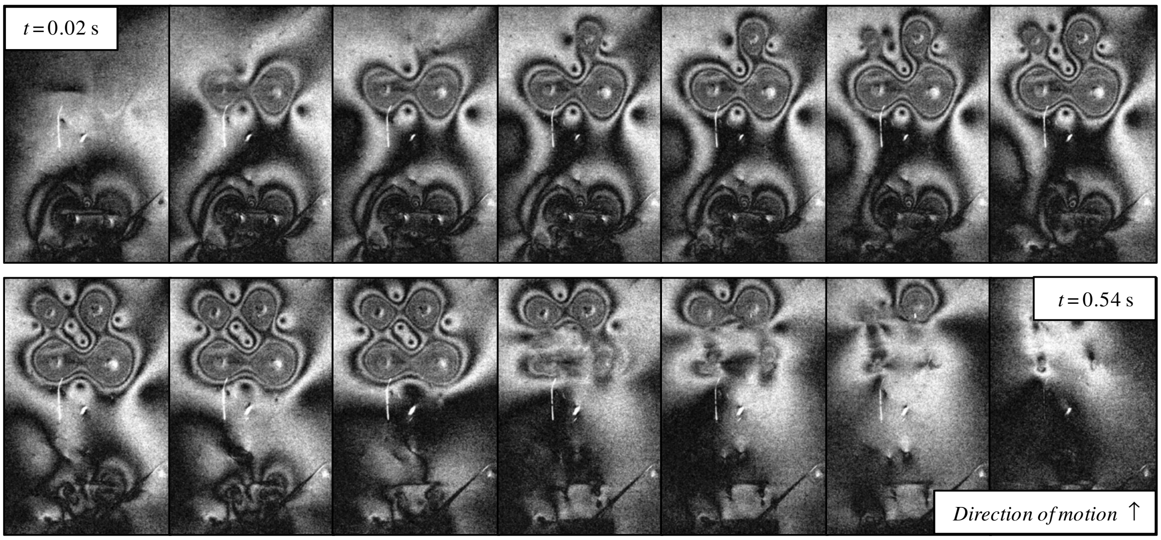


Figure 3 - Time series of stress patterns. Heel-strike and forefoot push-off photoelastic images during running in studded outsoles (Δt = 0.04 s).

Figure 3 shows the growth of the photoelastic fringes for the foot-strike. Upon the initial heel-strike, the shear stresses radiated from the stud contact points along the direction of motion. When the forefoot came into contact, the influence of the heel shear stresses decreased, and the fringes around the forefoot studs grew indicating maximum shear stresses acting predominately in the opposing direction to motion.

5. Analysis

To identify the location of the fringes, greyscale intensity profiles were drawn radiating from the centre of each stud on the image. The intensity profiles showed clear peaks for the light fringes and troughs for the dark fringes. A contact zone directly beneath the stud placement has been defined. This is the region in which the stresses are no longer directly related to out-of-plane shear stresses, and are instead a result of stresses arising from the normal force during contact. The contact zone produced a large number of fringes tightly spaced together; as such, the fringes could not be easily distinguished on the intensity profile and the overall zone is instead identified. Figure 4 illustrates the intensity profile for one stud in the forefoot during a translational movement (push-off after heel-strike, t = 0.2 s). A profile line 45^{o} to the direction of motion was chosen (Figure 4d) as the distinction between fringes can be clearly observed.

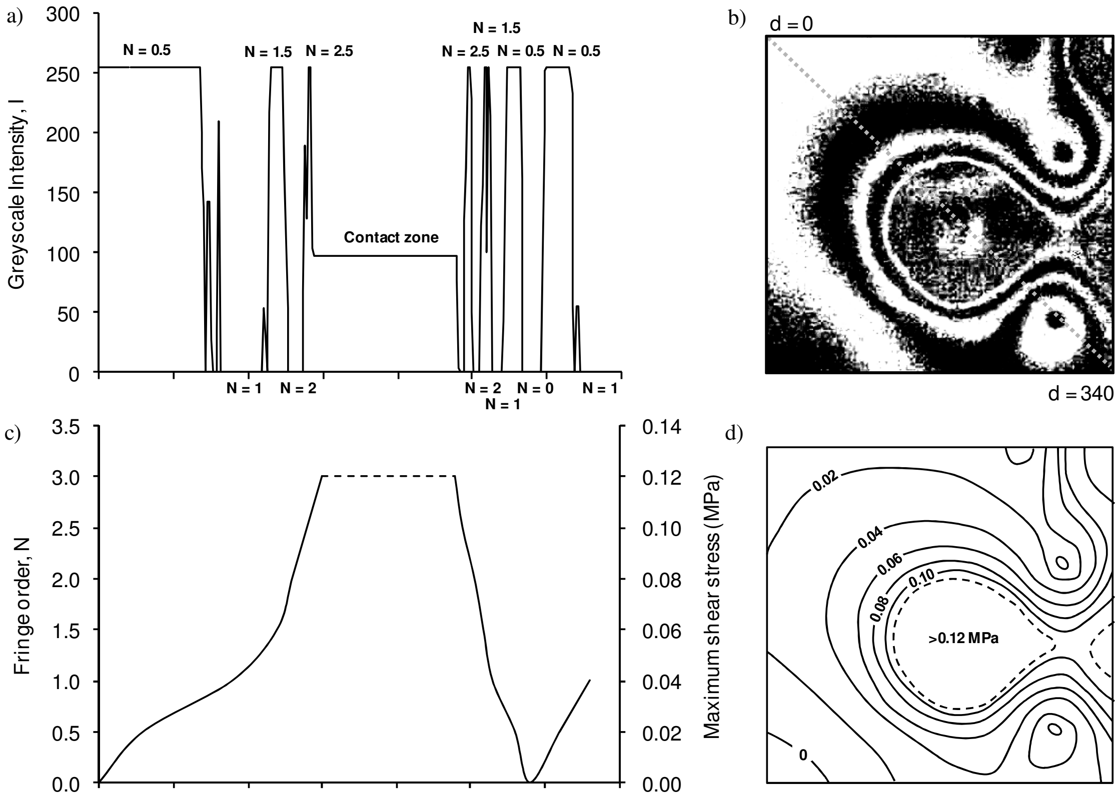


Figure 4 - Identifying maximum shear stress using greyscale intensity profiles a) The intensity profile indicates clear peaks for the light fringes (I ~ 255) and troughs for the dark fringes (I ~ 0) b) Processed image - focussed on lower left forefoot stud c) Fringe order is proportional to the maximum shear stress using Equation 1 d) The contour maps of the fringes indicate the increase in maximum shear towards the contact zone.

The fringe orders determined in Figure 4a can be used to estimate the maximum shear stress by use of the stress-optic law (Equation 1). Further calibration of the material is required to determine the stress fringe coefficient (f_σ), however using an estimation of 0.20-0.28 kN/m [13,14], rudimentary analysis of the fringe pattern suggested that shear stresses of 0.12-0.16 MPa were evident in the heel-surface during initial impact and approximately 0.08-0.12 MPa at the forefoot-surface during push-off (Figure 4b).

6. Conclusion

Identification of the shear stresses between a studded outsole and the surface has been achieved by use of a bespoke photoelastic system. Initial testing has proven it is possible to record dynamic photoelastic images, these images can be analysed to provide maximum shear stresses and stress trajectories. The method described is still in development and additional research is planned to further the analysis; namely validation of vertical loads and shear stresses using experimental methods. It is hoped that the photoelastic method and analysis techniques can be used in the next stage of the study; to develop a detailed picture of the shear stresses and the outsole during varying loading conditions.

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