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# Study of Mode-I and Mixed-Mode Fracture in Wood using Digital Image Correlation Method

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## Abstract

This paper presents results of an investigation conducted to study displacement and strain field surrounding a crack tip in timber in tension using the Digital Image Correlation (DIC) technique. Opening mode fracture was studied with a crack parallel and perpendicular to grain and mixed-mode fracture was studied with a crack parallel to grain but located 30°, 45°, and 60° with respect to the applied tensile force. Crack system was LT or TL with the thickness in the radial (R) direction. In Mode-I with a crack parallel to grain, crack tip deflection and strain concentration were clearly visible. Opening mode behaviour with crack perpendicular to grain was entirely different to that shown by a parallel to grain crack indicating a different mechanism of load transfer. Crack tip displacements were clearly visible and in some specimens strain concentrations could be identified. In mixed-mode fracture, realistic displacements parallel and perpendicular to crack were given by the DIC and normal and shear strains showed a highly irregular pattern which warrants further examination. All cracks propagated in the natural RL plane of timber.

Keywords: Digital Image Correlation, Mode-I fracture, Mixed-mode fracture

## Introduction

Structural wood members contain natural or artificial defects such as knots, drying checks, splits, and machined notches and holes. These defects represent discontinuities in the path of load transmission and therefore become stress raisers within the material. The nature and influence of such stress raisers on the stresses and strains in their vicinity has been the focus of fracture mechanics. For convenience of investigation, three fracture modes are generally specified: These are opening mode (Mode-I), shear-mode (Mode-II), and twisting-mode (Mode-III). In opening mode fracture forces are applied perpendicular to crack, in shear-mode forces are applied in the crack plane parallel to crack, and in twisting-mode they are

applied in the crack plane but perpendicular to the crack. Each of these modes is associated with a stress intensity factor,  $K_I$ ,  $K_{II}$ ,  $K_{III}$ , respectively, which indicates the level of stress increase in the vicinity of a crack. For an orthotropic material like timber, there are six fracture systems for the three orthotropic planes but in many practical situations, fracture is relevant in TL and RL planes only and many a time fracture occurs in mixed-mode, ie., a combination of opening and shear mode in RL, TL, and LT planes. (Here, first letter denotes direction normal to crack plane and second one denotes direction of crack.) Examples are horizontal and vertical cracks in beams and cracks emanating from holes of loaded bolted connections.

The stress intensity factors are derived from the solution of governing differential equations of equilibrium (Sih et al. 1965). In this approach, the stress field surrounding the crack tip is formulated. Another approach used to address fracture is the energy formulation dealing with work to fracture. The parameter derived in this approach is the strain energy release rate ( $G$ ) and it is generally accepted that the energy approach describes fracture phenomena in a more fundamental manner than the differential equation approach. However, results from the two approaches (stress intensity factor and strain energy release rate) are related as derived and shown by Sih et al. (1965). Cracks are believed to propagate when a critical stress intensity factor  $K_c$  (or critical strain energy release rate  $G_c$ ) for the corresponding mode has been reached. Thus, study of fracture generally involves characterization of stress intensity factors and or strain energy release rate associated with various loading and geometrical configurations of the crack.

Wood fracture has been studied fairly extensively (Patton-Mallory and Cramer, 1987). However, due to the complex nature of fracture processes in wood, a consensus approaches to study wood fracture have not been standardised and much work needs to be done before integrating our knowledge of wood fracture into wood design procedures. Approaches taken to study wood fracture ranges from experimental, theoretical, and numerical techniques all having limitations in

different areas. In experimental studies, either formulae derived for fracture in isotropic materials to relate stress intensity factors to applied stress and specimen geometry are used to obtain stress intensity factors, or the crack tip opening displacement is measured to obtain strain energy release rate. Sih et al. (1965) showed that formulae relating stress intensity factor to remote stress are equivalent for both isotropic and orthotropic materials for self-balancing loads applied at infinity. However, the effect of orthotropy on the finite size members is still not clear.

Theoretical wood fracture studies on timber has been based on the Griffith-Irwin fracture theory which postulates that fracture occurs when strain energy release rate exceeds crack growth resistance (Porter 1964). Due to experimental difficulties, finite element method has been used to obtain stress intensity factors for timber (Patton-Mallory and Cramer 1987). Here, orthotropic properties can be incorporated and the stress intensity factors can be based on energy formulations or on stress field surrounding the crack tip. However, these results need to be validated with experimental results in order to assess their reliability. Very little work has been done on mixed-mode fracture in wood. Mall et al. (1983) emphasized the interaction between Mode I and Mode II stress intensity factors in mixed-mode fracture and evaluated several mixed-mode failure criteria.

## Objectives

The objective of this study is to use the Digital Image Correlation (DIC) method to obtain displacement and strain profiles around the tip of a crack in specimens of New Zealand radiata pine. Specifically, displacement and strain fields for a through crack oriented parallel (TL) and perpendicular (LT) to the grain is studied in tension. In addition, mixed-mode fracture for a crack positioned parallel-to-grain but loaded at various angles to grain (mixed-mode) are studied. It is hoped that the crack tip displacements thus obtained can be used to determine stress intensity factors for opening and mixed-mode fracture using the formulae such as those derived by Sih et al. (1965) for orthotropic materials and these will be presented in a forthcoming paper.

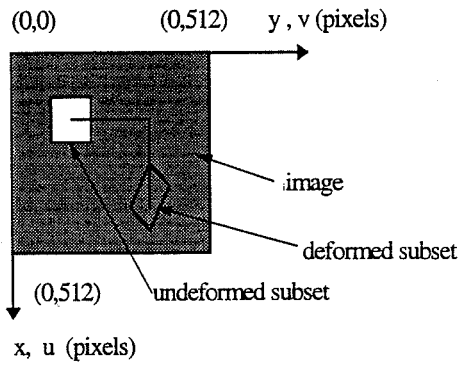
## Digital image correlation

Digital Image Correlation (DIC) is a non-contacting full-field strain measuring technique that has been developed to obtain full field surface displacements and their gradients (strains) of objects under stress.

The method involves comparison of two digitized video images of the surface of the object before and after deformation using an appropriate correlation technique. The DIC method has evolved over the last decade and vast improvements have been made in the efficiency and reliability of computations. Program used in this study was developed by Dr. Steve McNeill and his group in University of South Carolina, Columbia, USA. The method has been successfully applied to determine displacements and gradients of steel and aluminium with sub-pixel accuracy (Chu et al. 1985) and has recently been applied to study tension, compression and bending behavior of small wood specimens and glued wood joints (Zink et al. 1995; Zink 1992). These investigators confirm that DIC can be a valuable tool in understanding the mechanism of load transfer in wood. Durig et al. (1991) applied the method to determine stress intensity factors for Aluminium in mixed-mode fracture and McNeill et al. (1987) used it to obtain mode I stress intensity factors for plexiglass. It has not been used to study fracture in wood.

## Theory of digital image correlation

The theory of digital image correlation has been described in detail by several researchers and a detail treatment of the subject can be found in Sutton et al. (1983). Therefore, only a brief description is given here. The underlying principle of DIC is that points on the undeformed surface can be tracked to new positions on the deformed image using a least square error minimisation technique. To achieve this, the object surface must have a random light intensity pattern that makes a small area surrounding a point unique and able to be tracked. Therefore, specimens are usually speckled with paint or carbon toner particles to obtain a random speckle pattern on the surface. Surface is illuminated with a white light source (fiber optic light used here) and the intensity distribution of light reflected by the surface is captured by a CCD camera and digitized by a digitizer and stored as a two dimensional array of grey intensity values on a computer. Typically, light intensity signals are discretely sampled by an array of sensors (480x640) of the CCD camera. The experimental setup used is shown in Figure 2 and a detailed discussion is given in the section on the experimental method. Images captured in this study were 512x512 where each point is described by its x and y coordinates in pixels (Figure 1) and the light intensity ranging from 0 to 256 with 0 representing black and 256 white. Digitized images captured before and after deformation are then compared by a digital image correlation routine to obtain displacements and strains.



**Figure 1- Coordinate axes and an undeformed and deformed subset of an image**

Before correlation, discrete grey intensity level array is reconstructed using bilinear interpolation to obtain a continuous intensity distribution over the whole image. This is because, a point in the undeformed image can map into a gap between the pixels in the deformed image. To obtain displacements and gradients, a mathematical relationship between the actual displacement of a point (Figure 1) and the light intensity of a small area (subset, 20x20 used here) surrounding the point must be established. Values of interest for surface measurements are displacements in  $x$  and  $y$  directions ( $u$  and  $v$ ), normal strains ( $\partial u/\partial x$ ,  $\partial v/\partial y$ ) and components of shear strain ( $\partial u/\partial y$ ,  $\partial v/\partial x$ ). It is assumed that the light intensity of points do not change as a result of object motion and therefore, a subset in the undeformed image can be mapped to a subset of similar intensity in the deformed image. Thus it is critical that the object is illuminated uniformly. For each small subset with center  $x$  in the undeformed image, the subset center displacement can be defined using linear elastic theory (Sutton et al. 1983) as:

$$(x')_i = (x)_i + (u)_i + \frac{\partial \{u_i(x)\}}{\partial x_j} dx_j \quad (1)$$

$i, j = 1, 2$

where  $x'$  = deformed position of the center of the subset,  $u$  = displacement vector,  $\partial u_i/\partial x_j$  = components of the deformation gradient, and  $i$  and  $j$  are coordinate axes directions.

The displacements and gradients for a particular subset in the undeformed image is obtained by minimising the square of the difference in light intensity between the points in the subset and all other subsets of the same size in the deformed image. For this purpose, a correlation coefficient,  $C$ , is defined as follows:

$$C(u_i, \frac{\partial u_i}{\partial x_j}) = \iint_{\delta M} [A(x) - B(x')]^2 dx \quad (2)$$

where,  $A(x)$  is light intensity of a point  $x$  in a subset ( $\delta M$ ) of the undeformed image and  $B(x')$  is light intensity of a point  $x'$  in a subset of the deformed image. The subset that minimizes  $C$  with respect to displacements and each of the gradients locates the new position of the subset after deformation. This is accomplished in the program by a least square error estimation technique in conjunction with a Newton Raphson correlation technique. To initiate the search process, known initial vertical and horizontal displacements ( $u, v$ ) of a point in the image is specified. Thus for each desired point displacements and gradients are obtained.

## Experimental Method

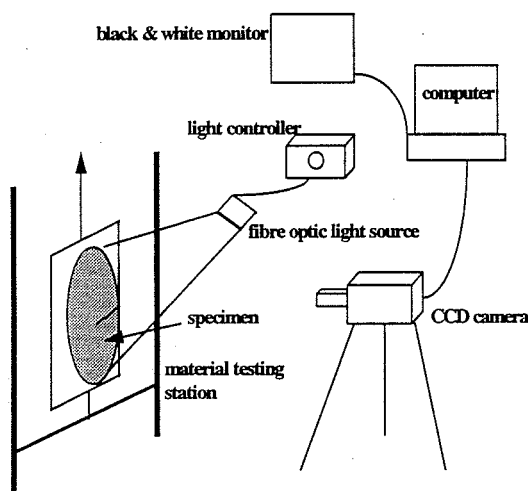
Specimens were prepared from kiln-dried structural grade New Zealand radiata pine (*pinus radiata*) boards obtained from a local timber yard in Christchurch, New Zealand. The boards were left in the laboratory where it is heated but humidity is not maintained for about 8 months.

Tensile specimens (180x90x20mm) were prepared in such a way that (i) effects of a 10, 20, 35, and 55 mm crack aligned parallel and perpendicular to grain can be studied in opening mode, and (ii) mixed -mode fracture where a 10mm crack oriented parallel-to-grain but loaded at an angle (30°, 45°, 60°) can be studied. Specimens were of LT orientation with thickness in radial (R) direction. There were two specimens in each category. Cracks were cut using a fine saw blade. At the time of testing moisture content of the specimens was about 11%. Young's modulus of timber has not been determined yet but it is expected to be around 10 Gpa. Since wood is a highly variable material, a piece of industrial rubber (6mm thick, 40mm wide, 100 mm long) with a 10 mm edge crack at the center of one edge was put on a vice, stretched in increments of 1 mm and images were captured in order to compare results with more variable timber.

## Tensile Testing and Image Capture

Tests were conducted on a computer controlled SINTECH material testing workstation. Special tensile jigs were manufactured to hold 90 mm wide and 10 to 20mm thick specimens in the jaws. The test setup with equipment used to capture images are shown in Figure 2. Specimens were speckled with black and white paint to obtain a random speckle pattern and grey level intensity histograms showed a normal distribution

around the mean of 120-130. Intensities at the tail ends closer to zero and 256 were not achieved. Specimens were illuminated by a fiber optic ring light level of which could be controlled. This allowed a very uniform level of illumination throughout the surface. Images were captured by an Ikgami CCD (Charge Couple Device) video camera with 25 frames per second capture rate and a lens with x4 magnification. Images were digitized to 512x512 size by a high accuracy 8 bit monochrome CX100 frame grabber/digitizer on an IBM 486DX66 computer. Live analogue video signal from the frame grabber was shown on a black and white monitor and the digitized image was shown on the computer monitor.



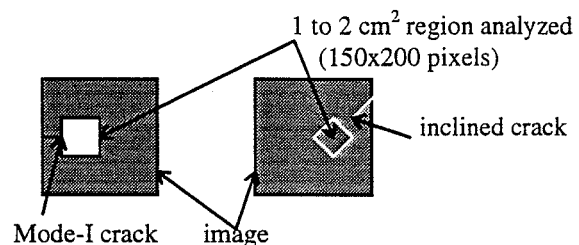
**Figure 2- Schematic diagram of the test setup and image capture**

Specimens with a crack parallel to grain and mixed-mode specimens were tested at 1 mm/min and those with a crack perpendicular to grain at 2 mm/min. Software that drives the testing machine provided a load-time curve which was used to capture images at various load levels upto failure. Generally, 2 to 5 images were captured in each test. Prior to testing, a graph paper was placed against the specimen surface and its image was captured to calibrate the image distances to real distances. A typical resolution for the current setup was 54 pixels/cm in the horizontal and 83 pixels/cm in the vertical directions. Camera was about a metre away from the specimens. Processing of the images is discussed in the next section.

## Image Processing

Captured images (in TIF format) were analyzed by the Video Image Correlation Program mentioned earlier

(Manual for video image correlation 1993). An area of 1.0 to 2.0 cm<sup>2</sup> (upto 200x150 pixels) in front of the crack with the crack tip close (1 to 2 mm) to the center of one edge as shown in Figure 3 was selected for analysis. A typical subset size used was 20x20 and displacements and gradients for points located at 10 pixel intervals horizontally and vertically were obtained. Thus for a particular pair of images, displacements and gradients of 100 to 200 points were determined.

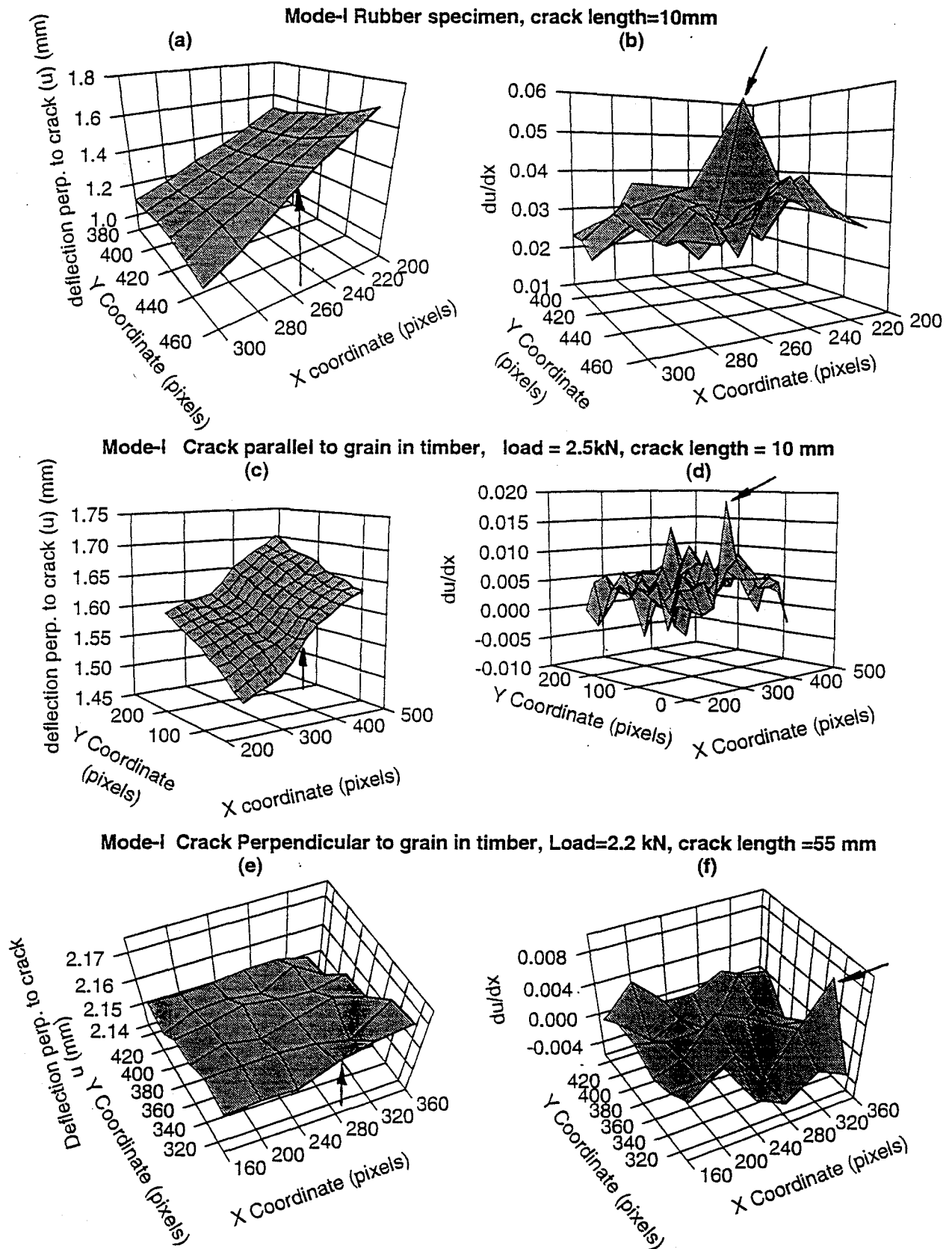


**Figure 3- Location of the analyzed area with respect to Mode-I and inclined cracks**

## Results and Discussion

**Mode-I fracture-** Figure 4 shows deflection perpendicular to the crack ( $u$ ) and its gradient ( $\partial u / \partial x$ ) as a function of pixel position for the rubber specimen (a, b), for a 10 mm crack located parallel to grain and loaded at 2.5 kN (c, d), and for a 50 mm crack located perpendicular to the grain and loaded at 2.2 kN (e, f). Crack tip is denoted by an arrow on the plots. For rubber and timber specimen with crack parallel to grain, deflection occurred in horizontal bands perpendicular to load direction, which were disturbed near the crack tip. These bands in timber may be due to lignin matrix deforming uniformly across the cross section upto the crack region where the crack tip disturbance is met. Increased tension above the tip and increased compression below the tip are seen in Figures 3(a) and 3(c). For timber and rubber specimens, highest strain occurred at the crack tip and these values are 5.5% and 1.9%, respectively. In timber specimens, cracks propagated in the natural LR plane of timber even if the prepared crack plane slightly differed from the RL plane. The propagated end of the specimen showed a perfect crack plane perpendicular to growth rings.

An entirely different observation was made for timber with a crack located perpendicular to grain as shown in Figures 3(e) and 3(f). Deflection occurred in vertical bands aligned with the load direction. It is hypothesized that these bands represent vertically oriented cells transmitting load differently across the

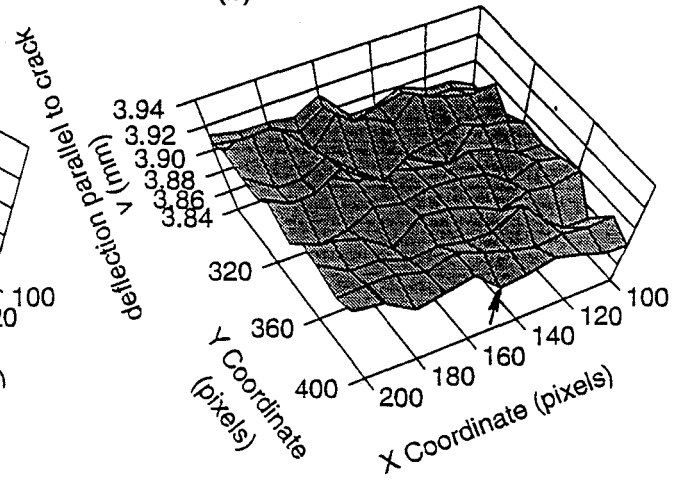
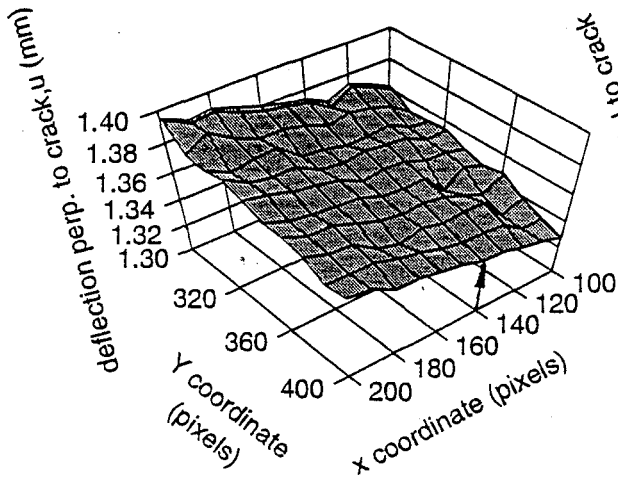


**Figure 4- Deflection perpendicular to crack ( $u$ ) and normal strain ( $du/dx$ ) near crack tip for Mode-I for rubber (a,b), crack parallel to grain (c,d), crack perpendicular to grain (e,f) (arrow indicates crack tip)**

30 degree crack angle, load = 3.0kN

(a)

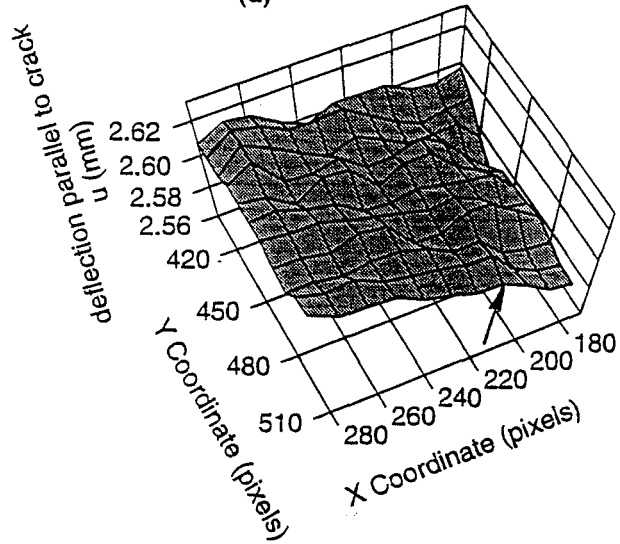
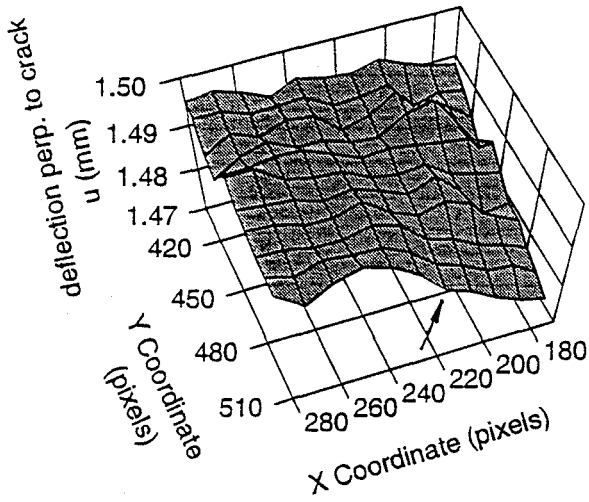
(b)



45 degree crack angle, Load = 3.0kN

(c)

(d)



60 degree crack angle, Load = 3.0 kN

(e)

(f)

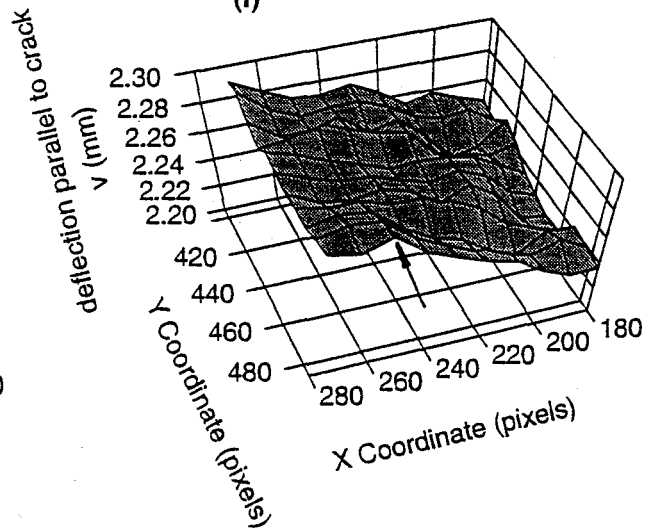
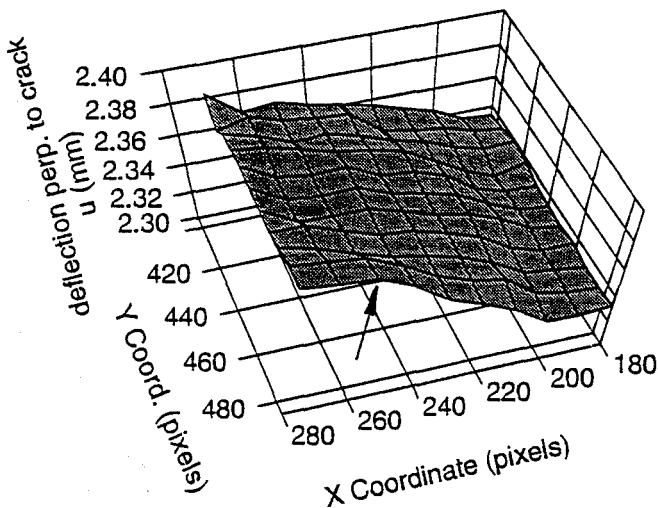


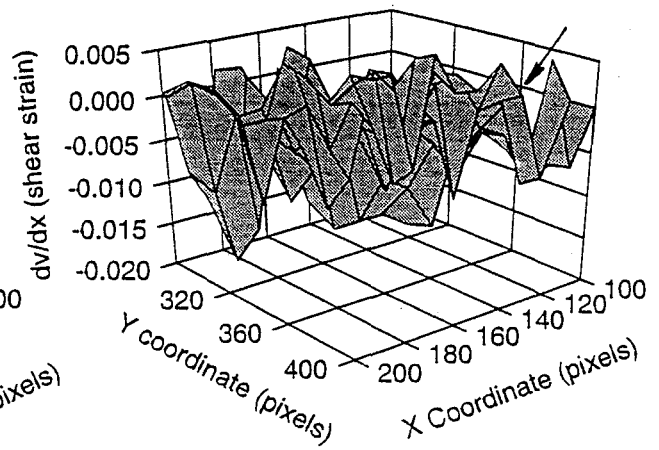
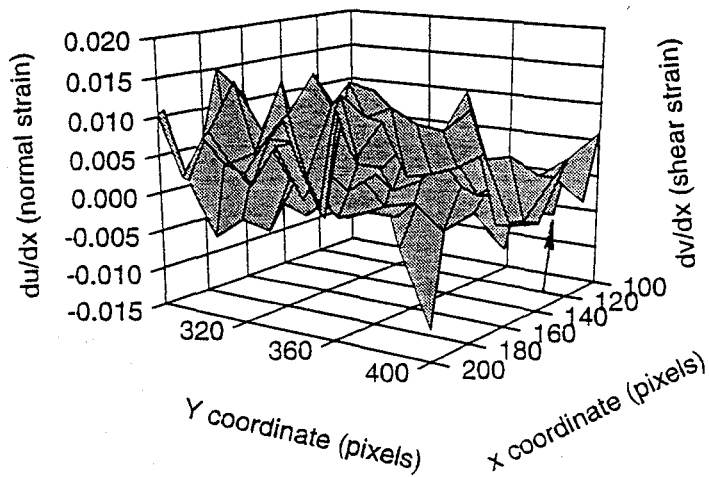
Figure 5- Deflection perpendicular (u) and parallel (v) to crack for 30 degree (a,b), 45 degree (c,d), and 60 degree (e,f) crack angle (arrow indicates crack tip)



30 degree crack angle, Load=3.0kN

(a)

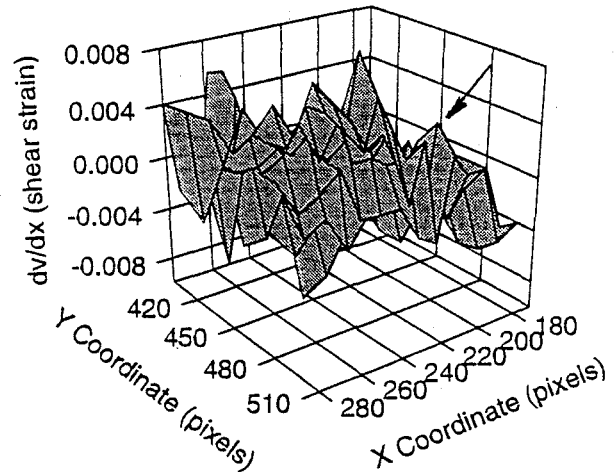
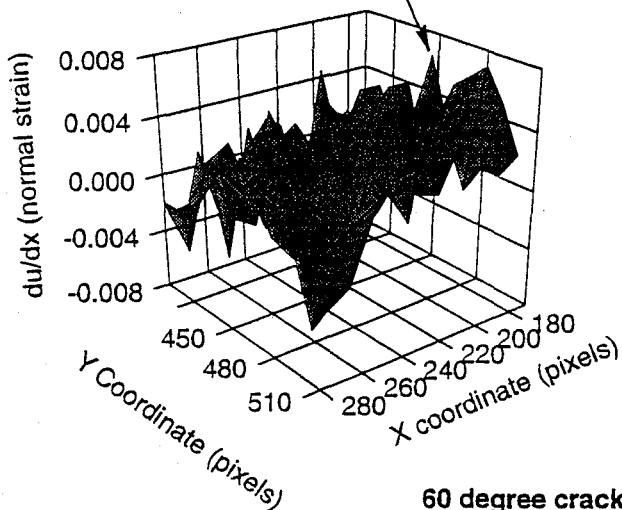
(b)



45 degree crack angle, Load=3.0kN

(c)

(d)



60 degree crack angle, Load= 3.0kN

(e)

(f)

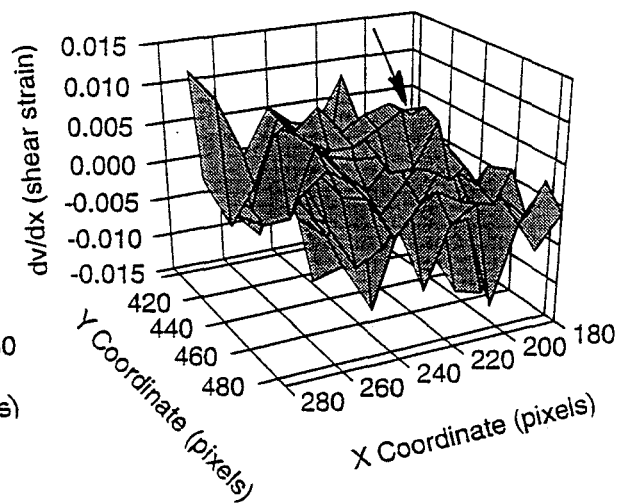
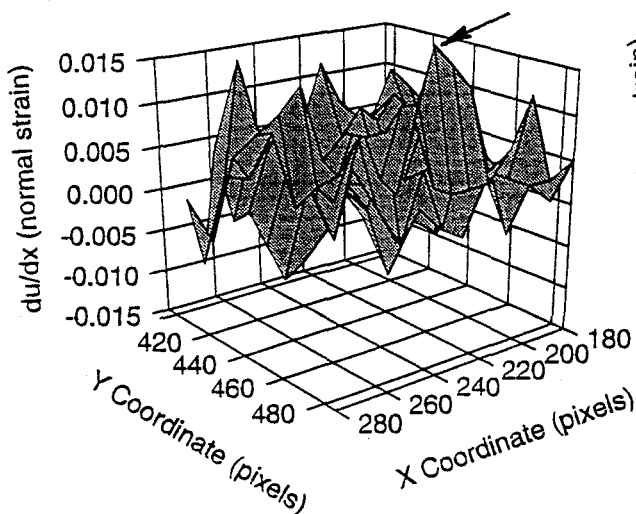


Figure 6- Normal ( $du/dx$ ) and shear ( $dv/dx$ ) strains near the crack tip for 30 degree (a,b) and 45 degree (c,d) and 60 degree (e,f) crack angle (arrow indicates crack tip)

cross section. Area above the tip experienced an extra tension and that below the tip experienced extra compression that disturbed the overall pattern. For the specimen shown, strain concentration occurred at the tip but for some other specimens it did not coincide with the tip. Cracks propagated either from the tip or a few millimetres inside from the tip down toward the fixed grip along the LR plane of timber. Cracks found this plane right from the beginning and therefore, failure was at an angle less than  $90^{\circ}$  to the original crack plane. The propagated end of the specimens showed a perfect crack plane perpendicular to growth rings. Results on the effect of crack length will be reported in a forthcoming paper.

**Mixed-Mode fracture-** Results for mixed mode fracture for load to crack angles of  $30^{\circ}$ ,  $45^{\circ}$ , and  $60^{\circ}$ , and for a load of 3 kN are shown in Figures 5 and 6. In mixed-mode fracture,  $u$  and  $v$  deflections and normal and shear strains around the crack tip become important. Deflection perpendicular to crack ( $u$ ) and parallel to crack ( $v$ ) are in Figure 5 and associated normal and shear strain are in Figure 6. Deflection perpendicular to the crack ( $u$ ) increased with crack angle and that parallel to crack ( $v$ ) decreased with crack angle as expected (Figures 5 (a) to (f)). Crack tip influence can be explained as done before for opening mode fracture, i.e. crack tip region experienced positive and negative deflections in both  $u$  and  $v$  thus disturbing the overall trend in the vicinity of the crack. Normal and shear strains show a highly variable pattern owing to rough  $u$  and  $v$  function surfaces. Positive and negative strains occur in all plots and in some cases ( $45^{\circ}$  and  $60^{\circ}$ ) crack tip concentration is shown. However in others, higher strains occur elsewhere in the region analyzed. Overall, deflections seem to portray the expected behaviour. The nature of strain patterns are unknown in timber and therefore, results warrant further analysis and scrutiny. At higher load levels, a proportionately similar behaviour was observed.

## Conclusions

A digital image correlation (DIC) method was used to study deflection and strains near the crack tip in opening and mixed mode fracture in timber. In opening mode fracture with a crack parallel to grain, the influence of crack tip deflections and strain concentrations were clearly visible. Results were analogous to those obtained for the rubber specimen but were more irregular. The deflection pattern in opening -mode fracture with a crack perpendicular to grain is entirely different to that with a crack parallel to grain. The influence of tip deflection could be clearly

identified and crack tip strain concentrations were visible for some specimens but not for others. In mixed-mode fracture, DIC gives realistic deflections parallel and perpendicular to the crack for various crack angles. But, normal and shear strains are highly irregular. In LT and TL system, cracks always followed the natural LR plane.

## References

- Chu, T.C.; Ranson, W.F.; Sutton, M.A.; Peters, W.H. 1985. Application of digital image correlation techniques to experimental mechanics. *Experimental Mechanics*: 232-244.
- Durig, B; Zhang, F; McNeill, S.R.; Chao, Y.J.; Peter III, W.H. 1991. A study of mixed mode fracture by Photoelasticity and digital image analysis. *Optics and Laser engineering*. 14.
- Mall, S; Murphy, J.F; Shottafer, J.E. 1983. Criterion for mixed-mode fracture in wood. *Journal of Engineering Mechanics*. 109(3):680-690.
- Manual for 2-D sub-pixel digital video image correlation. Version 9-16-93. Cimpiter Inc. Columbia, South Carolina, USA.
- McNeill, S.R.; Peters, W.H.; Sutton, M.A. 1987. Estimation of stress intensity factor by digital image correlation. *Engineering Fracture Mechanics* 28(1):101-112.
- Patton-Mallory, Marcia; Cramer, Steven M. 1987. Fracture Mechanics: A tool for predicting wood component strength. *Forest Products Journal* 37(7/8):39-47.
- Porter, Andrew W. 1964. On the mechanics of fracture in wood. *Forest Products Journal* xiv:325-331.
- Sutton, M.A.; Wolters, W.J.; Peters, W.H.; Rawson, W.F.; McNeill, S.R. 1983. Determination of displacements using an improved digital image correlation method. *Image and Vision Computing* 1(3):133-139.
- Sih, G.C.; Paris, P.C.; Irwin, G.R. 1965. On cracks in rectilinearly anisotropic bodies. *International Journal of Fracture* 1:189-203.
- Zink, Audrey, G. 1992. The influence of overlap length on the stress distribution and strength of a bonded wood double lap joint. PhD thesis, State University of New York, Syracuse.
- Zink, Audrey G; Davidson, Robert W; Hanna Robert B. 1995. Strain measurement in wood using a digital image correlation technique. *Wood and Fiber Science* 27(4):346-359.