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Bamboo-glue interface thermography for non-destructive testing

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Abstract: The present work explores the possibility of employing non-destructive testing (NDT) technique of thermal wave imaging, using infrared radiations, to study the interface between bamboo and glue, and gaps in glue application therein. This is a relatively unexplored area as regards bamboo, and thus a novelty, though thermal imaging of detecting glue deficiency in laminated wood has been reported. Active thermography technique using Frequency Modulated Thermal Wave Imaging (FMTWI) has been used to identify frequencies which would give good images of the glue deficiencies.Glue bands and gaps up to 5 mm, could be imaged using lock-in thermography through slivers of 2 mm thickness. The inspection time ranged from 65 s to 350 s depending on the glue type. These findings point to the possibility of using thermal NDT for applications of bamboo and its composites/laminates.

Keywords: Non-destructive testing (NDT), bamboo, glue, thermography, FMTWI.

INTRODUCTION

Global warming concerns have prompted researchers to have a relook at alternatives to existing materials and technologies for housing. The search for alternatives to timber as a measure to check deforestation has prompted research on replacing timber with bamboo as a ëgreení option for housing. By going for shorter gestation period, species like bamboo can be used as a mitigation option through carbon sequestration. Moreover unlike long gestation trees, bamboo culms require regular harvesting from the time the culms become 3 to 4-years-old, to keep the bush healthy. Thus continuous availability of bamboo is an ecofriendly option.

Bamboo applications require use of bamboo slivers glued to bamboo slivers/substrate. However, gaps in glue application are likely to occur, which if detected non-destructively could be helpful in addressing failures on this account. Thermography

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is a non-contact and non-destructive test (NDT) method, which uses an infrared (IR) camera to obtain information about the thermal structure beneath the surface of an object up to a limited depth. (Wu *et al.*, 1997) have noted that other alternatives of NDT techniques like ultrasonics or x-ray cannot be applied successfully to wood-based products because of the composite layered structure of these products. Bamboo also has a composite layered structure (Hidalgo-Lopez, 2003). Therefore there is a need to investigate the use of thermography, as a non-destructive tool, for testing bamboo, which has been hitherto a relatively unexplored area.

While Wu *et al*. (1997) have used thermography for inspection of wood particle boards, Berglind *et al.* (2003) have studied glue deficiency in laminated wood using thermography. Recently, Tuli *et al*. (2009) have reported effective use of thermography for imaging defects of 5 mm dia in bamboo up to a depth of 4 mm. Figure1 reproduces a typical thermal image of a sub-surface defect in a bamboo sample, at a depth of 2 mm, which is not visible to the naked eye but shows up using thermography. This gives a reasonable basis to assume that thermography could similarly be used for non-destructive testing of bamboo-glue interface and regions of glue deficiency, therein. This then could develop into a convenient tool for monitoring defects of bamboo structures.

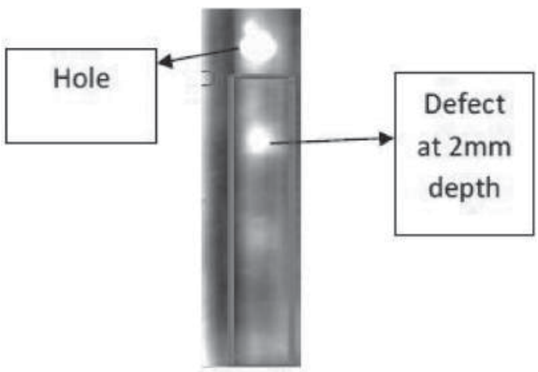

Figure1. Thermography image of subsurface defect, in a bamboo sample, not visible to naked eye (Tuli *et.al*. 2009).

Active thermography

Thermography for non-destructive testing is a non-contact technique which employs infrared imaging to map subsurface features. Active thermography further involves irridiating the specimen and thus infusing energy into it. The resultant heat propagator thermal waves so generated interact with the sample and are detected and imaged remotely. The depth of probing by thermal waves is related to its wavelength (λ) which in turn is a function of thermal conductivity k, density ρ, specific heat C and modulation frequency f (Wu *et al.,*1997). This is embodied in the following equation:

$$\lambda = \sqrt{(4\pi k/f\rho C)} \qquad (1)$$

Therefore, to image to a certain depth, the frequency of modulation is different for different materials *i.e.* bamboo, air (gap), glue (on sliver). Active thermography technique using Frequency Modulated Thermal Wave Imaging (FMTWI) has been used to identify the frequencies which would give good images of subsurface defects (Tuli and Mulaveesala, 2005). Lock in imaging is used for imaging defects using thermal waves at a particular frequency. Fourier transform of captured raw images enables viewing the phase images at various frequencies. The phase images are relatively independent of local optical and infrared features (Maldague, 2001).

Test samples

The test samples consisted of slivers of *D. strictus*. Their thickness was around 2 mm, breadth around 3 cm and length around 10 cm, and was pasted on a flat split bamboo substrate, through glue bands of pre-determined width. Experiments on three such samples are reported here. Glue in samples 1 and 2 consisted of Araldite epoxy standard resin and Araldite standard hardner made available by Huntsman Advanced Materials (India) Private Limited at retail outlets, mixed with bamboo dust as per Table1. In sample 3 the glue used was Epoxy resin Araldite LY 556, a condensate product of Bisphenol A and Epichlorohydrin, used with hardener Aradur HY951 (liquid aliphatic amine type) supplied by Huntsman for General Industry. The sliver was thereafter pasted on the bamboo substrate. Figure 2 shows typical test samples. Glue bands of width of 10 mm, 7 mm and 5 mm were placed on the slivers at gaps of 10 mm, 7 mm and 5 mm. A through hole was drilled at one end into the sample, for reference in

Table 1. Details on samples and glue

Sample No.	Weight of glue per unit area in gm/m^2	% of bamboo dust by weight in the glue	Pressure on the glue bands for adhesive act in MPa	Glue type bands	Placement of glue
1.	120.48	3.45	0.075	Huntsmanís Araldite epoxy standard resin and Araldite standard hardner mixed with bamboo dust	Gap of 10mm in between glue bands of 10 mm, 7 mm, 5 mm width
2.	108.51	3.45	0.099	Huntsmanís Araldite epoxy standard resin and Araldite standard hardner mixed with bamboo dust	Gaps of 10 mm, 7 mm, 5 mm in between glue bands of 10 mm width
3.	105.7	Nil	Nil	Huntsmanís Araldite LY556 with Huntsmanís hardener Aradur HY951	Gap of 10 mm in between glue bands of 10 mm, 7 mm, 5 mm width

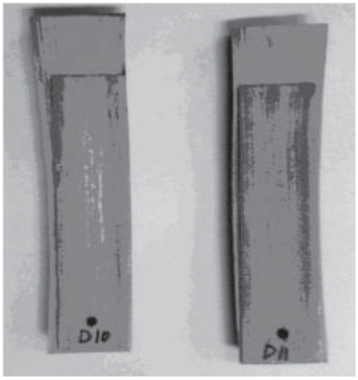

Figure 2. Test samples with sliver pasted on bamboo substrate.

identifying the placement of glue bands and gaps. The test pieces, after the pasting of slivers on the substrate with glue, were cured for a period of 17 h at room temperature of around 22^{o}C. The sliver thickness was kept at around 2 mm, in view of the findings of thermal wave imaging of defects in bamboo (Tuli *et al.,* 2009).

Experiments

The test set up (Figs.3, 4) consists of an IR camera, connected to a computer, the sample irradiated by two halogen lamps whose output is modulated through an arbitrary wave form generator (AWG) developed in-house. The AWG generates wave forms as per instructions fed through a controlling computer program. Each of the lamps was fed with 300 W electrical power. The test pieces were placed for imaging so that the slivers pasted on the bamboo substrate face the lamp radiations and the IR camera. The light from each of the lamps was incident on the test piece at 45^{o} angle with the camera placed directly in front of the test piece as shown in Figure 4. The wave form used was a raised sinusoidal chirp for FMTWI and a raised sine wave for Lock-in

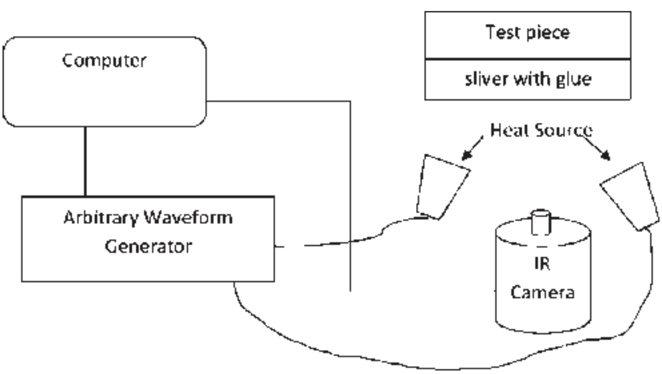

Figure 3. Experimental set up for thermal wave imaging.

Figure 4. Test set up: shows test piece, IR camera and the two halogen lamps.

imaging. The duration of the chirp was selected to enable full capture of the image at the lowest frequency in the chirp. Sampling frequency of the images captured by the IR camera was 4 Hz.

Fourier transform of these images using Thermoview, locally developed software, generated phase and amplitude images. Phase images were used for further analysis since it is independent of local optical and infrared features. Since phase contrast depends on modulation frequency of heating, therefore identification of the frequency at which images are obtained, is the first requirement. FMTWI was used for the purpose. Selection of the highest frequency which gave good images was preferred so that the duration of exposure is minimal. Once a frequency of imaging was identified, images were taken using lock-in technique at that frequency. The frequency of imaging using lock in technique for samples 1 and 2 was 17 mHz. The irridation cycle time was kept at 65 s to ensure at least a cycle within this duration. For sample 3 however the frequency identified was 3 mHz and therefore the inspection time was 350 s. To get a good contrast in the phase images Thermoview has a feature of selection of automatic gain control region of interest. This was demarcated and appears in phase images with a red outline (Fig. 5).

RESULTS AND DISCUSSION

Figures 5(a) and 5(b) are the typical phase images for the two glue types. Figure 5(a) is the phase images of sample 1 for lock-in imaging for 65 s. Figure 5(b) is the phase image for lock in imaging for 350 s for sample 3. The images show distinct glue bands and gaps.

Frequency of imaging and inspection time

The highest frequency of imaging, which gave the best images for bamboo and various

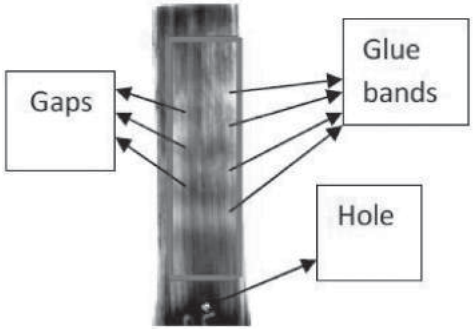

Figure 5 (a). Phase image at the bamboo glue interface of sub surface glue bands. Glue consists of Araldite standard epoxy resin with Araldite standard hardener mixed with bamboo dust. Imaged through a sliver of thickness 2 mm. Width of glue bands is 10 mm, 7 mm and 5 mm placed at gaps of 10 mm. Inspection time 65 s.

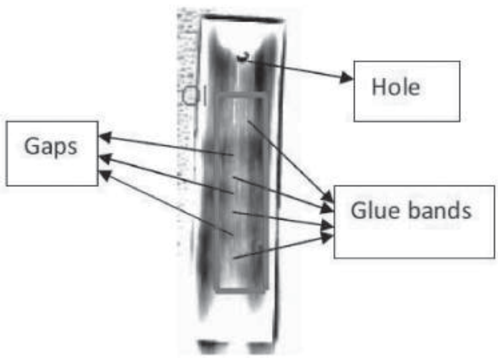

Figure 5 (b). Phase image at the bamboo glue interface of sub surface glue bands. Glue consists of Araldite LY 556 with hardener Aradur HY951. Imaged through a sliver of thickness 2 mm. Width of glue bands is 10 mm, 7 mm and 5 mm placed at gaps of 10 mm. Inspection time 350 s.

glue types, so as to get the shortest time for irridation, was identified. For samples 1 and 2 good phase images of glue bands and gaps therein with FMTWI and lock-in was obtained at a frequency of 17 mHz. The inspection time was 65 s. However for sample 3 the frequency identified was 3 mHz with inspection time of 350 s.

Resolution capability

Gaps of 10 mm, 7 mm and 5 mm are clearly seen and so are glue bands of 10 mm, 7 mm, and 5 mm.

Penetration depth

Glue bands through slivers of thickness 2 mm gave good images for both glue types.

CONCLUSION

The use of thermography as a method of non-destructive testing for the interface between bamboo and glue and thus detecting glue deficiencies has been amply demostrated through experiments. Glue gaps and glue bands up to 5 mm width can be easily imaged through slivers of thickness 2 mm. The inspection time required varies from 65 s to 350 s depending on the glue type. Thus rapid non-destructive detection of glue deficiencies at the bamboo glue interface is feasible using this technique. This method of testing could have far reaching implications in bamboo applications.

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