Experimental analysis of flexural behaviour of glued lamellar wood by speckle interferometry

Salvatore Benfratello, Alessia Camera

Department of Structural, Aerospatial and Geotechnical Engineering, University of Palermo, Italy
E-mail: *salvatore.benfratello@unipa.it, alessia.camera@unipa.it*

Keywords: Speckle interferometry, glued lamellar wood, strain, displacement field.

SUMMARY. Specimens of Red Spruce derived from on-sale rectangular glued lamellar beam are investigated by means of speckle interferometry under four-point bending tests. Two different areas of the specimens are investigated, one in order to analyze the behaviour under pure (constant) bending and the other one for analyzing the response to mixed linear bending – constant shear. The set-up is configured in such a way that the in-plane displacement is measured and the phase stepping technique is adopted. A custom software developed in LabView® 8.6 environment has been used for assisting the operator in all the experimental steps. The obtained results confirm the complexity of the mechanical behaviour of wood and show that at the applied load levels no influence is due to the glue interface.

1 INTRODUCTION

Since many years the role of glued laminated timber in structural engineering, restoration and modern architecture is rapidly increasing. Mainly this is due to the versatility of structural elements made of glued laminated wood which can be realized practically in any shape. From a structural point of view glued laminated timber elements suffer two main drawbacks: 1) they are made of wood, which is a complex, polymer-based, cellular, inhomogeneous material; 2) they are realized gluing together two or more "lamellae". Another important aspect is related to the natural presence of defects (such knots or resin pockets) in wood, which strongly influences the esthetical quality of wood as well as its mechanical behavior. The technological progress in last years makes today the gluing process more reliable, however the role played by the glue interface in the evaluation of mechanical behavior is still under investigation, especially with respect to the fiber orientation, the presence of defects and the finger joints. As it is well known, at the cellular scale wood is not a continuum due to the presence of vascular vacuums. All these features strongly influence the mechanical behaviour which can differ even from one specimen to another and depends upon the direction of loading with respect to fibre orientation. It follows that the real mechanical behaviour of wood is that of an anisotropic material. Conversely, at a macroscopic scale when the analysis is carried out on a structural member which is large in comparison to the size of cell, wood is usually considered as a continuous homogeneous orthotropic material and its mechanical behaviour is usually approached in cylindrical or rectangular coordinates [1][2][3][4]. The above considerations emphasize the importance of experimental techniques able to investigate the behaviour of glued wood either at fibre or at macroscopic scale. Strain measurement at the fibre level has not yet been accomplished due to the loading effect on the measured quantity. In this framework an ideal experimental technique should have two fundamental properties: 1) it should perform full-field analysis in order to capture more detailed information; 2) the analysis should be performed in a contactless way in order to avoid possible influences of the instrumentation on the specimen behaviour. With such a technique it is also possible to provide the potential for further developments toward optimizing the use of wooden structural members [5]. In past years some authors [6],[7] have studied the applicability of other contactless techniques (digital image correlation, thermal stress analysis, moiré) to measure strain in wood and in wood assemblies, obtaining an accurate evaluation of the advantages of these techniques. In the last years, due to either the technological improvements of the laser sources as well as to their reduced costs, speckle interferometry has been asserted as very effective in the framework of contactless techniques for analysing displacement fields. One of the significant advantages of Electronic Speckle-Pattern Interferometry (ESPI) is its capability to produce real-time fringe patterns on objects with optically rough surfaces, with a displacement sensitivity of the order of the wavelength of light.

Aim of the paper is to apply Electronic Speckle-Pattern Interferometry handled by phase-stepping technique to the experimental study of glued wood. The attention is focused to specimens obtained from Red Spruce on-sale rectangular beam. The mechanical test adopted in the paper is the four-point bending test (UNI EN 408:1995 [8]) since it allows the evaluation of both pure (constant) bending and mixed linear bending - constant shear responses of the material; the dimensions of the specimens (in mm) are the following: 120 x 20 x 10. The obtained results are compared with those for a non-glued wood specimen in order to show the differences in mechanical behaviour. All the analysis are carried out with an in-plane set-up configuration and filtering the obtained images by means of an appropriate developed iterative filter.

2 EXPERIMENTAL ANALYSIS

2.1 *Speckle interferometry*

Various techniques based on speckle interferometry have been implemented in the last years and are suitable for analysing displacement fields. One of the significant advantages of Electronic Speckle-Pattern Interferometry (ESPI) is its capability to produce real-time fringe patterns on objects with optically rough surfaces, with a displacement sensitivity of the order of the wavelength of light. The contactless approach of this technique is very relevant for the analysis of materials with low Young's modulus and with a porous surface, because the use of other classical techniques such as strain gauges, for example, is affected by the well know reinforcement effect that introduces a measurement error. In this paper a "*phase stepping speckle interferometry technique*" has been implemented. This technique offers high sensitivity together with a high contrast of the acquired fringes, the latter being a fundamental feature for subsequently using accurate automatic processing techniques. ESPI technique is used to obtain displacement fields from fringe patterns representing contour maps of the phase difference induced by the specimen deformation. A set-up suitable for in-plane displacements measurement was used. This set-up is characterized by the fact that the beam originating from the laser source is divided by the beam splitter in two beams which symmetrically impinge on the specimen surface with incidence angle α as shown in Figure 1. In the same Figure 1 the optical hardware setup used in this work is reported. The in-plane displacement sensitivity of the set-up is within 0.3÷0.6 μm while there is no influence of out-of-plane displacement. A custom software developed in LabView® 8.6 environment has been used for assisting the operator in the setup configuration, image acquisition and post-processing. The iterative filter adopted in the post-processing step has been developed by Ing. Antonino Cirello.

2.2 *Experimental set-up*

The experimental setup adopted in this paper (sketched in Figure 1) is composed by: a) Laser Quantum GEM 532 nm (green) TEM00 120 mW laser head driven by a Laser Quantum SMD 6000 amplifier; b) Melles Griot laser-to-fibre coupler with FC/APC connector; c) OZOptics fibre divider with split ratio 50:50; d) Optiphase PZ2 fibre stretcher driven by NI-DAQPAD 6015; e) OZOptics beam expander/collimators with output diameter equal to 25 mm; f) The Imaging Source IEEE1394 41BF02 camera with 1280 x 960 resolution. All the fibres adopted in this set-up possess NA equal to 0.11.

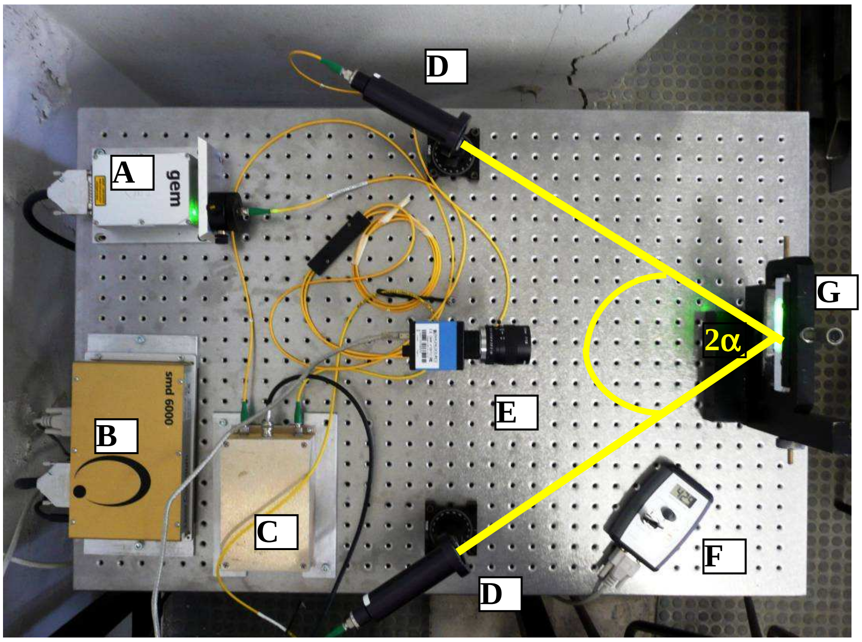


Figure 1: Experimental set-up – A: Laser head; B Laser amplifier; C: Fibre stretcher; D: Beam collimators; E: IEEE1394 Camera; F: Laser controller; G: Loading system.

The loading system is sketched in Figure 2 and, as it can be easily seen, it is able to reproduce the four-point bending test by imposing a selected displacement at points A and B by appropriately driving the micrometer screw.

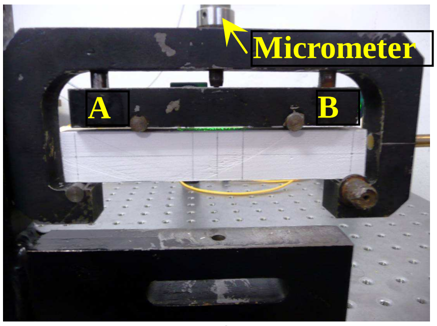


Figure 2: Particular of the loading system.

2.3 *Specimens*

In order to test effective sample in this paper attention has been focused only on specimens obtained from Red Spruce on-sale rectangular beam. The sketch of the specimen, whose selected dimensions (in mm) are the 120 x 20 x 10, is reported in Figure 3. In the same figure two areas are evidenced and will be investigated in the applications: the yellow one in order to analyze the pure (constant) bending response, while the green one in order to analyze the mixed linear bending – constant shear response. The characteristic stress and Young modulus of Red Spruce are the following: $\sigma_k = 26$ MPa, $E = 14$ GPa.

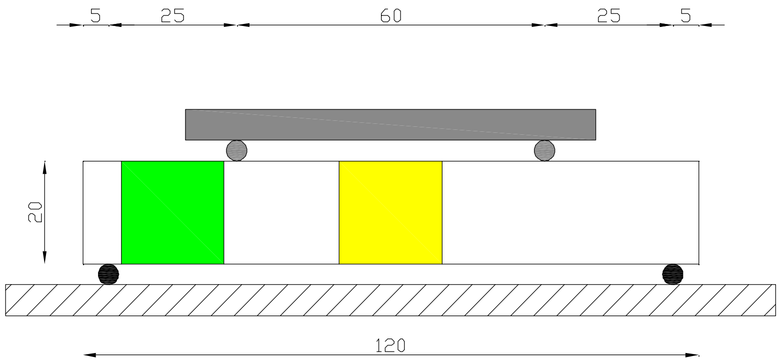


Figure 3: Sketch of the specimen (quotes in mm).

Two different sets of specimens have been studied in this paper and have been obtained by cutting a piece (120 x 300 x 150 mm) of an on-sale rectangular beam (see Figures 4). The first one is composed by two specimens obtained from two consecutive lamellae showing a practically coincident fibre pattern, as it can be easily deduced by examining the terminal sections reported in Figures 5. One of these specimen has been obtained only from one lamella and shows no glue interface. The second one, from the other hand, has been obtained from both lamellae and, clearly, shows a glue interface (see Figure 5). This set has been selected in order to test the role played by the glue interface taking constant the fibre pattern. The second set is composed by four specimens obtained from two consecutive lamellae (different from the previous ones) and have been obtained along the depth of the on-sale beam. The terminal sections of this set of specimens are showed in Figure 6. This set has been selected in order to test the role played by the glue interface varying the fibre pattern.

a) b) c)

Figure 4: a) On-sale rectangular beam; b) piece from which the specimens have been obtained; c) cross section of the piece in b).

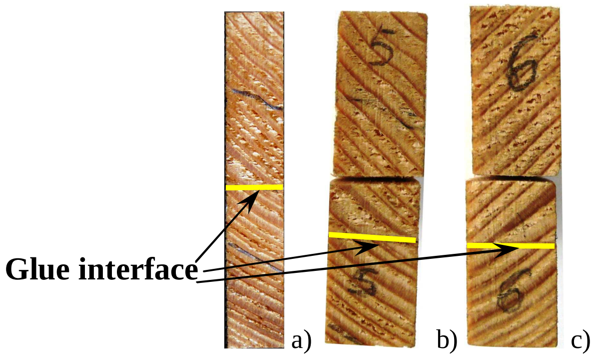


Figure 5: First set of specimens: a) slice of beam from which the specimens have been obtained; b) c) particular of the terminal sections.

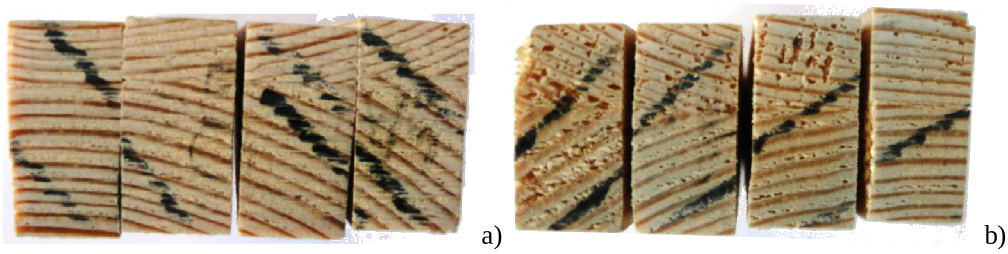


Figure 6: Particular of the terminal sections of the second set of specimens (glued): a) from left to right D, C, B, A specimen; b) from left to right A, B, C, D specimen.

3 RESULTS

Many different tests have been performed on both sets of specimens described in the foregoing section but for sake of simplicity only the results obtained for an imposed displacement equal to 0.04 mm are reported in the following. It is important to emphasize that the maximum stress, calculated in the case of homogeneous material, corresponding to such an imposed displacement is equal to about 16% of the characteristic stress of the material. The acquired fringe patterns for each specimen have been processed and the strain ε_x and $\partial s / \partial y$ have been numerically calculated by an 2nd Order central Method algorithm. The coordinate system has origin in the upper left corner of each area indicated in Figure 3 with the x-axis oriented from left to right and the y-axis from top to bottom.

First of all the tests have been performed on the first set of specimen. In Figures 7-9 the fringe patterns and the colour maps of calculated strain components are respectively depicted for non glued specimen (Figures 7a, 8a, 9a) and glued one (Figures 7b, 8b, 9b) in the case of green zone. From the other hand in Figures 10-12 the same quantities are reported in the case of yellow zone. An examination of these figures clearly shows that the presence of glue interface (which is located at 1/3 of the height from the top) does not influence the results. As second step the tests have been performed on the second set of specimens in order to investigate the role of fibre pattern with respect of glue interface. In Figures 13-15 the fringe patterns and the colour maps of calculated strain components are respectively depicted for specimen A (Figures 13a, 14a, 15a) and specimen B (Figures 13b, 14b, 15b). From the other hand in Figures 16-18 the same quantities are reported in the case of yellow zone. It is important to emphasize that no different behaviour has been evidenced in analyzing the response of specimen C and D which are not reported only for brevity sake. An examination of these figures shows that even in this second set the glue interface (which is always at 1/3 of the height from the top) seems not to influence the results. This result indicates that at the examined load levels the glue interface perfectly transmits the mechanical strain with no influence.

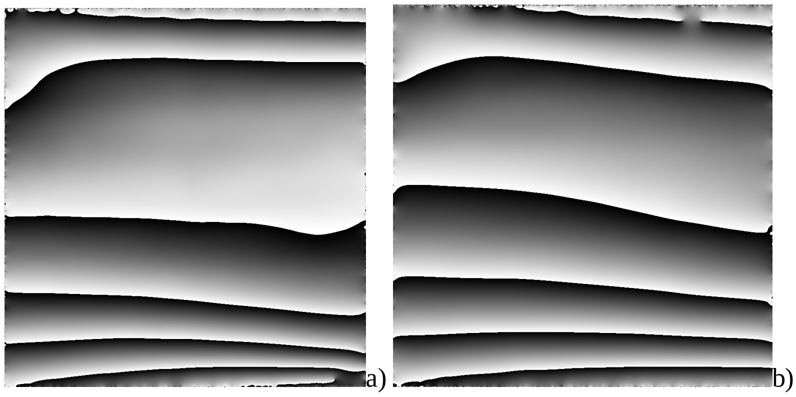


Figure 7: Fringe patterns (green zone) first specimens set: a) non glued; b) glued.

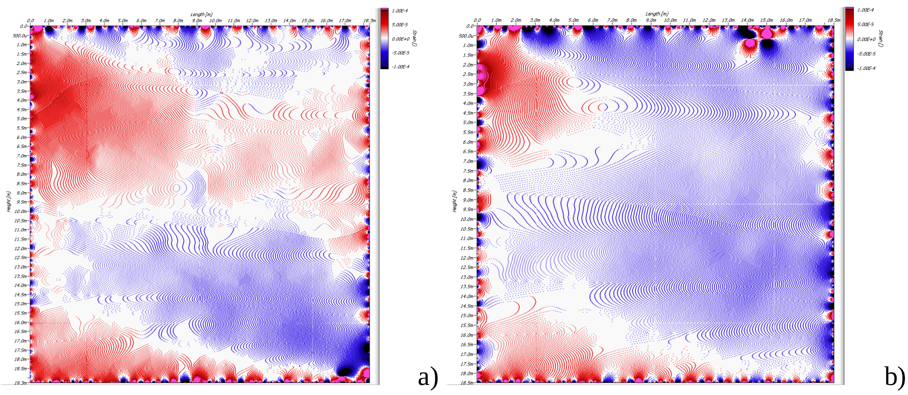


Figure 8: Calculated strain ε_x (green zone) first specimens set: a) non glued; b) glued.

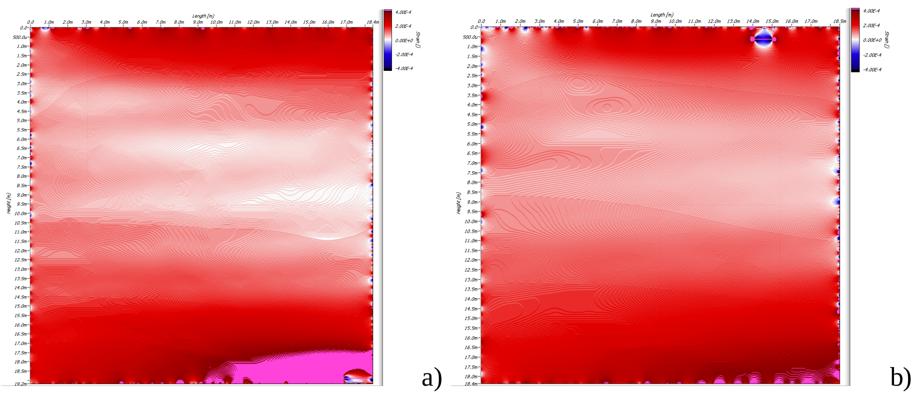
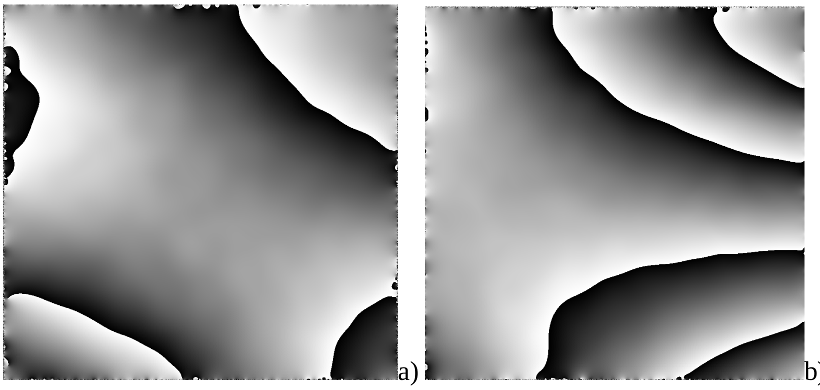
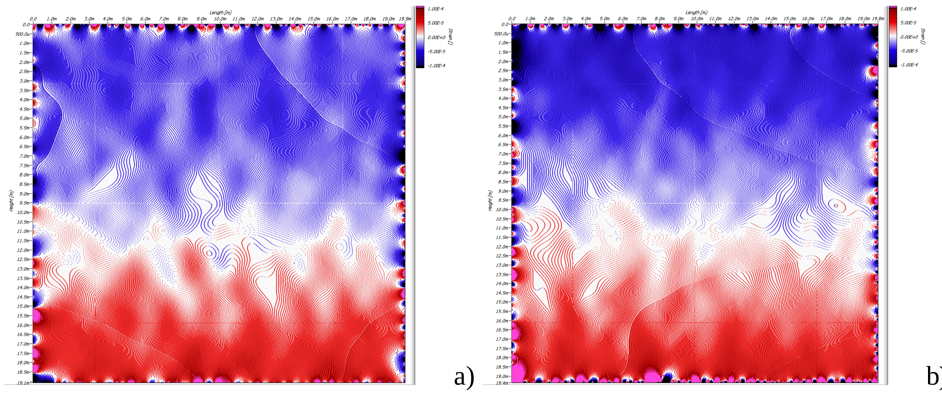


Figure 9: Calculated strain $\partial s / \partial y$ (green zone) first specimens set: a) non glued; b) glued.



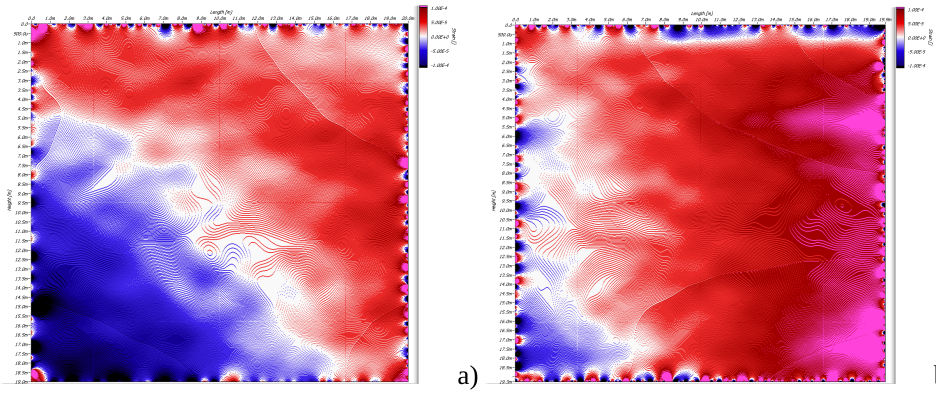
a) b)

Figure 10: Fringe patterns (yellow zone) first specimens set: a) non glued; b) glued.



a) b)

Figure 11: Calculated strain ε_x (yellow zone) first specimens set: a) non glued; b) glued.



a) b)

Figure 12: Calculated strain $\partial s / \partial y$ (yellow zone) first specimens set: a) non glued; b) glued.

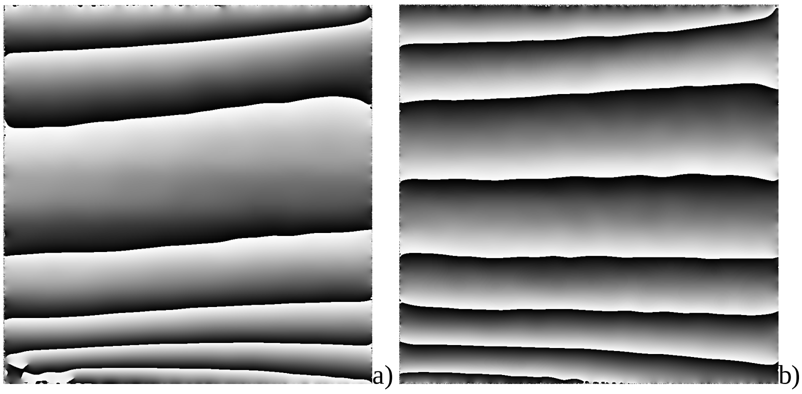


Figure 13: Fringe patterns (green zone) second specimens set: a) specimen A; b) specimen B.

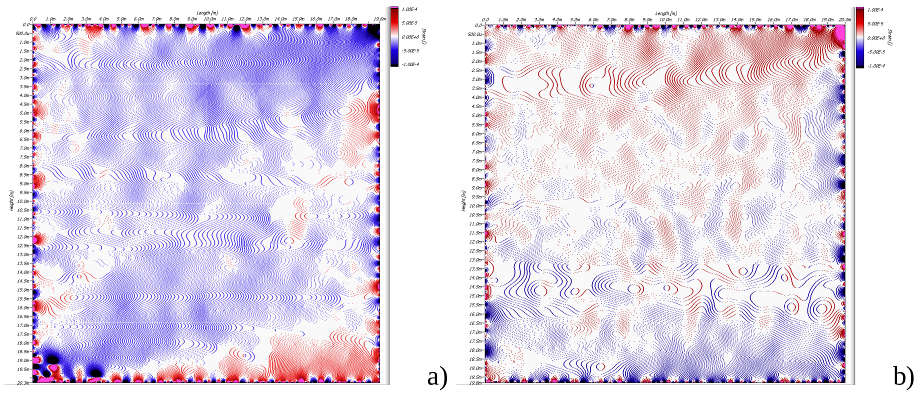


Figure 14: Calculated strain ε_x (green zone) second specimens set: a) specimen A; b) specimen B.

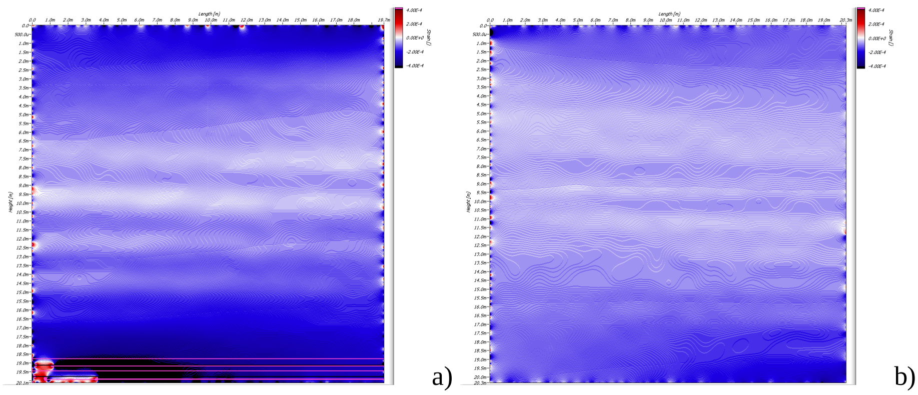


Figure 15: Calculated strain $\partial s / \partial y$ (green zone) second specimens set: a) specimen A; b) specimen B.

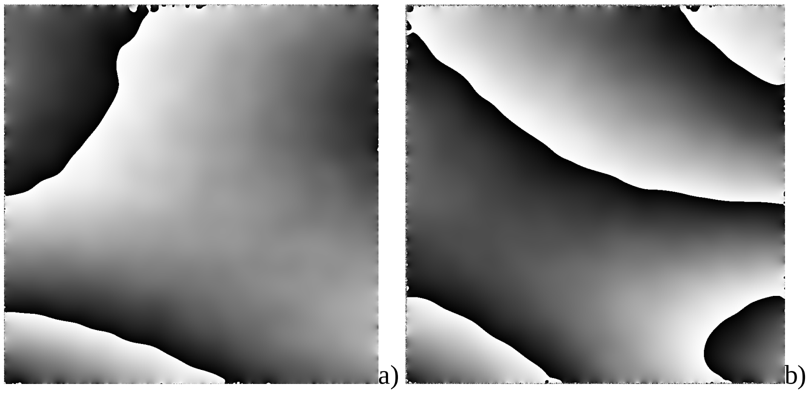


Figure 16: Fringe patterns (yellow zone) second specimens set: a) specimen A; b) specimen B.

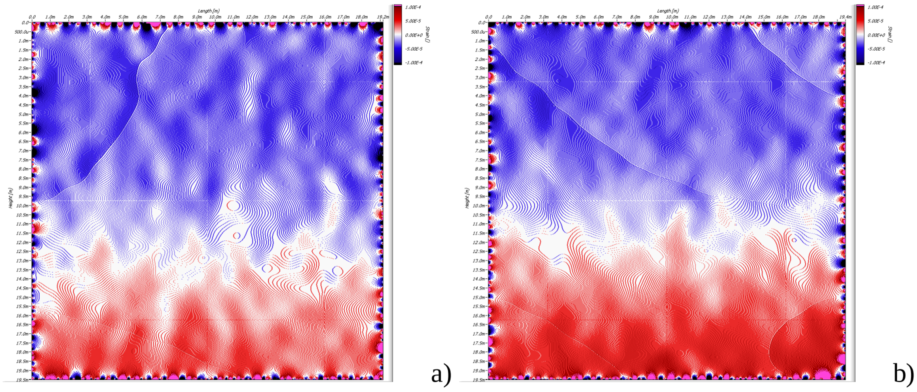


Figure 17:Calculated strain ε_x (yellow zone) second specimens set:a) specimen A; b) specimen B.

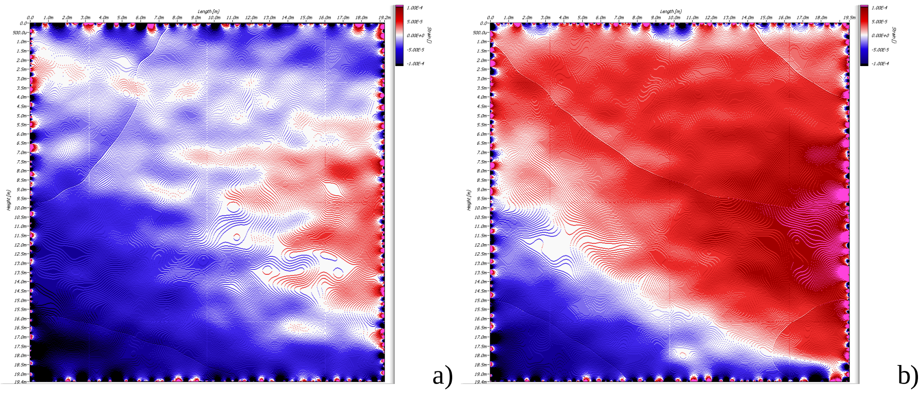


Figure 18: Calculated strain $\partial s/\partial y$ (yellow zone) second specimens set: a) specimen A; b) specimen B.

Another important remark is that while the calculated strain ε_x in both sets of specimens shows a behaviour close to that of homogeneous material, the calculated strain $\partial s/\partial y$ shows always a behaviour very different from that of homogeneous material.

4 CONCLUSIONS

The behaviour of both glued and non-glued Red Spruce specimens with different fibre pattern under both pure bending and mixed linear bending – constant shear have been investigated. The results in terms of colour map of the two strain components ε_x and $\partial s / \partial y$ clearly show that the behaviour is very different, especially for $\partial s / \partial y$, from that of an homogeneous material and that for the case under examination no influence of the glue interface can be noted. The latter result is important since it means that the glue interface perfectly transfers the strain from one lamella to the consecutive one. As developments the tests have to be extended to more higher loads, to very different fibre pattern and to different wood species.

5 ACKNOWLEDGMENT

Authors are grateful to Mr. Giuseppe Seminara of the DISAG for his support during the preparation of the specimens, to Dr. Antonino Cirello for his suggestions during all the study and to Dr. Alessandro Busacca of the DIEE of the University of Palermo for his support in optimizing the fibre launcher. Grant ex60%-2006 from University of Palermo is gratefully acknowledged.

References

[1] Hearmon, R. F.S., *An introduction to applied anisotropic elasticity*, Oxford Univ. Press (1961)

[2] Bodig, J., Goodman, J.R., "Prediction of elastic parameters for wood", *Wood Science*, **5** (4), 249-264 (1973)

[3] Patton-Mallory, M., Cramer, S. M., Smith, F. W., Pellicane, P.J., "Nonlinear material models for analysis of bolted wood connections", *Journal of Structural Engineering, ASCE,* **123** (8), 1063-1070, (1997)

[4] Tabiei, A., Wu, J., "Three-dimensional nonlinear orthotropic finite element material model for wood", *Composite Structures*, **50**, 143-149, (2000)

[5] Mott, L., Shaler, S. M., Groom, L. H., "Application of imaging technologies to experimental mechanics" in *Techniques in Experimental mechanics applicable to forest product research, Proc. of the Experimental mechanics plenary session at the Forest Product Research Society Annual Meet.*, Portland, ME, (1994)

[6] Zink, A. G., Davidson R. W., Hanna, R. B., "Image correlation for measuring strain in wood and wood-based composites", in *Techniques in Experimental mechanics applicable to forest product research, Proc. of the Experimental mechanics plenary session at the Forest Product Research Society Annual Meeting*, Portland, ME, (1994)

[7] Wolfe, R. W., Rowlands, R., Lin, C. H., "Full field stress/strain analysis: use of Moiré and TSA for wood structural assemblies", in *Techniques in Experimental mechanics applicable to forest product research, Proceedings of the Experimental mechanics plenary session at the Forest Product Research Society Annual Meeting*, Portland, ME, (1994)

[8] UNI EN 408:1995, Timber structures. Structural timber and glue laminated timber. Determination of some physical and mechanical properties.