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INVESTIGATION OF NAILED TIMBER CONNECTIONS USING THE LASER INTERFEROMETRY METHOD

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Abstract

The paper presents an adapted methodology of laser holographic interferometry for an investigation of the stress-strain state of nailed timber connections. During the study the possibility of detecting local deformations in the connection were verified. The optimum conditions for fixing the samples and the loading ranges to ensure an optimal interference pattern were determined. An investigation of the peculiarities of the interaction between the elements and the stress-strain behavior of nailed timber connections was performed. The experimental data obtained on the stress-strain behavior of a nailed timber connection using the laser holographic interferometry method have sufficient repeatability between different series and can also be used as a criterion verification for a finite-element model.

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Key words

- Timber,
- Nailed connection,
- Laser interferometry.

1 INTRODUCTION

Nailed joints are one of the most popular types of connections in timber structures owing to their simplicity in use, relatively low price and market availability. The design methodology of nailed connections is well established and described in Eurocode 5. The determination and evaluation of their basic mechanical and elastic properties (e.g., slip modulus, embedding strength, yield moment, etc.) are performed by standard procedures (EN 26891:1991, ASTM D1761-12, ГОСТ 33082-2014 etc.), which involve displacement measurements as the load is rising as well as through determining the failure load. In most cases such data is sufficient for a conservative assessment of the bearing capacity and stiffness of a connection.

Nevertheless, the use of standard techniques leads to a lack of information about the actual distribution of stresses in a joint and the nature of its deformation (Mascia et al., 2008). These problems in the study of connections are caused by the following assumptions:

- The three-dimensional stress distribution around the wall of the hole is approximated by a bidimensional stress distribution along the nail axis;
- timber is considered as a continuous material with uniformly distributed characteristics;
- timber displacement at any point changes proportionally to the acting force, i.e., wood is considered as a Winkler foundation;
- the static scheme of the forces acting on the nail does not depend on its deformed shape;
- the effect of frictional forces on the contact surface between a nail and timber can be ignored.

Difficulties in obtaining credibly clean data using standard test methods are also caused by the peculiarities of the structure of timber, which is an orthotropic material with unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential directions.

The above factors are reflected in the simplifications and inaccuracies in the development of computational models, particularly those implemented in current codes. For example, data of the comparative analysis of the load-carrying capacity and the slip modulus of timber-to-timber nailed connections obtained experimentally and by calculations in accordance with design standards (Branco, Cruz, 2004) have shown that the norms predict the nature of the failure and the bearing capacity of the nailed connection with sufficient reliability. On the other hand, the slip modulus from a shear test is up to 2 times smaller than that predicted by Eurocode 5. The current design standards are based on linear approaches, while a number of studies of timber joints with different connectors such as nails, bolts, punched metal plates, etc. (Benfratello et al., 2009; Tonon et al., 2015; Savytskyi et al., 2010), have shown that the behavior of a connection under a load is characterized by nonlinearity and that the designed connection has a significant margin of the load-bearing capacity.

Thus, for the development of more accurate design methods as well as in a case of a newly developed or optimized connector type or shape, it may become necessary to understand and consider its actual stress-strain state. This, in turn, requires the use of more informative research methods that ensure the registration of the stress-strain state in the form of fields over the surface or the volume of the connection.

An effective tool for solving the above problems could be the holographic laser interferometry method. An important advantage of this method is the possibility of taking measurements without a special surface treatment of the object studied. Also, the dimensions of the object investigated do not have a considerable effect. The area controlled is determined by the technical characteristics of the laser equipment. The accuracy of this method is equal to the laser wave length, which is 0.1 – 0.3 micrometer. The displacement field registered permits obtaining its values for a set of the points of the object. The information received can be represented through spatial displacement vectors.

Currently, the holographic laser interferometry method is applied to investigations of the construction of isotropic materials (e.g., steel or aluminium), where the physical and mechanical properties, the general mode of deformation, and the load response could be relatively easily predicted (Gascón and Salazar, 1996; Pagnotta L., 2008). At the same time there have been several works on the application of laser interferometry for investigations of the operability of complex structure materials, for example, processes of destruction in structural concrete (Kesariiskyi, et al., 2010). The electronic speckle-pattern interferometry method was adopted for testing the bending of solid and glued timber elements (Benfratello et al., 2009), as well as for characterizing the deformation of timber in a finger joint area (Konnerth et al. 2006). The results of both research studies have showed that the behavior of timber is very different from that of homogeneous material. There are also works which use interferometry for investigations of the strain state of the wood surrounding nails (Klimenko, 2012) as well as determining a safe distance between nails for preventing timber from forming cracks (Stolpovskyi, 2011). Nevertheless, these investigations have used samples made of one piece of timber with an embedded nail, i.e., the effect of the combined interaction between the elements in a connection has not been considered but may appreciably affect the result. It can therefore be concluded that a well-grounded and approved method for the experimental investigation of nailed timber connections using laser holographic interferometry is currently lacking.

The purpose of this study is to adopt the laser holographic interferometry method for an experimental study of nailed timber connections and to evaluate the effectiveness of this method for solving problems of the structural mechanics of timber through an investigation of the peculiarities of the force transfer in the nail-timber system.

2 MATERIALS AND METHODS

According to the purposes of the study, the experiment was divided into three stages:

1) verification of the possibility of detecting local deformations in a connection using the laser holographic interferometry method, determination of the optimum conditions for fixing samples, and revelation of the loading ranges that will ensure an optimal interference pattern;
2) registration of fields of normal displacements and displacements on the plane of the surface investigated;
3) determination of the mode of the deformation of connection elements during the consecutive increases in a load.

In addition, at each stage, the identified features of the interaction between the elements in the connection were registered.

The configuration of the samples, as well as the position of the nail, was adopted to enable the registering of the displacement fields as close as possible to the contact surface between the timber and the nail, as well as ensuring the samples' integrity.

Three samples were prepared for the experimental studies. Each sample consisted of three timber prisms connected by a nail. The dimensions of each prism had a height of 215 mm and a cross section of 50 mm x 50 mm. The physical and mechanical characteristics of the wood corresponded to the strength class of C14 according to EN 338. Before the samples were made, the wood was conditioned at a constant temperature and relative humidity until the equilibrium moisture content reached 12%. To ensure the possibility of the vertical movement of the prisms relative to each other, the middle prism was shifted 15 mm upwards. The load was applied on the middle prism, and the axis of the load passed through the plane of the nail's longitudinal axis; hence the occurrence of a tipping moment was prevented. The nail connecting the timber elements was made of a smooth steel wire with a diameter of 6 mm, according to DSTU GOST 4028:2008. To prevent the timber from forming cracks, a hole was pre-drilled into which the nail was then embedded. A general configuration of the sample is presented in Fig.1.

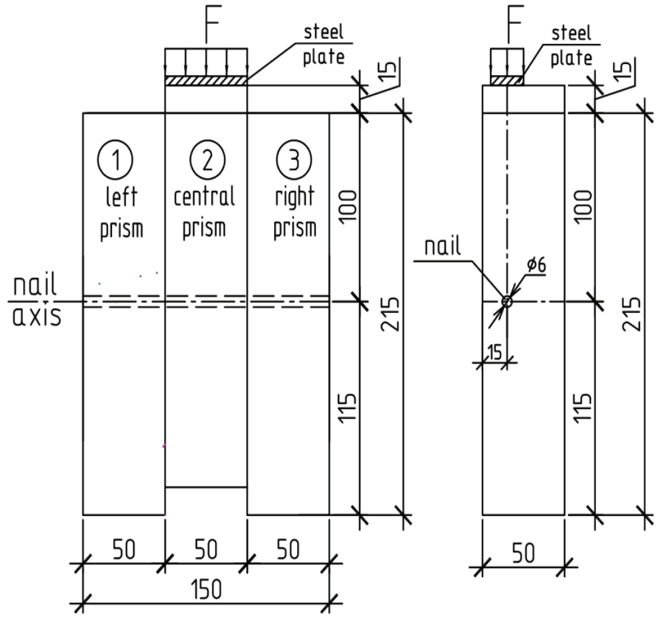

Fig. 1. *General configuration of the sample*

Fig. 2 shows a 3D scheme of the equipment for the registration of the displacement fields using the laser holographic interferometry method. The dimensions of the samples were the reason for choosing the Leight-Upatnieks hologram recording scheme for the registration of the interferograms. The hologram of the zone of 200 x 300 mm in which the object studied was placed was recorded on a 90 x 120 mm photographic plate. The optical scheme was adjusted to ensure the compliance of the maximum sensitivity of the measurements of the deformations of the surface under investigation. The application of the special facilities for protection against vibrations (positions 2 and 3) was determined by the high sensitivity of the method, which corresponds with the fraction of the light wave's length (0.3-0.1 μm). The samples were loaded with a hydraulic press that has a capacity of 200 kN. A general view of the mounted equipment is shown in Fig. 3.

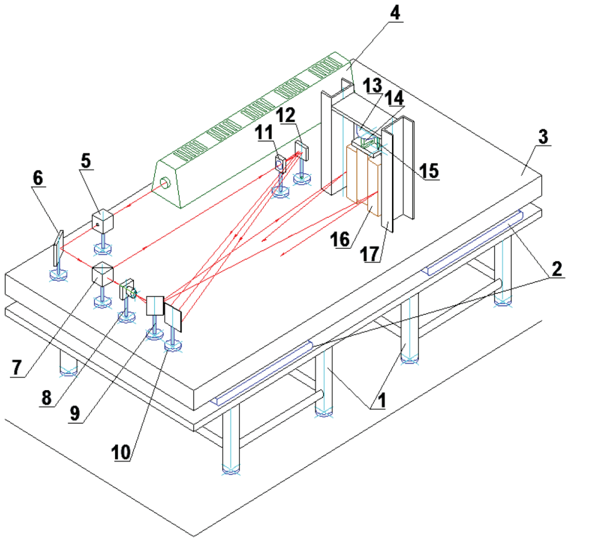

Fig. 2. *3D scheme of the equipment for the registration of the holographic interferograms by the Leight-Upatnieks method: 1- equipment supports; 2 - pneumodamper pads; 3 - vibroprotected platform; 4 - laser; 5 - light shutter; 6, 9, 12 - mirrors; 7 - image divider; 8 - objective microscope; 10 - photographic plate with a holder; 11- lens of the base light beam; 13- hydraulic cylinder; 14 - force sensor; 15 - longitudinal displacement sensor; 16 - sample investigated; 17 - loading device.*

The interferograms were recorded by a two-exposure method. For this purpose, holographic images of the object of the research in its initial and loaded states were recorded on the same photographic plate, according to generally accepted recommendations (Ostrovskiy et al., 2009). A further analysis of the interferograms obtained was performed according to the method, where it was proposed to determine the displacement of a point as (Aleksandrov and Bonch-Bruyevich, 1967):

$$\vec{d}(\vec{r}_0 + \vec{r}_{\text{н}}) = \lambda n ,$$

where

$\vec{d}$ - displacement vector of a point on surface investigated;
$\vec{r}_0$- unit vector of illumination;
$\vec{r}_{\text{н}}$ - unit vector of observation direction;
λ - wave length of laser light;
n - order of interference band.

Each of the interference bands on the interferogram was assigned a number *n* corresponding to its order. The zero interference band was determined considering the features of the formation of the optical scheme and the sample's fixing conditions; it was also controlled by the displacement sensor. The displacement values were determined for each interference band. Then using an AutoCAD graphic complex, displacement diagrams were drawn for representative cross sections as well as three-dimensional diagrams of the displacement fields for each timber prism in the sample.

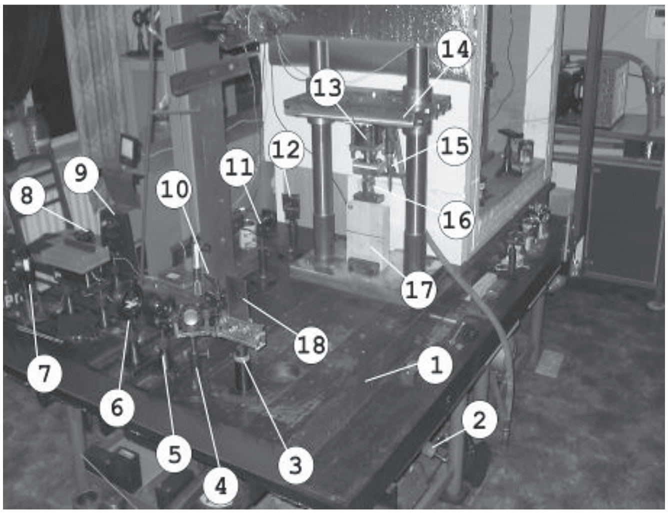

Fig. 3. *General view of the equipment installed: 1 – base slab, 2- pneumatic vibroprotection, 3 - photographic plate holder, 4 – mirror of the object's beam of light, 5 – objective of the microscope of the object's beam of light, 6 - image divider, 7 - mirror, 8 - light shutter, 9 - helium-neon laser with a wave length of 633 nm, 10 - pointing mirror of the reference light beam, 11 - objective of the microscope of the reference light beam, 12 –mirror for compensating the difference in the path length; 13 – hydraulic force cylinder; 14 – loading device; 15 - longitudinal displacement sensor, 16 - force sensor, 17 - sample investigated, 18 - photographic plate*

3 RESULTS

During the first stage of the study, it was found that the local bearing failure of the support surfaces leads to a rotation of the object as a whole at an angle of 14.5". This leads to the essential masking of the sought-for local deformations in the nail zone that were masked by the movements caused by the rotation. To eliminate this effect, the support surfaces of the timber prisms were subjected to polishing on a milling machine, and the side prisms were fixed from rotating on the table of the loading device.

Further, by varying the drop of the test load, i.e., the differences between the load value at the initial and the subsequent loading stages, interferograms of a sample with the optimum frequency of the interference bands for an analysis of the features of the connection state under a load were obtained. The optimum range of the test load drop amounted to 300-900 N. As an illustration of the results obtained, Fig. 4 shows the interferogram of the sample and a three-dimensional visualization of the displacement fields for the left prism of the connection, which corresponds to a test load drop of 370 kN. The displacement diagrams for representative cross sections of the right prism are presented in Fig. 5.

An analysis of the interferograms obtained has shown that the zone of the maximum displacement of the prism surfaces investigated is situated 10-15 mm below the nail axis and 5-8 mm horizontally from the contact surface of the central loaded prism. Such a peculiarity can be explained by the intensive local compression of the timber under the nail's near contact surface between prisms in the sample. Also, it was revealed that the length of the deformation zone of the lateral

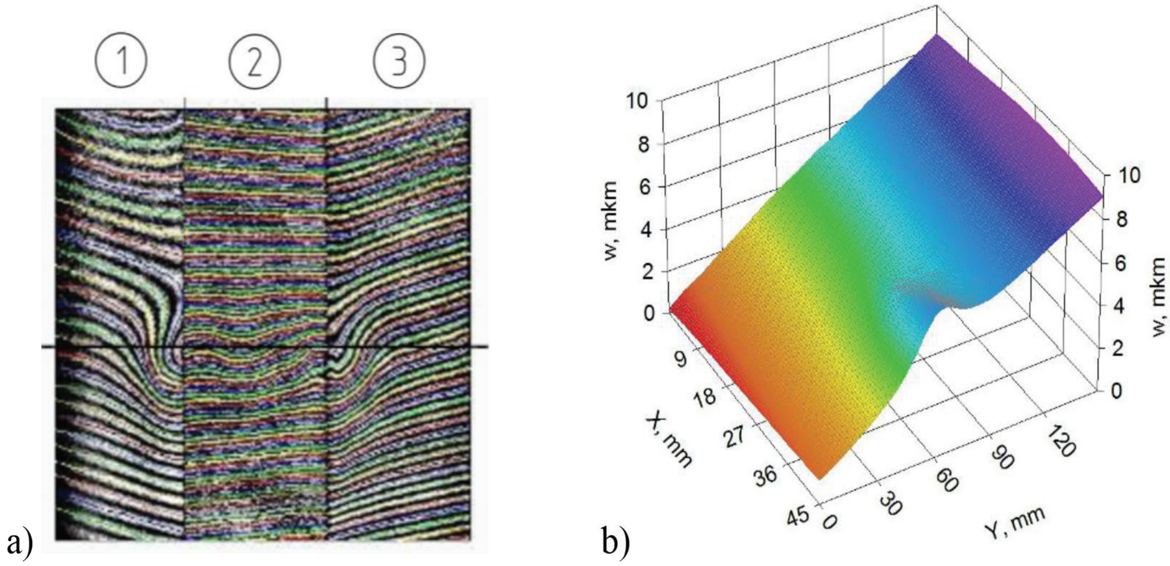

Fig. 4. *Sample interferogram for a test load drop of 370 kN (a) and 3D visualization of the displacement fields for the left prism of the connection (b)*

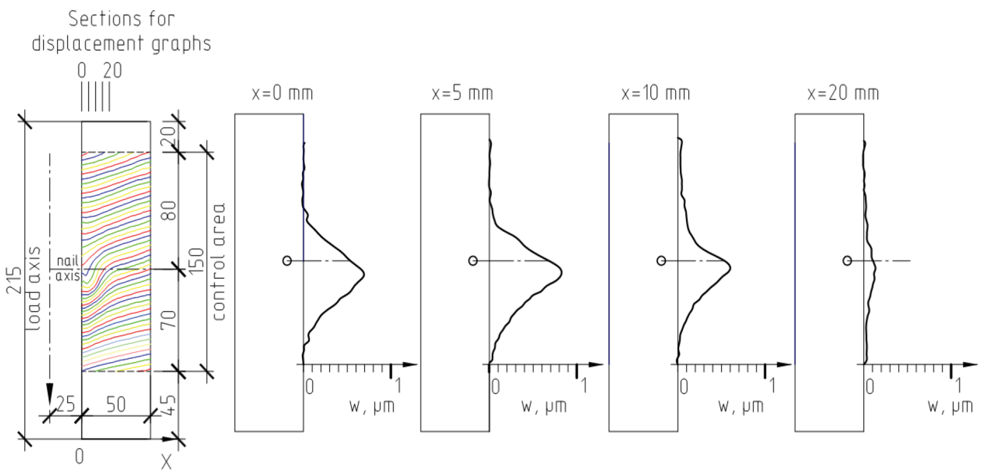

Fig. 5. *Displacement diagrams for representative cross sections of the right prism*

prism corresponds to an area with a length equal to 0.25 – 0.3 of the prism's width from the contact surface between the central loaded and lateral prisms.

In the second stage of the experimental program, in addition to the registration of the displacement fields normal to the surface investigated, a fixation of displacements in the plane of the surface investigated (i.e., vertical displacement) was performed. For this purpose, a method combining holographic and speckle interferometry was used (Kapustin et al., 1977). This method is based on the fact that the double exposure holographic interferogram registered according to the Denisyuk scheme at a short distance (5-10 mm) from the surface studied has the properties of speckle photography (Denisyuk, 1962). The speckle structure of the scattered laser radiation carries information about the shape and spatial position of the object surface. Micro displacement or deformation of the surface leads to a spatial movement of the speckle structure, the measurement of which allows for a determination of the displacement of the surface. For these purposes, a double-exposure speckle pattern is used. When analyzing an interferogram recorded by the Kapustin's method, the methods of speckle photography are used to determine vertical displacements of the surface investigated and out-of-plane displacements are determined using well-known methods of holographic interferometry (Jones R., Wykes C., 1983). This approach significantly simplifies the processing of the experimental data and the determination of the spatial displacements vectors of the surface studied.

The results of the data processing obtained are shown in Fig. 6, 7.

As can be seen in Fig. 6, the pattern of the surface deformation and localization of the maximum of the out-of-plane displacement of the sample from the second series is similar to the sample from the first series. The maximum of the out-of-plane displacements is shifted horizontally by 15 mm from the contact plane with the middle block and by 5-8 mm below the axis of the nail. The analysis of the displacement field on the plane of the sample showed results slightly different from those expected. The displacement vectors are oriented not in the direction of the action of the force (i.e., vertically) as expected, but are almost parallel to the axis of the nail, as can be seen in Fig. 6. This indicates that the nail in the formed contact zone is significantly bent. The maximum size of the displacement vector on the plane of the surface investigated is 8.5 μm, which corresponds to a test load drop from 1.2 kN to 1.69 kN (a test load drop of 490 N).

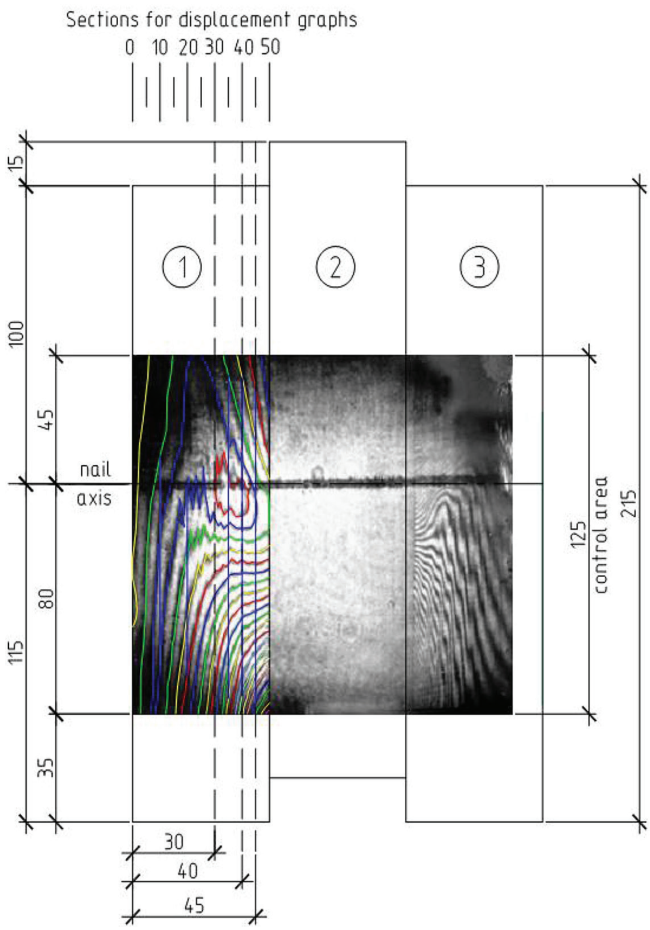

Fig. 6. *Configuration and interferogram of sample in the second series*

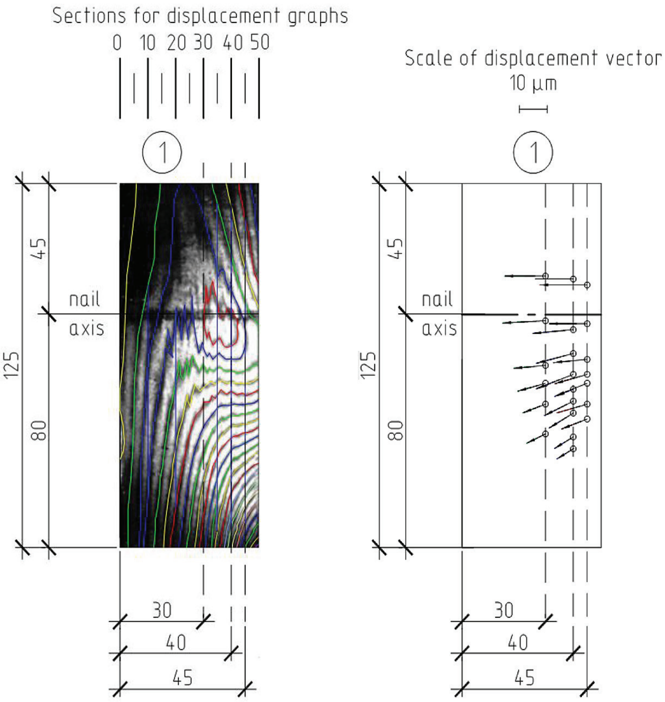

Fig. 7. *Displacement field in the plane of the surface of left prism investigated (sample from the second series)*

The magnitude of the vertical displacements is much larger (6-8 times more) than the out-of-plane displacements, which is quite expected for a complex structured material with highly anisotropic properties.

An experiment was carried out in the third stage with a step-by-step increase in the load, registration of the interferograms, and a vertical displacement of the sample elements relative to one another at every step. The vertical displacement diagram of the sample elements obtained is presented in Fig. 7.

An analysis of the interferograms obtained at every step of the loading allows for an assessment of the nail-timber contact area formation as well as the peculiarities of the deformation of the sample investigated. The interferograms corresponding to the different loading stages are presented in Fig. 9.

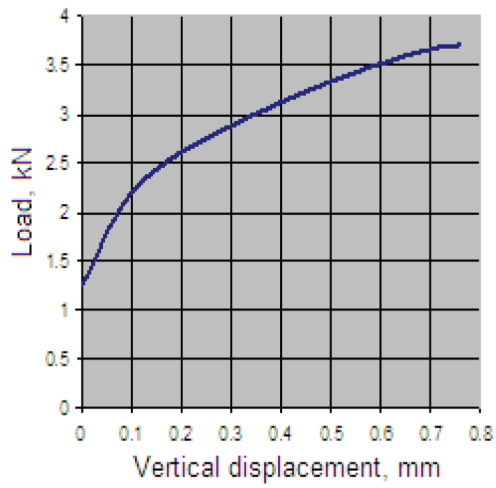

Fig. 8. *Vertical displacement diagram of sample elements with increase in load*

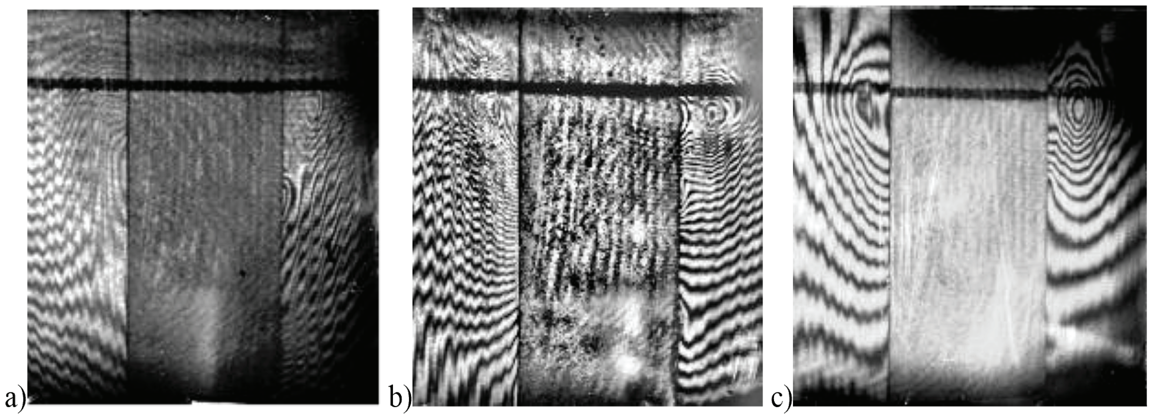

Fig. 9. *Interferograms corresponding to different loading stages: (a) at 1.3 kN; (b) at 3.5 kN, and (c) at 3.7 kN*

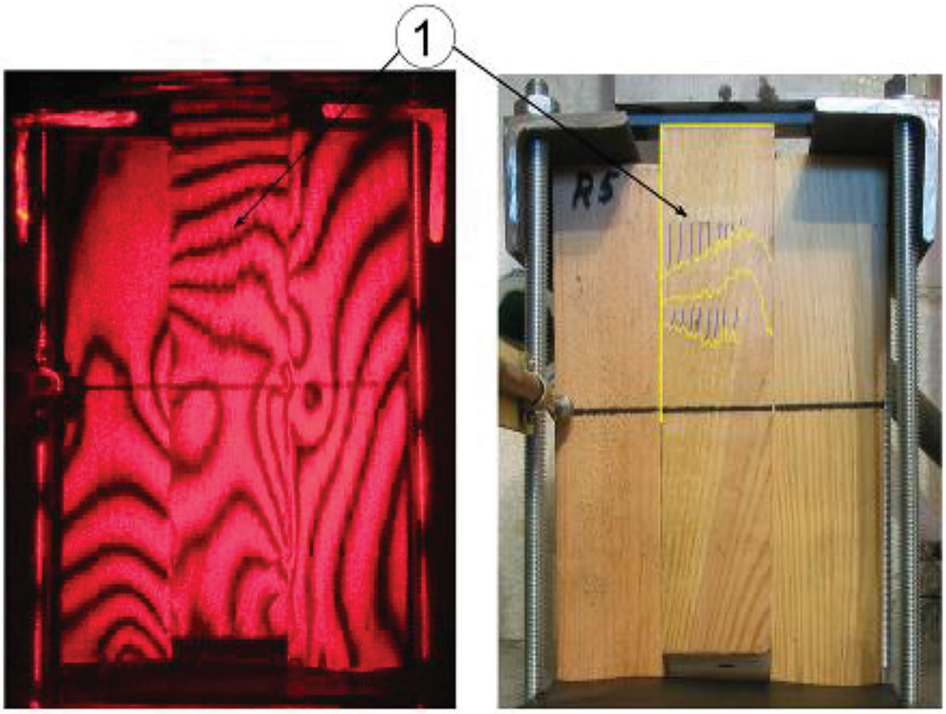

Fig. 10. *Direction of the annual rings on the surface of the timber and their correlation with the local distortions of the interference fringes*

The assymetry of the displacement fields on the interferograms can be explained by the non-uniform contortion of the contact surfaces and the formation of the nail foundation as well as the pattern and form of the timber's annual rings. A comparison of the interferograms with the annual ring patterns also shows that the holographic interferometry reveals differences between the modulus of elasticity of the summer and spring timber, which is evidence of the high sensitivity of this method. As can be seen in Fig. 9, the peaks in the interference bands of the interferogram of the sample of the left image coincide with the boundaries of the annual rings in the photograph of the sample on the right.

It should be noted that when we performed the experimental work to determine the displacement fields of the nailed timber connections, we determined that the loading and unloading cycles have a significant effect on the nail-timber contact zone formation due to the effect of the accumulation of residual deformations.

The data obtained have shown that in general, the stress-strain behavior of the sample elements corresponds to the common performance of nailed timber connections. The pattern and localization of the maximum on the displacement fields have sufficient repeatability between different series. The results derived allow for an investigation of a wide range of the deformation characteristics of a connection. Thus, the experimental data obtained with the holographic interferometry method can be used as a criterion for verification of a finite-element model.

4 CONCLUSIONS

The study performed has shown that the laser holographic interferometry method is an effective and highly sensitive tool for an investigation of the stress-strain state of nailed timber connections.

The method for recording the displacement fields using laser interferometry was adapted for the experimental study of the nailed connection of the timber elements. Recommendations for testing to ensure an optimum interference pattern have been developed, i.e., necessary measures for preparation of the sample, the optimum conditions for fixing the sample, and the optimum range of the test load drop (300-900 N) were revealed.

In accordance with the methodology developed, an investigation of the peculiarities of the interaction between the elements and stress-strain behavior of the nailed timber connection was performed. The maximum value of the normal displacement is situated 12-15 mm horizontally from the contact surface between the elements of the sample and 5-8 mm lower than the nail axis.

The experimental data on the stress-strain behavior of the nailed timber connection obtained using the laser holographic interferometry method allowed for an investigation of a broad range of deformation characteristics; it has sufficient repeatability between different series and thus can be used as a criterion for verification of a finite-element model.

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