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A NEW DIAGNOSTIC DEVICE FOR *IN-SITU* DETERMINATION OF STRENGTH AND MODULUS OF DEFORMABILITY IN COMPRESSION OF WOOD PARALLEL TO FIBER

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Abstract. *The article presents a conception and prototype of a new diagnostic tool for in-situ evaluation of wood inbuilt into constructions. Current techniques and tools for structural assessment miss the solution that enables measuring of mechanical properties of wood with help of semi-destructive approach that focuses on longitudinal wood properties in a pre-drilled hole. The proposed device uses the principle of pushing jaws ("mini compression test") apart from each other in drilled hole of 12mm diameter to get as close as possible to pure compression loading mode in a laboratory. The measurement can be carried out in arbitrary depth in a wooden beam. The output from the device is the conventional strength and the modulus of deformability in compression (MOD_L) parallel to fiber direction. The principle implemented in the new device was tested both ways the experimental and numerical based finite element analysis. Numerical analyses based on probabilistic approach were performed in ANSYS computational software. Results show an influence of material elastic properties on output measured force that is being measured by the proposed device. The longitudinal modulus of elasticity has the strongest impact on the output force (correl. coeff. 0.96); the radial and tangential moduli and also shear moduli have negligible influence (coeff. lower then 0.1). Experimental determination of the same correlations was done for both loaded and not loaded beam that had real-size dimensions (cross-section was 200x240 mm). Correlations between in-situ and laboratory tests were also generally strong (0.8-0.92), so we can claim the measurement with use of the new device predict the material property very well. Lastly, the preliminary study of the compression in a drilled hole was studied with use of digital image correlation (DIC). This returned information about the imprint of the jaws into the wood and strain distribution around the hole.*

1 INTRODUCTION

High-quality plan of a restoration of historic timber structures cannot be carried out without *in-situ* control and assessment of mechanical properties. Investigation of mechanical properties of structural members is the first step in an inspection of any construction. The inspection is usually accompanied by identification of biotic degradation and determination of the extent of the damage. Visual assessment provides global look at a situation and certain qualitative data about outer surfaces of inspected members and belongs among fundamental diagnostic tools [1, 2]. Nonetheless, the visual assessment does not evaluate inner structure of structural members and at the same time it does not determine exact mechanical properties and strength grades important for structural design [3].

The key activity in further structural assessment is to apply non-destructive evaluation (NDE) that may be divided into global techniques (GT) and local techniques (LT)[4]. GT includes ultrasonic and vibration-based methods [5, 6]. LT usually helps to locate defects inside the material that is not possible to detect with use of visual assessment. The Resistography and the Pilodyn belongs to the most used local techniques [7, 8, 9]. LT also includes techniques that measure mechanical properties of samples taken from the construction to a laboratory. Radial borehole analysis and micropulling test present these techniques [10, 11]. Recently, new methods were successfully used to, such as Pin Pushing [12, 13], Screw withdrawal [14] and Hardness test [15]. Disadvantages of mentioned techniques lay in the fact their results correlates better with physical properties than with the mechanical ones and the fact that it is necessary to take samples for laboratory test, which increases time and financial expenses of the assessment.

The global aim of this work was initiated by rapidly increasing requirements of structural engineers that assess historical timber constructions in the Czech Republic and call for accurate and fast (*in situ*) mechanical properties of structural timber elements. Therefore, the specific objectives of this work are: a) to present newly-developed semi-destructive instrument for *in-situ* measurement of mechanical properties of timber; b) to determine the conventional strength and modulus of deformability with use of the instrument; c) to verify the instrument data based on compression tests in laboratory providing the strength and stiffness parallel to fiber; d) to perform probabilistic, contact finite element analyses that examine the correlations between measured properties and properties of wood simulating the instrument operation, e) to make a preliminary study of strain distribution around a hole in which the jaws of the new instrument operates.

2 MATERIALS AND METHODOLOGY

2.1 Construction of the new device

The device (Fig. 1) is designed to measure mechanical properties of wood using non-destructive or semi-destructive investigation of its behaviour when loaded by a small size jack inserted in a pre-drilled hole. The device can be used both in a laboratory and in the field to determine the condition and quality of timber. The device provides the dependence of deformation on the tension brought about by pushing symmetrically placed jaws apart in a pre-drilled radial hole with 12 mm in diameter.

The advantage of the device is its possible gradual recording of the force and displacement of jaws (loading jack) at different depths corresponding to the required dimensions of commonly investigated constructions. The device is laid on the tested unit (usually a constructional element of a rectangular profile) by means of a cylindrical shell, which allows measuring in four depth positions of the pre-drilled hole. The shell arresting is provided by two grooved screws, for positions (core depths) 5–25 mm, 35–55 mm, 65–85 mm, and 95–115 mm. When the measuring part of the device is inserted in the drilled hole and the device is laid on the tested element, the rounded jaws (Fig. 2) are pushed apart into the walls of the hole. The maximum depth of jaws' displacement on both sides is 1.5 mm. The rounded jaws are 5 mm wide and 20 mm long. The jaws also include flexible arms whose movement during pushing is provided by a push-apart bronze wedge fitted to the lower end of the drawbar by means of a pin and screw. The apex angle of the wedge is 15°. This angle is not self-locking and to release the jaws it is sufficient to release the push-apart force withdrawal [16].

Figure 1: left – overall view of the newly designed device; center – detail of the drawbar with the wedge and rounded jaws; right – example of random two-component pattern for DIC analysis

The force of pulling of the drawbar is continually recorded. It is calibrated to the real force of the loading jack and simultaneously related to the measured distance of movement of the jaws (Fig. 2).

The signals are transmitted wireless to a portable computer where they are further processed. Mechanical properties were determined using the record of the measured data in the form of a stress-strain diagram with the record of the force used for the drawbar drawing out, (Fig. 2). Axis X represents the displacement when the jaws are pushed from each other, axis Y shows the force necessary for the jaws to be pushed. The maximum force (F_{max}) – yield point, was established from the intersection of tangents of the elastic and the plastic parts of the stress-strain diagram. Conventional compressive strength ($CS_{C\,(L)}$) was determined from the proportion of the ultimate load and the area of the pushed jaws. The modulus of elasticity cannot be calculated directly from the diagram; the modulus of deformability was established using the angle of the curve fit through the linear part of the force record and deformation.

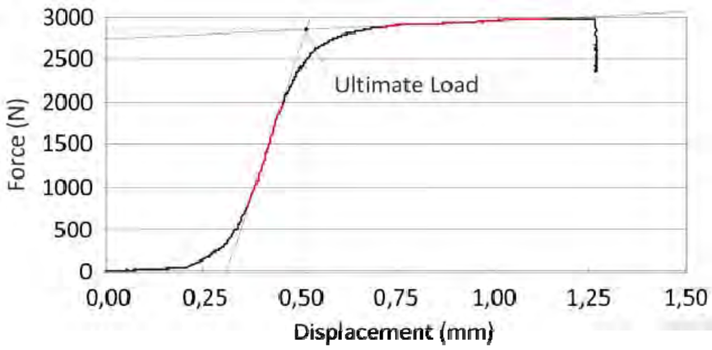

Figure 2: an example of the device output and sketch of determination of the conventional strength

2.2 Experiment

The verification of the prediction of mechanical properties using semi-destructive device was carried out by measuring of sixteen 8 m long beams made of Norway spruce (*Picea abies* L. Karst.), commonly used in historical constructions in the Czech Republic. The cross-section of the beam was 200×240 mm, which corresponds to the dimensions usually appearing in timber inbuilt in historical constructions. After gradual drying of all sixteen beams and their conditioning to 12% moisture content, holes were made by a drill with 12 mm diameter. Two holes were made in each beam. The drilled holes were done in purely radial direction and the distance between the holes was 100 mm. The depth of the drilling was about 130 mm, which enabled us to perform the measuring using the jaw pushing apart in the hole in four depth layers: layer 1 (5–25 mm), layer 2 (35–55 mm), layer 3 (65–85 mm), and layer 4 (95–115 mm), see Fig. 2 centre. The depths of the layers are given by the device construction. The measuring part of the device was then inserted in the radial hole and the device was laid on the tested piece of timber using a cylindrical shell. The jaws were pushed apart parallel to the grain while the drawbar was drawn out with the push-apart wedge on which the jaws moved. The prints of the jaws in the timber are obvious in Fig. 1center, which also shows the distances between the individual layers of measurement across the element. In total, we measured 128 positions (16 beams, always 2 holes) using the newly constructed device.

The function of the semi-destructive device was verified using comparison of the measured quantities from the particular devices and those obtained by testing of standard samples. This tests were destructive and were performed on the universal testing device Zwick Z050 in compliance with the standard test procedure. The results were processed by TestXpert v 11.01. The basic parameters included the analysis for device verification were: wood density (*Density*), wood strength in compression parallel to the grain ($S_{C\,(L)}$), and the modulus of elasticity in compression parallel to the grain ($E_{(L)}$). The tests were performed in compliance with standard European regulations using 20×20×30 mm samples taken at individual positions adjacent to places of measuring by the semi-destructive devices. Two samples with dimensions 20×20×30 mm (compression parallel to the grain) were made for each place of measuring by the device for jaws pushing apart. The data was further processed in Statistica 10.0 (survey analysis of data, verification of distribution normality, independence of elements of the selection, correlation analysis, linear and non-linear regression).

2.3 FE modelling

The finite element analysis was used to predict the behaviour of the device and sensitivity of measured outputs to common factors. This paper presents using of probabilistic analyses to describe the influence of grain declination and properties of materials. The influence of the bottom of a hole to reaction forces in the case of measuring near the bottom was analyzed as well. The 3D model was made in ANSYS Mechanical APDL 14.5 software with using the Ansys Parametric Design Language. The final unsymmetrical geometry model consists of the wood specimen (cube 50×50×50 mm) with a hole of 12 mm diameter and the jaws simplified to prismatic deformable bars made of steel. The FE model uses a regular sweep mesh with quadratic hexahedral solid elements (SOLID186) in all domains. The interaction between jaws and wood was defined by symmetric contact pairs using contact (CONTA 174) and target (TARGE170) elements on the surfaces. Material model of specimen was based on the elastic orthotropic properties of Norway spruce with respect to literature data (derived ratios of constants) and the experimentally obtained density and $E_{(L)}$. The material of jaws is considered as elastic isotropic steel. Boundary conditions were applied as displacements on back sides of the moving jaws and boundary areas of wood specimen as well. Nonlinear large displacement contact analysis was performed to compute displacements, strains, stresses and reaction forces in 50 substeps of load step with the jaws imprint. Parametric definition of model allowed to test influence of 5% changing of grain declination (in all 3 possible directions, in practice slight turning of the device in the hole, drilling in non-radial direction) on reaction forces, comparison of measuring in different depth of a hole. Further, the ANSYS Probabilistic Design System was used to describe correlation between all moduli of elasticity and reaction forces. Randomizing by Monte Carlo method was used in probabilistic analyzes, input range of parameters was defined with Gaussian distribution by average value of parameter and standard deviation (matches coefficient of variance 0.15 in all cases, which corresponds to common variability of mechanical properties of wood). The FE analysis consists of 300 cycles.

2.4 Analysis using Digital Image Correlation

For DIC analyses, the specimens were cut into halves to enable to see the surface around the drilled hole along its longitudinal axis. On the specimens' surfaces a random pattern (see Fig.1 right) was applied using a two-component spray. This provided a unique and anisotropic pattern that is required for DIC computations. For image acquisition the CCD camera Cannon EOS 600D with a resolution of 17 MP (75 px/mm) was used. The camera lens had a focal length 55 mm which together with its distance from the specimens (~ 1 m) assured the negligible barrel distortion of images. All captured images were with standard grey scale of 256 levels. The camera was oriented perpendicularly to an area of interest (AoI) which assured valid subsequent calculation of displacement and strain fields in horizontal and vertical directions [17]. The acquisition rate was set up to 1 Hz which was appropriate in respect to induced slow loading rate. To enhance a contrast between the pattern components and to suppress natural light from surrounding environment a couple of LED lights lit up the AoI. The DIC calculation was carried out and further processed in Vic-2D 2009 (Correlated Solutions Inc.)

3 RESULTS AND ANALYSIS

3.1 Experiments

Experimental values measured at the 17 beams (strength in compression parallel to the grain, conventional compressive strength, modulus of elasticity parallel to the grain, modulus of deformability) are presented in Fig. 3. The results of analyses prove statistically significant differences between the beams. Mainly beams 2, 9, 17 manifested considerably higher measured properties of wood than the other beams. Considerably lower measured properties than is common in spruce wood were found in beams 4 and 5. The progress of the values of strength in compression parallel to the grain $S_{C\,(L)}$ corresponds to the progress of the values of conventional compressive strength $CS_{C\,(L)}$. Similarly, there is a very good correspondence between values of $E_{(L)}$ and $MOD_{(L)}$ of all measured beams (Fig. 3). Influence of material stiffness (longitudinal Young's modulus) and computed reaction force in relation to displacement was also revealed by sensitivity FE analysis (very strong correlation). The absolute differences between values of the parameters measured on testing specimens and values obtained from the new device could be also explained by sensitivity analysis. The influence of other parameters cannot be neglected in the complicated mode of jaws' imprint into wood (see correlation coefficients from PDS analyses above). The higher values of properties from “imprint“ method probably correspond to high stiffness of material. Tab. 2 shows correlations between the parameters (*Density*, $S_{C\,(L)}$, $E_{(L)}$) and measuring by semi-destructive devices method ($CS_{C\,(L)}$, $MOD_{(L)}$). Tab. 2 indicates that there is a very high correlation between compression strength measured in laboratory and conventional strength obtained by the proposed semi-destructive device.

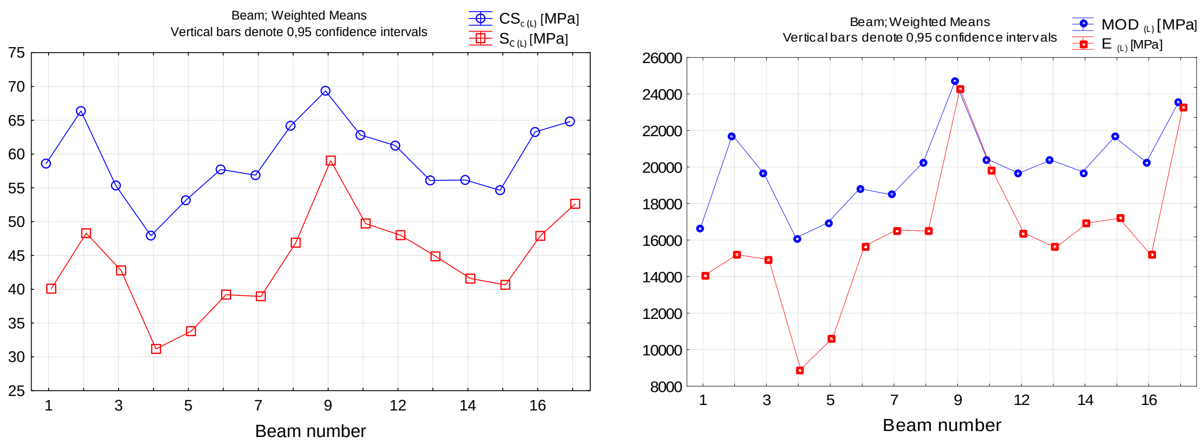

Figure 3 left: Compressive strength $S_{C\,(L)}$ and conventional compressive strength $CS_{C\,(L)}$ parallel to grain for individual beams (pushing jaws in the hole apart); right: elastic modulus $E_{(L)}$ and modulus of deformability $MOD_{(L)}$ parallel to grain for individual beams (pushing jaws in the hole apart)

Table 2: Correlations between the explored parameters (*Density*, $S_{C\,(L)}$, E_L) and the measuring by semi-destructive device ($CS_{C\,(L)}$, $MOD_{(L)}$,).

	$CS_{C\,(L)}$	$MOD_{(L)}$
Density	0,87	0,61
$S_{C\,(L)}$	0,92	0,88
$E_{(L)}$	0,75	0,87

3.2 FE modelling

Fig. 4 illustrates the distribution of displacement and strain in direction of applied force (transversal direction in respect to wood fibres) at radial-longitudinal plane. Despite the small contact area of jaws, there is a large theoretical area of impacted material, which suggests a good potential for estimation of non-local properties of wood. Common measurement in distance 5 mm above the hole bottom gives us unbiased results of reaction forces.

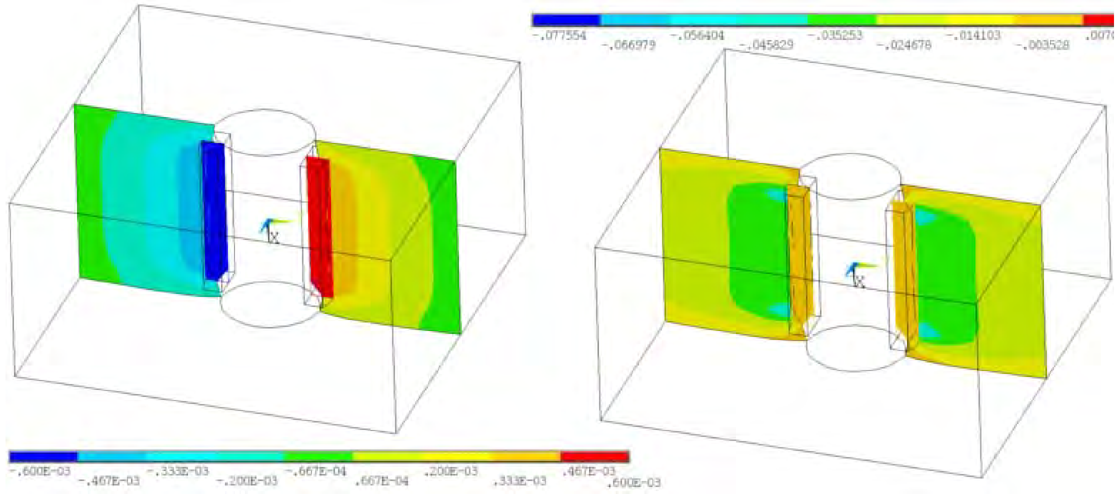

Figure 4: results from the FEA; left – displacement in the direction of applied force (u); right – strain in the direction of applied force (ε_{xx})

Tab. 1 shows correlation coefficients between input parameters retrieved by probabilistic FE analysis, whereas the Spearman rank order correlation coefficients are shown. For the values closer to zero, the two variables are weakly correlated, for the values closer to 1, the two variables are highly correlated. Table shows only results for the reaction force in the direction of loading. Reactions in other directions were small: the direction of hole axis is about 0.2 % of reaction force in loading direction and reactions in tangential direction of tested material slightly higher (about 1%) but still negligible. The values of coefficients of correlations show strong influence of longitudinal elastic modulus (correlation coefficient 0.96). A weak correlation for the case of all other parameters was found. Negligible influence was described also for modulus of elasticity of the jaws material – steel. In practical conclusion: 15% changes of material properties cause changes of reaction forces only in the case of longitudinal elastic modulus and other material properties have no effect; 5% changes of grain declination caused by turning of device in the hole or drilling in non-radial direction has also no effect on reaction forces (on the force based outputs from measurement respectively). Presented linear analysis was not able to describe all necessary behaviour of the process due the high plasticity of real imprint of jaws to wood. The FE model including plasticity phenomena with description of influence on conventional strength will be subject of further papers.

Table 1: Correlation coef. from sensitivity FE analysis – F_R (reaction force) vs. E_L, E_R, E_T (normal elastic moduli), G_{RT}, G_{LT}, G_{RL} (shear elastic moduli), A_L, (declination in longitudinal direction or turning of device in hole), A_T, A_R (declination in tangential and radial direction or deviation of hole axis from radial direction)

	E_L	E_R	E_T	G_{RT}	G_{LT}	G_{LT}	A_L	A_T	A_R
F_R	**0.959**	0.013	0.048	0.035	0.073	0.014	0.030	0.019	0.027

3.3 DIC analysis

The full-field data obtained with use of DIC is depicted in Fig. 5. From pictures it is clear the displacement fields (Fig. 5c and 5d) around the place where jaws came into the contact are easily interpretable and show the kinematics of the compression. All depicted results in Fig. 5 are within the elastic region of strain. We see the jaws compressed wood along its all length in a parabolic distribution (Fig. 5a and 5c) which was predicted by means of FEA above. The differences may be attributed to wood heterogeneity and complex contact behaviour that is usually occurring during the measurement.

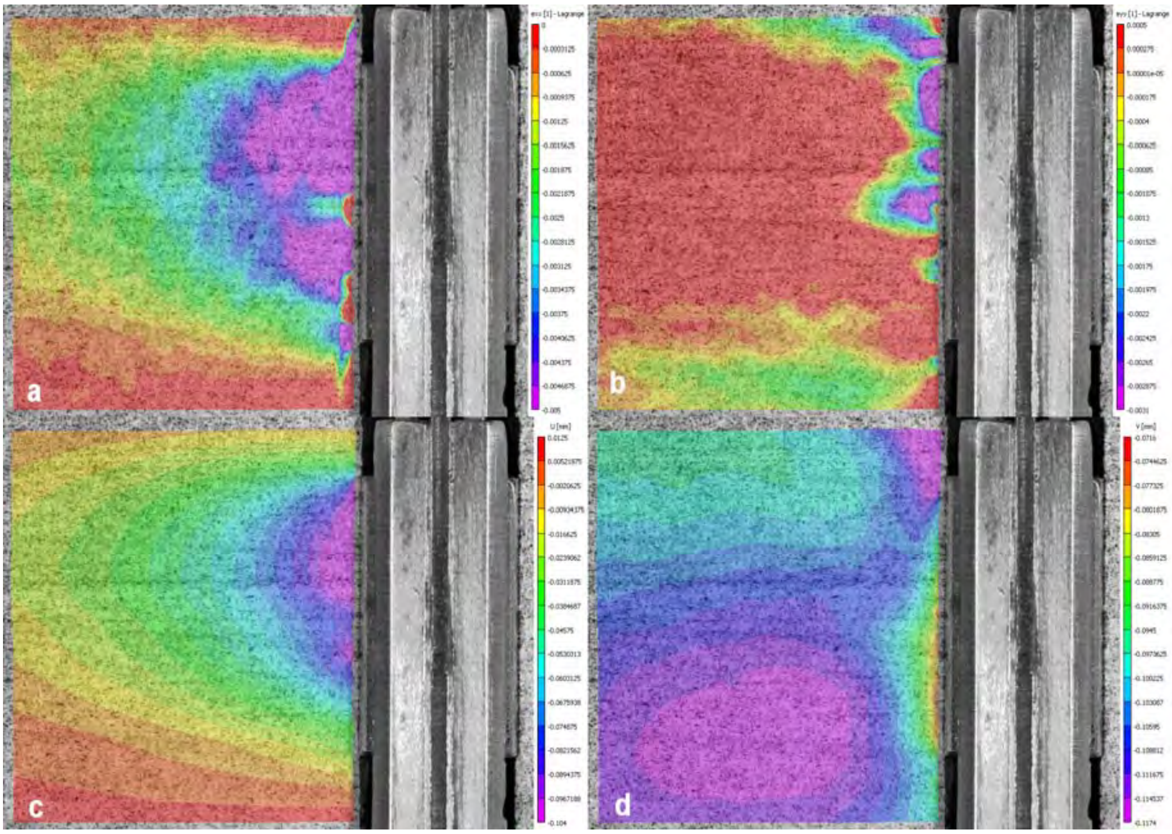

Figure 5: Full-field results obtained by DIC and computed on the left side of the jaws; a) strain in the direction of applied force (ε_{xx}); b) Strain in the direction perpendicular to applied force (ε_{yy}); c) displacement in the direction of applied force (u); displacement in the direction of applied force (v)

Visual comparison of results obtained by DIC and FEA indicates both full-field field provide comparable information even despite the FE analysis was considering situation as it would be in a real construction, meanwhile the DIC measurement was carried out on specimens that were halves of the real specimens. This is also the reason why the strains and displacements are higher for the experiment than obtained by FEA at the same force level. Looking at the accuracy of the used DIC system, it is clear that this factor most likely did not contribute to the measurement uncertainty because the setup met all necessary assumptions for 2D measurement. The DIC system accuracy was about 0.02 px which means that for the used resolution (75 px/mm), the smallest detectable displacement increment would be ~ 0.00026 mm. The calculation of strain at flat surfaces as ours holds similar accuracy because the triangulation scheme of strain calculation and subsequent data filtering lies in a same level, ie. in-plane.

4 CONCLUSIONS

This paper presents the construction and usage of a new device for *in-situ* assessment of inbuilt timber. The use of the device, which is sufficiently sensitive to natural differences among the individual beams, has been verified. The theoretical analysis of relationships between input material properties and output evaluated parameters was performed by probabilistic FE analysis. The longitudinal elastic modulus has the strongest impact on the output force (from which output parameters of device are derived) (correl. coeff. 0.96); the radial and tangential moduli and also shear moduli have non-negligible influence (coefficients lower than 0.1). The influence of angle inaccuracy in drilling of hole (practically 5%) has no impact on reaction forces (correl. coeff. lower than 0.1). The FE model also shows a negligible difference in forces obtained by measurement near the hole bottom and measurements in higher positions. As regards experimental verification, strong correlations were mainly found between $CS_{C(L)}$ conventional compression strength parallel to the grain and $S_{C(L)}$ strength of standard samples (correl. coeff. 0.92). The relationships were closer described by practically usable linear regression models. The compression strength parallel to the grain correlates with the other explored parameters, e.g. density (correl. coeff. 0.87). The other parameter for the assessment of mechanical properties using the new device was $MOD_{(L)}$ modulus of deformability, which correlates very well with $E_{(L)}$ elastic modulus parallel to the grain (correl. coeff. 0.87). The construction of the new device is light and because it does not require electric grid, it can be easily used at the site. In contrast to other methods, the new device enables us to establish mechanical properties in the depth profile of the assessed elements very accurately. The preliminary DIC analysis of the new instrument agreed with predictions done by FEA if distributions of displacement and strain fields are of concern. This analysis revealed strongly non-uniform behaviour at contact surfaces, which was attributed to local materials of wood and physical situation of contact.

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