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Rheology in wood engineering

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Abstract

The system strains under external loads in a certain amount of time and under the influence of the environmental factors define the rheological behavior. Rheological phenomena depend on many factors: temperature such as air humidity or moisture content of rheological system, radiations in term of intensity, duration, type - UV, IR, X, geometry of the parts; loadings in terms of intensity, variation, duration; defects; aggressive environment; composition, material properties; combinations of these factors. Rheology science is based on the theories of the strength of materials, thermodynamics, chemistry and materials science, but in terms of application, it provides a personalized analysis or diagnosis according to the condition of the structures/systems used. Wooden constructions are subjected to various loadings on both short and long durations. The joints can be elastic (flexible) if the failure occurs gradually, or plastic, if the failure occurs suddenly. Sudden failure of joints is caused by shear as predominant load because wood does not resist at shear stresses. In order to study the rheological behavior of the wood joints with metal rods under constant load, three types of joints in terms of diameters of bolts and stiffening systems were tested. They were stressed to traction force of 500 to 900 N for 200 days, in real conditions of temperature *(-7°C la +30°C)* and humidity (from *47.8% to 83.8%).* The aim of the tests were to determine the rheological behavior of wooden joints; variation of deformations in relation to the relative humidity and temperature; rate of strain and connections in determining rheological model of wood with threaded rods. It was found that the low temperatures during winter (-7…0°C) correlated with high relative humidity led to sudden changes in strain. It was observed that the high-speed deformation had a joint with the largest diameter rod (8 mm). The paper highlights the rheological analysis of joints in wooden rods in real conditions of temperature and humidity, with regards to applied tension and the determination of the creep function that characterizes these types of connections, establishing the optimum diameter rods.

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1. Introduction

Both in Romania and in various parts of the world, the construction of wood components is widely used, constantly evolving and finding new techniques. Over time, construction joints have evolved by increasing the complexity of the structures to which they belong. If simple joints were used at the beginning for house joints, today keyed joints based on metal elements that increase their resistance and performance are used [1, 2]. Evolution of construction is reflected in the overall geometry: from straight bars and simple structures to the curved girder and arcs of different sizes, different positioning angles, high and complex structures. Wood has lower resistance to the concentrated load compared with other materials. The transmission of efforts should be made taking into account the direction of the fibers and provided a sufficient contact surface. Studies of the joints with one or more bolts, made by Chaplain M. (et al, 1994), have shown that the life of the joint is higher for higher frequencies than for lower and the strains evolution depends on the stress value and not on the frequency load [3]. In case of wood - metal joints, breaking of connection is caused by wood fracture. Bocquet studied static behavior of joints in wood with metal rods and pin type brooch [4]. Progressively increasing the load, it was proved that there is a limit for the load applied to this type of assembly. Irreversible deformations occur after reaching the first threshold of effort. The rods adopt a curvature that may become important, and the wood is crushed in the regions close to the areas of contact with the rod. K. Öiger analyzed the structural capacity of resistance of the joints in case of traditional wooden structure buildings, 150-200 years old [5]. From the point of view of behavior in time, the rheological deformation of wood is characterized by Burgers model equation (1) [6,7].

$$\varepsilon = \varepsilon_e + \varepsilon_{ei} + \varepsilon_c = \frac{\sigma}{E_1} + \frac{\sigma}{E_2}(1 - e^{\frac{E_t}{\lambda_2}}) + \frac{\sigma * t}{\lambda_1} \tag{1}$$

We can say that, so far, there are not enough studies to precisely describe the behavior of wood joints for long periods of time, nor theoretically and experimentally. Experimental studies have been limited to the analysis of the properties of solid wood as such, and did not analyze the structures such as joints; they were tested for static starins, in the laboratory conditions, for a short period of time. The paper highlights the behavior in time – during 200 days of mixed wood-metal joints in conditions of varying diameter rod and solidarity elements joints (nuts, Bulldog half spike, etc.).

Nomenclature

ε	strain [%]
ε_e	elastic strain [%]
ε_{ei}	delayed elastic strain [%]
ε_c	flow strain [%]
ε_L	strain of wood [%]
ε_{OL}	strain of steel [%]
$\dot{\varepsilon}$	strain rate [s^{-1}]
E	Young's Modulus of material [MPa]
λ	viscosity [Pa*s]
σ	stress [MPa]
t	time [s] or [hours] or [days]
F	force [N] or [kN]
Φ	diameter [mm]
Δ	displacement [mm]
L_e	total storage energy [N*mm]
L_{ei}	initiation of fracture energy [N*mm]
D	tenacity rate [%]
U	moisture content of wood [%]

2. Studied joint

In the survey, the following categories of joints were analyzed (at 1:2 scale): Case 1 - plain rod joint with diameters of 6, 8, 10 mm, without fasteners (Fig. 1 a); Case 2 - threaded bolt connections with diameters of 6, 8, 10 mm, without washers, nuts fastened only (Fig. 1 b); Case 3 - threaded rod joint with a diameter of 6, 8, 10 mm, fixed at both ends with washers and nuts (Fig. 1 c); Case 4 - Screw the threaded rod with the diameter of 6, 8, 10 mm, with Bulldog half spike, fastened with nuts (Fig.1 d). The final dimensions of the specimens are shown in Fig. 2. Side and central elements of the connection were made of half edge-sawn timber of spruce. To measure the moisture content of wood (U) a device with electromagnetic waves has been used. At the time of the first experimental test, the elements of the joints had moisture content values between 10.2 to 21.9%. In the present study, two types of tests were performed: static tensile test by determining the force-displacement curves and the total energy absorbed and static tensile test under continuous load tension for a period of 200 days, determining the rheological behavior in terms of displacements and strains occurred due to the variation of relative humidity and temperature of the environment, and the speed of deformation of parts and creep.

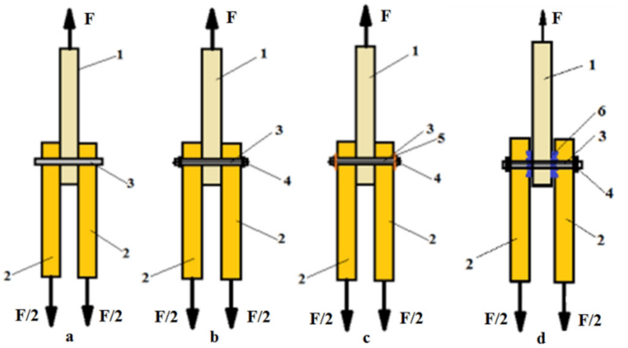

Fig. 1. Types of studied joints (1 – central element, 2 - lateral elements, 3 - rod, 4 - nuts, 5 - washer, 6 – Bulldog half spike): (a) pin joint; (b) joint with threaded rod fixed with nuts; (c) rod joint fixed with washers and nuts; (d) threaded rod joint fixed with nuts and Bulldog keys inserted between wooden elements.

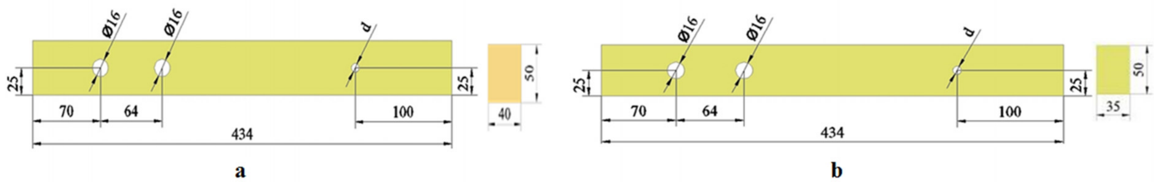

Fig. 2. Specimen size: (a) the central element; (b) lateral element.

3. Static behavior analysis of joints subjected to tensile

3.1. Test equipment

In order to determine the force – displacement curve during the tensile test, a mechanical testing machine of traction - compression type Walter Bai was used (Fig 3) [8]. The analyzed joints were fixed in devices designed for them (Fig. 3 b). Studied structures were fixed successively to mechanical testing machine and subjected to tensile forces up to the maximum breaking strength of the assembly [9]. Application default speed was of 1 mm/min.

3.2. Results and discussion

General behavior of the joints under load was similar for all three rod diameters. Fracture occurred at joints with rod diameters 8 mm and 10 mm, in the central element of the joint and at least on one of the sides, for case 3 (the rod fixed with washers and nuts). For the rod joint having a diameter of 6 mm, breakage occurred only in one tested joint, the other bolts just deformed. In cases 1 and 4, the fracture occurred only on the side elements of the assembly. There have been strong snatching fibers, especially when using Bulldog type spikes and on the side elements in the areas of the shear due to the metal rod deformation. These special keys maintained the joint until breaking of wooden parts. In practice, cylindrical rod holds the assembly, even after damage to the Bulldog half -spikes type, breaking of rod leading to the ultimate destruction of the joint. In Fig. 4, the breakage mode of tested joints is presented. In the case of joint where nuts were not used (Case 1), there was the lowest breaking force with the minimum displacement between the jointing elements.

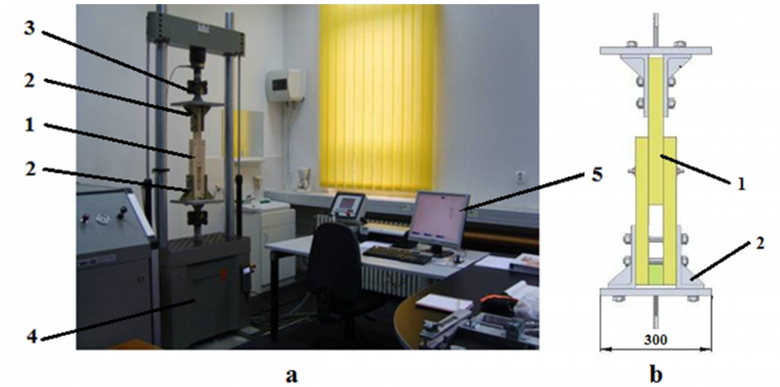

Fig. 3. Equipment and testing devices: (a) mechanical testing machine (1 – studied joint; 2 – fasteners device; 3 – cell application of tensile forces; 4 – machine frame; 5 – data acquisition and software); (b) device for fixing of structure.

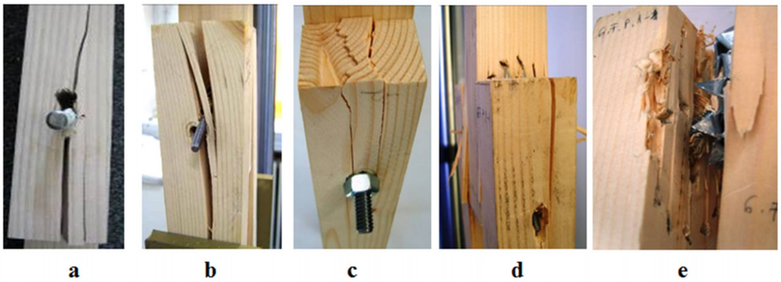

Fig. 4. Type of joints fractures: (a) rupture of side element in case 1; (b) splitting of wood in case 1; (c) shear of wood element and strain of rod in case 2; (d) splitting of wood element in case of Bulldog key – case 4; (e) destruction of the joints between wood and Bulldog half spike.

In Table 1, the experimental results of the four cases of joints in terms of displacement, Δ, the storage energy L_e, and tenacity rate D are summarized [10]. By overlaying the force-displacement diagrams, it was noticed that with the increasing of rod diameter the maximum breaking strength increases and the displacement decreases (Fig. 5 a). By overlaying the force-displacement diagrams of one type of joint, it was observed that with the increasing of moisture content, the mechanical properties of wood decrease, by decreasing the maximum force (Fig. 5 b). The total storage energy and the initial energy of rupture varied from case to case, this phenomenon being explained by the anisotropy and the moisture content and also by the way the joint was made (Fig. 6).

Table 1. Maximum force and displacement values determined for each type of analyzed joint

Type of joint	Rod Diameter Φ (mm)	Maximum Load F (kN)	Displacement Δ_{max} (mm)	Storage Energy L_e (x10^8 N*mm)	Tenacity rate D
Case 1	6	6	27	0,2445	1,1059
	8	9,8	16	0,2141	0,5288
	10	16,4	21	0,4769	0,0288
Case 2	6	11,53	42,44	0,2501	0,6820
	8	16,99	36,34	0,2571	0,4598
	10	19,32	14,61	0,2116	-
Case 3	6	14,42	35,44	0,4171	2,0353
	8	19,00	33,63	0,2481	0,2502
	10	23,46	26,40	0,1629	0,2891
Case 4	6	12,8	50	1,4140	0,2412
	8	13,7	48	1,0540	0,7915
	10	19	41,5	0,1302	0,5745

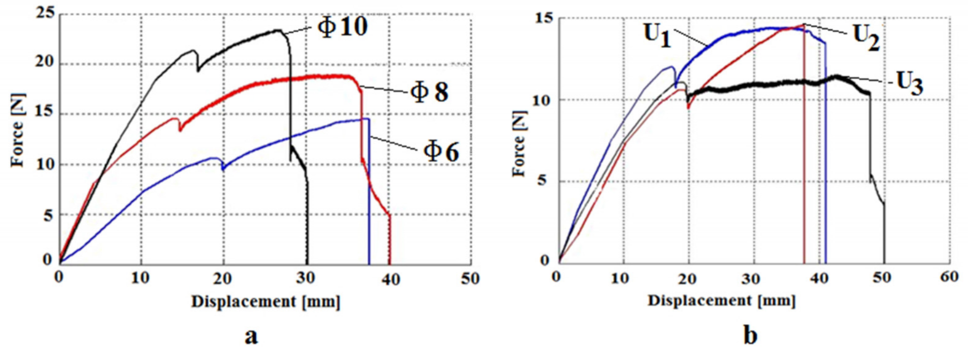

Fig. 5. Variation of force – displacement: (a) for the three rod diameters (Φ 6, Φ 8, Φ 10 mm in case 3 - joint threaded rod with ends fixed with washers and nuts); (b) for different moisture content (U_1=11.3 ⇗17.7%; U_2= 10.2⇗16.2%; U_3=18.4⇗21.9%) of wood joint structure with rods diameter of Φ 6 mm.

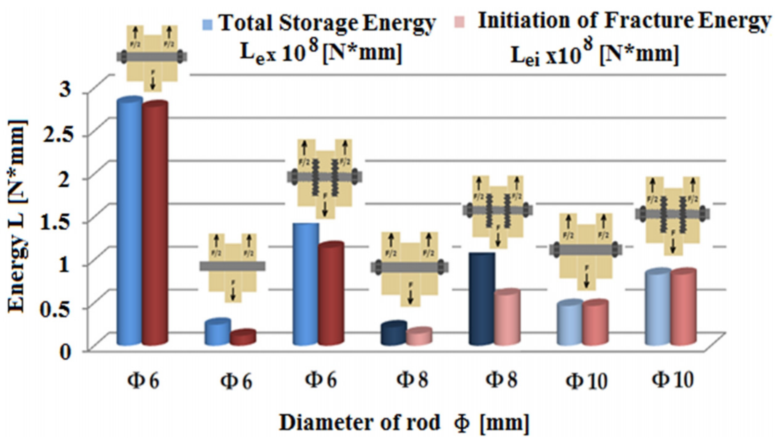

Fig. 6. Comparative analysis of the values of the total storage energy by the specimen and the initiation energy.

Strains of joint parts during tensile testing occurred successively (Fig. 7 a and b). The first stage was represented by the specimen in the initial state, second stage 2 - specimen is load with force F, stage where deformations due to local crushing of pieces of wood in contact with fasteners were registered, than stage 3 - when crushing between wood and rod appeared, followed by plastic deformation of wood at the contact between the rod and wooden parts during the stress, 5 - appearance of plastic strain of rod and cracks in wooden parts by achieving breaking strength of wood, 6 - deformed shape of the piece after downloading (F = 0) (Fig. 7) [11,12].

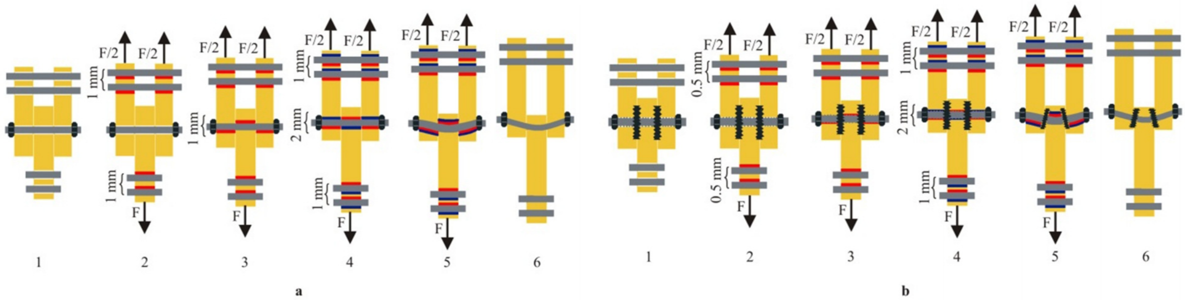

Fig. 7. Sequences strain during tensile testing of joints: (a) case 1; (b) case 4.

4. Time behavior of joints subjected to tensile under constant load

To study rheological behavior of wooden joints with the metal rods (bolts) under permanent load, the test bench was designed and built. Joints with unthreaded rods with diameters of Φ6, Φ8, Φ10 mm were tested, having the same sizes as the ones subjected to static tensile tests. The tests followed the time evolution under continuous load in terms of displacement and strain rate. Joints were fixed in the device made from steel. A disk with possibility of attaching other disc in order to increase the load was attached at the free end of the joint. The weight of the first backing disc was F_1=300 N, and the second was F_2=250 N. It has been ensured that the total load was substantially equal with approximately force of 500 N. After stabilization of joint strain, the third disc was attached to the weight of 300 N, reaching at the end of the experimental program the total weighing of about 900 N. The total test period were 200 days, the displacement, temperature and relative humidity being measured at each 12 hours.

In the Fig. 8 is highlighted the strain and creep curve. *The environment temperature varied between -7 °C and +30.01 °C, and relative humidity of the air between 47.8% and 83.8%.*

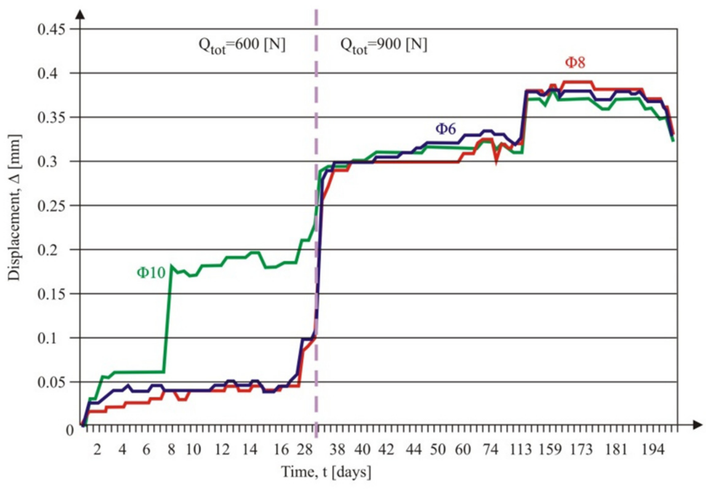

Fig. 8. Variation of joint displacement in time related to temperature and air humidity.

The low temperatures and the increasing relative humidity of the air in winter time had driven to the sudden changes of deformations for all three diameters of the rods [13]. The highest deformation speed was recorded for the 10 mm diameter rod joint, and the lowest one for the diameter of 6 mm. In the same trend, the maximum displacements were recorded for a diameter of 10 mm, and the lowest one for a diameter of 8 mm. The deformations/displacements were small, not visible, both for wooden parts and metal rods.

The literature describes three strains areas, each one having a strain rate [14, 15 and 16]. In the first one, the primary flow occurs where the strain rate decreases. In the second one, the secondary flow occurs when the strain rate remains approximately constant, the phenomenon taking place constantly and for a long time, depending on the load. In the third area, the tertiary flow occurs with relatively high strain rate, which is accelerated as the break moment approaches [17,18]. Following the recorded data, the strain rate was calculated as derivative of specific strain related to time using the method of finite differences (Fig.9).

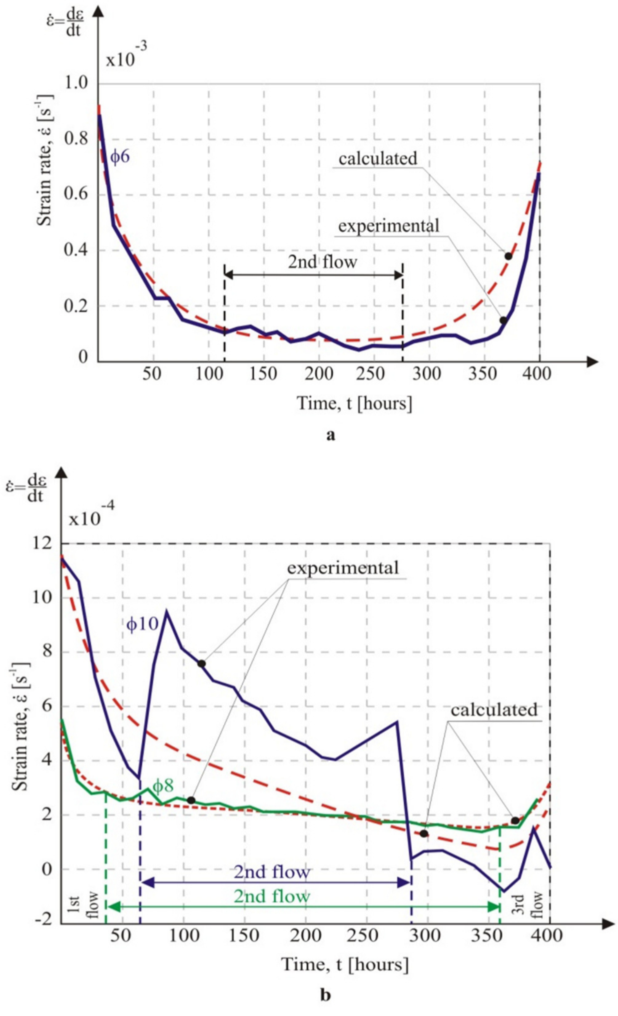

Fig. 9. *Strain rate in case of rod joint loaded with 600 N measured for 400 hour.*

It is noted the existence of the three phases: beginning, increasing flow and decreasing flow rate. Then, the flow decreases and the flow rate keep constantly. In the third part, the flow rate is fast. In this stage beginning and evolution of progressive degradation of the wood before the break are highlighted. It is the confirmation of the existence of various non-linear behaviors. Rheological behavior in terms of strain rate recorded in the experimental tests corresponds to that of a viscoelastic solid. If the loading intensity is changed, a delayed deformation occurs in time, converging to a constant value. This behavior can be described by the type of rheological models Hooke and Newton. Elastic deformation which occurs directly it is described by Young's modulus of the material. In the studied cases, four stages of flow were noticed: step 1 - when the specimen is loaded and timber elements have an elastic strain, rod being rigid; step 2 - during loading, when the plastic domain is reached and elastic deformation of the rod begins; step 3 - when it is recorded only residual deformations of wooden elements and rod; crack propagation and fracture appearance in the wood elements occur; step 4 - the strain of the assembly after reaching the maximum force, when the breaking of the side elements of the joint is recorded, a plastic deformation of the rod and of the central element without breaking.

5. Conclusion

An important parameter of the quality of wood structures is the quality of their joints. Joints store forces, depending on the shape connected with the structure of the joint, on the environment parameters (humidity, temperature), duration of application, size and direction of forces. One of the limits of energy dissipation is breaking of wood in the joints. The creep phenomenon appeared in the timber are explained by the development of dislocation between the molecules chains and the destruction of the primary and secondary links, by occurrence of cracks and shears between the wood fibers. With the increasing of the diameter of rod, the breaking force is higher and the displacements are smaller. The total storage energy and the initiation of the fracture were recorded in case of unthreaded rod joints of 6 mm diameter. Low temperatures in winter and high air humidity caused instantaneous variations of displacements. In the case of rod joint of 10 mm diameter, the recorded strain rate was higher than in the case of rod joint of 6 mm diameter, when the strain rate was smaller. As a conclusion, the rod joint of 8 mm diameter might be recommended to be used in different applications, because of the relatively low strain compared to other of the studied diameters.

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