EXPERIMENTAL AND STATISTICAL STUDIES OF THE INITIAL MODULE OF ELASTICITY AND THE MODULE OF DEFORMATIONS OF CONTINUOUS WOOD AT DIFFERENT AGES AND MOISTURE CONTENT

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Abstract: A brief overview of the determination of the initial modulus of elasticity and the modulus of deformation of different elastic and elastic-plastic materials is carried out. A universal method for determining the initial modulus of elasticity and the modulus of deformation of solid and modified wood is proposed. It is established that when the age of wood changes from 60 to 20 years, the initial modulus of elasticity and the modulus of deformation decreases: for birch prisms by 17.1%; for alder by 12.1%; ash by 14.3%; larch by 13.2%; pines by 13.1%; spruce by 17.0%. It was also found that the initial modulus of elasticity of all studied species due to drying from 30 to 12% increases, in particular for birch 1.23 times, alder – 1.61 times, ash – 1.18 times, larch – 1.29 times, pines – 1.33 times, spruce – 1.35 times. The change of initial modulus of elasticity of deciduous and coniferous species of wood depending on age in the range from 60 to 20 years and from moisture content from 30 to 12% is given.

Keywords: Age, Initial modulus of elasticity, Modulus of deformation, Moisture content, Solid wood, Strain, Stress, Stress level.

1 Introduction

Wood is an elastic-plastic material with its own special properties. Materials, parts, products, elements, and structures of wood are found at every step in everyday life [3, 9, 10, 17-20, 21, 24, 26, 28-30, 33, 37]. Therefore, a very important factor is that its physical and mechanical properties are variable and depend on age, moisture content, rate of deformation, and many other components. All these features must be taken into account in the design and manufacture. A very important characteristic of wood is the initial modulus of elasticity and the modulus of deformation. The correct definition of these two important parameters directly affects the design of materials, products, parts, elements, and structures based on wood. It is also very important to be able to observe how the modulus of deformation changes when the samples are loaded directly to the top point of the deformation diagram of the material "stress-strain".

A special aspect is the influence of age and moisture content on the mechanical properties of wood and composite materials based on it. These factors must also be taken into account when determining the initial modulus of elasticity and the modulus of deformation.

2 Materials and Methods

The mechanical properties of solid wood have been studied since the beginning of the last century. This process of rapid development has taken place since the middle of the last century. But until recently, experimental studies of compression, tension, bending were conducted on hydraulic installations on the increase in loads [1, 3, 7, 10, 12, 15, 17], which did not allow establishing the true values of strength and deformation in the supercritical stage of the material. It also did not allow building a complete deformation diagram of "stress-strain" with a descending branch.

In recent years, engineers have proposed electromechanical and servo-hydraulic systems [6, 16, 22, 31, 32, 34], which allow testing different materials for increasing displacement, i.e., studying samples, both of precritical and supercritical stages of samples of different origins.

We conducted experimental studies of wood at different ages and moisture content on a modern test machine STM-100 [22, 34-36] and built complete diagrams of deformation of hardwood and coniferous species by axial compression along the fibers under short-term load. This installation allows testing samples of different sizes for compression, tension, bending according to current world standards [1, 5, 11 – 13, 15] and establishing the basic mechanical characteristics of materials, in particular, wood, both on the ascending and descending branches of the deformation diagram "stress-strain". Therefore, it remains to propose a method and determine the initial modulus of elasticity and modulus of deformation of solid wood at different ages and moisture content. The purpose of the study is to propose a method for determining the initial modulus of elasticity and the modulus of deformation of solid wood of deciduous and coniferous species of different ages and moisture content.

The method used in the current standards [8, 15] is a multiple re-loading-unloading (cyclic loading to a certain level with unloading) to select plastic deformations of wood does not lead to a purely linear relationship between stresses and strains. Therefore, it is not possible to establish the true value of the initial modulus of elasticity in this way. Therefore, the initial modulus of elasticity of wood can be set from the condition of the limit position of the cutting modulus of elastic-plasticity E' under conditions when the angle of inclination and relative deformations are striving to 0.

3 Results and Discussion

Based on experimental studies, it was found that the dependence of "stress σ_c – strain u_c" on a single short-term compression along the fibers with a constant rate of deformation due to plastic deformations occurring at the lowest stresses is nonlinear from the beginning of loading. But with increasing stress, the curvature of the diagram with longitudinal compression of the wood also increases. Therefore, when determining the initial modulus of elasticity and modulus of deformation, it is necessary to take into account the following laws of the material. The modulus of deformation (cutting modulus of elastic-plasticity) of wood and composite materials based on it E' depends on the stress level σ_c.

Given our experimental and theoretical studies of samples of structural dimensions of solid wood birch, alder, ash, larch, pine, spruce of different ages (60, 40, 20 years) and moisture content (30, 21, 12%) axial compression along the fibers short-term load under hard mode of application of load with constant deformation rate [22, 35] and the proposals given in [25], the deformation (cutting) module can be written as follows:

$$E' = E_o(1 \pm \lambda_{f_{c,0,d}} \eta), \quad (1)$$

where $\lambda_{f_{c,0,d}}$ – the coefficient of plasticity of solid wood by compression along the fibers; η – stress level in solid wood

Based on the experiment [22], formula (1), and taking into account [25], we construct diagrams "E'-η" and determine the initial modulus of elasticity and modulus of deformation of deciduous (birch, alder, ash) and coniferous (pine, spruce, larch) wood species at a standard moisture content of 12% aged 60 (Figure 1), 40 (Figure 2), 20 (Figure 3) years and conduct a statistical evaluation of the values obtained (Table 1).

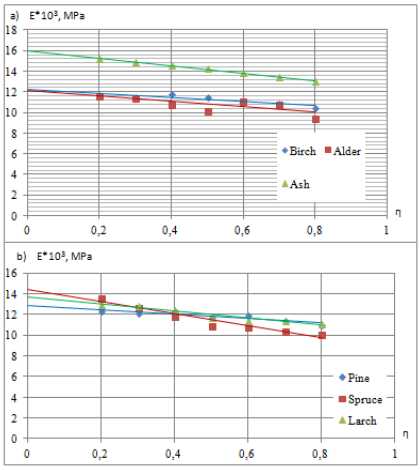

Figure 1 – Diagrams "E-η" (cutting module – stress level) of different species of solid wood at the age of 60 years at a moisture content of 12%: a) deciduous; b) conifers

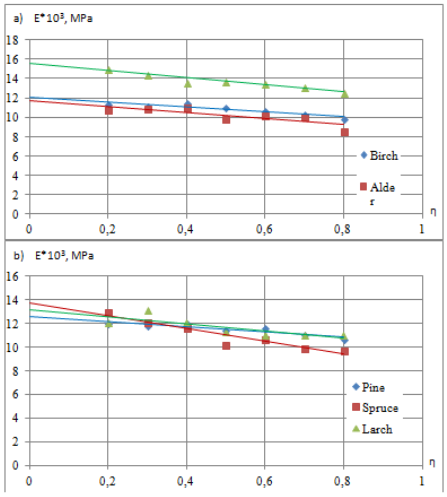

Figure 2 – Diagrams "E-η" (cutting module – the level of strain) of the older generations of the succinct tree in 40 years of age for 12% moisture content of the following: a) deciduous; b) conifers

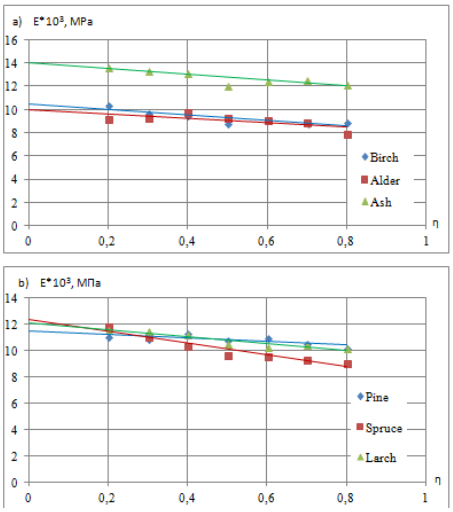

Figure 3 – Diagrams "E-η" (the cutting module – the level of strain) of the younger generations of the succulent tree in 20 years of age for 12% moisture content of the following: a) deciduous; b) conifers

Table 1: Basic Parameters and Statistics of the Correlation Equations of Regression "E-η" of solid wood of deciduous and coniferous species of different ages at a standard moisture content of 12%

Name of the sample	Correlation equation	r	m_r	$\frac{r}{m_r}$	V,%
The age of the wood is 60 years					
Birch-12-60	E'=12,286·(1-0,044· η)	0,948	0,045	13	1,71
Alder-12-60	E'=12,061·(1-0,057· η)	0,939	0,044	12	1,78
Ash-12-60	E'=15,989·(1-0,064· η)	0,998	0,001	732	3,13
Pine-12-60	E'=12,910·(1-0,047· η)	0,925	0,057	16	4,07
Larch-12-60	E=13,716·(1-0,058 η)	0,966	0,058	38	1,55
Spruce-12-60	E=14,386·(1-0,090· η)	0,969	0,023	42	2.57
The age of the wood is 40 years					
Birch-12-40	E'=12,138·(1-0,045· η)	0,924	0,056	17	2,30
Alder-12-40	E'=11,757 ·(1-0,106η)	0,886	0,008	111	3,81
Ash-12-40	E'=15,487·(1-0,066· η)	0,940	0,019	49	3,13
Pine-12-40	E'=12,540·(1-0,048· η)	0,831	0,068	12	4,59
Larch-12-40	E'=13,291·(1-0,060· η)	0,898	0,030	30	1,78
Spruce-12-40	E'=13,726·(1-0,139· η)	0,914	0,018	50	2,57
The age of the wood is 20 years					
Birch-12-20	E'=10,585·(1-0,034· η)	0,772	0,153	5	1,93
Alder-12-20	E'=9,957·(1-0,106η)	0,786	0,145	5	4,81
Ash-12-20	E'=14,099·(1-0,055· η)	0,987	0,010	101	0,62
Pine-12-20	E'=11,432·(1-0,037· η)	0,753	0,164	5	2,10
Larch-12-20	E'=12,061·(1-0,057· η)	0,939	0,044	21	0,62
Spruce-12-20	E'=12,322·(1-0,139· η)	0,954	0,034	28	1,78

We also present a histogram of the dynamics of change of the initial modulus of elasticity (Figure 4). This figure also decreases in the interval from 60 to 20 years: for birch prisms – by 17.1%; alder – by 12.1%; ash – by 14.3%; larch – by 13.2%; pines – by 13.1%; spruce – by 17.0%.

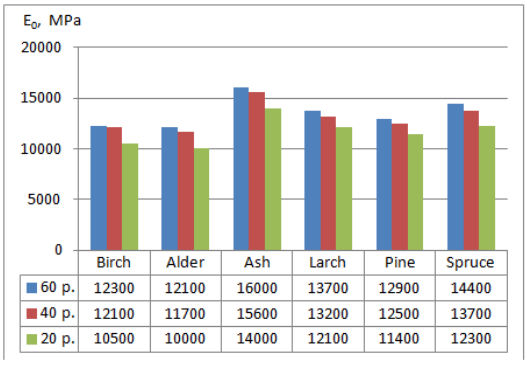

Figure 4 – Dynamics of change of the initial modulus of elasticity of solid wood of deciduous and coniferous breeds at different ages

Different scientists paid very little attention to the mechanical characteristics of solid wood of different ages, including the initial modulus of elasticity and the modulus of deformation. There are virtually no such studies in the literature. Therefore, it is important to provide information from our own research of such parameters that would take into account when designing structural materials, parts, products, elements, structures of wood, considering the age factor not only for 20, 40, and 60 years, but also intermediate.

Thus, on the basis of experimental studies [22], we establish the dependence of the initial modulus of elasticity of prisms with the corresponding age of deciduous (Figure 5a) and coniferous (Figure 5b) species, while setting this parameter of all studied wood species in the range of 20-60 years after 5 years (Table 2).

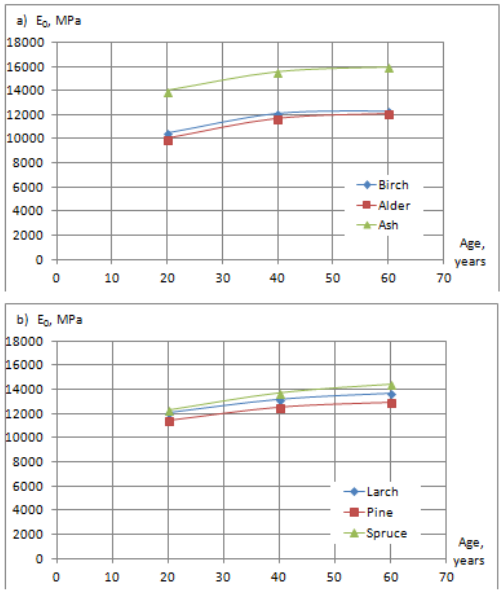

Figure 5 – For determining the initial modulus of elasticity of wood aged from 20 to 60 years at a standard moisture content of 12%: a) deciduous species; b) conifers

Table 2: The value of the initial modulus of elasticity E_0 of solid wood by age determined in Fig.5a and 5b

Age, years	Wood species					
	Deciduous species			Conifers		
	Birch	Alder	Ash	Larch	Pine	Spruce
	E_0, MPa	E_0, MPa	E_0, MPa	E_0, MPa	E_0, MPa	E_0, MPa
60	12300	12100	16000	13700	12900	14400
55	12300	12000	15900	13600	12800	14300
50	12200	11900	15800	13500	12700	14100
45	12100	11800	15700	13300	12600	13900
40	12100	11700	15600	13200	12500	13700
35	11900	11600	15300	13000	12300	13500
30	11400	10900	14900	12700	11900	13000
25	11000	10500	14400	12400	11600	12700
20	10500	10000	14000	12100	11400	12300

Based on the experiment [35], formula (1), and taking into account [25] we construct diagrams "E'-η" and similarly determine the initial modulus of elasticity and modulus of deformation of deciduous (birch, alder, ash) and coniferous (pine, spruce, larch) wood species aged 60 years at a moisture content of 30% (Figure 6), 21% (Figure 7) and conduct a statistical evaluation of the values obtained (Table 3).

The diagram "E'-η" for a standard moisture content of 12% is shown in Figure 6.

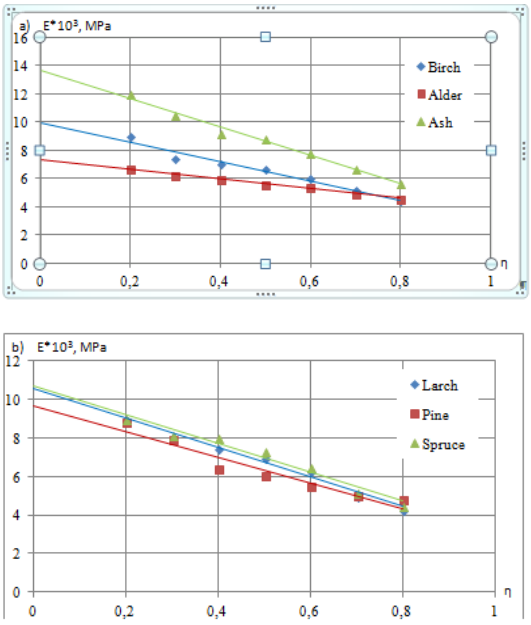

Figure 6 – Diagrams "E-η" (cutting module – stress level) of different solid wood species by moisture content of 30% at the age of 60 years: a) deciduous; b) conifers

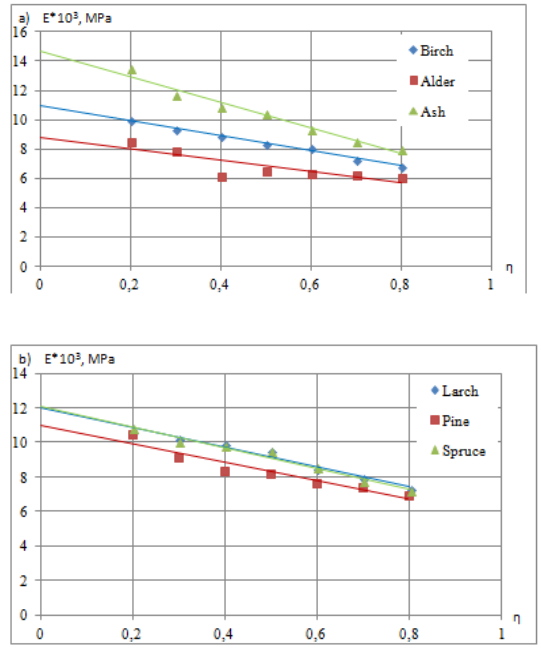

Figure 7 – Diagrams "E-η" (cutting module – strain level) of different species of solid wood at a moisture content of 21% at the age of 60 years: a) deciduous; b) conifers

Table 3: Basic parameters and statistics of correlation equations of regression "E-η" of solid wood of deciduous and coniferous species at different moisture content at the age of 60

Name of the sample	Correlation equation	r	m_r	$\frac{r}{m_r}$	V, %
Wood moisture content 30%					
Birch-30-60	E'=9,957·(1-0,346 η)	0,981	0,015	67	3,58
Alder-30-60	E' =7,457 ·(1-0,173η)	0,950	0,037	25	3,29
Ash-30-60	E' =13,644·(1-0,321· η)	0,993	0,005	188	2,37

Larch-30-60	$E' = 10{,}582 \cdot (1 - 0{,}310 \cdot \eta)$	0,992	0,006	164	3,26
Pine-30-60	$E' = 9{,}682 \cdot (1 - 0{,}314 \cdot \eta)$	0,963	0,028	35	6,15
Spruce-30-60	$E' = 10{,}707 \cdot (1 - 0{,}387 \cdot \eta)$	0,984	0,012	84	4,05
Wood moisture content 21%					
Birch-21-60	$E' = 10{,}947 \cdot (1 - 0{,}173 \eta)$	0,990	0,059	17	2,16
Alder-21-60	$E' = 8{,}757 \cdot (1 - 0{,}106\eta)$	0,886	0,068	11	3,81
Ash-21-60	$E' = 14{,}704 \cdot (1 - 0{,}232 \cdot \eta)$	0,945	0,074	15	2,77
Larch-21-60	$E' = 11{,}968 \cdot (1 - 0{,}146 \cdot \eta)$	0,986	0,011	13	2,09
Pine-21-60	$E' = 10{,}986 \cdot (1 - 0{,}180 \cdot \eta)$	0,958	0,031	31	3,51
Spruce-21-60	$E' = 12{,}073 \cdot (1 - 0{,}197 \cdot \eta)$	0,891	0,009	99	2,35

Let us present the dynamics of changes in the initial modulus of elasticity at the same moisture content (Fig. 8).

Thus, the initial modulus of elasticity of all studied species due to drying from 30 to 12% increases, in particular, for birch 1.23 times, alder – 1.61 times, ash – 1.18 times, larch – 1.29 times, pines – 1.33 times, spruces – 1.35 times.

Figure 8 – Dynamics of change of the initial modulus of elasticity of solid wood of deciduous and coniferous breeds at different moisture content

Wood in operation may have different moisture content values than those we studied. Conducting experimental studies of coniferous and deciduous species of wood of structural dimensions [35], and then processing the results, it was observed that at different moisture content parameters, the mechanical parameters are variable.

Therefore, it is important to determine such indicators also at other levels. This can be done by plotting moisture content in the range of 12-50% of such characteristics. These diagrams will allow us to determine the basic mechanical parameters at any moisture content, and as a result have real values of such indicators, including the initial modulus of elasticity. This will allow in the future to take into account even more widely the changing properties of wood, as well as the correct operation of materials, parts, products, elements, structures in aggressive environments. On the other hand, it will allow designers to more accurately calculate the elements and structures of wood, taking into account different moisture content indicators within 12…50%, which in turn will increase the durability of such elements or structures.

Therefore, it is of great importance for us to understand the change the values of the initial modulus of elasticity depending from different indicators of moisture content, which is shown in Figure 9a for deciduous species and Figure 9b for conifers. Similarly, the change in this parameter by 1% is given in Table 4.

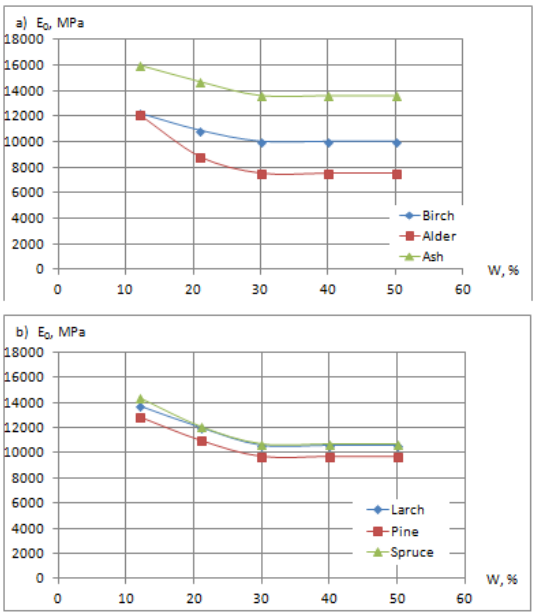

Figure 9 – To determine the initial modulus of elasticity of wood of different moisture content in the range from 12 to 30% at the age of 60 years: a) deciduous species; b) conifers

Table 4: The value of the initial modulus of elasticity E_0 of solid wood with moisture content in the range of 12-30% determined in Figure 9a and Figure 9b

Moisture content W,%	Wood species					
	Deciduous species			Conifers		
	Birch	Alder	Ash	Larch	Pine	Spruce
	$E_{0,}$ MPa	$E_{0,}$ MPa	$E_{0,}$ MPa	$E_{0,}$ MPa	$E_{0,}$ MPa	$E_{0,}$ MPa
30	10000	7500	13600	10600	9700	10700
29	10100	7600	13700	10700	9800	10800
28	10200	7700	13800	10800	9900	10900
27	10300	7800	13900	11000	10000	11100
26	10400	7900	14000	11100	10200	11200
25	10500	8100	14200	11300	10400	11300
24	10600	8200	14300	11500	10500	11500
23	10700	8400	14500	11700	10700	11600
22	10800	8700	14600	11800	10800	11900
21	10900	8800	14700	12000	11000	12100
20	11000	9000	14800	12200	11300	12400
19	11200	9400	14900	12400	11500	12600
18	11300	9900	15000	12600	11700	12800
17	11500	10200	15100	12800	11900	13200
16	11700	10600	15300	13000	12100	13400
15	11900	11100	15600	13200	12500	13600
14	12000	11300	15700	13300	12600	13900
13	12200	11800	15800	13500	12800	14200
12	12300	12100	16000	13700	12900	14400

According to the results of such experimental and statistical studies, the existence of linear correlations between the modulus of deformation and the strain level was confirmed. The linearity of the dependences is confirmed by a good degree of correspondence between the correlation and experimental values of relative deformations, which were taken within the limits according to [25].

To some extent, according to Figures 1a, 1b, 2a, 2b, 3a, 3b, 6a, 6b, 7a, 7b, the closest modulus of elastic-plasticity E' to the initial modulus of elasticity is possible only at small values of stresses σ_c.

It is almost impossible to establish the initial modulus of elasticity at the angle of inclination of the line that will be tangent to the curve "strain σ_c – deformation u_c" at the coordinate origin without establishing the analytical dependence of this curve.

Thus, it can be stated that the initial modulus of elasticity and modulus of deformation (cutting modulus) of wood of different ages and moisture content can be set with great accuracy analytically by formula (1) or graphically using the diagram "cutting modulus – strain level" at $\eta = 0$.

4 Conclusion

A method for determining the initial modulus of elasticity and the modulus of deformation of solid wood of deciduous and coniferous species of different ages and moisture content by axial compression along the fibers under short-term load is proposed.

The formula for determining the initial modulus of elasticity and the modulus of deformation of solid wood of deciduous and coniferous species of different ages and moisture content is proposed.

It is established that when the age of wood changes from 60 to 20 years, the initial modulus of elasticity and the modulus of deformation decreases: for birch prisms – by 17.1%; alder – by 12.1%; ash – by 14.3%; larch – by 13.2%; pines – by 13.1%; spruce – by 17.0%.

It was also found that the initial modulus of elasticity of all studied species due to drying from 30 to 12% increases, in particular for birch 1.23 times, alder – 1.61 times, ash – 1.18 times, larch – 1, 29 times, pines – 1.33 times, spruces – 1.35 times.

The change of initial modulus of elasticity of deciduous and coniferous species of wood depending on age in the range from 60 to 20 years and from moisture content - from 30 to 12% is given.

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Primary Paper Section: J

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