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FATIGUE STRENGTH OF WOOD POLYMER COMPOSITE

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Abstract

This paper presents the results of a study on the fatigue strength in pendulum bending natural and modified pinewood. The contents of polymethyl methacrylate (PMMA) were determined in wood-polymer for mechanical and rheological properties. The study of the bending fatigue strength and creep was realized on suitably prepared samples and research positions. Test results were documented in the form of charts and scraps. Differences in the decay of the natural and modified wood samples were observed after the attempt of the fatigue strength. The various mechanical properties of the sapwood, hardwood, and the polymer, influence on the stiffness of the individual components and consequently the whole composite. The process of fatigue degrades the structure of natural wood and wood polymer composite, the result is a gradual reduction of its stiffness. The Study of the creep behaviour was realized in stress in the sample of the level of 30% of the tensile strength. The samples were loaded longitudinally and transversely to the direction of the fibres. Significant differences of composite deformations were observed both as for the direction of the loaded fibres as well as the natural and modified wood. The character of changes in the fatigue strength and creep behaviour of the studied materials is implies to the influence of the polymer content on mechanical properties of modified wood. The tests carried out on account of the possibility of using wood polymer composite in sea constructions. Research carried out in connection with the possibility of the use of wood polymer composite marine construction. Modified wood can be used for keel blocks, decks, fender beam, bearings cantilevered shaft lines and the construction of yachts.

Keywords*: modified wood, mechanical properties, fatigue strength, device to inflict plane stress*

1. Introduction

Wood is a natural composite built from early wood (soft) and sapwood (hard) rings. It is a porous material, which easily absorbs the moisture, soaks up water and changes its specific weight. This property of wood as a porous material was used to modify its properties. Filling the pores of wood with appropriate chemical substances results in obtaining material in which its natural negative properties were eliminated [3, 6].

The paper presents the modification of the pinewood with polymethyl methacrylate (PMMA). Modification of wood provides effective protection against its degradation, prolongs its operating life, and improves its mechanical properties [1-8].

Composites, which are obtained from wood on the polystyrene and polymethyl methacrylate basis, can be applied where the following are required: a magnetism, high strength in combination with springiness and lightness, the easiness of mechanical processing and joining elements, good deadening and isolation properties with reference to vibrations, noises and the temperature.

Extensive results of the study of the property and methodology of producing modified wood and its property were presented in the papers [3, 5-7]. Besides, the article reports the study results of the fatigue strength of surface modified wood- polymethylmethacrylate composite.

The research on the fatigue strength requires much workload and is very expensive. Defining the influence of the mass polymer content in the wood polymer composite on the fatigue strength is a fundamental aim of the research.

2. Wood as chemically modified material

The modification of wood consists in synthetic polymer saturation, eliminates natural defects of wood and additionally increases its properties. The wood structure strengthens the used plastic in a way that is better than synthetic fibres.

Studies have shown that wood composites on the polymer base are useful for use wherever good dimensional stability and consistency of shape and precision machining are required [1, 2, 8, 11]. The process of modification of the polymethylmethacrylate (PMM) wood is presented in the studies [3, 6, 8].

Samples made from soft parts of pinewood were used for the research. Tab. 1 presents the contents of the PMM (kg PMM/kg of dry wood) and a defining way the polymer content of the composite. As a result of the modification, the wood becomes harder and stronger [3].

Tab. 1. The content of polymer in the wood composite

The content of polymer, kg/kg of dry wood	K0.0	K0.35	K0.43	K0.48	K0.56

3. The mechanical properties of the modified wood

Wood is a heterogeneous and anisotropic material, which makes it difficult to describe its strength characteristic [8-10].

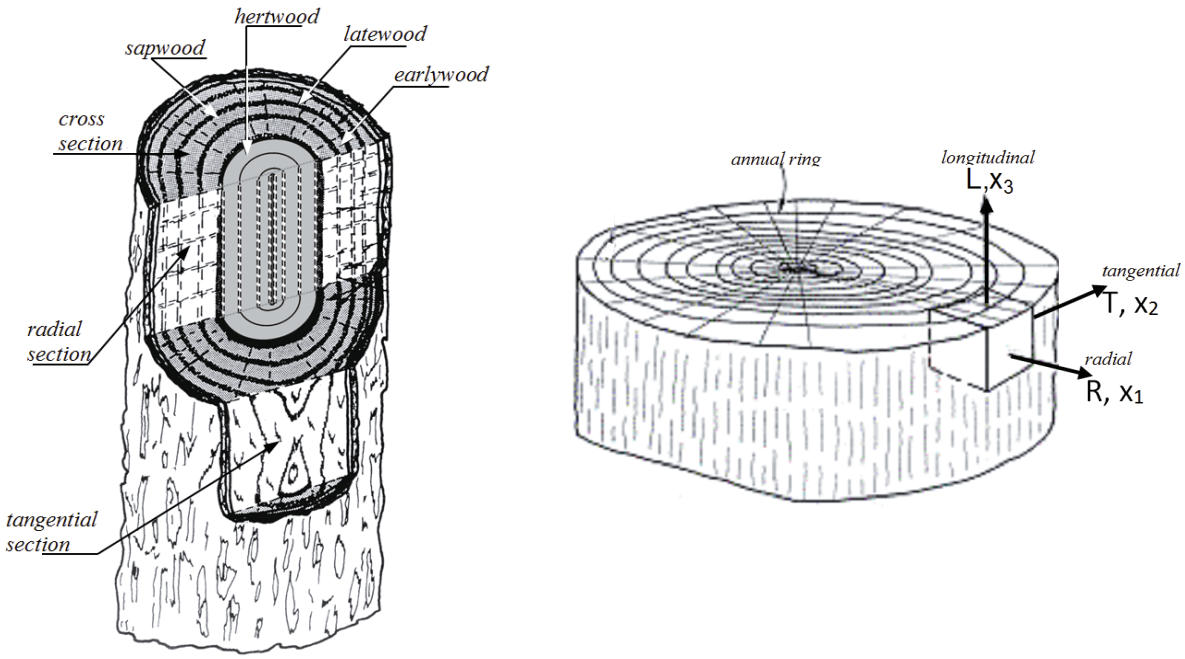

Fig. 1. Portion of a tree showing anatomical directions

Due to various arrangements of rings in a given volume of wood, there are three main directions (three planes of symmetry): radial, axial and tangential – (Fig. 1).

To determine the tensile strength of wood and wood polymer composite of the various polymer content samples from the prepared material have been made. The form and dimensions of the samples are shown in Fig. 2. The direction of the load was in accordance with the direction of the longitudinal L (x_3) rings. Each sample had at least four layers of softwood and hardwood [3, 5, 7, 8].

The samples were stretched on the universal material testing machine MTS-810. Mean values of tensile strength for the longitudinal direction for natural wood K 0.0 and modified K 0.35-0.55 are shown in Tab. 2.

Tab. 2. The properties of natural wood K0.0 and modified PMMA [2]

Material	K0.0	K0.35	K0.43	K0.48	K0.56
R_m, MPa	95	102	110	112	118

a) b)

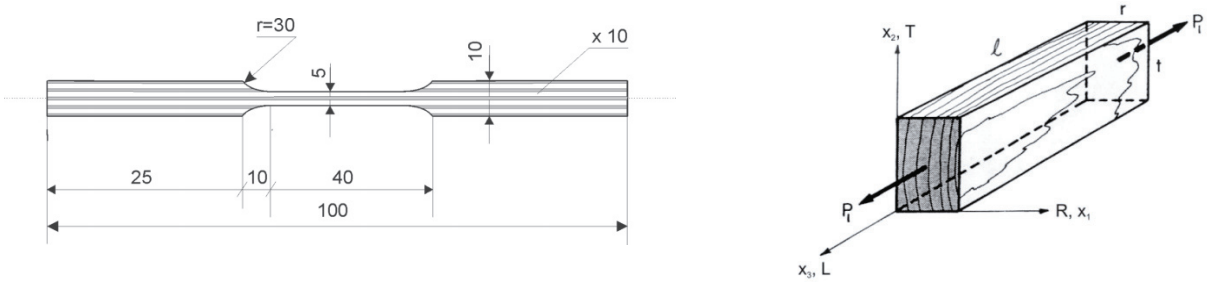

Fig. 2. The sample geometry a) dimensions), b) anatomical directions

4. Fatigue strength and creep behaviour of wood composites

The structure of natural wood and in particular wood polymer composite is complicated because it is made of several components that differ the mechanical properties. Furthermore, the rigidity of the layer depends on the direction of the load causing the various mechanical phenomena, different from the behaviour of metals. The destruction mechanism in the composite structure is complex due to its heterogeneous structure.

The various mechanical properties of the layers of soft, hard, and the polymer as a binder, influence a different on the stiffness of the individual components and consequently the whole composite. The process of fatigue degrades the structure of natural wood and wood polymer composite, the result is a gradual reduction of its stiffness.

The polymethyl methacrylate has no permanent fatigue strength, therefore it was the supposition that under the influence of cyclic loads may initiate cracking and as a result reduce the fatigue strength of modified wood. Purposeful was to determine the effect of the polymer content on the fatigue strength of the materials tested. Studies have shown that natural and artificial materials have variable elastic modulus values due to the creep behaviour or the relaxation [1, 8, 9]. Therefore had to be made on the samples research the creep behaviour of natural wood K0.0 and modified with the highest polymer content K0.56 (Tab. 2). In these materials, changes of the modulus of elasticity are for small deformations or stresses. This is due to the phenomenon of energy dissipation, which is produced as a result of occurring irreversible of the thermokinetic processes. In the process of fatigue of composite materials should be determine the mechanism of destruction of test samples caused by the mechanical or thermal load.

The composite materials are characterized by accumulation of heat because it has are badly conductors of heat. The heat is the cause of self-excited temperature increases, mainly in the central portion of the sample [9].

The fatigue tests of composite materials are very important to determine the degradation of the structure. There are not data concerning on the fatigue test the polymer composite wood. One of the models of artificial fiber composites degradation presupposes that the destruction process can be described the local rigidity [9]:

$$\sigma = E(D) \cdot \varepsilon\,,\ E(D) = E_0(1 - D)\,, \tag{1}$$

where:

D – the function describing the degradation of the structure,

speed the development of degradation is described relationship:

$$\frac{dD}{dN} = \frac{A(\Delta\varepsilon)^c}{(1-D)^b}, \tag{2}$$

where:
A, b, c – constants determined experimentally.

If the results of the fatigue life can save in the coordinates $\log\sigma - \log N$ and can its approximated by a straight line, it is possible determine the rigidity degradation by the equation:

$$\log N = \log A - m\log\sigma, \tag{3}$$

where:
A, m – constants determined experimentally [9].

For a case when the destruction process depends on the increments cyclic load $\Delta\sigma$, the cycle asymmetry R and the present value of the destruction D, but is omitted the frequency, temperature, humidity, (assuming a constant value), then the speed of degradation of rigidity can be written the equation [9]:

$$\frac{dD}{dN} = f(\Delta\sigma, R, D), \tag{4}$$

The integration this equation allows to determine the number of cycles to destruction N_f to the critical level of destruction D_f:

$$N_f = \int_{D_i}^{D_f} \frac{dD}{f(\Delta\sigma,\ R,\ D)}. \tag{5}$$

The function $f(\Delta\sigma,\ R,\ D)$ can be written by the equation:

$$f(\Delta\sigma,\ R,\ D) = \frac{1}{g\left[g^{-1}\left(\dfrac{E}{E_0}\right)\right]}\left(\frac{1}{E_0}\right)\frac{dE}{dN}, \tag{6}$$

where:

$D = g^{-1}\left(\dfrac{E}{E_0}\right)$ – depends on properties of the composite, and is determined experimentally,

E_0 – initial modulus of elasticity of the material.

The creep is the deformation of the structure (samples) at the time for constant stress and temperature.

For T = constant the creep equation can be written $\varepsilon = f(\sigma,\ t)$ [14].

The total creep deformation can be expressed using dependence:

$$\varepsilon(t) = \varepsilon^0 + \varepsilon^p(t), \tag{7}$$

where:

ε^0 – strain immediate, which is the sum of elastic strain $\varepsilon^s = \sigma / E$ and inelastic strain ε^{ns}.

Creeps deformation $\varepsilon^p(t)$ can be divided into a residual and partially reversible, $\varepsilon^{cn}(t)$. The creeper speed has the form of the dependence:

$$\dot{\varepsilon}(t) = \dot{\varepsilon}^p(t) = \frac{d\varepsilon(t)}{dt}. \tag{8}$$

Fig. 3 shows the creep curve of the three characteristic periods. In the first phase, there is a rapid the process of creep, in the second creep is almost constant in the third period the creep sharply increases and terminates by the destruction of the sample. On the basis of creep curve (Fig. 3) after unloading at the moment t_1 the strain spontaneously decrease and is equal – ε^s, and strain $\varepsilon^p(t)$ can be completely or partially reversible.

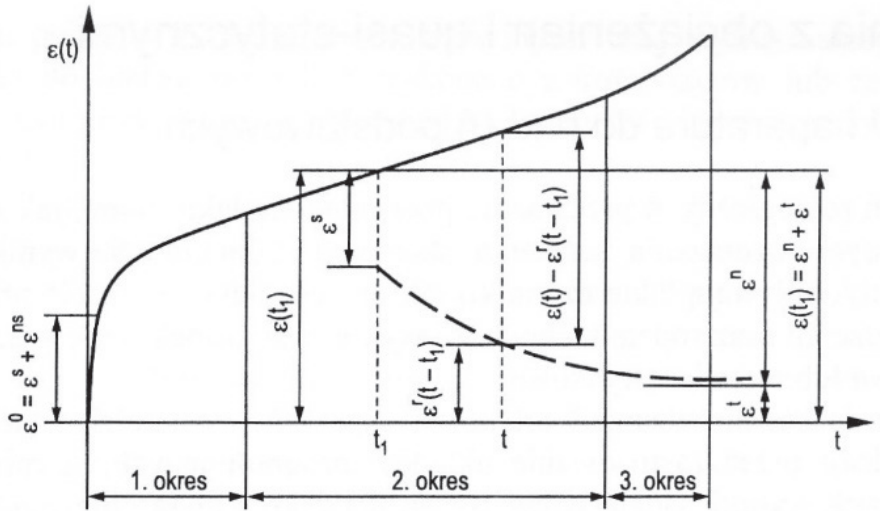

Fig. 3. The periods sample deformation during the creep [14]

If the strains $\varepsilon^{p}(t)$ aren`t completely reversible with the residual strain, $\varepsilon^{r}(t)$, the permanent strain arise ε^{t}. In the process of creep the strain due to the internal structure of the material takes place simultaneously the deformation of elastic, viscous (relaxation) and plastic (slippages). The detailed description the process of creep the composite materials and rheological models is presented in [3, 9].

5. Proceedings and results

Figure 4 shows the shape and dimensions of the samples for fatigue tests. Samples of natural wood and modified K0.56 have been subjected to bending oscillating at a frequency of 24 Hz.

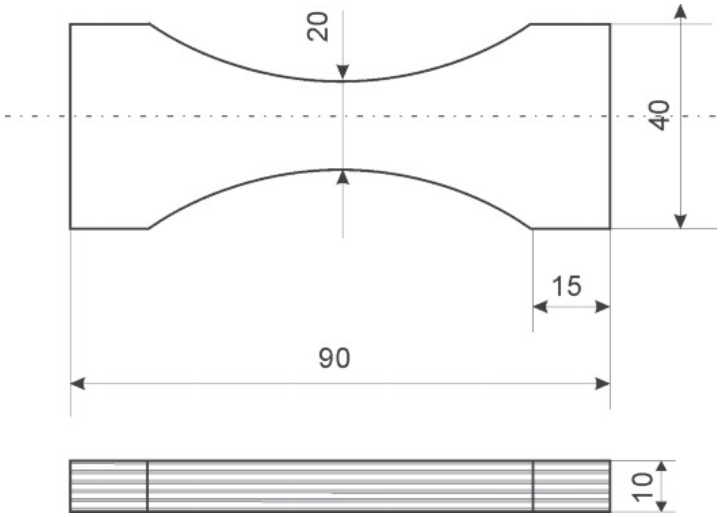

Fig. 4. The shape and dimensions of samples for the testing fatigue

Figure 5 shows the results of fatigue tests the natural and modified wood. The fatigue strength was determined on the basis of the contractual border number of stress cycles which is equal to $2 \cdot 10^{6}$.

The limits of fatigue strength for pendulum bending have been determined for individual materials. The results of research are shown in Fig. 6. Studies have shown that the fatigue strength of the modified wood for bending pendulum is almost double that of natural wood. The polymer strengthens the structure of the wood, therefore increases its fatigue strength.

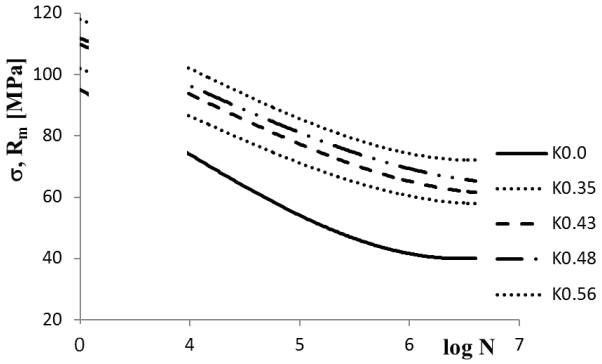

Fig. 5. Wohler curves of natural and modified wood

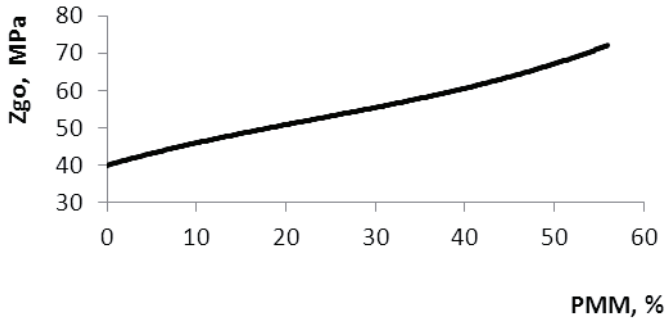

Fig. 6. Dependence of fatigue strength the wood – PMM composite for the polymer content for pendulum bending

The image destruction the samples subjected to the load above the limit of fatigue strength did not resembles the image of the destruction of metal samples (Fig. 7). The samples were not undergoing completely destroyed, as in the case of steel. The outer layers were destroyed and shifted deep into material.

a) b)

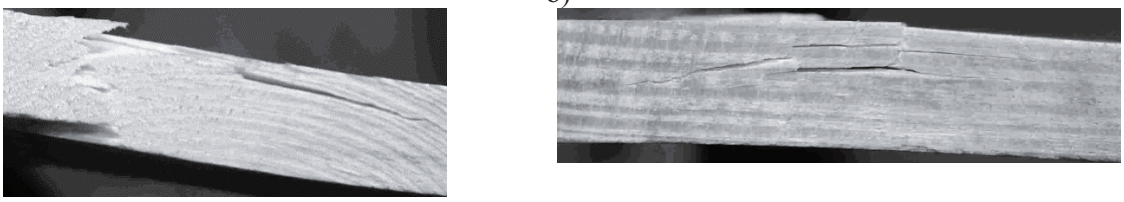

Fig. 7. The image of damaged of wood – PMM composite samples after the fatigue process: natural wood, b) modified wood

The beginning of the destruction of natural wood samples was initiated at the base of the notch, the site of the largest concentration of stresses. The samples were fastened by means of overlays. The natural wood is soft material. The pressure of overlays caused the preliminary stresses in the material sample, which are added together with the set points stress.

The fatigue destruction of modified wood sample was originated at the place of smallest cross-section in the middle part of the sample. The strengthened polymer of material has demonstrated greater resistance to changing load. This material is hard, homogeneous and initial stresses in the sample holder involved were such as small that they had no influence on the forced stress. The fatigue strength of the tested materials was determined using the method of Wohler. The method consists in periodically changing load with a constant amplitude.

The number of stress cycles is defined as the beginning of the uprising fatigue breakthrough of samples. On this basis, the graph was plotted in semi-logarithmic the coordinate system. Fig. 5 and 6 show the results of the test fatigue strength. The biggest strength of pendulum bending showed

the samples of the wood – PMMA composite with the highest polymer content. Studies showed that the increase of the polymer content in the composite increases the fatigue strength limit.

The permanent connection the molecules of the synthetic polymer with the structural components shall of wood strengthens the structure of the polymer. Particularly the adhesion forces of polymer increases and the components of the wood. Wohler curves of polymethyl methacrylate show no permanent of fatigue strength. Means that such materials are characterized by a fatigue strength at a predetermined number of cycles. Probably the excessive amount of polymer while completing the total pore volume may cause decreased of fatigue strength.

Basically, the fatigue strength determines the amount of copolymer which formed by the polymerization reaction. The rest of polymer fills the free wood pores and creates a so-called homopolymer structure. Excess the free unbound homopolymer with wood structure, exhibiting a high fragility, may in the course of cyclic loads lead to of increased vibrations of thermal particles. The mobility of the chains increases and this leads to mechanical – chemical destruction in the structure of the homopolymer.

The result is a reduction in the fatigue strength limit. The studies performed on creep of natural wood K0.0 and modified wood K0.56 were to determine the effect of surficial modification the pine wood of creep. Attempts were carried out on 6-position creep – testing machine [3].

The process of creep tested materials is divided into two intervals: the first interval corresponds to the short duration of creep – sampling time initially to 240 s was measured every 1 sec, then from 5 min to 360 min every 1 min, the second interval of creep corresponds to long-lasting of creep – sampling time of 360-30240 min was measured every 30 min.

Deformations were measured along the direction of fibres (ε_3) and in the radial direction (ε_1) using the strain rosettes glued on the samples. Influence of the time on the limiting stress specified during the creep test. The samples were subjected to a constant stress of 30% of the tensile strength: K0.0 – 30 MPa and K0.56 – 55 MPa [3]. This ensures the creep with descending gradients in time and the linearly resilient of range. Creep tests were carried out under isothermal conditions at a temperature of 291 K.

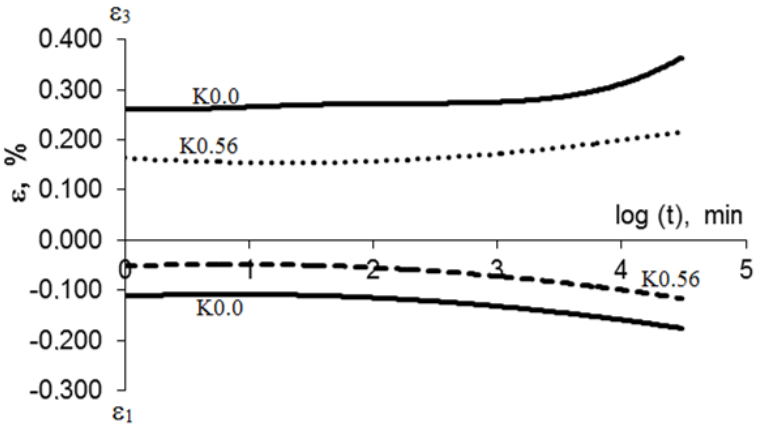

Fig. 8. The deformation curves ε at the time t the process of creep natural K0.0 and modified K0.56 wood in the system semi-logarithmic

Figure 8 are showed the results of creep samples made from the K0.0 and K0.56. The cylindrical samples of natural and modified wood were subjected stretched along the fibres.

The polymer contained in the wood significantly reduces the deformation in the longitudinal and the transverse fibres. If the wood pores are filled a polymer, the material forms a hard and the compact structure. Therefore, the ability of a material to deformation reduces at a constant load, temperature and humidity. The composite K0.56, which is long lasting, loaded deformed to a much lesser extent than natural wood. This is a very big advantage for the material, which can be applied for marine structures.

6. Conclusions

The research allowed defining the fatigue strength for the bending pendulum the natural and modified methyl methacrylate pine. The modification of wood PMM very much strengthens the wood structure by which the fatigue strength limit of the modified wood is two times higher than the natural wood ($Z_{goM} \approx 80\,\text{MPa}$, $Z_{goN} \approx 40\,\text{MPa}$).

This is caused to the compact and hard structure exhibiting a high resistance to dynamic loads. These are evidenced the images of destruction the samples resembling more homogeneous material than heterogeneous material.

Rheological studies have shown that the polymer content in the wood decreases almost twice the deformation in the longitudinal and transverse to the fibres. The structure of the modified wood is hard and compact, and therefore significantly lowered ability of the material to deformation. The modified wood is deformed to a much lesser extent than the natural wood. This is a big advantage of the material in the case of using it for marine structures exposed to marine environment.

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