BUILDING STRUCTURES, BUILDINGS AND CONSTRUCTIONS

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Lipetsk State Technical University
D. Sc. in Engineering, Prof. of Building Materials Department
B. A. Bondarev
Russia, Lipetsk

Kursk State Technical University
Ph. D. in Engineering, Assoc. Prof. of Department of Industrial and Civil Engineering
S. V. Povetkin
Russia, Kursk, tel.: +7(910)-317-18-11; e-mail: carese@yandex.ru

B. A. Bondarev, S. V. Povetkin

FLEXURAL FATIGUE OF LAMINATED WOOD

Problem statement. Local damage accumulation in goods and construction elements ultimately leading to a failure occurs due to fluctuating load effect.

Results and conclusions. The results of the analysis of the experimentally obtained analytical dependences of strength characteristics and resistance to cracks of profiled laminated wood during bending in products and designs are presented. This products and designs operate under static and cyclic loading. Stresses under which cracks form in pilot samples are established from the results, as well as maximum permissible lengths of cracks for static and cyclic load. Effect of natural and technological defects of laminated wood is taken into account. Recommendations on application of laminated wood in products and designs which experience force cyclic loading under operation are given.

Keywords: laminated wood, cyclic loading, material fatigue and endurance, natural and technological defects of wood.

Introduction

Since the production of wood laminate elements and goods is growing, their field of application is rapidly expanding. In many cases laminated wood endurance is determined not only by static but also dynamic force resistance such as wind, crane, transport and reassembling. Local damage accumulation in goods and construction elements ultimately leading to a failure occurs due to fluctuating load effect.

Such a process is called material fatigue and the ability to take repeated loads is its endurance.

Flexural fatigue of laminated wood is governed by resistance of layers which a laminated wood stock is made of to operation effects and by laminated junctures stability. As this takes place, any fiber bending results in lower external action resistance. Fibre disorientation relates to knobs, cracks, cross fibre and other defects of wood.

In order to acquire information on flexural fatigue of laminated wood, it is essential to gain reliable data on how laminated wood stretches and compresses bent under flexural loading, since this very kind of stressed state is most frequently found during operation.

The research is aimed at investigating what happens to sorted laminated wood when bent under the effect of long-term cycling load in a wide range of loading cycle asymmetry value.

Owing to various research undertaken by different authors [1, 2], it may be considered proved that for a metal, concrete or wooden construction relationship σ-LgN in absolute endurance is a straight line with the ordinate equal to the fatigue limit. Generally, fatigue process can be divided into three stages: local plastic deformations, formation of microcracks, their development and transformation to macro destruction. In the area of low-cycle fatigue plastic deformations develop spontaneously after several loading cycles. Fatigue limit area exhibits active changes in material construction structure when microcracks start to develop intensely. The increase of cracks leads to construction failure. If loaded below endurance limit in a product material, no changes occur and if there are any, they do not cause macroscopic destruction.

Endurance of glued-laminated wood is influenced by different factors such as:

- loading level $\sigma_{max}/R_{вр}$, where $R_{вр}$ is the temporary resistance, σ_{max} is the maximum stress occurring during fatigue stress process.;
- asymmetry coefficient $\rho = \sigma_{min}/\sigma_{max}$, where σ_{min} is the minimum stress occurring in the construction material during cycling;
- stress appliance frequency ω;

- stress concentration;
- wood breed;
- presence of natural and technological defects;
- temperature and humidity conditions of operation.

Depending on product material properties, this or that factor influences in various degrees. However, there are general laws of change in building materials endurance in case of variations of any of the above factors.

1. Experimental research

Laminated wood products used for experimental research were made of deal boards on mass production glue in accordance with all production rules. Sawn timber was selected in accordance with GOST (State Standard) 8486-86. Sawn timber of I, II and III grades were used for test models. Laminate wood elements sizes were 120×120×2000 mm. The tests were performed using a two-point loading scheme with concentrated effort at 3/8 span from a support.

In order to determine initial mechanical characteristics of laminated wood during the bending, samples were tested to destruction under momentary static loading. The results of short-term tests on laminated elements from wood of I, II and III grade and data for mechanical static conversion are in Table 1.

Table 1

Short-term tests on bending wood elements

Wood grade	Element specification	Ultimate strength R_{bp}, *MPa*	Statistical processing			
			$\bar{M}_R$, MPa	$\bar{S}_R$, MPa	*γ*, %	*P*, %
I	1K-1…6K-1	52.997…62.856	57.322	4.311	7.521	3.070
II	1K-2…7K-2	41.509…53.253	47.400	4.895	10.326	3.903
III	1K-3…9K-3	33.000…43.115	36.760	3.544	9.641	3.213

In order to determine modulus of elasticity and rigidity during static bending, a general formula for movement was applied.

$$\Delta = \int_0^l \frac{\bar{M} M_P d_x}{EJ} + \mu \int_0^l \frac{\bar{Q} Q_P d_x}{GF} + \int_0^l \frac{\bar{N} N_P d_x}{FE}\,, \tag{1}$$

where *E* is modulus of elasticity; *G* is rigidity modulus; *J* is moment of samples cut inertia, *F* is elements area of section; μ is coefficient depending on a form of section.

Bendings in the middle of a span *fC* and in places of load application *fM* were obtained with the formula (1). Integrals were calculated by the rules of multiplication of epures. As a result of calculation, we get the following analytical expressions:

$$f_C = \frac{39 \cdot PL_P^3}{2048 \cdot EJ} + \frac{9 \cdot PL_P}{40 \cdot GF}, \tag{2}$$

$$f_M = \frac{9 \cdot PL_P^3}{512 \cdot EJ} + \frac{9 \cdot PL_P}{40 \cdot GF}. \tag{3}$$

Experimental values for bendings during short-term tests on laminated elements from wood of I, II and III grade are in Table 2.

Table 2

Bendings of samples under short-term static loading

Loading value, kN	Sawn timber grade					
	I		II		III	
	f_C, mm	f_M, mm	f_C, mm	f_M, mm	f_C, mm	f_M, mm
5.00	2.61	2.43	2.87	2.63	3.04	2.79
10.00	5.22	4.84	5.73	5.25	6.08	5.57
15.00	7.84	7.28	8.62	7.88	9.15	8.38
20.00	10.52	9.73	11.50	10.54	12.27	11.26
25.00	13.15	12.16	14.45	13.21	15.98	14.55
30.00	15.84	14.61	17.38	15.90	21.10	18.85
35.00	18.57	17.10	21.34	19.37	-	-
40.00	21.36	19.73	26.70	24.00	-	-
45.00	26.90	24.85	-	-	-	-
50.00	32.60	30.00	-	-	-	-

Thus, with the help of formulas (2) and (3) actual modulus of elasticity and modulus of rigidity for samples were found. The mean value for E and G for bending elements from laminated wood of I, II and III grades are given in Table 3.

Table 3

Mean values of sample modulus of elasticity
and modulus of rigidity during the static bending under short-term loading

Elastic responses	Sawn timber grade		
	I	II	III
Modulus of elasticity E, MPa	12986	10364	9637
Modulus of rigidity G, MPa	541	535	563

While relative sizes of wood defects increase, modulus of elasticity during the static bending decreases due to loosening of laminated element working section. Laminated wood modulus of rigidity value during bending depends on type and size of defects and also on their location relative to plane of shear. Knobs crossing the plane of shear act as pegs increasing the modulus of rigidity, while presence of cracks or fibre bendings on plane of shear decreases modulus of rigidity G.

Destruction of laminated elements under short-term loading according to the accepted scheme was caused by tear of wood strained fibre in the middle of the span.

Elements made from low-grade wood failed in places of defects in tension regions of cross-sections. After end fibres tore, process of destruction rapidly spread through cross-sectional height of a bending element until load-carrying capacity of the construction was lost.

A fatigue test was carried out in order to determine elastic responses of graded laminated wood during bending.

No fewer than two sample series were tested at certain value of coefficient of loading cycle asymmetry for each single type of sawn timber Fatigue tests results are given in Table 4.

Failure of an element occurred at high levels of tension $\sigma_{max}/R_{вр}$ = (0.75…0.90) due to the rupture of three or four layers in tension region of a bent sample. The high loading level was, the fewer cycles an element endured before its load-carrying capacity was lost. During fatigue tests rapid appearance and development of faults resulting in failure of a stretched layer or two was accepted as a failure criterion.

This was accompanied by a sharp increase in deformations and changes in test mode due to a lessening of the rigidity of an element. At medium loading levels $\sigma_{max}/R_{вp} = (0.60\ldots0.80)$ destruction occurred at a number of cycles of $N_p \geq (10^4\ldots10^6)$.

Table 4

Results of laminated wood elements fatigue tests

Element specification	ρ	$\sigma_{max}/R_{вp}$	N_p, centner	LgN_p	Statistical processing		
					Average value LgN_p	Quality of standard deviation	Variation coefficient, %
Laminated wood of I grade							
7B-1	0.30	0.7	216200	5.335	5.040	0.105	6.433
8B-1	0.30	0.7	123470	5.092			
9B-1	0.30	0.7	49300	4.693			
10B-1	0.30	0.8	37890	4.579	3.921	0.398	16.083
11B-1	0.30	0.8	7300	3.863			
12B-1	0.30	0.8	2095	3.321			
13B-1	0.30	0.9	1090	3.037	2.634	0.266	19.578
14B-1	0.30	0.9	343	2.535			
15B-1	0.30	0.9	213	2.328			
38B-1	0.80	0.9	163000	5.212	4.472	0.548	16.544
39B-1	0.80	0.9	5400	3.732			
Laminated wood of II grade							
3B-2	0.30	0.5	2227600	6.348	6.278	0.005	1.105
4B-2	0.30	0.6	1618000	6.209			
5B-2	0.30	0.6	161300	5.208	5.097	0.012	2.166
6B-2	0.30	0.6	97000	4.987			

End of Table 4

Element specification	ρ	$\sigma_{max}/R_{вр}$	N_p, centner	LgN_p	Statistical processing		
					Average value LgN_p	Quality of standard deviation	Variation coefficient, %
7B-2					3.780	0.134	9.671
8B-2	0.30	0.7	2600	3.415			
9B-2	0.30	0.7	1100	3.041	2.609	0.187	16.582
10B-2	0.30	0.8	150	2.176			
15B-2	0.80	0.9	209800	5.322	4.590	0.536	15.956
16B-2	0.80	0.9	7200	3.857			
Laminated wood of III grade							
5B-3	0.30	0.7	183700	5.264	5.146	0.014	2.301
6B-3	0.30	0.7	106500	5.027			
7B-3	0.30	0.8	63000	4.799	4.119	0.462	16.508
8B-3	0.30	0.8	2750	3.439			
9B-3	0.30	0.9	850	2.929	2.505	0.180	16.956
10B-3	0.30	0.9	120	2.079			
15B-3	0.80	0.9	215200	5.333	5.149	0.034	3.560
16B-3	0.80	0.9	92500	4.966			

Deformation process of the samples did not stop until the moment of their failure. At low loading levels not exceeding endurance limit deformation process of the samples died down with the lapse of time and further loading did not cause failure. After fatigue test data was processed, analytical expressions for endurance curve of bending elements of graded laminated wood were obtained. The calculation results are given in Table 5 and in the Figure.

According to the results of experimental investigation of laminated wood fatigue during bending, it was found that endurance limit increases when lumber grade in laminated wood decreases during basic loading cycle $N = (2\ldots5)\cdot10^6$. This may be accounted for by effort reallocation in relatively less loaded low-grade wood goods.

Table 5

Equations for endurance curve of bending elements of graded laminated wood

Laminated wood grade	ρ	Correlating equation type	Endurance coefficient
I	0.30	$\sigma_{max}/R_{\text{вр}} = 1.126-0.085\, LgN_p$	0.590
I	0.80	$\sigma_{max}/R_{\text{вр}} = 1.021-0.027\, LgN_p$	0.851
II	0.30	$\sigma_{max}/R_{\text{вр}} = 1.110-0.081\, LgN_p$	0.600
II	0.80	$\sigma_{max}/R_{\text{вр}} = 1.016-0.025\, LgN_p$	0.858
III	0.30	$\sigma_{max}/R_{\text{вр}} = 1.092-0.074\, LgN_p$	0.626
III	0.80	$\sigma_{max}/R_{\text{вр}} = 1.018-0.023\, LgN_p$	0.873

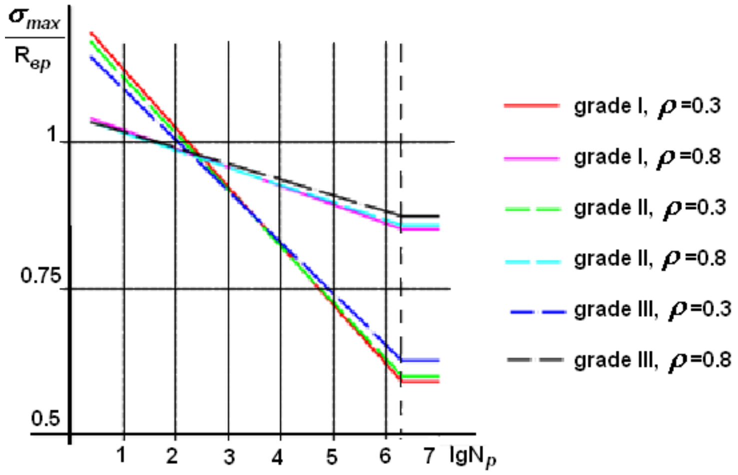

Fig. Endurance tests results

2. Analysis of sample failure patterns

During endurance tests failure of bending elements of graded laminated wood took place due to rupture of outer stretched fibres in places of location of largest faults. Crease formation in compressed zone of element section were not observed.

At loading levels which do not exceed the endurance limit cracks did not form during tests. If loading level exceed the endurance limit, occasional cracks appeared in construction material which was accompanied by an increase in deformations. A pattern of further development of cracks depended on a loading level and a crack size itself. At medium loading levels crack growth process proceeds gradually and may not lead to ultimate failure at base loading levels $N = (2\ldots5)\cdot10^6$ cycles. Further loading finally lead to complete failure. Process of vibrocreep in elements with cracks does not decay completely during endurance tests. At high loading levels a construction does not suffer a failure at a low amount of cycles due to intensive development of cracks formation process.

Wood building defects in a construction volume influence the size of a crack and its further development pattern. An increase in relative sizes of defects reduces the cyclic endurance of elements, that is to say an amount of cycles before the failure diminishes if such defects are located in most stressed layers. At the same time presence of faults in the other layers of a laminated element practically did not influence the operation of construction.

Analysis of patterns of cracks development on the surface of an element during fatigue tests on laminated wood helps to draw the following conclusions: 1)wood building effects prevent cracks from developing and reduce their growth speed; 2) glue lines and differences in mechanical characteristics of layers affect the direction of cracks development in a construction. A change in the direction of cracks development is conducive to a decrease in their growth intensity and a rise in cyclic endurance.

Failure of solid bodies is brought about by the development of their real faults. Taking into account current element cracks and also laminated wood natural defects is essential for durability and endurance assessment. At the initial time of loading some final perturbation is preset in the shape of initial cracks and structural faults of laminated wood.

The stress under which microcracks begin to increase abruptly and turn into macrocracks is bigger than one needed for macrocracks growth. The value of stresses necessary for macrocracks extension decreases as they grow. During the process of growth some cracks cease to develop running into various obstacles.

At some point growth process localizes: basically several cracks ahead of the rest in their development due to concentration of faults and material building defects in this particular area. Further development of main cracks eventually leads to a construction failure owing to a decrease in its load-carrying capacity. In contrast to first stages of appearance and growth of cracks developing for quite a long amount of time, the ultimate failure occurs rapidly and looks like a brittle fracture.

In real conditions processes of formation and development of cracks depend upon the material construction, external load application pattern and deformation speed. It was experimentally found that: 1) failure of bending laminated wood elements began with grade-forming wood building defects located in the most stressed stretched layer; 2) cracks development process is mostly influenced by sawn timber building defects, lamination of glued construction, possibility to recombine forces from loading speed; 3) relative endurance and construction vibrocreep increase as sawn-timber grades decrease; 4) cyclic endurance decreases as a grade rises to a greater extent than static endurance does.

Conclusions

A decrease in sawn-timber grades results in a decline in resistance of bending laminated wood constructions most stressed layers and enhances construction endurance at the expense of rising chances for force transfer.

Bending laminated wood constructions are classified as anisotropic viscoelastic solid bodies. In order to design strength and endurance it is necessary to know stress intensity factor and its limit value typical of given material and loading conditions. Stress intensity factor may be calculated for a specified direction of a crack growth in relation to fibre direction and laminated wood layers. Thus, application of stress intensity factor limit value only during the first approximation makes it possible to find the critical length of a crack at a specified reliability coefficient.

In real conditions cracks form in location of natural faults and laminated wood technological building defects. The results of the present study help to find stresses under which cracks appear in the samples and maximum permissible crack lengths for static and cyclic loading. The influence of natural faults and laminated wood building defects are taken into consideration as well.

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