Features of structural plywood operation in conditions of flat stress state

I N Boytemirova¹, F A Boytemirov², D D Koroteev³,⁴*

¹ Department of Civil Engineering, State University of Land Use Planning, Moscow, Russia
² Department of Metal and Wooden Structures, Moscow State University of Civil Engineering, Moscow, Russia
³ Department of Civil Engineering, Peoples Friendship University of Russia (RUDN University), Moscow, Russia
⁴ Department of Hydraulics, Moscow Automobile and Road Construction State Technical University (MADI), Moscow, Russia

*kooteev_dd@rudn.university

Abstract. The aim of our research work was to study operation features of plywood structures in flat stress state, which takes place in conditions of real operation of sheet structural materials. The method of study the materials in such conditions was developed. It includes determination of optimal form of specimens and equipment, providing tests of structural plywood under various ratio of values and signs of loads, made in mutually perpendicular directions. The research results of plywood operation from larch timber in conditions of biaxial tension and the assessment of its strength criterion under biaxial tension are shown in the research paper. The values of destructive stresses under various ratio of tension stress, directed along the main axes of elastic anisotropy of the tested material, were obtained. The experimental research results testify to possibility of using the test results of plywood specimens in conditions of biaxial tension and show that addition of extra stress almost does not reduce the strength limit of structural plywood.

Keywords: Structural plywood, flat stress state, biaxial tension, strength limit, sheet structural material.

1. Introduction

Strength and deformability research of sheet structural materials is connected with features of their operation in flat stress state, which takes place in various types of structures [1, 2]. For example, plywood parts of beams, frames, round and pointed arches, domes and other types of structures are exposed to different combinations of complex stress state [3, 4]. The wide range of research was carried out in direction of development of strength criterions due to appearance of new polymer materials, which have anisotropy of elastic and strength features as well as timber sheet materials [5, 6, 7].

Experimental tests results of the existing strength criterions under flat stress state, which were obtained for plywood structures, have a great practical importance, because such results can highlight in some ways problem of applicability of those criterions for sheet timber materials. In this connection, the research of strength features of plywood structures under flat stress state were carried out for possible assessment of plywood operation in real structures, it means under different combinations of flat stress state.

It should be noted that problems of plywood strength and deformability in flat stress state are described in technical literature insufficiently and there is not data about plywood strength from larch and birch timber under biaxial stress state [8, 9, 10]. Taking into account the above, the aim of our research work is to study operation features of plywood structures in flat stress state, which takes place in conditions of real operation of sheet structural materials.
There is a range of equipment nowadays, which can be used to load specimens from sheet materials in a plane of the sheet. The most famous equipment is equipment, which is used to test prism, cube or tubular specimens from polymer materials on biaxial tension and joint tension and compression. Disadvantage of such equipment is impossibility without complex reconfigure to change in a wide range the ratio values and the sign between pairwise loads during the tests of specimens [11, 12].

Taking into account the above, a new methodic of testing sheet timber materials was developed, including design of special equipment, which provides various ratio and sign of loads, made in mutually perpendicular directions.

2. Materials and methods of research
The plywood tests in conditions of flat stress state were carried out based on the developed methodic, which imitated the material work in building structures.

![Design of the specimen](image-url)

**Figure 1.** Design of the specimen.
The plate form of specimens was taken for the tests according to GOST 20800-75 [13]. The specimens had a cross form, sides of the cross were oriented on the main axis of the material anisotropy. The protruding parts of the specimens were designed to fix them from four sides in locks of the test equipment. Other part of specimens was plate with sizes of workspace 100x100 mm (figure 1).

The pointed sizes of workspace, taking into account conducted tests, sowed that bigger sizes of workspace almost do not influence on physical-mechanical properties of plywood. It means that the accepted sizes of workspace allow avoiding significant influence of stress concentration on the tests results.

Special equipment was developed to carry out the tests, which allowed testing sheet materials, in particular, plywood, under various ratio of loads values and various combinations of signs of those loads, covering all four quadrants of flat stress state.

The developed equipment consist of lever unit, made in form of swivel jointed with each other elements; side-locks and upright locks; brackets with shanks; working platforms with blades, elastic elements and centering units (figure 2).

![Figure 2. The equipment to test the plywood specimens:](image)

1 - swivel jointed elements; 2 - side-locks; 3 - upright locks; 4 – brackets; 5 - shanks; 6 - working platforms; 7 – blades; 8 - elastic elements; 9 - centering units.

Compressive and tension load, attached to upright locks, transfers to side-locks through the elements of lever unit, working platform, elastic elements, brackets and shanks. The stress of one sign (compressive and tension) acts on the specimens from all four sides under that scheme of loading. Acting of different signs stress in mutual perpendicular directions on the specimens is provided by the brackets.
removing. In the result, load from shanks transfers to nearest side-lock, causing stress in horizontal direction, which has different sign as compared with vertical direction.

The ratio change between loads values is carried out by the elastic elements. Their thickness may vary from 2 mm up to 20 mm. The load value, reduced by passing through the elastic element, is recorded by strain gage, which is glued on the element.

The developed equipment has centering units to avoid stability loss of specimens under compressive stress.

The testing load was attached to the specimens by 2 kN step under constant speed of loading 20±5 kN/min till the specimen destruction with keeping each step during 1 minute. Constant ratio between stresses was kept during the whole process of loading. It provided imitation of stress state on different stages of the test. The value of occurred cross stress, which satisfied each step of acting longitudinal stress, was determined by using strain gages, glued on the elastic element and connected to controlling devices. The elastic elements 5 mm and 8 mm provided ratio between cross and longitudinal stress equal to 1/6 and 1/3 respectively. Ratio between acting stresses equal to 3 and 6 was made in the equipment using those elastic elements by changing the specimen location on 90°. Graphs of the elastic elements with thickness 5 mm and 8 mm were made using the average values under ripple loading of each of them.

Possible changes of ratio between the stress directions was controlled by measuring deformations by using strain gages.

3. Results and discussion

The test results of plywood from larch timber under flat stress state (biaxial tension) are shown in table 1.

| Number of specimens | $K=\sigma_2/\sigma_1$ | $\sigma_1$, MPa | $\sigma_2$, MPa |
|---------------------|----------------------|----------------|----------------|
| 1                   | 1/6                  | 41.7           | 6.95           |
| 2                   | 1/6                  | 39.7           | 6.6            |
| 3                   | 1/6                  | 43.5           | 7.25           |
| 4                   | 1/3                  | 41.9           | 14             |
| 5                   | 1/3                  | 50.0           | 16.7           |
| 6                   | 1/3                  | 47.6           | 15.9           |
| 7                   | 3                    | 14.7           | 44.1           |
| 8                   | 3                    | 11.7           | 35.1           |
| 9                   | 3                    | 13.5           | 40.5           |
| 10                  | 6                    | 5.9            | 35.4           |
| 11                  | 6                    | 6.7            | 40.2           |
| 12                  | 6                    | 5.4            | 32.4           |

Three specimens were tested for each value of ratio $K=\sigma_2/\sigma_1$, where $\sigma_1$ and $\sigma_2$ – values of tension stresses along and across fibres of the plywood external layers. Special case of flat stress state when $K=0$ and $K=\infty$ was obtained under directions of stress along one of the main axes of elastic anisotropy.

Visual observation identified that the main type of destruction was destruction under angle of 45° to the main axes of the material anisotropy. In most case the destruction line went through veneer and had broken characteristic, stipulated by presence of defects in adjacent area (figure 3).

It is necessary to have experimental data about the strength limits under shift for areas, which are bended to direction of the external layers veneer under angle of 45° ($\tau_{45}$ and $\tau_{-45}$) to use the strength criterions of anisotropic materials. Such data was obtained by testing rhombic specimens under standard method of determination of temporary resistance to shift [14, 15].
Figure 3. Picture of the specimen destruction.

The average arithmetic values of the strength limits of plywood and statistical data of the test results processing (the average quadratic deviation $V$, the average error of the average arithmetic $m$, the strength parameter $P$, number of specimens $n$) are shown in table 2.

Table 2. Values of the strength limits and the statistical processing results

| Type of stress state | The veneer direction of external layers | Data of statistical processing |
|----------------------|----------------------------------------|-------------------------------|
|                      |                                        | $M$, MPa | $\tau$, MPa | $V$, % | $m$, MPa | $P$, % | $n$ |
| Tension              | Along                                  | 40.8     | 8.02        | 19.67  | 1.11     | 2.72   | 58  |
|                      | Across                                 | 34.5     | 6.31        | 18.29  | 1.35     | 3.91   | 28  |
| Shift                | $45^0$                                 | 22.8     | 3.38        | 14.85  | 9.76     | 4.28   | 12  |
|                      | $135^0$                                | 23       | 3.1         | 13.44  | 8        | 3.47   | 15  |

As we can see in table 2, the strength parameter does not exceed 5%. It indicates possibility to use those characteristics as parameters of the strength criterions.

The average values of destructive stresses under various ratio of tension stress, directed along the main axes of elastic anisotropy of the tested material $\sigma_1$ and $\sigma_2$, determined using Malmeister criterion, are shown in table 3.

Table 3. The average values of destructive stresses

| $K=\sigma_2/\sigma_1$ | $\sigma_1$, MPa | $\sigma_2$, MPa |
|-----------------------|-----------------|-----------------|
| 0                     | 40.8            | 0               |
| 1/6                   | 41.6            | 6.95            |
| 1/3                   | 46.5            | 15.5            |
| 3                     | 13.3            | 39.9            |
| 6                     | 6               | 36              |
| $\infty$              | 0               | 34.5            |
Data from table 3 shows that the material has explicit strength anisotropy. Ratio of the strength limit on tension along fibres of external layers to the strength limit across fibres is 1.19. If we put experimental data of the strength limits under biaxial stress state in flat $\sigma_1-\sigma_2$, we will see that they are situated outside rectangle, made by lines $\sigma_1=\sigma_1^p$ and $\sigma_2=\sigma_2^p$. That fact points out that theory of maximum perpendicular stresses and theory of maximum tangential stresses are hardly acceptable to describe the plywood strength under biaxial tension because contour of destruction according to these theories is rectangle, made by those lines and coordinate axes. It means that the use of those theories leads to understatement of values of destructive stresses to the side of the strength reserve.

Besides, the research of plywood operation in conditions of flat stress state shows that additional stress (under angle of $90^\circ$) across or along fibres of the external layers almost do not reduce the plywood strength limit, which obtained under stress, acting along or across fibres of the external layers.

4. Conclusion
The methodic of research of sheet structure materials in conditions of flat stress state was developed. The special equipment, providing various ratio and sign of loads, made in mutually perpendicular directions and covering all four quadrants of flat stress stat, was designed.

The research results of plywood operation from larch timber in conditions of biaxial tension are shown.

The values of destructive stresses under various ratio of tension stress, directed along the main axes of elastic anisotropy of the tested material, were obtained.

The research results show that the use of theory of maximum perpendicular stresses and theory of maximum tangential stresses leads to understatement of values of destructive stresses to the side of the strength reserve.

5. Acknowledgment
This paper is financially supported by the Ministry of Education and Science of the Russian Federation on the program to improve the competitiveness of Peoples' Friendship University of Russia (RUDN University) among the world's leading research and education centers in the 2016-2020.

6. References
[1] Wang P, Ge P, Bi W, Ge M and Li L 2018 The interaction of periodically distributed parallel cracks in anisotropic materials subjected to concentrated loads Engineering Fracture Mechanics 199 131-142
[2] Shiah Y C, Hwu C and Yao J J 2019 Boundary element analysis of the stress intensity factors of plane interface cracks between dissimilarly adjoined anisotropic materials Engineering Analysis with Boundary Elements 106 68-74
[3] Asdrubali F, Ferracuti B, Lombardi L, Guattari C, Evangelisti L and Grazieschi G 2017 A review of structural, thermo-physical, acoustical, and environmental properties of wooden materials for building applications Building and Environment 114 307-332
[4] Cheung K C 2015 Wooden Structures. Reference Module in Materials Science and Materials Engineering (USA: Western Wood Products Association).
[5] Bekhta P, Hiziroglu S and Shepelyuk O (2009) Properties of plywood manufactured from compressed veneer as building material Materials & Design 30(4) 947-953
[6] Demirkir C, Özsahin S, Aydin I and Colakoglu G 2013 Optimization of some panel manufacturing parameters for the best bonding strength of plywood International Journal of Adhesion and Adhesives 46 14-20
[7] Kim J, Park D, Lee C, Park K and Lee J 2015 Effects of cryogenic thermal cycle and immersion on the mechanical characteristics of phenol-resin bonded plywood Cryogenics 72(1) 90-102
[8] Custodio J, Broughton J and Cruz H 2009 A review of factors influencing the durability of structural bonded timber joints International Journal of Adhesion and Adhesives 29(2) 173-185.
[9] Li W, Zhang Z, Zhou G, Leng W and Mei C 2020 Understanding the interaction between bonding strength and strain distribution of plywood International Journal of Adhesion and Adhesives 98 102506

[10] De Windt I, Li W, Van den Bulcke J and Van Acker J 2018 Classification of uncoated plywood based on moisture dynamics Construction and Building Materials 158 814-822

[11] GOST 9624-2009 Laminated glued wood. Method for determination of shear strength (Moscow: Standardinform) URL: http://docs.cntd.ru/document/1200077907

[12] Koroteev D D, Boytemirov F A 2019 Analysis of Physical-Mechanical Characteristics and Advantages of Bakelite Plywood as Constructional Material Journal of Mechanics of Continua and Mathematical Sciences Special Issue-1 146-154

[13] GOST 20800-75 Rotary cut veneer. Test methods (Moscow: Standardinform) URL: http://docs.cntd.ru/document/1200017738

[14] GOST 3916.1-2018 Plywood for general use with outer layers of deciduous veneer. Specifications (Moscow: Standardinform) URL: http://docs.cntd.ru/document/1200159718

[15] SP 64.13330.2017 Timber structures (Moscow: Standardinform) URL: http://docs.cntd.ru/document/456082589