Load-carrying capacity of bolted joints of timber structures under static loading

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Abstract. The paper is devoted to the study of the single loads effect on the load-carrying capacity and deformability of bolted joints of wooden structures. The introduction substantiates the relevance of the topic, gives a general description of the work, its scientific novelty and practical value. The authors propose an experimental technique for determining the load-carrying capacity of bolted joints when separating the deformation of the dowel hole and that of tensile strain of bolts. The operation of such joints was experimentally and theoretically investigated. The study resulted in statistical confirmation of satisfactory convergence between the theoretical data obtained by the proposed method and the experimental data of the authors, as well as the recommendations on practical application of the suggested calculation method were developed. The deformations of the bolt and the wood were experimentally separated, the diagrams of the deformation of the stretched zone of the bolt were made, and the percentage ratio of the bolt deformations to the total deformations of the entire joint was calculated. To describe the process of the bolt joint deformation due to the action of single static loads, it is recommended to use a hyperbolic dependence, which well reflects the relationship between the load-strain values \( (F-\Delta) \). A new method is proposed for calculating the bearing capacity of bolted joints, which is based on the use of the initial modulus of strain capacity \( E_0 \) and the strain capacity coefficient of the joint \( \beta \). According to this technique, the load-carrying capacity of bolted joints with various geometric characteristics was calculated. The ratio of theoretical values of load-carrying capacity to the experimental values by, on average, 30% showed a greater convergence when compared to the load-carrying capacity calculated according to the current regulatory documents.

1. Introduction

One of the most important areas of scientific and technological progress in construction is to ensure the operation of building structures in the conditions as close as possible to the real ones. In this regard, the issues of improving the calculations and design of building elements and structures are becoming increasingly important [1-16]. Of great importance are the studies of the strength and deformation characteristics of the dowel-type joints of timber elements. Steel cylindrical dowels (including nails and bolts) are widely used in the joints of modern timber structures, in knots and butt joints of multi-spanning trusses, in rigid frame joints, in non-cut beams of wooden floor slabs, etc. At the same time, the joints under high loads are designed as multi-dowelled, which allows their designing in different options. Due to this, there is a practical need to optimize such joints.
The methods for calculating the load-carrying capacity of dowel joints of timber structures are constantly being improved, but the existing calculation methods, recommended by the current design standards [17], do not allow to sufficiently take into account the numerous factors influencing the nature of the stress-strain state of the elements leading to frequent material overruns and high complexity of manufacturing joints, and sometimes lack of structures reliability. Therefore, it is of increasing practical importance to study the development of the deformable state and determine the load-carrying capacity of the dowel joints of timber structures, as well as to optimize such joints, to establish the operating features and develop a calculation method that would most fully use the mechanical characteristics of materials for connections.

The ultimate goal of this work is to determine the actual load-carrying capacity of the joints of dowel-type timber structures and to develop a method for their calculating, as well as to compare them with the current design standards and the methods proposed by the authors [21].

2. Methods

2.1 Arch Survey Results.

To establish the effect of single loads on the operation of bolted joints of timber structures. To develop a method for calculating the bolted joints of timber structures according to their load-carrying capacity, depending on the ultimate deformation capacity and characteristics of the strain joint capacity.

2.2 Design, materials and features of manufacturing prototypes.

In order to achieve this task, the joints were manufactured to study the operation of bolted joints under the action of single loads in the research laboratory. All prototypes were made in accordance with the guidelines for testing timber joints [11, 18-20]. The specimens were symmetrical nailed and bolted joints of 260 mm high timber elements.

Pinewood with 1-5 mm wide annual layers, without destructive defects and decay, was selected for the manufacture of timber joint elements of all series. To achieve less dispersion of the test results, every three twin specimens were made with the same composition of timber elements, i.e. all the left elements were made from the same lumber, the middle ones from the second, and the right ones from the third. In this way, in each individual joint, the elements were made of the same lumber. Testing of the samples was carried out at the pine wood moisture W = 12%. Nomenclature of the prototypes are given in Table 1.

| Code connection | Number cuts | Dimensions, mm | Number samples | Bolt diameter, mm | Number bolts |
|-----------------|-------------|----------------|----------------|------------------|--------------|
| 3CB1            | 30 35       | 6 360          | 6              | 6.0              | 4            |
| 3CB2            | 35 35       | 6              | 6              | 6.0              | 4            |
| 3CB3            | 40 35       | 3              | 6              | 6.0              | 4            |
| 3CB4            | 30 35       | 6              | 8.0            | 3                |
| 3CB5            | 35 35       | 6              | 8.0            | 3                |
| 3CB6            | 40 35       | 3              | 8.0            | 3                |
| 3CB7            | 35 35       | 3              | 6.0            | 3                |
| 3CB8            | 20 25       | 3              | 6.0            | 3                |
| 3CB9            | 35 35       | 3              | 8.0            | 2                |
| 3CB10           | 25 30       | 3              | 8.0            | 2                |

Table 1. Nomenclature of bolted joints.
Samples must be tested in a condition, which is achieved as a result of the prolonged operation. The reliable operation of the joints, when determining their load-carrying capacity, must be guaranteed throughout the service life of the structures. Due to these requirements [18-20], the friction forces on the side faces of the connecting elements were eliminated. To do this, the 2 mm gaps were left between the junction planes of the elements.

The compressive strength of timber was determined by testing the prisms of 20x20x30 mm size including 24 pieces on the P-5 press (with a split price of 0.1 kN and a measurement range of 50 kN). The average calculated compression resistance of timber was 13.21 MPa. Mechanical properties of the bolts were determined by the test results on the P-50 bursting machine. Test preparation and experimental studies of the dowelled joints of timber elements were performed in the following sequence:

- manufacturing samples;
- fastening measuring instruments to the samples;
- installing the sample in the press;
- testing the joint with recording the necessary parameters at all the stages of loading.

To measure the deformation of the mutual displacement of the elements of the dowel joints of all series, we used clock indicators IC-10 with a split price of 0.01 mm, which were fixed on opposite sides of the joint. The indicators were fastened to the middle joint element using a bracket fixed with a couple of screws. To support the measuring instruments, we used add-on devices – the tables, which were screwed to the timber extreme elements (Figure 1).

![Figure 1. Research scheme of bolted joints (a) and general view of equipment (b): 1 – clock indicators of IC-10 type, 2 – tables for supporting measuring devices, 3 – strain gauges](image)

Measurements of the bolts tension strain were carried out using strain gauges with a 20 mm base, glued in the middle of each of the bolt sides (Figure 1). SIIT-3M tensometric measuring system was used to record gauges readings. The deformations were fixed twice at each stage: immediately after application of the load and at the end of its 5... 10 minutes exposure.

All the joints were tested under compression on P-5 machine (Figure 2). To ensure the necessary accuracy of the experiment, the press scale during the tests was 25 kN and did not exceed the expected amount of the destructive force by more than 1.5-2 times. The magnitude of the force increase rate under loading of all the samples is accepted to be not more than 0.08 of the destructive force $F_t$. Loading on the samples was applied in steps, the magnitude of the load on all samples was $\Delta F_t=1kN$. The indicators readouts were recorded at the beginning and end of each stage. Loading was carried out until the average joint shear deformation reached $\Delta u=2.0 \text{ mm}$ [21].
3. Results and discussion

It is proved that, when working on the shear along the fibres, the dowel joints of timber structures with a constant rate of stresses increase, due to the appearance of plastic deformations, the dependence “$F - \Delta$” for short-term loading is nonlinear from the beginning of the loading. As the load level increases, the curvature of the diagram “$F - \Delta$” increases.

The main characteristics of the deformation properties of the dowel joints are the following:

a) the initial modulus of strain capacity of the dowel joints

$$E_0 = \tan \alpha_0 = \frac{F}{\Delta_{pl}}; \quad (1)$$

b) section modulus of strain capacity of the dowel joints

$$E' = \tan \alpha' = \frac{F}{\Delta} = E_0 \cdot (1 + \beta \cdot F); \quad (2)$$

c) tangential modulus of strain capacity of the dowel joints

$$E = \tan \alpha = \frac{dF}{d\Delta}; \quad (3)$$

where $F$ – loading on the joint;
$\Delta_{pl}$ – plastic deformation;
$\Delta_{el}$ – elastic deformation;
$E'$ – section strain capacity modulus;
$E_0$ – initial strain capacity modulus;
$\beta$ – the coefficient of the joint strain capacity.

Figure 3 shows the physical values of these parameters.
The proposed method of calculating the load-carrying capacity of the centrally loaded bolted joints under the action of single loads is based on the use of the initial modulus of strain capacity and the coefficient of the joint strain capacity suggested by the authors on the basis of experimental and theoretical studies.

The calculated value of the load-carrying capacity of the bolted joints, provided that the maximum shear deformation can be represented as

$$T = \frac{E_0 \cdot \Delta}{1 - \Delta \cdot E_0 \cdot \beta},$$

where $T$ – the calculated value of the load-carrying capacity of the bolted joints; 
$\Delta$ – the ultimate deformation of the joint equal to 2.0 mm [21]; 
$E_0$ – initial strain capacity modulus; 
$\beta$ – the coefficient of the joint strain capacity.

To determine the values of the initial modulus of the joint strain capacity $E_0$ and the coefficient of the joint strain capacity $\beta$, the equation (4) is necessary to be stated as a straight line equation, which takes the form

$$E' = \frac{F}{\Delta} = a \cdot (1 + b \cdot T)$$

where $E'$ – section strain capacity modulus, 
from which the method of the least squares is used to determine the coefficients of regression equations $a$ and $b$ corresponding to the values $a = E_0$ and $\frac{b}{a} = \beta$.

To describe the process of deformation of the bolted dowel joints ($F - \Delta$), we will use a hyperbolic dependence, which can be described by linear functions, which simplify the processing of data and give a high convergence of experimental and correlation values.
In the statistical and mathematical study of the bolted joints operation, the main purpose is to test the possibility of describing the data regression with a straight line obtained experimentally (dependence $E - F$). In case of confirmation of the linear dependence $E' = a + b \cdot F$, from the equation of the obtained line we determine:

- $\beta$ – the coefficient of the joint strain capacity;
- $E_0$ – initial strain capacity modulus.

Figure 4 shows the dependence diagrams of the section strain capacity modulus and the loads for the 3CB2 and 3CB5 bolted joints.

As it can be seen from Figure 4 for the joints 3CB2 and 3CB5 in the dependencies $E - F$ without significant error, it can be assumed that the experimental points lie on or close enough to the correlation line. The basic parameters and statistics for all joints are given in Table 2.

| Connection number | Correlation equation |
|-------------------|----------------------|
| 3CB1              | $E' = 5.903 \cdot (1 - 0.461 \cdot F)$ |
| 3CB2              | $E' = 5.780 \cdot (1 - 0.415 \cdot F)$ |
| 3CB3              | $E' = 5.615 \cdot (1 - 0.383 \cdot F)$ |
| 3CB4              | $E' = 10.115 \cdot (1 - 0.328 \cdot F)$ |
| 3CB5              | $E' = 9.853 \cdot (1 - 0.305 \cdot F)$ |
| 3CB6              | $E' = 9.678 \cdot (1 - 0.260 \cdot F)$ |
| 3CB7              | $E' = 4.855 \cdot (1 - 0.385 \cdot F)$ |
| 3CB8              | $E' = 4.704 \cdot (1 - 0.342 \cdot F)$ |
| 3CB9              | $E' = 8.506 \cdot (1 - 0.298 \cdot F)$ |
| 3CB10             | $E' = 8.207 \cdot (1 - 0.275 \cdot F)$ |

Analyzing the statistics of correlation equations (Table 2), we can conclude that the dependencies $E - F$ without a large error can be considered linear, giving the opportunity to determine the initial modulus of joints strain capacity $E_0$ and the coefficient of the joints strain capacity $\beta$ (Table 3).
Table 3. Initial strain capacity modulus and the coefficient of the joints strain capacity

| Connection number | $E_0$, kN/mm | $\beta$ | $T_{exp}$, kN | $T$, kN | $\delta_a$, % | $T_{[21]}$, kN | $\delta_b$, % | $T_{Ecode}$, kN | $\delta_c$, % |
|-------------------|--------------|---------|---------------|---------|---------------|---------------|---------------|----------------|--------------|
| 3CB1              | 5.903        | 0.461   | 2.063         | 1.832   | 11.2          | 1.255         | 39.2          | 2.484          | -20.4        |
| 3CB2              | 5.780        | 0.415   | 2.125         | 1.994   | 6.2           | 1.353         | 36.3          | 2.484          | -16.9        |
| 3CB3              | 5.615        | 0.383   | 2.313         | 2.118   | 8.4           | 1.364         | 41.0          | 2.484          | -7.4         |
| 3CB4              | 10.115       | 0.328   | 3.083         | 2.649   | 14.1          | 2.015         | 34.6          | 3.076          | 0.2          |
| 3CB5              | 9.853        | 0.305   | 3.117         | 2.811   | 9.8           | 2.121         | 32.0          | 3.076          | 1.3          |
| 3CB6              | 9.678        | 0.260   | 3.541         | 3.209   | 9.4           | 2.227         | 37.1          | 3.076          | 13.1         |
| 3CB7              | 4.855        | 0.385   | 2.0           | 1.854   | 7.3           | 0.735         | 63.3          | 2.015          | -0.8         |
| 3CB8              | 4.704        | 0.342   | 1.333         | 1.205   | 9.6           | 0.46          | 65.5          | 1.545          | -21.0        |
| 3CB9              | 8.506        | 0.298   | 3.25          | 2.987   | 8.1           | 0.98          | 69.8          | 3.016          | 7.2          |
| 3CB10             | 8.207        | 0.275   | 3.0           | 2.695   | 10.1          | 0.76          | 74.7          | 2.887          | 3.8          |

The analysis data of the results of theoretical studies and their comparison with the experimental data and the values of the current regulatory documents are given in Table 4. As it can be seen from Table 4, for single bolted joints, the ratio of theoretical load-carrying capacity $T$ to the experimental $T_{exp}$ is within $0.86...0.94$, i.e. there is a discrepancy between the theoretical and the experimental values $\delta = 6.2...14.2\%$.

Table 4. Comparison of experimental and theoretical load-carrying capacity of centrally loaded bolted joints under the action of a single static load.

| Connection number | $E_0$, kN/mm | $\beta$ | $T_{exp}$, kN | $T$, kN | $\delta_a$, % | $T_{[21]}$, kN | $\delta_b$, % | $T_{Ecode}$, kN | $\delta_c$, % |
|-------------------|--------------|---------|---------------|---------|---------------|---------------|---------------|----------------|--------------|
| 1                 | 2            | 3       | 4             | 5       | 6             | 7             | 8             | 9              | 10           |
| 3CB1              | 5.903        | 0.461   | 2.063         | 1.832   | 11.2          | 1.255         | 39.2          | 2.484          | -20.4        |
| 3CB2              | 5.780        | 0.415   | 2.125         | 1.994   | 6.2           | 1.353         | 36.3          | 2.484          | -16.9        |
| 3CB3              | 5.615        | 0.383   | 2.313         | 2.118   | 8.4           | 1.364         | 41.0          | 2.484          | -7.4         |
| 3CB4              | 10.115       | 0.328   | 3.083         | 2.649   | 14.1          | 2.015         | 34.6          | 3.076          | 0.2          |
| 3CB5              | 9.853        | 0.305   | 3.117         | 2.811   | 9.8           | 2.121         | 32.0          | 3.076          | 1.3          |
| 3CB6              | 9.678        | 0.260   | 3.541         | 3.209   | 9.4           | 2.227         | 37.1          | 3.076          | 13.1         |
| 3CB7              | 4.855        | 0.385   | 2.0           | 1.854   | 7.3           | 0.735         | 63.3          | 2.015          | -0.8         |
| 3CB8              | 4.704        | 0.342   | 1.333         | 1.205   | 9.6           | 0.46          | 65.5          | 1.545          | -21.0        |
| 3CB9              | 8.506        | 0.298   | 3.25          | 2.987   | 8.1           | 0.98          | 69.8          | 3.016          | 7.2          |
| 3CB10             | 8.207        | 0.275   | 3.0           | 2.695   | 10.1          | 0.76          | 74.7          | 2.887          | 3.8          |

The ratio of the load-carrying capacity, calculated by the method [21], to the experimental one, with the variable thickness of the middle joint elements, is within $0.59...0.68$, i.e. the discrepancy between the theoretical norms and the experimental values is $\delta = 32.0...41.0\%$. To systematize the obtained data, the test results are summarized in Tables 5 and 6, where, depending on the ratio of $a/c$ and the bolt diameter, the characteristics of the initial modulus of strain capacity of the dowel joint and the coefficient of strain capacity are shown $\beta$. 


Table 5. The values $E_0$ and $\beta$ for the symmetrical double-shear bolted joints

| a/c | Bolt diameter, mm | $6.0$ (5.8) | $8.0$ (5.8) |
|-----|-------------------|-------------|-------------|
|     | $\beta$, kN$^{-1}$ | $E_0$, kN/mm | $\beta$, kN$^{-1}$ | $E_0$, kN/mm |
| 1.15| -0.383            | 5.615       | -0.260       | 9.678       |
| 1.0 | -0.415            | 5.780       | -0.305       | 9.853       |
| 0.85| -0.461            | 5.903       | -0.328       | 10.115      |

* - bolts strength grade is indicated in the parentheses

Table 6. The values for symmetrical single-shear bolted joints

| a/c | Bolt diameter, mm | $6.0$ (5.8) | $8.0$ (5.8) |
|-----|-------------------|-------------|-------------|
|     | $\beta$, kN$^{-1}$ | $E_0$, kN/mm | $\beta$, kN$^{-1}$ | $E_0$, kN/mm |
| 1.0 | -0.415            | 5.780       | -0.305       | 9.853       |
| 0.85| -0.461            | 5.903       | -0.328       | 10.115      |

* - bolts strength grade is indicated in the parentheses

To describe the deformation process of the bolted joint under a single load, it is recommended to use a hyperbolic dependence that well reflects the relationship between the values of $F$-$\Delta$.

4. Conclusions

A new method for calculating the load-carrying capacity of bolted joints is proposed, based on the use of the initial modulus of strain capacity $E_0$ and the coefficient of the joint strain capacity $\beta$. According to this method, the load-carrying capacity of the bolted dowel joints with different geometric characteristics was calculated. The ratio of the theoretical values of the load-carrying capacity to the experimental ones by, on average, 30% showed greater convergence compared to the load-carrying capacity calculated according to the current regulatory documents.

It is established that with the increase of the bolt diameter, the deformation component changes towards decreasing. For the bolts with a diameter of 6 mm, the deformation of the bolts is 53… 56% of the total marginal shear deformation, which is 2 mm, with a bolt diameter of 8 mm, the component of the bolt deformation is 31… 33%, when the formation of the plastic hinge did not occur, because normal stresses did not reach the conditional limit of the steel liquid properties.

The proposed method of calculating bolted joints allows obtaining savings of up to 40% and reducing the complexity of the joints manufacturing.

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