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Foschi's method of strain calculation of the metal plate connectors compared to program complex APM Wood

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ABSTRACT

Metal plate connectors (MPC) are used for attaching together different parts of wooden structures, especially truss joints. Plates have rectangular form, they usually are made out of steel and sometimes can be covered by protection layer, for example, by zinc. Teeth of the plate can have different shape, length and mutual position. In order to connect wooden bars, MPC are pressed symmetrically on both sides of the structure, that is why attached elements should have the same cross-sectional width. For better adjustment of the elements, their ends are usually polished. Compression is carried out with special equipment and can take place both at the plants and at the construction site. The simplest algorithm of strain calculation of the joints with MPC can described, as follows: the construction is computed by usual methods of structural mechanics (FEM, flexibility method, force method) assuming all the nodes connected with plates are absolutely rigid. Then, using obtained internal forces and reference data about loads, leading to destruction or pulling MPC out of wood (laboratory tests are made by the manufacturer), appropriate plates are chosen. One of the program complexes using this pattern is APM Wood, the part of computer-aided design software APM Civil Engineering. The disadvantage of this algorithm is that it does not consider uneven distribution of forces on the various teeth of a plate and deformations appearing in the plates themselves, which leads to considerable error in found internal forces and inaccurate selection of plates. The model proposed by Foschi [1] is free of these disadvantages and can be used to estimate deformations and forces in MPS's teeth. The paper gives an analysis of algorithm of calculation the nodes attached with metal plate connector and comparison to the program complex APM Wood. As an example, the problem of wooden bar fixed on both sides by MPC and under the influence of a force applied along the longitudinal axis is solved. As a result, it is concluded that consideration of plate and teeth flexibility in finite-element scheme is very essential for calculation accuracy, uneven stress distribution between the dowels has big influence on strain computation of the whole construction.

Contents

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1. Introduction

Metal plate connectors are widely used in modern construction. Their application is caused by relatively simple arrangement of joints in wooden structures, reducing the cost and installation time. MPC has higher strength properties than the compounds with nails and glue, and when used in trusses, allows constructing a roof of any architectural complexity. MPC strain calculation methods were considered in many articles, for example, in [2-11], including talking into account the deformability of connections. In [12] and [13] subgrade reactions for nodal connections on MPC were obtained and experimentally determined. Also in [13] nonlinear analysis of contact interaction of the tooth of the plate GNA 20 with wood. In [14] improvements of the Foschi’s model were proposed. Load-to-failure bending test of wood elements connected by metal plate connectors was described in [15]. Experimental investigations of stress-strain state in the tooth-wood contact zone were made in [16]. When calculating the nodal connections on MPC, anisotropy of wood is very important, that is the influence of the inclination of fibers on the mechanical properties of wood, which were considered, for example in [17]. In paper [18] connection of wooden elements using butt joint was described. Principles of manufacturing constructions on metal plate connectors were considered in [19]. In [20] and [21] recommendations for designing of structures on MPC are presented. Dependence of bearing capacity of the nodes with MPC on thickness and orientation of the plate was considered in [22]. In [23-25] behavior of plates under the high temperatures was described. Program complex APM Wood is the only one software system available on Russian market nowadays, that can design wooden constructions with MPC, but its strain calculation lacks the consideration of deformations in dowels and plate.

2. Method of calculation

Let us assume that it is required to calculate some wooden construction with nodes on MPC.

This construction is presented by finite element model, and we will consider the following types of elements:

- Beam element – standard finite element, modelling wooden bar of the truss. It has simple local stiffness matrix:

$$K = \begin{bmatrix} \frac{EA}{L} & 0 & 0 & -\frac{EA}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{EA}{L} & 0 & 0 & \frac{EA}{L} & 0 & 0 \\ 0 & -\frac{12EI}{L^3} & -\frac{6EI}{L^2} & 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{2EI}{L} & 0 & \frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} \quad (1)$$

- “Tooth” element – it models dowels of any plate, pressed into the wood. Each plate always has at least two “teeth”. Nodes of this element are located in geometrical center of the group of dowels that belong to one bar.

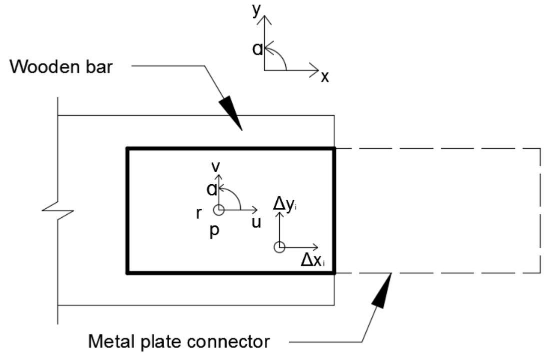

Figure1. “Tooth” element

Points p and r – nodes of the “tooth” element. Node p belongs to the plate, node r – to the wooden bar. Displacement vector of this element is given by:

$$u = \begin{bmatrix} U_p & V_p & \alpha_p & U_r & V_r & \alpha_r \end{bmatrix}^{\mathrm{T}} \quad (2)$$

As result of load’s influence on the construction the dowels deform. The projections of dowel’s deformation can be presents as follows:

$$\begin{aligned} \Delta_x &= q_x^{\mathrm{T}} u \\ \Delta_y &= q_y^{\mathrm{T}} u \end{aligned}, \text{ where:} \quad (3)$$

$$\begin{aligned} q_x &= \begin{bmatrix} 1 & 0 & -(y_i - y_p) & -1 & 0 & (y_i - y_r) \end{bmatrix}^{\mathrm{T}} \\ q_y &= \begin{bmatrix} 0 & 1 & (x_i - x_p) & 0 & -1 & -(x_i - x_r) \end{bmatrix}^{\mathrm{T}} \end{aligned} \quad (4)$$

Absolute deformation of any dowel and shear force in it are connected as follows [1]:

$$p(\Delta) = (p_0 + k_1\Delta)(1 - e^{(\frac{-k_0\Delta}{p_0})}), \quad (5)$$

where: Δ - dowel deformation, p_0, k_0, k_1 - parametres, depending on stiffness of the dowel and angle between fibres in bar and the main axis of the plate. This parametres can be estimated using following graph, obtained on the basis of experiment:

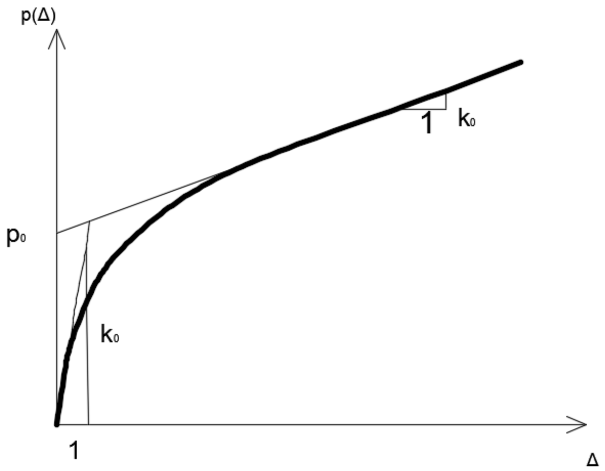

Figure2. Relation between dowel deformation and force

This curve varies depending on type of MCP, that is why in application tasks in order to obtain this diagram, available plates should be shear-tested.

Using principle of virtual displacements, following formula of “tooth” element’s local stiffness matrix can be obtained [1]:

$$\mathrm{K} = \iint\limits_{\mathrm{A}} \rho \frac{p(\Delta)}{\Delta}(q_x q_x^{\mathrm{T}} + q_y q_y^{\mathrm{T}})dA, \quad (6)$$

where ρ - dowel’s density distribution in plate’s area.

It’s difficult to obtain the analytical solution of this integral, although we can use numerical methods, for example Gauss-Legendre method [26, 27].

The main idea of this method is that the integrable region is divided into n intervals, that are not necessarily equal to one another (n can be chosen arbitrarily). And the integral is taken to be equal to the sum of the integrand function values at the nodes based on the weighting coefficients. The nodes (values of variables) are roots of n-degree Legendre polynomial, and weighting coefficients are defined using values of nodes and first derivative of the Legendre polynomial, that is:

$$\iint\limits_{A} f(x,y)dxdxy \approx \sum_{i=1}^{n}\sum_{j=1}^{n} c_i c_j f(x_i, y_j)\,, \tag{7}$$

where: $c_i = \dfrac{2}{(1-x_i^2)P_n^{'}(x_i)^2}$, $P_n^{'}$ - derivative of the Legendre polynomial.

There tables of weighting coefficients and roots of the Legendre polynomial, so there is no need to calculate it manually every time.

Relation between vector of nodal forces and nodal displacement vector is written in a standard way:

$$Ku = f \tag{8}$$

- Element “plate” – it is meant to connect two “teeth” with each other. In modelling of the “plate” it is assumed that two “teeth” are connected with each other by some small beams, we will call it elementary beams, which have ordinary stiffness properties and stiffness matrix of ordinary beams. The width of the cross section of the beam is equal to the plate’s thickness, usually 1-2 mm. Distance between teeth of the plate can be taken for the beam’s length L, although plastic deformation should be considered for better accuracy (then L is bigger than just distance between teeth)

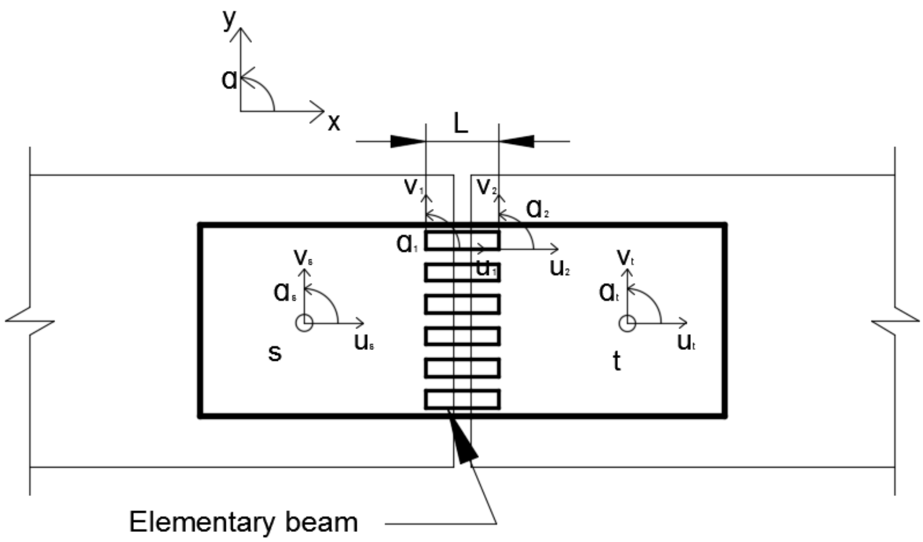

Figure3. “Plate” element

Vector of nodal forces and nodal displacement vector for each elementary beam are denoted as follows:

$$f_i = \begin{bmatrix} R_1 & H_1 & M_1 & R_2 & H_2 & M_2 \end{bmatrix}^{\mathrm{T}} \tag{9}$$

$$u_i = \begin{bmatrix} U_1 & V_1 & \alpha_1 & U_2 & V_2 & \alpha_2 \end{bmatrix}^{\mathrm{T}} \tag{10}$$

Vector of nodal forces and nodal displacement vector for “plate” element, similarly:

$$f = \begin{bmatrix} R_s & H_s & M_s & R_t & H_t & M_t \end{bmatrix}^{\mathrm{T}} \tag{11}$$

$$u = \begin{bmatrix} U_s & V_s & \alpha_s & U_t & V_t & \alpha_t \end{bmatrix}^{\mathrm{T}} \tag{12}$$

Displacement vector of each beam expressed by displacement vector of “plate” element.

$u_i = P_i u$, where:

$$\mathrm{P_i} = \begin{bmatrix} 1 & 0 & y_s - y_{1,i} & 0 & 0 & 0 \\ 0 & 1 & \mathrm{x_{1,i}} - x_s & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & y_t - y_{2,i} \\ 0 & 0 & 0 & 0 & 1 & x_{2,i} - x_t \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

Vectors of nodal forces are related as follows:

$$f = \sum_{i=1}^{n} P_i^T f_i \tag{14}$$

and besides, for each beam it can be written:

$$f_i = K_i u_i \tag{15}$$

Then stiffness matrix of the “plate” element is given by:

$$K = \sum_{i=1}^{n} P_i^T K_i P_i , \tag{16}$$

where:

K_i - stiffness matrix of elementary beam.

And relation between vector of nodal forces and displacement vector is given by standard expression:

$$Ku = f \tag{17}$$

Thereafter, global stiffness matrix is composed of local stiffness matrixes of separate elements, vector of external nodal forces is written and FEM system of equations is solved.

3. Strain calculation and comparison of results with software system

This algorithm considers deformations of every node of the construction and therefore it provides more accurate strain analysis. In order to demonstrate this, consider simple example: wooden bar fixed on both sides by metal plate connectors and under the influence of a force applied along the longitudinal axis. This example was selected to reduce to a minimum the use of calculations on a computer and to better demonstrate the advantages of this calculation method.

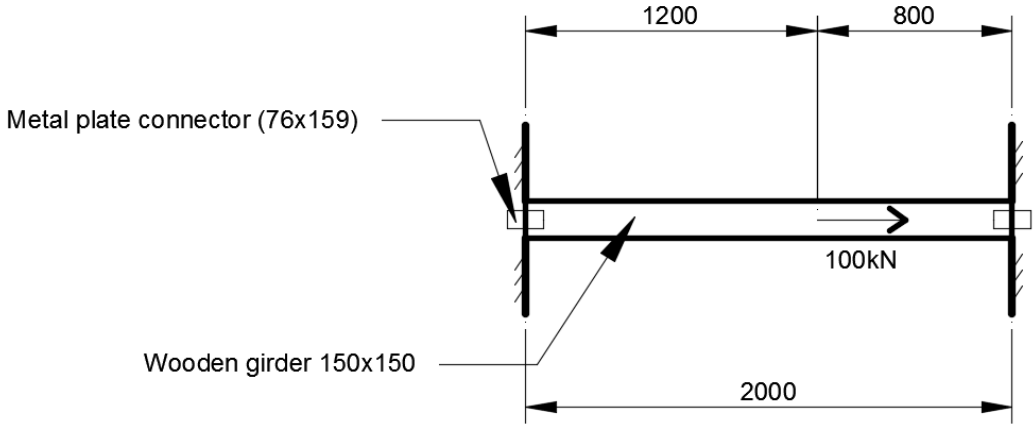

Figure4. Wooden bar under the load

FEM scheme:

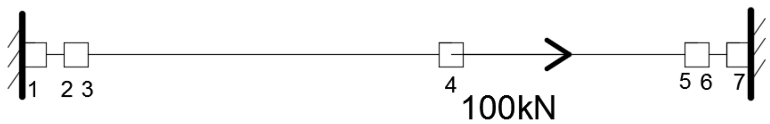

Figure5. Finite-element scheme

1-2, 6-7 – “plate” elements, 2-3, 5-6 –“tooth” elements, 3-4, 4-5 – beams.

The plate considered in this task has thickness of 1mm, length of dowels – 8mm, size – 76x159 mm. Such plates have designation GNA 20 and are manufactured, including in Russia, for example by company MiTek.

“Tooth” element:

$$\mathrm{K}_з = \iint_{\mathrm{A}} \rho \frac{p(\Delta)}{\Delta} (q_x q_x^{\mathrm{T}} + q_y q_y^{\mathrm{T}}) dA \tag{18}$$

Dowel's density distribution in plate's area ρ is equal to 0,0146 $\frac{dowel}{mm^2}$, because the whole plate has total 176 dowels and it's area is equal to 12084 mm^2

Since the problem is one-dimensional, then q_x and q_y will consist of only two elements:

$$q_x = \begin{bmatrix} 1 & -1 \end{bmatrix}^T \quad (19)$$

$$q_y = \begin{bmatrix} 0 & 0 \end{bmatrix}^T \quad (20)$$

Nodal displacement vector:

$$u_з = \begin{bmatrix} U_2 & U_3 \end{bmatrix}^T \quad (21)$$

Stiffness matrix is given by:

$$\mathrm{K}_з = \iint_A \rho \frac{p(\Delta)}{\Delta} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} dA \quad (22)$$

Deformation of one dowel:

$$\Delta = \sqrt{\Delta_x^2 + \Delta_y^2} \quad \Delta_x = q_x^T u_з \quad \Delta_y = 0 \quad (23)$$

Then:

$$\mathrm{K}_з = \iint_A \rho \frac{(p_0 + k_1\sqrt{(U_2-U_3)^2})(1-e^{\frac{-k_0\sqrt{(U_2-U_3)^2}}{p_0}})}{\sqrt{(U_2-U_3)^2}} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} dA = \frac{(p_0 + k_1\sqrt{(U_2-U_3)^2})(1-e^{\frac{-k_0\sqrt{(U_2-U_3)^2}}{p_0}})}{\sqrt{(U_2-U_3)^2}} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \rho A \quad (24)$$

Where: $p_0 = 150N$, $k_0 = 900\frac{N}{mm}$, $k_1 = 80\frac{N}{mm}$, these parameters were taken approximately equal to those which were obtained in [28]. In general case, they should be estimated from the experiment (fig. 2) [29, 30].

"Plate" element:

Siffness matrix of elementary beam:

$$K_i = \begin{bmatrix} \frac{E_{st}A_{eb}}{L_{eb}} & -\frac{E_{st}A_{eb}}{L_{eb}} \\ -\frac{E_{st}A_{eb}}{L_{eb}} & \frac{E_{st}A_{eb}}{L_{eb}} \end{bmatrix} \quad (25)$$

Where: E_{st} - steel elastic modulus (200000 MPa), A_{eb} - cross-sectional area of the elementary beam, L_{eb} - it's length, considered equal to the distance between the teeth (8 mm).

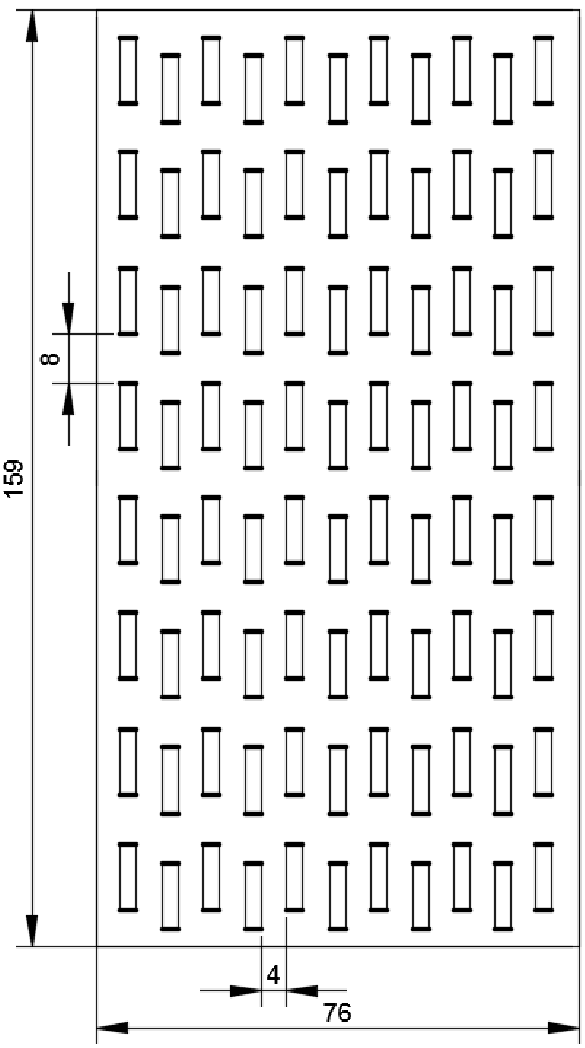

Figure6. Plate dimentions

$$P_i = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{26}$$

Then, in this case, the stiffness matrix of “plate” element is equal to the sum of the stiffness matrixes of elementary beams:

$$K = \sum_{i=1}^{n} P_i^T K_i P_i = \sum_{i=1}^{n} K_i \tag{27}$$

Formation of the global stiffness matrix and solving the system of equations of FEM $Ku = f$ were performed in program Maple:

> restart;

> $u1 := 0$

$$u1 := 0$$

> $u7 := 0$

$$u7 := 0$$

> $K1 := \frac{200 \cdot 76}{8 \cdot 10^{-3}}$

$$K1 := 1900000$$

> $K2 := \frac{5 \cdot 225 \cdot 12 \cdot 10^{2}}{3 \cdot 2}$

$$K2 := 225000$$

> $K3 := \frac{5 \cdot 225 \cdot 12 \cdot 10^{2}}{2 \cdot 2}$

$$K3 := 337500$$

> $K4 := \frac{76 \cdot 159}{1} \cdot 0.0146 \cdot \frac{\left(0.15 + 80\left(\sqrt{(u3-u2)^2}\right)\right)\left(1 - e^{-\frac{900\left(\sqrt{(u3-u2)^2}\right)}{0.15}}\right)}{\sqrt{(u3-u2)^2}}$

$$K4 := \frac{176.4264\left(0.15 + 80\sqrt{(u3-u2)^2}\right)\left(1 - e^{-6000.000000\sqrt{(u3-u2)^2}}\right)}{\sqrt{(u3-u2)^2}}$$

> $K5 := \frac{76 \cdot 159}{1} \cdot 0.0146 \cdot \frac{\left(0.15 + 80\left(\sqrt{(u6-u5)^2}\right)\right)\left(1 - e^{-\frac{900\left(\sqrt{(u6-u5)^2}\right)}{0.15}}\right)}{\sqrt{(u6-u5)^2}}$

$$K5 := \frac{176.4264\left(0.15 + 80\sqrt{(u6-u5)^2}\right)\left(1 - e^{-6000.000000\sqrt{(u6-u5)^2}}\right)}{\sqrt{(u6-u5)^2}}$$

> $sys := \{(K1 + K4)\cdot u2 - K4\cdot u3 = 0,\ -K4\cdot u2 + (K4 + K2)\cdot u3 - K2\cdot u4 = 0,\ -K2\cdot u3 + (K2 + K3)\cdot u4 - K3\cdot u5 = 100,\ -K3\cdot u4 + (K3 + K5)\cdot u5 - K5\cdot u6 = 0,\ -K5\cdot u5 + (K5 + K1)\cdot u6\}$

Figure7. Stiffness matrix formation using Maple

> $s := fsolve(sys)$

$$s := \{u2 = 0.00002605593580,\ u3 = 0.001658824097,\ u4 = 0.001878851999,\ u5 = 0.001729240971,\ u6 = 0.00002657564315\}$$

> $u2 := 0.00002605593580$

$$u2 := 0.00002605593580$$

> $f1 := K1 \cdot u2$

$$f1 := 49.50627802$$

> $u6 := 0.00002657564315$

$$u6 := 0.00002657564315$$

> $f2 := K1 \cdot u6$

$$f2 := 50.49372198$$

> $f1 + f2$

$$100.0000000$$

>

Figure8. Solution of FEM system of equasion using Maple

Epure of the longitudinal force N was drawn using obtained data:

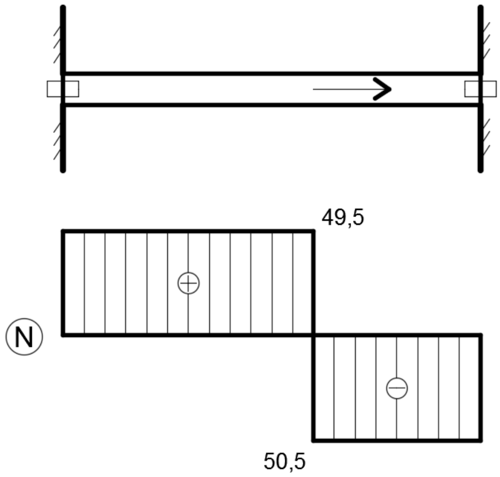

Figure9. Epure “N”

Then, we can solve the same problem using program APM Wood. The design procedure in this software is carried out the usual way like in other CAD programs. Scheme of the construction can be presented as follows:

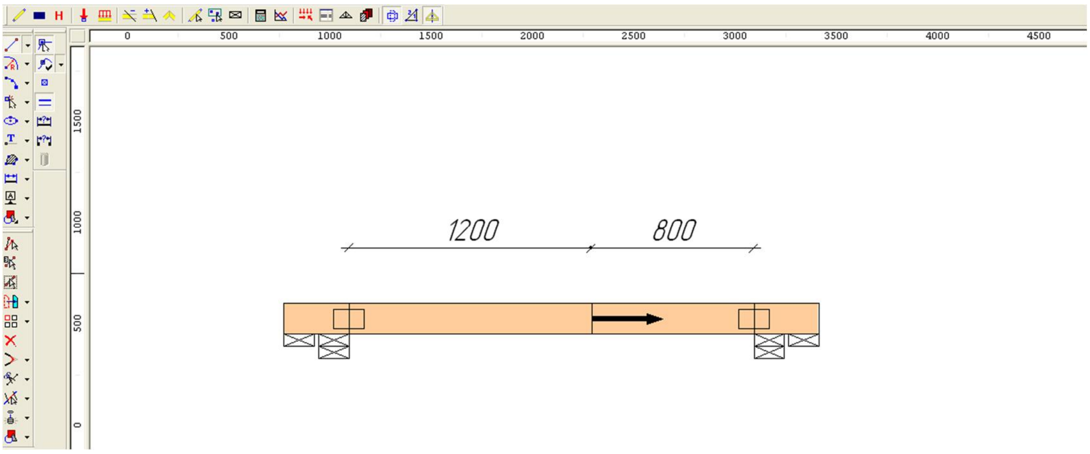

Figure10. Constuction scheme in APM Wood

The parameters of cross section and material:

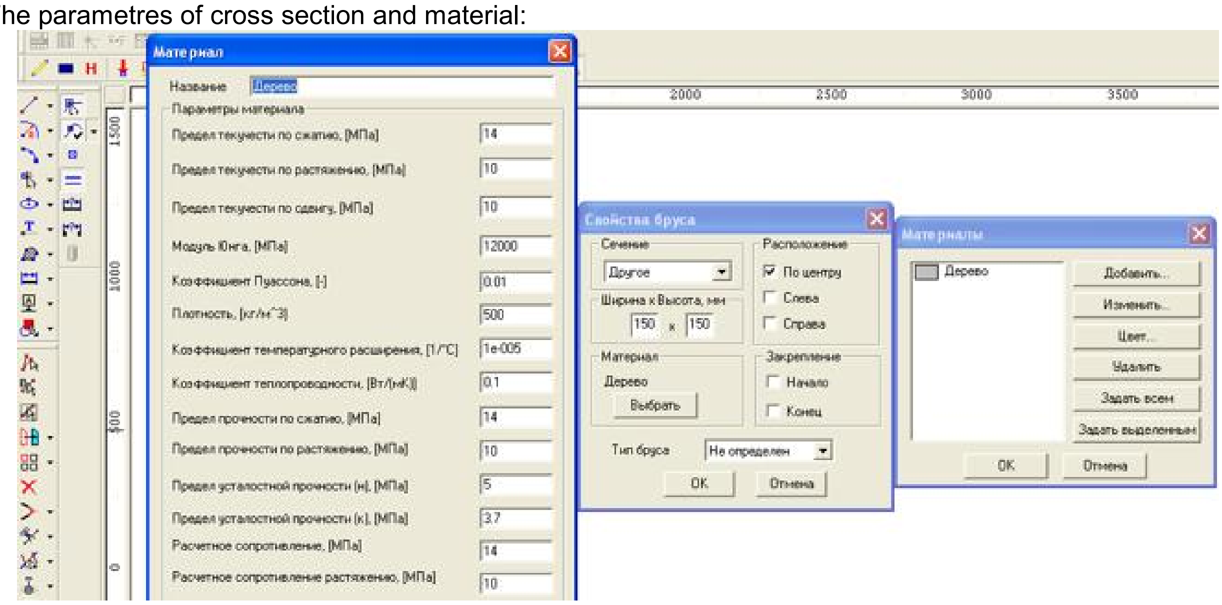

Figure11. Beam parametres in APM Wood

The numbering of nodes and rods:

Название конструкции: 1
Количество ферм: 1

Figure12. Element numeration

After calculating the program displays the following result:

Таблица: Нагрузка на стержни. Загружение: Загружение 0.

N	Узлы	Осевые силы, Н
0	0 - 1	0
1	1 - 2	40000
2	2 - 3	-60000
3	3 - 4	0

Figure13. Results provided by APM Wood

Epure of the longitudinal force N was plotted using obtained data:

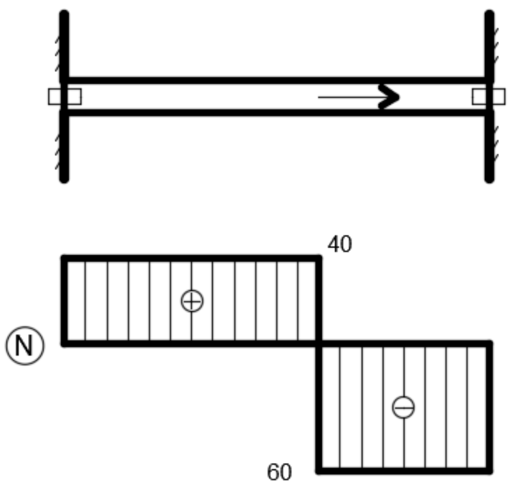

Figure14. Epure “N”

4. Results and discussion

Obviously, epure N on fig.14 differs radically from the one that was obtained earlier (fig.9). From these values of the longitudinal force, it can be concluded that the program APM Wood considers nodes on MPC as absolutely rigid, as the epure on fig.14 coincides with the one that can be obtained by calculation bar with built-up ends using ordinary methods of structural mechanics.

Described example shows how important to consider deformations of the nodal connection on MPC whilst calculating rod systems.

Despite the fact that the type and size of metal plate connectors were given initially in this task, it is possible to solve the problem of determination the area of MPC using ultimate tensile strength of steel of which MPC was made, and what is more, this algorithm can be realized as a computer program. Some steps in this direction were made in [12] where computer program algorithm for analysis of structures on MPC was suggested.

It is worth noting that discussed example of strain calculation lacks consideration of wood anisotropy. Differences of mechanical properties of wood depending on the angle between fibers and imposed force were included in model offered in [13].

The issue of taking into account MPC deformations is slightly covered in normative literature. SNiP [21] dictates to take deformation of bars in node area equal to 1,5 mm and this is the only mention of MPC pliability in the whole normative document.

The main problem of realization of described method in design practice is definition of the parametres p_0, k_0, k_1 used in formula (5). This parameters should be estimated experimentally for each model of MPC. Plotting and analysis of load-deflection curves were described in [29].

Obtained results show that automatized Foschi’s algorithm can give more accurate solution of strain analysis of wooden constructions with nodes on MPC than ordinary computation, and therefore can reduce cross-sectional dimensions of structural elements saving some material costs.

5. Conclusions

1. It is necessary to consider the deformations of the nodal connection when calculating wooden constructions with joints on MPC for more accurate determination of forces in its elements.

2. Uneven distribution of forces in different teeth can be very essential for plate selection, so it should also be considered when performing stress analysis.

3. Foschi's method allows performing strain calculation of the construction on MPC with a higher precision than program complex APM Wood.

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Расчет соединений на металло-зубчатых пластинах методом Foschi и с использованием программного комплекса APM Wood

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АННОТАЦИЯ

Металло-зубчатые пластины (МЗП) используются для соединения различных частей деревянных конструкций, в особенности для устройства стыков ферм. Пластины имеют прямоугольную форму, обычно изготавливаются из стали, иногда покрываются защитным слоем, например, из цинка. Зубья пластины могут иметь различную форму, длину и шаг. Для соединения деревянных брусков, МЗП впрессовывают симметрично с двух сторон конструкции, поэтому присоединяемые элементы должны иметь одинаковую ширину поперечного сечения. Для лучшего сопряжения элементов, их торцы обычно шлифуют. Запрессовка проводится с помощью специального оборудования и может происходить как на заводах, так и на строительной площадке. Простейший алгоритм расчета соединений на МЗП можно описать следующим образом: конструкция рассчитывается обычными методами строительной механики, в предположении, что все узлы, скрепляемые пластинами, абсолютно жесткие, затем, из найденных внутренних усилий и справочных данных о нагрузки, приводящей к разрушению или выдергиванию различных пластин (лабораторные испытания проводятся компанией-производителем), подбирают нужные пластины. Одним из программных комплексов, действующих по такому пути, является программа APM Wood, входящая в состав системы автоматизированного проектирования APM Civil Engineering. Данный алгоритм не учитывает неравномерность распределения усилий по различным зубьям одного узлового соединения и деформаций, возникающих в самих металло-зубчатых пластинах, что приводит к существенной погрешности в нахождении внутренних усилий и неточному подбору пластин. Модель, которую предложил Foschi [1], лишена этих недостатков и может быть использована, в том числе, для определения деформаций и силовых факторов в зубьях МЗП. В данной статье рассмотрен алгоритм расчета узлов с металло-зубчатыми пластинами и проведено сравнение с программным комплексом APM Wood. В качестве примера решена задача о стержне, прикрепленном к неподвижному основанию с обоих концов при помощи МЗП и находящемся под действием продольной нагрузки. В результате делается вывод о необходимости учета податливости пластины и ее зубьев в конечно-элементной схеме, а также о влиянии неравномерного распределения усилий в зубьях на расчет напряженного состояния всей конструкции.

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