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ANALYSIS OF THE TIMBER FRAME CONNECTION WITH DOWEL TYPE MECHANICAL METAL FASTENERS

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ABSTRACT

Timber as a material in the construction industry gets more and more into the foreground for the construction of various structures. To improve the properties of timber, new composite materials or new joints, which ensure better bearing capacity and stiffness of the structure, are developed. One of the uses of timber is, among other things, the construction of hall buildings, where are interesting frame connections, which are joints of the diaphragm beam and frame column. The timber frame connections can be solved in several ways, for example by means of glued rods, toothed - plate joints, by means of pinned joints and a frame connection made by a V-shaped frame column. In common practice, these are the types of joints between the diaphragm beam and the frame column. However, the object of this article is a frame connection where the connection of the frame column and the diaphragm beam is created by means of the Rothoblaas VGS11400 screws, which are not normally used as fasteners for this type of joint. The reason for choosing this fastener is to find out how it behaves in this type of construction and to compare it with normative documents, taking into account the use of this type of joint in practice.

Keywords: timber, timber frame, numerical analysis, experimental test, screws, joints, FEM model.

1. INTRODUCTION

Hall objects with frames up to 50 m are very often designed using variable height elements, using a one-piece diaphragm beam and two-piece frame column. The choice of a static system is either a two-hinged frame with hinged supports or a three-hinged frame with hinged supports and top hinge, which is less prone to stress due to settling of support and humidity volume changes. The frame system is created by connecting the frame column and the diaphragm beam in the frame connection. In the timber frame connections, the internal forces are transmitted by mechanical fasteners generally placed in a circle or rectangular. The main disadvantage of a bending rigid joint with mechanical fasteners is the risk of timber splitting due to moisture and stress fluctuations in the joint area. The design of a frame connection with mechanical fasteners is frequently used in common practice. Such approach to the frame connection design (using the VGS11400 screws) can be considered innovative because the reference to its use has not been found. This type of joint was processed and numerically solved by the student of the VSB - Technical University of Ostrava, Faculty of Civil Engineering, Department of Structures, in his final thesis, which attracted construction companies who requested and financially supported the experimental testing of the joint for eventual use in practice.

2. DESCRIPTION OF THE ISSUE

As mentioned in the previous chapter, the subject of this article is the timber frame connection of a supporting timber frame of a single-nave hall. The solved frame connection (Figure-1) is designed as a joint of a pair of frame columns and diaphragm beam from glued laminated timber GL24h. The frame columns are 120/700 mm at the frame connection and the diaphragm beam is 180/700 mm. The joint of the two-part frame column and the diaphragm beam is designed as a bending rigid joint; the beam is inserted between the parts of the frame column. Assembly connection is realized using Rothoblaas VGS11400 screws with a diameter of 11 mm and a length of 400 mm. The screw arrangement is made in two concentric circles with a radiusr_1 = 273 mm in the number of 24 screws for the outer circle and with a radius r_2 = 218 mm in the number of 20 screws.

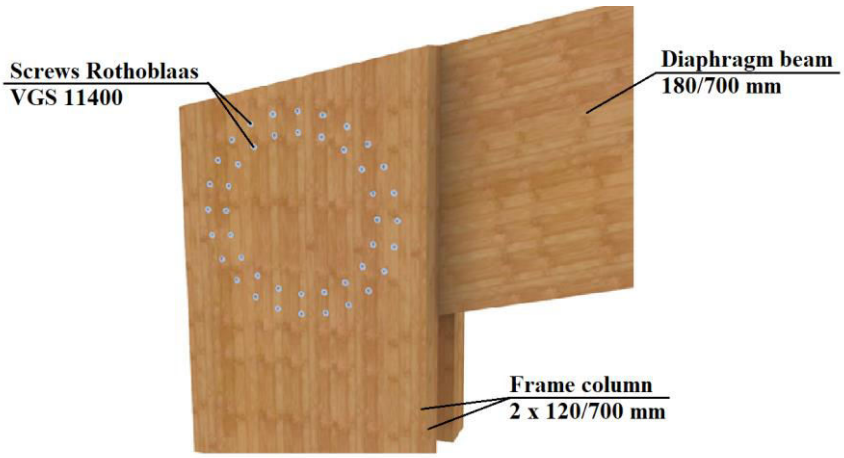


Figure-1. Timber frame connection.

3. NUMERICAL ANALYSIS OF THE TIMBER FRAME CONNECTION

The aim of the numerical analysis was to elucidate the behavior of the frame connection caused by the load from the bending moment. The analysis was performed by manual calculation and using numerical FEM models created in Scia Engineer 17.1 and ANSYS 18.1.

3.1 Analysis of the timber frame connection in Scia Engineer 17.1 and Ansys 18.1

The timber frame connection was modeled in Scia Engineer 17.1 with equivalent boundary conditions and was loaded with point force at the end of the diaphragm beam (Figure-2). Three numerical FEM models were created for the analysis. It was a beam model, a model with isotropic timber properties and an orthotropic shell model with timber properties. The beam and isotropic model of the frame connection was created primarily for the comparison because it is not correct due to the structure of the timber. Since timber is an orthotropic (generally anisotropic) material, thus it has different properties in perpendicular directions, it was necessary to define these properties in the FEM model. In the program, the orthotropic properties of timber were defined by the input of physical constants, depending on the thickness of the element, the modulus of elasticity parallel to the grain, the modulus of elasticity perpendicular to the grain, the modulus of elasticity in torsion, the Poisson constant parallel to the grain, and perpendicular to the grain for the used timber class GL24h. Physical constants (see Table-1) were entered for the wall and plate element and determined according to [1].

Table-1. Element's physical constants.

Physical constants	Frame column 120 mm	Diaphragm beam 180 mm	Units
D11	1.681	5.675	MNm
D22	0.219	0.740	MNm
D12	0.075	0.252	MNm
D21	0.075	0.252	MNm
D33	0.266	0.899	MNm
D44	84.000	126.000	MN/m
D55	84.000	126.000	MN/m
d11	1401.127	2101.690	MN/m
d22	182.756	274.133	MN/m
d12	62.137	93.205	MN/m
d21	62.137	93.205	MN/m
d33	221.950	333.920	MN/m

For correct calculation, it is necessary to create a finite element network properly. The timber frame connection model was divided into individual areas with different finite element sizes ranging from 3 to 50 mm (see Figure-3).

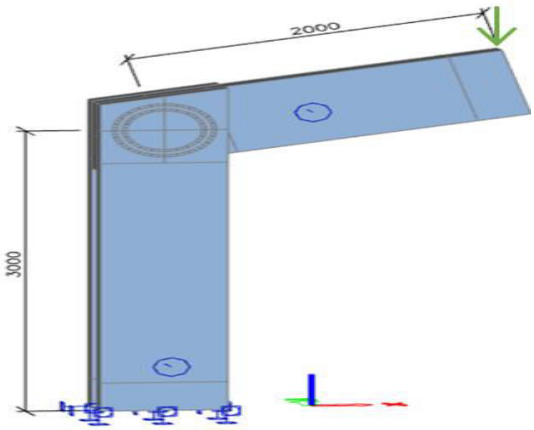


Figure-2. Joint modelled in Scia Engineer 17.1.

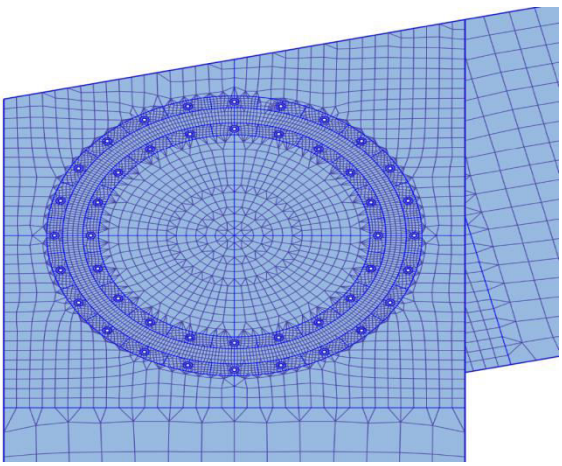


Figure-3. Finite element mesh.

The model created in the computational program Scia Engineer 17.1 can be used to compare deformations and the mode of failure with a physical test.

To determine the force that would cause the collapse of the structure, it was necessary to create a computational model in ANSYS 18.1.The model was created by means of volume elements, and it would be possible to determine the translational stiffness on the basis of crushing of the timber by screws.

Within the model's functionality, the stability of the model was verified to determine the input force inducing collapse of the structure calculated by nonlinear stability mode. The value of this force was set using Ansys 18.1 at F = 159.94 kN.Depending on the load force obtained from the program Ansys 18.1, which was inserted into the model in Scia Engineer 17.1, the stability number α_{cr} = 4.86 was determined, in which the structure would lose its stability. For this test, it was possible to state, depending on the values found, that the structure could be considered sufficiently stable in terms of the realized experiment.

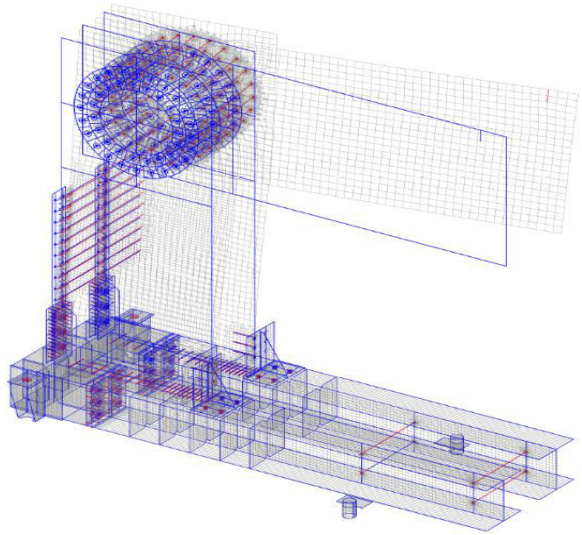


Figure-4. The Loss of model stability - axonometric view.

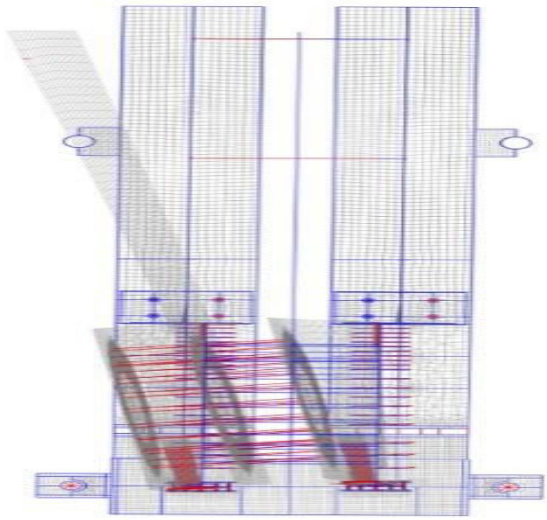


Figure-5. The loss of model stability - top view.

4. EXPERIMENTAL MEASUREMENT

The objective of the experimental test was to find out how large load in the form of a point force will the joint withstand and find out how it will be broken. An important part was to determine the similarity between the numerical model and the experimental sample in the case of rotational and translational stiffness, because this property of the joint is used in beam models for more accurate construction behaviour.

The experimental test of the joint that was accomplished thanks to the support of the VSB - Technical University of Ostrava, Faculty of Civil Engineering and of the companies ROTHOBLAAS, INGENIA and EXTEN spol. s.r.o., was carried out on the real scale with which the frame connection would be realized in practice. In the experimental measurement there was a change in the inclination of the diaphragm beam (design 13.00 %, tested

timber frame connection 0.00 %). However, this change is considered insignificant in this case as it is a circular joint and the inclination does not have a significant effect on the calculated and measured values.

The static loading test of the timber frame connection construction was carried out by means of a hydraulic press and the test sample was equipped with strain gauge sensors for recording deformations and displacements.

4.1Realization of the test sample

Before performing the test, it was necessary to create a computational model that would match the test sample (Chapter 3.1). The computational model also includes the beam boundary conditions used during testing.

The tested structure was carried out as described in Chapter 2, i.e. a doubled frame column and a diaphragm beam from glued laminated timber GL24h, connected by Rothoblaas VGS11400 screws in a total of 44 pieces located in two concentric circles.

The Figure-9 shows the joint, which determined the boundary conditions of the test sample. Its task was to ensure the transfer of tensile force generated during testing. The transfer of the compressive force was provided by means of the contact surface between the frame columns and the steel structure.

Figure-6. Test sample.

Figure-7. Frame connection.

Figure-8. Assembly of the joint to ensure boundary conditions.

Figure-9. The joint to ensure boundary conditions.

4.2The course of the static load test

The load test was realized in several phases. In the initial phase, the tested structure was loaded to approximately 30% of the design load bearing capacity determined according to the standard ČSN EN 1995-1-1. After loading to 30% the value, the structure was relieved. In the second phase, a load of approximately 60% of the total design load bearing capacity was applied, after which it was again relieved. The last, third phase involved the loading of the sample until the timber frame connection was broken.

5. EVALUATION AND DISCUSSIONS

5.1Evaluation of the experimental test

During the experimental testing of the frame connection structure, the frame column was damaged during the third load cycle, with the occurrence of a crack. The cause of this disturbance was imperfect boundary conditions where the increasing vertical (load) force increased the horizontal forces. These horizontal forces were caused by the friction between the timber frame

column and the steel structure simulating the boundary conditions. The loading of the structure continued further until the joint was broken, because the formed crack had no significant effect on the load bearing capacity of the joint.

In the fourth phase, the examined joint was broken. The disturbance occurred in the tension perpendicular to the grain at the top of the diaphragm beam and it confirmed the assumptions from the numerical analysis. The joint failure occurred at a force of F= 233.33 kN.

Figure-10. View of broken diaphragm beam and column frame.

The Figure-11 shows the VGS11400 Rothoblaas screws after the experiment.

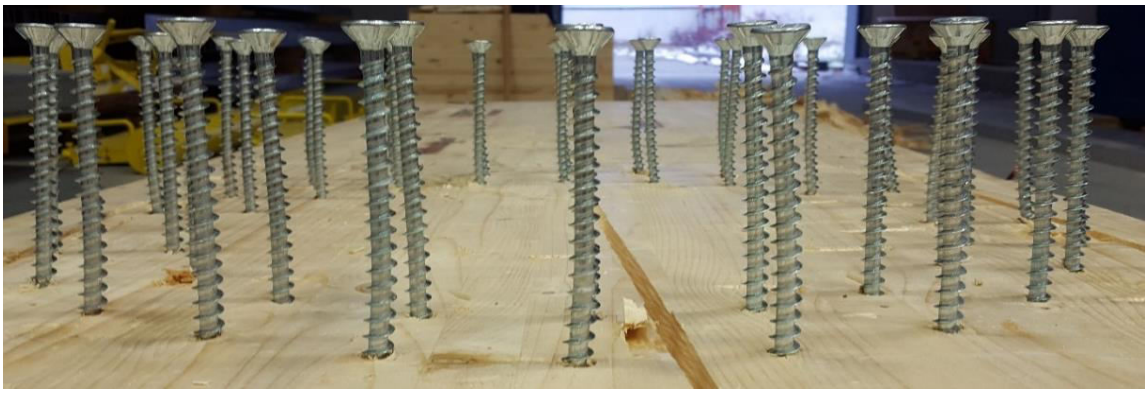


Figure-11. View of plasticized Rothoblaas VGS11400 screws after removing the column frame.

5.2 Comparing the results

Individual ways of carrying out the timber frame connection (manual calculation, numerical FEM models and experimental testing) was compared to each other through some parameters, such as the collapse force of the timber frame connection construction and the deformation.

5.2.1 Way of the timber frame connection failure

Testing of the frame connection was also focused on the way of its failure and the force causing the collapse of the structure. The assumption was that, depending on numerical calculations, the disturbance would occur in the tension perpendicular to the grain, and this was confirmed during the experiment.

The maximum force that the timber frame connection can withstand was determined in several ways. The individual values of the collapse force and the approaches by which the forces were determined are given in the Table-2 Chyba! Nenalezen zdroj odkazů.. The most resistant is the timber frame connection in the case of the numerical model with a material-linear approach from ANSYS 18.1. However, during the experiment, it was shown that the failure occurred at a measured load force of F = 233.33 kN, which is approximately 1.60 to 1.75 times the design load bearing capacity determined according to the standard ČSN EN 1995-1-1. The value of the multiplier is dependent on the arm change during loading.

Table-2. Comparing of the load forced causing the collapse of the structure.

Calculation method	Force caused the collapse F [kN]	Bending moment caused the collapse M [kNm]	Multiplier of M
Standard approach - EC5	133.33	202.66	-
Ansys – linear calculation	308.89	469.51	2.32
Ansys – nonlinear calculation	159.94	240.07	1.18
Physical test	233.33	354.66	1.75

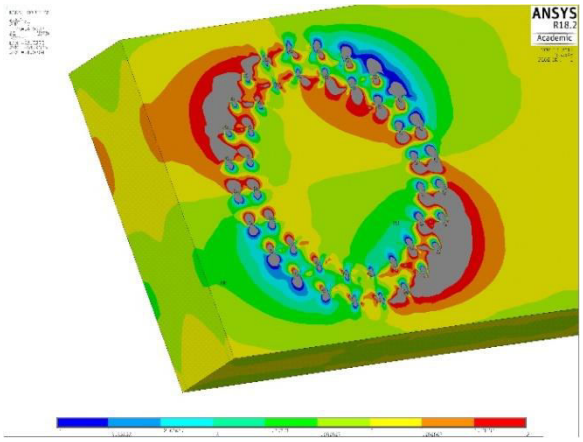


Figure-12. Tensile stress perpendicular to the grain - Ansys18.1 program.

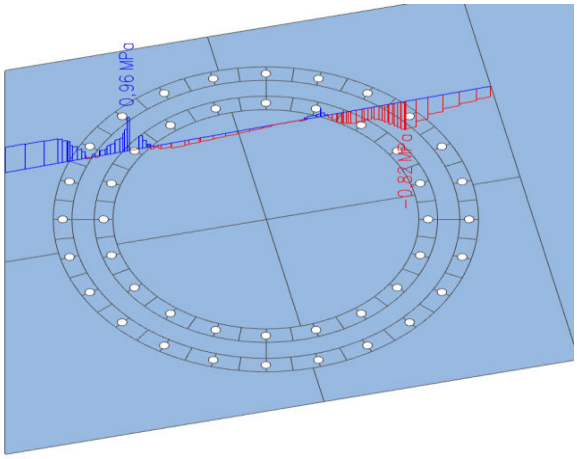


Figure-13. Tensile stress perpendicular to the grain -Scia Engineer 17.1 program.

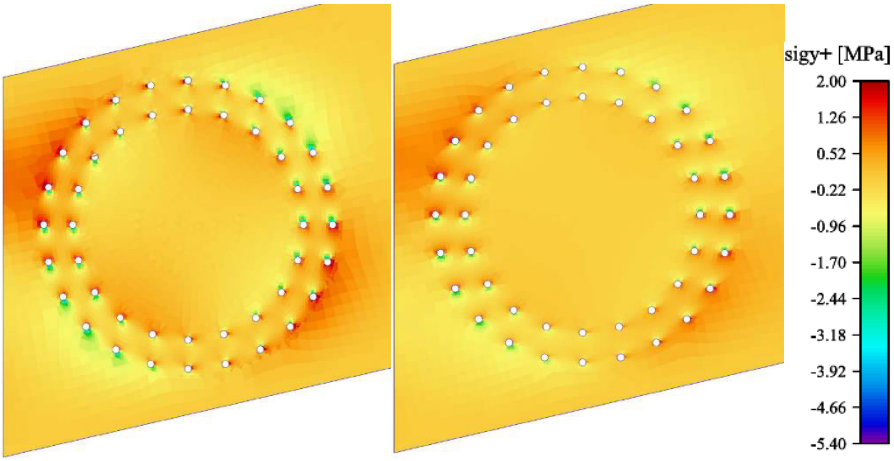


Figure-14. Tensile stress perpendicular to the grain (on the left - isotropic model, on the right orthotropic model) –Scia Engineer 17.1program.

In the figures above (Figure-12 - Figure-14), the values of the tensile stress perpendicular to the grain are shown here. In the case of Scia Engineer, a picture of the stress obtained on the isotropic model is presented for comparison. The difference in the stress value of the models obtained in the computational program Scia Engineer 17.1 is 18.88% excluding stress peak located near the holes. Taking into account the orthotropy of the material, the stress reaches a maximum value near the aperture of 0.96 MPa and outside the aperture of 0.73 MPa. The stress reaches values greater than those determined by the calculation according to ČSN EN 1995-1-1, but the collapse of the joint occurs within the range of 1.7 - 2.5 MPa, which is derived from physical tests for this type of timber

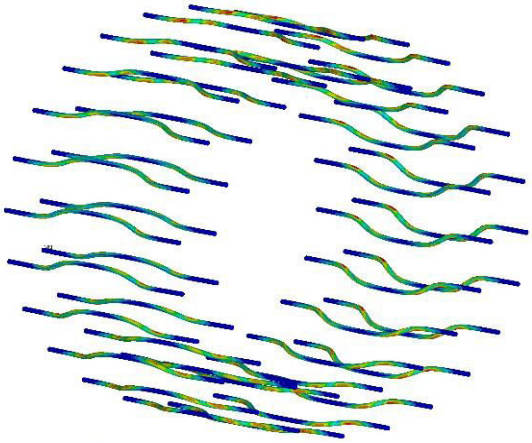


Figure-15. Plasticized of VGS11400 screwsin in numerical FEM model (Ansys 18.1).

Figure-16. Plasticized of VGS11400 screws in frame connection.

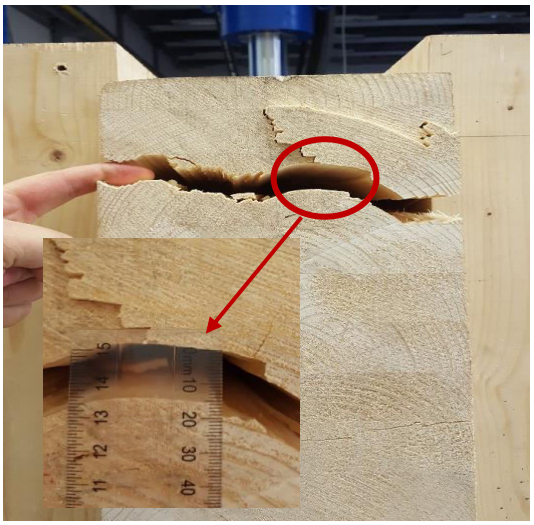


Figure-17. Breach of diaphragm beam caused by tension perpendicular to the grain.

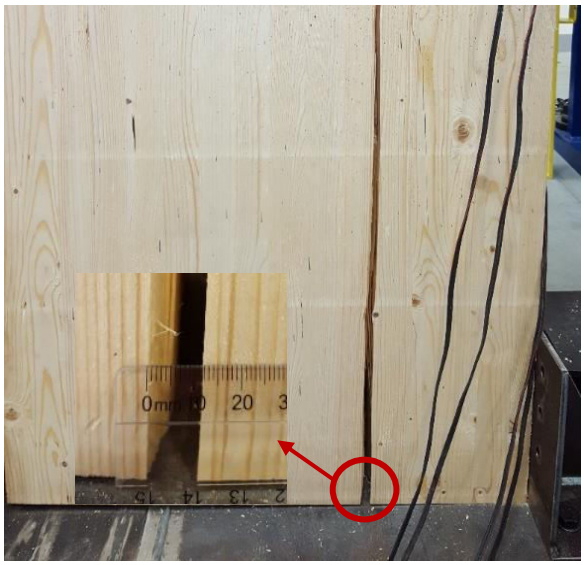


Figure-18. Crack in the frame column caused by tension perpendicular to the grain.

Figure-15 andFigure 16shows the plasticizing of the VGS11400 screws in the numerical model and, after the experiment was ended and the wooden diaphragm beam and the frame columns were removed.

The Figure-17confirms outputs from numerical models and assumptions about the failure of the structure in the tension perpendicular to the grain.

5.2.2 Comparison of timber frame connection deformation and relevance of numerical FEM model created in ANSYS 18.1

The vertical deformation was compared at the end of the diaphragm beam of the timber frame connection. This displacement was determined by computational FEM models, determined from the experimental measurement and calculated manually by the force method.

In the case of numerical FEM models, this is a comparison of the deformation at the end of the diaphragm beam obtained from Scia Engineer 17.1. The stiffness, obtained from manual calculation according to [3], was inserted into each model at the joint of the diaphragm beam and the frame column. For this comparison, 3 models were created. In the first case, it was the beam model, in the second case it was the shell model with isotropic properties and in the third case it was the shell model with orthotropic properties. In the case of shell models, these were combined models where the shell was supplemented with beam finite elements. These models favorably combine the advantages of both finite elements.

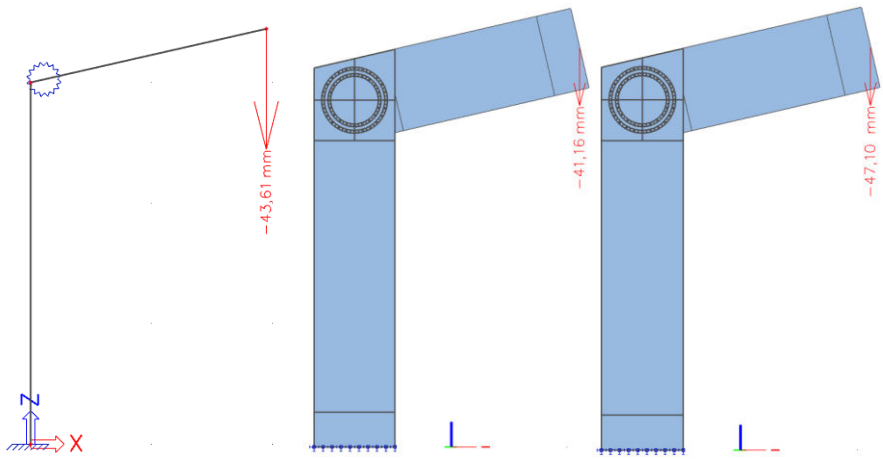


Figure-19. Deformation of the frame connection - from left beam model, isotropic shell model, orthotropic shell model.

It can be seen from Table-3 that the greatest difference between the vertical deformation determined by the force method occurs in the case of a shell-based FEM model with orthogonal properties. The force method was determined based on the calculation according to the formulas (1) and (2). The difference is 7.71 %, and precisely the deformation derived from this modelmay be the closest approach to the actual behaviour of the timber glued laminated structure

$$u_z = \int_0^{l_1} \frac{M_0 \cdot \overline{M}_1}{E_1 \cdot I_1} \cdot d_x + \int_0^{l_2} \frac{M_0 \cdot \overline{M}_1}{E_2 \cdot I_2} \cdot d_x + \int_0^{l_2} \frac{M_0}{K_r} \cdot d_x \quad (1)$$

$$u_z = \frac{M_0 \cdot \overline{M}_1}{E_1 \cdot I_1} \cdot l_1 + \frac{M_0 \cdot \overline{M}_1}{2 \cdot E_2 \cdot I_2} \cdot l_2 + \frac{M_0}{K_r} \cdot l_2 \quad (2)$$

$$u_z = \frac{168.85 \cdot 1.95 \cdot 10^3}{11.5 \cdot 10^9 \cdot 0.0069} \cdot 3 + \frac{168.85 \cdot 1.95 \cdot 10^3}{2 \cdot 11.5 \cdot 10^9 \cdot 0.0051} \cdot 1.95 + \frac{168.85 \cdot 10^3}{12.90 \cdot 10^6} \cdot 1.95$$

$$u_z = 0.04347\ m$$

where

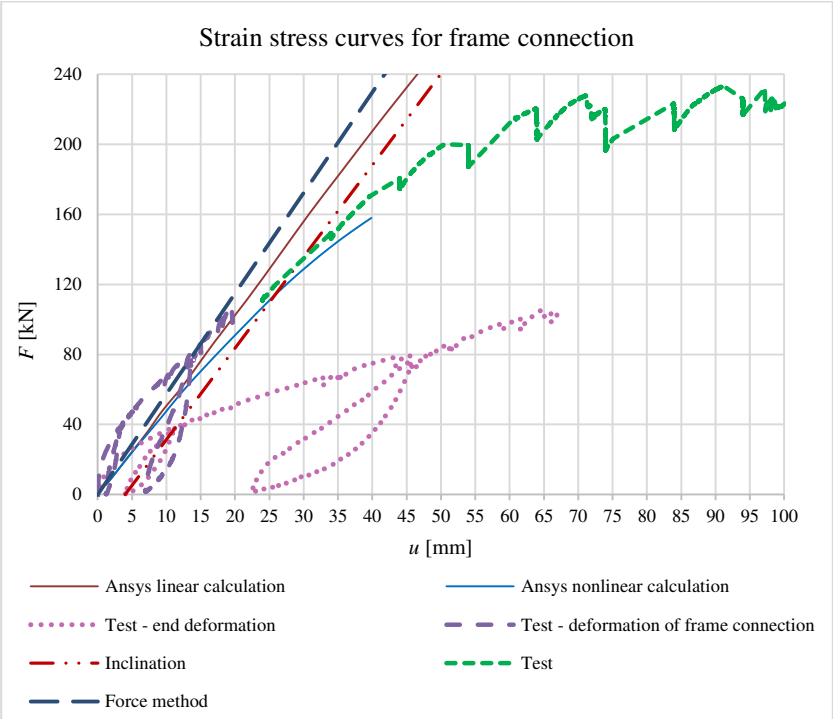
M_0 is	bending moment from real loading;
$\overline{M}_1$	bending moment from virtual unit load;
L_1	frame column length;
L_2	diaphragm beam length;
E_1	frame column Modulus of Elasticity;
E_2	diaphragm beam Modulus of Elasticity;
I_1	frame column inertia moment;
I_2	diaphragm beam inertia moment;
K_r	rotational stiffness of connection of frame column and diaphragm beam according to [3].

The deformation obtained from the numerical FEM model and from the experimental test is different due to the loading and relieving during the test. Another reason is the difference between input and actual imperfections and displacements because the joint and contacts were not active during the first phase of the experimental loading.

Table-3. Comparison of vertical deformations.

Method of determining vertical deformations	u_z [mm]
Manual calculation - forced method	43.47
FEM beam model - Scia Engineer 17.1	43.61
FEM shell model with isotropic parameters - Scia Engineer 17.1	41.16
FEM shell model with orthotropic parameters - Scia Engineer 17.1	47.10
Experimental measurement	59.00

Graph-1 describes the dependence of the applied deformation load and displacement of the extensometers during the experimental test. The purple curve describes the vertical deformation at the end of the diaphragm beam. This curve further describes the hysteresis of the timber frame connection according to the chosen diagram representing the dependence between the displacement of the press head and the deformation of the selected points. Important is the fact that according to this curve it was possible to observe the change in the stiffness of the tested frame connection.



Graph-1. Stain stress curves for frame connection.

In the graph, the blue curve shows the deformation course from the force method using the rotational stiffness $Kr,_{ser}$ = 19.50 MNm/rad (calculated as the characteristic value according to the standard ČSN EN 1995-1-1) at the point of contact of the diaphragm beam and the frame column.

Depending on the interleaved linear abscissa indicating the inclination (red curve) over the loading and relieving cycle, it was possible to estimate the stiffness of the entire frame connection system, including the steel structure and the frame connection. When separating the displacements, associated stiffnesses, and mathematically converting the displacement and forces into rotation and moment, its inclination indicates the searched stiffness, which will be used to determine the rotational and translational stiffness to compare stiffnesses obtained from [2] and used in the case of beam models. When comparing the results from the numerical FEM model that was just loaded and the physical test, it is confirmed that the consistency in the resulting stiffness is good. On the Graph 1it is the same inclination of the red curve (experimental test) and the orange and blue curves (numerical values).

6. CONCLUSIONS

The article was focused on the problems of joint of the diaphragm beam and the frame column using mechanical fasteners. In this case, the diaphragm beam and the frame column are connected using the Rothoblaas VGS11400 screws. The thesis required the creation of numerical models, which were the basis for experimental testing and subsequently were used for comparison.

Through experimental testing it has been shown that Rothoblaas VGS11400 screws, which are not normally used for timber frame connections, have sufficient bearing capacity for this use. In this case, the higher bearing capacity was demonstrated than the bearing capacity determined by normative documents ČSN EN 1995-1-1. This assumption is expected because the standards assume, in addition to the maximum given bearing capacity, a certain reserve to break the joint or element. The frame connection was disturbed during the experiment by tension perpendicular to the grain in the upper corner of the diaphragm beam, which only supported the correctness of the numerical model. The test structure was without any reinforcement of the diaphragm beam, with its reinforcement the bearing capacity would increase. To confirm this theory, however, it is necessary to carry out further experimental measurements with and without the reinforcement of the diaphragm beam.

In the framework of cooperation with the practice and research activity at the VSB - Technical University of Ostrava, Faculty of Civil Engineering, it is expected to continue with this study by other physical experiments. These tests would be aimed at comparing the efficiency of timber frame connections created by screws and pins. The tests would also be extended to loading and relieving cycles along with a dynamic response to input load.

ACKNOWLEDGEMENT

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