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SEGMENT OF WALL PANEL FOR TIMBER STRUCTURES UNDER VERTICAL LOAD

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ABSTRACT

The subject of this paper is an experimental and numerical analysis of the stability of the wall panels with one-side board sheathing for timber structures. The reinforcement of the panel is provided using glued timber composite I-shaped element consisting of a web made of a wood-based desk embedded into flanges of solid timber. The mechanism of the behaviour of these panels, mode of the failure and reliable procedure to determine the buckling load-bearing capacity not been fully explored so far. This work describes the behaviour of the wall panel under vertical load and the method of failure using experimental and numerical analysis. The reduction coefficient k_J was determined, which can be used for a simple calculation of the buckling capacity of a wall panel.

KEYWORDS: Timber structures, wall panel, I-stud, one-sided board sheathing, stability, experiments.

INTRODUCTION

A modern and responsible lifestyle focused on sustainable production, higher living comfort, low environmental impact and high quality of production generally brings new and new challenges in the field of civil engineering, to which it is necessary to adequately respond professionally. In the field of fire resistance of timber structures, for example, the question arises of the residual load-bearing capacity of a wall timber panel, the inner load-bearing layer of which has been significantly damaged by fire. The research of ribbed panels with one-sided cladding with a wood-based board took place in recent years at the Faculty of Civil Engineering of the Czech Technical University in Prague.

The light timber frames are one of the most used construction systems for timber structures. Research and experiments of wall panels using studs with a classical rectangular cross-section were performed in history many times. The reinforcing load-bearing capacity of the walls was determined using advanced methods several times in the past (Brandejs 2006, Girhammar and Källsner 2009, Källsner and Girhammar 2009). Another problem that was solved is e.g. anchoring methods and its stiffness of wall panels (Jára 2018, Tomasi and Sartori 2013) and sheathing-to-framing connections (Sartori and Tomasi 2013, Premrov and Kuhta 2009). Furthermore, experiments of wall panels were performed to show the effect of openings on the overall load-bearing capacity of these elements (Šilih and Premrov 2010, Šilih and Premrov 2011). The load-bearing element in wall panels is often a timber stud with a rectangular cross-section, its behaviour during loading and various failure modes depending on the load is described in (Bäckström and Kliger 2008, Bäckström et al. 2009).

To improve the thermal technical properties of the wall panel, it is possible to replace the classic stud with a rectangular cross-section with a stud with an I-shaped cross-section, or I-stud. Elements with an I-shaped cross-section are now commonly used for beams, i.e. an element in a horizontal position, or I-beams (Racher et al. 2006, Jára et al. 2014, 2015). For I-beams, it is sometimes necessary to make round, square and rectangular openings for installations. The influence of holes on the load-bearing capacity of the beam has been presented in many publications (Zhu et al. 2005, Guan and Zhu 2009, Jára et al. 2015, Afzal et al. 2006). Another possibility of making holes in the web of I-beams represent so-called castellated timber I-joists (Harte and Baylor 2011, Baylor and Harte 2013).

Elements with an I-shaped cross-section are also commonly used in wall panels with double-sided sheathing. I-studs are prone to loss of stability by deviation (buckling) in the plane of the wall. The stability of these panels is ensured by double-sided board sheathing. Stability is not ensured, when one-side sheathing burns out during fire or sheathing is not made from a load-bearing material. The aim of this work is to clarify the behaviour of wall panels with a one-sided board sheathing and with an I-shaped cross-section consisting of a web made of a wood-based desk embedded into flanges of solid timber. The sheathing-to-framing connections were performed using steel staples. The choice of the I-stud was performed with the current requirements for heat-technical properties of exterior perimeter walls. It was especially crucial to achieving the values of the coefficient of heat transfer U ($W \cdot m^{-2} K^{-1}$) across the walls that correspond to normative values for low-energy and passive houses according to ČSN 73 0540-2 (2012).

MATERIAL AND METHODS

The buckling capacity of the wall panel section was determined by experimental and numerical analyses. Before performing experiments, preliminary analytical calculation and numerical model were created for the purpose of the estimation of the behaviour of the wall panels. The particular steps which have been performed before the experiment including the calculation of the buckling capacity in accordance with (EN 1995-1-1 2004, EN 1999-1-1 2007) were presented in (Celler J. et al. 2016).

Static tests on wall panels with an I-shaped cross-section stiffener made of the wood-glued composite element and one-sided board sheathing were designed and performed within the experimental part of the work. A detailed description of the preparation of the experiment, execution of the experiment and evaluation of the results were presented in (Celler J. et al. 2019). For completeness of this paper, basic information about the samples for the experiment is also presented. The test set up, the dimensions of each component and the whole sample and method of load are shown in Fig. 1.

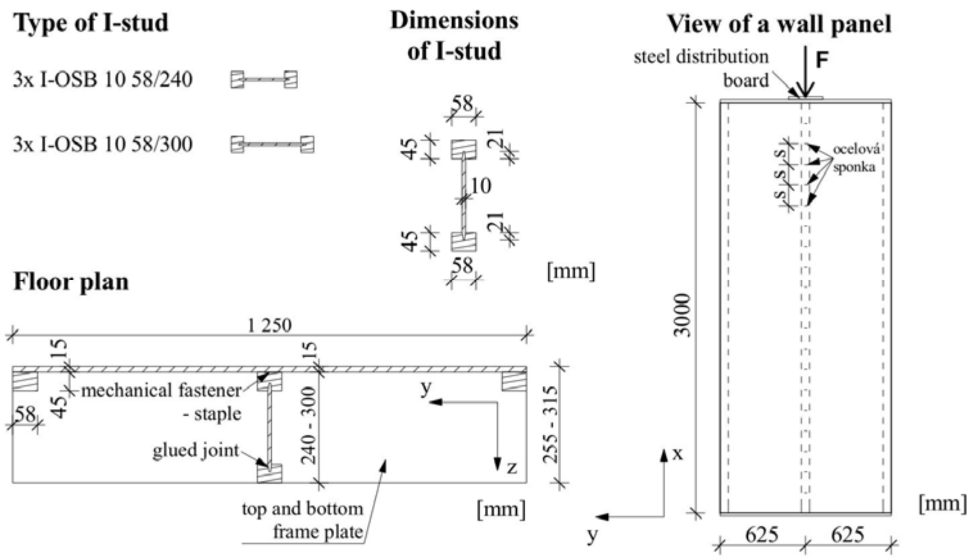

Fig. 1: The test set up for a series of experiments of the wall panel and method of load.

The dimensions of the wall panel were adapted to the real construction. The dimensions of the wall panels are 1250 × 3000 mm. 6 samples of the wall panel section were tested: I-studs with a cross-sectional height of 240 mm (3 samples) and 300 mm (3 samples) were used. The wall panel was placed at the test area gate, fastened with textile straps and loaded (Fig. 2, on the left), the deformed wall panel is shown in Fig. 2 (on the right). The load was applied to the I-stud through the upper frame plate made from the OSB board and the steel distribution board.

Fig. 2: Wall panel placed to the test area: axonometry and front view (on the left), deformed structure: buckling of the free flange of I-stud and deflection of the entire I-stud in the plane of the wall (on the right).

The results of the experiment corresponded to the assumptions from the preliminary analytical calculation and numerical model results.

After performing the experiments, the wall panels were cut and their parts used for material tests and staple joint tests. The material tests were performed for wood and OSB boards. The description of individual experiments and the results of material tests were presented in (Celler J. et al. 2019). The results of material tests were compared with the results obtained in the literature (Dolejš 1997, Pošta 2015).

RESULTS AND DISCUSSION

An important part of the entire wall panel is the connection between the held timber flange and the sheathing from the OSB board. This connection is made using steel staples. In the experimental part, the load-bearing capacity of the staple joint for cutting and pulling out was determined.

Shear capacity of staples: four test specimens were prepared from timber prisms and OSB boards, which were cut from wall panels. The dimensions of the individual components and the whole sample are in Fig. 3.

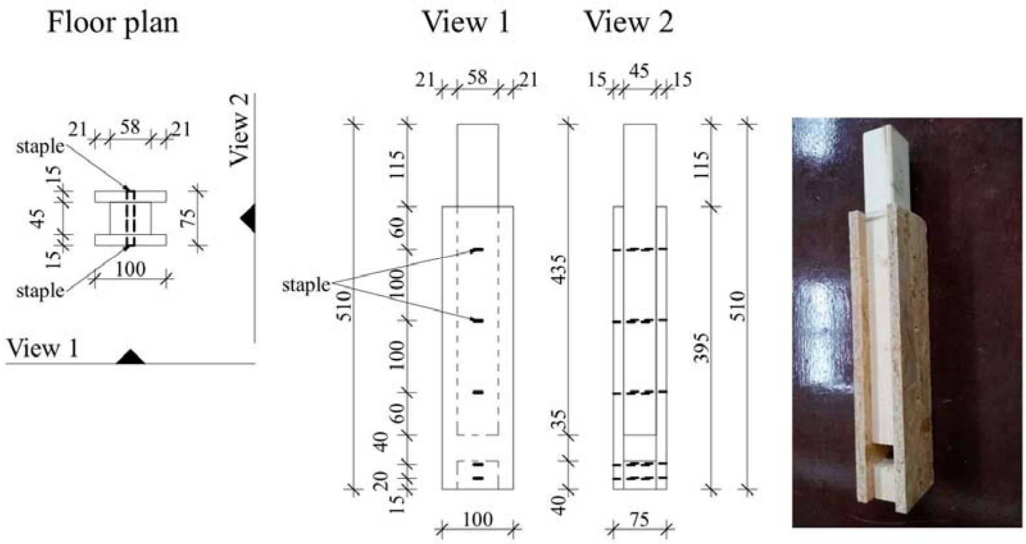

Fig. 3: Dimensions and arrangement of the test specimen for performing staple joints in shear.

The average value of the maximum applied force is 5.71 kN at a displacement of 6.75 mm. For the validation of the numerical model, the stiffness of the staple joint in the shear „$K_{s,exp}$“ is determined from the performed experiments as the average value of the stiffness of individual test specimens. The average value of the stiffness of the staple joint in the shear „$K_{s,exp,ø}$“ is 1241 $N \cdot mm^{-1}$.

Axial capacity of staples: six test specimens were prepared from a timber prism and OSB board, which were cut from the wall panels. Connection of prism and OSB board using one steel staple. The dimensions of the individual components and the whole sample are in Fig. 4.

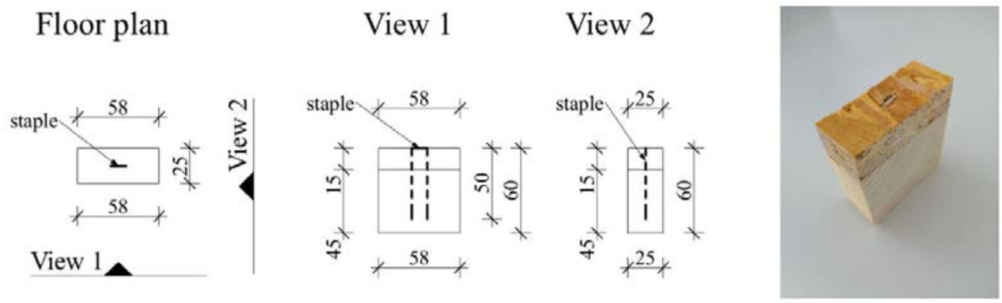

Fig. 4: Dimensions and arrangement of the test specimen for performing the staple joint to pull out the staple.

The average value of the maximum applied force is 361.6 N at a displacement of 0.85 mm. For the validation of the numerical model, the stiffness of the staple joint for extraction „$K_{v,exp}$“ is determined from the performed experiments as the average value of the stiffness of individual test specimens. The average value of the stiffness of the staple joint for pulling out „$K_{v,exp,ø}$“ is 807 N·mm^{-1}.

Furthermore, a 3D numerical model of a section of a wall panel with a stiffener made of a wood-glued composite element with an I-shaped cross-section and one-sided board sheathing was created within the numerical part of this work. For numerical analysis, knowledge about modelling the timber according to (Hataj 2019, Celler V. 2020, Mikolášek 2012).

Based on preliminary calculations and models, the static calculation program SCIA Engineer working with the finite element method was chosen for the resulting 3D numerical model, which in the current version contains all the necessary tools for numerical analysis, taking into account nonlinearities of all kinds. The model was modified and validated based on performed wall panel experiments, staple joint experiments and material tests. The dimensions, arrangement and material design of the individual elements of the wall panel in the 3D numerical model are the same as in the wall panel assembled for the experiment. The 3D numerical model and dimensions of the individual components are shown in Fig. 5.

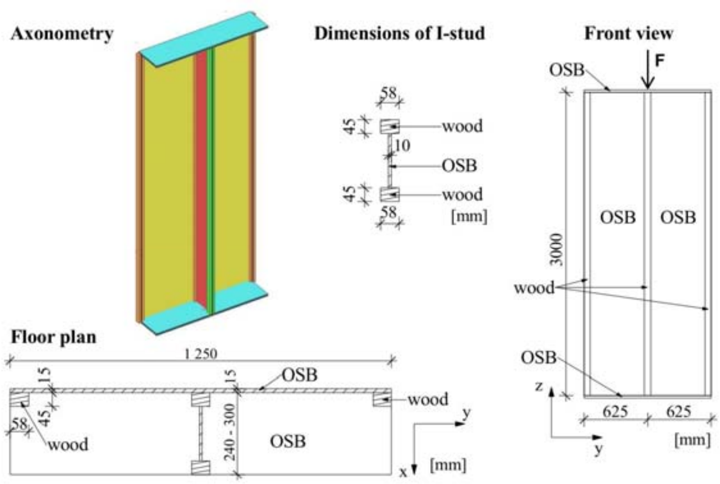

Fig. 5: 2D-elements numerical model: axonometry (on the left), dimensions of the model and individual components (bottom, right).

The 3D model is created using slab-wall elements modelled using the centerline and thickness of the element. Boundary conditions corresponding to the performed experiment were introduced in the model. The semi-rigid connection between the flange of the I-stud and the sheathing is created using an internal joint on the edge of the surface. The individual stiffnesses of the joint are entered as nonlinear using a load-deflection diagram of the dependence of the applied force on the displacement according to the performed experiments. Geometric imperfection - the initial curvature of the free flange of the I-stud and the side timber prisms was introduced into the model using a horizontal line load. A mesh with the size of the elements of a finite element mesh measuring 30 x 30 mm was created on the whole model. The load was considered in several ways. Finally, the line load to the centerline of the flanges and the web of the I-stud was considered for the numerical model. For the analysis of the structure, a nonlinear calculation was performed, taking into account the initial imperfections of the structure using the stability calculation. A modified Newton-Raphson method was chosen for the nonlinear calculation, which is sufficiently accurate and fast for the given type of model.

The deformed structure was drawn for individual nonlinear combinations. For the I-stud with a cross-sectional height of 300 mm (hereinafter I-stud 300), deformed structures were drawn for loads of approximately 30%, 70% and 100% of the maximum applied force (Fig. 6). From the beginning of the loading, the free flange of the I-stud deviates and at the same time, the sheathing is deformed, which corresponds to the experiment. As the load increases, the free flange of the I-stud, including the web, becomes more significantly deformed, which again corresponds to the experiment, where the dominant deformations occurred on the free flange of the I-stud.

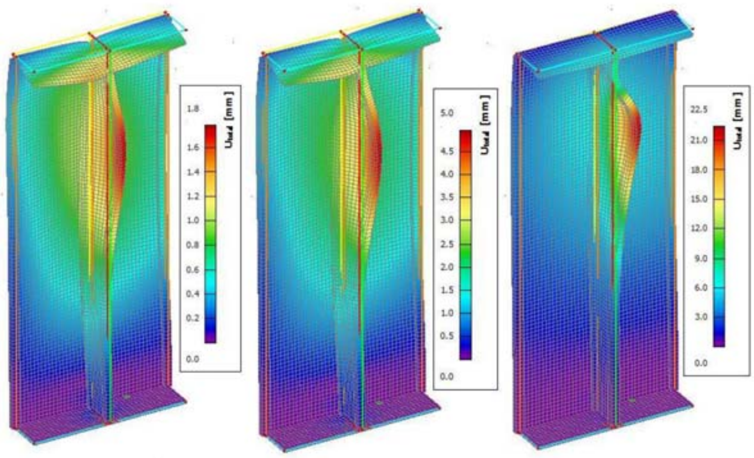

Fig. 6: I-stud 300 - deformed structure for nonlinear calculation, percentage of maximum applied force: 30% (left), 70% (middle), 100% (right).

The results of the numerical model were compared with the experiment. The maximum displacement that occurred on the structure on the free flange of the I-stud was monitored. The dependence of the applied force on the maximum displacement in the numerical model and during the experiment is compared in Fig. 7.

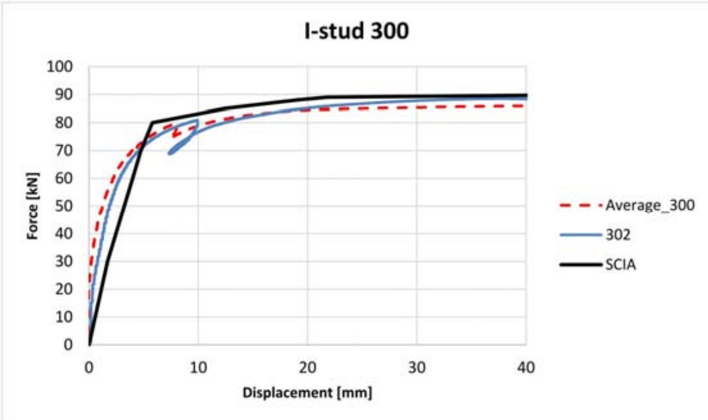

Fig. 7: Comparison of load-deflection diagrams from the experiment and a numerical model for an I-stud with a cross-sectional height of 300 mm.

The maximum force achieved for a test specimen of an I-stud 300 and a distance of steel staples of 100 mm is 88.5 kN. For the numerical model, the maximum force at the top of the load-deflection diagram is 89.0 kN.

To verify the correct setting of all parameters, a numerical experiment was also performed for a section of a wall panel with an I-stud with a cross-sectional height of 240 mm (hereinafter I-stud 240). The course of loading and deformation of the structure was similar to the wall panel with I-stud 300. The dependence of the applied force on the maximum displacement in the numerical model and during the experiment is compared in Fig. 8.

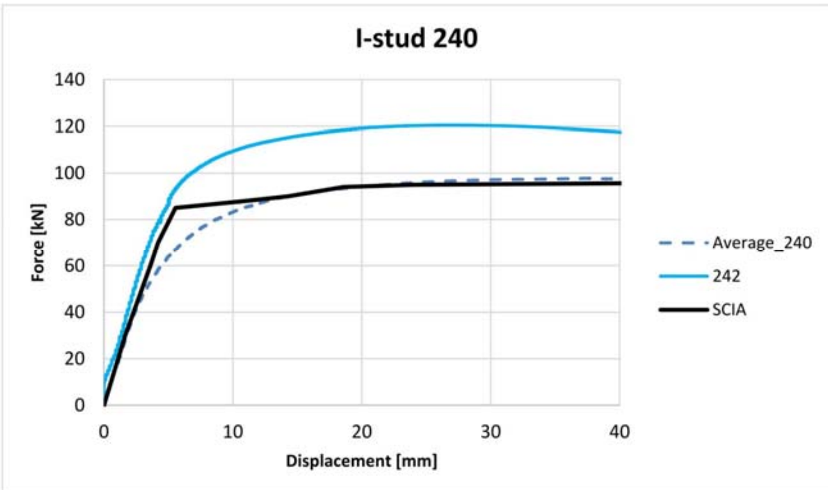

Fig. 8: Comparison of load-deflection diagrams from the experiment and a numerical model for an I-stud with a cross-sectional height of 240 mm.

For test specimens with an I-stud 240, an initial imperfection was measured with much greater variance than for an I-stud 300. In addition, for the I-stud test specimen with the smallest measured imperfection, the smallest distances of steel staples are used. For this reason, the result of the numerical analysis is compared with a test specimen 242, in which the distance of the steel staples is 100 mm, and also with an average load-deflection diagram for all test specimens of the I-stud 240.

The maximum average achieved force for I-stud test specimens with a cross-sectional height of 240 mm is 99.1 kN. In the numerical model, the maximum force at the top of the load-deflection diagram is 94.0 kN, which is 5.1% lower than the average force obtained in the experiment. Compared to sample 242, in which the maximum force reached is 120.4 kN, a larger difference can already be seen compared to the numerical model, which gives a safe reserve for possible larger initial imperfections (geometric and structural) of the I-stud.

When comparing the load-deflection diagrams for an I-stud 240 and an I-stud 300, it can be seen that for I-stud 240, the initial branch of the load-deflection diagram corresponds more to the experiment performed than for I-stud 300. This corresponds to much larger initial imperfections in the I-stud 240 samples than in the I-stud 300.

Based on the results of experiments and a numerical model, a parametric study was prepared. At the beginning of the parametric study, the load-bearing capacity of the wall panel section with dimensional modifications for the tested I-stud cross-sectional heights was determined. Based on the results of the parametric study, the analytical calculation was validated and verified.

From the preliminary analytical calculation considered for several possible ways of deflection of the cross-section of the wall panel performed by I-stud with one-sided board sheathing, the load-bearing capacities were calculated with a large variance of values. None of these values accurately describes the actual state of failure of the wall panel, described in detail in (Celler J. et al. 2016). For this reason, it is necessary to modify the analytical calculation so that the results correspond to the performed experiments and numerical analysis.

First, a numerical analysis was performed for several selected wall panel heights that are used in common construction practice.

Subsequently, the reduction coefficient „$\boldsymbol{k_J}$“ of the total load-bearing capacity of the wall panel section was determined, taking into account the cross-sectional height of the I-stud according to Eq. 1. The reduction factor was determined by back analysis of the analytical calculation and the results of the numerical analysis. The reduction factor was determined for the method of analytical calculation of the flat-plate buckling perpendicular to the "z" axis, i.e. the deviation of the cross-section in the wall plane.

$$\boldsymbol{k_J} = 1.08 - h_2/1\mathrm{m} \quad (-) \tag{1}$$

where: k_J - reduction factor (-), h_2 - cross-sectional height of the I-stud (m).

The load-bearing capacity of the segment of wall panel from the analytical calculation according to Eq. 2 taking into account the reduction factor „k_J“ is plotted in a graph, in which the dependence of load-bearing capacity of the wall panel cross-section and the panel height for I-stud 240 and 300 are plotted (Fig. 9).

$$\boldsymbol{N_{c,z}} = k_J \cdot k_{c,z} \cdot A' \cdot f_{f,c,0,d} \quad (-) \tag{2}$$

where: k_J - reduction factor (-), $k_{c,z}$ - buckling coefficient for deflection of the wall cross-section perpendicular to the "z" axis, ie in the plane of the wall (-), $A^{'}$ - effective cross-sectional area of the wall panel (mm^2), $f_{f,c,0,d}$ - design value of compressive strength parallel to the fibers of structural timber of strength class C24 ($N \cdot mm^{-2}$).

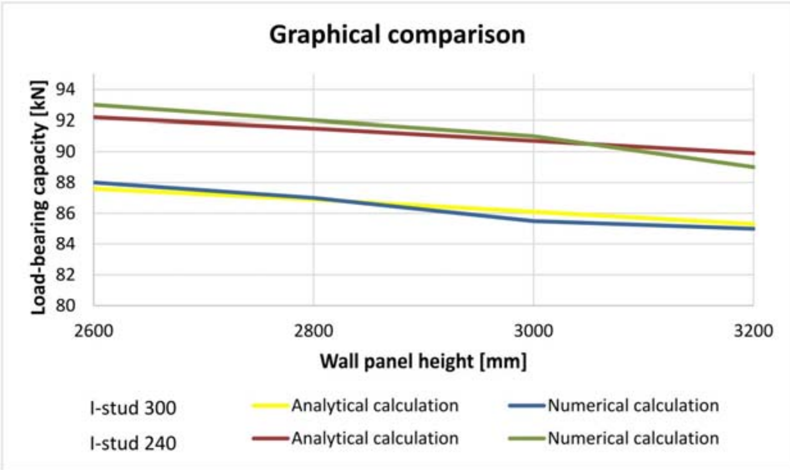

Fig. 9: Comparison of the load-bearing capacity of a wall panel from the analytical calculation and numerical analysis for an I-stud with a cross-sectional height of 240 mm and 300 mm with different wall panel heights.

Within the range of given wall panel heights, which are selected for use in common construction practice, it is clear from the previous results that it is sufficient to consider the linear course of the reduction factor.

The validity of the formula for calculating the load-bearing capacity of a segment of wall panel is for panel heights in the range of 2600 mm to 3200 mm, for the axial distance of I-studs 625 mm and a given type of I-stud with a cross-sectional height of 240 mm and 300 mm. The distance of the steel staples for connecting the OSB board cladding to the flange of the I-stud must not exceed 100 mm.

CONCLUSIONS

Based on experimental and numerical analysis, the mechanism of the behaviour of a section of a wall panel with a reinforcement formed by a stud with an I-shaped cross-section and a one-sided board sheathing under vertical load was clarified and described. Furthermore, a method of failure was described, which occurred either by deflection of the entire I-stud or a free flange of I-stud in the plane of the wall depending on the rigidity of the connection of the sheathing from OSB board to the I-stud flange using steel staples. Based on the analysis of the failure mode of individual test specimens, it is recommended to observe the maximum distance of steel staples given in the standard (DIN 1052: 2004-08 2004). It is 100 mm for the tested specimens.

The results of experiments on the section of wall panels show that the influence of the initial geometric imperfections is crucial for the load-bearing capacity on the buckling. In particular, the deflection of the free I-stud flange is one of the important factors influencing the result. The author recommends limiting the amplitude of this imperfection for similar configurations to 5 mm.

An analytical calculation of the load-bearing capacity of the wall panel was performed for various failure methods (deviation of the cross-section from the wall plane and in the wall plane, spatial buckling). Based on the results of the parametric study and back analysis of the analytical model, the reduction coefficient „k_J“ was determined, which can be used for a simple calculation of the buckling capacity of a wall panel consisting of a load-bearing element with an I-shaped cross-section with one-sided board sheathing. In simple terms, the use of this reduction factor can be recommended for wall panels with a height in the range of 2600 to 3200 mm, for the axial distance of I-stud 625 mm and a given type of I-stud with across-sectional height of 240 mm and 300 mm. The distance of the staples in the connection of the OSB sheathing to the flange must not exceed 100 mm.

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