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ANALYTICAL MODELS TRACING DEFORMATION OF WOOD-FRAMED WALLS DURING VERTICAL TRANSPORT

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Vertical transport of wall-panels is a part of the prefabrication process of wood-framed buildings. The total dead weight of a wall is suspended on several lifting slings, pointwise clasping the top plate of the wall. This indicates, that all the weight of a wall is cumulated in sheathing-to-framing fasteners, usually staples. This article presents experimental investigations and analytical models evaluated for the description of light wood-framed walls in the process of lifting. Three different models cover the analytical approach: a model of a simple beam on elastic supports (BSS), a model of assembled beams (ACBS), three-dimensional (3D) spatial FE model of the wall (WFEM). Board-to-beam joint material parameters are determined on the base of experimental results. These connections are converted into two variants in the form of spring elements for 2D analysis, and beam elements for 3D analysis.

The numerical results exhibit that the proposed models may correctly represent behavior of a real wall in lifting, applying elastic materials parameters.

Keywords: wood-framed wall, vertical lifting, analytical model, fastener

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1. INTRODUCTION

Ecological and environmentally friendly wood framed buildings remain very popular in the construction world. Despite different opinions on the durability and long technical life of concrete and masonry structures, the popularity of timber buildings is still rising and also in individual investments. During many decades of improvement of wood-framed with sheathing buildings, they are undergoing a metamorphosis and different stages of construction from the structure that had been completely built directly at the site up to automated plants where large wall, floor and roof panels are fabricated and finally transported to the location and then assembled with a crane and constructed. Prefabricated systems of construction with wood framed panels have been studied in Hu et al. 2007 [1], where transport and lifting of panels were considered. Lifting requirements are dependent upon the type of structural element being placed. Larger walls required the use of a spreader bar, while it was decided that a short wall or other type of structure would be lifted without the use of this tool, as indicated in Mohsen et al. 2008 [2]. Different types of lifting devices are used in case of heavy elements CLT or even modular elements, where methods of lifting determine the use of stiffer sling elements as discussed in Liu et al 2018 [10]. Dowel type connection, its materials characteristics, embedment strength, and axial withdrawal are strongly influencing parameters examined in the article from Ottenhaus [3]. Also considered are load-deformation characteristics and stiffness Jockwer R. [5], where variability of stiffness is evaluated for a row of fasteners and diameter of dowel. A beam on foundation modelling where nonlinear springs are used to model the contact zone between wood and a steel dowel, is examined in Lemaitre et al. [4]. Problems in assembly and construction of high buildings is discussed in Mills et al. [6]. Models analyzing wood framed structures were examined in Malesza [7], Malesza [8]. Three dimensional structure modelling is discussed in Malesza [9]. Process of failure of the wall in the final stage of loading can be evaluated applying the plasticity criterion formulated as the strength criterion for anisotropic material as it is presented in Dudziak et al 2016 [11]. Lifting pre-assembled trussed rafter roofs or other timber structural elements shall be avoided due to overstressing or buckling the structure Reynolds [12].

In the process of prefabrication in a factory, panels of walls are transported between different work-stands, being repeatedly picked-up, lifted and conveyed. Vertical transport of wall-panels out of a factory is performed when they are loaded to transport facilities and finally within the assembling process at the construction site. The total dead weight of a wall is suspended in this stage by several lifting slings, pointwise clasping, top plate of the wall panel. The cross-section of the wall top plate secures its required stiffness. This indicates that all weight of a wall is, in fact, cumulated in sheathing-to-framing fasteners, conventionally used staples linking sheathing boards with top plate of the panel. The staples in close vicinity of lifting slings are under the highest effort being mostly stressed. Figure 1 shows the procedure of picking up the wall (figure 1a) with a view on the lifting slings (figure 1b).

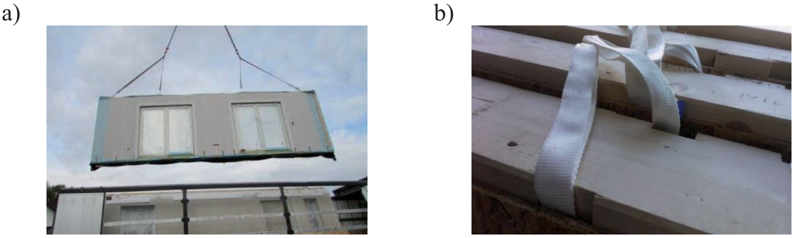

Fig.1. Wall lifting: a) at the stage of wall assembling on site, b) polyester sling braiding the top plate of panel

Walls are lifted applying polyester slings with the allowable working load (WLL) specified in the certificate submitted by the devices producer.

This article presents experimental investigations and analytical models evaluated for description of the light wood-framed walls in the process of lifting. Three different models are proposed in the article:

- model of beam on elastic spring supports (simple system with single beam) – BSS,
- model of assembled beams composing the top plate of wall frame linked through spring fasteners with the lower beams simulated boards of sheathing (assembled composite beam system) – ACBS,
- three-dimensional (3D) spatial FE model of wall with shell and beam element system – WFEM.

Adequate assumptions of the stapled connection and evaluation of board-to-beam joint material parameters covers the first stage of the analysis. These connections are converted in two variants in the form of spring elements in the walls beam models, and beam elements model in 3D of the FE method.

2. EXPERIMENTAL INVESTIGATIONS OF THE LIFTING SLING ZONES

2.1. WALL ELEMENTS FOR TESTS

Walls dimensions of 2.40x2.50 m were designed for experimental tests. Four full wall panels without any openings marked SP1, SP2, SP3 and SP4 and four walls SO1, SO2, SO3 and SO4 containing openings for windows were constructed. Walls of spruce *(Picea)* solid wood framings, as in Standards [15], [16], [17], incorporate studs of cross-section 50x180 mm distanced axially on 600 mm, bottom plate 60x180 mm and top plate 90x180 mm. Samples of wood used in walls construction were tested according to Standard [13]. Wooden framing elements were segmentally glued along its length. Both side walls were stiffened applying OSB3 boards linked to timber framing with staples Senco N19 with arms 1.53x44 mm, distanced at 60 mm in a single row each side of the beam.

In the walls constructed for the tests, the woven polyester slings detached braiding round the top without any fixing plate to the panel. Lifting slings were placed in the vicinity of the second stud from the wall edges

2.2. CONDUCTION OF TESTS

The test set up was assembled on a setting stand shown in figure 2. The wall was positioned and fixed to the steel setting stand and to the reinforced concrete heavy floor.

Wall handling polyester slings were attached to the traverse beam connected with a chain to the hydraulic motor-operator suspended and fixed to the upper beam of the stand. Loading P was increased with 2 kN increment up to a level of limited displacements of the top wooden plate of the wall. Top beam displacements were measured with a set of inductive gauges. Additional measurements were conducted in the other places of the wall (at the bottom plate). Displacements data were collected corresponding to varying stages of loadings. The obtained set of results was registered and collected to the computer system of deformation data.

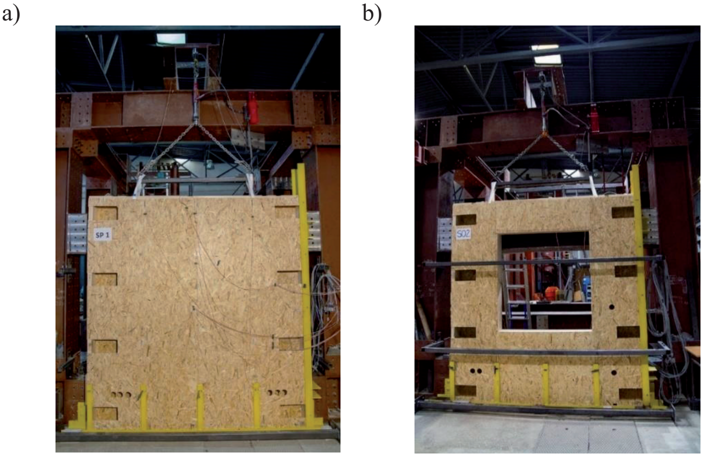

Fig.2. Walls and testing stand up: a) full wall, b) wall with opening

2.3. DEFORMATION AND DAMAGE RECORDED IN TESTS

The rising-up top beam (figure 3a) was observed within the test, as the main effect of active loading applied to the top plate of the wall, lead in consequence to the separation of this element from the remaining timber structure and sheathing. In figure 3b these effects are underlined as visible nails and a line drawn on the side plane of beam above the top edge of the OSB board. A noted displacement developed deformations of all fastening staples along the total length of the top plate. The highest values of these deformations were observed very close to the lifting slings as a result of active vertical loading. Simultaneously, deformations of linking staples along the timber studs of the wall were not observed even those located very near to the top beam (figure 3b).

Material defects of solid wood in the form of evident knots in the ending stage of loading led to the failure of the top plate. Displacement diagrams indicate that one line of deformation among the others significantly indicates receding compared to the remaining results.

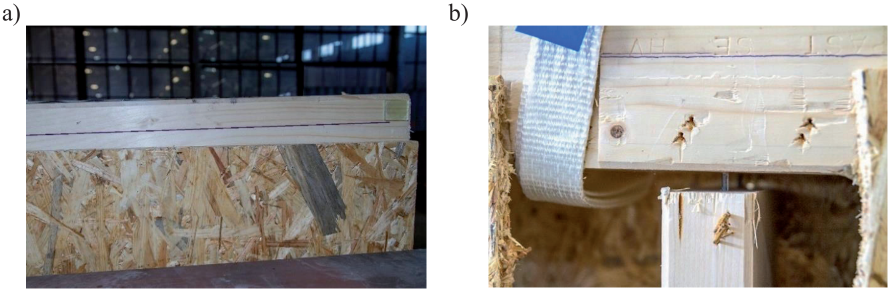

Fig.3. Deformations of wall without any openings: a) noticeable rising-up the top plate, b) visible deformation of linking staples along the top plate and no deformation of staples along the stud

The effect of uplift of the header with the top plate over the window opening has been observed in the perforated wall (figure 4). This phenomenon was observed during the first stage of loading presumably caused by the result of clearance elimination in the connection. This effect is shown in figure 4a and 4b, where a line marked on the side of the top beam is more remote (distant) from the edge of sheathing board on the lintel than in the case of the full wall sheathing board.

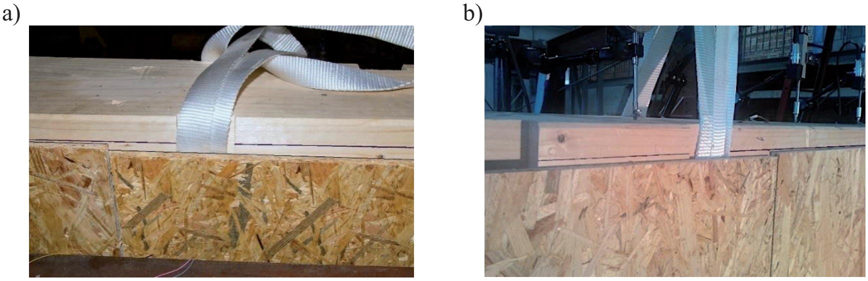

Fig.4. Apparent uplifting of the header with the top plate of wall with opening

3. THEORETICAL DEFORMATION ANALYSIS OF WALL IN THE LIGHT OF PROPOSED MODELS

3.1. MATERIAL PARAMETERS OF BOARD-TO-TIMBER STAPLED CONNECTION IN THE LIGHT OF STANDARD REGULATIONS

Fastener deformability slip modulus K_{ser} of stapled connection on the base of PN-EN1995-1-1:2010 adopted in the analysis is evaluated from the formula: $K_{ser} = \rho_m^{1,5} \cdot \frac{d^{0,8}}{80}$, where: d - fastener diameter, ρ_m – the mean value of connected materials density $\rho_m = 522.494 \frac{kg}{m^3}$.

According to the Standard, parameters of a single arm of a staple is considered as a nail of rounded section and it is calculated on the base of staple arms cross-section. For staples arm cross-section $1.3 \times 1.6\ mm$ the equivalent diameter of the arm shall be taken as $d = 1.44\ mm$, hence considering linking sheathing board-to-timber top plate fasteners on both sides of the header; the modulus of deformation can be taken as the value of $K_{ser2} = 2 \cdot K_{ser1} = 799.44 \frac{N}{mm}$.

3.2. MATERIAL PARAMETERS OF THE STAPLED CONNECTION IN THE LIGHT OF CARRIED OUT TESTS OF CONNECTIONS

To obtain the required parameters of stapled connections, 6 samples were made and their load-slip characteristics tested as in Standard [14] are shown in figure 5. The elastic stage of a single fastener characteristic is isolated for load close to $F_1 = 350N$. Mean results of connection deformability leads to evaluation of the slip modulus for the stapled connection as the value of $K_1 = 506.11\ N/mm$.

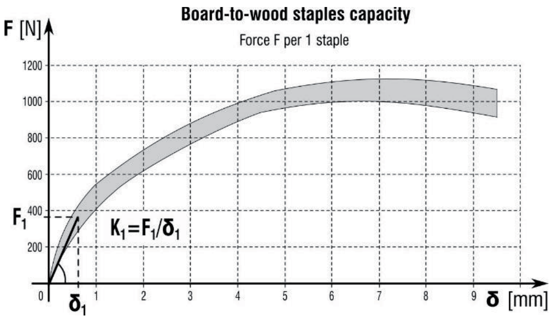

Fig.5. Experimental capacity of board to wood staples connection.

This result is adopted as a basic parameter to the proposed theoretical models to obtain results of deformations convergent with results of the test on walls.

3.3. MODEL OF BEAM ON ELASTIC SUPPORTS (SIMPLE SYSTEM) BSS

At the early stage of analysis the adapted model correctly projected the behavior of the header beam, however, it was not reflecting deformability in the other wall elements. Adapted simplification results from observed deformations of the top plate, were many times higher than those of the other parts of wall, during the experimental test.

The proposed model assumes fasteners sheathing-to-framing are regularly spaced along the top plate and is described as the spring supports K_1 characteristic. Modulus of the spring support is assumed as the slip modulus of two staples in value $K_2 = 2 \cdot K_1$ as shown in figure 6.

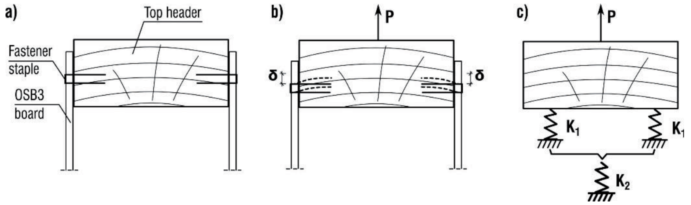

Fig.6. Connection of the timber top plate with sheathing boards: a) fasteners allocation in one cross-section of beam, b) deformation of staples in tests, c) spring elements describing fastening staples

Top plate modeled as a simple beam on spring supports representing BSS model is shown on the figure 7.

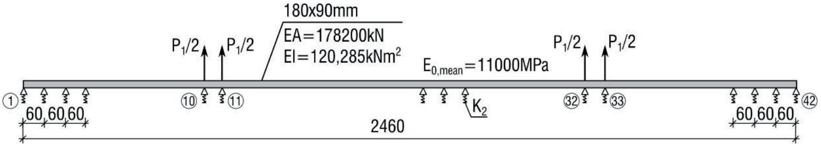

Fig.7. Top plate modeled as a simple beam on spring supports – BSS model.

Loading P_1 is applied along the top plate between two staples, hence in the analysis, the acting force is divided as acting to two adjoining nodes.

3.4. MODELS OF CO-ACTING BEAMS ACBS

In the succeeding stage an assembling model was proposed, where the top plate of the wall is linked applying springs to beam elements, substituting boards of sheathing elastically supported at the nodes where sheathing is linked to timber studs. The cross-section of those bottom beams corresponds, assumably, to the sections of two sheathing boards on an adequate wall section. The model allows to evaluate the deformation of the top plate and also the whole wall. Stiffness of the bottom beams supports is assumed to be the sum of staples stiffness along the height of studs. Figure 8 shows the conversion of the full wall into a system of contributed beams.

The top plate section of $180 \times 90\ mm$ and the bottom beams of section equivalent to two boards OSB $2 \times 12 \times 2500\ mm$ are adapted in the analysis of the full wall. Stiffness of springs elements linking top and bottom beams were K_1 and stiffness of the bottom beam supports were taken as $42 \cdot 2 \cdot K_1 = 42 \cdot K_2$ each.

In the wall with an opening, the beam of stiffness corresponding two OSB boards $2 \times 12 \times 350\ mm$ represents the header over the window. The header along the studs were linking by 2x8 staples, hence the stiffness of the beam spring supports over the opening was taken at an equivalent for 8 of K_2.

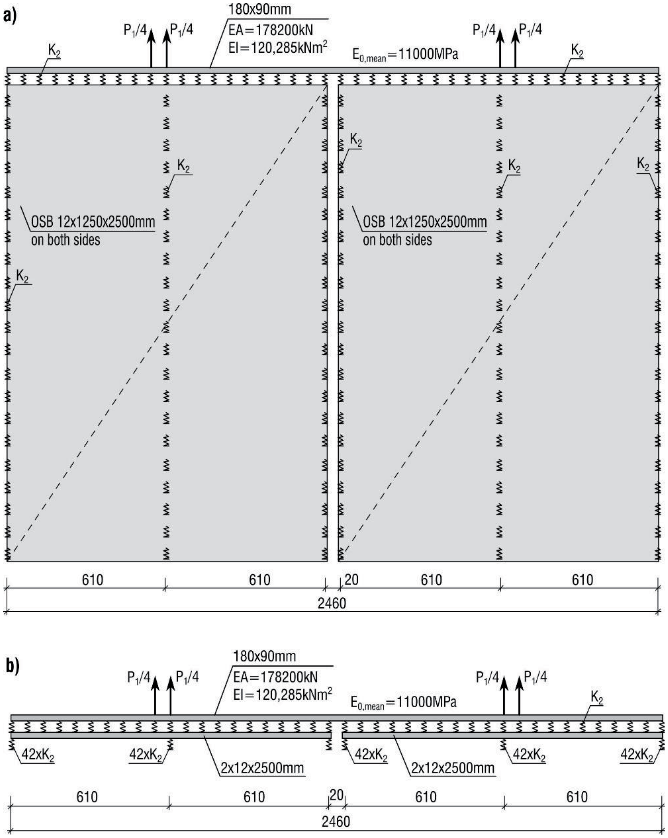

Fig.8. Conversion of full wall into system of contributed beams: a) connection of sheathing boards to timber framing and to the top plate in the form of spring fasteners, b) beams system linked with spring elements projecting the full wall – ACBS model.

The equivalent beams system model of the wall with an opening where two boards OSB $2 \times 12 \times 350\ mm$ are substituted by a beam of corresponding stiffness. Headers were connected through both sides of the boards with studs by 2x8 staples, hence stiffness of spring supports of the beam over the opening is taken as $8 \times K_2$. The diagram of the converted wall into the corresponding beam system is shown in figure 9.

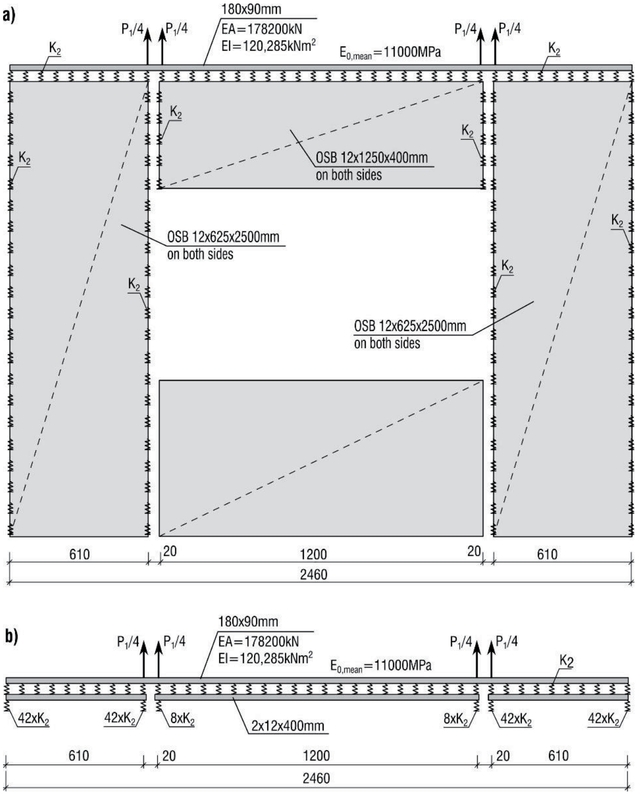

Fig.9. Conversion of wall with opening into corresponding system of beams: a) diagram of sheathing boards connected through springs of fasteners with timber frame and top plate, b) transformation of wall into beam connected with adequate stiffness springs – ACBS model.

3.5. COMPLETE FEM MODEL OF WALL APPLYING SHELL AND BEAM ELEMENTS WFEM

The walls models were evaluated utilizing the solution proposed in works [7] and [8], where studs, horizontal timber beams and sheathings are described applying shell elements of corresponding material parameters for timber and wood-derivative board (figure 10). Modulus of Elasticity for wood along the grain is taken adequately as $11000\,MPa$, and OSB board Modulus of Elasticity correspondingly $3500\,MPa$.

Beam elements were adapted as a sheathing to framing stapled fasteners in the FE method model of wall analysis. On the base of deformation, stapled fasteners in the experiment the length from the mode of failure was established at 12 mm. The diameter of the beam element was established from the characteristic load-carrying capacity per stapled fastener per one plane of shear $F_{vRk} = 627.74\,N$ that corresponds to a single nail with diameter $d = 2.23\,mm$. The modulus of elasticity of linear elastic material (metal stapled fastener embeded in wood) $E = 60024.71\,MPa$ is computed assuming transformation formulae of displacements method for both sides of a fixed beam with modulus of deformability $K_1 = 506.11\,N/mm$ according to the experimental test.

Shell elements dimensions adapted in discretization for the FE method model are adjusted to 60 mm of staple spacing. All analysis were conducted utilizing Siemens Femap software.

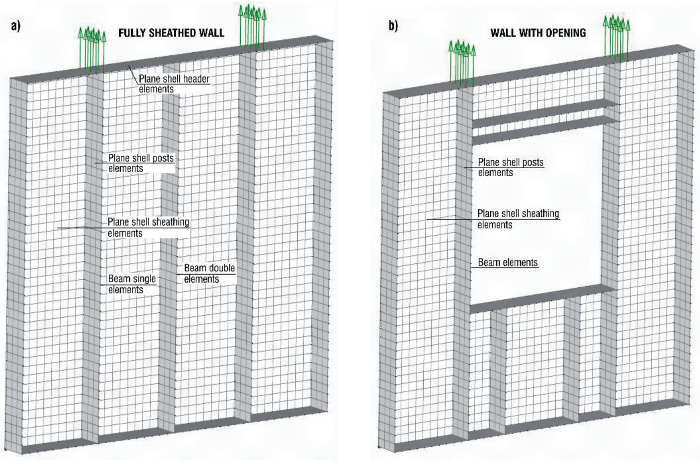

Fig.10. FEM 3D model of walls: a) full wall, b) wall with opening

4. RESULTS OF EXPERIMENTAL TESTS AND NUMERICAL ANALYSES

The results of displacement measurements and calculated from different models are shown in the form of diagrams. In figures 11, 12 are shown measured deflections of the top plates of full walls (SP1, SP2, SP3, SP4) compared with displacements obtained for varying models: beam on elastic supports (BSS), assembling beam system (ACBS) and 3D model of FE method (WFEM).

Some results vary significantly from the rest of the obtained data under rising level of loading in consequence of varying natural faults of materials (solid wood) or inadequately realized connections.

It is noticeable from the elaborated sets of results that there is convergence in the analytic models with experimental tests results in the range of $P = 8.0\ kN$ to $P = 20.0\ kN$ of imposed loadings to walls. Above these loadings theoretical models demonstrated higher stiffness than found in experimental behavior of structures. To a certain extent, applied linear-elastic stage of analysis indicates such behavior.

The model of beam on elastic supports (BSS) potentially allows for analysis and displacements evaluation of the top plate of the wall without any possibility of securing deformations of the rest of the structural elements. This structure indicates higher stiffness than from experimental tests. On the drawn diagrams, a straight line is located at the lowest level.

Models of co-acting beams (ACBS) indicate the lowest stiffness taking into account stapled connections of wall sheathing with timber framing. The row of stapled connections along the studs is substituted with a single spring element representing the sum of links stiffness, what seems to be a kind of analytic defect, nevertheless, in respect of displacements the obtained results are satisfactory.

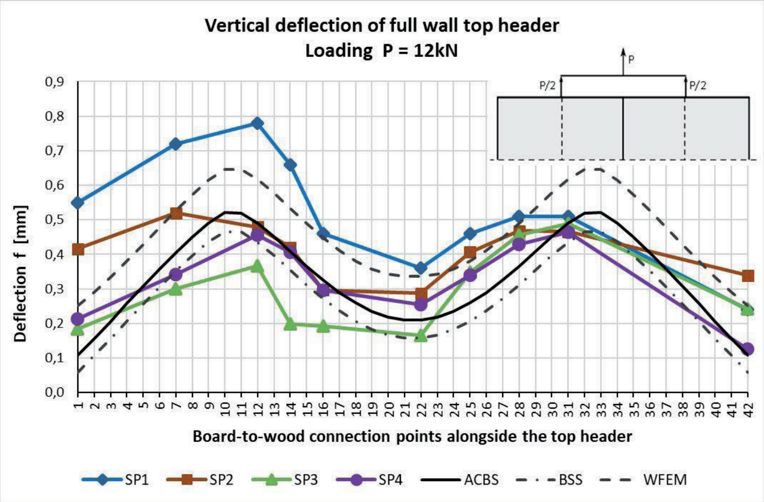

Fig.11. Vertical deformation of full wall top header obtained experimentally and numerically

The full 3D FE method model (WFEM) indicates the lowest stiffness and in the range of 16 kN to 20 kN shows adequate coincidence with the experimental test results. This model describes all connections in the wall.

Experiment and model obtained displacements of the top plate of a full wall under $P = 12\ kN$ loading are shown in figure 11.

The model of a beam on elastic supports (BSS) cannot be recommended for use in the analysis of walls with window or door openings (SO1, SO2, SO3, SO4), hence in figure 12 displacements are marked of the top plate and header above the window opening measured within the experimental test and results of deflections obtained from the model of co-existing beams (ACBS) and 3D FE method model of wall (WFEM).

In anticipation, the 3D model of the FE method displayed lower stiffness than the ACBS model of co-existing beams. Nevertheless, it was observed in the results of both models adequate projection of tests results obtained in experiments in the similar range of loading from $P = 8.0kN$ to $P = 20.0kN$ as for full walls.

The obtained experimental and o model displacements of the top plate and header of wall with an opening under $P = 12.0\ kN$ are presented in figure 12.

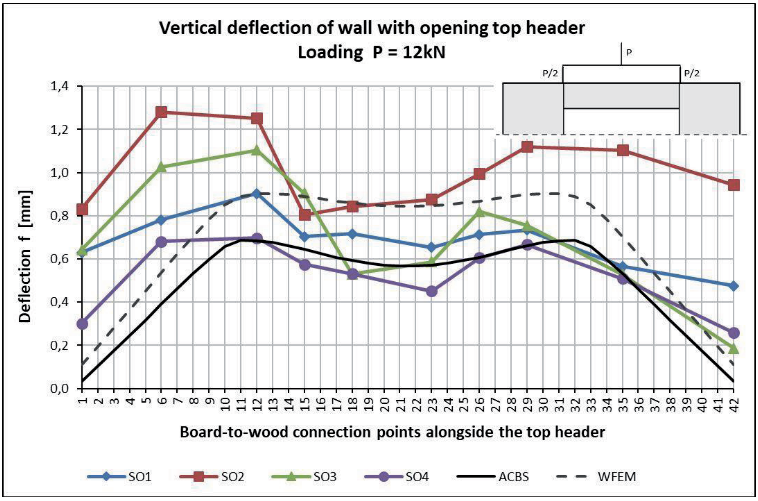

Fig.12. Vertical deformation of wall with opening top header obtained experimentally and numerically

5. SUMMARY

This article presents results of experimental and analytical investigations of wood-framed with sheathing full walls and walls with window opening. Tests and analyses refer to these parts of structures which are important from the point of view of up-lifting and vertical transportation. Locations of installing and fastening slings for lifting to the top plates in the wall without openings and fixed to the headers in the case of walls with openings have significant influence on static behavior of the whole structure. The effect of natural faults in solid wood and their impact on static work of the structure was additionally investigated.

Experimental investigations were conducted up to the failure stage appearing under loading $P = 50.0\ kN$ in the walls without openings and without any visible material natural faults, while in the case of wall with significant faults they undergo destruction under loading $P = 34.0\ kN$.

Forms of the top plate and linking sheathing-to-framing fasteners deformations and pattern of failures, specifically in the regions of active loading from lifting-up slings were obtained in the result of investigations.

Numerical and model analysis demonstrated adequate convergence with the experimental test results in the range of loading from $P = 8.0\ kN$ to $P = 20.0\ kN$. These varying loadings were determined on the basis of real weights of up-lifting wall elements and it was resulted from the linear-elastic stage of static behavior of stapled fasteners linking sheathing-to-framing of structures. Loadings exceeding $P = 20.0\ kN$ indicates in modeling investigations higher stiffness of structure than obtained from experimental tests.

The new proposed model of assembled beams (ACBS) projects with adequate precision factual behavior of wall structures under own weight-dead load in the process of up-lifting. It can be adapted in the design of different length of wall up to 12.00 m of varying geometry-configuration in respect of openings.

The proposed model can be easily used in the evaluation of fastener stressing, specifically allowing determination of spacing between lifting-up slings, securing safe transportation of suspended wall in assembling or placing to transporting trucks. As a criterion of safety, limited load-carrying capacity per fastener or limited deformation or load-slip characteristic of fastener can be used.

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List of figures and tables:

Fig.1. Wall lifting: a) at the stage of wall assembling on site, b) polyester sling braiding the top plate of panel

Fig.1. Podnoszenie ścian: a) w czasie montażu ścian na placu budowy, b) zawiesia poliestrowe okalające górny rygiel ściany

Fig.2. Walls and testing stand up: a) full wall, b) wall with opening

Fig.2. Ściany oraz stanowisko do badań: a) ściana pełna, b) ściana z otworem

Fig.3. Deformations of wall without any openings: a) noticeable rising-up the top plate, b) visible deformation of linking staples along the top plate and no deformation of staples along the stud

Fig.3. Deformacje pełnej ściany: a) zauważalne podnoszenie górnego rygla, b) widoczne deformacje zszywek w ryglu górnym i brak deformacji zszywek w słupku

Fig.4. Apparent uplifting of the header with the top plate of wall with opening

Fig.4. Widoczne unoszenie nadproża wraz z górnym ryglem

Fig.5. Experimental capacity of board to wood staples connection.

Fig.5. Nośność doświadczalna złącza na zszywki.

Fig.6. Connection of the timber top plate with sheathing boards: a) fasteners allocation in one cross-section of beam, b) deformation of staples in tests, c) spring elements describing fastening staples

Fig.6. Połączenie górnego rygla z płytami poszycia: a) rozmieszczenie łączników w jednym przekroju belki, b) deformacja zszywek, c) opis zszywek elementami sprężynowymi

Fig.7. Top plate modeled as a simple beam on spring supports – BSS model.

Fig.7. Górny rygiel ściany jako belka na sprężystych podporach – model BSS

Fig.8. Conversion of full wall into system of contributed beams: a) connection of sheathing boards to timber framing and to the top plate in the form of spring fasteners, b) beams system linked with spring elements projecting the full wall – ACBS model.

Fig.8. Zamiana konstrukcji ściany pełnej na układ współpracujących belek: a) połączenie płyt poszycia ze szkieletem drewnianym i ryglem górnym za pomocą łączników sprężynowych, b) odwzorowanie ściany za pomocą belek połączonych łącznikami sprężynowymi – model ACBS

Fig.9. Conversion of wall with opening into corresponding system of beams: a) diagram of sheathing boards connected through springs of fasteners with timber frame and top plate, b) transformation of wall into beam connected with adequate stiffness springs – ACBS model.

Fig.9. Zamiana konstrukcji ściany z otworem na układ współpracujących belek: a) połączenie płyt poszycia ze szkieletem drewnianym i ryglem górnym za pomocą łączników sprężynowych, b) odwzorowanie ściany za pomocą belek połączonych łącznikami sprężynowymi – model ACBS

Fig.10. FEM 3D model of walls: a) full wall, b) wall with opening

Fig.10. Przestrzenny model MES ścian: a) ściana pełna, b) ściana z otworem

Fig.11. Vertical deformation of full wall top header obtained experimentally and numerically

Fig.11. Pionowe deformacje górnego rygla ścian pełnych uzyskane w badaniach doświadczalnych i numerycznych

Fig.12. Vertical deformation of wall with opening top header obtained experimentally and numerically

Fig.12. Pionowe deformacje górnego rygla ścian z otworami uzyskane w badaniach doświadczalnych i numerycznych

ANALITYCZNE MODELE DREWNIANYCH SZKIELETOWYCH ŚCIAN DO OPISU DEFORMACJI W TRANSPORCIE PIONOWYM

Streszczenie:

Transport pionowy tarcz ściennych jest częścią procesu prefabrykacji szkieletowych budynków drewnianych. Cały ciężar ściany spoczywa wówczas na kilku zawiesiach zaplecionych wokół górnej belki ściany. Oznacza to, iż obciążenie to kumuluje się w łącznikach (zszywkach) łączących górną belkę z poszyciem ściany. W artykule opisano badania doświadczalne oraz zaproponowano modele obliczeniowe ścian poddanych odkształceniom w procesie podnoszenia. W badaniach szczególną uwagę zwrócono na miejsca zaczepienia zawiesi i ich wpływ na pracę statyczną elementów

konstrukcji. Dodatkowym efektem badań był wpływ wad materiałowych na zachowanie się konstrukcji.

Badania eksperymentalne prowadzono do zniszczenia, które dla tarcz bez otworów i bez widocznych wad materiałowych obserwowano przy obciążeniu około P=50kN, natomiast w przypadku tarczy z wadami materiałowymi obciążenie niszczące osiągnęło wartość P=34kN.

Dzięki badaniom uzyskano obraz deformacji górnego rygla oraz łączników poszycia i konstrukcji drewnianej w szczególności w obszarze bezpośrednich oddziaływań sił pochodzących od zawiesi.

W artykule zaproponowano trzy modele obliczeniowe do oceny deformacji ścian: model belki na sprężystych podporach (BSS), model belek złożonych z połączeniami w postaci sprężyn (ACBS) i przestrzenny model MES (WFEM). W modelach belkowych połączenia opisano za pomocą elementów sprężynowych, a w modelu 3D za pomocą elementów belkowych. Parametry materiałowe użyte w opisie połączeń określono na podstawie badań złączy na zszywki.

Analizy teoretyczne wykazała bardzo dobrą zbieżność modeli teoretycznych z badaniami doświadczalnymi w zakresie obciążeń P od około 8kN do 20kN. Ten zakres obciążeń określono na podstawie rzeczywistych obciążeń wynikających z ciężarów podnoszonych elementów, ponadto wielkości tych obciążeń wynikają z liniowo-sprężystej fazy pracy łącznika w połączeniu płyty poszycia z konstrukcją. Obciążenia powyżej P=20,00 kN wykazują w analizach modelowych większą sztywność niż to wynika z rezultatów badań doświadczalnych tarcz.

Zaproponowany nowy, złożony model belkowy (ACBS) z dużą dokładnością odwzorowuje rzeczywistą pracę konstrukcji ścian na obciążenia ciężarem własnym w procesie podnoszenia. Może być zastosowany do ścian o różnej długości i konfiguracji otworów.

Model ten w łatwy sposób może służyć ocenie wytężenia łączników, a w szczególności określeniu takiego rozstawu zawiesi, w którym zagwarantowane jest bezpieczne przenoszenie ściany. Jako kryterium bezpieczeństwa można, w zależności od wymagań, przyjąć: dopuszczalną nośność, dopuszczalną deformację lub dopuszczalną podatność łącznika.

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