NEW APPROACH IN CONSTRUCTION OF THE WOOD-FRAMED RESIDENTIAL BUILDINGS

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Summary:
Work presents actual directions in development of the wood-framed construction and examples of construction as well as the methods of industrial production of elements in practice.
Light wood-framed buildings constitutes significant percentage of constructed residential single family and multi families as well; as small commercial buildings realized in many countries. At about 47% building materials is based on wood and wood derivatives, in advanced technologically countries, while for their production is used 4% of total value of energy used in building industries. Buildings of this type are constructed in the form of large panels elements (walls, floors and roofs) or directly constructed on the site using previously made individual elements like studs, beams, lintels, bottom plates, rafters, top plates. Nowadays more buildings are constructed using large panel construction achieving better quality of industrially made elements and shorter time of assembling of building.
Problems of formation, static and dynamic analysis and construction of the light wood-framed varying structures are presented in the work. Due to specifics of these structures in the phase of construction and exploitation all problems shall be considered together. Special attention shall be paid to deformation of light wood-framed structure and their sensibility on environmental conditions, flammability. Adequate selection of analytical models in static analysis and models reflecting thermal and moisture behavior of timber structures are to considered at the stage of design. Quality of assembling at the site comparably to the quality of elements obtained from factory production shall be always considered because of high level of prefabrication.

Keywords: wood-framed structure, 3D behavior, modular structure, transport and lifting, analytical models

Introduction

Light wood-framed buildings constitutes significant percentage of constructed residential single family and multi families as well; as small commercial buildings realized in many countries. Economic transformation in Poland forced energy saving also in building industry. Search of new solution brought to conclusion, that the light wood-framed construction is one of the highest energy saving and ecological type of buildings. These kinds of buildings are commonly constructed in USA, Canada, Scandinavian countries, as well as in Australia and Japan (Asiz et al. 2005), (Breyer 1993), (Miedzialowski, Malesza 2006). Within last three decades industry and construction of these buildings is also developed in Germany and Austria (Schulze 1996), (DIN 1988). Lumber used in the wood-framed structure is a renewed material in case if management of forest resources is planned and provided according to economic roles, and in addition preserving pro-ecological activity. In advanced technologically countries, at about 47% building materials is based on wood and wood derivatives, while for their production is used 4 % of total value of energy used in building industries. Hence, selection of wood as a building and structural materials is well grounded. Low own weight in the wood-framed construction in the range of 0,30 ÷ 1,00 kN/m^2 and its profitable proportion comparing to the live load increases effect of energy saving due to lower energy consumption within realization and assembling of building.

Light wood-framed buildings are constructed in the form of large panels elements (walls, floors and roofs) or directly constructed on the site using previously made individual elements like studs, beams, lintels, bottom plates, rafters, top plates. Actually more buildings are constructed using large panel construction achieving better quality of industrially made elements and shorter time of assembling of building. Structurally, the most sensitive elements provided on the site are all types of connections (Mohammad 2006).

Work presents actual directions of development of the wood-framed construction and examples of construction as well as the methods of industrial production of elements in practice.

Varying building construction on the base of timber

Timber is one of the oldest building material used in varying structures. Widely known buildings with timber bar (vertical) or timber log (horizontal) construction - figure 1a, solid timber posts and beams constructions with masonry bricks or hollow-blocks infill (Prussia masonry) - figure 1b, studs and beams construction with diagonal bracings – figure 1c, Wood-framed with sheathing – figure 1d.

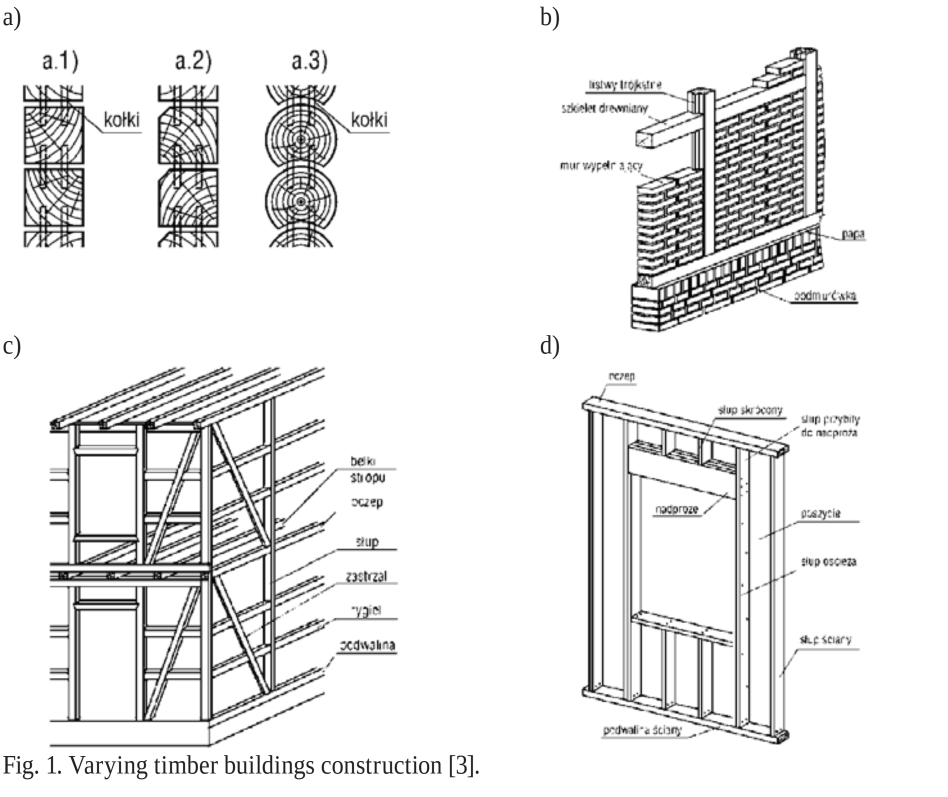


Fig. 1. Varying timber buildings construction [3].

Actually timber buildings are constructed in the wood-framed with sheathing technology, being the most economic and elastic in formation and technology. Low own weight facilitates their full prefabrication, hence industrial production of wall, floor and roof panels, decreasing time of elements production and whole building assembling. Assortment and products line of large wood-framed with sheathing elements: wall, floors and roof diaphragms raises quality of production, decreasing time of assembling of the buildings. Products line and varying light wood-framed elements do not need labor - consuming processes and intricate moulds or shuttering indispensable in reinforced concrete framed or large panel structures.

Different structure-technological systems of timber based construction were developed abroad. These systems can be divided into three groups:

- system of stud and beams as a separately constructed elements (assembler on the site studs, joists, girders, rafters and boards of sheathings),
- system of precast construction using plane elements (wall, floor and roof slabs) – slab-type of precasts,
- system of 3D spatial elements – modular construction.

Plane elements were industrially produced in Poland under name of Stolbud, Namysłów, Sępólno, Mikołajki, and lately were organized precast unit production plants: PRIBO in Suwałki, Danwood and UNIBEP in Bielsk Podlaski. At the beginning, systems of the wood-framed construction were mainly transferring without any objection examples from USA and Canada. In this way in dependence to the sections of elements and details of construction it is recognized an American or Canadian system of construction. It is very well known troubles in Poland with these construction due to their low stiffness and thermal-moisture problems.

Foundations of the light wood-framed buildings are similiar to those traditionally constructed, but there are to be considered the following factors:

- low dead load of the structure requires adequate anchorage in the foundations,
- wood sensitivity on moisture conditions, possibility of biological corrosion requires careful design of moisture protecting isolation, adequately high level of foundation setting and possibility of drying wood (specifically girder beams and ends of the floor joists),
- the thermal insulation of foundation should be carefully designer and constructed.

Three-dimensional behavior of buildings

In building of the light wood-framed, structure spatial 3D stiffness remains the main requirements in the process of the bearing structure design (Schmidt et al. 2000), (BS 1988), (BS 1991). The main principle in securing of the 3D stiffness in the framed or wall structures remains providing of the shear wall. This walls with big lateral stiffness, which are transferring all horizontal forces and loadings acting to building. Remaining structural elements in building like columns bearing the girders or bidding rafter (purlins) can be dimensioned for vertical load only. Lateral load is acting from different directions, what requires allocation of shear walls longitudinally and transversally in the building. These longitudinal and transverse stiffening walls create in joint and connections spatial sets of elements being stiff enough in both directions.

Floors cooperating with walls are acting as the horizontal diaphragms, securing uniform share in transfer ring the lateral load. This share is adequate to wall stiffness under bending in the wall plane. Check of the 3D building stiffness remains import ant part of static analysis of structure. Correctness of this computations depends on fulfilling of adequate structural requirements, specifically, connections continuity in vertical joint of walls and floors and walls in horizontal joints. Horizontally, ties along the walls are securing of spatial building stiffness and in case of girders, continuity of transferring load shall be secured on both sides of the bearing beam where wall diaphragms are to be adequately joined to the foundations or lower structure. Significant part in spatial stiffness of the light wood-framed building takes fire separating walls constructed as a masonry structure specifically in case of row building construction.

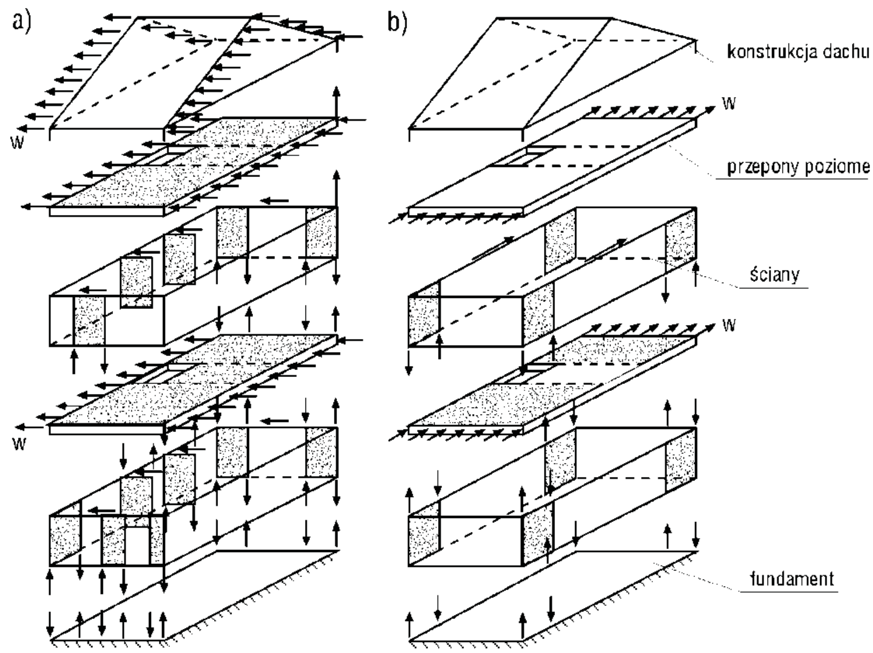


Fig.2. Redistribution of lateral loads to structural elements of building (Schulze et al. 1996), (Kuttinger et al. 1992): a) wind load to the longitudinal wall, b) wind load to the transversal wall.

Diagram of wind loading to building and arrangement of the stiffening walls as well as the principles of load distribution on individual walls is presented in figure 2.

Methods of analysis and design of modular structures are based on analysis of design of timber diaphragms with sheathing including in the process of design selected aspects of transportation, lifting and assembling. Construction of individual module in the range of vertical and horizontal loadings is similar to the assumption taken in the diaphragm of light wood-framed structure analysis according to figure 3. Specific approach is required in case of lateral loading and stability problem, hence combination EQU in EC0 and PN-EN 1990 shall be included in analysis. In case of higher buildings (multi storey buildings) and adequately not high value of vertical loadings in adequate configuration and geometry of building, the tie-up module forces can arise and effect of anchoring shall be necessary. Proposals of assembling and stabilization of structure with securing of 3D stiffness of the structure is presented in (Schmidt et al. 2000).

Buildings in traditional construction

The first buildings in technology wood-framed Baloon Framing were designed and constructed at the beginning of XIX centaury. In this type of structure the external walls are continuously constructed from foundation bottom plate up to the horizontal top plate where roof rafters are supporting and the studs are not divided into the first (ground) and the second floor. In this solution consumption of lumber is rather low due to elimination of top plate in the wall of the first floor and bottom plate of the second floor wall. This solution shortens the time of assembling and makes lighter in result of use studs with smaller dimensions of the cross-sections than in the other types of construction. Diagram of building constructed in the Baloon Framing technology is presented in figure 3a.

Buiding in technology of panel construction

New solution developed in the wood-framed technology construction leads to industrial production of building elements. Platform Framing technology, where in sequence walls of the ground floor, floors over the ground floor and walls of the second floor and finally roof are installed, replaced the Baloon Framing technology at the beginning of XX centaury. This system of construction allows for higher degree of prefabrication and panels are built in industrial manner in factories-plants.

a) b)

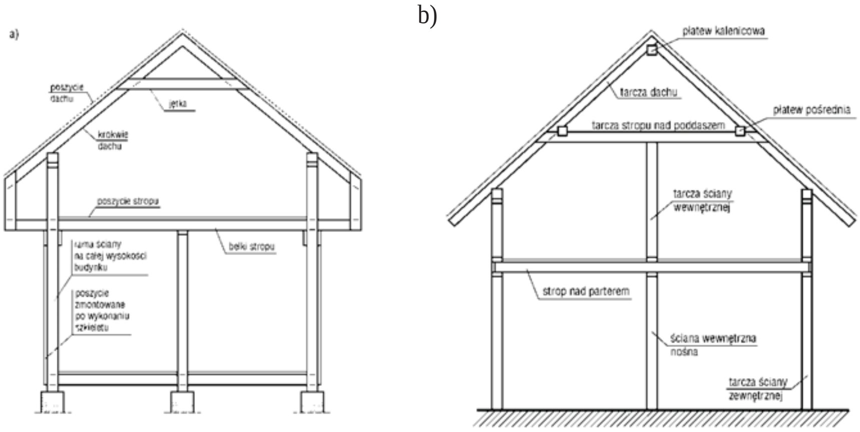


Fig.3. Diagram of buildings constructed in: a) Baloon Framing technology, b) platform technology.

As far as the dimensions are concerned, there are buildings constructed of large panels or small panels (figure 4).

a) b)

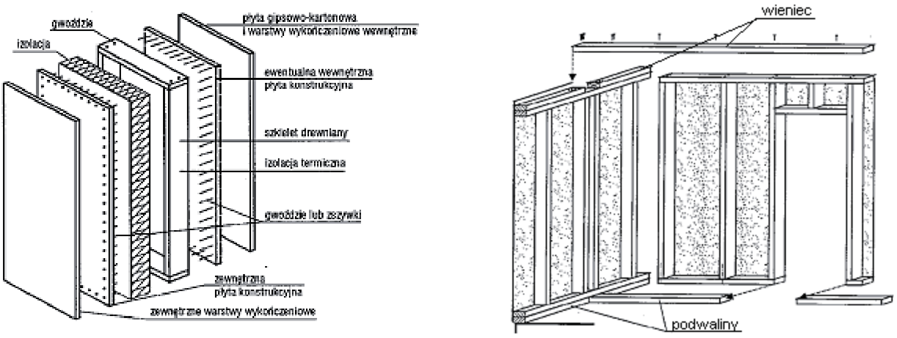


Fig. 4. Wall diaphragms (panel) construction in plate buildings construction:
a) structure of the single unit wall plate, b) joining of the neighboring walls using timber tie.

In the process of the light wood-framed buildings design, the long-term behavior of structure like: rheological factors, degradation of material parameters and influence of temperature and moisture shall be taken into account.

Plants processing elements used in the wood-framed structure is based on the stream method of production, stationary method or combined methods of panel construction. In the stream method, wall, floor or roof element moves to succeding workplace where they are completed. At the sequent workplaces elements are completed, obtaining final form of product. At the commencement of the process, elements are in horizontal position where studs and top and bottom plates are positioned giving the framing of diaphragms, and then the panel is positioned vertically for final completion and finishing phase of wall or floor.

Part of line with horizontally positioned elements is presented in figure 5a, while vertical stand is shown in figure 5b.

a) b)

Fig.5. Stands of stream line production: a) horizontal, b) vertical.

In the stationar method, the composition of diaphragm is conducted on one workplace, where all assembling operations are done sequently. These stands are horizontally positioned or they are inclined (tilt stand).

Industrially composed diaphragms are transported to the site and directly from the trucks they are assembler as it is show in figure 6.

a)

b)

Fig. 6. Building assembling using large panel directly from the transportation truck.

Modular types of buildings

Modular buildings are prefabricated buildings consisting of so-called modules, the six sided boxes (cuboidal) constructed in a remote facilities, then transported to their intended site of assembling. The modules are set on the building's foundation and then joined together to make a residential, hotels, school, office or commercial building. Similar way of construction using three-dimensional modular reinforced concrete precast elements was used in Poland, but it was limited to the WC units and partly kitchen in multi storey large panel construction of block of flats. Low own weight of the 3D elements in use of the wood-framed structure allow to construct also multi storey residential buildings. The module are placed side-by-side, end-to-end or stacked up to four or five stories in height assembling various configuration and style in designed building layout.

Modular buildings should conform to all building codes for their expected use. Residential modular buildings can be built on the steel frame or in the technology of wood-framed with sheathing construction (CSA 1992), (NAHB 2002). The modular buildings may be used for long-term, temporary or permanent facilities in construction of different use. Modular components are typically constructed on assembly lines, and then completed modular segment is transported and assembled on the site, hence they are essentially indistinguishable from typical site construction structures. Materials used in modular homes are the same as site constructed homes. Wood-frame with sheathing floors, walls and roof are typical conforming to typical light wood-framed constructions. Usually modular structure is designed to be stronger than traditionally constructed building even when large panel construction. Nails and staples joints are usually replaced by screws in addition glued to help modules maintain their structural integrity while they are transported on trucks to the construction site. Prediction of building strength is rather difficult since the modules need to endure transportation stresses and assembling while handling by crane all segment, where the traditionally constructed houses never experience these stressing (Asiz et al. 2005). For this reason modular houses usually contain higher use of lumber. On the opposite site it is obtained final result in the form of ready for finishing works building in shorter time than traditional or even large panel construction based on the wood-framed structure with sheathing.

Modules assembled wall-to-wall or one on the other in four to seven stories construction create buildings of varying configuration, geometry and architecture style. Figure 7 presents completion of module segment and assembling phase. Figure 7c presents assembling of traditional building structure composed of large dimension panel (Miedziałowski, Malesza 2006).

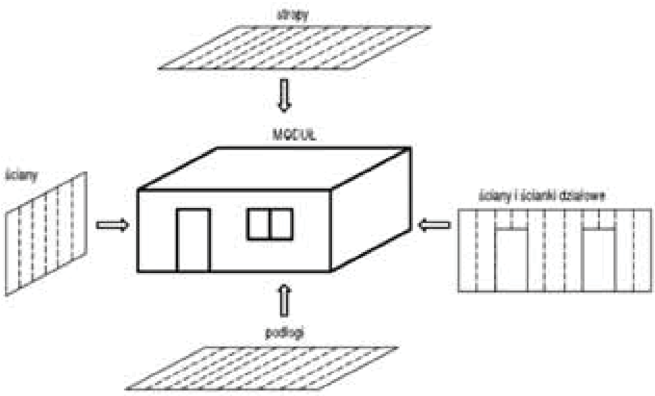
Design and method of analysis in case of modular structure is based on analysis of wood-framed diaphragms including some aspects of analysis concerning the handling, transportation and assembling as well as the dynamic aspects of analysis.

Strengthening of all structure and increase of its stiffness is required due to additional load resulting from lifting of module segment and process of transportation to the site of construction very often several hundred kilometres. Final product in the form of module building is ready for final finishing works in any possible time, even comparing to large panel technology, where industrially constructed in factory panels also reduce the works at the site. Modular segments consist light wood-framed horizontal, inclined as the roof or vertical diaphragms, hence they constructions are similar like individual panels. These diaphragm-panels are assembled in segment-building not at the construction site, but in the plant where they were provided, what is shown in figure 7.

Transportation phase depends on the distance from plant (CSA 1992), for example:

- transport by trucks to the other transportation equipment,
- railway transport or transport shipping,
- truck transport to the assembling site.

a)



b) c)

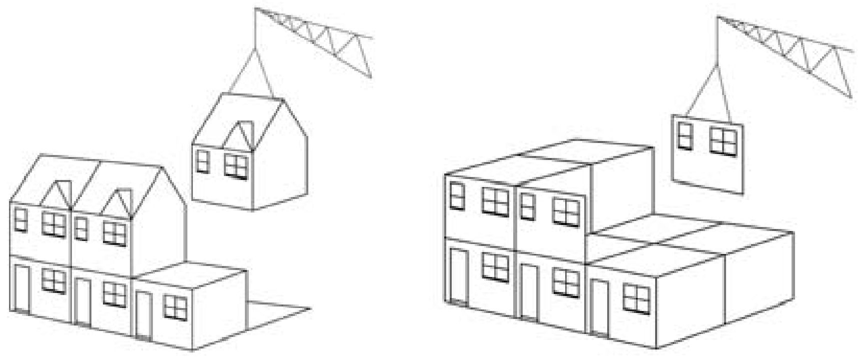


Fig.7. Completion and assembling of modular structure: a) completion of module, b) assembling of modular building, c) assembling of large panel building.

At each stage repeatedly occurs very sensitive lifting and handling of module by crane, and concurrent forces are acting on the 3D element. These forces and loadings are not acting in normal exploitation. There are for instance centrifugal forces during transport by the truck along the road horizontal curve (CSA 1992), or action to the module in result of impact or tilt during the see transport (NAHB 2002).

Prediction and evaluation of load bearing capacity of modular structure is complicated because structural module elements are subjected to stressing not only in exploitation but also within production, transportation and using crane. Traditional structures assembler at the site are not subjected these kinds of stressing under 3D form of module and acting varying forces.

Numerical model of the wood-framed with sheathing structure and selected results of experimental tests are presented in (Miedziałowski, Malesza 2006) to explain the behaviour of composite wood framed three-dimensional wall and floor panel. Wall and floor diaphragms as the three-dimensional composite structure are modelled applying plane shell elements representing framing and sheathing and beam element describing the fasteners. Experimental tests were conducted on typically disposed the wood-framed wall and floor diaphragms in residential housing in Poland. Associated tests of materials and connections and their results are also included in the paper. Nonlinear behaviour of fastener is examined in the numerical model. Results obtained from model and experiments conducted on wood framed panel construction are coincident.

Design and method of analysis in the range of exploitation, transport and assembling including lifting are completely different in the dynamic aspect of analysis. Analytical model of 3D structure is more complicated and cannot be conducted for individual diaphragms. Assembling of module is in stationary factories. Sub-assembling of individual module elements – ceiling, walls, floor is on the special automated production lines, and then they are completed and assembled in three-dimensional structure. Individual elements are assembled in stationary or stream system. Usually ceilings and floor diaphragms are sub-assembled on stationary stands while walls are sub-assembled in the stream system. Figure 8 presents sub-assembling of module composing elements and their completion.

a) b)

c)

Fig. 8. Stages of module assembling: a) sub-assembling of floor elements, production of wall panels, c) assembling of module structure (UNIBEP)

Phase of transportation is very often compared to repeated dynamic action, however the values of these action are not so high. Except typical transport conditions, during transportation; semi-trailer undergoes deformation, slide down of module from trailer or traffic collision causing additional loadings. Experience from varying countries (CSA 1992), ((UNIBEP) shows, that structure of module not always undergoes damages, sometime defects and failure occur in the finishing inside. Correct structure and construction play significant role in module behavior. The longest distance of transport is 400-600 km. The route of transport and Road existing engineering infrastructures are limiting the dimensions of module. Usually 485 cm wide and 410 cm height are limiting dimensions of module in case of road transportation due to keep clearance gauge of engineering structure existing along the route. The length is limited to 1830-1980cm. Figure 9 presents stage of trailer loading and unloading and readiness to transport, and figure 8 presents scheme of static behavior of segment in transportation.

a) b)

Fig.9. Loading (a) and transport of modules (b)

Modules at the site are assembled „one on the other", creating form of building. In this phase are used the same lifting sling like in phase of transport. Usually assembling from the wheels – directly from the trailer is used. At the site module require cranes dependely on number of floors and range of lifting.

Bolts along the ceiling and floor joists are used for connection, and twin-walls are linked with fasteners (BS 1988). Assembled and connected according to the arrangement modules are ready for finishing works. Modules with their installations and partly ferniture make 80-90% of whole work to be conducted with building. Module assembling is shown in figure 10.

Single module unit weight is equal to 15 – 16 tons (150 kN). Module should be designer as to fulfill ULS and SLS (CSA 1992), (PN-EN 2010) as the basic in design of according to limit state requirements. In all stages and in the phase of realization with lifting and transportation the stressing appearing within the exploitation phase is exceeding. Some parts of structure requires higher use of material then in traditional structure. In referencing sources are not described parts of structure overstressed and defected under overloading in the range of excessive deformations under transport and lifting. Hence, advanced 3D analysis of module structure and its loading or overloading is required and highly recommended. However, it shall be taken into account fact, that sometime not significant defects and discontinuity of connections may lead to unfavorable effects in exploitation of whole building. Also dynamic analysis of vibration influence on structure remains the significant element in analysis, especially when we consider the height of multi-storey modular building (NAHB 2002).

a) b)

Fig.10. System of lifting of module: a) System of lifting slings in the chase of lifting, b) assembling of modular building

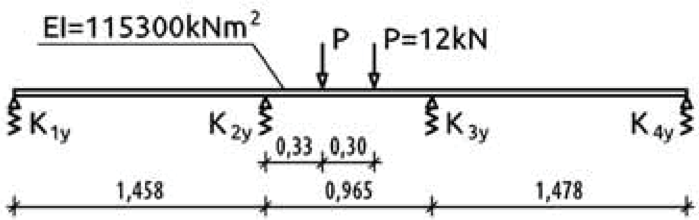
Summary

Problems of formation, static and dynamic analysis and construction of the light wood-framed varying structures are presented in the work. Due to specifics of these structures in the phase of construction and exploitation all problems shall be considered together. Special attention shall be paid to deformation of light wood-framed structure and their sensibility on environmental conditions, flammability. Adequate selection of analytical models in static analysis and models reflecting thermal and moisture behavior of timber structures are to considered at the stage of design. Quality of assembling at the site comparably to the quality of elements obtained from factory production shall be always considered because of high level of prefabrication.

Design analysis are conducted according to the following models: beam on elastic supports, 2D diaphragm (plate) elastically supported and 3D - three dimensional discrete model. The idea of modelling is presented in figure 11.

Spatial 3D numeric model of modular building based on the light wood-framed with sheathing structure is the only tool, leading to reliable analysis in the phase of lifting and specifically unfavorable phase of transportation of modular structure. Experimental tests of connections and properties of materials are to be conducted in the investigations. This model should be built on the basis of experimental and numerical analysis of diaphragms and their stiffness characteristics. The advanced analytical model with implementation of super-elements can be built, what may facilitate the analytical solution of problem (Asiz et al. 2005), (Schmidt et al. 2000), (NAHB 2002).

a)



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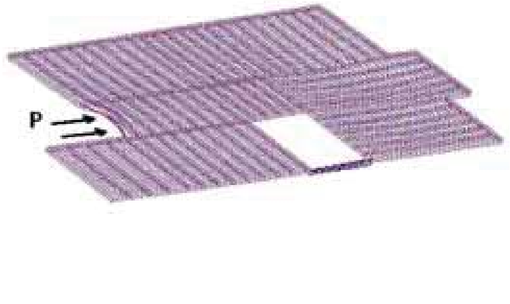

c)

Fig.11. Analytical models used in design of the light wood-framed structures: a) beam model, b) diaphragm 2D (plate) model, c) 3D model

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