Development of wood based sustainable construction methods for high-rise buildings under lateral loading

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ABSTRACT: The main objective of this paper is to show the benefits of using modern wood-based constructions for the more widespread practical applications in high-rise buildings. The advantages of using wood-based constructions, structural behavior, concerning constructive aspects and economy will be illustrated by the presentation of several research projects.

In modern timber buildings big openings in the façade are getting more common. This is why innovative bracing systems are desirable and should be more investigated. The idea is to create a bracing system without stiffening cores and bracing diagonals. The concept is to develop a so called “birdcage” where the stiffening elements are located just in the façade with using a shear stiff flooring system. Semi rigid joints between the vertical and horizontal elements are necessary to transfer the lateral loads.

1 INTRODUCTION

In modern high-rise buildings big openings in the façade are getting more common. This is the reason why innovative bracing systems are desirable and should be more investigated. In this paper several research projects related to this topic are presented.

The stiffness of a system with rigid connections is compared to the stiffness of a system with diagonal bracing (Figures 1 and 2). The systems consist in three bays. For the comparison the same amount of cubage is used. Just the cross sections are adapted to the system. These elements are made out of glued laminated timber with an E-modulus of 110 kN/cm². To all systems a lateral unit load of 100 kN is applied.

1.1 Bracing with diagonals

In the diagonal bracing system the posts have cross section of 3 900 cm² and the beams have 100 cm². For the diagonal bracing system the diagonals are simulated with the ½ E-Modulus for taking into account the diagonal connection. The cross section is 10cm/10cm.

Fig. 1a: Diagonal bracing system

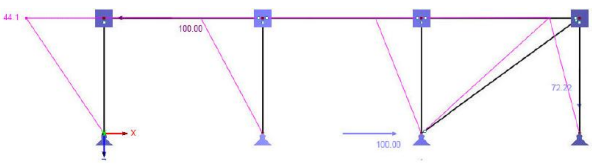

Fig. 1b: Displacement for diagonal bracing system

For the diagonal bracing system the horizontal displacement is about 44 mm (see Fig. 1b).

1.2 Bracing with (semi)-rigid joints

In the rigid connections system the posts have rectangular cross section of 900 cm² and the beams 100 cm².

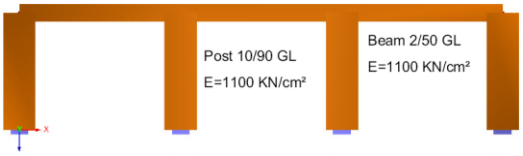

Fig. 2a: Rigid connections system

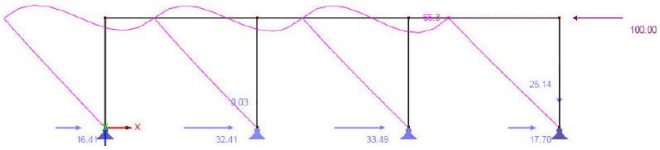

Fig. 2b: Displacement for rigid connections system

For the rigid connections system the horizontal displacement is about 66 mm (see Fig. 2b).

The comparison between the diagonal bracing system and the rigid connections system shows a one and a half time better performance in terms of stiffness for the diagonal system.

2 STIFFENING ELEMENTS OF “BIRDCAGE” SYSTEM

2.1 Vertical elements

2.1.1 Wall elements and anchorage system

The aim of research projects conducted together with a producer of cross-laminated timber (CLT) and the Austrian forest products laboratory was to minimize the number and size of the shear walls provided to resist seismic loads by using stiff massive panels and non-conventional high performance anchorage systems in steel. The shear walls should be produced in an economic production process using vacuum pressing equipment under a pressure of 1-2 kg/cm².

One objective was the optimal board configuration of CLT walls for resistance against lateral forces. These elements were optimized by the variation of the number of layers and their geometry. 12 wall types were produced. The dimension of all test samples was 120 by 280 cm (Fig. 3a). The quality of the boards was C24 according to EN 338 [1]. For estimation and comparison of static and dynamic resistance of different wall types against lateral loading several monotonic full size tests (referring to EN 594 [2]) were carried out (Fig. 3b, 3c). Finally 2 configuration types were selected for further cyclic tests referring to ISO 16670 [3] (Fig. 3d). The damping capacity of the whole element (shear wall in combination with the tension elements and the anchorage system) had been significant influenced by the plastification of the steel plates and the local plastification of the compressed wood.

The tests showed the similar efficiency of multilayer shear walls produced by vacuum presses in comparison to walls produced under high pressure with hydraulic presses. No fracture could be observed for the majority of tested walls. A vertical layer increased the load carrying capacity considerably and was necessary for such high loads. Under cyclic loading perpendicular laminated timber panels decreased their stiffness more significant compared to inclined laminated timber panels.

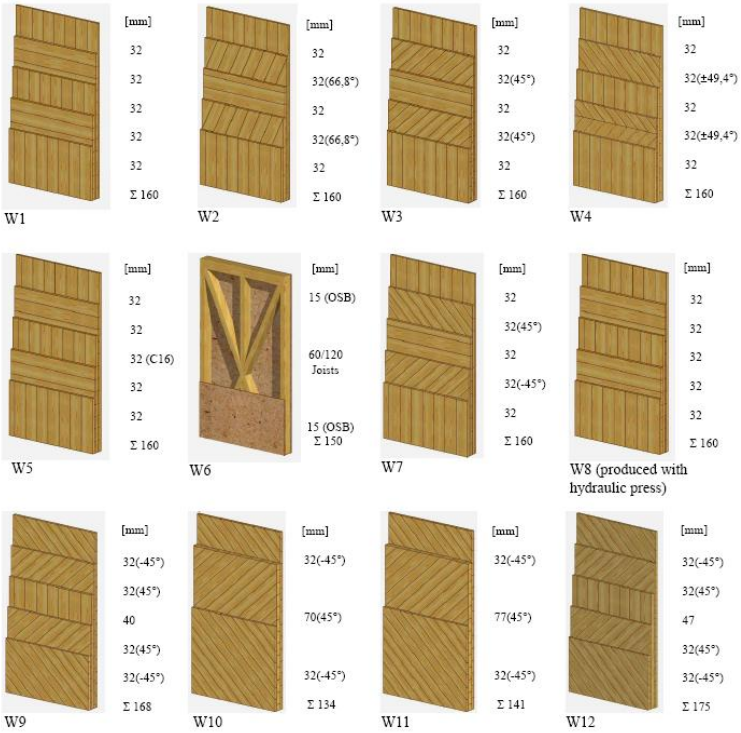

Fig. 3a: Panel types with thickness (mm) and angle of inclined laminated boards

Fig. 3b: Steel to steel connection of the tension element to the anchor

Fig. 3c: Dynamic testing of hybrid wall system with inclined boards

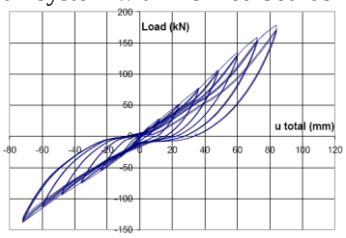

Fig. 3d: Load-displacement diagram of hybrid wall system with inclined boards (including displacement of the test apparatus)

2.1.2 Steel reinforced timber hybrid columns

An objective of the research projects was to develop innovative wood-steel composites as structural building components e.g., beams, columns or walls with distinctly improved fire performance characteristics [4]. The aim was to investigate and exploit beneficial thermal effects that arise when wood is combined with steel under the extreme conditions of a fire load, while keeping or, ideally, improving the structural efficiency of the building components under regularly assumed mechanical loads.

First attempts to exploit the effect of a possible thermodynamic interaction within wood-steel composites at the larger scale of structural components have been carried out at the Building Research Institute in Japan [5] where 4-hour fire-resistance tests were executed with steel sections encased in different types of glue-laminated timber (Fig. 4). The 60 minutes of fire exposure in accordance with ISO 834-1 [6] was appended with a 3-hour cooling phase. The most striking result is that certain steel-beam configurations displayed “self-extinguishing” behavior during the latter phase of oven cooling.

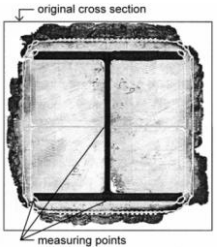

Fig. 4: Element section after the full 4-hour fire resistance test of the BRI [5]

To qualitatively assess the impact of contrary material properties on thermodynamic behavior, geometrically identical solid sections of wood and steel were simulated under the conditions of a standard fire load. The extremely high thermal conductivity of steel results in a fairly uniform temperature distribution over the section and most of the material's heat capacity is instantaneously activated as thermal inertia. Given the applied, non-linear temperature curve, the high mass density of steel produces a thermal response that is effectively linear and strongly damped, with a relatively small temperature gradient over the section.

By contrast, the weak conductivity of wood is further reinforced in the case of fire by the formation of a thermally protective charcoal layer that impedes heat penetration into deeper regions of the section.

Together with the minimal heat capacity given by wood's low mass density, these material properties result in surface temperatures that closely follow the applied temperature load. Within the section, the temperature rise is strongly delayed due to the high thermal resistance of the material. This thermally beneficial quality of wood as a construction material can be significantly enhanced under the extreme temperature conditions of fire by strategically embedding steel in the section. Steel that is fully encased in wood and thus protected from the immediate fire load can contribute its high thermal inertia to the composite behavior over a considerably extended time period.

2.2 Horizontal elements

2.2.1 Shear stiff floors

An aim of the research project was to develop innovative shear stiff floor systems in respect of reduction of the dead load and increasing the thermal insulation as well as minimization of the dimensions of the floor components [7]. These were optimized by the variation of construction layers and their geometry (Fig. 5).

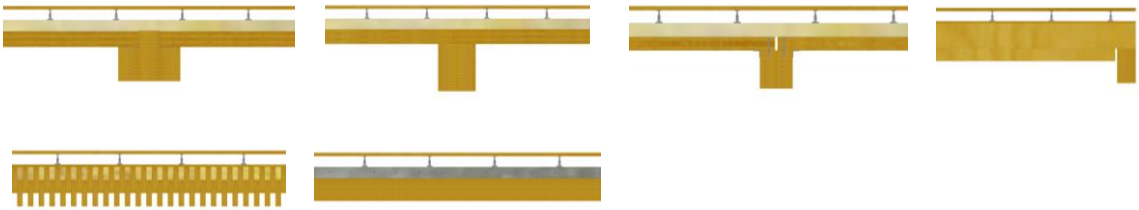

Fig. 5: variation of floor construction systems

In order to develop a multi-layer shear wall and shear stiff floor system composed of lightweight wood-concrete, the lightweight wood-concrete composites, the adhesives as well as the connection between these components and the timber sections were investigated with respect to strength, reduced dead load, fire safety, thermal performance and environmental consideration.
It included design concepts, feasibility studies and performance assessments as well as the optimization of manufacturing methods of the components in order to improve the overall performance. To achieve relevant results compatible to industrial applications following issues were evaluated:

- Strength tests and evaluation of the physical properties of the lightweight wood-concrete,
- Design of wall and floor components made of lightweight concrete connected to timber sections,
- Development of various sets of prototypes for testing,
- Shear and bending tests of the prototypes,
- Analysis of the experimental results to develop design concepts,

- using recycled wood particles and new additives
- Optimization of the manufacturing methods,
- Studies regarding the ecological impact,
- Evaluation of the thermal and sound insulation behavior.

This new technology involves the addition of wood material such as chips; saw dust, residual or recycled wood as permanent aggregate in concrete.

The composite of cement and wood-particles has been developed about 80 years ago and found its application in non-load-bearing building materials such as insulating boards. More recent applications concern wood-concrete bricks for formwork.

Wood was the first principal component of bearing systems in olden times, often completed by heavy layers of earth, plaster or other mineral materials to provide noise and fire protection

The upcoming concrete technology later conducted to heavy monolithic floor systems. Since 1980s, the idea of connected wood-concrete systems has been developed in Europe as an alternative to the European heavy concrete floors and to the North-American light wood floors (Fig. 6).

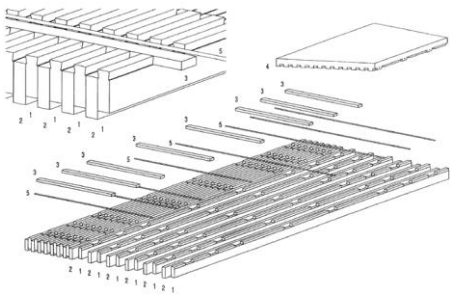

Fig. 6: Wood-concrete floor system development by D.Molard and W. Winter

The lightweight wood-concrete construction systems allowed:

- Use of wood both as permanent formwork and as concrete reinforcement;
- Reduction of the dead load and increasing the thermal insulation;
- Minimization of the dimensions of the timber and concrete components;
- Creation of environmental-friendly construction made of renewable resources;
- Reduction of energy consumption by using low-energy materials and energy-efficient systems.

The results provide a marketable component system for buildings that optimally uses timber sections and lightweight wood-concrete. The innovative technology combines the existing concrete tradition with the use of organic renewable resources.

Furthermore, this technology provides statically and energy-efficient components for low-energy constructions. Such products support rapid-assembly construction methods which use prefabricated dry elements to increase the efficiency of the construction (Fig. 7). Wood-based alternatives to conventional concrete or masonry construction also open opportunities to reduce the carbon emissions.

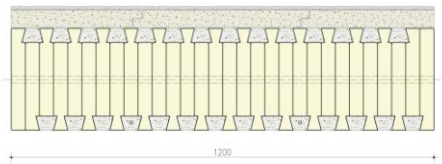

Fig. 7a: Timber wood chip concrete composite floors

Fig. 7b: Timber wood chip concrete composite wall

2.2.2. Steel reinforced timber hybrid beams

Similar to ordinary timber or steel beams, a hybrid structure requires verification of its safety against self weight, live load and horizontal load under a horizontal force, such as an earthquake or wind. Fire resistive buildings are also required to maintain building integrity in the event of a fire. Based on these structural performance requirements, the following hybrid construction system was developed (Fig. 8).

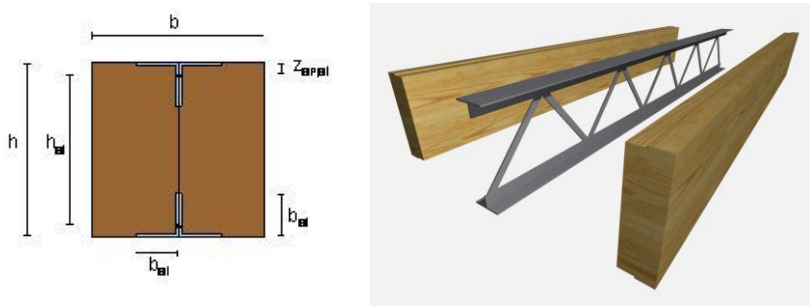

Fig. 8: Timber steel beams

Since the vertical deformation is equal between the timber and the steel frame, vertical load should be shared depending on their ratio of flexural rigidity, EI (E: Young's modulus, I: Geometric moment of inertia).

The timber and steel frame of the hybrid beam are joined at a beam edge using drift pins to transmit the load from the timber to the steel frame, so the steel frame bears all the shear force at the edge [7]. A lateral timber-based hybrid beam bears axial force and produces a reaction force of braces during an earthquake. The steel frame bears axial force, the timber frame functions as a buckling restraint, and calculations confirmed the absence of buckling within the safety limits of applied axial force.

3 DYNAMIC ANALYSES OF “BIRDCAGE” SYSTEM

The aim of this project is to investigate the seismic behaviour of a highrise timber building without diagonal bracing. The analysed building is 20 storeys high with 16 timber storeys based on 4 rigid reinforced concrete storeys which are not taken into account for the further dynamic analysis. A square plan of 27 by 27 meters with a plan area of 729 m² was chosen (Fig. 9).

The bracing system is located in the façade. It consists of vertical hybrid wall elements rigid connected with horizontal oriented glue laminated beams. The assumption of rigid connections is an approximation. The floor is supposed to be shearing stiff. Static and dynamic analyses were computed with finite element software [8]. The seismic calculation (response spectrum analysis) was based on the EN 1998 [9]. The stiffness of the wall panels for this calculated multi-storey building was fitted to the stiffness of the hybrid panel with inclined boards tested (Fig. 9).

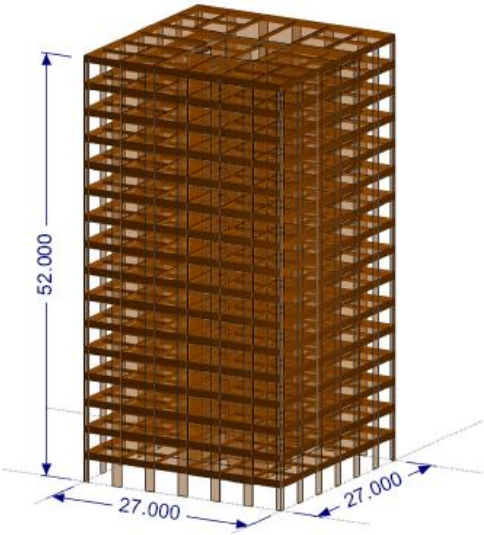

Fig. 9: Perspective view of investigated building

This fitting was based on the equivalence of elastic deformation in 3 static load increments.
For a first optimization there is a 20% grading of the cross sections of vertical elements every five/six storeys related to the increasing vertical load.
The assumed non variable input data's for calculations are:

- ground type "D"
- constant damping value of 5%
- type 1 spectrum (relevant for Austria)

The assumed variable input data's for calculations are:

- design ground acceleration "ag" of 1 m/s^2 (the ground acceleration for Vienna is ag = 0,87 m/s^2) and 3 m/s^2
- behaviour factor "q" of 2 and 4

The assumed fundamental basic wind velocity v_{10} is 135 km/h.
The calculated results for significant load combinations are presented in table 1.

Table 1: Results of static and dynamic analyses

		Ultimate Limit State				Serviceability Limit State		
Load combination		1,35G+1,5P	1G+1,5W	1G+1E+0,3P				1G+1W+0,5P
design groundacceleration[m/s²]	ag			1	3	1	3	
behaviour factor	q			2	4	1	1	
Period[s]	1 (x-direction)		3,96	4,58				4,95
	2 (y-direction)							
	3 (rotation)			2,6				
	4 (x-direction)			1,21				
	5 (y-direction)							
Support reaction[kN]	compression	1237	952	685	893			
	tension			0	88			
Displacement[cm]	total					~28,5	~85	49
	interstorey drift					~1,8	~5,8	
Displacement limit[cm]	$d_r^{\nu} \leq 0{,}01h$					0,9≤3,25	2,9≤3,25	

G… Dead Load; P… Live Load; W…Wind Load; E… Earthquake Load

The resulting loads of the dynamic analysis are very low due to the high flexibility of the structure.

4 CONCLUSIONS

Timber as an ecological and sustainable building material has a lot of potential to be discovered. Owners, contactors and architects benefit from a well designed multi storey wood-based structures. The advantages of such construction are:

- In case of earthquake the reduced weight and the high flexibility of the structure due to the bracing system are advantageous.
- The slender shear wall elements which are multifunctional as load bearing and stiffening and as façade elements which allow big openings are advantageous in ecological and economical reasons.
- The “birdcage” bracing permit very flexible arrangement for the useable area.
- With timber composite elements the use of the materials can be optimized in technical and economical terms and the connections can be executed in a simple way.

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