WOOD BASED CONSTRUCTION FOR MULTI-STOREY BUILDINGS. THE POTENTIAL OF CEMENT BONDED WOOD COMPOSITES AS STRUCTURAL SANDWICH PANELS

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ABSTRACT: The innovative combination of timber products with conventional concrete components and industrial textile will request investigations on the composition of lightweight wood-concrete, on the interfaces, compatibility, and composite action between the different components and materials, and on the optimisation of manufacturing methods in order to optimise a composite system by using the best characteristics of each material. Engineering knowledge shall be amended and stimulated by development of design rules and approaches, supported by comprehensive and scientifically robust background data presented in user-friendly and adapted tools.

KEYWORDS: Timber-lightweight concrete, wood chip concrete, building construction, structural engineering

1 INTRODUCTION

The building market has always been the most important mass market for timber products. Until First World War timber had always been together with bricks, clay and natural stone the most important building material. Even in the big multi-storey urban buildings at least the floors and the roofs had always been made out of timber since there was no other material which could be used in bending besides the expensive steel profiles.

In the 19th century, when all European cities grew very rapidly, the consumption of structural wooden elements for roofs and for long span floors (up to 10 m span made out of half trees) was very high and caused even a shortage in the timber supply and a dangerous overexploitation of the forests. The building techniques changed completely when cement based building components as cement blocks and reinforced concrete slabs and walls had been developed around First World War. Very rapidly the cast on site reinforced concrete floors replaced the wooden floors and the wood was only used as formwork made out of bad quality wood.

Structural elements in wood lost completely the multi-storey building market, at one side since the fire regulations did only admit combustible materials as wood for small buildings up to two storeys on the other side in view of the fact that the building companies which had been organised in the past as craftsmen associations; e.g. as the carpenters, had been overruled by big commercial and industrial companies using building components as cement, steel bars, bricks produced in big industrialised units and engaging unskilled labour on site. The small craftsmen companies as the saw millers and the carpenters had not the organisation and the capital to guarantee the fast erection of big urban buildings.

The “wood wisdom” of the craftsmen tradition of saw millers and carpenters was no longer used to develop urban timber buildings however to invent and to organise the production of prefabricated timber houses (in Austria 25% of the one family houses are prefabricated and in timber [8]), to invent formwork technology and to realise complicated formwork. Finally the cost of a building structure in reinforced concrete is composed by 1/3 for the concrete, 1/3 for the steel and at 1/3 for the formwork.

In this context very successful wood based panels had been developed, e.g. the three layer formwork panel composed of thin cross laminated layers of sawn boards which could easily be reused for several formworks or the cement bonded wood particle panels used mainly as

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lost formwork as thermal insulation, as fire protection and as support for the stucco. Austria was and is a key country for the production and the use of this type of wood based products.

Developments and applications of wood-concrete-based technologies have also been achieved in countries, where gravel and cement for concrete production are scarcely available, or where wood is available in great volumes and the local climate demands less insulation. Early and recent research of cement-bond wood particles or strand boards focuses on dimensional stability of such boards and their durability, while more recent research also investigates other options such as thermal storage capacity of the lightweight material [4] or finite element modelling [5].

2 MOTIVATION

In the most European countries, the building stock is dominated by multi-storey buildings from 3 to 8-10 floors (historically, European cities are “mid-rise” up to 20-25 meters at street front). High rise buildings and 1- or 2-storey family houses together count for far less than 50 % of the realized buildings. Today 80 to 90 % of the structures of new multi-storey urban buildings are realized in reinforced concrete; only 10 to 15 % of the structures are in steel. Timber as structural material could reach a market share of 5-10 % (Latin and Eastern countries) up to 10-25 % (German speaking countries) among the family houses in Europe but far less than 5 % of the new multi-storey buildings are in timber. Instead the importance of one and two family houses is decreasing because 70 to 80 % of the European population is already living in urban areas and there is no sufficient space to live in small houses. Multi-storey buildings for Infrastructure, for offices and for habitation mainly in the range between 3 and 8 to 10 stories are the most important sector of the future building market.

Relatively simple systems of timber-concrete composite elements for floor elements as well as shear connections have also been developed and applied in practice; however, these structural systems generally use heavy regular concrete and shear connectors with time-consuming installation methods. Additionally, these systems often need further installations to meet fire safety, thermal and acoustic insulation requirements.

The demolition of concrete structures is time-consuming, and the incurring concrete waste is laborious to recycle; furthermore, recycled concrete is only at the beginning of its practical acceptance for its application in structural elements.

These gaps can be filled in by multi-layer elements with a maximum use of wood (light wood-concrete compound instead of heavy regular concrete, in composite action with structural timber elements), appropriate shear connections and corresponding structural design approaches.

Mixtures of cement and wood-particles have already been developed around 1900, but they found their application mainly in non-structural building material such as insulating boards; many products are on the market using cement-bond wood wool, wood fibres or prefabricated powder for applications in surface finishing. More recent developments deal with wood-concrete bricks, complete walls for housing and wooden chips as insulation material. Manufacturers are from Austria, Belgium, Brazil, France, Italy, The Netherlands, Spain, Sweden, Switzerland etc. Many products have been patented and industrialised.

The development of these lightweight wood-concrete systems leads to a new, highly competitive generation of polyvalent multi-material building components (Figure 1). The application of wood-based, cement-bonded products could be considerably increased if applicability in structural elements is given.

Figure 1: Lightweight wood-concrete slab

These propose to develop wood-concrete compounds as a structural material, and to combine it with timber components into structural composite floor and wall elements, additionally providing further benefits for building physics and fire safety.

By using renewable resources, waste and manufactured wood products of the forest industry, this technology provides structurally efficient components for low-energy constructions, supporting rapid-assembly modular construction with increased efficiency through the use of prefabricated dry elements [13].

3 SCIENTIFIC AND TECHNOLOGICAL OBJECTIVES

The innovative combination of timber products with conventional concrete components and industrial textile will request investigations on the composition of lightweight wood-concrete, on the interfaces, compatibility, and composite action between the different components and materials, and on the optimization of manufacturing methods in order to optimize a composite system by using the best characteristics of each material. Engineering knowledge shall be amended and stimulated by development of design rules and approaches, supported by comprehensive and scientifically robust background data presented in user-friendly and adapted tools.
The innovative technology combines existing concrete tradition with organic renewable resources as an alternative to conventional concrete or masonry, thereby opening opportunities to reduce carbon emissions through the reduction of cement use and increased use of wood for construction since the carbon dioxide stocked in the wood is preserved for several decades instead of burning it.

Various research projects of Department of Structural Design and Timber Engineering (ITI) focus on the analysis and design particularities of elastically composed systems, especially with regard to girders in bending, on mechanical fasteners or other devices used to generate the composite action, on the long-term behaviour of such composite structures due to shrinkage and creep, and on methods appropriate for numerical and spreadsheet calculations [1, 11, 15].

4 RELEVANT RESULTS

As a structural model analogy on material level, the wood fibres in different forms, i.e. saw dust, chips, strands, wool etc., in the wood-concrete compound allow for a load-bearing truss embedded in the concrete, being able to transmit compression and also a certain tension.

To increase the effective depth, structural timber elements are combined with the wood-concrete compounds, since timber is an excellent material for tensile loading (parallel to the fibres, of course), and the wood-concrete compounds should primarily be loaded in compression and shear. It is principally possible to develop wood-concrete compound compositions such that they provide a sufficient resistance in compression, and also in tension to absorb local stress concentrations.

To create composite action between the wood-concrete compounds and the structural timber, mechanical fasteners are not used, since their punctual loading provoke high, unfavourable transverse tensile stresses in the timber. Shear connection are provided by form fit loading the timber elements locally in compression parallel to the fibres.

Different wood-concrete compound compositions can be arranged in the section of a structural element such, that they provide the necessary structural performance where it is needed: higher compression strength in the compressive (bending) zone where little tensile strength is required; well-balanced tensile and compression strength in the section core to absorb shear forces; higher tensile strength and little compression strength in the tension zone to support the structural timber elements in tension and for absorbing local stress concentrations in shear connections to the timber components. Shear connection between the different wood-concrete compounds are ensured by appropriate production processes (wood-concrete pouring “wet-in-wet”).

The elements provide a certain fire resistance, beneficial effects with regard to building physics and thermal energy after use, and above all, lead to more extensive and cascaded use of wood through substitution or completion of other building construction technologies.

The use of composite products of timber and lightweight wood-concrete was to be supported and stimulated by comprehensive and scientifically robust background data, which was presented in user-friendly and adapted tools for engineers [1, 2 and 3]. The following stages were proposed to achieve relevant results compatible to industrial applications:

- Development and optimisation of wood lightweight concrete using recycled wood particles, new additives, and textile reinforcement,
- Application of recycled wood particles and new additives,
- 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 (Figure 2)
- Evaluation of the thermal and sound insulation behaviour,
- Analysis of the experimental results to develop design concepts,
- Optimisation of the manufacturing methods,
- Studies regarding the ecological impact and the fire resistance by explorative tests (Figure 10).

![Figure 2: Shear tests](image)

4.1 Development and optimisation of wood lightweight concrete

Wood-based concrete mixtures were developed using forest and wood industry waste (hardwood particles and chips, saw dust, pellets, wood and clay mixtures, etc.) and recycled minerals as permanent aggregates and further additives. The mixtures were optimised with regard to structural strength, self-weight reduction, workability, manufacturing cost, environmental impact, thermal insulation and storage capacity, noise insulation capacity, and fire safety (Figure 3).
Combining wood production chain by-products ("wood waste") such as saw dust, chips, strands, wool etc. with traditional concrete were resulted in

- A light-weight wood-concrete compound with an increased tensile strength and practical compression strength, resulting in all corresponding benefits on structural level.
- A pourable construction material with all corresponding benefits for manufacturing.
- A decreased density (i.e. in comparison to regular concrete), being beneficial with regard to thermal insulation and storage capacity, acoustic insulation, and structural loading.
- A wood-based construction material with improved fire resistance, due to the mineral components in the compound.
- A partially combustible construction material (contrary to regular concrete), being useable in energy and warmth production, thus allowing for a cascaded use of wood.
- An intensified and cascaded use of wood production chain by-products.

4.2 Strength testing

The goal of the experimental analyses was the evaluation of the global behaviour of a building as well as derivation of further mechanical properties and optimisation of light-weight wood-concrete compositions. To this purpose, several tests were scheduled in order to optimise the wood-concrete elements, and to obtain a complete mechanical characterization (strength, stiffness) of those elements, so to be able to use the values obtained for the structural modelling of a whole building (Figure 4).

The research activity was addressed on the structural characterisation of light-weight wood-concrete assemblies to be used as wall or floor structures.

Considering the three most promising compositions from 4.1 constitutive laws in compression and tension were developed for the analytical modelling of the material under short-term loading up to failure, based on a statistically significant but limited number of tests: stress-strain behaviour in compression by strain-gauge measurements on cylinder specimens; tensile strength on double-punch cylinder specimens; effective bending tensile strength and specific rupture energy on square plate specimens; and residual bending tensile strength on notched beam specimens.
The test arrangements correspond to standardised quality testing for hardened concrete according to Eurocode EN 12390-3 [12]. All tests were executed 28 days after concreting (Figure 5).

![Compression tests](image1)

The results were statistically evaluated. The results were compared among the different compounds and to the constitutive laws for regular structural concrete [11]. Information on densities was a by-product of all tests (Table 1).

4.2.1 Identification of long-term structural behaviour characteristics

Long-term properties of the wood-concrete compound compositions, which are essential for structural element design (i.e. shrinkage and creep), were determined in standard tests on three small-scale specimens each for shrinkage and creep (per composition). Creep tests were additionally performed on small-scale beam specimens (Figure 6).

![Long-term tests](image2)

The results were compared to the corresponding properties of regular structural concrete and preliminary proposals for structural design values for the wood-concrete compounds are deduced [11].

4.3 Design of structural elements

Practice-friendly approaches for the design of slab and wall elements made of light-weight wood-based concrete and timber were developed, supported by illustrative examples for practical engineers, and verified by comparisons to experimental test results. Analytical and numerical modelling was envisaged for reliably predicting the structural behaviour, to be subsequently broken down into simpler models formulated for the daily engineering practice. Embedment of the findings in codes, standards and regulations, is also sought. Preparation of analytical formulas were preceded by calibration of numerical model - finite element method (FEM) - to gain even more accurate information about stresses and strains in the system elements (Figure 7).

![Analysis model – Finite element simulation](image3)
The works describe and interpret the static behaviour of concrete - wood composite walls, slabs and connectors made of steel and fibre composites. The investigations on composite wall/floor panels deal with the analysis and test of the composite elements.

Special attention was provided on the experimental research activity addressed on the structural characterisation of light-weight wood-concrete assemblies to be used as wall or floor structures particularly on in-plane shear tests on large wall elements (shear wall tests), as well as in bending tests on large slab elements. The experimental campaigns were focused on the three most promising element layouts and were performed on three specimens per layout type.

It is definitely of strong importance to develop and to define technical details to improve the ductility of such structures, so that those structures can be profitably used in earthquake resistant structures. Ductility can be obtained working on the connections between concrete and wood (ductility of the component elements) and on the connections between single wall panels and between walls and floors (ductility at a structural level). It must be remembered that “dissipative zones” shall be regarded as located at the joint level, according to the European Standard EN 1998 [10].

The determination of in-plane stiffness and resistance of composite walls is compulsory for a correct and reliable analysis of the building subjected to horizontal actions (mainly wind and earthquake). Consequently a calculation model to evaluate strength and stiffness of walls (used as resisting diaphragms) were be developed, in order to define an equivalent shear stiffness to be used for simplified analysis of the so-called “regular” buildings.

The experimental campaign were directed also to the investigation of the mechanical behaviour of the connections, in order to guarantee the safety concerning the ultimate and serviceability limit states, to withstand large displacements in the plastic field without reaching collapse, to assure a good mechanical resistance in case of fire, to determine and, possibly, to improve the “behaviour factor q” of the structure in order to reduce the seismic actions.

To this purpose, the below mentioned tests were scheduled in order to optimise the wood-concrete elements, and to obtain a complete mechanical characterization of those elements, so to be able to use the values obtained for the structural modelling of a whole building:

a. Experimental tests on full-scale specimens of floor structures, until collapse (Figure 8)
b. Experimental tests on full-scale specimens of wall structures (racking strength and stiffness of wall)
c. Analysis of the interaction (full/partial) between wood and concrete in the composite elements, with special regard to ductility

Using the results of 4.1 and 4.2, prototypes of multi-layer composite wall and slab elements were developed, designed, and tested experimentally, and evaluated with regard to their structural performance (i.e. stiffness, strength, and ductility). Special attention was provided on the potential use of hardwood. Experimental campaigns consist in in-plane shear tests on large wall elements (shear wall tests), as well as in bending tests on large slab elements. The experimental campaigns were focused on the three most promising element layouts and were performed on three specimens per layout type [11].

4.4 Properties with regard to building physics

The main properties with regard to building physics of the most promising conceptual designs for floor and wall elements were developed and analysed. The properties for building physics parameters of the system, i.e. thermal insulation and storage capacity, humidity transport, and noise insulation, were identified by explorative testing.

4.4.1 Thermal insulation properties

Thermal insulation characteristics of timber wood-concrete composite elements were determined in tests according to current standards on three specimens (Figure 9).
Figure 9: Thermal conductivity tests

The test results were compared to traditional configurations elements in timber and concrete (Table 1).

4.4.2 Thermal storage capacity
To receive an impression about the thermo physical behaviour of timber wood-concrete composite floor elements, the thermal storage capacity characteristics of wood light concrete were experimentally determined in tests on three specimens. The pivotal material properties as the thermal conductivity and specific heat capacity are stated in Table 1. The test results and multi-layer system configurations are compared to traditional floor configurations in timber, concrete and timber-concrete composite [11].

Table 1: Material characteristics of wood, concrete and wood light concrete [11]

<table>
<thead>
<tr>
<th>Unit</th>
<th>Wood</th>
<th>Concrete</th>
<th>Wood Light Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ kg/m³</td>
<td>400-800</td>
<td>1600-2400</td>
<td>450-1000</td>
</tr>
<tr>
<td>$\lambda$ W/mK</td>
<td>0.11-0.2</td>
<td>0.98-1.71</td>
<td>0.11-0.37</td>
</tr>
<tr>
<td>$\varepsilon_p$ kJ/kgK</td>
<td>1.6-2.5</td>
<td>1.08</td>
<td>1.1-1.4</td>
</tr>
<tr>
<td>$\varepsilon_c$ kJ/m³K</td>
<td>-1000-2000</td>
<td>-1700-2600</td>
<td>-500-1400</td>
</tr>
</tbody>
</table>

4.5 Fire safety characteristics

New fire regulations allow building construction in timber for buildings up to six floors; higher buildings could be realised with timber-based products in combination with other construction materials providing fire safety.

The multi-layer composite elements should also provide a certain fire resistance, beneficial effects with regard to building physics and thermal energy. Therefore fire safety characteristics of the most promising conceptual designs for floor and wall elements, developed and analysed in 4.1, are established through pilot testing.

4.5.1 Large-scale test on fire resistance

Two floor and wall element specimens were tested and evaluated in pilot fire safety tests (Figure 10). The test results were compared to traditional configurations of floor and wall elements in timber/timber-concrete composite. First appraisals of the new multi-layer composite elements with regard to building physics, fire safety as well as economic and ecological feasibility are available in [11].

Figure 10: Fire tests

4.6 Ecological impact and the economic feasibility

In order to check on the potential for future market implementation, the ecological impact of the most performing structural elements and the economic feasibility were analysed in case studies with regard to life-cycle analysis, following the whole fabrication chain of all components, and comparing the results to conventional ways of construction in order to demonstrate the competitiveness of the developed multi-layer systems. Consequently, further improvements with regard to life-cycle costs were tracked down.

The first generation of timber based multi-storey buildings are characterised by an “abundant” use of massif timber panels (cross-laminated timber - CLT) and a prudent overdesign of additional layers to fulfil or overfill the requirements concerning acoustic and fire behaviour [14].

The structural systems for the floors and the structures for the vertical loads were often not optimised- thick massive floor panels instead of less wood consuming rib or sandwich construction and massive wood panels for all wall elements instead of optimised use of structural columns and the minimum quantity of structural shear walls together with a maximum of light non structural separation walls.

Other cost reduction measures could be the use of vertically orientated “balloon” systems (vertical elements more than one storey high) instead of horizontal platform systems (one-storey high elements, protection needed for the “open” platform).

Further cost optimisation is possible by replacing parts of the expensive timber material by mineral-based materials as cement, anhydrite, magnesia, clay or dry sand and to combine these mineral layers with the timber parts to structural sandwich elements. These sandwiches should be prefabricated and allow a rapid erection without use of much water. A good example for this kind of composites is the cement bonded wood particleboards.
(or wood wool boards) which are used and produced since several decades in the European countries (Figure 11).

Figure 11: Production Process [6]

The combination of theses cement bonded panels with structural timber panels is a promising strategy to reduce cost, increase fire resistance and sound protection (mainly impact sound on floors and walls) to increase the thermal storage capacity (24 hours cycle) and to maintain the good recyclability with the possibility to burn the composite after use to profit of the thermal capacity of the wood.

In order to reach a similar or higher market share in the multi-storey sector – necessary to guarantee a constant high demand of timber products able to absorb the production capacity of the reforested forests – timber-based buildings must be economically competitive.

Already the comparison of today’s market prices for the basic building materials (concrete and sawn timber boards) shows that, in spite of the high energy consumption for production and distribution, the price of 1 m³ concrete delivered on the site is surprisingly low (approx. 50 €/m³). On the other hand, sawn timber boards cost 5 times more (ca. 250 €/m³), representing the real cost (mainly labour for planting and harvesting trees, secondary transformation with a small percentage of non-renewable energy).

- Combination of (broadleaf) wood with cheaper, non-combustible mineral materials for cost and fire resistance optimisation,
- Full use of prefabrication with the goal of reducing erection time,
- Realise intelligent and attractive pilot projects, diffuse information on them internationally,
- Increase specific knowledge about timber by professionals, students and builders.

5 CONCLUSIONS

The European countries have to face profound changes in the demand for buildings. The basic requirements for new apartments or new office spaces are very different from the post war decencies, e.g. the quantity, the quality, the size, the functionality, the flexiblity, the expected lifetime for new or for refurbished buildings have changed.

The technical possibilities have multiplied, new materials and new construction methods appeared and finally a set of completely new requirements concerning environmental aspects and criteria of sustainability have to be translated into the built reality. Especially the urban agglomerations have to deal with the effects of migration, the increasing number of singles and elderly people, with other forms of labour, education, consumption, cultural live etc. This leads to other types of buildings; more flexible, faster erection and transformation, low energy consumption for heating and cooling etc. The City planning as well needs other urban strategies, less traffic, higher density, less one family houses and more densification and remodelling of the existing buildings [7].

The research projects target practical market implementations of innovative timber/wood-concrete composite elements, leading to increased market shares of timber and wood-based products and components for polyvalent modular multi-storey building technology.

The research project results benefit at several levels of the European industry. Firstly, it offers utilization for waste products of the wood industry, thereby improving the exploitation of the utilisation chain of forest products. Secondly, it provides a marketable component system for building construction that optimally uses timber sections and lightweight wood-concrete. Thirdly, it contributes to reducing carbon emissions by storing forest waste in construction elements for a long period instead of burning it for warmth or energy. The results are especially beneficial to wood-rich countries in Europe with wood production chains as well as a concrete tradition. In a larger context, such products support rapid-assembly construction methods that use prefabricated dry elements to increase construction efficiency.

These products open new markets to the wood industry with a potential of 10 to 20% of the European construction market. Wood-based alternatives to conventional concrete or masonry construction also open opportunities to European countries to reduce their carbon emissions in agreement with the Kyoto protocol [15]. Furthermore, the European timber construction industry will have the opportunity to export this new composite technology even worldwide. Owners, contractors, architects and engineers benefit from well-designed wood-based structures [7].
The newly developed system shall be promoted through the initiation of pilot applications. Initiation of pilot projects will provide the possibility to experience the practicality and applicability of the developed composite systems, and create different design and application solutions. Any modification proved to be necessary at architectural and structural design stages may be reached as a result. Local architectural and structural design techniques, traditional structural culture and national structural requirements as earthquake and environmental conditions shall be considered at this stage.

Unquestionably, there are also certain risks related to the research: suboptimal structural, manufacturing performance of the multi-layer system; too little economic and/or ecological competitiveness; and insufficient market acceptance of the proposed building technology due to the aforementioned risks.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of the Austrian Research Promotion Agency (FFG, project number 824892) and company VELOX Werk Ltd. for funding the research work.

The partnership with the industrial company VELOX Werk Ltd. manufacturing cement-bonded boards made of wood chips, allowed the development and optimisation of the production and manufacturing process.

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