1. Introduction in timber-concrete compound

Composite structures of timber and concrete were originally introduced to substitute expensive materials as concrete and steel in floor constructions partly with local grown timber in a time of severe shortage of goods and energy in Germany in between world war 1 and 2. Today in Central Europe they are favored in refurbishments and in new timber constructions for qualities according to stiffness, noise insulation and fire safety.
The construction method exploits the high compressive strength of concrete and the high tensile strength of wood fibres. The bending force that acts on the floor slab creates a compression zone in the upper part and a tension zone in the lower part of the section.

2. Application to a light weight structure

In 2015 the secondary school of Kibwigwa in Tanzania was extended by an assembly hall mainly used as dining hall for 400 students. The tunnel vaulted building has a span of 14 meters, a height of 6 meters, an overall length of 40 meters and is designed as a grid shell of timber-lamellas with a length of less than two meters. According to its light weight and form, wind load would cause heavy and destructive deformation of the open edges of the shell. Arches of timber-concrete compound complement the qualities of the timber structure in an optimal way:

- The additional materials – concrete, screws and reinforcement steel bars - required are of every day use and easily available.
- Expensive, sophisticated and vulnerable junctures are replaced by very simple and common workmanship.
- The extra load of the concrete layer works against the uplifting wind loads and reduces the negative effect of resulting traction forces within the structure.
- The compound effect conducts forces between the stiff edge arches and the linear elements of the grid shell directly and over the whole length of the section. Adverse punctual load application is avoided.
- The amount of concrete and steel required for the compound construction corresponds with the amount required for the foundations of an alternative steel cable bracing. Instead of going under ground, the concrete is used to be an integral component of the structure.

3. Results and Conclusion

Regarding to the lessons learned from the assembly hall in Kibwigwa timber-concrete compound construction can complement light weight structures with its specific qualities optimally. Weight and stiffness can be implemented targeted and without questioning the structural principle. Since only common materials and basic skills are required, it very well meets the needs and possibilities of rural areas in developing countries in the global south. It can very well help to save material and expenses as a substitute of different bracing systems. The construction method can easily be adapted to similar structures by the neighbouring rural community.

But timber-concrete as well as in some areas bamboo-concrete compound structures have also a great potential in substituting regular concrete floors. This way up to 50% of concrete and steel can be replaced by renewable raw materials and therefore the ecological quality, sustainability and carbon capturing of the construction can be far improved. At the same time, building costs can be reduced, particularly with bamboo-concrete compound structures.
Composites structures of timber or bamboo and concrete are on the one hand able to reduce cost and upgrade the ecological qualities of ordinary building elements like floor construction without degrading its structural qualities. On the other hand, light weight structures of timber or bamboo also benefit of its performance in very simple, but effective ways. The paper will have a closer look at the timber concrete composite structure complementing the timber light weight structure of the assembly hall for Kibigwa secondary school in Tanzania.

Keywords: Sustainable construction; wood-concrete composite; bamboo-concrete composite; resource efficiency; biogenic building materials

1. Introduction

1.2 History of timber-concrete composite

Composite structures of timber and concrete were originally introduced to substitute expensive materials as concrete and steel in floor constructions partly with local grown timber in a time of severe shortage of goods and energy in Germany in between World War I and II. In 1922 Paul Müller received with the patent on “Decke aus hochkantig stehenden Holzbohlen oder Holzbrettern und Betondeckschicht” the first known patent on timber-concrete composite within German speaking countries [1]. In the 1930s timber-concrete composite was object of substantial research in North
America in order to improve economic efficiency in construction [2]. E. g. at the Oregon State Highway Department basic bridge construction methods for small and medium spans were developed. In bridge constructions, timber and concrete as composites not only work together as structural elements and the substitution of concrete lowers weight and costs, but also the upper concrete layer protects the timber structure from exposure to weathering. Until 1943 180 examples of the examined construction were built. Some of them are in use today, like the Newbury Viaduct or the Vermont Street Viaduct [3]. In 1943 Eugen Sperle used timber as substitute of steel reinforcement in his ribbet concrete ceiling system, similar to the nowadays common use of bamboo as concrete reinforcement in the global South.

Already in 1939 Otto Schaub had invented Z- and I-formed steel elements to connect concrete and timber layers [4]. In his patent he mentions explicitly the possibility to use in refurbishment of wood-beamed ceilings, which turned out to be the main application for timber-concrete compound after World War II until the 1990s. This way, the geometry of deformed wood beam ceilings can rather easily be restored and its performance regarding load capacity, stiffness, fire safety and noise insulation can be improved at the same time.

Since the 1980s timber-concrete composite structures are object of substantial research in Central Europe again for both applications, new construction and refurbishment. The characteristics of concrete, heaviness and stiffness complements the qualities of timber and allows to improve some of its inferior properties. Since building with timber opens up more and more fields of implementation like high rise, multi storage housing and office buildings, the improvement of fire safety, noise insulation and stiffness opens up a lot of possibilities. Since the 1990s various build examples were implemented, e. g. the Illwerke headquarter in Austria, an office building of over 10,000 m² GFA, using even prefabricated composite elements to minimize execution time and moisture (Fig. 1). But it is more common and less expensive to place concrete on the erected timber structure.

![ILLWERKE HEADQUARTER IN RODUND, AUSTRIA, MOUNTING OF PREFABRICATED FLOOR ELEMENTS / OFFICE SPACE WITH VISIBLE STRUCTURAL ELEMENTS LIKE BEAMS AND COLUMNS OF TIMBER](image)

**Fig. 1 Illwerke Headquater in Rodund, Austria, mounting of prefabricated floor elements / office space with visible structural elements like beams and columns of timber**

### 1.1 Operation principles of timber-concrete composite

Timber-concrete composite elements are mostly used for areal horizontal load bearing structures like floors or bridges. Compared to all timber structures it improves sound insulation and fire resistance. The additional mass reduces undesirable vibrations by dampening the floor’s ability to flex. The combination of materials makes optimal use of their respective qualities.

The timber-concrete composite construction method can be used with all kinds of common timber floor constructions. The resulting composite floor elements range from combined panel and joist floor assemblies to planar composite panels.

The concrete topping layer is usually 6 - 12 cm thick and reinforced to prevent crack formation. In most cases, it is poured as a layer of in-situ concrete.
The construction method exploits the high compressive strength of concrete and the high tensile strength of wood fibres. The bending force that acts on the floor slab creates a compression zone in the upper part and a tension zone in the lower part of the section. For both layers to act in combination, the two layers must have a shear-resistant connection (Fig. 2). Horizontal loads are distributed by the concrete layer which, in all variants, ensures the dimensional rigidity of the floor slab. Concrete-timber floors are suitable for use as single-span elements subject to bending loads. They are usable for continuous beam situations in certain circumstances and not suitable for large cantilevers because here the tension and compression forces are reversed [5].

Fig. 2 Structural behaviour – Timber-concrete composite floor, longitudinal section

Since the shear-resistant connection between concrete and timber is the most sophisticated part of the system, most attention in research goes into it. Often the connection is made of screws that protrude long enough from the upper surface of the timber construction to be cast by the concrete layer and to enable force transmission. But also all kind of steel connections like metal mesh strips or flat steel plates are common. The creation of a shear-resistant connection via so-called “birdsmouths” is currently the subject of numerous research projects. The connection is a product of the locking fit between the concrete topping and the timber element. Shear connection screws are sometimes also used to resist uplift forces that can arise under eccentrically applied loads.

Various different kinds of peg-like connectors are available on the market as certified products. Special fully threaded locking screws, for example, are screw-inserted at angles of 45° or 90° into the timber construction. The screw heads protrude and have a specially profiled head to ensure the best possible connection with the concrete layer [5].
2. Application to a light weight structure

2.1 Zollinger roof

In 2015 the secondary school of Kibwigwa in Tanzania was extended by an assembly hall mainly used as dining hall for 400 students. Design, execution planning and site supervision as well as execution of the timber structure was done by the design-build studio of the Department of Timber Construction of the Technical University of Munich. The tunnel vaulted building has a span of 14 meters, a height of 6 meters and an overall length of 40 meters and is designed as a grid shell of timber-lamellas with a length of less than two meters (Fig. 3).

The design uses the historical construction method of Friedrich Zollinger, the “Zollinger roof”. This method allows wide span structures made of fairly short single components. A span of up to 40 meters by using individual parts with dimensions of 2.0 x 0.2 x 0.02 m (length x width x thickness) is not unusual in historical constructions. The section of the grid shell is a circular segment in order to need not more than one length and two different shapes – a left and a right one – of lamellas. The joints of the lamellas within the shell are made by simple bolts, of which each connects three timber pieces. Once the construction is set up, the timber parts grip against each other by being loaded and the whole construction works as a shell (Fig. 4).

This very sophisticated construction method not only allows mass prefabrication of its elements and mounting of the structure by unskilled workers, but also saves about 40% material compared to linear structures of the same span. These qualities explain the success of the Zollinger roof in a time of shortage and poverty in Germany in between World War I and II.

Fig. 3: Assembly hall Kibwigwa during construction; erecting of the grid shell without necessity of scaffolding

Fig. 4: Joint of three lamellas with only one simple bolt; additional two screws help stiffen the structure and reduce lamella size
2.2 Challenges of design and situation

The historical context shows similarities to nowadays conditions in the rural region of Western Tanzania. Building materials – especially steel and cement – are rather expensive, labour costs are low. Long and straight timber is hardly available, laminated timber is not common. Wider span structures are usually made of nailed timber trusses of low quality.

Against this background, the Zollinger roof seems a very suitable construction method. Even more though since the design of the structure and a 1:1 scale model of a 6 meter long section at full span built in Munich during execution planning brought up a mountig method avoiding the need of any scaffolding (Fig. 5).

Fig. 5: Assembling the Zollinger structure by uplifting one side and adding the next row of lamellas

In contrast to historical Zollinger constructions, which almost always had walled gable ends, the design for the assembly hall in Kibwigwa uses complete openigns on both end of the vault to form entrance spaces.

Since the Zollinger vault is not a double bended form but a tunnel vault, it doesn't have a rigid geometry. The shell must be stiffened by the joints of the elements, in particular by the geometry of the lamellas. Above that the ending of the continuously working grid shell on both sides means a mayor interference to the system. Horizontal forces like wind loads not only attack from both sides – interior and exterior surface – and are higher on the edges than in the middle, but also the lamellas situated close to both rims are burdened additionally by their geometrical position within the structure (Fig. 6).

Asymmetric load and deformation resulting in bending of the shell is even more problematic since the joints of the lamellas are designed for absorbing pressure along the shell and perform very poorly on traction. Therefore historical Zollinger roofs always prevent lifting loads by using heavy roofing like tiles. But in Kibwigw the only suitable, available and affordable roofing material was corrugated iron sheets.

Fig. 6: Wind load and deformation at the open edges of the grid shell
Calculating the structural performance of the design with the program RSTAB led to inappropriate results. Even though the lamellas were – shaped by topical calculated joints – already of a larger profile than the historical pattern, single lamellas would be loaded by 205% of their capacity.

Two different strategies were discussed and planned at first: Reinforcement of the rim by an arch made as nailed timber truss as well as a bracing of steel cables to the interior of the building. But with poor quality of the available timber – mainly regarding to geometric steadiness – and with lacking possibilities of handling big building elements on site the nailed timber arch was quickly recognised as insufficient option.

Even though steel cable bracing would narrow the spatial and architectural design painfully, it was integrated into the execution planning and calculated as only possible option left. In order to find a sustainable and economic solution the design move forward through different steps to an acceptable lamella size (2.0 x 0.25 x 0.04m) and a supportive construction of steel cables spanning from the most loaded parts of the roof structure to a heavy concrete foundation in the ground. Calculations showed that several additional steel bars of 4 m length each overlaying the structure would be necessary to avoid destructively high forces of punctual junctures from cables to grid shell.

High effort and costs of these many and very sophisticated steel applications and joints started to question suitability, sustainability and architectural quality of the whole construction.

2.3 Concrete as appropriate complement to the structure

Historical Zollinger roofs often use an over all shuttering of wooden boards to distribute frontal horizontal loads within the areal structure of the shell. In Kibwigwa, the shuttering was reduced to a minimum of 4 m depth at both edges of the vault in order to reduce costs. Analysing the structural performance of the construction and of each of its members very carefully, the idea of an arch of concrete cast on the shuttering – working as timber-concrete compound – on both edges of the structure appeared to be most promising.

By implementing a reinforced concrete layer of 100 mm thickness and 1 m depth on both edges of the structure most of the previous problems could be solved:

- The additional materials – concrete, screws and reinforcement steel bars - required are of every day use and easily available.
- Expensive, sophisticated and vulnerable junctures are replaced by very simple and common workmanship.
- The extra load of the concrete layer works against the uplifting wind loads and reduces the negative effect of resulting traction forces within the structure.
- The compound effect conducts forces between the stiff edge arches and the linear elements of the grid shell directly and over the whole length of the section. Adverse punctual load application is avoided.
- The amount of concrete and steel required for the compound construction corresponds to the amount required for the foundations of the alternative steel cable bracing. Instead of going under ground, the concrete is used to be an integral member of the structure.
- Table 1 shows these positive effects on the most stressed elements of the grid shell. Both calculated kinds of timber-concrete compound arches advance the performance of the structure distinctly. If the concrete layer is connected rigidly to the footing of the grid shell, the best effect is achieved. While the lamellas of the structure would be loaded by 205% of their capacity using the unaltered Zollinger construction, it would still be 130% using the steel cable bracing. Only using the timber-concrete compound structure the lamellas are loaded by 74% respectively 62% and this way less than 100% of their capacity. Therefore the
lamellas could be dimensioned by parameters like the grid shell joints and regular forces within the shell and didn’t have to be supersized by the interfering effects of the open edges.

Table 1: Comparison of Normal force (N), Sher force (V), Bending Moment (M) and degree of material utilization (h) within the most loaded timber-lamellas of the grid shell under wind load dependend on different types of endings of the shell.

<table>
<thead>
<tr>
<th></th>
<th>unaltered Zollinger grid shell</th>
<th>anchoring steel cables rigid connection to foundations</th>
<th>timber-concrete compound without rigid connection to foundations</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nmax</td>
<td>25,12</td>
<td>12,09</td>
<td>16,19</td>
<td>10,53 kN</td>
</tr>
<tr>
<td>Nmin</td>
<td>-39,39</td>
<td>-11,9</td>
<td>-22,13</td>
<td>-12,12 kN</td>
</tr>
<tr>
<td>Vy max</td>
<td>10,15</td>
<td>0,62</td>
<td>0,13</td>
<td>0,2 kN</td>
</tr>
<tr>
<td>Vy min</td>
<td>-11,08</td>
<td>-0,85</td>
<td>-0,12</td>
<td>-0,19 kN</td>
</tr>
<tr>
<td>Vz max</td>
<td>7,19</td>
<td>4,75</td>
<td>2,43</td>
<td>3,11 kN</td>
</tr>
<tr>
<td>Vz min</td>
<td>-7,47</td>
<td>-4,74</td>
<td>-2,56</td>
<td>-3,15 kN</td>
</tr>
<tr>
<td>Mmax</td>
<td>0,3</td>
<td>0</td>
<td>0,05</td>
<td>0,07 kNm</td>
</tr>
<tr>
<td>Mmin</td>
<td>-0,26</td>
<td>-0,04</td>
<td>-0,04</td>
<td>-0,07 kNm</td>
</tr>
<tr>
<td>Mmax</td>
<td>7,21</td>
<td>4,59</td>
<td>2,34</td>
<td>3,01 kNm</td>
</tr>
<tr>
<td>Mmax</td>
<td>-3,48</td>
<td>-3,12</td>
<td>-2,46</td>
<td>-3,04 kNm</td>
</tr>
<tr>
<td>Mz max</td>
<td>5,06</td>
<td>0,62</td>
<td>0,1</td>
<td>0,16 kNm</td>
</tr>
<tr>
<td>Mz min</td>
<td>-8,42</td>
<td>-0,49</td>
<td>-0,11</td>
<td>-0,16 kNm</td>
</tr>
</tbody>
</table>

h | 2,05 | 1,3 | 0,62 | 0,74 |

The sher resistant connection between the Zollinger structure and the concrete layer was incorporated by screws and nails inserted in the timber structure and protruding long enough to make a proper conection to the cast concrete (Fig. 7). The uneven surface of the shuttering resulting of different thickness and roughness of the boards increases the sher resistance.

Fig. 7: Casting the concrete layer on site; sher resistant connections with protruding screws
3. Further Fields of Application

Adapting the principle of concrete-timber compound to bamboo construction appears to be very promising. Bamboo is already widely used as concrete reinforcement material, making use of its extraordinary tensile strength. That characteristic makes bamboo a qualified material for the lower layer of horizontal compound building elements. The indigenous bamboo Yushania Alpina is a very suitable and environmentally friendly substitute to construction materials like timber or steel in East Africa and at the same time is much more cost efficient [6].

Natural bamboo poles suffer disadvantage from their hollow and knotty form. It is complicated to manufacture areal and tight building elements from it. Bamboo concrete compound floors could be a proper answer, adaptable to developing countries. The construction of the skills centre in Malaa near Nairobi uses edge fixed bamboo structures for the roof construction of dormitories (Fig. 8). A layer of earth on top of the bamboo structure improves the thermal performance. In a similar construction an upper layer of concrete could serve the same way but additionally double the structural capability of the construction.

Building with bamboo poles, joints and connections often are rather sophisticated and need very proper execution. Bamboo-concrete compounds can meet that challenge by forming concrete fittings, that are easily to assemble. This way, also prefabricated building elements are possible.

Depening research on bamboo-concrete compound structures is about to be done at the Department of Tectonics in Timber Construction at the Technical University of Kaiserslautern in Germany.

Fig. 8: Roof structure of dormitories at the Skills Centre Malaa near Nairobi, Kenya.

4. Conclusion

Since the first invention of timber-concrete compound construction about a hundred years ago a lot of research has been done in Central Europe and in North America. Many built examples prove it to be a capable, sustainable and persistent constructing method for many applications. It can be used for floor systems – especially in multi-storey buildings –, for bridges but also to improve the performance of wide spanning structures made of timber or bamboo.

Regarding to the lessons learned from the assembly hall in Kibwigwa timber-concrete compound construction can complement light weight structures with its specific qualities
optimally. Weight and stiffness can be implemented targeted and without questioning the structural principle. Since only common materials and basic skills are required, it very well meets the needs and possibilities of rural areas in developing countries in the global south. It can very well help to save material and expenses as a substitute of different bracing systems. The construction method can easily be adapted to similar structures by the neighbouring rural community.

But timber-concrete as well as bamboo-concrete compound structures have also a great potential in substituting regular concrete floors. This way up to 50% of concrete and steel can be replaced by renewable raw materials and therefore the ecological quality, sustainability and carbon capturing of the construction can be far improved. At the same time, building costs can be reduced, particularly with bamboo-concrete compound structures.

5. References


