Steel reinforced timber structures for multi storey buildings

Kamyar Tavoussi¹, Wolfgang Winter², Tamir Pixner³, Michael Kist⁴

ABSTRACT: For modern multi-storey buildings timber-steel-hybrid elements present a very efficient construction method. The combination of these two materials leads to economic and ecologic benefits as the construction height can be optimized, the fire resistance can be increased, the earthquake resistance can be improved and the assembling can be executed more efficient. Steel reinforced timber structures are light, fast and clean.

KEYWORDS: Hybrid, multi-storey, earthquake, fire

1 INTRODUCTION
Europe has a long tradition of multi-storey timber based urban buildings. In the last century cement based buildings dominated completely the market in central Europe but for several years modern timber constructions have been developed. The application of timber-steel-hybrid-elements for multi-storey buildings will be one objective in the future. Several ideas and details have been carried out. First economical calculations and dynamic analyses are presented in this paper.

2 BENEFITS OF TIMBER-STEEL-HYBRID CONSTRUCTIONS
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. Chapter 2.1 points out the economic considerations. The research project presented in chapter 2.2 had as objective to develop innovative timber-steel composites as structural building components e.g., beams, columns or walls with distinctly improved fire performance characteristics [1].

2.1 ECONOMIC ADVANTAGES
Based on these structural performance requirements, the following hybrid construction system was analyzed (Figure 1) [2].

![Timber-steel-hybrid beam](image)

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). Furthermore the timber frame functions as a buckling restraint.

In the following diagrams (Figure 2) this hybrid system is compared to usual steel-beams and glue laminated-beams.

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A comparison of the three different types of beams for spans between 6 meters and 10 meters regarding the construction height, the weight and the material cost has been carried out. The required construction height for the hybrid-beam is about 0.7 times a comparable glue laminated beam and 1.4 times a comparable steel-beam. The cost comparison shows a coefficient of about 1.2 for the glue laminated beam and 0.65 for the steel-beam. The calculated weight does not differ significantly.

First attempts to exploit the effect of a possible thermodynamic interaction within timber-steel composites at the larger scale of structural components have been carried out at the Building Research Institute in Japan [3] where 4-hour fire-resistance tests were executed with steel sections encased in different types of glue-laminated timber (Figure 3). The 60 minutes of fire exposure in accordance with ISO 834-1 [4] 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.

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 FIRE RESISTANCE ADVANTAGES

The aim of the research project 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.
2.3 ASSEMBLY ADVANTAGES

The usage of steel connectors in timber construction is standard. Working with prefabricated timber-steel-hybrid elements will shorten the construction time and make the transmission of high loads easily possible (Figure 4). The execution of shear or bending stiff connections will not cause a big effort.

Figure 4: Construction with timber-steel-hybrid elements

One possible assembling method present the shooting nails from “Hilti” [5] (Figure 5).

3 APPLICATION OF HYBRID ELEMENTS FOR HIGH RISE BUILDINGS

In the following subchapters two different ideas of application are presented. The aim of the first project (chap. 3.1) is to investigate the seismic behaviour of a highrise timber building without diagonal bracing. The second project (chap. 3.2) describes a nine storey high timber-steel-hybrid system implemented in a core-outrigger system in reinforced concrete.

3.1 Project “Birdcage”

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 (Figure 6). A square plan of 27 by 27 meters with a plan area of 729 m² was chosen. 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 [6]. The seismic calculation (response spectrum analysis) was based on the EN 1998 [7]. 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 in a former research project presented in 2008 at WCTE in Miyazaki [8].

Figure 6: 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/s² (the ground acceleration for Vienna is ag = 0.87 m/s²) and 3 m/s²
- behaviour factor “q” of 2 and 4

The assumed fundamental basic wind velocity v₁₀ is 135 km/h.

The calculated results for significant load combinations are presented in table 1.

### Table 1: Results of static and dynamic analyses

<table>
<thead>
<tr>
<th>Load combination</th>
<th>Ultimate Limit State</th>
<th>Serviceability Limit State</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.50/1.15/0.85/0.65</td>
<td>0.50/0.80/0.60/0.50</td>
</tr>
<tr>
<td>design ground acceleration “ag”</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>behaviour factor “q”</td>
<td>2</td>
<td>4</td>
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<tr>
<td>Period“T”</td>
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</tr>
<tr>
<td>(x-direction)</td>
<td>3.96</td>
<td>4.58</td>
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<tr>
<td>(y-direction)</td>
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<tr>
<td>(x-direction)</td>
<td>1.21</td>
<td></td>
</tr>
<tr>
<td>(y-direction)</td>
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<td></td>
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<tr>
<td>Support reaction(kN)</td>
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<tr>
<td>(maximum)</td>
<td>1237</td>
<td>352</td>
</tr>
<tr>
<td>Displacement(mm)</td>
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<tr>
<td>(maximum)</td>
<td>28.5</td>
<td>35.5</td>
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<tr>
<td>Displacement (mm)</td>
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<td></td>
</tr>
<tr>
<td>(in y-direction)</td>
<td>1.9</td>
<td>3.25</td>
</tr>
</tbody>
</table>

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

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

### 3.2 Project “Woodstock” [9]

The Woodstock project is a 176.5 m office-building with a net surface of 900 m² per floor and a front width of 40 m (Figure 7). The core-surface ratio of the building amounts to 15%. In the construction a discrete core-outrigger structure from reinforced concrete is used as primary framework. Nine wooden standard floors are stacked on each of the four outrigger platforms which house service engineering (Figure 8). Thus a total of max. 44 wooden floors can be reached in this building.

The wooden floors are designed as timber-steel hybrids; however the top three floors of each 9-floor stack can be built without steel-inlays. In addition to that each 9th wooden floor is used as form work for the outrigger platform above it.
wood leads to this construction system being cost-efficient, ecologic and easy to build.

4 CONCLUSION

Prefabricated timber-steel-hybrid building components seem to be very advantageous for multi-storey structural systems. The hybrid elements both in horizontal and in vertical direction have an increased load bearing capacity without increasing cross sections. High loads can be transmitted with simple connections which accelerate the construction time. The total weight stays very low which is advantageous in case of earthquake. In case of fire the steel members are protected by the wooden elements and the temperature of the wood cross sections increase less rapid.

Steel reinforced timber structures present a light, fast and clean construction method.

REFERENCES


