Hurricane proof buildings – An innovative solution using prefabricated modular wood-concrete-composite elements

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1. Summary

Recent work at the University of Applied Sciences in Wiesbaden / Germany has indicated that wood-concrete-composite systems develop a strong position against contemporary designs like reinforced concrete and steel-concrete composite systems. In order to improve the range of applications this research was conducted to analyze the response of continuous wood-concrete-composite systems under hurricane loading conditions with wind speeds up to 250 mph (400 km/h). The wood-concrete-composite building (wcc-building) system is based on individual module components. These prefabricated rib-shaped elements consist of wooden beams inner connected with a concrete slab. Both cross sections are connected through a single row of HBV-shear connectors. The wcc-building system allows for a cost efficient hurricane-proof design. It furthermore provides enormous advantages over contemporary American and European building systems under seismic loads. The study shows structural details of prefabricated wcc-elements as well as a design proposal.

2. Introduction

The wcc-building system and in particular the HBV-Building System (www.hbv-system.de) is based on individual modular components derived from the HBV-Rib element. It can be used in floors, walls and roofs. The composite action of the HBV-Rib element provides an optimum in strength and stability. It therefore allows for an improvement in structural reliability and endurance. The HBV-Building System allows for a cost efficient hurricane-proof design approach for buildings in both residential and commercial use.

In Fig. 1 the structural elements of a wood-concrete-composite (wcc) building are illustrated. It shows the side view of multiple prefabricated wcc-modules. The wcc-modules consist of a concrete slab preferably 100 mm in thickness and 2500 mm width of individual length according to the building geometry. Multiple timber cross sections (i.e. 76/203mm) which are spaced approximately 625 mm apart from each other are connected with the concrete slab through HBV-Shear connectors.
For applications in hurricane regions it is most suitable to put the concrete slab on the out-side. Therefore the timber cross section is reaching into the inner part of the building. In that way the external sustainable concrete protects the inside of the building and produces a sustainable surface against high wind loads as well as dynamic load impacts. Fig.1 also shows a continuous layer of insulation within the wall and roof and therefore allows for an energy friendly building system in both warm and cold climates. The HBV-Building system was developed to combine the advantages of contemporary wooden houses, masonry buildings as well as concrete buildings.

3. **HBV-System**

The performance of a wcc-system depends solemnly on the performance of the shear connection. The HBV-System uses the HBV-Shear connector which consists of a steel mesh of St. 37 (equivalent to A36). On half of the HBV-Shear connector reaches 40 mm into a 3 mm wide channel within the timber and is secured through adhesive action. The other half is reaching into the concrete. In order to provide a hurricane proof building system it is desirable to use a stiff but ductile connection system.

While many wood-concrete shear connector systems in use today are inherently soft in terms of the latter slip plane the HBV-Shear connector provides a stiff connection between wood and concrete. Fig. 2 shows various connectors commonly used in wcc-structures. It shows that the glued-connection provides stiffer composite action with no initial slip in comparison with all mechanical connections like bolts, nails and screws.

![Fig. 2: Wood-concrete-composite system. Load-displacement curves of different shear connectors](image-url)
The HBV-System is commonly used in new building design. Especially the HBV-Rib cross section provides an alternative for contemporary concrete floors and walls. Many applications of the HBV-Systems are also found in the upgrade of old buildings and bridges. In these cases the HBV-Shear connectors are imbedded within the existing timber cross sections before the concrete is pored on sight. The use of the HBV-System in new bridges is a promising new approach due to the advantages in terms of durability and dynamic response in comparison to contemporary timber bridges.

4. Elements of HBV-Buildings

The HBV-Buildings consist of wall-, floor- and roof-elements which are prefabricated modular systems. A preferable application of the prefabricated modular HBV-Building elements consists of a concrete slab (i.e. 100 thick and 2500 mm wide with altering length) and multiple girders with a cross section of 76/203mm and a spacing of approximately 625 mm to each other. The stiff but ductile connection between timber and concrete is done through the HBV-Shear connectors.

It would be most preferable in a common refection procedure of a standardized residential house that the prefabricated modular wcc-sections are delivered, assembled and inner connected within a day. In that way one can provide for cities like New Orleans a modular building systems that allows a fast rebuild with a sustainable system approach. It furthermore allows the local carpenters to “finish” the prefabricated protective shell with common techniques.

Fig. 3 shows the individual building components used in a HBV-Building. Derived from the HBV-Rib element (www.hbv-system.de) one can see the common ground of the wall-, floor- and roof-element.

Fig. 3: Elements of wood-concrete-composite buildings
For hurricane regions it is most desirable to provide just the wcc-shell in terms of prefabricated modular elements and allow therefore the local craftsmen to add their experiences and complete the building. In that case a fast rebuild of large quantities of housing can be achieved.

5. Construction details

In order to allow a fast assembling of the prefabricated modular wcc-systems it is important to provide couplings which inner connect the individual units. The following Fig. 4 shows examples of these couplings. The research showed that the coupling can be embedded along with adequate reinforcement within the concrete slab prior to the pouring of the concrete. This procedure allows for a precise location of the prefabricated couplings as well as a tight interlock within the concrete itself. On the construction side one just has to connect the individual wcc-elements through high strength bolts.

![Fig. 4: Construction details of wood-concrete-composite buildings](image)

6. Design proposal

The design of the wood-concrete-composite constructions is based of the European codes DIN 1052 (timber design) as well as DIN 1045 (concrete design) as well as the code approval of the HBV-System ([www.hbv-system.de](http://www.hbv-system.de)). The basic design approach is derived from elastic composite beam theory. In accordance with this theory, the effective bending stiffness (used in calculating stiffness and stress) of a bi-material system with non-rigid shear connectors is calculated as:

\[
\langle EI \rangle_{ef} = \sum_{i=1}^{2} \left( E_i l_i + \gamma_i E_i A_i a_i^2 \right) \]

\[
\gamma_1 = \frac{1}{1 + \frac{\pi^2 E_i A_i}{K l^2}}; \quad \gamma_2 = 1
\]

\[
a_2 = \frac{\gamma_1 E_i A_i (h_1 + h_2)}{2 \sum_{i=1}^{2} \gamma_i E_i A_i}
\]

These equations were used to develop an analysis program that allows the design of wood-concrete-composite systems using the HBV-Shear connectors. Therefore every prefabricated wood-concrete-composite element used in hurricane proof buildings as a wall-, floor- or roof-element is calculated and design based on this theory imbedded in this analysis program.
The most important load condition of a building design in a hurricane region is the wind load. Hurricanes commonly create forces which lead to wind speeds up to 250 mph (400 km/h). The following example of a hurricane proof building under dynamic loads is based on a wind load of 250 mph (400 km/h). Based on this wind dynamic the designer introduces a lateral uniform load of \(q = 7,72 \text{ kN/m}^2\) based on the DIN 1055.

\[
q = \frac{v^2}{1600} = \left(\frac{400}{3,6}\right)^2 = 7,72 \text{ kN/m}^2
\]

Due to a housing geometry shown below one can determine a uniform lateral load on the floor level of 42,9 kN/m as well as 36,9 kN/m.

\[
V_A = V_B = q \cdot \frac{1}{2} = 42,9 \cdot \frac{12}{2} = 257,4 \text{ kN}
\]

\[
V_C = V_D = q \cdot \frac{1}{2} = 36,9 \cdot \frac{11}{2} = 203,0 \text{ kN}
\]

Fig. 6 shows various shear forces based on the number of couplings. The individual floor units are inner connected through 11 couplings. 3 couplings transmit only tensile forces and the remaining 8 couplings transmit the indicated shear forces. Based on a maximum shear force of 150 kN, each of the 8 couplings has to transmit 18,75 kN in shear force. The results in Fig. 6 shows that the inner connection of two bordering wcc-elements – due to the diaphragm effect – cause the highest shear force of 18,75 kN.

<table>
<thead>
<tr>
<th>Connection</th>
<th>Maximum shear force [kN]</th>
<th>Number of couplings</th>
<th>shear force / coupling [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor – Floor</td>
<td>150.0</td>
<td>8 [11]</td>
<td>18.75</td>
</tr>
<tr>
<td>Floor – Gable Wall</td>
<td>257.4</td>
<td>14 [17]</td>
<td>18.39</td>
</tr>
<tr>
<td>Floor – Drip Wall</td>
<td>203.0</td>
<td>14</td>
<td>14.50</td>
</tr>
</tbody>
</table>

Fig. 6: Shear forces within the individual couplings
Fig. 7: Arrangement of the couplings. Distribution of shear forces in the floor level.

Fig. 7 shows the arrangement of the couplings as well as the calculated distribution of shear forces within the floor level. Equation [7] shows the design of the bolts M16 – 4.6-SL used to transmit the coupling shear forces. The bolts M16 can transmit a shear force of up to 22.5 kN. Using 8 bolts one can derive a degree of efficiency of 83% within this design approach.

$$\eta = \frac{F_{\text{existing}}}{\Sigma F_{\text{allowable}}} = \frac{150\text{kN}}{8 \cdot 22.5\text{kN}} = 0.83 \leq 1.0$$  \hspace{1cm} [7]

The prefabricated coupling steel box is 180 mm long, 90 mm wide and 90 mm in height. The steel plates used are 8 mm thick and welded together to create a rigid unit. The bolts M16 - 4.6 - SL used provide a tension capacity of 35,84 kN for a sheet thickness of 8 mm.

$$\eta = \frac{F_{\text{existing}}}{F_{\text{allowable}}} = \frac{22.5\text{kN}}{35.84\text{kN}} = 0.63 \leq 1.0$$  \hspace{1cm} [8]

Fig. 8 shows a design approach for the transmission of the shear forces from the concrete slab through the coupling steel box into the connecting bolt. Due to the bolt capacity of 22.5 kN the rest of the design approach has been based on this load level. The design of the compression stress in the concrete section bordering the steel box is shown in equation [9].

Fig. 8: Free body diagram of coupling forces. Detail of the couplings.
The concrete used in this design approach is a C 20/25 based on DIN 1045. The acting shear forces transmitted from the concrete slab into the coupling steel box create a reacting moment. Two rebars (European grade BSt 500 with a diameter of 10 mm, cross sectional area of 79 mm²) connected to the coupling steel box transmit this reacting moment back into the concrete slab of the bordering wcc-element. In order to anchor these reacting forces within the concrete slab, an effective length \( l_{\text{req}} \) of 300 mm for the rebar is chosen based on the European code for concrete DIN 1045 (equation [13]).

\[
M = 22500 \cdot 45 \text{mm} = 1.01 \cdot 10^6 \text{Nmm} \quad [10]
\]

\[
Z = \frac{1.01 \cdot 10^6 \text{Nmm}}{170 \text{mm}} = 5956 \text{N} \quad [11]
\]

\[
\eta = \frac{a_{\text{st,req}}}{a_{\text{st,existing}}} = \frac{286 \text{N/mm}^2}{79 \text{mm}^2} = 0.26 \leq 1.0 \quad [12]
\]

\[
l_{\text{req}} = \alpha_1 \cdot \frac{a_{\text{st,req}}}{a_{\text{st,existing}}} \cdot \frac{d_s \cdot \beta_s}{7 \cdot zl_{\tau_1}} = 1.0 \cdot \frac{2107 \text{mm}^2}{79 \text{mm}^2} \cdot \frac{10 \text{mm} \cdot 500 \text{N/mm}^2}{7 \cdot 1.8 \text{N/mm}^2} = 106 \text{mm (min 300 mm)} \quad [13]
\]

In order to create a diaphragm effect within the floor level, 3 of the 11 couplings transmit only tension forces. These tension forces therefore inner connect the individual wcc-floor-elements (Fig. 7). Fig. 5 shows the design approach of 2 arches within the floor-slab inner connected by two tension rods. The tension force of the arch-model due to an effective inner lever of 4.50 m is 87.8 kN [14].

\[
Z = \frac{M}{h} = \frac{q \cdot l^2}{8 \cdot h} = \frac{2 \cdot (12 \text{m})^2}{8 \cdot 4.50 \text{m}} = 87.8 \text{kN} \quad [14]
\]

A steel rod M20 - 10.9 - SL with an allowable tensile force of 88.2 kN is embedded within the concrete slab connecting two opposite steel coupling boxes within one wcc-element.

\[
\eta = \frac{Z_{\text{st,existing}}}{Z_{\text{st,allowable}}} = \frac{87.8 \text{kN}}{88.2 \text{kN}} = 0.99 \leq 1.0 \quad [15]
\]

The steel coupling box (steel grade St. 52 equivalent to A50) for tension forces only is 100 mm long, 100 mm wide and 90 mm in height. Due to the high bending forces within the connected steel plates the required thickness turns out to be 25 mm.

\[
\eta = \frac{\sigma_{\text{existing}}}{\sigma_{\text{allowable}}} = \frac{6 \cdot F \cdot l}{4 \cdot b \cdot t^2} = \frac{6 \cdot 87800 \text{N} \cdot 100 \text{mm}}{4 \cdot 100 \text{mm} \cdot (25 \text{mm})^2} = 0.88 \leq 1.0 \quad [16]
\]
7. Conclusion

Wood-concrete-composite buildings for residential and commercial use were developed to combine the advantages and eliminate the disadvantages of conventional wooden buildings, masonry buildings and concrete structures. The timber section allows for a light open structure which reduces dead load and provides wide openings for insulation and installations. The concrete section provides high sustainability, more fire resistance and more stiffness due to the diaphragm effect.

Contractors in the fields of timber and concrete structures can work hand in hand to build these wcc-elements. Their doing creates prefabricated modular elements which allow for a fast assembling of a structural shell. In cooperation with local craftsman these hurricane proof shells can then be finished in contemporary ways.

The study shows the development of a hurricane proof building system using prefabricated modular wood-concrete-composite elements. The wcc-elements are more sustainable and at the same time more economical than contemporary timber or concrete buildings. The study introduces a solution on how to connect these modular elements with a modular coupling system. It therefore introduces an innovative path of reconstructing sustainable buildings in hurricane regions.

8. References