HILTI COUPLER WOOD (HCW)

Timber-to-concrete connections using HCW and post-installed anchors

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1. INTRODUCTION

No other challenge keeps the construction industry busier than the need to increase efficiency. Becoming more productive, providing more safety and at the same time building more sustainably are all burning topics. An answer to these challenges is the prefabrication of construction elements which has long been standard in other industries.

The concept of prefabrication or off-site fabrication is predominant in timber construction. An example is shown in Fig. 1.1 of the prefabrication of timber elements for residential construction. Optimized processes provide significant advantages with respect to speed and flexibility. One important aspect is how to bring this speed and flexibility to the construction site. To allow a quick and easy connection between two timber elements or a timber element and the concrete member (e.g. foundation) both in the inhouse prefabrication and on the job site, Hilti developed a special connector which is described in Section 2. This paper focuses on the connection between the timber elements and the concrete member, explains challenges in design and provides guidance how to design the connection detail. The verifications of relevant failure modes in the timber element and in the concrete member are explained in Section 3. Modifications are needed in design to account for the distance between the timber element and the concrete member (stand-off condition) which results in an overturning moment on the connection. A new design approach was developed and verified by testing which is described in Section 4. In Section 5 and 6 the realization in a software module is described and a calculation example is provided.

Fig. 1.1: Example of how early and integrated planning in combination with digital processes help to speed up construction

2. HILTI COUPLER WOOD (HCW)

Hilti developed a new connector named HCW for faster and more efficient assembly of prefabricated timber elements carrying a European Technical Assessment (ETA-21/0357 [1]) according to EAD 130186-00-0603 [2]. There are two different versions of the coupler available (HCW and HCW-L). The HCW can be used to transfer both tension and shear loads from the timber member via the coupler and anchor to the base material, whereas HCW-L only transfers tension loads to the base material (realized by slotted holes in the sole plate and the smooth outside of the connector) (see Fig. 2.1). Within a timber frame element, HCW connectors transfer horizontal loads into the sole plate while HCW-L connectors hold down the structure (uplift).
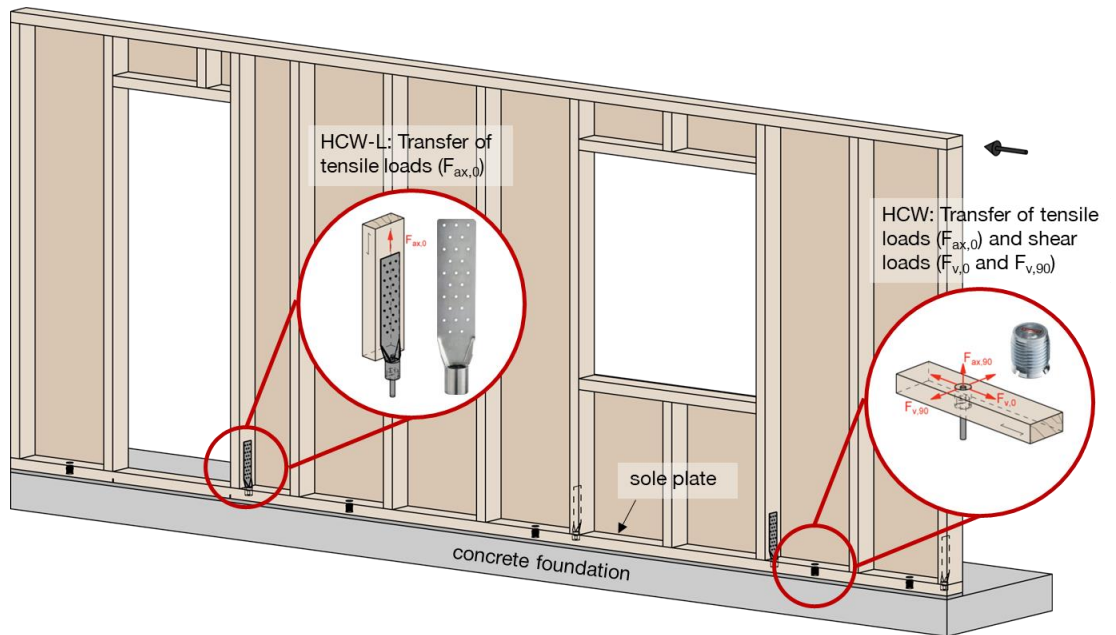
Fig. 2.1: The Hilti Coupler Wood is available in two different versions (HCW-L (left), HCW (right))

The Hilti Coupler Wood (HCW) can be used to connect two timber elements or a timber element to a concrete member. For the connection between two timber elements the HCW is connected with a hanger bolt (HSW or equivalent). For the connection between a timber element and a concrete member, the HCW is connected with a Hilti post-installed mechanical or chemical anchoring system (e.g. HST3, HAS-U in combination with a Hilti injection mortar). The Hilti anchoring systems are illustrated in Fig. 2.2 and Fig. 2.3.
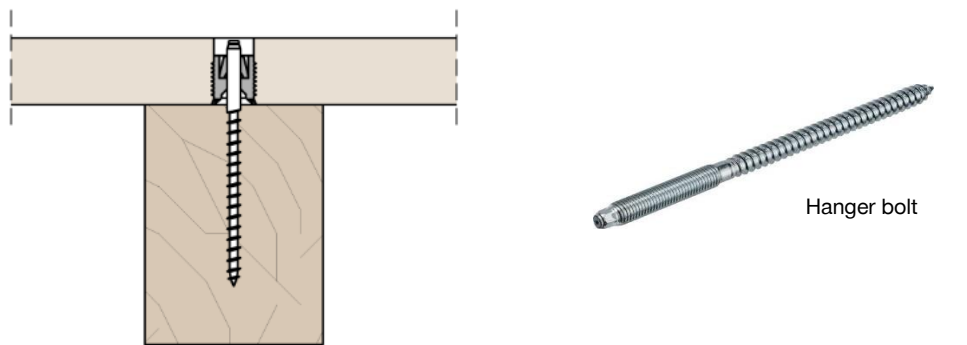

Hanger bolt

Fig. 2.2: Connection between two timber elements with HCW and hanger bolt

Stud anchor (e.g. HST3)

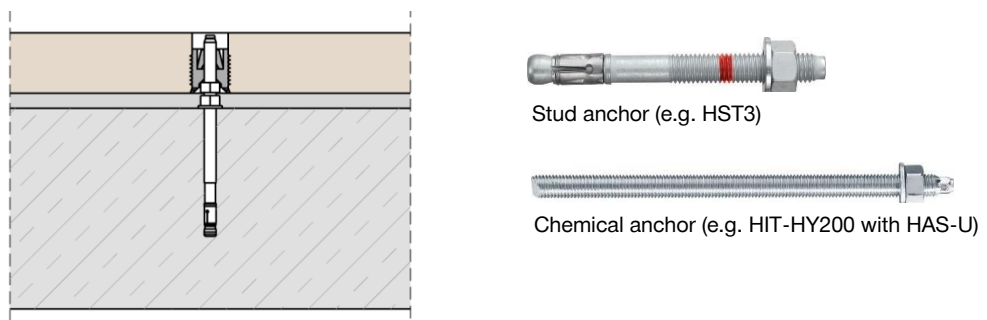Chemical anchor (e.g. HIT-HY200 with HAS-U)

Fig. 2.3: Connection between a timber element and a concrete member with HCW and post-installed anchors

A clamping mechanism is integrated in the steel body of the HCW which connects the threaded part of the Hilti anchoring system with the clamping jaws by a push-to-fit mechanism. The diameter of the HCW is 37 mm (outer diameter 40mm) and the inner diameter is 12.2 mm (compatible for an anchor size M12) (see Fig. 2.4).
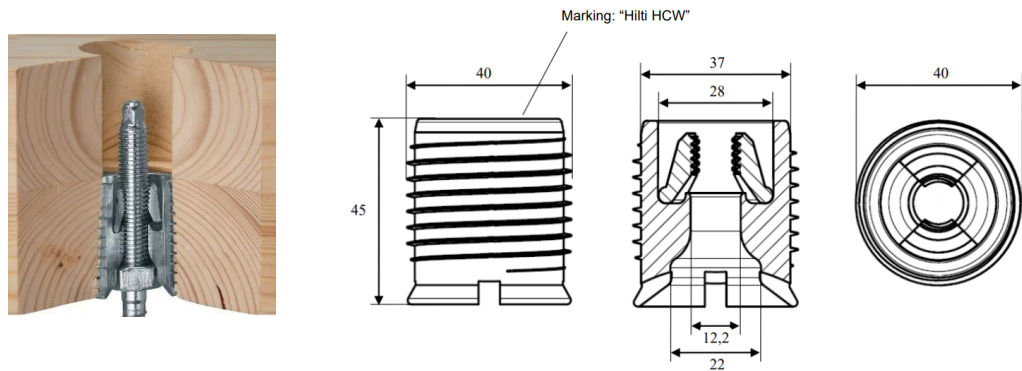

Fig. 2.4: Clamping mechanism in the HCW

2.1 Applications

One of the main applications for the Hilti Coupler Wood (HCW) is the connection of prefabricated timber panels with the concrete foundation (Fig. 2.5). The position of the HCW in the sole plate matches the exact position of the anchors in the concrete member. To help ensure a horizontal position of the timber panel, leveling nuts are used. This results in a stand-off condition. The gap between concrete surface and timber panel is filled with grout. The timber panels can be both located close to the edge of the concrete member or away from the concrete edge.

Fig. 2.5: Installation of a prefabricated timber panel on site

Fig. 2.6: Positioning of the HCW on top of the post-installed anchor with a levelling nut

3. DESIGN OF A TIMBER-TO-CONCRETE CONNECTION WITH HCW

The Hilti Coupler Wood (HCW) in the timber element can transfer tensile loads ($F_{ax,90}$), shear loads parallel to the grain ($F_{v,0}$) and shear loads perpendicular to the grain ($F_{v,90}$) via a Hilti post-installed anchoring system into the concrete member (Fig. 3.1).
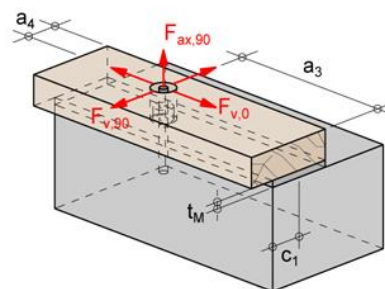

Fig. 3.1: Loading directions

3.1 Verifications in the timber member

For the design of the connection in the timber element, the relevant verifications are given in the European Technical Assessment ETA-21/0357 [1]. The timber specific verifications are in accordance with the Eurocode 5. The following verifications need to be done:

- Tension failure perpendicular to the grain (HCW pulls out of the timber element)
  ($F_{ax,90,Ed} \leq F_{ax,90,Rd}$)
- Tension failure of the clamping mechanism (anchor pulls out of the HCW)
  ($F_{ax,90,Ed} \leq F_{t,Rd}$)
- Shear failure parallel to the grain ($F_{v,0,Ed} \leq F_{v,0,Rd}$)
- Shear failure perpendicular to the grain ($F_{v,90,Ed} \leq F_{v,90,Rd}$)

In case of tension and shear loads, the following interaction equation needs to be fulfilled.

$$(F_{ax,90,Ed}/F_{ax,Rd})^2 + (F_{v,0,Ed}/F_{v,0,Rd})^2 + (F_{v,90,Ed}/F_{v,90,Rd})^2 \leq 1$$

3.2 Verifications of the connection in concrete

For the design of the connection in concrete, the provisions given in EN 1992-4 [3] can be used even though the load is introduced by the HCW and a timber element via the Hilti anchoring system to the concrete instead of a rigid baseplate as required by EN 1992-4 [3]. This is justified since the verification is done for a single anchor. The approach is verified by internal testing.

The following verifications under tension loading need to be done:

- Steel failure ($F_{ax,90,Ed} \leq N_{Rd,s}$)
- Pull-out failure (in case of mechanical anchors) ($F_{ax,90,Ed} \leq N_{Rd,p}$)
- Combined pull-out and concrete failure (in case of bonded anchors) ($F_{ax,90,Ed} \leq N_{Rd,p}$)
- Concrete cone failure ($F_{ax,90,Ed} \leq N_{Rd,c}$)
- Concrete splitting failure ($F_{ax,90,Ed} \leq N_{Rd,sp}$)

The following verifications under shear loading need to be done ($F_{v,Ed} = \left(F_{v,0,Ed}^2 + F_{v,90,Ed}^2\right)^{0.5}$):

- Steel failure with lever arm ($F_{v,Ed} \leq V_{Rd,s,M}$)
- Concrete pryout failure ($F_{v,Ed} \leq V_{Rd,cp}$)
- Concrete edge failure ($F_{v,Ed} \leq V_{Rd,c}$)

For the calculation of the lever arm, the thickness of the fixture (t_{fix}) is defined in the European Technical Assessment ETA-21/0357 [1].
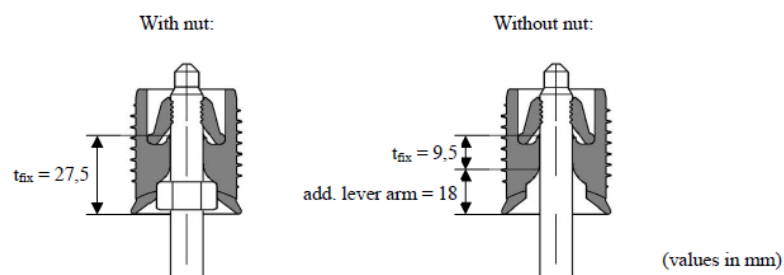

Fig. 3.2: Definition of t_{fix} in case of a levelling nut and t_{fix} and the additional lever arm in case of no levelling nut

In case of tension and shear loads one of the following interaction equations needs to be fulfilled for failure modes other than steel failure.

$$(F_{ax,90,Ed}/N_{Rd})^{1.5} + (F_{v,0,Ed}/V_{Rd,i})^{1.5} \leq 1 \quad \text{or} \quad (F_{ax,90,Ed}/N_{Rd,i}) + (F_{v,0,Ed}/V_{Rd,i}) \leq 1.2$$

In case of steel failure, the interaction between tension and shear is described in Section 4.

4. STAND OFF DESIGN

As described in Section 2.1, levelling of the prefabricated timber panels leads to a stand-off condition. The shear load induces a secondary overturning moment in the connection. The resolution of the secondary overturning moment in the anchor results in an additional shear component. The net effect is to reduce the capacity of the anchoring system as governed by concrete and steel failure. For steel failure, EN 1992-4 [3] provides guidance on how to reduce the steel capacity of the connection in case of a stand-off condition. The verification is described in detail in Section 4.1. In case of anchoring close to an edge of a concrete member, concrete edge failure can occur. If the shear load acts with a lever arm, the effect of the secondary overturning moment on the concrete edge resistance is not considered in EN 1992-4 [3]. To overcome this limitation, Hilti developed a design approach for stand-off conditions

close to the edge of a concrete member which 1) provides a calculation model close to concrete edges and 2) gives improved provisions for steel failure in shear with lever arm. The new design approach is an extension of the provisions given in EN 1992-4 [3]. It is described in Section 4.2 Experimental investigations were performed to verify the model (see Section 4.3).

4.1   Stand-off design according to EN 1992-4

Steel failure in shear with lever arm

In EN 1992-4 [3] provisions, the characteristic steel resistance of anchors in stand-off connections is given in 7.2.2.3.2. EN 1992-4 eq. (7.37) is provided as Eq. (1) below.

$$V_{Rk,s,M} = \frac{\alpha_M \cdot M_{Rk,s}}{l_a} \tag{1}$$

where

α_M =   1.0 (single curvature) or 2.0 (double curvature) as determined by the user

$M_{Rk,s}$ =   characteristic bending resistance of the anchor accounting for the presence of a tension load

          = $M_{Rk,s}^0 \left(1 - N_{Ed}/N_{Rd,s} \right)$

$M_{Rk,s}^0$ =   characteristic bending resistance of a single anchor taken from the European Technical Assessment

W_{el} =   elastic section modulus of the threaded portion of the anchor; should be taken in relation to the net tensile area of the anchor

l_a =   effective lever arm

          = $e_1 + a_3$ (see illustration in Fig. 4.1)

e_1 =   distance between the concrete surface and the centerline of the steel plate

a_3 = $0.5d$ where clamping at the concrete surface is not present

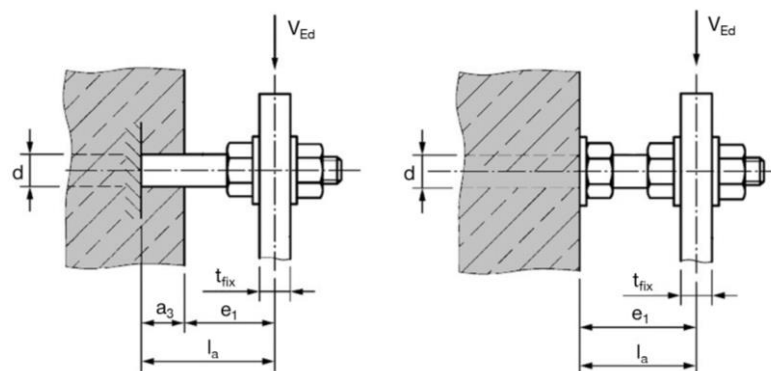   =   0 where clamping at the concrete surface is present

Fig. 4.1: Definition of the lever arm according to EN 1992-4

In case of combined tension and shear loading no interaction needs to be carried out since the tension load is already considered in Eq. (1).

Concrete edge failure in shear with lever arm

In EN 1992-4 [3] provisions, the effect of an overturning moment on the concrete edge breakout resistance is not considered and therefore, no design is possible according to EN 1992-4 [3] in case of a stand-off configuration close to the edge of a concrete member.

4.2   Improved approach for stand-off design

Steel failure in shear with lever arm

Eq. (2) provides an improved approach to calculate steel failure under shear load with lever arm. The approach is based on research performed by McBride (2014) [4].

$$V_{Rk,s,M} = \left(\sqrt{\alpha_{s,M}^2 + 1} - \alpha_{s,M} \right) \cdot V_{Rk,s} \leq V_{Rk,s} \qquad (2)$$

where

$V_{Rk,s}$	=	characteristic shear resistance taken from the European Technical Assessment
$\alpha_{s,M}$	=	$1.5 \cdot l_a / \alpha_M \cdot d$
α_M	=	1.0 (single curvature) or 2.0 (double curvature) as determined by the user
l_a	=	effective lever arm
	=	$e_1 + a_3$ (conservatively taken from EN 1992-4 [3], see Section 4.1, illustration in Fig. 4.1)
e_1	=	distance between the concrete surface and the centerline of the steel plate
a_3	=	$0.5d$ where clamping at the concrete surface is not present
	=	0 where clamping at the concrete surface is present

Since the tension load is not part of $V_{Rd,s,M}$ as per EN 1992-4 [3], the following verification needs to be fulfilled for combined tension and shear loading:

$$\left(\frac{F_{ax,90,Ed}}{N_{Rd,s}} \right)^2 + \frac{F_{v,Ed}}{V_{Rd,s,M}} \leq 1.0 \qquad (3)$$

Concrete edge failure in shear with lever arm

The basic equation to calculate concrete edge failure in a stand-off configuration is taken from EN 1992-4, Section 7.2.2.5. To take into account the secondary overturning moment on the concrete edge breakout resistance, a reduction factor ($\psi_{b,u}$) was developed and is used as a multiplier on the concrete edge resistance. $\psi_{b,u}$ is given in Eq. (4).

$$\psi_{b,u} = \frac{1}{1 + \frac{C}{d^{3/4}} \cdot \frac{l_a}{\alpha_M}} \qquad (4)$$

where

C = a constant representing the elastic interaction between the anchor and concrete

$$= 0.213 \ [1/\text{mm}^{0.25}]$$

l_a = effective exposed length (conservatively taken from EN 1992-4 [3], see Section 4.1, illustration in Fig. 4.1)

α_M = curvature coefficient for the anchor

4.3 Experimental investigations

To verify the reduction of the concrete breakout resistance due to the secondary overturning moment, Hilti performed experimental investigations. The test program is given in Table 4.1. Tests were performed with HST3 M12, h_{ef} = 70 mm clamped to the concrete surface. The tests were performed with two different edge distances (c_1 = 55 mm, 105 mm) and three stand-off conditions (t_m = 0 mm, 30 mm, 50mm). No grout pad was used. The tests were performed on the conservative side with a gap between concrete surface and timber element using a levelling nut. The measured concrete compressive strength on a cube with a side length of 150 mm was between 30,3 and 35,6 MPa. All test results were normalized to a compressive strength of 30 MPa.

Table 4.1: Test program (HCW + HST3 M12 loaded in shear close to the edge)

	c_1 [mm]	t_m [mm]	h_2 [mm]	No. of tests	l_a [mm]
	55	0		3	13,8
	55	30		3	43,8
	55	50	260	3	63,8
	105	0		3	13,8
	105	30		3	43,8
	105	50		3	63,8

Fig. 4.2: Concrete edge failure, Example c_1 = 105 mm, t_m = 50 mm

In all tests, the controlling failure mode was concrete edge failure (see Fig. 4.2). The reduction of the failure load with increasing lever arm can be seen in Fig. 4.3. In Fig. 4.4 the calculated reduction is compared with the reduction of the concrete edge breakout resistance observed in the tests. It can be seen that the modifier according to Equation (4) leads to a conservative prediction of the effect of the overturning moment.
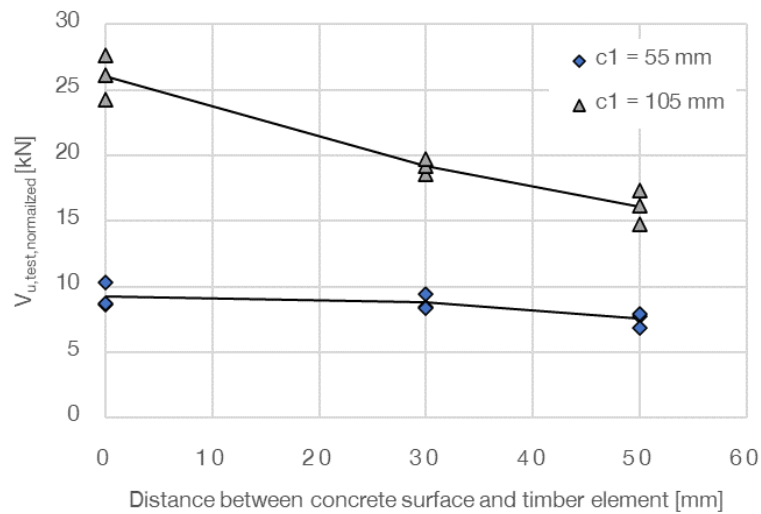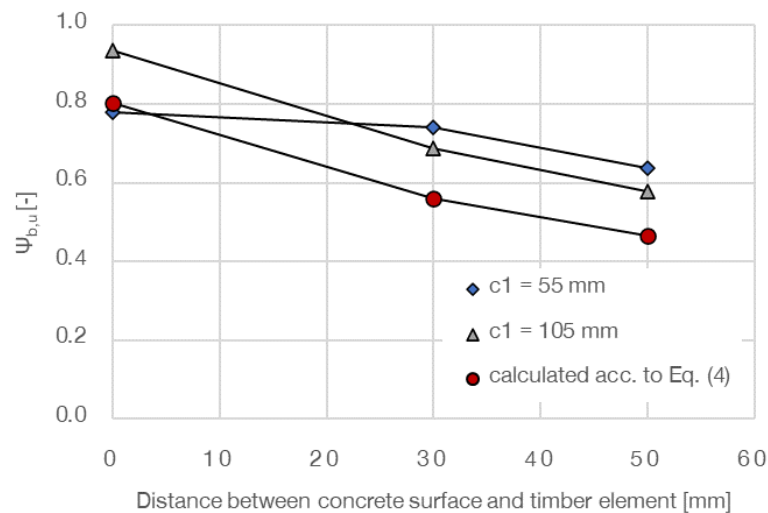
Fig. 4.3: Measured failure loads

Fig. 4.4: Reduction of failure load with increasing lever arm

5. SOFTWARE

In timber construction, the connection of structural members defines the innovative character of a building. The company Ingtools provides tools to design connections and combinations in a simple and pragmatic way. The online platform has a modular structure. Each module can be used separately.

The self-explanatory user interface allows intuitive handling. Drawings and three-dimensional visualizations provide a vivid depiction of the calculation results. Formulas and the design flow are presented in detail in the design report.

The Hilti Coupler Wood (HCW) can be designed in timber-to-timber and timber-to-concrete connections. All verifications of the HCW in wood, as well as of the anchor in concrete, are performed in the software module. Calculations can be saved as project specific by the user in a project management module. A report can be generated as a pdf file. Use of the HCW module is free of charge (https://software.ing-tools.de/modul/HiltiHCW).

6. DESIGN EXAMPLE

A design example of a connection with Hilti HCW with HST3 M12 close to the edge of a concrete member is shown below on one side to not only explain the verification steps in detail, but also to show the benefit of using the improved approach for stand-off design described in Section 4.2.

Connection and geometry
Timber-to-concrete connection
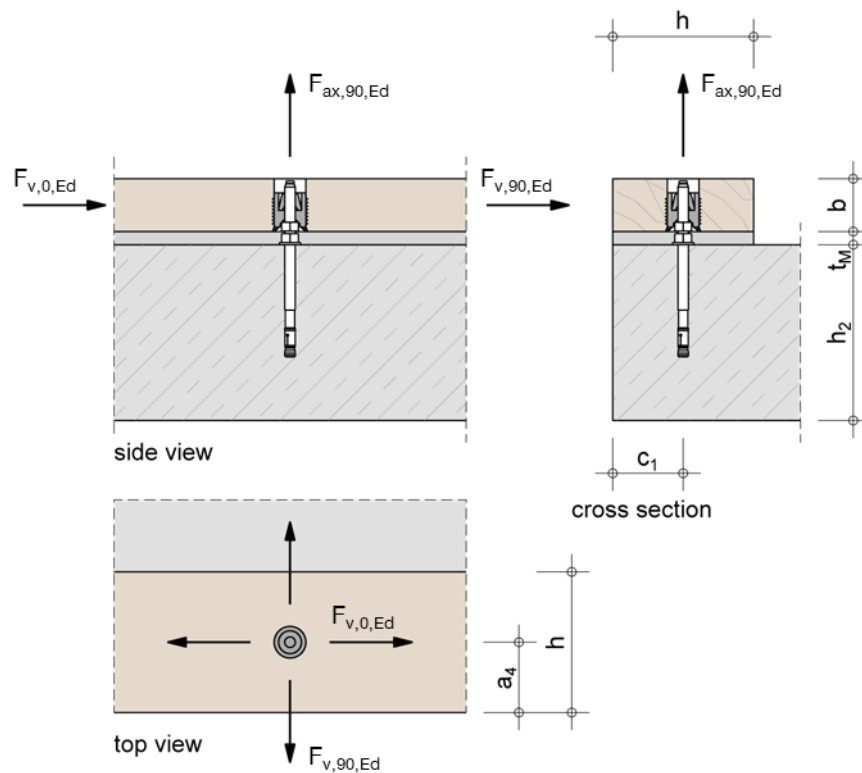
Fig. 6.1: Details of the connection

Components

Timber element: Softwood, C24 $b/h = 60/160\ mm$ $\rho_k = 350\ kg/m^3$ $a_4 = 80\ mm$

Base material: Concrete, C20/25, cracked $h_2 = 200\ mm$ $c_1 = 70\ mm$

Mortar layer: $t_M = 20\ mm$

Connections

HCW 37x45 M12 (ETA-21/0357)

HST3 M12x165 90/70 (ETA-98/0001) $h_{ef} = 70\ mm$ $h_{nom} = 80\ mm$ $T_{inst} = 60\ Nm$

Borehole: hammer drilled

Installation condition: dry

Loads

Service class: NKL1 – heated interiors

$F_{v,0,Ed} = 6.0\ kN$ KLED: short $k_{mod} = 0.9$

$F_{v,90,Ed} = 1.0\ kN$ KLED: short $k_{mod} = 0.9$

$F_{ax,90,Ed} = 1.0\ kN$ KLED: short $k_{mod} = 0.9$

Design – verifications in the timber member

Tension failure perpendicular to the grain (HCW pulls out of the timber element)

$F_{ax,90,Rk} = 12.7\ kN$ ETA-21/0357, Table C1

$F_{ax,90,Rd} = k_{mod} \cdot \dfrac{F_{ax,90,Rk}}{\gamma_M} = 0.9 \cdot \dfrac{12.7}{1.3} = 8.8\ kN$

$\dfrac{F_{ax,90,Ed}}{F_{ax,90,Rd}} = \dfrac{1.0}{8.8} = 0.11 \leq 1.0$

verification fulfilled ✅

Tension failure of the clamping mechanism (anchor pulls out of the HCW)

$F_{t,Rk} = 37.5\ kN$ ETA-21/0357, Table C1

$F_{t,Rd} = \dfrac{F_{t,Rk}}{\gamma_{M2}} = \dfrac{37.5}{1.25} = 30\ kN$

$\dfrac{F_{ax,90,Ed}}{F_{t,Rd}} = \dfrac{1.0}{30} = 0.03 \leq 1.0$

verification fulfilled ✅

Shear failure parallel to the grain

$F_{v,0,Rk} = 28.8\ kN$ ETA-21/0357, Table C1

$F_{v,0,Rd} = k_{mod} \cdot \dfrac{F_{v,0,Rk}}{\gamma_M} = 0.9 \cdot \dfrac{28.8}{1.3} = 19.9\ kN$

$\dfrac{F_{v,0,Ed}}{F_{v,0,Rd}} = \dfrac{6.0}{19.9} = 0.3 \leq 1.0$

verification fulfilled ✅

Shear failure perpendicular to the grain

$F_{v,90,Rk} = 12.5\ kN$ ETA-21/0357, Table C1

$F_{v,90,Rd} = k_{mod} \cdot \dfrac{F_{v,90,Rk}}{\gamma_M} = 0.9 \cdot \dfrac{12.5}{1.3} = 8.7\ kN$

$\dfrac{F_{v,90,Ed}}{F_{v,90,Rd}} = \dfrac{1.0}{8.7} = 0.12 \leq 1.0$

verification fulfilled ✅

Combined tension and shear loads

$(F_{ax,90,Ed}/F_{ax,Rd})^2 + (F_{v,0,Ed}/F_{v,0,Rd})^2 + (F_{v,90,Ed}/F_{v,90,Rd})^2 = 0.12 \leq 1$

verification fulfilled ✅

Design – verifications in the concrete member

Tension loads

Steel failure

$N_{Rk,s} = 45.1 \; kN$ ETA-98/0001, Table C2

$\gamma_{Ms} = 1.4$

$N_{Rd,s} = \dfrac{N_{Rk,s}}{\gamma_{Ms}} = \dfrac{45.1}{1.4} = 32.2 \; kN$

$\dfrac{F_{ax,90,Ed}}{N_{Rd,s}} = \dfrac{1.0}{32.2} = 0.03 \leq 1.0$

verification fulfilled ✅

Pull-out failure

$\psi_c = 1.0$ ETA-98/0001, Table C2

$N_{Rk,p} = 20 \; kN$ ETA-98/0001, Table C2

$\gamma_{Mp} = 1.5$

$N_{Rd,p} = \dfrac{\psi_c \cdot N_{Rk,p}}{\gamma_{Mp}} = \dfrac{1.0 \cdot 20}{1.5} = 13.3 \; kN$

$\dfrac{F_{ax,90,Ed}}{N_{Rd,p}} = \dfrac{1.0}{13.3} = 0.08 \leq 1.0$

verification fulfilled ✅

Concrete cone failure

$k_1 = k_{cr,N} = 7.7$ EN 1992-4, 7.2.1.4

$h_{ef} = 70 \; mm$

$N^0_{Rkc} = k_1 \cdot \sqrt{f_{ck}} \cdot h_{ef}^{1.5} = 7.7 \cdot \sqrt{20} \cdot 70^{1.5} \cdot 10^{-3} = 20.2 \; kN$ EN 1992-4, Eq. (7.2)

$s_{cr,N} = 3 \cdot h_{ef} = 3 \cdot 70 = 210 \; mm$

$A^0_{c,N} = s_{cr,N} \cdot s_{cr,N} = 210 \cdot 210 = 44100 \; mm^2$

$A_{c,N} = \left(c_1 + 0.5 \cdot s_{cr,N}\right) \cdot \left(2 \cdot 0.5 \cdot s_{cr,N}\right)$

$\qquad = (70 + 0.5 \cdot 210) \cdot (2 \cdot 0.5 \cdot 210) = 36750 \; mm^2$

$\psi_{s,N} = 0.7 + 0.3 \cdot \dfrac{c}{c_{cr,N}} = 0.7 + 0.3 \cdot \dfrac{70}{105} = 0.9 \leq 1.0$

$\psi_{re,N} = 1.0$

$\psi_{ec,N} = 1.0$

$\psi_{M,N} = 1.0$

$N_{Rk,c} = N^0_{Rk,c} \cdot \dfrac{A_{c,N}}{A^0_{c,N}} \cdot \psi_{s,N} \cdot \psi_{re,N} \cdot \psi_{ec,N} \cdot \psi_{M,N}$

$\qquad = 20.17 \cdot \dfrac{36750}{44100} \cdot 0.9 \cdot 1.0 \cdot 1.0 \cdot 1.0 = 15.1 \; kN$

$\gamma_{Mc} = 1.5$

$N_{Rd,c} = \dfrac{N_{Rk,c}}{\gamma_{Mc}} = \dfrac{15.1}{1.5} = 10.1 \; kN$

$\dfrac{F_{ax,90,Ed}}{N_{Rd,c}} = \dfrac{1.0}{10.1} = 0.1 \leq 1.0$

verification fulfilled ✅

Splitting failure

$$N_{Rk,sp,ETA}^0 = 25 \; kN$$

<div style="text-align: right">ETA-98/0001, Table C2</div>

$$N_{Rk,sp}^0 = \psi_c \cdot N_{Rk,sp,ETA}^0 = 1.0 \cdot 25 = 25 \; kN$$

$$s_{cr,sp} = 3 \cdot h_{ef} = 3 \cdot 70 = 210 \; mm$$

$$A_{c,N}^0 = s_{cr,sp} \cdot s_{cr,sp} = 210 \cdot 210 = 44100 \; mm^2$$

$$A_{c,N} = \left(c_1 + 0.5 \cdot s_{cr,sp} \right) \cdot \left(2 \cdot 0.5 \cdot s_{cr,sp} \right)$$

$$= (70 + 0.5 \cdot 210) \cdot (2 \cdot 0.5 \cdot 210) = 36750 \; mm^2$$

$$h_{ef,min} = 50 \; mm$$

<div style="text-align: right">ETA-98/0001, Table B12</div>

$$h_{min} = 100 + h_{ef} - h_{ef,min} = 100 + 70 - 50 = 120 \; mm$$

<div style="text-align: right">ETA-98/0001, Table B12</div>

$$\psi_{s,N} = 0.7 + 0.3 \cdot \frac{c_1}{c_{cr,sp}} = 0.7 + 0.3 \cdot \frac{70}{105} = 0.9 \le 1.0$$

$$\psi_{h,sp} = \left(\frac{h_2}{h_{min}} \right)^{2/3} \le \max \left\{ 1; \left(\frac{h_{ef} + 1.5 \cdot c_1}{h_{min}} \right)^{2/3} \right\} \le 2.0$$

$$= \left(\frac{200}{120} \right)^{2/3} \le \max \left\{ 1; \left(\frac{70 + 1.5 \cdot 70}{120} \right)^{2/3} \right\} \le 2.0$$

$$= 1.41 \le \max\{1; 1.29\} \le 2.0$$

$$= 1.29$$

$$N_{Rk,sp} = N_{Rk,sp}^0 \cdot \frac{A_{c,N}}{A_{c,N}^0} \cdot \psi_{s,N} \cdot \psi_{re,N} \cdot \psi_{ec,N} \cdot \psi_{h,sp} = 25 \cdot \frac{36750}{44100} \cdot 0.9 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.29 = 24.2 \; kN$$

$$\gamma_{M,sp} = 1.5$$

$$N_{Rd,sp} = \frac{N_{Rk,sp}}{\gamma_{Msp}} = \frac{24.2}{1.5} = 16.1 \; kN$$

$$\frac{F_{ax,90,Ed}}{N_{Rd,sp}} = \frac{1.0}{16.1} = 0.06 \le 1.0$$

verification fulfilled ✅

Shear loads

Steel failure without lever arm

$$V_{Rk,s}^0 = 35 \; kN$$

<div style="text-align: right">ETA-98/0001, Table C4</div>

$$V_{Rk,s} = k_7 \cdot V_{Rk,s}^0 = 1.0 \cdot 35.4 = 35.4 \; kN$$

<div style="text-align: right">EN 1992-4, Eq. (7.35)</div>

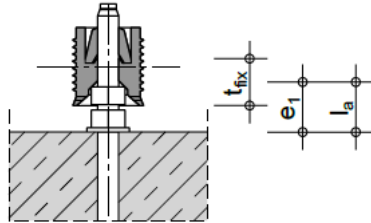$$V_{Rd,s} = \frac{V_{Rk,s}}{\gamma_{Ms}} = \frac{35.4}{1.25} = 28.3 \; kN$$

Loads:

$$F_{v,Ed} = \sqrt{F_{v,0,Ed}^2 + F_{v,90,Ed}^2} = \sqrt{6^2 + 1^2} = 6.1 \; kN$$

$$\frac{F_{v,Ed}}{V_{Rd,s}} = \frac{6.1}{28.3} = 0.22 \le 1.0$$

verification fulfilled ✅

Steel failure with lever arm

$$e_1 = \frac{t_{fix}}{2} + t_M = \frac{27.5}{2} + 20 = 33.8 \; mm$$

$$l_a = e_1 = 33.8 \; mm$$

$$\alpha_M = 2.0$$

Verification according to EN 1992-4 [3] (see Section 4.1)

$$M_{Rk,s} = M_{Rk,s}^0 \cdot \left(1 - \frac{F_{ax,90,d}}{N_{Rd,s}}\right) = 105 \cdot \left(1 - \frac{1}{32.21}\right) = 101.7 \; Nm$$

$$V_{Rk,s,M} = \frac{\alpha_M \cdot M_{Rk,s}}{l_a} = \frac{2 \cdot 101.74}{33.8} = 6.0 \; kN$$

$$V_{Rd,s,M} = \frac{V_{Rk,s,M}}{\gamma_{Ms}} = \frac{6.0}{1.25} = 4.8 \; kN$$

$$\frac{F_{v,Ed}}{V_{Rd,s,M}} = \frac{6.1}{4.8} = 1.26 > 1.0$$

verification not fulfilled ❌

(Resistance is not sufficient according to the calculation method given in EN 1992-4 [3])

Verification according to improved design method for stand-off configurations (see Section 4.2)

$$\alpha_{s,M} = \frac{1.5 \cdot l_a}{\alpha_M \cdot d} = \frac{1.5 \cdot 33.8}{2 \cdot 12} = 2.1$$

$$V_{Rk,s,M} = \left(\sqrt{\alpha_{s,M}^2 + 1} - \alpha_{s,M}\right) \cdot V_{Rk,s} = \left(\sqrt{2.1^2 + 1} - 2.1\right) \cdot 35.4 = 8.0 \; kN$$

$$= \frac{V_{Rk,s,M}}{\gamma_{Ms}} = \frac{8.0}{1.25} = 6.4 \; kN$$

$$\frac{F_{v,Ed}}{V_{Rd,s,M}} = \frac{6.1}{6.4} = 0.95 \leq 1.0$$

verification fulfilled ✅

Concrete pry-out failure

$$k_1 = k_{cr,N} = 7.7 \hspace{4cm} \text{EN 1992-4, 7.2.1.4}$$

$$h_{ef} = 70 \; mm \hspace{5cm} \text{ETA-98/0001}$$

$$N_{Rkc}^0 = k_1 \cdot \sqrt{f_{ck}} \cdot h_{ef}^{1.5} = 7.7 \cdot \sqrt{20} \cdot 70^{1.5} \cdot 10^{-3} = 20.2 \; kN \hspace{1cm} \text{EN 1992-4, Eq. (7.2)}$$

$$s_{cr,N} = 3 \cdot h_{ef} = 3 \cdot 70 = 210 \; mm$$

$$A_{c,N}^0 = s_{cr,N} \cdot s_{cr,N} = 210 \cdot 210 = 44100 \; mm^2$$

$$A_{c,N} = \left(c_1 + 0.5 \cdot s_{cr,N}\right) \cdot \left(2 \cdot 0.5 \cdot s_{cr,N}\right) = (70 + 0.5 \cdot 210) \cdot (2 \cdot 0.5 \cdot 210) = 36750 \; mm^2$$

$$\psi_{s,N} = 0.7 + 0.3 \cdot \frac{c_1}{c_{cr,N}} = 0.7 + 0.3 \cdot \frac{70}{105} = 0.9 \leq 1.0$$

$$\psi_{re,N} = 1.0$$

$$\psi_{ec,N} = 1.0$$

$$\psi_{M,N} = 1.0$$

$$N_{Rk,c} = N_{Rk,c}^0 \cdot \frac{A_{c,N}}{A_{c,N}^0} \cdot \psi_{s,N} \cdot \psi_{re,N} \cdot \psi_{ec,N} \cdot \psi_{M,N}$$

$$= 20.2 \cdot \frac{36750}{44100} \cdot 0.9 \cdot 1.0 \cdot 1.0 \cdot 1.0 = 15.1 \; kN$$

$$k_8 = 2.78 \hspace{6cm} \text{ETA-98/0001, Table C4}$$

$$V_{Rk,cp} = k_8 \cdot N_{Rkc} = 2.78 \cdot 15.1 = 42.1 \; kN$$

$$V_{Rd,cp} = \frac{V_{Rk,cp}}{\gamma_{Mc}} = \frac{42.1}{1.5} = 28.0 \; kN$$

Loads:

$$F_{v,Ed} = \sqrt{F_{v,0,Ed}^2 + F_{v,90,Ed}^2} = \sqrt{6^2 + 1^2} = 6.1 \; kN$$

$$\frac{F_{v,Ed}}{V_{Rd,s,M}} = \frac{6.1}{28.0} = 0.22 \leq 1.0$$

verification fulfilled ✅

Concrete edge failure

Verification according to EN 1992-4 [3] is not possible (see Section 4.1). EN 1992-4 [3] does not consider the effect of the secondary overturning moment on the concrete edge resistance.

Verification according to improved design method for stand-off configurations (see Section 4.2)

$$k_9 = 1.7 \hspace{6cm} \text{EN 1992-4, 7.2.2.5}$$

$$d_{nom} = 12 \; mm \hspace{5cm} \text{ETA-98/0001, Table C4}$$

$$l_f = 70 \; mm \hspace{5.5cm} \text{ETA-98/0001, Table C4}$$

$$\alpha = 0.1 \cdot \left(\frac{l_f}{c_1}\right)^{0.5} = 0.1 \cdot \left(\frac{70}{70}\right)^{0.5} = 0.1$$

$$\beta = 0.1 \cdot \left(\frac{d_{nom}}{c_1}\right)^{0.2} = 0.1 \cdot \left(\frac{12}{70}\right)^{0.2} = 0.07$$

$$V_{Rkc}^0 = k_9 \cdot d_{nom}^\alpha \cdot l_f^\beta \cdot \sqrt{f_{ck}} \cdot c_1^{1.5} = 1.7 \cdot 12^{0.1} \cdot 70^{0.07} \cdot \sqrt{20} \cdot 70^{1.5} \cdot 10^{-3} = 7.7 \; kN \hspace{0.5cm} \text{EN 1992-4, Eq. (7.41)}$$

$$A_{c,V}^0 = 4.5 \cdot c_1^2 = 4.5 \cdot 70 \cdot 70 = 22050 \; mm^2$$

$$A_{c,V} = (2 \cdot 1.5 \cdot c_1) \cdot 1.5 \cdot c_1 = (2 \cdot 1.5 \cdot 70) \cdot 1.5 \cdot 70 = 22050 \; mm^2$$

$$C = 0.213 \frac{1}{mm^{0.25}}$$

$$\psi_{b,u} = \frac{1}{1 + \dfrac{C}{d^{3/4}} \cdot \dfrac{l_a}{\alpha_M}} = \frac{1}{1 + \dfrac{0.213}{12^{3/4}} \cdot \dfrac{33.8}{2}} = 0.64$$

$$\psi_{s,V} = 1.0$$

$$\psi_{h,V} = \left(\frac{1.5 \cdot c_1}{h_2}\right)^{0.5} = \left(\frac{1.5 \cdot 70}{200}\right)^{0.5} \geq 1.0$$

$$\psi_{ec,V} = 1.0$$

$$\alpha_V = \arccos\left(\frac{F_{v,90,d}}{\sqrt{F_{v,0,d}^2 + F_{v,90,d}^2}}\right) = 80.54$$

$$\psi_{\alpha,V} = \sqrt{\frac{1}{(cos\alpha_v)^2 + (0.5 \cdot sin\alpha_v)^2}} = 1.924 \geq 1$$

$$\psi_{re,V} = 1.0$$

$$V_{Rk,c} = V_{Rk,c}^0 \cdot \frac{A_{c,N}}{A_{c,N}^0} \cdot \psi_{b,u} \cdot \psi_{s,V} \cdot \psi_{h,V} \cdot \psi_{cc,V} \cdot \psi_{\alpha,V} \cdot \psi_{re,V} = 7.7 \cdot \frac{22050}{22050} \cdot 0.64 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.924 \cdot 1.0$$

$$= 9.5 \; kN$$

$$V_{Rd,c} = \frac{V_{Rk,c}}{\gamma_{Mc}} = \frac{9.5}{1.5} = 6.3 \; kN$$

$$\frac{F_{v,Ed}}{V_{Rd,c}} = \frac{6.1}{6.3} = 0.96 \leq 1.0$$

verification fulfilled ✅

Combined tension and shear loads

Interaction of steel failure modes

$$\left(\frac{F_{ax,90,Ed}}{N_{Rd,s}}\right)^2 + \frac{F_{v,Ed}}{V_{Rd,s,M}} = \left(\frac{1.0}{32.2}\right)^2 + \frac{6.1}{6.4} = 0 + 0.95 = 0.95 \leq 1.0$$

verification fulfilled ✅

Interaction of concrete failure modes

$$N_{Rd,i} = \min\{N_{Rd,p}, N_{Rd,c}, N_{Rd,sp}\} = \min(13.3, 10.1, 16.1) = 10.1 \; kN$$

$$V_{Rd,i} = \min\{V_{Rd,cp}, V_{Rd,c}\} = \min(28.0, 6.3) = 6.3 \; kN$$

$$\left(\frac{F_{ax,90,Ed}}{N_{Rd,i}}\right) + \left(\frac{F_{v,Ed}}{V_{Rd,i}}\right) = \left(\frac{1.0}{10.1}\right) + \left(\frac{6.1}{6.3}\right) = 0.1 + 0.96 = 1.06 \leq 1.2$$

verification fulfilled ✅

Summary of verifications

Verifications in the timber member

Tension failure perpendicular to the grain: $\qquad \frac{F_{ax,90,Ed}}{F_{ax,90,Rd}} = \frac{1.0}{8.8} = 0.11 \leq 1.0$

Tension failure of the clamping mechanism: $\qquad \frac{F_{ax,90,Ed}}{F_{t,Rd}} = \frac{1.0}{30.0} = 0.03 \leq 1.0$

Shear failure parallel to the grain:

$$\frac{F_{v,0,Ed}}{F_{v,0,Rd}} = \frac{6.0}{19.9} = 0.30 \leq 1.0$$

Shear failure perpendicular to the grain:

$$\frac{F_{v,90,Ed}}{F_{v,90,Rd}} = \frac{1.0}{8.7} = 0.12 \leq 1.0$$

Combined tension and shear loads:

$$\left(\frac{F_{ax,90,Ed}}{F_{ax,90,Rd}}\right)^2 + \left(\frac{F_{v,0,Ed}}{F_{v,0,Rd}}\right)^2 + \left(\frac{F_{v,90,Ed}}{F_{v,90,Rd}}\right)^2 = 0.12 \leq 1.0$$

Verifications in the concrete member

Tension – steel failure:

$$\frac{F_{ax,90,Ed}}{N_{Rd,s}} = \frac{1.0}{32.2} = 0.03 \leq 1.0$$

Tension – pullout failure:

$$\frac{F_{ax,90,Ed}}{N_{Rd,p}} = \frac{1.0}{13.3} = 0.08 \leq 1.0$$

Tension – concrete cone failure:

$$\frac{F_{ax,90,Ed}}{N_{Rd,c}} = \frac{1.0}{10.1} = 0.10 \leq 1.0$$

Tension – splitting failure:

$$\frac{F_{ax,90,Ed}}{N_{Rd,sp}} = \frac{1.0}{16.1} = 0.06 \leq 1.0$$

Shear – steel failure without lever arm:

$$\frac{F_{v,Ed}}{V_{Rd,s}} = \frac{6.1}{28.3} = 0.22 \leq 1.0$$

Shear – steel failure with lever arm:

$$\frac{F_{v,Ed}}{V_{Rd,s,M}} = \frac{6.1}{6.4} = 0.95 \leq 1.0$$

Shear – concrete pry-out failure:

$$\frac{F_{v,Ed}}{V_{Rd,cp}} = \frac{6.1}{28.0} = 0.22 \leq 1.0$$

Shear – concrete edge failure:

$$\frac{F_{v,Ed}}{V_{Rd,c}} = \frac{6.1}{6.3} = 0.96 \leq 1.0$$

Combined tension and shear loads:

$$\left(\frac{F_{ax,90,Ed}}{N_{Rd,s}}\right)^2 + \frac{F_{v,Ed}}{V_{Rd,s,M}} = \left(\frac{1.0}{32.2}\right)^2 + \frac{6.1}{6.4} = 0.95 \leq 1.0$$

7. SUMMARY

The paper presents a new connector named HCW for faster and more efficient assembly of prefabricated timber elements. An advanced design method considering the effect of the secondary overturning moment created due to the stand-off condition was developed and verified by testing. The design method including the verifications in the timber element as well as the verifications in the concrete member is implemented in a software module which enables a fast and easy-to-understand design of the connection. It is noted that the concept is verified by experimental investigations with Hilti anchoring systems in combination with the Hilti Coupler Wood (HCW). An extension of the design method to other products should not be done without further consideration.

8. REFERENCES

[1] ETA-21/0357. *Fastening element Hilti HCW, HCW-L*, ETA Danmark A/S, April 25, 2022.

[2] EAD 130186-00-0603. *Three-Dimensional Nailing Plates*, EOTA, July 2018.

[3] EN 1992-4. *Eurocode 2 - Design of concrete structures - Part 4: Design of fastenings for use in concrete*, Brussels, 2018.

[4] K. McBride, *Steel strength of anchor bolts in stand-off base plate connections. Ph.D. Dissertation, University of Florida, Gainesville, FL, USA.,* Florida, 2014.

[5] K. McBride, D. Rocha and R. Figoli, *Hilti Method for Anchor Design in ungrouted stand-off connections. Whitepaper, Hilti Corporation,* Schaan, Liechtenstein, 2023.

[6] ETA 98/0001: *Hilti metal expansion anchor HST, HST-R, HST-HCR, HST3, HST3-R*, DIBt, November 3, 2022.

[7] EN 1995-1-1. *Eurocode 5 - Design of Timber Structures – Part 1-1: General – Common rules and rules for buildings*, Brussels, 2004.

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