WOOD-CONCRETE COMPOSITE CEILINGS

Design variants and dimensioning

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General engineering requirements

The available materials and dimensions used in timber construction help to create easily light structures with large span widths. Besides the load-bearing capacity of the structures, properties influencing the sense of use and comfort are very important. Already at an early stage of planning the requirements relating to these properties have to be defined having a considerable influence on the structure to be chosen.

Especially in the case of timber construction there is a particularly critical sense with regard to the before mentioned properties. For this reason the users of ceiling structures must have a choice of effective and low-cost solutions which meet the demands for fire protection, sound insulation and having a moderate vibration behavior at the same time.

Requirements on sound insulation

For ceiling structures the sound insulation is an important construction value. In this case it is mostly influenced by the ceiling structure, i.e. layer sequence. Usually the structure consists of a covering, a floating screed and a footfall sound insulation. The individual layers together with the structure form a mass-spring-mass system. The footfall sound insulation between the floating screed and the structure acts like a spring. Additional massive layers improve continuously and significantly the acoustic properties of timber ceilings. However, joist and solid timber ceilings with an appropriate ballasting are significantly lighter than reinforced concrete ceilings.

In combination with footfall sound insulations which have a low dynamic stiffness the ballasting of ceilings leads to better properties relating to frequencies above the resonance frequency. In the case of low frequencies these factors show no effects. Indeed bonding the mass with the wooden ceiling does lead to an increased stiffness, but simultaneously also to a poorer sound insulation in comparison to the screw-retained systems.

In contrast to fillings and weightings the concrete slab of a wood/concrete composite ceiling is not only an additional layer to increase the mass. The connection of the concrete slap with the substructure by means of screws is sufficiently stiff to increase considerably the overall stiffness of the structure. At the same time this connection is ductile enough to absorb vibrations to some extent.

Requirements on fire protection

With the amendment of the federal building regulation, buildings with up to eight floors can be built completely from wood. This results in an increased demand for fire resistance of the individual components. As far as the wood/-concrete composite ceilings are not protected by fireproofingfireproof cladding, the proof for the requested fire resistance duration can alternatively be provided according to the requirements after EN 1992-1-2 and EN 1995-1-2. Fire resistance durations of RI90 and more can be proved in calculations.

Composite action via screws

For a shear-resistant coupling of the concrete slab with the wooden substructure different systems are available on the market partly with a European Technical Approval. Among the various systems the following distinctions can be made:

- Coupling via connectors: The transfer of shear forces takes place via connectors stressed axially or laterally (e.g. screws, glued perforated plates etc.)
- Coupling via fit (millings in the wood which are poured out with concrete): The transfer of the shear forces takes place via contact.

The choice of the shear connectors for coupling the concrete slab with the wooden substructure depends on several factors. The wood construction screws are especially characterized by their easy and simple processing. No special requirements relating to staff and materials have to be met for their processing and application. The screws approved for wood/concrete composite structures are either special screws exclusively certified for this specific application or standard fully threaded screws (e.g. Würth ASSY® plus VG) which can be applied universally.

Mode of action

In wood/concrete composite structures screws as shear connectors can be stressed laterally or axially. The alignment of the screw with regard to the shear band is relevant for the stress variant:

Arrangement of the screws below 90° to the shear band

Screws arranged vertically to the shear band are subjected to shearing. Such connections have a comparatively low load-bearing capacity and stiffness. Under the aspect of cost-efficiency this type of screw arrangement should only be applied in exceptional cases (e.g. in cases of poor or only constructive bond).

Arrangement of the screws below an angle of 30° to 45° to the shear band in direction of the shear forces

Due to the very high load-bearing capacity and stiffness of screws stressed axially these should be arranged diagonally in a possibly flat angle to the shear force. With this arrangement the force is divided into two resulting load components. One part works towards the screw axis and exerts tensile stress on the screw. The corresponding force acts vertically to the shear band. This force component is transferred via contact between concrete and wood and presses the concrete slab onto the substructure. In the case of a screw arrangement in pairs and crosswise the shear force is divided into two load components which are absorbed by a crossed pair of screws. Here one of the screws is subjected to tensile and one to compression load. With this kind of arrangement a positively acting contact force cannot be developed.

For assembly the screws are inserted into the wood construction in such a way that their screw heads extend into the concrete in sufficient length. In the case of finished composite constructions the screw is encased in concrete. The load resulting from the screw is transferred via contact below the screw head or via the thread flanks or profilings into the concrete.

Depending on the selected screw, its length or the chosen connection variant, the calculation of the composite screw is subject to the pull out load-bearing capacity or to its tear-off sustainability (steel failure).

Installation of a finished product slab with finished product (FP) connectors even during winter conditions

Installation

There are two possibilities of installing or making composite ceilings:

1. The screws are inserted into the existing or pre-assembled wood construction (joist or solid timber elements). For inserting screws into joists a formwork or something similar has to be arranged for absorbing the concrete. A film has to be applied between the wood or formwork and the concrete layer to protect the wood against moisture resulting from the wet concrete. Subsequently the concrete is poured. In order to prevent permanent deformations through construction loads (wet concrete) the construction must be supported until the concrete has set (usually 28 days).

2. For new buildings the ceilings can be pre-fabricated element by element. Thus in a first step the screws are inserted into the joists/wooden panels. Subsequently the joists are immersed the other way round into the formwork system so that the screws submerge completely in concrete in a straight manner. The joists must remain in this position until the concrete became hard. Then the components can be transported and assembled in one piece to the construction site. This version requires precise working when pre-assembling the wood construction and manufacturing the ceiling elements. Even the slightest dimensional deviations can lead to difficulties with the installation at the construction site.

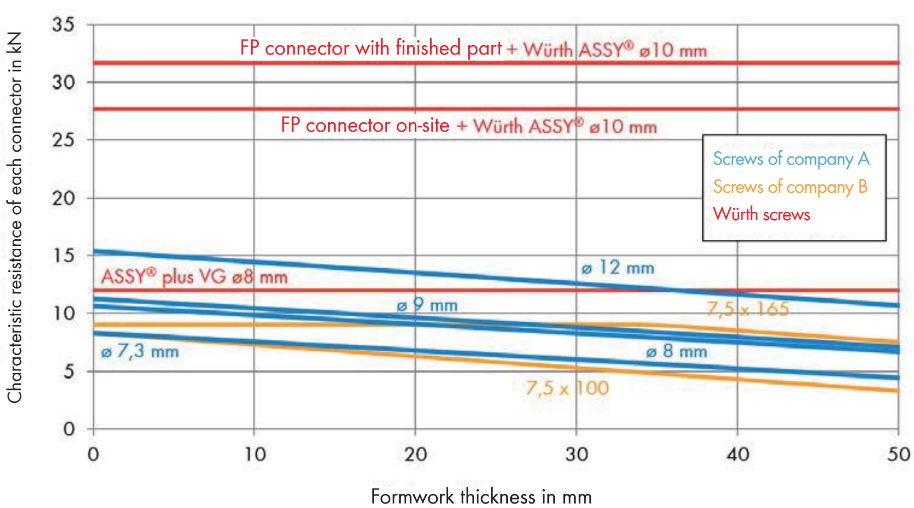
Finished product (FP) connectors – an extended screw system

With the FP connector from Würth and SWG Schraubenwerk Gaisbach available since 2012 a shear connector for wood/concrete composite constructions is at hand. It combines a high load-bearing capacity with a high degree of pre-fabrication referring to the existing infrastructure of the reinforced concrete pre-cast units industry.

FP connectors are suitable for manufacturing wood-concrete composite ceilings using wet and dry methods.out of prefabricated elements or by concreting at the construction site.

Mechanism of the FP connectors

A steel plate/washer placed at the head side, a flat insertion angle and a high load-bearing capacity of the Würth fully threaded screw (ASSY® plus VG) applied lead to a very high force transmission in combination with a corresponding high stiffness. The concrete transmits its load via pressure to the steel plate. The later transmits the force to the screw head of the Würth ASSY® plus fully threaded screw which again is anchored in the subjacent wood. The force resulting from the load deflection acts perpendicularly to the component joint and produces a contact pressure that increases the frictional resistance between concrete and wood.



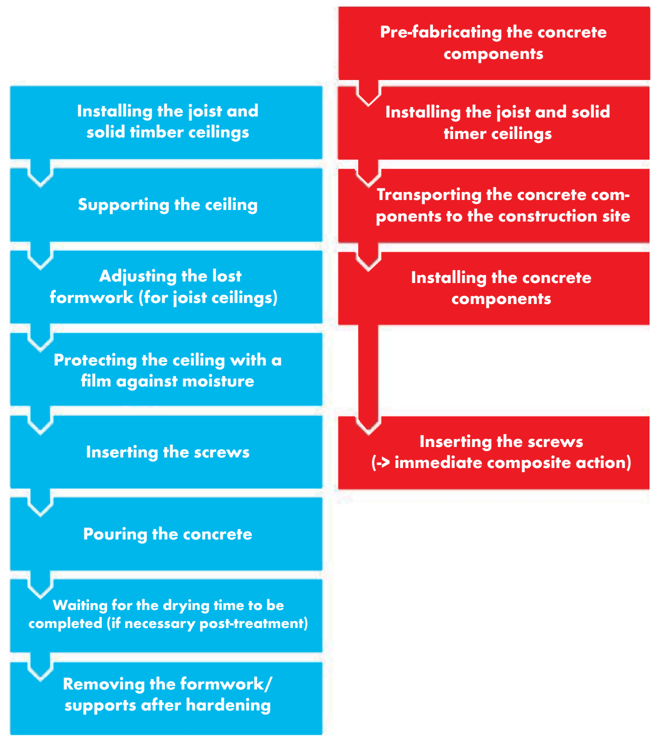
Picture 1: Load-bearing capacities of different wood/-concrete composite shear connectors (screw systems)

Installation with FP connectors and pre-cast concrete slabs

While in "conventional systems" the concrete always has to be applied on the wood construction this system offers the option of pre-fabricating the concrete slab separately from the timber construction. As it is the case in solid building the pre-cast concrete slabs are transported to the construction site, then installed and fastened on the wood construction on the spot. The subsequent bond between concrete and wood construction immediately takes place when inserting the screws, however, the screw connection of the concrete slabs with the substructure can be carried out later. Depending on the requirements a complex support of the ceiling construction for concrete setting can be dropped completely. The installation of the further construction can be continued immediately. There is no need for hardening and drying times. Owing to the pre-fabrication of the components no moisture or dirt from water eliminations resulting from the concrete penetrates into the wooden components. There is no need for a separating layer to protect the wood. Transport and installation costs as well as construction periods can be drastically reduced by the high level of pre-fabrication. Provided the quality is good enough the underside of the concrete slab may remain visible. Using wood-concrete composite ceilings with pre-fabricated concrete slabs visually appealing and wide spanning wood-beamed ceilings can be completed in a short time.

Alternatively the FP connector can also be used "conventionally" for casting the concrete on-site. With only a few shear connectors both methods allow a high bond resistance through a combination of the appropriate component cross-sections, material grades and a high bearing capacity of the pre-fabricated connectors.

The benefits relating to installation and installation speed are highlighted in below flowchart showing the installation process of both methods.



Installing pre-fabricated slabs with FP connectors on board stack elements

Installing pre-fabricated slabs with FP connectors on a layer of beams (here integrated mass activation for heating and cooling included)

Design

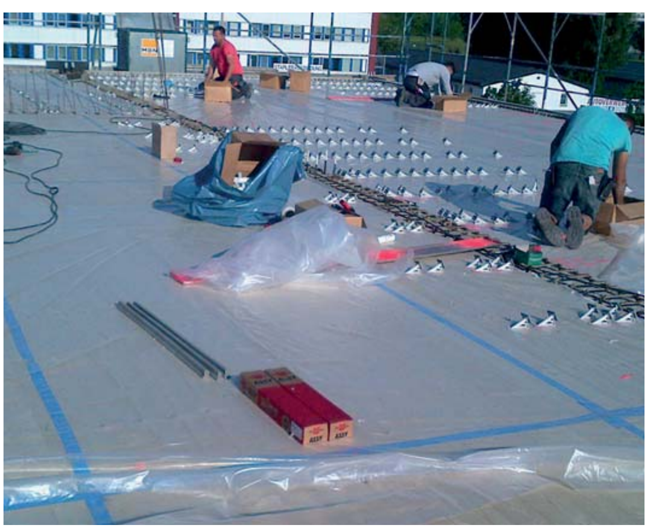
To calculate cutting forces different practical calculation models are available. Apart from the calculation method suggested by the standard EN1995-1-1 for "mechanically jointed beams" also a truss model according to the shear force analogy, i.e. the finite difference method can be used.

Within the scope of designing wood/concrete composite ceilings it is also essential to consider different important influence factors:

Different creep and shrinkage behaviors of the materials

For this purpose the strain and deformation conditions are determined both before usage (t = 0) and at a stage that comprises the planned service life of the support structure (t = ∞). The different creep behavior is taken into account through a corresponding material-differentiated reduction of the stiffness parameters.

The concrete shrinkage is taken into account by simulating an additional external load. However, this step can be left out when using FP connectors together with pre-fabricated concrete slabs because the shrinkage of the concrete will have largely been completed by the time of installation.



Reduction of the effective concrete cross-sections – concrete cross-section in condition II

Depending on the geometry, the influences, the cross-section dimensions and the static system not only the bending moment but also the normal forces (in the case of the single span girder only compressive forces) have an effect on the concrete slab.

If the tension stresses resulting from the bending moment are higher than the normal stresses and thus the limit moment is exceeded (exceeding the tensile strength of the concrete) cracks in the concrete arise, i.e. transition from condition I to condition II of the concrete cross-section. This leads to a reduction of the concrete cross-section and perhaps to a loss of stiffness. This change relating to the effective cross-sections can lead to a change in the stiffness ratio between concrete and wood. This again can cause a shift of the cutting forces.

Bracing

If the bracing takes place by means of the concrete of the composite ceiling, appropriate shear connectors have to be applied at the edge of the concrete slab that divert the forces resulting from the plate effect in the actual bearing structure. Additionally these peripheral components must be dimensioned to hold and transmit the chord loads. Joints must be performed with a high compressive and tensile stiffness. The load introduction into the vertically stiffening components has to be ensured.

Usability

In terms of usability apart from complying with the deformation limits special attention has to be paid to checking the vibration susceptibility of the ceilings. An economic wooden ceiling construction with span widths of more than 6 meters for which the limiting criteria of 8 Hz for the resonance frequency is observed is not possible. An appropriate combination of wood and concrete leads to extremely sturdy and light ceiling constructions which comply with the enhanced requirements on the vibration behavior of ceilings for apartment separations (Hamm, P.: Schwingungen bei Holzdecken – Konstruktionsregeln für die Praxis (transl.: Vibrations relating to wooden ceilings – design rules in practice). In: 2. International forum for wooden construction Beaune 202. 8./9. March 2012. Beaune, France. Issued by Forum-Holzbau, CH-Biel).

Fire protection

Proof of unprotected components and their composites can be made according to EN 1992-1-2 and EN 1995-1-2. For the wood the charring rate needs to be taken into account with which the remaining cross-section can be defined for the fire resistance design. The increase of temperature in the concrete and the wood also leads to a reduction of the stiffness and reduces the load capacities of the reinforcing steel and fasteners. Proof of fire-resistance of 90 minutes and more is possible by means of these methods providing the component dimensions are adapted according to these requirements.

Above: bottom view of a wood-concrete composite ceiling with FP connectors, fully assembled pre-fabricated slabs

Below: Pre-assembly of FP connectors and the screws for the subsequent concrete pouring of the ceiling plate.

Comparison between wood-concrete composite ceilings and reinforced concrete ceilings

For the dimensioning of the ceiling thickness the criterion of usability is decisive not only with regard to light ceiling constructions out of wood but also reinforced concrete ceilings. For loosely reinforced concrete ceilings the following requirement on the deformation limits are applicable: $(\ell/d)_{max} \leq K^2 \cdot 150/\ell$ mit K = 1 (for single span girders. (Criterion for enhanced requirements to avoid damages to adjacent components, e.g. light partition walls)

Also in EN1995-1-1 appropriate deformation limits are defined which are supposed to ensure a pleasant feeling for the user (e.g. vibrations) and the adjacent components are not damaged by deformations.

Comparative calculations considering the mentioned criteria lead to the ceiling thicknesses shown in illustration 2. For the impacts in addition to the resulting dead loads also a dead weight of the ceiling structure of 1.50 kN/m² as well as the lower surface with a dead weight of 0.15 kN/m² were assumed. The traffic loads were estimated at 2.30 kN/m² (apartment ceilings plus light partition walls). Basically several alternatives for composite ceilings are possible because the overall stiffness of a ceiling and therefore the distribution of the cutting sizes can be influenced by the number of applied shear connectors. For the calculation of the wood-concrete composite ceilings full-surface laminated timber ceilings were assumed. On average this leads to an exploitation of only 62 % of the timber cross-sections. The arrangement and the number of shear connectors were optimized to ensure an almost 100 % exploitation. For the versions with the screws ASSY® plus VG directly embedded in concrete with a diameter of 8 mm there is a need for about 10.5 to 16.6 screws per square meter (on average 13.6 screws/m²) depending on the span and the ratio of the component stiffness. For ceilings with pre-fabricated slabs and subsequent bond with FP connectors and screws ASSY® plus VG with a diameter of 10 mm screw quantities of 2.4 to 9.3/m² are required. This results in a demand for approximately 5.1 screws/m² on average. Also in this case the above mentioned parameters are decisive influencing factors for the necessary number of shear connectors.

If the horizontal bracing takes place via the concrete slab additional shear connectors, set around the plates, are necessary for the transmission of the forces resulting from the plate effect. Wood-concrete composite ceilings for which the bond is realized with FP connectors tend to require a minimally larger component thickness than wood-concrete composite ceilings for which the bond is made with ASSY® plus VG diameter 8 mm (see picture 2).

This is because only about 35 to 40 % of the shear connectors are used and because the stiffness of the combination FP connectors with ASSY® plus VG diameter 10 mm is inferior to the ASSY® plus VG diameter 8 mm. This low stiffness can be explained by the available screw length within the FP connector.

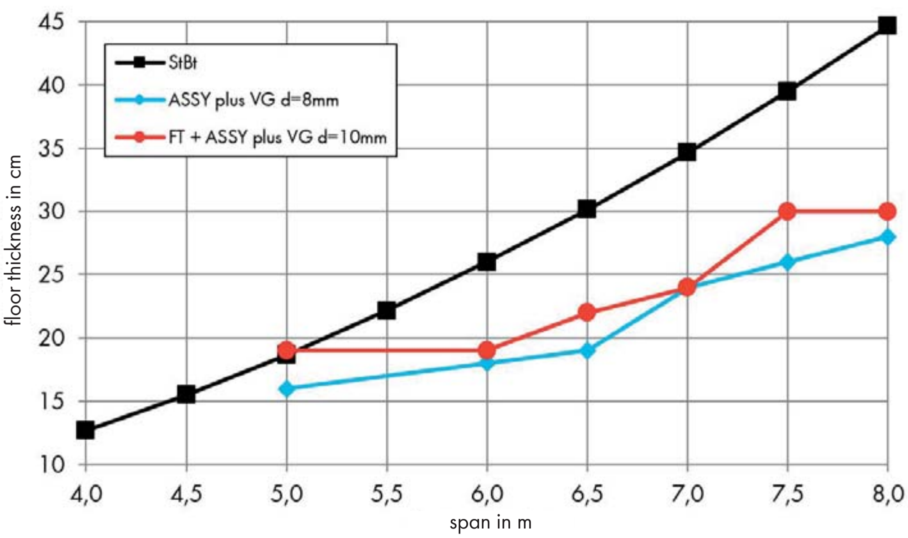


Figure 2: Required floor thickness depending on the span design variant

Table 1 and 2 show a compilation of the calculation results for different ceiling spans, whereby in each case alternative solutions are possible (component thicknesses and number of shear connectors).

L	g	con.	con./ m²	t_{Tim}	t_{Con}	t_{ges}	I_{Tim}	I_{Con}	$(EI)_{Tim}/[(EI)_{Tim}+(EI)_{Con}]$	β_{Tim}	$F_{VM,Ed}$	w (t=0)	w (t=∞)
m	kN/m²	-	-	cm	cm	cm	cm⁴	cm⁴	-	-	kN	cm	cm
5,0	3,65	82	16,4	10	6	16	8333	1800	0,63	60 %	4,26	1,29	1,89
6,0	3,85	92	15,3	12	6	18	14400	1800	0,75	66 %	5,54	1,78	2,63
6,5	4,00	108	16,6	12	7	19	14400	2858	0,65	72 %	5,69	2,05	3,13
7,0	4,45	76	10,9	16	8	24	34133	4267	0,75	56 %	7,65	1,52	2,32
7,5	4,95	88	11,7	16	10	26	34133	8333	0,60	59 %	7,84	1,65	2,63
8,0	5,05	84	10,5	18	10	28	48600	8333	0,68	58 %	8,85	1,69	2,70

Ceiling thicknesses for wood-concrete composite ceilings with shear connectors ASSY® plus VG diameter 8 mm; dimensioning results for different ceiling spans; concrete slab on board stack.

L	g	con.	con./ m²	t_{Tim}	t_{Con}	t_{ges}	I_{Tim}	I_{Con}	$(EI)_{Tim}$/ $[(EI)_{Tim} + (EI)_{Con}]$	β_{Tim}	$F_{VM,Ed}$	w (t=0)	w (t=∞)
m	kN/m²	-	-	cm	cm	cm	cm⁴	cm⁴	-	-	kN	cm	cm
5,0	4,00	12	2,4	12	7	19	14400	2858	0,65	60 %	9,21	1,54	2,19
6,0	4,00	56	9,3	12	7	19	14400	2858	0,65	70 %	10,1	1,98	2,86
6,5	4,35	40	6,2	14	8	22	22867	4267	0,66	65 %	11,9	2,08	3,01
7,0	4,45	40	5,7	16	8	24	34133	4267	0,75	63 %	14,0	2,05	2,93
7,0	4,95	36	5,1	16	10	26	34133	8333	0,60	62 %	12,3	2,02	3,03
7,5	5,15	18	2,4	20	10	30	66667	8333	0,75	54 %	16,9	1,95	2,80
8,0	5,15	38	4,8	20	10	30	66667	8333	0,75	59 %	16,3	2,02	2,96

Table 2: Ceiling thicknesses for wood-concrete composite ceilings with FP connectors and ASSY® plus VG diameter 10 mm; dimensioning results for different ceiling spans; concrete slab on board stack

The optimal use of FP connectors is obtained when instead of full-surface board stack elements ceiling joists are used. Overstress in transverse direction can occur exclusively via the reinforced concrete slab. The composite is only employed in the main stress direction. Through the cross-section height of the ceiling joists the stiffness is introduced intently into the system. In this way the material requirement for "wood" can be reduced by up to 60 % and more in comparison to ceilings made from solid wood boards. Also the necessary number of shear connectors can be significantly reduced while the results remain the same.

L	g	con.	con./ m²	(b/h) Tim	e	t_{Con}	t_{ges}	I_{Tim}	I_{Con}	$(EI)_{Tim}$/ $[(EI)_{Tim} + (EI)_{Con}]$	β_{Tim}	$F_{VM,Ed}$	w (t=0)	w (t=∞)
m	kN/m²	-	-	cm/cm	m	cm	cm	cm⁴	cm⁴	-	-	kN	cm	cm
8,0	5,15	22	2,2	24/32	1,25	10	42	65536	10417	0,73	92 %	24,1	2,02	2,70

Table 3: Ceiling thicknesses for wood/concrete composite ceilings with FP connectors and ASSY® plus VG diameter 10 mm; dimensioning results for different ceiling spans; concrete slab on ceiling joist with distance.

Summary

With inclined ASSY® plus fully threaded screws economic wood/concrete composite ceilings with large spans are possible without any problems. Also high performance requirements can be met with regard to fire protection and the vibration behavior of the ceiling. The FP connector in combination with the ASSY® plus fully threaded screw convinces through its very high bearing capacity in comparison with other screwed connectors. Through the combination of FP connectors and pre-fabricated concrete components the construction time is significantly reduced, long drying times as it is the case for concrete pouring on the construction site are saved.

L = span width	I_{Con} = Moment of inertia of the reinforced concrete slab
g = arithmetical dead weight	β_{Tim} = Utilization factor of the tensions in the wood
con. = necessary number of shear connectors per ceiling strip with 1 m width	$F_{VM,Ed}$ = design value of the forces which act upon the connectors (shear forces)
con./m² = necessary number of shear connectors per m² ceiling surface	**w(t=0) =** initial deformations
t_{Tim} = Thickness solid wood board	**w(t=∞) =** expected final deformations
t_{Con} = Thickness reinforced concrete slab	**b/h =** width/height of the joist
t_{ges} = Total thickness of the ceiling	**e =** beam distance
I_{Tim} = Moment of inertia of the solid wood board	

APPROVALS AND DIMENSIOING SOFTWARE FOR WOOD-CONCRETE COMPOSITE CEILINGS

Product and approval

The FP connector enables the use of precast concrete parts in the construction of wood-concrete composite ceilings. This avoids moisture penetration into the wood construction and assembly times are drastically reduced. The FP connector is designed for a concrete thickness of 70 mm. Through a lath put underneath during concrete pouring the concrete thickness can be increased to 120 mm following the expert opinion of Prof. Dr. Blaß of 20. April 2013. If the concrete is poured on the construction site Würth offers the possibility to use diagonally applied Würth ASSY® fully threaded screws to produce the wood-concrete composite. Normally 8 mm screws are used therefore. The FP connector can also be used. The number of fixing points is reduced by an optimized applied force. The FP connector you can find in the Würth Online-Shop (ww.wuerth.de) under part number 0165 300 10. For approvals and expert reports please also refer to www.wuerth.de/assy.

Dimensioning

Under www.wuerth.de/assy you can also find the dimensioning software for wood/concrete composites. Here a fixed mounted version and an online version are available.