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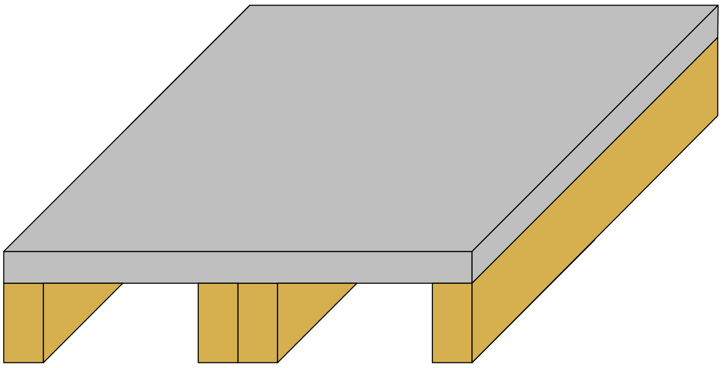
TIMBER CONCRETE COMPOSITE FLOOR SYSTEMS FOR MORE EFFICIENT STRUCTURES

Samverkansbjälklag av trä och betong för effektivare konstruktioner



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ROBERT JOCKWER

SAMMANFATTNING

Översikt

I den här rapporten sammanfattas resultaten av forskningsprojektet "Samverkansbjälklag av trä och betong för effektivare konstruktioner". Målet med projektet var att utvärdera hinder och incitament för tillämpningen av bjälklagsystem av trä-betongkomposit (Timber concrete composite, TCC) i Sverige samt att beskriva och föreslå effektiva och konkurrenskraftiga system för den svenska marknaden.

Befintliga tekniska lösningar för TCC analyserades och sammanfattades i en litteraturstudie. Detaljer och erfarenheter från byggda projekt samlades in. Olika aspekter av de tekniska lösningarna och byggda projekten utvärderades med avseende på strukturell prestanda, effektivitet, ekonomi och hållbarhet. Möjliga utmaningar och lösningar på frågor som t.ex. fuktintag sammanfattas i rapporten.

De olika kompetenser (prefabricerade eller platsbyggda), affärsidéer och verksamheter hos de företag som är involverade i produktion och byggande av TCC i Centraleuropa utvärderades. Strategier och potentiella lösningar för genomförandet av TCC-bjälklagsystem på den svenska marknaden utvärderades tillsammans med de deltagande företagen i projektet.

De olika konstruktionsförfaranden som finns i handböcker och riktlinjer samlades in och utvärderades. Med hjälp av dessa riktlinjer utvecklades lösningar för TCC-bjälklagsystem och en kostnads- och genomförandeanalys genomfördes.

I denna kostnads- och genomförandeanalys påvisades TCC-bjälklagsystem allmänna tillämpbarhet och olika punkter för optimering avseende effektivitet, konkurrenskraft och prestanda identifierades.

Ett stort tack till Svenska Byggbranschens Utvecklingsfond SBUF (med projektnummer 13979) och Västra Götalandsregionen VGR (med projektnummer MN 2020-00235) för finansieringen av detta projekt.

Projektet

I projektet har olika aspekter av TCC-bjälklagsystem utvärderats. Målet var att identifiera potentialen för prefabricerade TCC-bjälklagsystem som en ny lösning för standardbjälklag för kontor och bostäder. Följande huvudsakliga aktiviteter har genomförts inom projektet:

1. Sammanställning och utvärdering av olika tekniska lösningar för produktion av TCC med avseende på teknisk prestanda, pris, hållbarhetspåverkan och cirkulär användning.
2. Utvärdering av olika kompetenser, affärsidéer och verksamheter hos företag som är involverade i design och produktion av TCC i Centraleuropa.

3. Översyn av konstruktionsförfaranden och rekommendationer för olika tekniska lösningar för TCC och utvärdering av kraven på balkelement för den svenska byggmarknaden.
4. Kostnadsberäkningar med hänsyn till den byggtid som krävs för olika system för vissa tillämpningar av vissa TCC-system, jämfört med traditionella svenska system.

Projektets huvudsyfte var att utvärdera hinder och incitament för tillämpningen av TCC-balkbärande system i Sverige samt att beskriva och föreslå effektiva och konkurrenskraftiga system för det svenska klimatet som skulle kunna användas här. Utifrån erfarenheterna av att använda TCC-bjälklagsystem i Centraleuropa fokuserades det på:

- Utvärdering av prefabricerade TCC-bjälklagsystem när de används som standardlösningar integrerade i konventionella byggnader med hänsyn till minskad vikt, snabbare färdigställande, hög kvalitet, lägre miljöpåverkan och möjlighet till demontering.
- Identifiering av eventuella kunskapsluckor om TCC-bjälklagsystem i Sverige för att uppfylla slutanvändarnas krav för olika tillämpningar.

Hinder och incitament för tillämpningen i Sverige

På den svenska marknaden har TCC-bjälklagsystem för närvarande inte nått den volym som krävs för att vara konkurrenskraftiga jämfört med konventionella lösningar med ihåliga betongkärnor eller rena boxbalklösningar av trä.

Orsakerna till detta är att de befintliga entreprenörerna, leverantörerna och relaterade företag i Sverige ofta är mycket materialrelaterade och antingen specialiserade på betong- eller trälösningar. Inga specialiserade tillverkare av TCC-lösningar har hittills etablerats på den svenska marknaden.

Dessutom saknas det erfarenhet av TCC bland materialleverantörer, arkitekter, konsultexperter och entreprenörer.

På grund av denna brist på erfarenhet anses riskerna vara stora att föreslå nya lösningar för slutanvändaren, särskilt när man kombinerar olika expertområden och affärsverksamheter.

Alla dessa punkter bidrar till att TCC-lösningar blir för dyra och för riskabla för att vara konkurrenskraftiga och föredras i nya projekt.

För att TCC-bjälklagsystem ska bli mer konkurrenskraftiga och framgångsrika på marknaden bör de betraktas som en produkt för vilken ytterligare tjänster för arkitekter, konsultexperter och entreprenörer tillhandahålls, t.ex. omfattande anbudstexter och dokument samt kostnadsplanering. Dessutom kan följande tjänster vara till nytta för att minska riskerna för intressenterna och öka deras förtroende för systemet:

- Stöd till konceptuell utformning och planering.
- Rådgivning om optimering av materialval (byggnadsfysik, ekologi, kostnader).
- Kostnadsberäkning och tillhörande kostnadsoptimering.
- Stöd till strukturella analyser, inklusive brandskydd och vibrationsverifiering.
- Kostnads- och genomförbarhetsanalyser.
- Stöd vid inlämning, genomförande och detaljplanering.

- Optimering av byggtiden och planering av byggnadsordningen
- Stöd till certifiering av byggnader (livscykelanalys)

För att kunna leverera dessa produktegenskaper och tjänster kan ett samarbete med erfarna TCC-leverantörer från Centraleuropa vara fördelaktigt.

Tekniska lösningar för TCC

Det finns ett stort antal olika tekniska lösningar för att skapa en samverkan mellan trä och betong i bjälklagkonstruktioner. Dessa olika lösningar är delvis optimerade för olika specialtillämpningar. Vissa av dessa lösningar används för renovering av befintliga konstruktioner, medan andra är mer lämpade för användning med massiva träpaneler. För prefabricerade TCC-bjälklagsystem eftersträvas en billig och snabbt installerbar förbindelselösning som ger en styv förbindelse mellan trä och betong för att maximera den sammansatta effekten. Inlimmade förband eller inskjutna lösningar har identifierats som mest lämpliga.

Anslutningssystem

Det allmänna syftet med kompositkonstruktioner är att dra nytta av de enskilda fördelarna med olika element och kombinera deras prestanda. När de olika delarna monteras ihop strävar man efter att begränsa deformationen mellan delarna genom lämpliga anslutningar och att göra hela tvärsnittet aktivt. Nivån på den sammansatta effekten beror bland annat på styvheten hos anslutningsskiktet eller anslutningselementen. Med ökande styvhet ökar samverkan.

Trots optimeringen av samverkanselementen med avseende på förbindelsernas styvhet finns det olika andra aspekter som bör beaktas för att välja den optimala anslutningstekniken och monteringsprocessen. Det gäller bland annat hur lätt monteringen är, hur enkel processen är med avseende på personal, kvalifikationer, utrustning, randvillkor osv. Inte minst spelar priset på anslutningssystemen en viktig roll.

Det finns olika tekniker och system på marknaden för att åstadkomma en sammansättning mellan trä och betong:

- Fasthållningssystem där typiska fästelement av dymeltyp belastas axiellt eller lateralt. Fästelementen kan t.ex. skruvas eller limmas fast i virket. Belastningskapaciteten och styvheten hos anslutningar med skruvar beror på vinkeln mellan belastningen och skruvens axel. Skruvar ger hög axiell kapacitet och styvhet men endast måttliga nivåer av lateral kapacitet och styvhet. Genom att vinkla skruvarna i förhållande till lastriktningen kan skruven aktiveras axiellt och den kan dra nytta av de goda egenskaperna. Ur hållfasthets- och styvhetssynpunkt bör skruven lutas så mycket som möjligt. Skruvarnas lutning bör väljas noggrant utifrån den förväntade belastningsriktningen. Genom att använda par av skruvar som är placerade i ett kors kan man bära omställbara laster i leden. Förbindelsen med en axiellt belastad skruv kan brista genom att skruven dras ut ur virket eller på grund av spänningsbrott i själva skruven. Med ökande skruvlängd ökar skruvans utdragskapacitet, men den är begränsad till sitt dragmotstånd. Båda dessa brottsformer bör naturligtvisbeaktas vid konstruktionsarbetet.
- Formpassningssystem: Skåror och spår fräses in i virket och fylls med betong under gjutningen. Skjuvkraften mellan virke och betong överförs via kontakt. Lösningar med inskjutna anslutningar utnyttjar kontakten mellan träets änd ytor och betongen i de spår som frästs in i träelementen för överföring av skjuvkrafter

mellan de båda elementen. På grund av den typiskt stora kontaktytan och den höga styvheten hos båda komponenterna (särskilt när virket belastas parallellt med fibern) är skåror effektiva förbindare som skapar en hög sammansatt verkan. Avsaknaden av metallfästen för överföring av skjuvkrafter tillsammans med den enkla tillverkningen av skårorna med konventionella CNC-maskiner gör skårorna till en billig lösning för nya konstruktioner. Bjälklagelementen kan vara helt prefabricerade och förgjutna i fabriken eller gjutna på plats. Det finns också lösningar där träelement och förgjutna betongplattor kopplas samman på plats genom att man fogar in skårorna i träet och fickorna i betongen. Särskilt vid djupare skåror bör anslutningar mellan timmer och betong vara inplacerade, och betongfogarna måste förstärkas på lämpligt sätt för att kunna bära de skjuv- och dragkrafter som uppstår på grund av excentriciteten.

- Särskilda system, t.ex. limmade system eller fackverkselement:
  Särskilda system utvecklas och studeras inom forskningen, där trä- och betongelementen binds samman med hjälp av lim. Som exempel används prefabricerade ultra-högpresterande betongskikt som limmas på träbalkar. Fördelen med systemet är att full samverkan kan uppnås.

Samverkansbjälklag av träbetong kan förverkligas med olika bjälklaglayout. Var och en av dem har olika för- och nackdelar och olika måltillämpningar kan identifieras.

I allmänhet kan man skilja mellan bjälklag med ett kontinuerligt bottenskikt av trä, t.ex. av KL-Trä eller Brettstapel (se nedan), eller bjälklag med enstaka träbjälk.

Olika system med kontinuerligt träskikt:

- Brettstapel: Bjälklag med ett parallellt arrangemang av enskilda massiva träbrädor kallas Brettstapel. Brädorna kan vara sammankopplade t.ex. med spik eller träpluggar. De ger en enaxlig lastöverföring. Den enkla tillverkningen gör dem till mycket kostnadseffektiva kontinuerliga bjälklaglösningar. I samverkanslösningar av träbetong skapas ofta en förbindelse med hjälp av skåror eller plattstålslås, vilket gör det möjligt att överföra skjuvningen mellan betongen och stora delar av träet. Bjälklagen kan prefabriceras eller gjutas på plats.
- Platta limträbalkar: I likhet med Brettstapelelementen har platta limträbalkar sin huvudsakliga bärande riktning längs huvudspannet. Bjälklag med platta limträbalkar kan skapas antingen med ett kontinuerligt lager trä eller med ett avstånd mellan balkarna, vilket gör det möjligt att optimera materialanvändningen och integrera installationer i bjälklaget.
- KL-trä: Bjälklagkonstruktioner med KL-trä-bjälklag blir allt populärare, och det gör även användningen av KL-trä i samverkansbjälklag av trä och betong. Förbindelsen kan upprättas med hjälp av skåror, platta stållås, fästelement eller liknande och bjälklaget kan gjutas på plats eller prefabriceras. Det tjocka skiktet av KL-trä-bjälklag gör att man i stor utsträckning kan undvika stämpning vid gjutning av betongen. Potentiell biaxial lastöverföring i KL-trä-panelerna förenklar utformningen av detaljer som öppningar.
- LVL (laminatet veneer lumber eller plywood): Samverkansbjälklag av träbetong med LVL-skivor som bottenskikt kan ses som en speciell typ. Man har studerat användningen av höghållfast LVL av lövträ som används som träslag i kombination med tjocka betongskikt. LVL-skivorna fungerar främst som förstärkningselement för betongen och som förlorad formsättning. Utmaningarna med denna typ av konstruktion är bland annat behovet av stöttning under byggtiden och medför risk för spänningar i betongen.

System med enstaka träbjälk

- Traditionella träbjälklag med bjälklag: I ombyggnadsprojekt läggs ofta betongskikt till traditionella träbjälklag med bjälk och plankor för att öka bärförmågan, minska nedböjningen och förbättra den dynamiska prestandan. Skruvförbandssystem är särskilt lämpliga för dessa projekt, eftersom de möjliggör ett mycket individuellt arrangemang och kombinationer med olika mellanskikt. Gjutningen på plats kan skapa utmaningar, bland annat krävs en lämplig tätning av en plastfolie för gjutningen.
- Ribbdäck: För nya konstruktioner kan ribbdäckslösningar med limträbalkar och ett översta betongskikt prefabriceras eller gjutas på plats. Limträbalkens relativa slankhet kräver lämpliga anslutningselement, t.ex. skruvar, inlimmade stänger eller inlimmade plattor. För bredare balkar kan man välja inskjutna lösningar. Prefabricerade lösningar kan upprättas endast med limträbalkar, vid gjutning på plats krävs ofta en formsättning, som kan vara kontinuerlig eller öppnas över limträbalkarna. När det gäller kontinuerliga formsystem bör man ta hänsyn till den minskade styvheten i fogarna på grund av dessa mellanlägg. Avståndet mellan limträbalkarna gör det möjligt att integrera installationer i bjälklagssystemet.

Generellt sett har samverkansbjälklag av träbetong ett bättre brandmotstånd än andra konventionella träbjälklagslösningar. Betongskiktet skapar en barriär mot rökgenomträngning medan virket isolerar betongen från värme och skadegörelse. Fästanordningar och anslutningar på insidan av skarven skyddas av träet från ökade temperaturer. Samverkansplattans bärande beteende vid ökade temperaturer kan bestämmas med hjälp av den metod med reducerat tvärsnitt som anges t.ex. i EN 1995-1-2.

Projekt och företag

För att etablera en prefabricerad TCC-bjälklaglösning på den svenska marknaden måste de olika aktörerna från träindustrin, betongindustrin och entreprenörerna förena sina krafter. Detta samarbete kan utformas på olika sätt med olika aktiviteter och ansvarsområden för de olika aktörerna. I befintliga projekt där TCC-bjälklagsystem har använts i olika skala kan olika produktionsprocesser observeras. En möjlig och lämplig process har identifierats där TCC-bjälklaget produceras genom att träelementen monteras i de förgjutna betongplattorna i betongelementtillverkarens fabrik. Dessa element kan sedan monteras på samma sätt som konventionella prefabricerade betongbjälklagelement.

Olika produktionsprocesser för samverkansbjälklag av trä och betong kan hittas på marknaden, där olika aktörer med olika kompetenser och verksamheter är inblandade. Generellt sett kan produktionen särskiljas mellan prefabricering i fabrik, gjutning på plats, montering på plats och en kombination av dessa processer.

Prefabricering hos betongelementtillverkaren

De prefabricerade träelementen inklusive kopplingar etc. levereras till betongelementtillverkaren. Där gjuts betongen på. Att inkludera träbalkarna i produktionsprocessen för att skapa ribbdäck kräver en viss anpassning, men de grundläggande produktionsstegen förblir likartade. En fördel med denna process är att betongen förblir oförändrad i processen. Entreprenören kan dessutom fortsätta att använda liknande element som leverantören av prefabbetong har levererat.

Prefabricering av timmertillverkaren

Den omvända processen kan etableras om produktionen av TCC-elementen hos trävarutillverkaren. Exempel på sådana processer finns i praktiken, särskilt när trävarutillverkare agerar som entreprenörer eller leverantörer av hela prefabricerade byggnadsdelar som väggar, fasader, tak osv. Att kunna prefabricera inte bara dessa delar utan även TCC-bjälklagelementen i fabriken kan vara fördelaktigt för trävarutillverkaren, men om betongplattan gjuts på trävaruelementen i fabriken kommer en ny produktionsmetod att införas i den gemensamma miljön och kan kräva att man vänjer sig vid den.

Montering på plats

I det här fallet levererar trävarutillverkaren och betongtillverkaren sina individuella produkter till byggarbetsplatsen. Där monteras dessa separata element ihop till TCC. De enskilda produkterna kan vara träbjälkar eller paneler med anslutningselement och helt eller delvis (filigran) prefabricerade betongplattor. Denna process gör att produktionen av TCC är oberoende av de enskilda trä- och betongproducenterna, men ansvaret och kraven läggs på entreprenören.

Producenter och entreprenörer

Olika tillverkare av samverkanslösningar av trä och betong har i mellaneuropa etablerat sig på marknaden. Specialiserade tillverkare tillverkar ofta inte enbart limträ eller träelement utan har specialiserat sig på träkonstruktion och montering. Systemleverantörerna har delvis uppstått från vanliga entreprenörer som huvudsakligen är verksamma inom betongkonstruktioner (CREE och Erne) eller som ett samriskföretag mellan en träproducent och en tillverkare av prefabricerade betongelement (MMK Holz-Beton-Fertigteile).

Utformning

För närvarande finns det ingen europeisk standard som specificerar utformningen av TCC-bjälklagelement. En teknisk specifikation är dock på väg att publiceras och det finns olika handböcker och riktlinjer på nationell nivå. Med hjälp av dessa riktlinjer för utformning har olika möjliga exempel på TCC-bjälklag tagits fram och studerats. De styrande gränsvärdena är oftast kriterier för funktionsduglighet, t.ex. deformationer och vibrationer. Det enskilda TCC-bjälklaget kan optimeras beroende på de specifika kraven i det enskilda byggprojektet.

Vid modellering av bjälklaget bör man ta hänsyn till krympning och krypning i betong och trä samt betongens tidsberoende härdning. Inverkan av krympning kan betraktas som en yttre kraft, medan krypning vanligtvis betraktas som en minskad styvhet hos elementen.

Eftersom nedböjningar vanligtvis är avgörande för utformningen av bjälklagelement bör användbarhetskriterierna först kontrolleras vid utformningen av samverkansbjälklagelement av träbetong. De långsiktiga deformationerna från krypning och krympning i trä och betong måste beaktas vid denna verifiering. Hållfasthetskriterierna i konstruktionen av det slutliga gränstillståndet kan vanligtvis uppfyllas som ett komplement.

Utvärdering av kostnader

Kostnaderna för produktion och installation av TCC-bjälklagsystemet uppskattades och fördelades på de olika parterna i produktions- och byggprocessen. Exemplet med TCC-bjälklagsystemet beräknas för närvarande vara mer än dubbelt så dyrt som ett konventionellt förspänt håldäckssystem.

Några specifika punkter som påverkar kostnaderna för produktion och byggande med TCC är bland annat följande: Förändringar i logistik och produktion av prefabelement på grund av ytterligare material (trä), ytterligare processteg under elementtillverkning eller montering på plats, lagring av TCC-bjälklag i fabriken eller på plats, transportkostnader, hanteringsmöjligheter i fabriken och på plats, montering och anslutning till konstruktionen, skydd av bjälklaget mot regn/väder efter installationen, skydd av synliga delar av bjälklaget under byggandet på plats, nödvändig bjälklaguppläggning för den slutliga konstruktionen, produktionstid (härdningstid) för TCC jämfört med rent trä eller ren betong.

Det går dock att identifiera olika optimeringspotentialer när det gäller materialbesparing, förbättring av den strukturella prestandan, enklare produktion och montering. När alla dessa optimeringspotentialer uppnås kan man förvänta sig att TCC-bjälklagsystemet blir mer konkurrenskraftigt jämfört med konventionella konstruktionssystem på den svenska marknaden. De olika påverkande parametrarna och faktorerna kan identifieras som:

- Trä: Priset på virket beror bland annat på hållfasthetsklass och dimensioner.
  - Limträbalkarnas höjd är beroende av antalet lamineringar och följer därför ett visst mönster. Den optimala höjden i förhållande till spännvidden måste optimeras för att uppnå en god utnyttjandegrad. I allmänhet är allmänt tillgängliga standarddimensioner mer önskvärda än specifika individuellt tillverkade balkar.
  - Bredare balkar som kan placeras på större avstånd är dyrare än tunnare balkar som placeras på mindre avstånd. Optimeringen av de bästa dimensionerna i förhållande till avståndet mellan bjälklagelementens ribbor påverkar också installationerna.
  - Utnyttjandegraden av träbjälkarnas styrka är relativt låg jämfört med kriterierna i bruksgränstillståndet. Därför kan man välja lägre hållfasthetsklasser som kan vara mer kostnadseffektiva. Den högre styvheten hos högre hållfasthetsklasser minskar dock nedböjningar etc.
- Betong:
  - Betongens krympning och krypning har en stor inverkan på bjälklagelementens långsiktiga deformation. Genom att använda betong med minskad krympning eller genom att ändra monteringssystemet från gjutning på träbalkar till användning av prefabricerade betongplattor som ansluts på plats till träbalkarna kan man minska de långsiktiga deformationerna.
  - Beroende på betongens tjocklek och användningen i det slutliga gränstillståndet krävs olika mängder armering av betongen eller så kan man använda andra typer av armering.
- Tillverkning av TCC-element
  - Tillverkningen av TCC-element kan göras på olika sätt som diskuterats tidigare. De olika metoderna kräver olika investeringar i tillverkningsanläggningar, men leder också till olika automatiseringsnivåer och förberedelser för massproduktion.

  Allt detta påverkar kostnaderna för de slutliga elementen och därmed elementens konkurrenskraft i jämförelse med andra lösningar.
  - Prefabricering av TCC-element kräver att man tar hänsyn till tillräcklig tid för betongens härdning innan den installeras på plats. Därför bör hela produktionsprocessen optimeras.
- Efterbehandling:
  - För att dra nytta av prefabriceringens fulla potential i modernt byggande bör så lite arbete som möjligt göras under och efter installationen på byggarbetsplatsen. Detta gäller även behandlingen av virke, betong och hela bjälklagelement efter monteringen. Helst bör virket levereras med sin slutliga ytbehandling, vilket i sin tur kräver särskild omsorg och eventuellt skydd och täckning.
  - Man bör vidareskräva efter att optimera prefabriceringsnivån för TCC-bjälklagsystemet tillsammans med alla installationer på ett sätt som minimerar det efterarbete som krävs på byggarbetsplatsen efter monteringen.
  - Olika upplagstyper för bjälklagen är möjliga, särskilt för kontors- och affärsbyggnader. Som exempel kan nämnas dubbla bjälklag som möjliggör integrering av installationer eller (flytande) avjämningslösningar, eventuellt även med värme- och kylinstallationer. Betonglagrets tjocklek och kraven på vibrationer och ljud måste anpassas i enlighet med detta. Betonglagrets kvalitet kan också skilja sig åt.
- Nivå av sammansatt verkan: Nivån på den sammansatta effekten är relativt hög med de anslutningssystem som finns tillgängliga. Det finns inget större behov av utveckling, eftersom en ytterligare ökning av den sammansatta effekten har endast en liten positiv inverkan på TCC-systemets prestanda.
- Monteringsmetod:
  - Genom att förbinda prefabricerade betongplattor med träbalkar, antingen på plats eller i fabriken, kan man minska en del av de tidsberoende deformationerna från betongens krympning och krypning.
- Relevanta SLS-kriterier:
  - Kriterierna för bruksgränstillstånd är bland annat deformationer och vibrationer (frekvens, acceleration, dämpning). Optimering av TCC-bjälklagsystemet med hänsyn till de individuella kraven i det specifika fallet ger stora möjligheter till en mer kostnadseffektiv optimering och förbättring. I den aktuella analysen valdes strikta kriterier.
  - Vid kostnadsjämförelser med andra produkter, lösningar och byggnadstyper måste samma kriterier väljas för att möjliggöra en rättvis och realistisk jämförelse. Olika lösningar och koncept kan vara fördelaktiga för olika projekt, krav och behov.
- Installationer:
  - Beroende på om byggnaden används för kontor, handel, bostäder eller hotell kan olika typer och mängder av installationer vara nödvändiga. En tidig diskussion med alla deltagande parter i byggprocessen är nödvändig för att uppnå bästa prestanda och resultat. Detta bör omfatta arkitekter, konstruktörer, experter på bygginstallationer, entreprenörer osv.
  - Ribbdäckslösningen erbjuder möjligheter att integrera vissa installationer i bjälklagelementen mellan ribborna. På så sätt kan den totala fria höjden garanteras. Nedan ges olika exempel på hur olika installationer kan integreras i bjälklagelementen.

Ytterligare utveckling

Följande optimeringsbehov som är direkt beroende av TCC-bjälklagelements kan identifieras:

- Trä: Optimering av avstånd och dimensioner för träelement.
- Anslutningselement: Kostnadseffektiva och effektiva kopplingar måste väljas beroende på typen av bjälklagelement.
- Betong: minska tjockleken på betongskiktet, optimera betongens långsiktiga deformationsbeteende (krympning, krypning), optimera armeringen i betongen.

Dessutom måste tillverknings- och monteringsprocessen optimeras och lösningar för inplacering måste utvecklas.

Placeringen av installationskanaler och rör i och under bjälklaget är en utmaning för samverkansbjälklagelement av träbetong. Genom att placera dessa fördelningskanaler nära kärnorna kan mindre störningar i dagsljusfördelningen i rummen garanteras. Från fördelningskanalerna når man de enskilda vikarna mellan elementens ribbor utan att störa rumshöjden.

Mycket forskning har fokuserat på styvheten och hållfastheten hos skjuvförbindelsen mellan betong och trä. Träets och betongens elastiska och långsiktiga materialegenskaper har dock en mycket större inverkan på det bärande och deformerande beteendet. Särskilt elasticitetsmodul, krypning, krympning och oavsiktliga höjdskillnader i betongen har en betydande inverkan på bjälklagpanelernas beteende. Alla dessa faktorer är vanligtvis inte exakt kända och kontrollerade i praktiken, men de är mycket relevanta.

Samverkansbjälklagsystem av träbetong måste planeras och utformas i kombination med anslutningen till andra komponenter i konstruktionen och byggnaden, t.ex. kärnan, pelare, ringbalkar eller fasadelement. Dessa anslutningar kan stå för upp till 30 % av kostnaderna per våningsyta.

Timber concrete composite floor systems for more efficient structures

ROBERT JOCKWER

ABSTRACT

In this report the results of the research project “Timber concrete composite floor systems for more efficient structures” are summarized. The goal of the project was to evaluate barriers and incentives for the application of Timber concrete composite (TCC) floor systems in Sweden, and to describe and propose efficient and competitive systems for the Swedish boundaries.

Existing technical solutions for TCC were analysed and summarized in a literature review. The details and experience from built project were collected. Different aspects of the technical solutions and built projects were evaluated in terms of structural performance, efficiency, economy and sustainability. Possible challenges and solutions to issues such as moisture intake are summarised in the report.

The different competences (prefab or site-built), business ideas and activities of the companies involved in TCC production and construction in Central Europe were evaluated. Strategies and potential solutions for the implementation of TCC floors in the Swedish market were evaluated with the participating companies in the project.

The different design procedures that exist in handbooks and guidelines were collected and evaluated. Using these guidelines, TCC floor solutions were developed, and a cost and implementation analysis was performed.

In this cost and implementation analysis the general applicability of the TCC floor system was demonstrated and various points for optimisation regarding efficiency, competitiveness, and performance were identified.

Many thanks to Svenska Byggbranschens Utvecklingsfond SBUF (with project number 13979) and Västra Götalandsregionen VGR (with project number MN 2020-00235) for the funding of this project.

Contents

Preface

The research project “Timber concrete composite floor systems for more efficient structures” (“Samverkansbjälklag av trä och betong för effektivare konstruktioner”) has been carried out from March – October 2021 at the Division of Structural Engineering at the Department of Architecture and Civil Engineering at Chalmers University of Technology. The project was funded by SBUF and VGR and was carried out in collaboration project with Besab, Thomas Concrete, Peab and Moelven.

The objective of the development project was to evaluate barriers and incentives for the application of Timber concrete composite (TCC) floor systems in Sweden, and to describe and propose efficient and competitive systems for the Swedish boundaries.

From the experience of using TCC in Central Europe it was focused on the evaluation of prefabricated TCC floor systems when used as standard solutions integrated in conventional buildings considering reduced weight, faster completion, high quality, lower environmental impact and possibility of dismantling. Form the evaluation possible knowledge gaps were identified regarding how TCC floor systems can meet achieve higher competitiveness and the end-user requirements for different applications in Sweden.

The project was carried out under the lead of Robert Jockwer at the Division for Structural Engineering at Chalmers University of Technology. Rolf Jonsson, Besab, Jan Adolfsson, Peab, Helene Wengholt Johnsson, Thomas Concrete, Johan Åhlen and Roberto Crocetti, Moelven, and Robert Kliger were members of the working group contributing to the project. The working group was supported by the members of FoU Väst.

The project was funded by Svenska Byggbranschens Utvecklingsfond SBUF with project number 13979 and Västra Götalandsregionen VGR with project number MN 2020-00235, for which the entire project team would like to express its sincere thanks.

Göteborg, October 2021

Robert Jockwer

1 Introduction

1.1 Composite structures in Sweden

For sound reasons in particular, it is sometimes desirable to combine a timber floor structures with concrete casting. Though this is not a common solution in Sweden, when it is used, then usually the static interaction between the concrete cover and underlying timber construction is not utilised. Thus, the timber floor is either used as a mould to cast a load-bearing concrete slab or concrete is cast on a load-bearing timber floor; in the former case the "mould" is very extensive and consisting of a "normal" timber floor and in the latter case the timber structure is loaded with heavy concrete and therefore becomes very strong. In either case, the structures are far too expensive!

In addition, the structural height of the floors will be much higher if the composite action between timber and concrete is not taken into account compared to traditional concrete or timber structures. In the worst case, this could lead to the loss of a storey as the height of the building is limited by the zoning plan. In any case, the building will be taller with an increased façade area as a consequence. This leads to a deterioration of the economy and to a low use of the construction type.

The combination of wood and concrete as composite elements for flooring systems makes it possible to exploit the individual advantages of both materials, i.e. the light weight and good tensile strength of timber and the low cost of concrete with good compressive strength (Yeoh David et al. 2011). These Timber-Concrete Composite (TCC) elements achieve good weight/strength ratios and show favourable behaviour in terms of vibration and acoustics. TCC can be used for the repair and reinforcement of existing timber floors but shows its full potential as an optimized floor system in new residential buildings and other multi-storey buildings such as offices. Columns in these multi-storey buildings can be made of wood, steel or concrete. Different techniques for the production of TCC are available for site casting, on-site assembly or as prefabricated elements. Depending on the structure and composition of the local construction industry, material suppliers and consultants, different business solutions can be chosen in different countries for the successful implementation of TCC floor systems.

TCC floor systems typically consist of timber beams or CLT panels and concrete slabs (either in traditional reinforced concrete, in fibre reinforced concrete or in other high-performance concrete) and fasteners connecting both main components, timber and concrete. The design and extent of the connections determine the degree of interaction between the timber beams and the concrete slab, which is crucial for properties such as load-bearing capacity as well as dynamic properties such as vibration and accelerations. In addition to the design and quantity of the wood and concrete components, the interconnections are very important from the point of view of fabrication and assembly. Therefore, they have a major impact on efficiency and economy and there are a variety of technical solutions (Lukaszewska 2009) that allow similar structural heights and floor coverings as conventional concrete floors.

Optimised TCC floor systems offer good strength and stiffness properties, achieve similar building heights to conventional concrete slabs, allow floor spans commonly used in residential and non-residential buildings to be achieved, and as a system, are universally suitable in a variety of building types (Dias, Schänzlin, and Dietsch 2018). Prefabricated TCC floors have the potential to integrate parts of the building installations already in place at the factory, thus reducing construction time on a job site. For the success of TCC floor systems, compatibility with conventional construction types (concrete, steel) should be facilitated and sufficient durability and robustness must be ensured.

The combination of wood and concrete raises questions regarding potential durability risks from moisture originating from fresh concrete during production or from weather conditions during installation. Although experience from other countries shows that there is little evidence that TCC floor systems in common indoor applications face moisture-related risks, the topic will be given special attention especially in view of the Swedish climate.

Construction process related parameters such as prefabrication and a fast assembly process of the building are important criteria to manage and minimize the effects of environmental conditions on TCC floor systems. The impact of creep and shrinkage deformations during the service life can be managed e.g. by using concrete with low shrinkage or tapering of timber beams.

Despite the success of TCC systems in Central European countries such as Germany, Switzerland, Austria, Benelux, and France and elsewhere in the world in a variety of projects as cast-in-place or factory prefabricated systems (e.g. Arbo Risch-Rotkreuz (Switzerland) , Hoho Wien (Austria) , or Eunoia Junior College (Singapore)), TCC has so far not established itself in the Swedish market. As the industry strives for more economical floor construction through e.g. reduced weight, faster assembly, higher quality and with society's demands for more sustainable construction, prefabricated TCC floor systems have a great potential to establish themselves on the Swedish market as a versatile solution.

In the future generation of the Timber Structures Eurocode 5 design code, a chapter on TCC elements will be implemented, which will further support the success of this system in Europe and worldwide (Dias, Schänzlin, and Dietsch 2018). Therefore, it is now time to set the limits for the success of TCC in Sweden.

In this project the requirements and boundaries for the successful implementation of TCC elements in the Swedish market are evaluated. Potential solutions are described for how TCC can be implemented in an efficient, safe and economical way for the Swedish construction industry. Thus, the study sets the foundation for taking the step to implementation and practical use of TCC in Sweden.

1.2 Possible benefits and perspectives of TCC

Timber concrete composite floor structures have different advantages but also disadvantages compared to other conventional systems. With regard to the building process, costs and building physics, some advantages and disadvantages are reported in literature (Bahmer and Hock 2015; Derix 2021). The advantages compared to pure timber ceilings are:

- The higher stiffness of the concrete increase the load-bearing capacity and stiffness of the composite floor by approx. 60% for the same construction height compared to pure timber ceilings. As a result, larger spans can be achieved, and higher loads can be carried.

- Due to the higher stiffness of the concrete the deformations of the composite floors are lower.
- The concrete layer helps to increase the duration of the fire resistant. It contributes in particular to the separating function of the floor.
- The increased weight of the concrete on top of the timber floor increases the dynamic performance of the floor with regard to vibrations and sound.
- The composite floor elements can be prefabricated partly or entirely and often do not require propping on site.
- A continues floor diaphragm can be easily created by a continues layer of concrete or by connecting the prefabricated elements with rebar and grouting.
- The concrete layer provides constructive protection to the timber elements already during the construction phase. Careful planning reduces the efforts for e.g. encasing.
- Good heat storage capacity due to the high mass of the concrete used
- A stiff but ductile connection between timber and concrete can be created by adequate connection systems

The following advantages compared to pure concrete ceilings are reported by (Bahmer and Hock 2015):

- The self-weight and dead load of pure concrete ceiling is reduced considerably
- A more optimal use of the material specific properties: In conventional timber slabs, the lower 2/3 of the concrete are cracked in the ULS and reinforcement is carrying tension force. In composite structures the concrete in tension is largely replaced by timber, which reduces weight and makes use of the good tensile and bending strength of the timber.
- The reduction of the amount of concrete reduces the ecological footprint of the structure
- The reduced weight of floor elements reduces the member sizes of beams, columns, but also foundations. Reduced weight facilitates the transport and assembly.
- A potential benefit can be achieved when making the joint detachable, then the materials can be separated after deconstruction.
- Different types of timber-floor elements have a high-quality bottom view and do not require any further cladding or postprocessing. Hence, after finalizing the structural works no finishing is necessary.
- The high surface temperature of the wood ceiling enhances the room atmosphere. As well room humidity can be compensated by the wooden ceiling.
- The room acoustics can be improvement by using wooden ceilings with certain acoustic surface optimization or by integrating the acoustic panels in the rib deck.

Some disadvantages can be seen with regard to:

- The two different sectors of timber and concrete construction must work together. This may lead to problems and challenges in the collaboration during different stages of the project, due to different building practices, procedures etc. Good communication and continued experience in the collaboration can reduce potential initial problems and create good procedures.

1.3 Objectives

The main objective of the project was to evaluate barriers and incentives for the application of TCC beam bearing systems in Sweden, and to describe and propose efficient and competitive systems for the Swedish climate that could be used here.

From the experience of using TCC floor systems in Central Europe it was focused on:

- Evaluation of prefabricated TCC floor systems when used as standard solutions integrated in conventional buildings considering reduced weight, faster completion, high quality, lower environmental impact and possibility of dismantling.
- Identifying possible knowledge gaps on TCC flooring systems in Sweden to meet end-user requirements for different applications.

1.4 Implementation

The following main activities will be carried out within the project:

1. Compilation and evaluation of different technical solutions for the production of TCC with regard to technical performance, price, sustainability impact and circular use
2. Evaluation of the different competences, business ideas and activities of companies involved in the design and production of TCC in Central Europe
3. Review of design procedures and recommendations for the different technical solutions for TCC and evaluation of the requirements for beam elements for the Swedish construction market
4. Cost estimates taking into account the required construction time of different systems for some applications of some TCC systems, compared to traditional Swedish systems

The study will focus on the evaluation of TCC beam systems used in the Central European markets such as Germany, Switzerland, Austria, Benelux and France as well as selected global projects and its potential for the Swedish market.

Particular emphasis will be placed on the challenges faced by TCC floor systems in terms of production efficiency, economy, durability and static and dynamic performance. It aims to achieve a similar performance of precast TCC floor systems to that of conventionally cast and precast concrete slabs in buildings but with much higher benefits.

In particular, the design of the various connection systems and details will be considered to facilitate the separation of wood and concrete materials during future demolition.

1.5 Limitations

The following limitations are set in the project

- It is aimed at typical floor spans in conventional systems
- The goal is to achieve small height of slab elements
- It should be possible to integrate building installations in the floor elements
- The system has to be compatible with conventional construction types
- The system should provide good durability and robustness

2 Technical solutions for TCC

In this chapter different technical solutions for TCC floor systems are compared and summarized. Literature is reviewed and a collection of experiences from completed built projects is provided. The different solutions are evaluated in terms of structural performance, efficiency, economy and sustainability.

2.1 General concept

2.1.1 Combined action of timber and concrete

The general aim of composite structures is to benefit from the individual benefits of different elements and combine their performance. When assembling the different members, it is aimed at limiting the differential deformation between the elements by adequate connections and activating the entire cross-section.

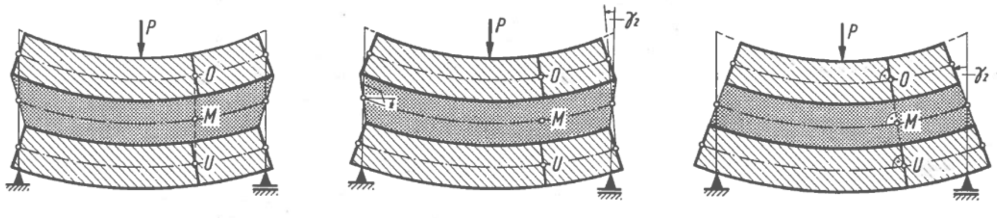


Figure 2.1 Illustration of members with no, partial and full composite action.

The level of composite action depends amongst others on the stiffness of the connection layer or connection elements. With increasing stiffness, the composite action increases as displayed in Figure 2.2.

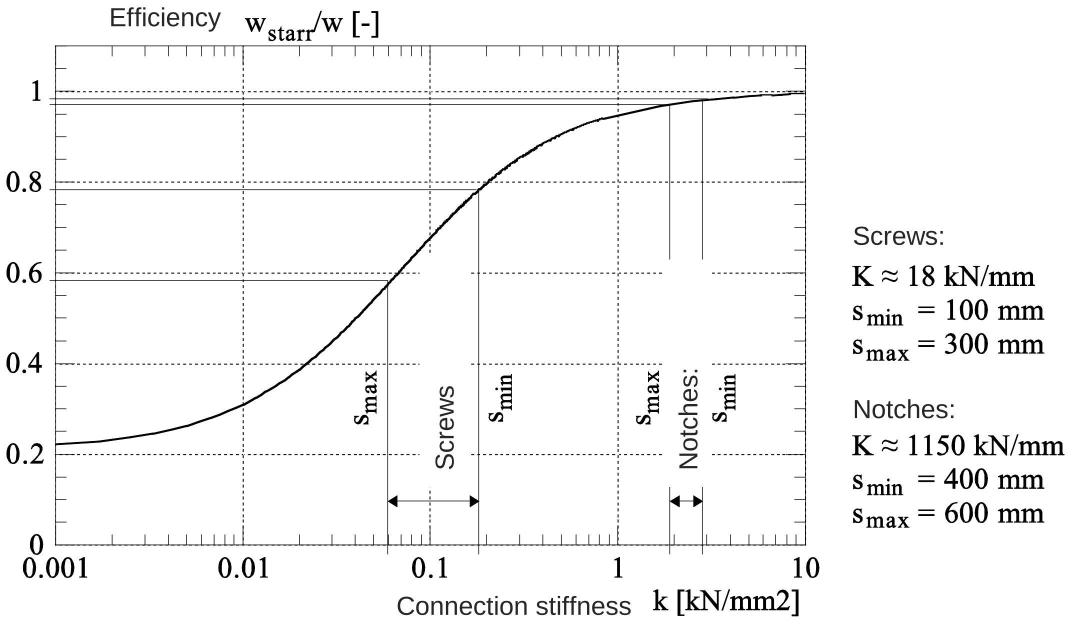


Figure 2.2 Influence of the connection stiffness on the composite action.

Despite the optimisation of the composite elements with regard to the connection stiffness, there are different other aspects that should be considered for selecting the optimal connection technology and assembly process. This includes the easy of assembly, simplicity of the process with regard to personnel, qualification, equipment, boundary condition, etc. Not least the individual price of the connector systems plays an important role.

When achieving the optimal composite action, it can be benefited from the strength of the individual materials:

- Timber:
    - light weight
    - high tensile strength
    - optimal use on the tension side
- Concrete:
    - heavy weight
    - high compression strength
    - optimal use on the compression side

2.1.2 Establishing the composite action

Different technologies and systems exist on the market in order to establish the composite action between the timber and the concrete:

- Fastener system where typically dowel type fasteners are loaded axially or laterally. The fasteners can e.g. screwed or bonded into the timber.
- Form fitting system: notches and grooves are milled into the timber and filled with the concrete during casting. The shear force between timber and concrete is transferred via contact.
- Special systems, such as glued systems or truss elements

The differences between connection solutions in TCC are discussed e.g. in (Blass and Schlager 1997; Yeoh David et al. 2011). Different technologies provided by manufacturers have European Technical Assessment or other national approvals.

2.1.3 Connector arrangement

The load carrying capacity and stiffness of connections with screws depends on the angle between the load and axis of the screw. In (Würth 2018) different aspects are discussed.

Screws provide high axial capacity and stiffness but only moderate levels of lateral capacity and stiffness. By inclining the screws with regard to the load direction, the screw can be activated axially, and it can be benefited from the good properties. From a strength and stiffness point of vie the screw should be inclined as much as possible, e.g. to achieve angles between 30° or 45°. The impact of the inclination of the screw on the load-deformation is shown in Figure 2.3.

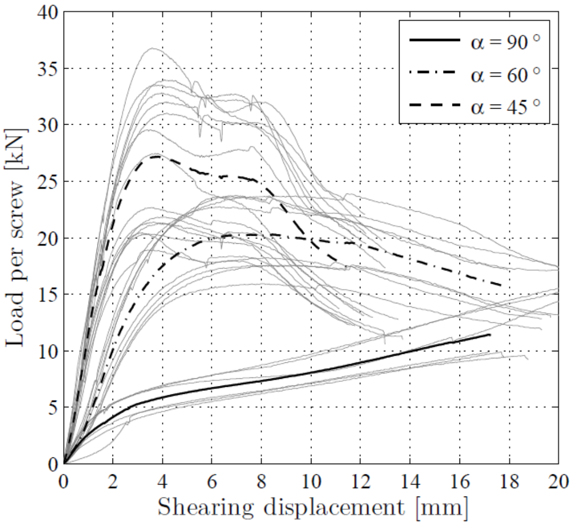


Figure 2.3 Impact of screw axis to loading direction in a shear connection with SFS WRT-13 screws (Jockwer, Steiger, and Frangi 2014)

Screws that are inclined and loaded in tension lead to compression force component in the shear joint, which increases with the deformation of the screw. This compression leads to additional friction, that increases the resistance of this type of joint.

In contrast, if screws are inclined against the direction of the acting load and are loaded in compression, buckling of the screw may occur, the connection separates and no friction can be utilized.

The inclination of the screws should be carefully chosen based on the expected load direction. Using pairs of screws that are arranged in a cross allows to carry reversable loads in the joint. One of the screws is loaded in tension, the other in compression. Buckling of the screws can be avoided by this arrangement, however, no frictional force develops in the contact area.

The connection with an axially loaded screw can fail in withdrawal of the screw thread from the timber or due to tension failure of the screw itself. With increasing screw in length, the withdrawal capacity of the screw increases but is limited to the tensile resistances. Both these failure modes should be considered in the design.

Sufficient distances to the timber edge and end as well as sufficient spacing of the screws parallel and perpendicular to the grain must be assured in order to prevent splitting and cracking. Different screw producers allow partly reduced spacing and distances for specific products.

2.2 Overview of technical connection systems

2.2.1 Screw systems

A variety of different screw solutions for creating timber concrete composite can be found. An overview over different products is given in Table 1.

Table 1: Overview of different producers of screw connectors with respective approvals

Subject concerned	Producer	Technical approval
SFS VB screws	SFS intec AG	Z-9.1-342 ETA-13/0699
BiFRi composite anchor	FRIEDRICH GmbH Verbundsysteme	Z-9.1-851
Elascon SFix HBV-System	Elascon GmbH	Z-9.1-886 ETA-18/0264
T II 7,3x150 screw	E.u.r.o. Tec GmbH	ETA-16/0864
Fischer CSC45 connector	fischerwerke GmbH & Co. KG	ETA-21/0154
ASSY plus VG screw for use in wood concrete slab kits	Adolf Würth GmbH & Co. KG	ETA-13/0029
Tecnaria CTL BASE, CTL MAXI and CVT 40 OMEGA connectors	TECNARIA SpA	ETA-18/0649

The screw connector SFS VB by SFS/Heco is a special screw with a smooth shaft and flat hat for anchorage in the concrete. The smooth shaft close to the head end must be located completely in the concrete slab. The screw has an intermediate head that defines the maximum screw depth into the timber. The connector is installed at an angle of 45° in order to benefit from the high stiffness of the inclined screw. A crosswise pattern of ± 45° allows to carry alternating loads. In a range of 50cm close to the support areas they may be arranged at inclinations of 45° and 90°.

Non-load-bearing formwork may be installed between the concrete slab and the timber beams. A separating layer may be inserted between the concrete slab and the timber or between the concrete slab and the formwork to protect the wood from moisture. The total thickness of the formwork and separating layer must not exceed 50 mm.

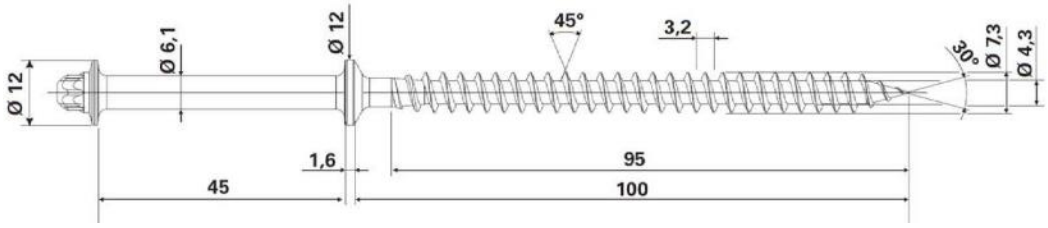


Figure 2.4 Specialised SFS VB screw for TCC (DiBt 2018; SFS intec 2016)

Another example of a screw connector is the SFix connector by Elascon GmbH (OiB 2018). The screw has a double thread, where second thread at close to the screw head shows a minor and wider pitch. The screw head is formed as a flat head.

Slip modulus	$d = 7{,}5mm$	$K_{ser} = 10300\ N/mm$
	$d = 9{,}5mm$	$K_{ser} = 13200\ N/mm$

Figure 2.5 Drawing of SFix screw and photo of insitu application (Elascon 2021).

E.u.r.o. Tec GmbH provides the T II 7,3x150 screws with the following stiffness values (ETA-Danmark 2016).

Slip modulus	$d = 7{,}3mm$ at 45°	$K_{ser} = 110 \cdot l_{ef}$

FRIEDRICH GmbH Verbundsysteme provides the BiFRi anchor with a german technical approval (DiBt 2020).

Slip modulus	$d = 8{,}5mm$ at 45°	$K_{ser} = 130 \cdot l_{ef}$

2.2.2 Other fastener systems

Würth provides the Assy Plus VG screw with 8 or 10mm diameter as a connector for timber concrete composite solutions. The screw itself is also used in other connection solutions in the timber engineering field and can be installed between 45° to 90°. In addition, the 10mm screw can be combined with the FT-connector, which results in a screw inclination of 30°. This connector provides guidance with regard to the angle and through a large head plate anchorage of the screw in the concrete. Through a hollow tube it may be integrated in prefabricated concrete slab, which allows the assembly of prefabricated slab and timber elements on site. An optional intermediate layer of thickness t_{ib} may be arranged between the concrete and the timber.

The part of the head end of the screw must be embedded with sufficient length in the concrete (≥ 50mm). The anchorage of the screw in the concrete is established by via contact below the screw head or via the thread.

$$K_u = \frac{2}{3} K_{ser}$$

Slip modulus	$d = 8mm$ at 45° $d = 10mm$ at 30°	$K_{ser} = 100 \cdot l_{ef}$ $K_{ser} = 45 \cdot \left(l_{ef} - 2 \cdot t_{ib}\right)$

Figure 2.6 Würth Assy Plus VG screw connection system with FT connector for TCC with prefab concrete assembly (ETA-Danmark 2017)

A similar connector with a steel anchorage and guidance plate is provided by Profix (www.pro-fix.ch). The 10mm PHBV-T screws is combined with PHBV-Z, which has two spikes, that facilitate the fixing of the connector on the wood surface. The screw and connector needs to be installed before casting the concrete.

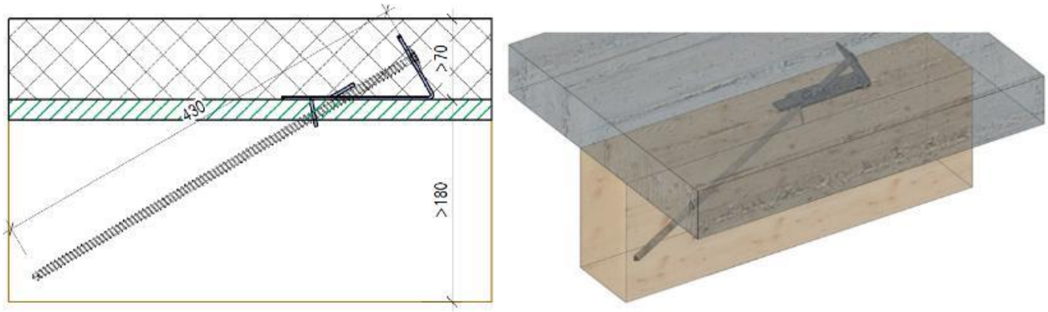


Figure 2.7 Screw connection system for TCC by Profix (www.pro-fix.ch)

Fischer provides a similar system, however, not a steel connector but a plastic element for two parallel screws. In addition to providing composite action between timber and concrete, the plastic element can be used as support for rebar in the concrete. The system can be used with interlayer or without, in case of an interlayer the friction between timber and concrete cannot be activated.

Slip modulus	$K_{ser} = (1+\mu)K_{II} + (1-\mu)K_{\perp}$ With $K_{II} = 780 \cdot d^{0,2} l_{ef}^{0,4}\ \ kN/mm$ $K_{\perp} = \rho_m^{1,5} \cdot d/23\ \ kN/mm$

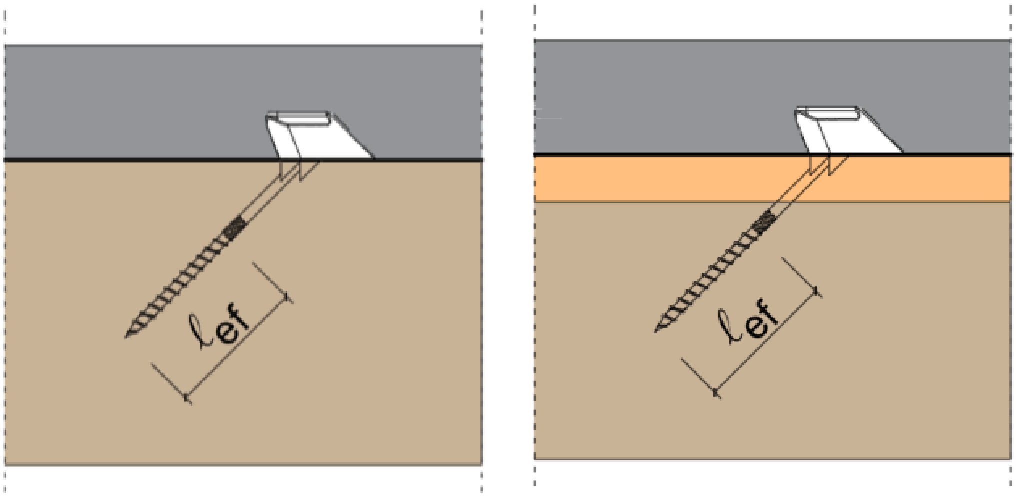


Figure 2.8 Fischer CSC 45 connector in application without and with interlayer (ETA-Danmark 2021).

A connector system, that consists of a steel cam perpendicular to the timber surface or a steel angle (see Figure 2.9), is provided by Tecnaria (ETA-Danmark 2018). The steel cam is screwed or angle is screwed on the timber by one or two screws. Interlayers such as formwork can be added.

Slip modulus without interlayer	CTL Base	$K_{ser} = 17{,}9\, kN/mm$
	CTL Maxi	$K_{ser} = 18{,}6\, kN/mm$

	CVT Omega	$K_{ser} = 2{,}09\ kN/mm$

The slip modulus at ultimate limit state is approximately between 50-66% of K_{ser}.

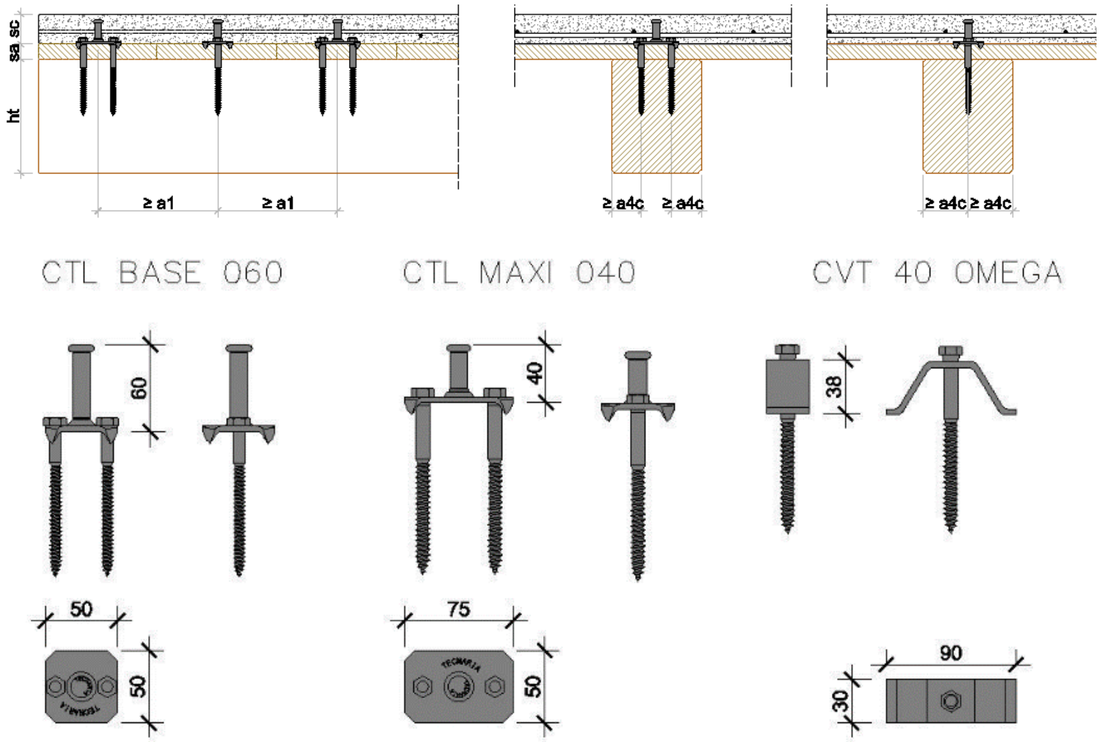


Figure 2.9 Tecnaria CTL BASE, CTL MAXI and CVT 40 OMEGA connectors (ETA-Danmark 2018).

Besides a screwed solution, Elascon provides also a dowelled solution with a round steel tube, that is inserted into a predrilled hole. The so called hybrid cam (Elascon 2021) provides a three times higher strength and stiffness compared to the screw, however, does not allow to transfer withdrawal and separation loads. The connectors are particularly suitable to provide extra strength and stiffness in the connections close to the support.

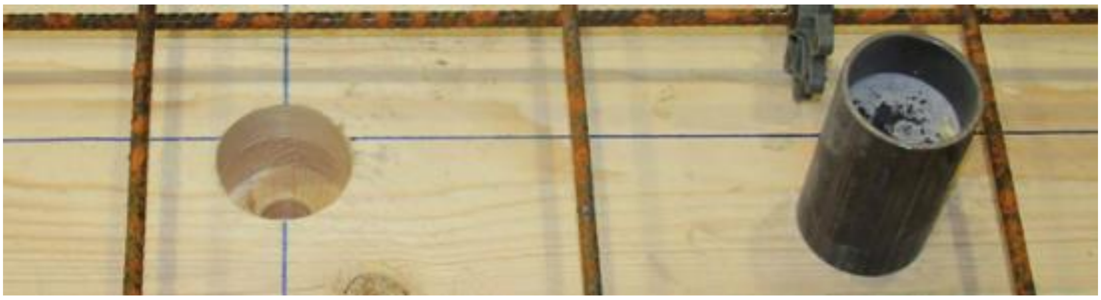


Figure 2.10 Elascon HybridCam (From (Elascon 2021)).

2.2.3 Flat-steel-locks

A simple shear connector can be established by inserting flat steel locks in timber slabs. The flat steel acts in contact compression in the timber and concrete and provide high stiffness as studied by (Lehmann, Grosse, and Rautenstrauch 2001; Grosse, Lehmann, and Rautenstrauch 2001). Additional anchors should be applied to carry lift off forces between the timber and concrete.

Slip modulus	$K_{ser} \approx 469\ kN/mm/m$

Figure 2.11 Examples of flat-steel-locks

2.2.4 Glued web solutions

The company TiComTec GmbH (https://ticomtec.de/en/) provides the HBV shear connector system, which is a steel mesh, that is glued into a slit in the timber. The HBV connectors has the German technical approval Z-9.1-557 and can be used for new constructions or refurbishment and can be applied e.g. in slab, beam, or ribbed floor solutions. The HBV connector can be used also in cases of not mainly stationary loads such as in case of bridges. The slip modulus of the HBV connector depends on the length of the steel mesh and can be adjusted according to the specific requirements.

The following properties are specified for HBV connectors:

Slip modulus	$K_{ser} = 825 - 250 \cdot \left(\frac{d_z}{1mm}\right)^{0,2}\ kN/mm/m$ where d_z is the thickness of an interlayer.
Shear load	$T_k = 160 - 8 \cdot \left(\frac{d_z}{1mm}\right)^{0,5}\ kN/mm/m$

$$K_u = K_{ser}$$

Figure 2.12 HBV glued in connector and casting process for a prefabricated timber concrete composite slab (Photos: Erne AG, TiComTec GmbH)

2.2.5 Bonded-in rod solutions

Bonded-in rods are steel rods with metric thread or with rebar profile, that are glued into the timber by means of PUR or Epoxy adhesives. The high bondline strength together with the possibility to use large diameter rods makes them suitable to transfer large forces between elements. The company neue Holzbau AG (https://neueholzbau.ch/en/)

The following properties of glued connection perpendicular to the shear plane is given in the FprCEN/TS 19103 for bonded-in rod connections with diameter d in mm in timber with MOE E_0 in N/mm^2:

Slip modulus	$K_{ser} = 0{,}1 \cdot E_0 \cdot d \; N/mm$

For inclined reinforcement higher stiffness can be expected.

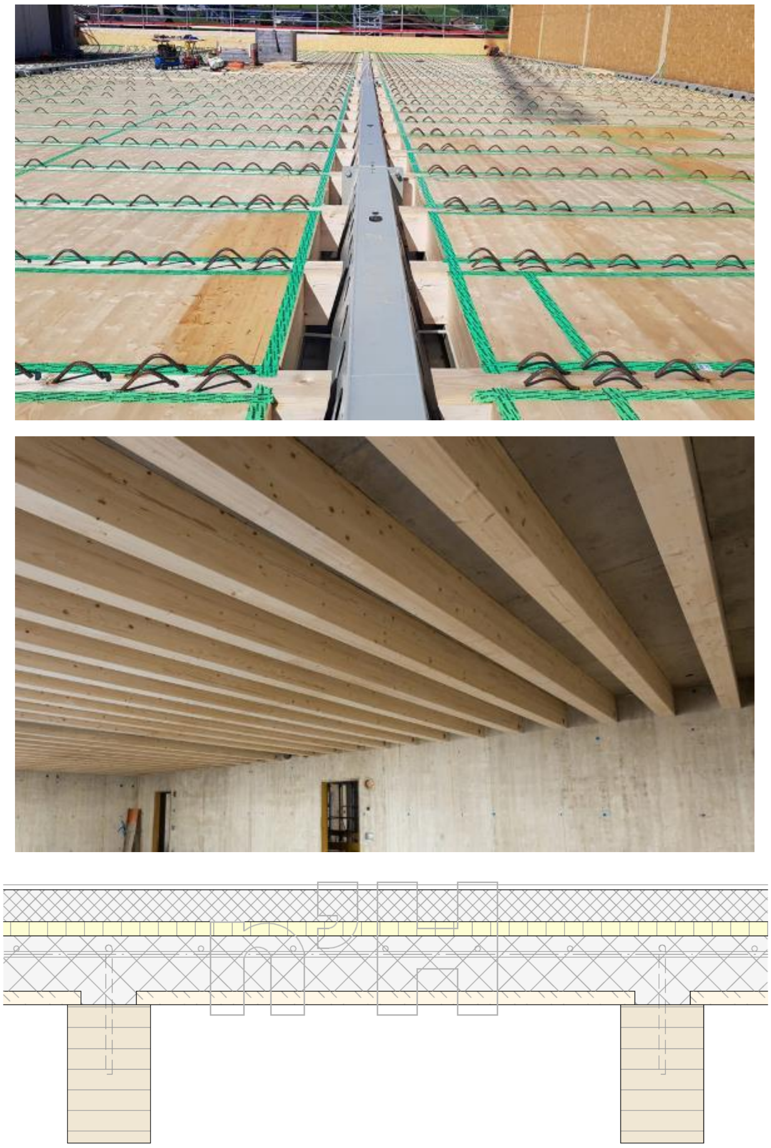


Figure 2.13 Examples of GSA-HBV connectors and composite slabs at different stages of construction (https://www.gsa-technologie.ch/en/gsa-technologie/gsa-hbv-system/?noredirect=en_US)

The GSA®- HBV System Heavy duty floor system provides examples of possible glulam beam dimensions for a rib deck solution with 120mm concrete layer according to Swiss standard SIA 265. The system is single span beams with self-weight $g_k = 3{,}5\ kN/m^2$ and permanent load $q_k = 2{,}0\ kN/m^2$. The beam distance is 1,0m. The fire resistance is REI 60.

Liveload q_k	$2{,}0\ kN/m^2$	$3{,}0\ kN/m^2$	$5{,}0\ kN/m^2$
Span [m]	Beam dimensions [mm]	Beam dimensions [mm]	Beam dimensions [mm]
7.0	200/240	200/240	200/280
8.0	200/280	200/280	200/320
9.0	200/320	200/320	240/360 or 200/400
10.0	240/360 or 200/400	240/360 or 200/400	240/400 or 200/440
11.0	240/400 or 200/440	240/400 or 200/440	240/440 or 200/480
12.0	240/440 or 200/480	240/440 or 200/480	240/480 or 200/520

2.2.6 Notch solutions

Notched connector solutions utilise the contact between the end grain of timber and the concrete in grooves cut into the timber elements for the transfer of shear forces between both elements. Due to the typically large contact area and the high stiffness of both components (especially for the timber being loaded parallel to the grain), notches are effective connectors creating a high composite action.

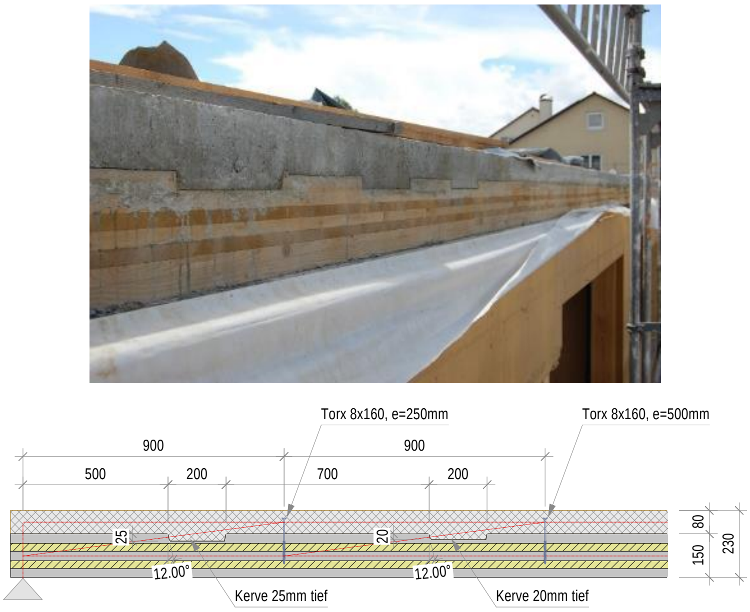


Figure 2.14 Example of a notched timber concrete composite CLT floor.

Especially in panel products such as Brettstapel or CLT panels, the notches are rather shallow with depths not smaller than 20mm. In situations with composite action between concrete elements and timber beams, the notch depth can be considerably deeper. Examples of such deeper notches can be found e.g. in (Kuhlmann and Aldi 2009; 2008).

The following properties are typically considered for notches:

Slip modulus	$K_{ser} \approx \begin{cases} 1000\,kN/mm/m \;\; for\; h_N = 20mm \\ 1500\,kN/mm/m \;\; for\; h_N \geq 30mm \end{cases}$ $K_u = K_{ser}$
Design value of shear strength	$R_d = min \begin{cases} F_{v,timber,d} \\ F_{c,timber.d} \\ F_{v,\,concrete,d} \\ F_{c,concrete,d} \end{cases}$

The absence of metal fasteners for the transfer of shear forces together with the easy manufacturing of the notches by conventional CNC machines makes the notches a cheap solution for new constructions. The floor elements can be fully prefabricated and pre-cast in factory or casted on site. There are also solutions where timber elements and pre-cast concrete slabs are connected on site by grouting the notches in the timber and pockets in the concrete.

Especially for deeper notches adequate reinforcement of the concrete cams is necessary in order to carry shear and tension forces induced from the eccentricities.

Figure 2.15 Prefabricated TCC elements with Brettstapel timber elements.

A solution for a continuous load transfer between timber and concrete was developed by (K. Müller 2020; K. Müller and Frangi 2021) and is produced by Sidler Holz AG (https://www.sidlerholz.ch/en/tccslabs): So called “micro”-notches of the SHARK® system have a sawtooth pattern and are spaced closely next to each others on the surface of Brettstapel or CLT panels. The micro-notches have a length of approx. 30mm and a depth of 4mm. They are milled into the surface of the plate by a special grooved tool. Groups of notches can be spaced along the panels according to the design requirements.

The following properties are specified for the micro-notches:

Slip modulus	$K_{ser} = K_u = 110\ kN/mm/m$
Design value of shear strength	$f_{v,d} = 0{,}5\ N/mm^2$

In case of a continuous arrangement of micro-notches on the surface of a panel, a full composite action with $\gamma = 1$ is proposed.

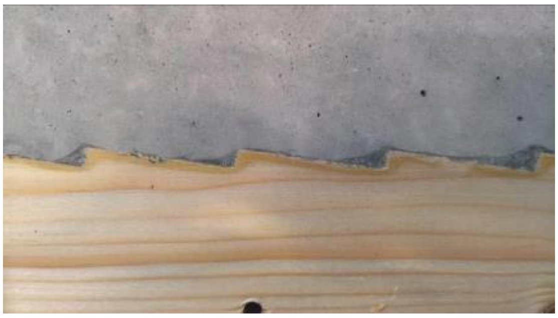


Figure 2.16 ”Micro”-notches by Sidler Holz AG

2.2.7 Special systems

Special systems are being developed and studied in research, where the timber and concrete elements are bonded together by adhesives. Examples of such developments can be found e.g. in (Schäfers and Seim 2008) where prefabricated ultra-high-performance concrete layers are bonded on timber beams. The benefit of the system is that full composite action can be achieved. However, developments regarding materials and production processes are ongoing, and quality control creates a challenge.

2.3 Floor solutions

Timber concrete composite floors can be realised with different floor layout. Each of them has different advantages and disadvantages and different target applications can be identified.

In general, it can be distinguished between floors with a continues bottom layer of timber e.g. made of CLT or Brettstapel, or slabs with single timber joists.

Continues timber layer:

- Brettstapel: Floors with a parallel arrangement of single solid timber boards are called Brettstapel. The boards can be connected e.g. by nails or wood dowels. They provide a uniaxial load transfer. The simple production makes them very cost-efficient continuous floor solutions. In timber concrete composite solutions, the connection is often created by notches or flat-steel-locks, which allows to transfer the shear between the concrete and large areas of timber. The floors can be prefabricated or casted on site. The careful arrangement of the boards can be used to create an attractive bottom view.
- Flat glulam beams: Similar to Brettstapel elements, flat glulam beams have their main load-bearing direction along the main span. Floor using flat glulam beams can be created either with a continuous layer of timber or with a spacing between the beams, which allows to optimize the material use and to integrate installations in the floor.
- CLT: Floor construction with CLT panels is gaining popularity and so does the use of CLT in timber concrete composite slabs. The connection can be established by notches, flat steel locks, fasteners or similar and floor can be casted on site or prefabricated. The thick layer of the CLT panels allows to avoid propping to a large extend. Potential biaxial load transfer in the CLT panels simplifies the design of details such as openings.
- LVL: Timber concrete composite slab with LVL panels as bottom layer can be seen as a special typology. Studied the use of high strength hardwood LVL used as the timber layer in combination with thick concrete layers. The LVL panels act mostly as reinforcing elements for the concrete and as lost formwork. Challenges with this type of construction are amongst others the need for propping during construction and tension stresses in the concrete.

Single timber joists

- Traditional timber floors with joists: In rehabilitation projects, concrete layers are often added to traditional timber floors with joists and planks in order to enhance the load-carrying capacity, reduce the deflection and enhance the dynamic performance. Screwed connection systems are particularly suitable for these rehabilitation projects, since they allow a very individual arrangement and combination with different interlayers. The casting on site may create challenges, amongst others a suitable sealing of a plastic foil is needed for the casting process.
- Rib decks: For new constructions rib deck solutions with glulam joists and a top concrete layer can be prefabricated or casted on site. The relative

slenderness of the glulam beams requires suitable connector elements such as screws, glued in rods or glued in webs. For wider beams notched solutions can be chosen. Prefabricated solution can be established with glulam beams only, when casting on site often a formwork is necessary, that can be continuous or is opened over the glulam beams. In case of continuous formwork panels, the reduced stiffness of the joints due to these interlayers should be considered. The spacing between the glulam beams allows to integrate installations in the floor system.

2.4 Additional aspects

2.4.1 Reinforcement of the concrete

In (SFS intec 2016) guidance regarding the reinforcement of the concrete slab is given. As a minimal requirement a reinforcement steel mesh Q 188 is recommended in the surrounding of the fasteners. The reinforcement needs to be positions below the screw heads and the necessary concrete covers must be satisfied. For concrete slab thickness larger than 100mm additional reinforcement should be added as well as in precast slabs.

2.4.2 Fire resistance

Generally timber concrete composite slabs have a superior fire resistance compared to other conventional timber floor solutions. The concrete layer creates a barrier against smoke penetration whereas the timber isolates the concrete from heat and spoiling. The fasteners and connectors in the inside of the joint are protected by the timber from increased temperatures.

The load-bearing behavior of the composite slab under increased temperatures can be determined by the reduced cross-section method specified e.g. in EN 1995-1-2. More detailed analysis and guidance is given e.g. in (Frangi 2001).

3 Market overview

Different players are active in the market of timber concrete composite floors. They provide different competences (prefab or site-built), have different business ideas and perform different activities.

The market consists of producers of entire TCC floor systems but also contractors assembling different products or suppliers and manufacturers of building products and kits. In the following a short overview over different players in the Central European market are given.

3.1 Production processes

3.1.1 General

Different production processes of timber concrete composite slabs can be found on the market, where different actors with different competences and activities are involved. Generally, the production can be distinguished between:

- Prefabrication in factory
- Cast on site
- Assembly on site
- Combination

The different players in the field are

- Timber manufacturer
- Suppliers
- Concrete-producers
- Contractor

In the following some possible production processes with different activities of the involved players are described.

3.1.2 Prefabrication by the concrete provider

A possible production process for the prefabrication of TCC elements is illustrated in Figure 3.1. The prefabricated timber elements including the connectors etc. are delivered to the concrete provider. There the concrete is cast on the timber elements and the TCC elements are prefabricated. Including the timber beams in the production process to create the rib-decks requires some adjustment, but basic production steps remain similar. A benefit of this process is that the delivery concrete remains unchanged in the process. In addition, the contractor can continue to use similar elements as provided by the prefab-concrete provider.

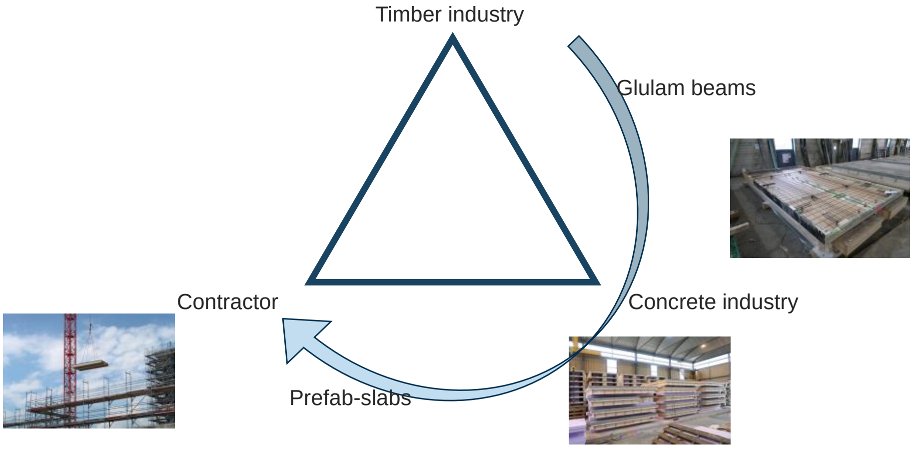


Figure 3.1 Illustration of the process flow of the TCC prefabrication by the concrete provider.

3.1.3 Prefabrication by the timber manufacturer

The reverse process can be established if the production of the TCC elements is based closer to the timber manufacturer. Examples of such processes can be found in practice, especially when timber manufacturers are acting as contractors or suppliers of entire prefabricated building parts such as walls, façades, roofs, etc. Being able to prefabricate not only these elements but also the TCC floor elements in the factory can be beneficial for the timber manufacturer, however, including the casting of the concrete slab on the timber elements in the factory will introduce a new production method into the common environment and may require getting used to.

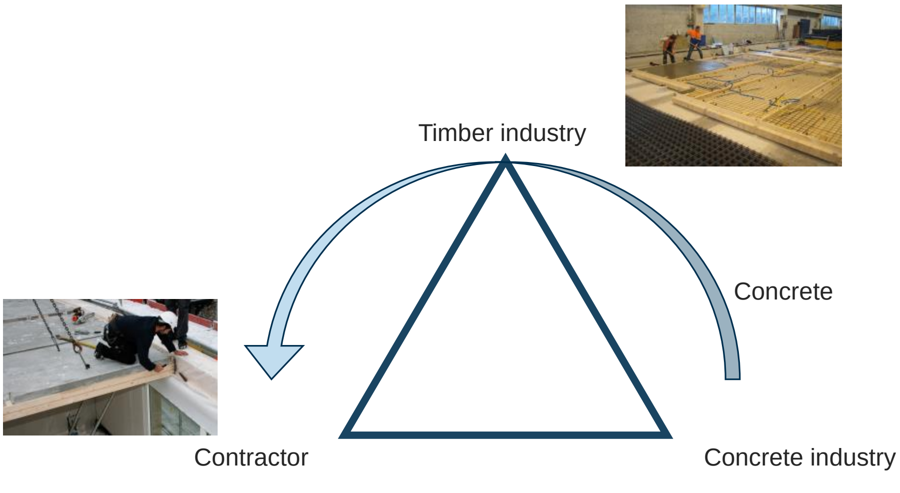


Figure 3.2 Illustration of the process flow of the TCC prefabrication by the timber manufacturer.

3.1.4 Assembly on site

A third potential process for the production of TCC floor systems is illustrated in Figure 3.3, where the timber manufacturer and the concrete producer deliver their individual products to the constructions site. There these separate elements are assembled together to for the TCC. The individual products can be timber beams or panels including the connector elements and the fully or partially (filigree) precast concrete slabs. This process keeps the production of TCC independent from the individual timber and concrete producers but put the responsibility and demands to the contractor.

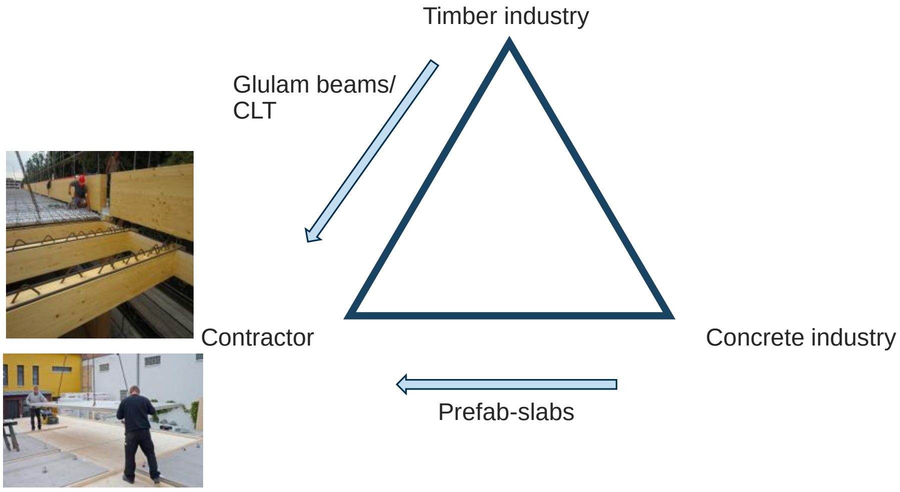


Figure 3.3 Illustration of the process flow of the separate production and TCC assembly on site.

3.2 Players in the field

There are currently no providers of specific TCC systems on the Swedish market. Examples of system provider can be mainly found in Central Europe, which are described in the following.

3.2.1 Suppliers of connector systems and components

An overview over different suppliers of connection products and fasteners is given in the previous chapter. Basically, many of the established screw producers have special fasteners for timber concrete composite slabs in the portfolio. For adhesive based solutions with bonded-in rods or glued-in steel meshes, the combination of the respective metal fasteners and the adhesive has to be considered.

3.2.2 Timber suppliers

A variety of SME but also larger timber producers can be found that are involved in projects around timber concrete composite. Besides pure provision of raw timber elements, some producers perform more specialized activities even up to prefabrication of entire TCC elements. Examples of timber companies in central Europe are:

- Sidler Holz AG
- Egger Holzbau AG
- Blumer-Lehmann AG
- Kost Holzbau AG
- Holzbau Gröber GmbH
- Holzbau Kurtanker
- neue Holzbau AG
- Haslacher

3.2.3 System providers

Different specialised producers of timber concrete composite solution have established in the market in central Europe. The specialised producers often do not produce glulam or timber elements alone but have focussed on timber construction and assembly:

- CREE GmbH www.creebuildings.com
- Erne AG Holzbau www.erne.net
- MMK Holz-Beton-Fertigteile GmbH www.holzbetonverbund.at

All three system providers emerged partly from conventional contractors mainly active in concrete structures (CREE and Erne) or as a joint venture of a timber producer and a precast concrete element manufacturer (MMK Holz-Beton-Fertigteile).

CREE hybrid building system

The company CREE offers an entire hybrid timber concrete composite buildings system, combining glulam columns, TCC floor elements, façade elements, central girders spanning 2-3 floor elements between columns if necessary (e.g. made of steel to minimize floor hight).

The TCC floor elements are advertised with aspects such as achieving the necessary fire protection between stores and large span of the panels allowing for great flexibility in planning interior layouts. The floor elements are available in ribbed or flat soffit. The TCC floor system is based on a grid structure, where the widths of the prefabricated elements is 2,5m-3,0m and the length two to three times the width.

The service CREE as a system provider offers a range of services to deliver integrated project planning, which enables a more effective project delivery process and greater efficiency for the whole construction

The planning process of buildings starts typically with the choice of the system and its components. Digital twins allow workflow simulations with alternative studies, material optimisation, and waste minimisation. The optimised and predefined system reduces complexity through fewer individual component types and results in related benefits in logistics etc.

The business of CREE as contractor is limited to regional range, but it serves as system provider in collaboration with selected international key partners. In this framework CREE provides knowledge to the manufacturer and ensures quality.

Product SupraFloor® by Erne AG Holzbau

SupraFloor is the timber concrete composite floor product by the company Erne AG Holzbau. It is advertised that the product meets easily “even the most stringent sound and fire protection requirements”. Further the general advantages are advertised such as:

- large spans
- high sound insulation
- high rigidity
- high fire protection
- dry construction

- ceiling elements made to measure and accurate to the millimeter thanks to industrial prefabrication
- high quality standard
- fast assembly

An integrated cooling and heating systems enable thermal activation of the floor system and achieving energy saving.

The prefabricated TCC elements are produced and cast in the companies own factory in northern Switzerland. Just-in-time delivery allows achieving reduced assembly time.

MMK XC ® elements

The XC® TCC floor product by MMK is available as ribbed or flat soffit. MMK offers services for planners and developers, such as comprehensive tender texts and documents as well as cost planning. The TCC products follows standardized performance specifications according to the new Austrian Industry Standard. In detail MMK advertises the following services and support:

- Support in conceptual design and planning
- Consulting regarding optimization of material selection (building physics, ecology, costs)
- Cost calculation and accompanying cost optimization
- Support with 3D planning and visualization
- Preliminary structural analysis including fire protection and vibration verification
- Costs and feasibility analyses
- Support for submission-, execution- and detailed-planning
- Optimization of construction time and construction sequence planning
- Depending on customer requirements, coordination with the individual trades on the construction site
- Support with building certification (life cycle analysis)

The TCC product by MMK, XC®, was developed towards (cost) efficiency, with a minimization of many complex work steps, the simplification of the interfaces between the timber and concrete construction, and efficient prefabrication under controlled environment.

3.3 Projects

Overviews over different projects can be found e.g. in (Jung 2015; Volk 2016; Strauch 2015).

Generally, it can be distinguished between residential and non-residential structures, with often considerable difference in the number of storey and the repetitiveness of the applied system. In the following some examples of multi-storey office buildings is given.

3.3.1 Arbo, Rothkreuz, Switzerland

The Arbo building is currently the tallest (i.e. high-rise) timber hybrid building in Switzerland with a height of 60m and 15 storeys. Details about the building, project and construction can be found in (Jung 2018). The construction time was between

04/2017 and 07/2019. The building is used as canteen, library, and office for the local university of applied sciences.

The project stakeholders are:

- Owner: Zug Estates, Zug
- Project management: Archobau AG, Chur
- Architects: Büro Konstrukt, Luzern und Manetsch Meyer AG, Zürich
- Fire safety planning: Pirmin Jung Ingenieure AG, Rain
- Consultants: Dr. Lüchinger + Meyer AG, Luzern
- Contractor: Implenia AG, Zürich
- Timber engineers: Pirmin Jung Ingenieure AG, Rain
- Timber manufacturer and contractor: Erne AG Holzbau, Stein

The building has a floor plan of 20.4m x 41.4m, with a central concrete core surrounded by the office space with approx. 6,5m span. One row of outer glulam and hardwood LVL columns is spaced at approx. 4m, with a ring beam supporting the timber concrete composite floors of approx. 2,7m width. The bracing is provided by the concrete core. The fire protection is achived with sprinklers to REI60 with the primary timber structure being unprotected.

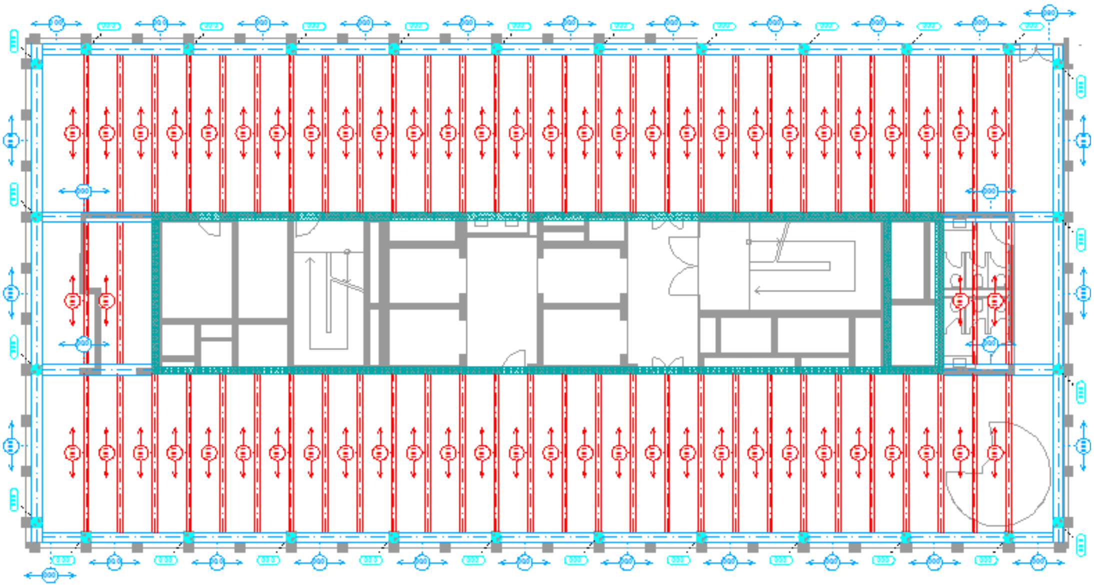


Figure 3.4 Floor plan of the Arbo building (Jung 2018).

The timber concrete composite floor elements glulam ribs 2x100/320mm with a 160mm thick concrete layer. Between the ribs, building services installations are arranged (ventilation, cooling, lighting, sprinkler system). On the lower 3 storeys an additional sound insulating screed is added to the concrete floor, on the upper storey as raised floor system is used. This allows to meet the sound insulating requirements and the thermal protection in summer.

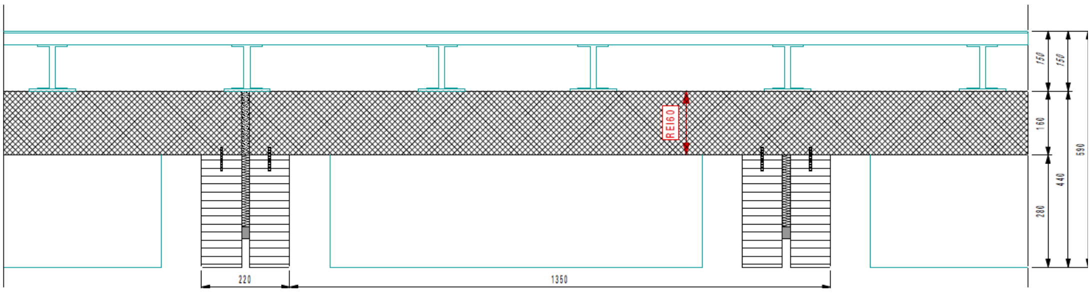


Figure 3.5 Floor cross-section of the timber concrete composite floor elements (Jung 2018).

Challenges in the project were seen with regard to the tolerances of ±30mm of the concrete works in the core, the high architectural demands, and the fire protection REI60.

The floor elements were supported on local steel brackets, that were welded to casted in steel plates in the core. At the ends the timber ribs are hung up via fully threaded screws into the concrete slab, which is supported on the local steel brackets in the concrete core. Between the steel brackets IPE100 beams are arranged as reinforcement. The steel elements are cladded to achieve fire resistance duration of 60 minutes.

On the façade side the floor elements are supported via the concrete slab on the timber ring beams. The timber beams and concrete slab are connected via large notches and create themselves timber concrete composite elements spanning between the façade columns.

Figure 3.6 Notches in the timber and corresponding recess in the concrete slab over the ring beam spanning between the façade columns (Jung 2018).

For the weather protection during construction three different strategies were evaluated:

1. **Protection of the elements**

- Achieved through e.g.:
    - Painting
    - Covering in foil
- Problems:
    - Weather impact

        - Potential scratches and damages
        - Optics

2. **Sealed top level**

- Achieved through e.g.:
    - Taping the wooden panel
    - Roofing felt
    - Concrete layer
- Problems
    - Weather impact
    - Tightness not 100% possible

3. **Encasing by roof**

- Achieved through e.g.:
    - Modular elements
    - Fixed temporary roof
    - Adaptive temporary roof
- Problems
    - Costs
    - Problems with preinstalled concrete core

In the project a closed and sealed top level together with a protection and individual element was chose. At the end of each day, the concrete layer on top of each timber concrete composite elements was grouted with the surrounding elements and the floor layer was sealed. Drainage pipes of the floor elements were integrated in the installations at the construction site. Ring beams and columns were protected against moisture, columns were also protected against mechanical damage.

3.3.2 LCT-One

The building LifeCycle Tower One – LCT One – is located in Dornbirn in Vorarlberg, western Austria. The office building is a result of a joint research project by the company Rhomberg and the partners Architekten Herman Kaufmann ZT GmbH, Arup GmbH, and Wiehag GmbH. The construction started in 2007. A summary of the project can be found in *(CREE Buildings, n.d.)* and is summarized in the following.

The timber concrete composite slab is made of glulam ribs and concrete cover. The beams are arranged as double beams in the middle of the slab. The single beams at the edges are joint together to double beams when assembly the slabs. At both ends the slab is supported by a concrete edge beam supporting both the glulam beams and the concrete slab. The elements have a length of 8,10m and width of 2,70m. The floor elements reach 90min fire resistance and guarantee fire separation between floors.

The concrete is C40/50 XC1 WO with shrinkage limitation of 0,45‰. The concrete contains reinforcing plastic fibres, and a steel mesh was inserted in the slab to carry minimal tensile forces. The glulam strength grade is GL28c with dimension 240 x 280 mm. The shear connection between the timber and concrete is achieved by notches 4 notches towards each end of the beams. The notches had a depth of 35mm, with of 200mm and length of 240mm. The notches were selected as connection method due to their simplicity and absence of additional fastening devices. In Figure 3.7 a notch and the casting bed can be seen.

Figure 3.7 Hybrid Slab in production (Image Copyright: CREE GmbH, www.creebuildings.com)

The slab elements are connected through evenly spaced shear recess notches in the concrete slab, that were grouted after installation of the neighbouring elements and sealing of the gap.

The floor elements and all other elements were fully prefabricated, so that no postprocessing was necessary on the construction site. The stable climate conditions in the factory hall of “Sohm HolzBautechnik GmbH” created optimal conditions for the prefabrication of the large number of repetitive elements.

Based on the good experience from the LCT One building and other buildings such as the IZM (Illwerke Zentrum Montafon) in Austriam the following potential for further development is defined (Strauch 2015), which create certain challenges for a more excessive application on projects:

- The long construction time of the conventionally casted concrete core diminishes the benefits in the construction with prefabricated elements.
- Depending on the possibilities for prefabrication of elements in the factory, the partially long lead time in the production of the elements should be considered and could be reduced whenever possible. In case of the IZM the lead time was 4 months.
- The costs of the prefabricated timber concrete composite floor elements was considerably higher compared to a conventional cast in place concrete slab, disregarding however the individual particularities.

Based on these disadvantages the following potential of further development can be defined:

- Full system integration of the prefabricated elements to achieve highest gain with regard to lead production time, construction and assembly time, weather protection, element and assembly costs.
- Cost reduction from around 200-250 € per m^2 floor area at the time of construction to approx. 100-150 € per m^2 floor area in order to make it compatible with conventional cast in place concrete systems.

3.3.3 HoHo Vienna

The HoHo building is a 84m tall timber concrete composite building built between 2016-2019 in the suburb Aspern in Vienna, Austria (Figure 3.8). It is built with 800 columns and 16’000m^2 CLT. Details about the building and construction process can be found e.g. in (Woschitz 2019).

The main building consists of three coupled components with 9, 15 and 23 storeys respectively and a smaller five-storey annex. The high-rise building has a double basement and stands on a combined pile and slab foundation.

A fundamental goal was visible timber surfaces of the load-bearing components without fire protection cladding.

Figure 3.8 HoHo in Vienna, Austria (www.hoho-wien.at cetus Baudevelopment GmbH)

In the interior the wood in the columns and ceilings was left visible. Sprinkler systems and careful sound proofing allowed to prevent capsulation with plastboard. The floor plans are kept rather flexible for different use (commercial, office, hotel, residentials). The main room spanning around the central concrete cores are made without interior load baring (shear) walls.

The primary load-bearing structure consists of a combination of a T-shaped bracing concrete core that was cast-in-place and the surrounding TCC floors and façade structure. The concrete core was constructed using climbing formwork in advance of the assembly of the TCC and timber elements.

The TCC and timber elements surrounding the core consist of the TCC floor elements, façade columns, and peripheral anchorage edge beams (see Figure 3.9).

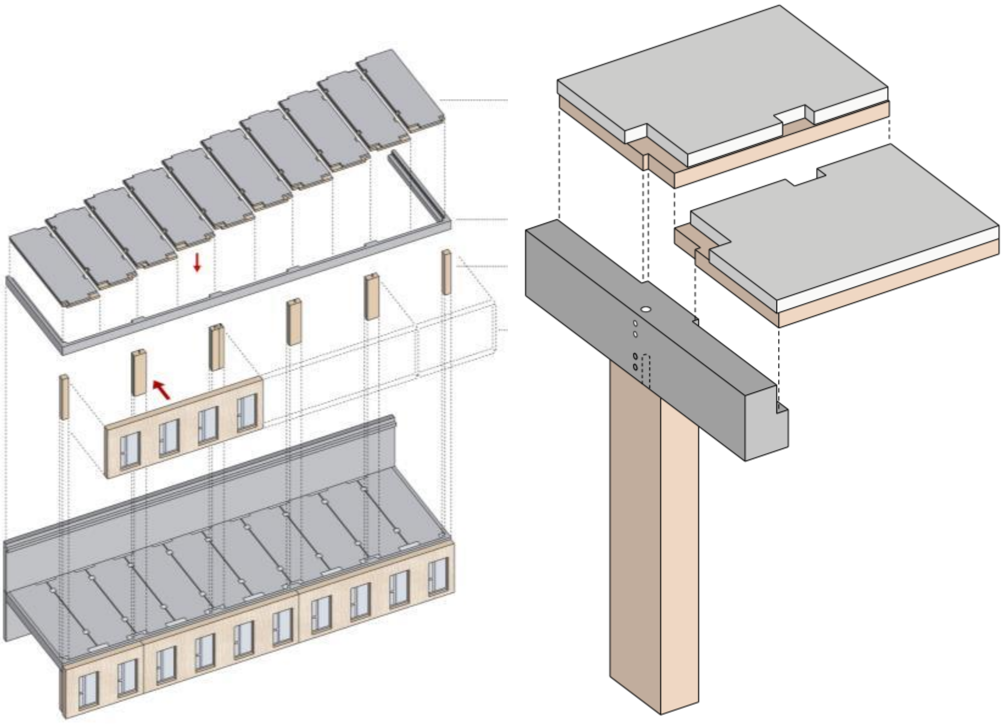


Figure 3.9 Assembly process and node between column, peripheral anchorage, and floor elements (Woschitz 2019)

The floor elements were made of CLT slab with concrete topping. The shear connection between different TCC floor panels was established by grouting recesses in the top concrete. The peripheral anchorage ring beam was made of precast concrete. The columns with a spacing of 4.8m are made of blocked glued glulam. The connection between column and ring beam is made by glued in rods. The façade is made of non-load bearing CLT panels of 4.8 m width and 3.2 m height. The windows are already inserted in the façade systems. All columns are connection by tension anchors to increase the robustness against column failure. Also, the TCC floor slabs are tied together to form a truss like action for robustness and seismic resistance.

The use of prefabricated TCC floor elements and façade elements facilitated the assemble process and speed and hence, increased the protection against rain.

4 Design recommendations

In this chapter existing design procedures from standards, guidelines etc. are collected. Recommendations for the design and implementation of the floor elements are given for designers, manufacturers and contractors.

4.1 Existing standards and guidelines

So far, no design guidance is given for timber concrete composite systems in the Eurocodes. It is intended to include guidelines in the future revised version of Eurocode, that can be expected to be published around 2025. So far only national guidelines and handbooks and the draft of a Technical Specification on European level are available.

4.1.1 Technical guidance

The State of the Art on research, development and practice of Timber Concrete Composite systems was summarized in a report by “WG4-Hybrid Structures” of COST Action FP1402 (Dias, Schänzlin, and Dietsch 2018). It summarized the existing knowledge in the different European countries and reflects the information and studies available. Special focus is put on the topics of input values, connections, evaluation of forces in the short and long term. It gives design examples and explains methods for the evaluation of forces.

A Canadian guide by (Auclair 2020) gives detailed information on TCC floor systems in buildings. Besides general background on TCC systems, it is focussed on the calculation theories using partial composite action of the beam to determine the effective bending stiffness in dependency of the spacing of the connectors. The effects of the materials and connectors on the behaviour of the floor system in terms of load-carrying capacity in ultimate limit state but also in terms of deflections and vibrations in the serviceability limit state are evaluated. The fire resistance is discussed in terms of charring depth of a panel type floor. A design example is shown at the end of the report.

4.1.2 TS TCC

Based on a mandate by CEN/TC 250 “Structural Eurocodes”, a working group within CEN/TC 250/SC5 was prepared a technical specification prCEN/TS 19103 with general design rules for timber-concrete composite structures.

The document is published as a technical specification, which covers work which is still under ongoing or expected development, and which is not fully settled and established in order to be covered by a full standard. The technical specification is published for immediate use, but as it has not the status as a standard it also provides a means to obtain feedback for further standard development.

The technical specification prCEN/TS 19103 provides requirements for materials, design parameters, connections, detailing and execution for TCC structures. If focussed on TCC systems with metal connection or notches typically used for floor structures, but not glued joints or for bridges. It contains both simple design rules for constant environmental conditions but also more complex rules for variable environmental conditions.

The technical specification covers the basis of design and relevant limit states, material and material properties under quasi-constant environmental conditions and variable environmental conditions. With regard to the durability of TCC floor systems the aspect of resistance against corrosion of the connectors is highlighted. The relevant aspects for the structural analysis of the composite action of the structure are specified and the impact of propping is considered. The relevant checks to be performed in the ultimate limit states for beams, floors and walls are specified. The serviceability limit states are covered in terms of deflections and vibrations, and the aspect of cracking of concrete is considered. For the connections to be used to establish composite action the values proposed in materials chapter or values from tests in the annex can be used. Besides these aspects covering the design of TCC floor systems also aspects regarding the detailing, execution, and quality control are specified.

In the Annexes further specification regarding environmental conditions, calculations, and tests are given. In the first annex the yearly variation of the moisture content for TCC used in variable environmental conditions is given. The second annex gives calculation examples for the determination of the effect of inelastic strains, of the effective bending stiffness, the bending moment in the concrete slab and timber beams, axial force and shear forces in the connection due to shrinkage in the concrete. In the third annex tests for the experimental determination of the load-carrying capacity and stiffness of connections in TCC systems and their evaluation are given.

The design example included in this report is primarily based on the calculations given in this technical specification.

4.2 Calculation models

(Gerold 2018; Dias, Schänzlin, and Dietsch 2018) discuss the available calculation methods for timber concrete composite structures. The methods range from simple analytical methods for single span systems to more complex FE methods:

- The γ-method is an analytical method. Benefits are its easy applicability. Disadvantages are the assumed boundary conditions e.g. with sinusoidal load or the smeared shear transfer in the joint.
- The shear analogy method according to Kreuzinger allows to model more complex systems, but requires the substitute modelling of the different layers
- Beam models allow to consider all possible structural systems and also to consider localised load introduction through notches; however, they require more efforts in the modelling.
- FE models are a universal method that allows to model the slabs with different degree of detail.

The consideration of shrinkage and creep in concrete and timber as well as the time dependent curing of the concrete should be considered in the modelling of the floor through different stages of the construction and service life. The impact of shrinkage can be considered as an external force whereas creep is typically considered through a reduced stiffness of the elements.

Since deflections are usually decisive in the design of floor elements, the serviceability criteria should be verified first in the design of the timber concrete composite floor elements. The long-term deformations from creep and shrinkage in the wood and concrete must be taken into account in this verification. The strength criteria in the ultimate limit state design can usually be fulfilled as a supplement.

4.3 Technical aspects

4.3.1 Assembly of elements on site and diaphragm action

Often the floor is not only utilised for carrying vertical (imposed) loads, but also for distributing horizontal (e.g. wind) loads to the respective load carrying members e.g. in the core. This means a diaphragm action must be achieved by the individual floor elements. This can be established e.g. either by connecting the individual floor elements to a diaphragm, or by casting additional layers of concrete on the prefab floor solutions.

An example where individual floor elements are joint to form a floor diaphragm together by means of welded connections is shown in Figure 4.1.

Figure 4.1 Welding of floor elements in the Suurstoffi S22 building

Another example where the prefabricated floor elements with CLT panels are screwed together with lap joints is shown in Figure 4.2.

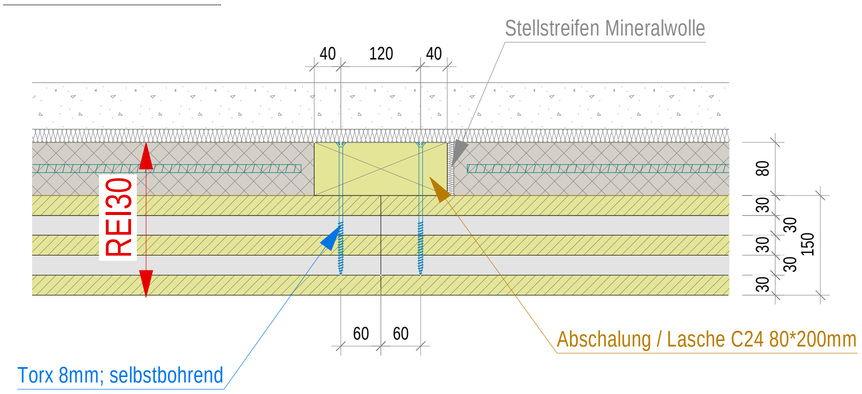


Figure 4.2 Screwed connection between TCC with CLT panels (Source: Merz Kley Partner www.mkp-ing.com)

The notched recesses in the concrete slab of the LCT. One building are shown in Figure 4.3. These notches were grouted after positioning of the adjacent floor elements.

Figure 4.3 Recesses in the concrete (Image Copyright: CREE GmbH, www.creebuildings.com)

5 Recycling of TCC and Life cycle analysis

5.1 Recycling of TCC

The different layers of a TCC floor system can be easily separated during deconstruction after reaching their intended service life in case timber and concrete are connected without mechanical fasteners or chemical systems. This is the case e.g. for the XC® floor elements by MMK.

The concrete can be crushed and fed to the general concrete recycling process whereas steel is fed to the corresponding cycles. (D. Müller and Moser 2022) refer to the challenges of recycling of concrete, which requires considerable primary resources in order to achieve beneficial properties.

The re-use and recycling of timber elements with wood from sustainably managed forests can be typically achieved through downcycling to engineered wood products, wood chips for the paper industry, or wood chips for the production of pellets thermal utilization.

An alternative approach can be gone when choosing an assembly of prefabricated concrete slab elements and glulam beams on the construction site. The prefabricated concrete slab elements with embedded screw fixings (such as Würth FT connector) are connected with screws (such as Würth Assy Plus VG) to the glulam beams or CLT panels. This connection allows for dis- and re-assembly of the prefabricated concrete slab elements and timber members. Disposable elements in this recycling process are only the self-tapping screws that are not specifically made for re-use.

5.2 Life cycle analysis and greenhouse gas emissions

For their TCC building system CREE specifies potential saving potential of up to 25% Cost, 30% Transport, 40% Material, 50% Time, and 80% CO2, compared to conventional cast in place concrete solutions. In order to achieve these high rates an early involvement of the company and all stakeholders in the design-and-build process is necessary.

Positive effects on the carbon balance of TCC systems can be seen in the negative CO2 balance of the timber components, reduction of transportation distances, optimized design for reduced material consumption, quicker construction time through prefabrication, and finally the use of timber instead of steel as tensile members in the floor system.

In the report by (D. Müller and Moser 2022) the circularity, recycling and live cycle assessment of timber and hybrid construction is evaluated and performed. In a comparison with timber box beam and CLT floor systems, the TCC floor system has the highest greenhouse gas emissions with approx. 63 kg CO2eq/m^2 (CLT approx. 48 kg CO2eq/m^2 and box beams 61 kg CO2eq/m^2). The cause for the high values can primarily found in the concrete layer on the TCC floor systems.

In a Bachelor thesis at Chalmers by (Johansson and Urbath 2022) the life cycle analysis of TCC rib elements was performed and greenhouse gas emissions were studied in comparison with other alternatives such as CLT floor elements and TCC elements with CLT slab flooring. It was focussed on carbon dioxide emissions measured in kg C02 equivalents based on data by NCC teknik.

In the LCA analysis only the stages that involve the construction phase of the building life cycle were considered, that means steps A1-A5 according to (Boverket 2019):

- A1 - Raw material supply
- A2 - Transport
- A3 - Manufacturing
- A4 - Transport
- A5 - Building process

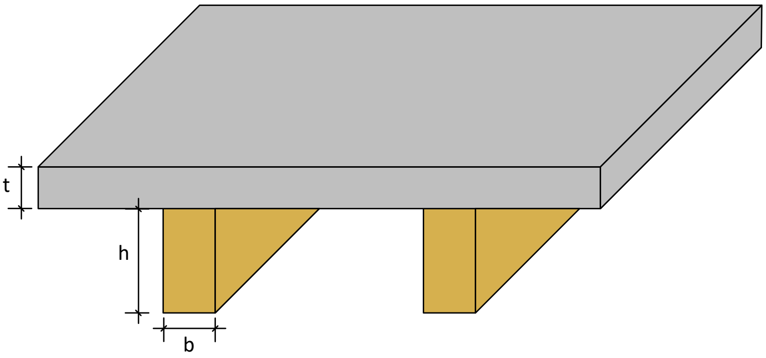
The simplified comparison shows that a pure CLT floor solution shows the best CO2 equivalent compared to TCC solutions with ribs or flat CLT slab. The TCC rib solution however, is better than a TCC flat slab solution with CLT. In the Bachelor thesis “green” concrete with a 30% to even 50% lower carbon footprint than conventual concrete was used, which is already standard in the construction industry. Nevertheless, the concrete dominates the CO2 equivalent of the TCC solutions.

The comparison with conventional concrete slabs can be made by comparing the thickness of the concrete layers. Benefits for the TCC compared to the conventional concrete floors can be expected here, nonetheless since less steel rebar is required for these solutions. Prefabricated hollow core solutions may however have a more beneficial outcome due to their optimised and hollow structure. Timber box beam solutions are expected to be more equivalent in these cases.

6 Development of a TCC floor system solution

6.1 Model and parameters

In a parameter study different possible TCC floor examples are studied in order to identify the relevant parameters and the optimize a reasonable floor example for the costs analysis.



Optimisation can be performed in various directions, such as:

- Dimension of timber and concrete
- Spacing of ribs
- Type and specification of the connectors
- Strength class of the concrete and timber

6.1.1 Connections

In the parameter study HBV glued in steel webs and notches were used as connectors.

The following stiffness properties are specified for HBV connectors:

Slip modulus	$K_{ser} = 825\ kN/mm$ per length of the webs in meter

The slip modulus in the ultimate limit state was assumed to be $K_u = \frac{2}{3} K_{ser}$, and the deformation factor to account for creep in the long term behavior was assumed to be $k_{def} = 2$.

The unit length of one glued in web of $s = 200mm$ was used in the examples and no interlayer between the timber beams and concrete slab was assumed.

For the notches a depth of $h_N = 20mm$ and length of $s = 250mm$ was used and the following stiffness properties were assumed:

Slip modulus	$K_{ser} \approx 1000\,kN/mm$ per beam width in meter

The slip modulus in the ultimate limit state was assumed to be $K_u = K_{ser}$, and the deformation factor to account for creep in the long term behavior was assumed to be $k_{def} = 2$.

The notches require additional screws to carry the tension uplift forces between the timber and concrete. In addition, the applicability of the notches in slim timber beams need to be checked.

6.1.2 Boundaries

In the parameter study, the following boundaries were set for the development of the timber concrete composite floor elements, if not clarified other:

- TCC rib floors with spacing of ribs between 600 and 1000mm
- Floor spans 6m, 8m, 10m
- Self-weight of timber and concrete included additional different g_k and q_k for office use
- ULS criteria right after construction $(t = 0)$ and at the planned end of the usage after 50 years $(t = 50a)$
- SLS for
  - $w_{init} \leq l/300$
  - $w_{fin,freq} \leq l/500$
  - $w_{fin,quasiperm} \leq l/350$
- Double glulam ribs in GL24h
- Concrete strength class C40/50

Minimal reinforcement e.g. according to EN 1992 or prCEN/TS to avoid cracking during and after curing should be considered.

In the analysis the following geometrical parameters are considered:

- concrete height
- concrete width
- timber height
- timber width
- total height
- span of the floor

6.1.3 Modelling

In the analysis one T-section was modelled consisting of one timber beam as a rib and the concrete slab spanning between the centres of the adjacent bays. In all considered cases the effective width of the concrete slab was not reduced (e.g. due to shear lag effect).

The model is based on the γ-method for beam in single span with a uniformly distributed load and using a smeared shear connection along the entire span.

In the analysis it is assumed that the floor elements are perfectly joint together with transverse connections.

Service class 1 was considered in all cases, representing the use of the TCC floor system in a heated building.

Ultimate limit state was checked right after construction $(t = 0)$ and at the planned end of the usage after 50 years $(t = 50a)$for:

- compression stresses in concrete at the top of the slab

- tension stresses in concrete at the bottom of the slab (which can be compensated by additional reinforcement)
- coupled bending and tension stresses in the timber
- shear stresses in timber
- shear force acting on the connector elements

Typically, the tension stresses in the concrete at $t = 50a$ govern the ULS.

The timber strength class has a minor impact on the design of the TCC floor elements, especially the governing deformations.

A higher concrete strength class slightly reduces the thickness of the concrete slab.

6.2 Preliminary examples of TCC floors

6.2.1 Glued-in web connectors with C25/30

Low deflection limit $w_{fin,quasiperm} \leq l/350$

		Span $6m$		**Span** $8m$		**Span** $10m$	
g_k [kN/m^2]	q_k [kN/m^2]	t_{con} [mm]	Timber b/h [mm/mm]	t_{con} [mm]	$Timber\ b/h$ [mm/mm]	t_{con} [mm]	$Timber\ b/h$ [mm/mm]
1	1	80	100/220	120	160/260	120	120/380
1	2	80	100/230	120	160/280	120	120/380
1	3	80	100/240	120	180/280	120	120/400
1	4	80	120/240	120	180/300	120	200/400
2	1	80	100/240	120	180/280	120	200/380
2	2	80	120/240	120	180/290	120	160/400
2	3	80	100/260	120	180/300	120	200/400
2	4	80	120/260	120	200/300	120	200/420

High deflection limit $w_{fin,freq} \leq l/500$

1	2	120	120/280	140	180/360	160	200/450
1	3	120	140/280	140	180/380	160	200/480
2	2	120	140/280	140	180/380	160	200/480
2	3	120	140/300	140	180/400	160	220/490

6.2.2 Glued-in web connectors with C30/37

Low deflection limit $w_{fin,quasiperm} \leq l/350$

		Span $6m$		**Span** $8m$		**Span** $10m$	
g_k [kN/m^2]	q_k [kN/m^2]	t_{con} [mm]	Timber b/h [mm/mm]	t_{con} [mm]	$Timber\ b/h$ [mm/mm]	t_{con} [mm]	$Timber\ b/h$ [mm/mm]
1	2	80	120/220	100	140/290	140	140/340
1	3	80	120/240	100	140/300	140	140/360
2	2	80	120/240	100	140/310	140	140/370
2	3	80	140/240	100	140/330	140	160/370

High deflection limit $w_{fin,freq} \leq l/500$

1	2	120	140/260	140	180/350	160	200/440
1	3	120	140/280	140	180/370	160	200/460
2	2	120	140/270	140	180/360	160	200/460
2	3	120	140/280	140	180/380	160	220/480

6.2.3 Glued-in web connectors with C40/50

Low deflection limit $w_{fin,quasiperm} \leq l/350$

		Span $6m$		**Span** $8m$		**Span** $10m$	
g_k [kN/m^2]	q_k [kN/m^2]	t_{con} [mm]	Timber b/h [mm/mm]	t_{con} [mm]	$Timber\ b/h$ [mm/mm]	t_{con} [mm]	$Timber\ b/h$ [mm/mm]
1	2	80	120/210	100	140/280	120	140/350
1	3	80	120/220	100	140/300	120	140/360
2	2	80	120/230	100	140/300	120	140/380
2	3	80	120/230	100	140/310	120	160/380

High deflection limit $w_{fin,freq} \leq l/500$

1	2	100	140/270	140	180/330	150	200/440
1	3	100	140/280	140	180/350	160	200/440
2	2	100	140/280	140	180/340	160	200/440
2	3	100	140/300	140	180/360	160	220/460

For selected configurations the vibrations were checked:

		Span $6m$	
g_k [kN/m^2]	q_k [kN/m^2]	t_{con} [mm]	Timber b/h [mm/mm]
1	2	80	120/210

- Stiffness $w_{1kN} \approx 0{,}97mm > 0{,}5mm$
- Frequency $f_1 = 10{,}3\ Hz > 8Hz$
- Velocity $v_{rms} = 0{,}0012\frac{m}{s} \approx 0{,}0012\ \frac{m}{s}$

		Span $6m$	
g_k [kN/m^2]	q_k [kN/m^2]	t_{con} [mm]	Timber b/h [mm/mm]
1	2	100	140/270

- Stiffness $w_{1kN} \approx 0{,}42mm < 0{,}5mm$
- Frequency $f_1 = 14\ Hz > 8Hz$
- Velocity $v_{rms} = 0{,}0006\frac{m}{s} < 0{,}0012\ \frac{m}{s}$

		Span $6m$	
g_k [kN/m^2]	q_k [kN/m^2]	t_{con} [mm]	Timber b/h [mm/mm]
1	2	120	140/350

- Stiffness $w_{1kN} \approx 0{,}92mm > 0{,}5mm$
- Frequency $f_1 = 7{,}1\ Hz < 8Hz$
- Acceleration $a_{rms} = 0{,}079\frac{m}{s^2} > 0{,}06\ \frac{m}{s^2}$

		Span $6m$	
g_k [kN/m^2]	q_k [kN/m^2]	t_{con} [mm]	Timber b/h [mm/mm]
1	2	150	200/440

- Stiffness $w_{1kN} \approx 0{,}36mm < 0{,}5mm$
- Frequency $f_1 = 10{,}3\ Hz > 8Hz$
- Velocity $v_{rms} = 0{,}0004\frac{m}{s} < 0{,}0012\ \frac{m}{s}$

6.2.4 Alternative example with optimisation

In a first optimisation the dimensions of the TCC were adjusted as follows:

- Concrete strength class
  - C40/50
- Timber strength class
  - GL24h
- Double beams
  - 2x90-2x165mm
- Spacing 1m

Low deflection limit $w_{fin,quasiperm} \leq l/350$

		Span $6m$		**Span** $8m$		**Span** $10m$	
g_k [kN/m^2]	q_k [kN/m^2]	t_{con} [mm]	Timber b/h [mm/mm]	t_{con} [mm]	$Timber\ b/h$ [mm/mm]	t_{con} [mm]	$Timber\ b/h$ [mm/mm]
1	2	80	180/225	100	230/315	140	330/360
1	3	100	180/225	100	230/315	150	330/360
2	2	100	230/225	110	280/315	120	330/405
2	3	100	230/225	120	280/315	130	330/405

For the lower deflection limits, the first eigenfrequency is $f_1 < 8Hz$.

High deflection limit $w_{fin,freq} \leq l/500$

1	2	120	180/270	140	280/360	160	330/450
1	3	100	180/315	160	280/360	180	330/450
2	2	100	180/315	140	280/360	180	330/450
2	3	100	230/315	160	280/360	180	330/450

For the higher deflection limit, the first eigenfrequency is always $f_1 > 8Hz$.

7 Cost and time analysis

7.1 General description and questions

Within this implementation and cost analysis the potential of the timber-concrete-composite floor system shall be compared with conventional solutions for the construction of a multi-storey office building.

The analysis covers all relevant aspects regarding

- Material
- Production
- Construction
- Time
- Etc.

The analysis can be roughly divided into two steps:

1. Production of the TCC floor elements
2. Use of the TCC floor elements in construction

The costs and analysis should be based on the reference buildings and solutions, i.e. the conventional concrete or timber solution.

Some specific points that affect the costs for the production and building with the TCC are amongst others:

- Changes in logistics and production of prefab elements due to additional material (timber)
- Additional process steps during element production or assembly on site
- Storage of TCC floor systems in factory or on site
- Transport costs
- Handling possibilities in factory and on-site
- Assembly and connection to the structure
- Protection of the floor from rain/weather after installation
- Protection of visible parts of the floor during the construction on site
- Necessary floor layup for final construction
- Production time (hardening time) of TCC compared to pure timber or pure concrete

7.2 Floor description

7.2.1 General

General criteria for the development and optimisation of floor layup can be defined as the following:

- Total thickness of the floor elements
- Thickness of the concrete slab
- Spacing of the ribs
- Concrete strength class
- Reinforcement in concrete
- Deflection criteria
- Dynamic and vibration performance

- Assembly on site vs. production in factory

The cost optimisation should consider the reasonable rating between the parameters.

7.2.2 Boundaries

After a pre-analysis study, the following boundaries were set for the development of the timber concrete composite floor elements:

- TCC rib floors with spacing of ribs 1000mm
- Floor spans 6m, 8m, 10m
- Self-weight of timber and concrete included additional different g_k and q_k for office use
- ULS criteria right after construction $(t = 0)$ and at the planned end of the usage after 50 years $(t = 50a)$
- SLS for
  - $w_{init} \leq l/300$
  - $w_{fin,freq} \leq l/500$
- Double glulam ribs in GL24h or higher with dimensions between 2x90-2x165mm
- Concrete C40/50

7.2.3 Connection systems

Alternative 1: HSK Glued-in web by TiComTec GmbH

The two glued-in webs of $s \approx 200mm$ length are glued in slits in each web (one in each of the double beams). The glued-in webs can be arranged with a smaller spacing $a_{1,min}$ towards the ends of the floor beams and with larger spacing $a_{1,max}$ in the middle. The minimum and possible maximum spacing depends on the span of the slab and the loading. For the 6m span $a_{1,min} \approx 100mm$ and $a_{1,max} \approx 600mm$. For the 10m span the web should be continuous at the ends and can have a spacing $a_{1,max} \approx 400mm$ in the center.

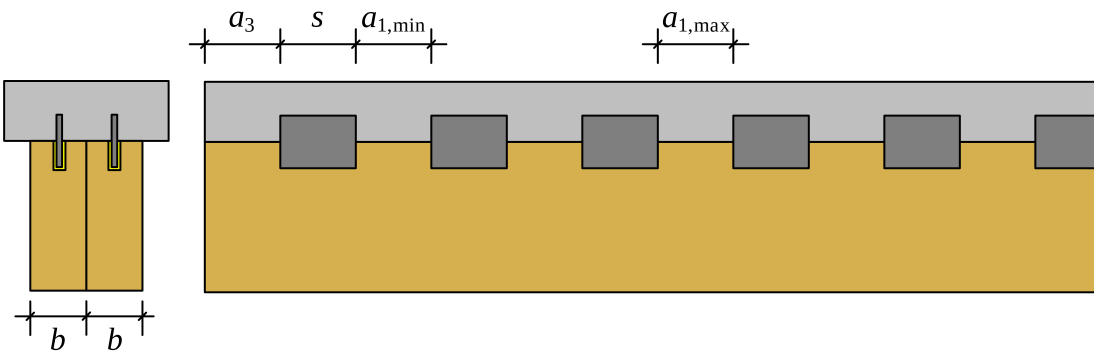


Figure 7.1 Illustration of the arrangement of glued in webs as connecting elements.

Alternative 2: Notch

In alternative 2 the shear force connection between timber and concrete is established by notches in the timber. Additional screws are placed to each notch in order to carry the uplift force introduced by the eccentricity of the forces and in order to allow for the lifting of the floor panels during transport.

The depth of the notches is approx. 20mm, the length is $s = 250mm$ with a spacing of $a_1 = 250mm$. Further increase of the spacing of the notches towards the center of the beam would be possible.

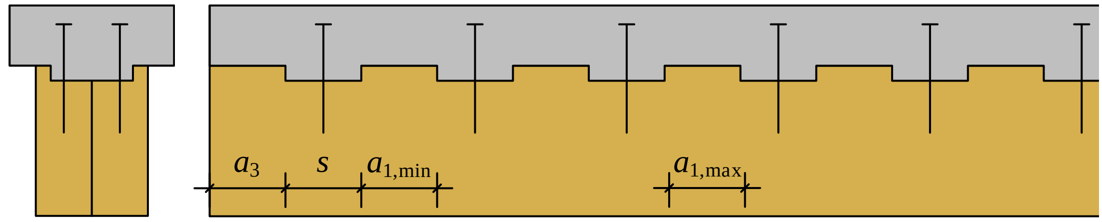


Figure 7.2 Illustration of the arrangement of notches as connecting elements.

7.2.4 Input data including all materials

The following parameters and materials are selected for the cost analysis:

- Glulam strength class: GL24h
- Concrete strength class: C40/50
- Double glulam ribs in GL24h or higher with dimensions between 2x90-2x165mm
- TCC rib floors with spacing of ribs 1000mm
- Floor spans 6m, 8m, 10m
- Self-weight of timber and concrete included additional different g_k and q_k for office use

The connector properties are the following:

- HBV glued in web connector: $K_{ser} = 165\ kN/mm$ per connector of length $s = 200mm$ with f the webs in meter $K_u = \frac{2}{3} K_{ser}$ and $k_{def} = 2$.
- Notch with $K_{ser} \approx 1000\, kN/mm$ per beam width in meter, with notch length $s = 250mm$, $K_u = K_{ser}$ and $k_{def} = 2$.

A concrete type with low shrinkage behavior is generally more beneficial.

7.2.5 Geometry

The floor elements have a 1m web spacing and made with double beams:

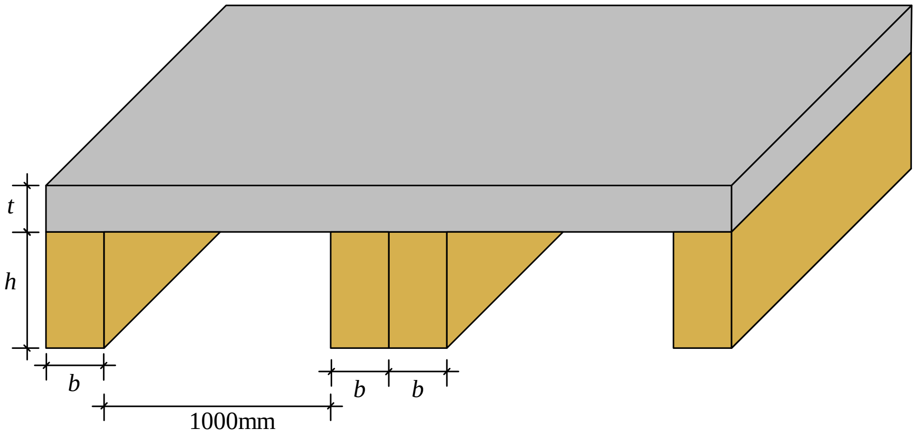


Figure 7.3 Illustration of one timber concrete composite floor element consisting of two bays.

Table 2: TCC floor system evaluated in the cost analysis

Loading		Span $6m$		Span $8m$		Span $10m$	
g_k	q_k	$t_{concrete}$	$Timber\ b/h$	$t_{concrete}$	$Timber\ b/h$	$t_{concrete}$	$Timber\ b/h$
[kN/m^2]	[kN/m^2]	[mm]	[mm/mm]	[mm]	[mm/mm]	[mm]	[mm/mm]
1	3	100	90/315	160	140/360	180	165/450
Total weight [kg]		3540	286	6144	677	7182	1247

For intermediate or other spans linear interpolation may be applied!

In all cases the deflection limits of $w_{init} \leq l/300$ and $w_{fin} \leq l/500$ are satisfied.

The frequency is $f_1 > 10\ Hz$, and the deflection under 1kN unit load is $w_{1kN} < 0{,}5mm$.

The velocity response is $v_{rms} < 0{,}0012\ m/s$.

7.3 Details

Connection between prefab element shall:

- activate diaphragm action of floor (-> shear and normal force action in connector elements).
- create transversal stiffness of floor
- should be sound-proof, airtight, fire barrier, etc.

7.3.1 Connection between floor elements

Connection via rebar and grouting

Cavities are spared e.g. every meter along the perimeter of the concrete slab with access to its rebar. After placing the TCC elements on site small rebar elements are placed into the cavities bridging the gap between elements. The cavities and gap are filled with grout to create the structural connection to the rebar and tightness of the gap.

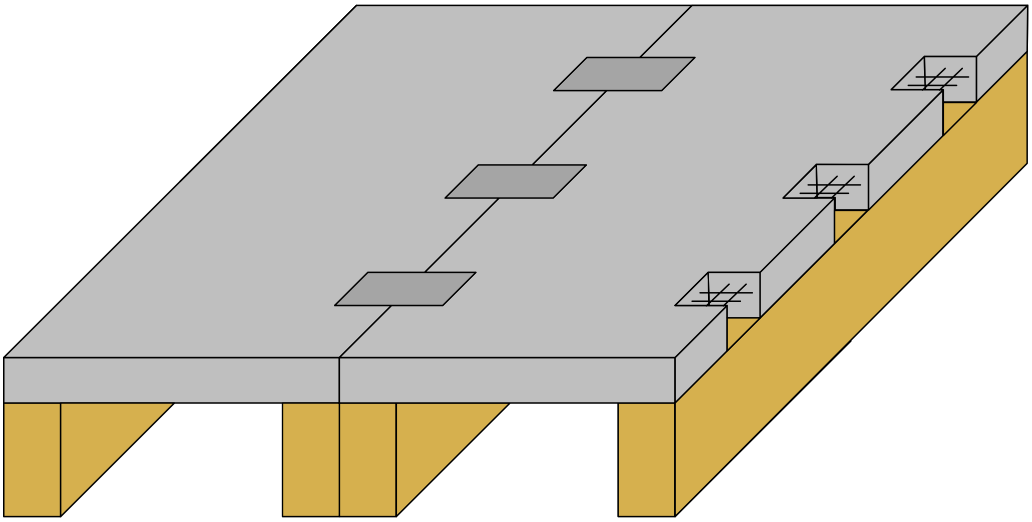


Figure 7.4 Illustration of an example of the connection between adjacent floor elements by recess notches connected by reinforcement and grouted on site.

7.3.2 Floor to beam/column connection

Basically, two different possibilities can be chosen to connect and support the floor elements on the beams and columns of the structure:

1. An extension of the concrete slab to hang up the floor element
2. Supporting the floor element via the timber member

The concrete slab is extended beyond the end of the timber beams and is used to hang up the floor element. This extension of the concrete slab can be easily supported on the (ring) beams of the timber or concrete structure. In that case additional reinforcement between the floor beam and the concrete slab is needed in order to hang up the tension force between both members. The reinforcement can be e.g. via the glued-in webs, additional screws, glued-in rods, etc.

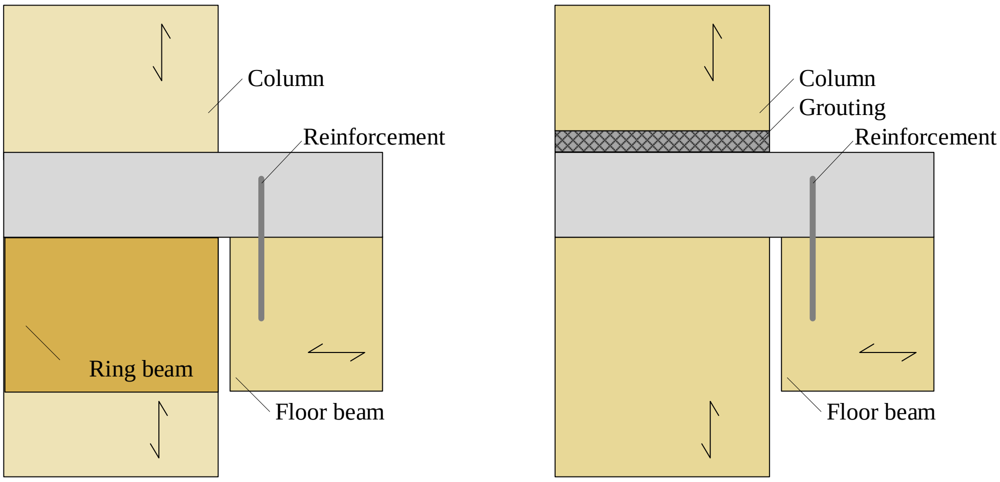
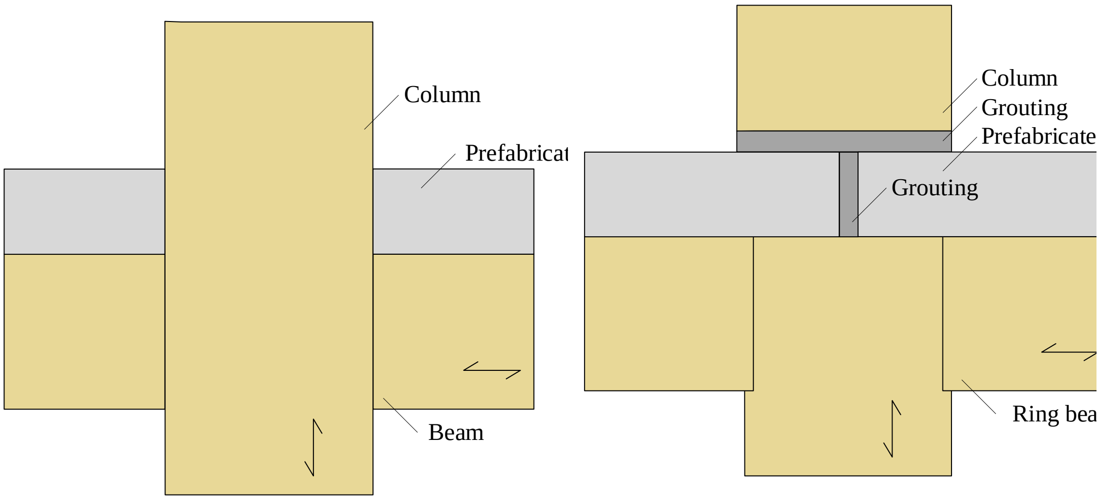


Figure 7.5 Illustration of examples of the connection between floor element and ring beams and columns. The concrete slab is supported on the ring beam (left) and is supported between the columns (right).

When extending the concrete slab and supporting it on the (ring) beam, the column can be either continuous or discontinuous (see Figure 7.6). In the first case the concrete slab should be recessed around the column, in the latter case a platform type of construction is performed with the upper column resting on the concrete slab. Grouting can be used to precisely level the upper columns.



Details with continuous column:

Detail with column joint and intersection by concrete floor:

Figure 7.6 *Illustration of examples of the details of the floor elements at the columns. The illustration on the left shows a continuous column surrounded by the concrete slab, the illustration on the right shows discontinuous columns separated by the concrete slab.*

7.3.3 Floor to core connection

As for the floor to column/beam connection also the connection between the floor elements and the (concrete) core can be made via the concrete slab or the timber beam.

By supporting the timber beam on socket in the core the shear forces can be easily transferred and by connecting the rebar concrete slab to the core tension and horizontal shear forces in the floor diaphragm can be transferred to the core.

In case the entire concrete core is finalized before installation of the TCC slabs, steel brackets can be welded to cast-in steel plates to establish the socket and to allow for potential height adjustment.

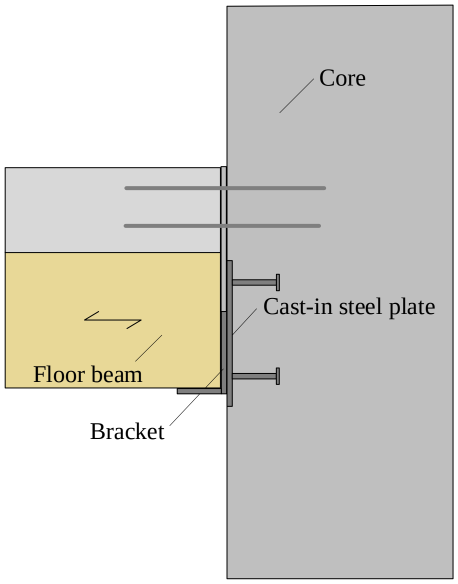


Figure 7.7 Illustration of an example of the connection between floor element and concrete core.

7.4 Cost evaluation of the TCC floor elements

7.4.1 Costs of timber

The costs of the glulam beams with the HBV connector elements are estimated with 12’000 SEK per m^3 including material, production, and transportation.

7.4.2 Costs of concrete and production of elements

The costs are based on the following estimates:

- Glulam delivered to element factory
- Glued connectors in the glulam hold for safe lifting in the TCC elements with concrete element and suspended glulam beams
- 8 m long elements
- Weight per element incl. glulam approx. 9 tons
- 4 elements per transport to construction site <100 km from element factory
- Annual production 30.000 m^2 is about 650 m^2 per week
- Hall approx. 2,000 m^2 with 15 tonnes of beam. Concrete purchased from nearby concrete factory
- 6-7 elements produced per day, requiring 20-21 m^3 of concrete per day

The price for the delivered to construction site <100 km is about 1.450 SEK/m^2.

7.4.3 Costs of assembly on site

The costs of the installation assembly of the prefabricated 8m long TCC floor elements on site are approx. 300 SEK/m^2. Additional approx. 150 SEK/m^2 may be necessary for post-treatment. A floor area of approx. up to 600 m^2 per week is typical in this context. This corresponds to approx. 40 elements of 8m x 2m or 10 truckloads.

7.4.4 Overview

TCC floor solution (8m)

Part and service	Costs	
Timber	900-950	SEK/m^2
Concrete and element production	1450	SEK/m^2
Installation and assembly	300	SEK/m^2
Possible additional post-treatment	*(150)*	SEK/m^2
Total	2650-2700 (+*150)*	SEK/m^2

When evaluating the costs of the sample TCC floor system, different influencing parameters and factors can be identified and discussed:

- Timber: The price of the timber depends amongst others on the strength class and dimensions.
    - The hight of the beams is dependent on the number of laminations and, hence, follows a certain pattern. The optimal hight in relation to span requires optimisation in order to achieve a good level of utilisation. In general, widely available standard dimensions are more desirable than specific individually produced beams.
    - Wider beams that can be positioned at greater spacing are more expensive than thinner beams positioned at smaller spacing. The optimisation of the best dimensions in relation to the spacing of the ribs of the floor elements effects also the installations.
    - The degree of utilisation of the strength of the timber beams is relatively low compared to the serviceability criteria. Hence, lower strength grades can be chosen that might be more cost effective. Nevertheless, the higher stiffness of the higher strength grades reduces deflections etc.
- Concrete:
    - The shrinkage and creep of the concrete has a major impact on the long-term deformation of the floor elements. Using concrete with reduced shrinkage or changing the assembly system from casting on the timber beams to the use of prefabricated concrete slabs connected on site with the timber beams, can reduce the long-term deformations.
    - Depending on the thickness of the concrete and the utilisation in ultimate limit state, different amounts of reinforcement of the concrete is necessary or the use of other reinforcement types becomes feasible.
- Fabrication of TCC elements
    - The fabrication of the TCC elements can be done in different ways as discussed earlier. The different methods require different levels of investment in manufacturing facilities, but also lead to different levels of automation and preparation for mass production. This all effect the costs of the final elements and, hence, the competitiveness of the elements in comparison with other solutions.
    - The prefabrication of the TCC elements requires to consider sufficient time for curing of the concrete before installation on site. Hence, the entire production process should be optimised.
- Post treatment:
    - In order to benefit from the full potential of prefabrication in modern construction, there should be as little as possible work been done during and after installation on the construction site. This refers also to the treatment of the timber, concrete and the entire floor elements after assembly. Ideally the timber is delivered with its final surface finish, which in return requires special care and potential protection and covering.
    - It should be aimed at optimising the level of prefabrication of the TCC floor system together with all installations in a way to minimize the amount of post treatment necessary on the construction site after assembly.
    - Different floor layups are possible, especially for office and commercial buildings. Examples are double floors, which allow the integration of installations or (floating) screed solutions potentially also with heating and cooling installations included. The thickness of the concrete layer and the

    requirements regarding vibrations and sound need to be adjusted accordingly. As well the surface qualities of the concrete layer may differ.
- Level of composite action: The level of composite action is relatively high with the connection systems available. A further increase of the composite action has only a minor impact on the performance of the TCC system.
- Assembly method:
    - By connecting prefabricated concrete slab elements with the timber beams, either on site or in factory can reduce some of the time dependent deformations from shrinkage and creep of the concrete.
- Relevant SLS criteria:
    - The criteria for the serviceability limit state are amongst others deflections and vibrations (frequency, acceleration, damping). The optimisation of the TCC floor system with regard to the individual requirements in the specific case allows for great potential for a more costs effective optimisation and improvement. In the current analysis strict criteria were chosen.
    - When making the cost comparison with other products, solutions, and building types, the same criteria need to be chose in order to allow for a fair and realistic comparison. Different solutions and concepts may be beneficial for different projects, demands, and requirements.
- Installations:
    - Depending on the building use as office, commercial, residential, or hotel use, different types and amount of installation may be necessary. An early discussion of all participating partners in the building process is necessary in order to achieve the best performance and result. This should include architects, structural engineers, building installation experts, contractors etc.
    - The rib deck solution offers possibilities to integrate certain installation in the floor elements between the ribs. That way the total free height can be guaranteed. In the following different examples are given of how different installations can be integrated in the floor elements.

In cost calculations in frame of a Bachelor thesis at Chalmers TCC rib elements were analysed. Individual material and labour were considered in the analysis and the TCC beams proved to be at minimum 30% cheaper than CLT floor.

The following need for optimisation with direct dependency on the TCC floor elements can be identified:

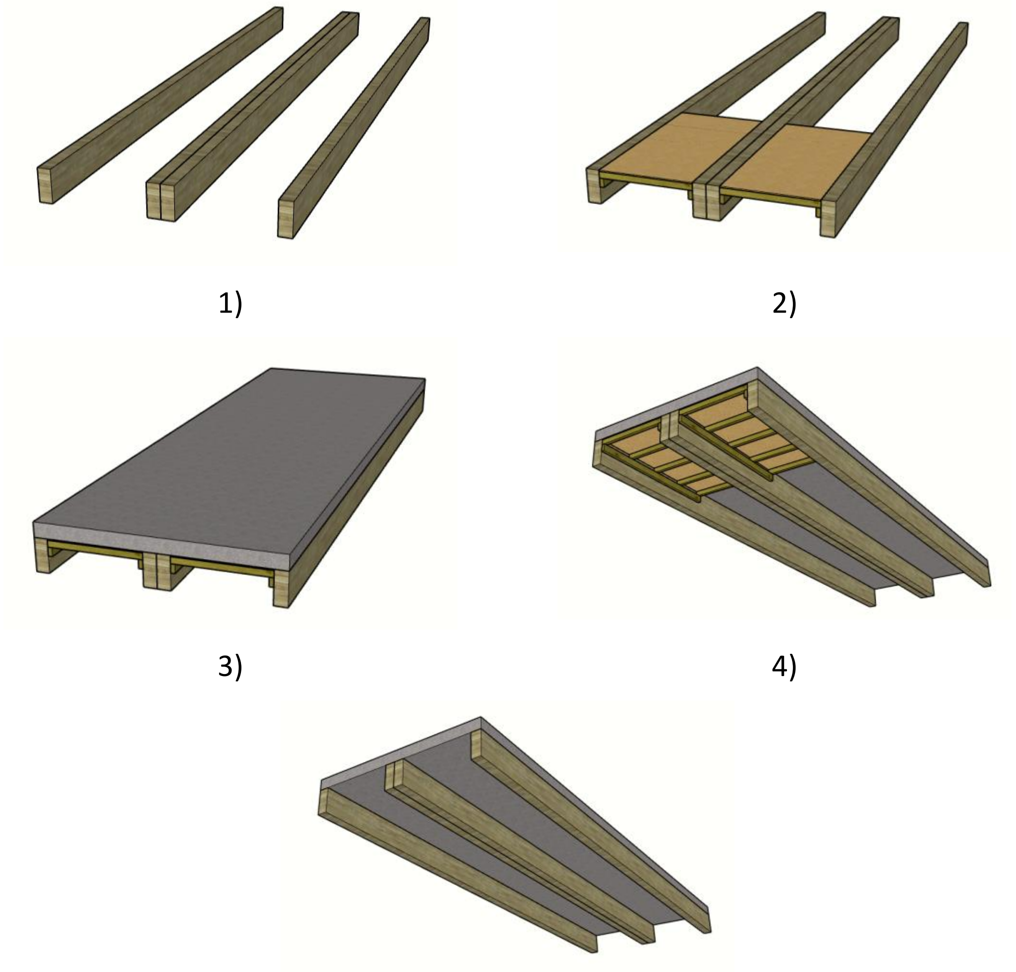
- Timber: Optimise spacing and dimension of timber elements
- Connectors: Cost effective and performant connectors have to be chosen in dependency of the type of floor elements.
- Concrete: reduce the thickness of the concrete layer, optimise long term deformation behaviour of concrete (shrinkage, creep), optimise the reinforcement in the concrete

In addition, the fabrication and assembly process needs to be optimised and solutions for installations needs to be developed.

7.5 Aspects about production

Figure 7.8 shows a possible production sequence with formwork between rips.

1. Glulam beams are position
2. Formwork is built between glulam beams
3. Reinforcement placed and concrete are casted
4. The element is moved and the formwork removed
5. Elements ready for delivery



1) 2) 3) 4) 5)

Figure 7.8 Possible production sequence for the production of the floor elements

7.6 Installations

The positioning of installation channels and pipes within and under the floor is a challenge for the timber concrete composite floor elements. Established solutions in existing buildings guide the distributing channels along the corridors and along cores across floor elements under the ribs of the panels (see Figure 7.9). This leads to a reduced free room height, however, by placing these distributing channels close the cores, minor disturbances regarding daylight distribution in the rooms can be guaranteed.

From the distributing channels the individual bays between the ribs of the elements are accessed without interfering with the room height.

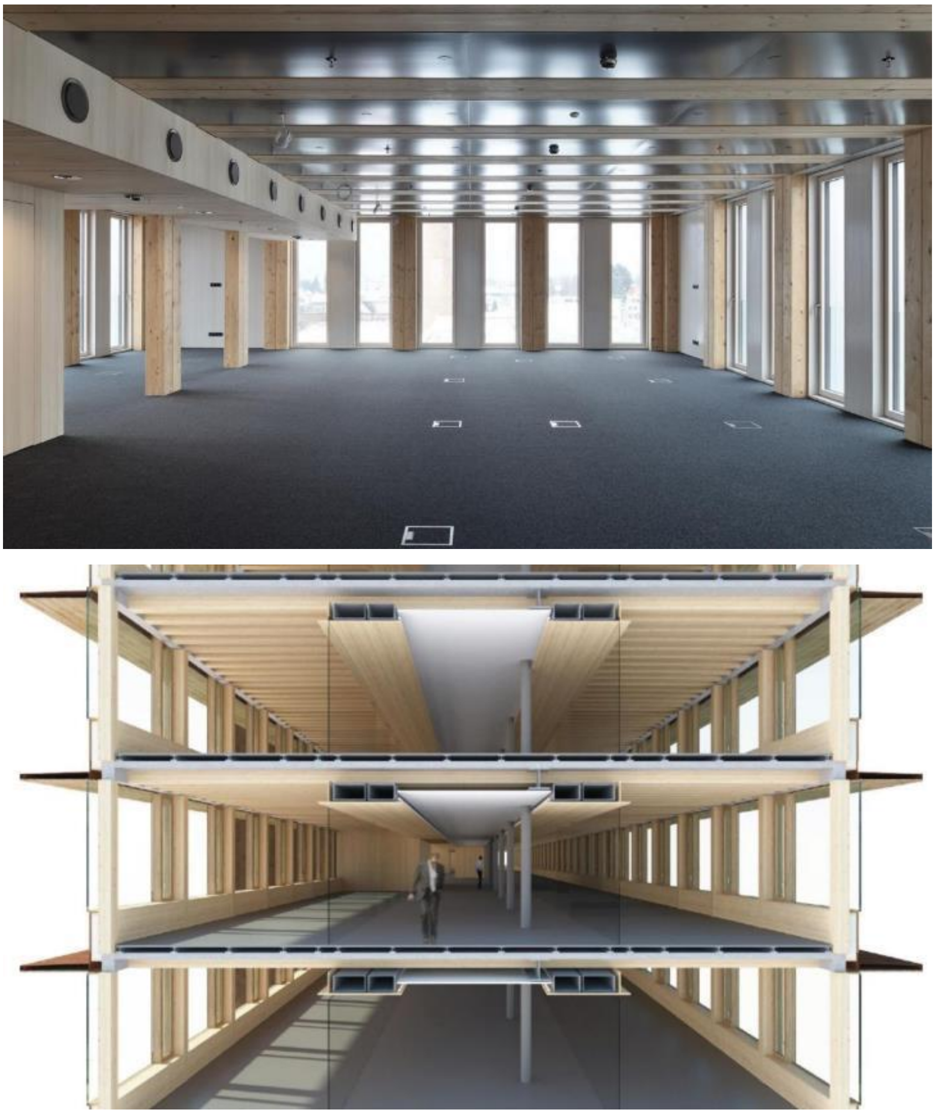


Figure 7.9 Illustration of position of installations channels in the LCTOne and IZM by CREE (www.creebuildings.com)

Due to the height of the glulam beams forming the ribs of the floor element, there is typically sufficient space to guide all necessary ventilation pipes, electric installations, heating and cooling units, or sprinkler systems. All these elements can be integrated with addition acoustic panels and already pre-installed in the factory, which reduces the installation time of site.

Figure 7.10 Examples of accessing the bays between the ribs of floor elements with various installations in the Arbo building and Suurstoffi S22.

In case the glulam beams of the ribs need to be crossed and penetrated, local holes can be added in case the degree of utilisation of the beam is low and serviceability criteria are governing. In these cases and together with adequate reinforcement, hole diameter of up to approx. 50% of the beam height may be achieved.

Figure 7.11 Examples of edge beams with holes for installations in the Arbo building.

7.7 Cost evaluation of alternative conventional systems

7.7.1 Hollow-core pre-stressed concrete solution

A widely used floor system for office and commercial buildings in the Swedish market is the pre-stressed hollow-core concrete solution. Different elements are available for different floor dimensions and demands. In the following cost example hollow core elements 120/27 with length of up to 12m are discussed. The weight of the elements is approx. 360 kg/m^2.

The costs for the production, installation, and finishing of these floor elements in a building are given in the following table:

Part and service	Costs	
Hollow-core concrete elements	650	SEK/m^2
Installation and assembly	250	SEK/m^2
Possible additional post-treatment	*150*	SEK/m^2
Total	900+*150*	SEK/m^2

The hollow core floor elements typically require an additional layer of screed on top in order to create a plane surface and diaphragm action of the floor. The floor layup can be chosen according to the requirements of the use.

From the example it can be seen that the costs of the floor made with hollow core elements is approx. only one third to half of the price of the TCC elements. Possible reasons for the difference are e.g.

- Higher degree of optimisation of the widely used hollow core elements
- Higher performance of the pre-stressed solution
- More optimised and lower production costs
- Lower material costs of the concrete
- Lower amount of material used per square meter floor

8 Summary

In the project, different aspects regarding TCC floor systems have been evaluated. The goal was to identify the potential for prefabricated TCC floor systems as a new standard floor solution for office and residential use. The following aspects have been considered in this analysis.

8.1 Technical solutions for TCC

A huge variety of different technical solutions exist for establishing composite action between timber and concrete in floor structures. These different solutions are partly optimised for different special applications. Some of these solutions are used for refurbishment of existing structures, other are more suitable for being used with massive wood panels. For prefabricated TCC floor systems a cheap and fast to install connector solution is sought, which provides a stiff connection between timber and concrete in order to maximise the composite action. Glued in web connections or notched solutions were identified as being most suitable.

8.2 Projects and companies

For establishing a prefabricated TCC floor solution in the Swedish market, the different actors from the timber industry, concrete industry, and the contractors have to join their forces. This collaboration can be formed in different ways with different activities and responsibilities of the different actors. In existing projects where TCC floor systems have been used at different scale, different production processes can be observed. A possible and suitable process has been identified where the TCC floor is produced by implementing the timber elements in the pre-cast concrete slabs in the factory of the concrete producer. These elements can be installed similar to conventional precast concrete floor elements.

8.3 Design

Currently there is not European standard specificying the design of TCC floor elements. Nevertheless, a Technical specification is about to be published and different other handbooks and guidelines exist in national level. Using this design guidance different possible TCC floor examples have been developed and studied. The governing limit states are mostly serviceability criteria such as deflections and vibration. The individual TCC floor can be optimised depending on the specific requirement in the individual construction project.

8.4 Costs evaluation

The costs for the production and installation of the TCC floor system were estimated and allocated to the different parties in the production and construction process. The example of the TCC floor system is currently estimated to be more than twice as expensive as a conventional prestressed hollow core system. Nevertheless, different optimisation potential can be identified with regard to materials saving, enhancement of the structural performance, easier production and assembly. When achieving all this optimisation potential, it can be expected that the TCC floor system is more competitive with conventional construction system in the Swedish market.

8.5 Further development

Besides further cost optimisation and enhanced of the building system as discussed by (Strauch 2015), some further need for development was discussed by (Jung 2015; Volk 2016) as follows.

8.5.1 Design and verification

A lot of research focused on the stiffness and strength of the shear connection between concrete and timber. However, the elastic and long-term material properties of the wood and of the concrete have much higher impact on the load-bearing and deformation behavior. In particular the modulus of elasticity, creep, shrinkage, and unintended height differences of the concrete have a considerable impact on the behavior of the floor panels. All these factors are commonly not precisely known and controlled in practice but are highly relevant.

8.5.2 Optimized connections to other components

Timber concrete composite floor systems have to be planned and design in combination with the connection to other components of the structure and building, such as the core, columns, ring beams, or façade elements. These connections can account for up to 30% of the costs per floor area.

8.5.3 Biaxial load-bearing behavior of timber concrete composite floor

Due to the requirements of sound insulation, the concrete layer must often be at least 120mm thick. This concrete layer carries and distributes the loads in the two directions along the floor span and transversally. Activating the load bearing action of floor elements e.g. when using CLT timber elements can lead to an optimized usage of the entire floor element.

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