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# COMPARATIVE LIFE CYCLE ASSESSMENT OF TIMBER-CONCRETE-COMPOSITE WALLS WITH CONCRETE AND CLT-WALL ELEMENTS

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**ABSTRACT:** In this study, Life Cycle Assessment of a new hybrid timber-concrete wall element was conducted. Furthermore, the results for the hybrid wall element were compared with the LCA results of a functional equivalent reinforced concrete wall element and a cross-laminated timber wall element. The thickness of the cross-section of the wall element (1 m² wall area) varied dependent on the applied load which was equal for every construction method. Modules A1-3, B4 as well as C1-4 and module D were considered. The results were analysed in terms of Global Warming Potential. The evaluation of the results indicated that, from an environmental impact point of view, the concrete-wall element is the least-reasonable option. The CLT wall element is the most suitable for small loads. However, with increasing load, a tipping point was reached. From this point on, the hybrid wall element showed lower environmental burden than the CLT wall element. This is because the thickness of the CLT used for the hybrid wall element and hence, its volume significantly increased compared with the volume of the hybrid wall element. Dependent on the applied load level, the difference in thickness among the cross-sections of the three construction methods can vary significantly.

**KEYWORDS:** comparative Life Cycle Assessment, hybrid construction element, timber-concrete wall

## 1 INTRODUCTION

In a completed research project, new hybrid timber-concrete wall elements were investigated by *Oberndorfer et al.* [1]. The wall elements consist of core lamellas in Ultra High Performance Concrete (UHPC) and exterior cross-laminated wooden lamellas. This composition should lead to a reduced use of concrete and at the same time, to a minimized component thickness compared to a Cross Laminated Timber (CLT) wall element. The reason for this is, that the combination of these two materials and their different properties enables an optimised utilisation for load-bearing purposes compared to CLT wall elements. [1]

The investigations of *Oberndorfer et al.* [1] focused on the force-fit adhesion of wooden lamellas to UHPC lamellas, showing promising results for a one-part polyurethane adhesive applied on a sanded UHPC lamella. In a follow-up research project, these hybrid CLT wall elements are now further investigated to evaluate their feasibility in practice. Thus, amongst other aspects such as hygrothermal behaviour and fire resistance, the environmental impacts of the wall elements are investigated.

To study the environmental performance of such wall elements, this article analyses the environmental impacts over their life cycle, in comparison with CLT and reinforced concrete (RC) wall elements dependent on the applied load.

By conducting a comparative assessment approach, the following research-questions should be answered:

- What are the environmental impacts of such hybrid CLT walls?
- What influence does the End-of-Life stage have on the results?
- Do these hybrid CLT walls have advantages over the environmental impact of common construction methods, such as reinforced concrete or CLT?

To enable prefabrication and the transport to the construction site, the focus is on wall elements. In this study, the term “wall” refers to wall elements.

## 2 BACKGROUND

### 2.1 Hybrid CLT walls

### 2.1.1 Composition of hybrid CLT walls

The investigated hybrid CLT wall resembles a common CLT wall. However, the core wooden lamella of the wall is replaced by an UHPC lamella (see Figure 1). This UHPC lamella can either be included continuously or, in the event of local load peaks, in an alternating way (see Figure 1).

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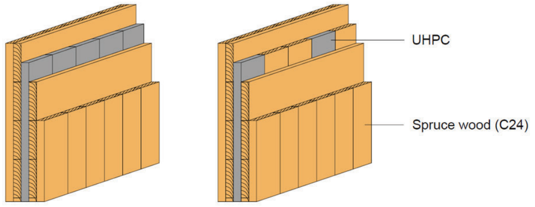

Hybrid CLT wall element with a continuous UHPC core

Hybrid CLT wall element with alternating UHPC lamellas

***Figure 1:*** *Exemplary composition of Hybrid CLT walls*

The advantage of UHPC is that it shows much higher compressive strength than commonly used concrete, leading to thinner elements in comparison to concrete elements [2]. A one-component polyurethane adhesive is used to bond the lamellas (not bonded on the narrow sides). For an optimised application of timber and concrete, the UHPC lamella mainly bears the compressive force, whereas the outer wooden lamellas bear both compressive and tensile forces resulting from bending.

### 2.1.2 Production of hybrid CLT walls

In this study, the production process described in *Oberndorfer et al.* [1] is considered (see Figure 2). The production of hybrid CLT walls within the scope of the research project was partly manually conducted. For future practical applications, it is intended to produce the hybrid CLT walls on an assembly line that is comparable to the assembly line of CLT. The UHPC lamellas can be manufactured precisely because they are dimensionally stable in the setting process and are then precisely ground to size. Therefore, the processing steps can be automated. The extent to which the energy input for automated production influences environmental impact will have to be further investigated in the future.

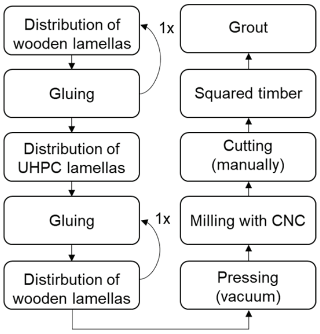

***Figure 2:*** *Production process of hybrid CLT wall according to [1]*

The production process is similar to that of CLT walls. To produce the hybrid CLT walls, the wooden lamellas are slightly longer than the UHPC lamellas. Hence, after pressing, the wooden lamellas are milled with a CNC mill and manually cut without damaging the blades. After this process, a squared timber is inserted on the narrow sides. A small gap between the wooden and the UHPC lamellas results, which is filled with grout. [1]

## 2.2 LCA of hybrid construction components and of UHPC

### 2.2.1 LCA of hybrid construction components

To investigate the environmental performance of complex construction components and to compare different construction methods, Life Cycle Assessment (LCA) can be applied [3].

In different studies [4,5], LCA of hybrid timber-concrete components was conducted. In these studies, only the production stage was investigated based on already existing product-datasets. However, for a holistic consideration, all life cycle stages should be considered [3], because, especially for hybrid structures, the End-of-Life stage influences the environmental impact results of the full life cycle [6].

According to the European waste directive [7] and in terms of resource conservation and avoiding emissions, reuse or high-level material recycling should be favoured, instead of final material recovery, energy recovery or disposal. In 2020, around 57 % of construction waste in Germany was used as recycling material for street and earth work, 16 % was used to produce asphalt and concrete, while the resting percentage was disposed or landfilled [8]. Moreover, approximately 80 % of waste wood in Germany is incinerated [9]. This shows that, for both concrete and construction wood, high-level recycling or even reuse as required by the European waste directive [7] is not yet broadly established in practice.

To enable the reuse or high-level recycling of construction products, separability into homogenous and identifiable materials must be given [10,11]. Hence, for hybrid timber-concrete construction components, it is necessary to ensure the separability of timber and concrete at End-of-Life to enable the recycling of the different materials [6]. Solutions such as deconstructable connectors for Timber-Concrete-Composite floors may ease separation [12]. Further, the adjustment of legislations is necessary to allow the use of secondary materials in new products [11].

### 2.2.2 LCA of UHPC

Several studies have been conducted to assess the environmental impacts and resource consumption of UHPC production [e.g. 12–14]. Additionally, standard UHPC mixtures with eventually more sustainable UHPC mixtures have been compared, for example, by partly replacing cement with blast furnace sly or fly ash [13]. The environmental performance of UHPC compared to common concrete is comparatively assessed by, for example, *Sameer at al.* [12] and *Ji et al.* [14]. The results show, that the environmental impacts of UHPC are much higher than of commonly used concrete related to a functional unit of 1 m³ [14]. This is mainly because less than 50 % of the amount of cement used in UHPC is necessary for the concrete [14]. For common German concrete C20/25, the cement production is responsible for 82 % of the global warming potential (178 kgCO2-eq./m³) and approximately 56 % of non-renewable primary energy consumption (912 MJ) of the concrete production [15]. This is significantly influenced by the deacidification process of limestone as well as the energy required for that process during the production of cement clinker [15,16]. Nevertheless, UHPC shows higher strength properties and hence, dependent on the boundary conditions such as geometry and load, smaller cross-sectional dimensions can be required for an UHPC element than for a common concrete element [13,17].

### 2.3 Functional equivalency in comparative LCA

For a comparative assessment of different construction components, a functional equivalent must be determined by defining the main functional requirements combined with the intended purpose of use [18,3]. In the study of *Kromoser and Holzhaider* [4] for example, for the comparison of different timber-concrete composite ceilings, the functional equivalent of load-bearing capacity was chosen. In other studies, the U-value of walls is taken into consideration, because outer walls and the secondary structure are considered [e.g. 10]. Nevertheless, it has to be mentioned, that according to the European Construction Product Regulation (EU CPR), construction products have to fulfil several basic requirements at once to ensure "[…] health and safety of persons involved throughout the life cycle […]" [19]. These requirements do not only include static and hygrothermal aspects, but also e.g. fire resistance, sound insulation, energy consumption, health aspects and sustainable resource consumption [19].

## 3 METHOD – GOAL AND SCOPE DEFINITION

### 3.1 GOAL

The aim is to conduct a life cycle analysis of the hybrid CLT walls in comparison with CLT and reinforced concrete walls. The comparison is intended to provide a comparative statement on the environmental performance of the walls in terms of the load-bearing capacity. In such way it should be investigated if the hybrid CLT wall brings advantages concerning the environmental impacts.

### 3.2 SCOPE

### 3.2.1 Product system

For the comparative life cycle assessment, walls in three different construction methods are evaluated: A hybrid CLT wall, a CLT wall and a reinforced concrete wall (see Figure 3)

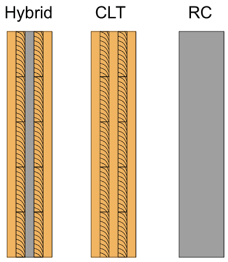

***Figure 3:*** *Vertical sections of the three studies product systems for the comparative LCA*

The hybrid CLT wall consists of lamellas equal to CLT-lamellas, but the core is replaced by ultra-high performing concrete (UHPC) lamellas. The number of layers can, equal to CLT, vary between three, five, and seven layers. In this study, the focus is only on 5 layered CLT and hybrid CLT walls, as this is a very commonly used composition in practice. This study considers a continuous UHPC lamella instead of accounting a squared timber and a specific amount of grout.

### 3.2.2 System boundaries and data

The LCA is conducted for the functional unit of 1 m² surface area of a wall. The thickness of the wall varies dependent on the applied load and is therefore part of the functional equivalent for the comparison.

For the assessment only *GaBi* Datasets with Germany as regional system boundary are considered.

The LCA covers the manufacturing stage A1-3 (A4-5 is neglected because of lacking data), as well as the deconstruction stage C1-4. The loads and advantages of recycling and recovery are separately shown outside the system boundary in module D [18]. An exchange of the primary load-bearing structure during the life cycle is not necessary (Module B4) because the secondary structure (e.g. insulation, cladding) is responsible for its durable protection during the life cycle. In this study, the consideration of the "full life cycle" refers to modules A1-3 (production stage), module B4 and modules C1-4 (End-of-Life stage).

This study does not consider material losses during production and waste treatment. Further, side streams during the production stage are assumed to be insignificant or are covered by the applied *GaBi* datasets. Moreover, concerning concrete and UHPC, it should be noted that the environmental benefits of carbonation during the life cycle are not considered in this research.

Concerning the consideration at End-of-Life, the instructions of DIN 15804 are followed [18]. The End-of-Life scenarios shown in Figure 4 are evaluated for the walls in different construction methods.

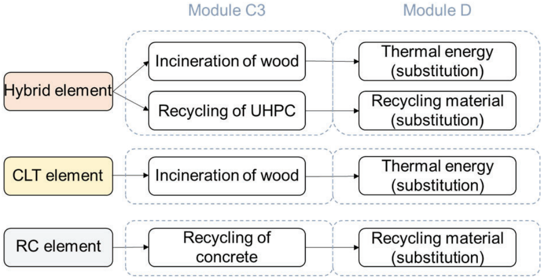

***Figure 4:*** *End-of-Life scenarios for the studied walls in different construction methods*

For the reinforced concrete wall, neither loads nor benefits are accounted for the steel in module C3, similar to the dataset for *ready-mixed concrete C20/25* of the *Ökobaudat* database [20]. Additionally, in the dataset, it is supposed that 25 % of the material is landfilled and 75 % of the inert material is further used as filling material e.g. for streets (substitution) [20]. In this research a

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simplified approach is used, assuming that 100 % of the inert material substitutes primary filling material.

For the CLT wall, a thermal recovery scenario is assumed. Hence, the environmental impacts due to the incineration of the wall are accounted in module C3 and only the benefits of the substitution of the recovered energy are accounted in module D.

For the hybrid CLT wall, a separation into wooden lamellas and UHPC-lamellas seems possible, because the two materials could be separated either by e.g. using an excavator to scrape off the wood or by using a mill or a saw to separate the wall. The milling or sawing is possible due to the very precise production of the hybrid CLT wall. In such way the thermal recovery of the wood as well as the treatment and use of the UHPC as filling material is seen as a realistic future scenario. Consequently, the assumptions and simplifications made for CLT and reinforced concrete are also made for the hybrid CLT wall.

### 3.3 Functional equivalent

Since the load-bearing capacity is the main functional requirement of the considered internal walls, this is the necessary functional equivalent for the comparison.

For this purpose, an equal load is applied to the walls of the different construction methods. This load is then linearly increased until the maximum load-bearing capacity of the walls is reached. The environmental impacts related to the resulting cross-sections of the walls should then give answers to the above-mentioned research questions. For the sake of simplicity, further basic functions required by the EU CPR [19], like fire safety or sound protection are neglected in this article. Moreover, the thermal conductivity is not part of the consideration, because this would be relevant for the assessment of external walls.

### 3.4 Impact indicators

To calculate information about the environmental impacts, the impact indicator climate change Global Warming Potential (GWP) is considered. As required in DIN EN 15804+A2 [18], the $GWP_{total}$ is separated into $GWP_{fossil}$, $GWP_{biogenic}$ and $GWP_{luluc}$ (land use and land use change). $GWP_{luluc}$ does not have to be declared when it contributes to less than 5% of the $GWP_{total}$ caused in the declared modules (module D excluded).

## 4 LIFE CYCLE INVENTORY

### 4.1 Variations of cross-sectional dimensions

To compare the environmental impacts of functionally equivalent walls in terms of their load-bearing capacity, an equal design load $F_d$ [kN] has been applied, as shown in Figure 2. By stepwise increasing the load, the cross-sectional dimensions of the walls of different construction methods change. Only five layered CLT and hybrid CLT walls were assessed. However, cross-sections of wooden lamellas with a longitudinal layer thickness of more than 40 mm consist of two adhered lamellas (see Figure 5). These seven layered walls were still considered, because the lamella orientation and consequently the load-bearing principle does not change.

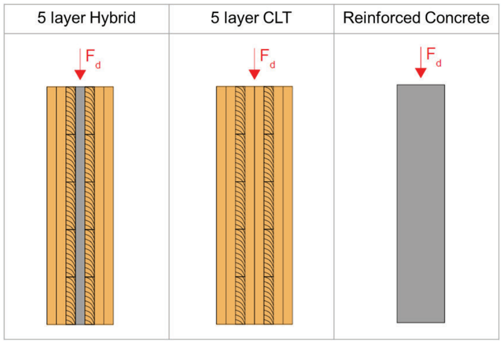

***Figure 5:*** *Vertical sections of the three different walls dependent on the construction method*

$F_d$ was stepwise increased by 100 kN/m considering a 1 m long wall. For dimensioning, a 3 m high hinged column was investigated. This leads to an imperfection of approximately 8 mm regarding 2nd order theory [21]. Fire safety was not included within the calculations.

The CLT and hybrid CLT walls were calculated according to shear-force analogy. All reinforced concrete walls were calculated according to DIN EN 1992-1-1:2011-01 [22]. Table 1 summarizes all strength values and further boundary conditions considered in the calculation.

***Table 1:*** *Boundary conditions for the calculation of the walls under a load increase in steps of 100 kN*

CLT

- CLT layers - strength class: C24

Hybrid CLT

- Separate wooden layers - strength class: C24
- UHPC lamella - strength values:

| | |
|---|---|
| Youngs modulus: | 45000 [MN/m²] |
| Shear modulus: | 19489 [MN/m²] |
| Compressive strength: | 132,5 [MN/m²] |

Reinforced concrete

- Exposure class: XC1
- Steel grade: S 355
- Strength class: C 25/30

To obtain functional equivalent results in terms of the load-bearing capacity, the aim was to consider the loads and respective cross-sectional dimensions with, at best, equal performance ratios. Since standard lamella thicknesses were used for the calculations, a performance ratio between 0.75 to 1.0 has been assumed as “equal”. For the reinforced concrete walls, a minimum thickness of 100 mm is required [22,23]. Nevertheless, in this study, a minimum thickness of 150 mm was considered to ensure the practical feasibility of mounting such walls and to compact the concrete despite the required minimum amount of reinforcement. Hence, due to the wall thickness of the reinforced concrete of 150 mm, the performance ratio is below 0.75 up to a load of 2100 kN.

Figure 6 exemplarily shows the results for different construction methods under increasing loads. Here, the thickness per 1 m² surface area, and hence, the volume of the different walls, is shown.

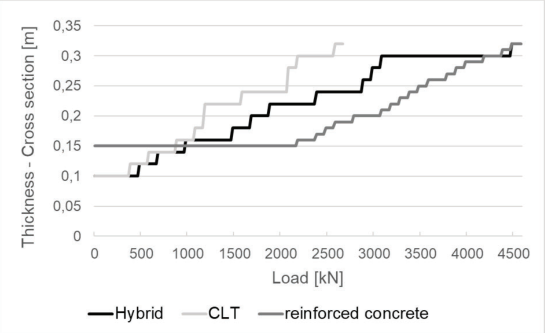

***Figure 6:*** *Wall thickness [m] dependent on the applied load for a hybrid CLT, a CLT and a reinforced concrete wall*

For a standard CLT wall with five layers, the maximum load is reached at 2600 kN (cross-section: 80-40-80-40-80). The hybrid CLT wall with five layers reaches a maximum possible load of 4500 kN. A further increase in the load would lead to larger CLT or hybrid CLT wall cross-sections, which are normally not available on the market. Therefore, no additional cross-sections are calculated for increased loads in the case of these two construction methods.

No such limitation regarding wall thickness exists when considering reinforced concrete. Therefore, the cross-sections for the reinforced concrete wall are shown for loads of up to 4600 kN. At load levels higher than 1000 kN, the cross-section of the reinforced concrete wall is constantly smaller than that of the CLT and the hybrid CLT wall. At 4400 kN, this changes and the cross-section of the reinforced concrete wall becomes ticker than that of the hybrid CLT wall. In this study, the strength class of the concrete is constantly set to C25/30. Under the same load, the use of a higher strength class could lead to thinner cross-sections. However, an equivalent volume of concrete with a higher strength class also has greater environmental impacts [15]. For simplification, the effect of this correlation on the environmental impact results for reinforced concrete, is not part of this study but should be further investigated in detail.

## 4.2 Production stage - LCI

### 4.2.1 UHPC lamellas - LCI and LCIA

To calculate the environmental impacts of a hybrid CLT wall, the environmental impacts of UHPC (raw density of 2.500 kg/m³) must be determined. For the LCA modelling of the UHPC, the walls and further background data, the *GaBi Software and Database for Life Cycle Engineering* (*GaBi*) from *Sphera Solutions* was used. The *GaBi* database does not provide any dataset for UHPC. Hence UHPC production had to be modelled.

The calculation of the environmental impacts of 1 m³ UHPC was based on a composition without reinforcing steel fibers, which has been used for the completed research project [1]. Additionally, the research results of *Sameer et al.* [12] for 1 m³ precast UHPC have been considered. The transportation distances as well as the consumption of fuel and electricity are calculated to produce 1 m³ of precast UHPC [12]. Similar to *Sameer et al.* [12], material losses during production are neglected in this consideration. Further, the formwork is not considered because, like for common concrete, it is assumed to have no significant impact due to the number of uses [24]. Moreover, the electricity and fuel consumption for the treatment of the UHPC lamella after stripping the formwork are neglected according to the cut-off criteria of DIN EN 15804 [18], because it is assumed, that they account for less than 5 % of the energy and resource inputs for UHPC production.

Figure 7 shows the $GWP_{fossil}$ results for 1 m³ UHPC in comparison with 1 m³ concrete C25/30. These results are used in the following sections to calculate the environmental impacts of the hybrid walls. Compared to the results for a concrete C25/30, the $GWP_{fossil.}$ of UHPC is nearly 60% higher.

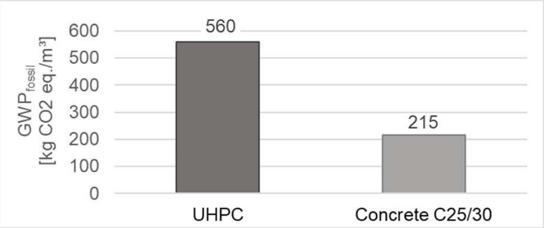

***Figure 7:*** *$GWP_{fossil}$ results for 1 m³ UHPC in comparison to 1 m³ concrete C25/30*

### 4.2.2 Hybrid CLT wall - LCI

To produce a hybrid CLT wall, the production steps described in the research of *Oberndorfer et al.* [1] are necessary. Table 2 lists the flows and processes required for the production stage of the hybrid CLT wall. Dependent on the cross-sectional dimensions of the wall and the corresponding thicknesses of the lamellas, the quantity of the input flows concerning the UHPC and the wooden lamellas varies.

***Table 2:*** *Input flows to produce 1 m² hybrid CLT wall*

| Input flow | quantity | Source |
|---|---|---|
| UHPC | *Varies [kg] | [*] |
| Wooden lamellas (adhesive included) | *Varies [kg] | [*] |
| Adhesive between UHPC and wooden lamellas | 0,34 [kg] | [1] |
| Truck transport | *Varies [tkm] | [**] |

*Dependent on applied load

**Dependent on amount of adhesive and UHPC-lamella thickness

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It is assumed that the production of the hybrid CLT wall takes place in a CLT-factory. As the hybrid CLT wall basically is a CLT wall with a different core lamella, the production process is supposed to be equal to the one of a CLT wall, except for the adhesion of the core UHPC-lamellas to the wooden lamellas. For 1 m² surface area, 170 g of adhesive was applied. Hence, both sides of the UHPC lamella require 340 g/m² [1]. As until now, the adhesion process is manually conducted, no further electricity or fuel is consumed.

Due to similar production steps and because the focus is on the comparison of the different construction methods, the data set being used for the CLT wall is used for the bonded lamellas of the hybrid CLT wall. Until now, the *GaBi* database does not contain any dataset for CLT. In the German database *Ökobaudat*, datasets for Glue Laminated Timber (GLT) and CLT can be found. These datasets are based on the findings of *Rüter and Diederichs* [25], who used *Gabi* for simulation. The dataset for modules A1-3 of 1 m³ GLT shows a slightly higher share of $GWP_{fossil}$ and a lower share of $GWP_{biogenic}$ than the dataset for 1 m³ CLT. This might result in slightly higher results for $GWP_{fossil}$ and lower results for $GWP_{biogenic}$. Hence, because the focus of this study is on the comparison of different walls, the dataset for GLT has been used.

### 4.3 Deconstruction stage - LCI

For the End-of-Life consideration, the deconstruction processes for the walls (module C1) as well as the transportation distances (module C2) are considered as equal for the three different construction methods.

For the demolition scenario, the findings of *Sameer et al.* [12], who focused on the demolition of precast UHPC, are taken into account. Due to lacking robust data for buildings, an average transport distance of 20 km from the demolition site to the waste treatment factory is considered.

For waste separation (module C3) of the hybrid CLT wall an electricity consumption for the milling process of 3,4 kWh/m² is assumed due to lacking robust data.

The benefits from the substitution of gravel as filling material with recycled concrete and the benefits of the energy substituted by the thermal recovery of wood are separately accounted in module D (see Figure 4).

## 5 ENVIRONMENTAL IMPACT ASSESSMENT AND COMPARISON

### 5.1 Production stage - LCIA

### 5.1.1 Hybrid CLT wall - LCIA

With increasing load steps, the UHPC lamella changes its thickness from 20 mm (0-1000 kN) to 40 mm (1000-3100 kN) to 80 mm (3100-4500 kN). Figure 8 presents $GWP_{fossil}$ and $GWP_{biogenic}$ of selected cross-sections. The cross-sections are selected at the minimum and maximum loads resulting in the three UHPC lamella thicknesses.

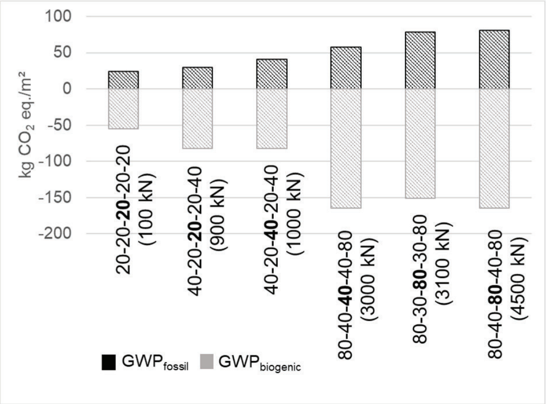

***Figure 8:*** *$GWP_{fossil}$ and $GWP_{biogenic}$ (modules A1-3) of 1 m² hybrid CLT wall for selected cross-sections at the corresponding minimum and maximum loads (UHPC lamella in* ***bold****)*

With increasing thickness of the cross-section, the $GWP_{fossil}$ increases. This is not only due to the increase in UHPC, but also due to the increasing amount of wood, because an increasing amount of these two materials requires higher process inputs. Moreover, $GWP_{biogenic}$ mainly depends on the overall thickness of the wooden lamellas. Looking at the cross-sections 80-40-40-40-80 (3000 kN) and 80-30-80-30-80 (3100 kN), the UHPC lamella becomes thicker and at the same time the total thickness of the wooden lamellas diminishes. As less carbon can be stored in the wooden lamellas, the $GWP_{biogenic}$ increases.

### 5.1.2 Comparison of different construction methods

Figure 9 exemplarily shows the results for $GWP_{fossil}$ for life cycle modules A1-3 for the different construction methods under increasing load steps. It must be mentioned that the reinforcement content of the reinforced concrete was constantly set to 4 %.

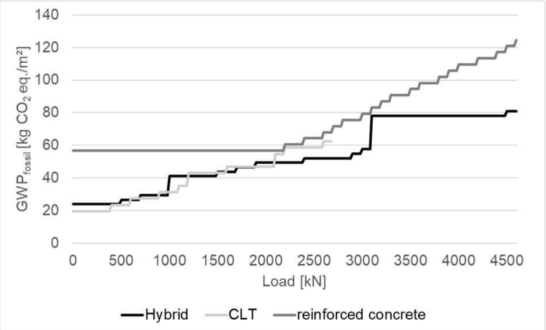

***Figure 9:*** *$GWP_{fossil}$ for 1 m² wall area (modules A1-3) for the different construction methods under increasing load*

The results indicate that, in general, the CLT and the hybrid wall have a lower environmental impact than the reinforced concrete wall. This is under small loads boosted due to the minimum thickness of the concrete wall of 150 mm. At 2100 kN, the $GWP_{fossil}$ of the CLT and reinforced concrete wall is nearly equal due to the difference in thicknesses of the walls. The thicknesses are directly related to the volume of the wall and hence, the amount of associated environmental impacts resulting from the corresponding production processes.

Until 2100 kN the CLT wall mostly performs slightly better than the hybrid wall. This is because of the comparatively low greenhouse gas emissions during the production processes of the CLT wall. As the environmental impacts of the CLT wall increase relative to the thickness (volume), the increase in the environmental impacts is higher than that of the hybrid CLT walls. Thus, at 2100kN, a tipping point is reached. From that point on, the hybrid CLT wall constantly shows lower environmental burdens than the CLT wall until the maximum carrying capacity of the CLT wall is reached.

As already shown in Figure 8, when the thickness of the UHPC-lamella changes from 20 to 40 mm (1000 kN) and from 40 to 80 mm (3100kN), a strong increase in the $GWP_{fossil}$ of the hybrid CLT wall results. When the UHPC lamella thickness turns to 80 mm, the $GWP_{fossil}$ of the hybrid CLT wall (300 m) nearly becomes as high as that of the reinforced concrete wall (220 mm). A further increase in the load does not change the cross-section of the hybrid CLT wall (300 mm) and hence, its environmental impacts. Simultaneously, the thickness of the reinforced concrete wall and consequently, $GWP_{fossil}$ increases.

To not only assess the $GWP_{fossil,}$, Figure 10 additionally shows the $GWP_{biogenic}$ of the walls for three selected load steps. $GWP_{luluc}$ is not shown, because it is responsible for less than 5 % of the $GWP_{total}$ caused in the considered modules.

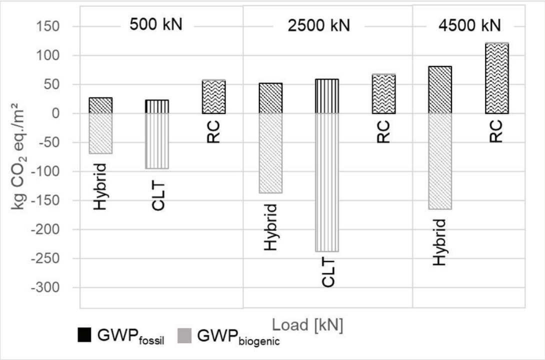

***Figure 10:*** *$GWP_{fossil}$ and $GWP_{biogenic}$ per 1 m² wall area (modules A1-3) of the different construction methods for three selected load steps*

$GWP_{biogenic}$ shows a negative value for both the CLT and the hybrid CLT wall. The reason for this is mainly the carbon stored inside the wooden lamellas during the life cycle. This biogenic carbon leaves the product system at End-of-Life in module C3. During the life cycle of a building the long-term storage of carbon might have a positive effect on counteracting climate change by contributing to cities as global carbon sinks [26].

## 5.2 End-of-Life - LCIA

To determine the influence of the End-of-Life stage, Figure 11 shows the $GWP_{fossil}$ and $GWP_{biogenic}$ results for the full life cycle as well as for module D (outside system boundaries) for a load level of 500 kN.

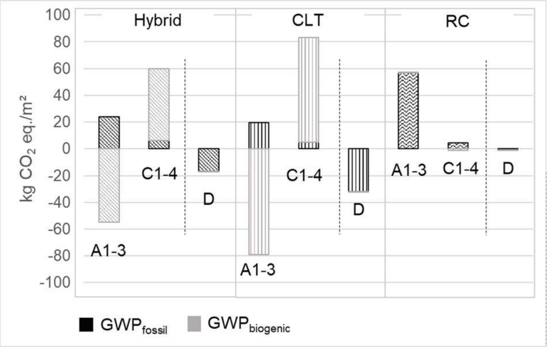

***Figure 11:*** *$GWP_{fossil}$ and $GWP_{biogenic}$ per 1 m² wall area for the full life cycle (modules A1-3, C1-4, D) of the three construction methods*

When considering modules A1-3 and C1-4, the $GWP_{biogenc}$ equals nearly zero, because the carbon stored in the wood is released at the end of the life cycle. This shows that fossil greenhouse gas emissions are dominant for all three walls. The highest share of $GWP_{fossil}$ for every construction method is caused in the production stage and the impact of the deconstruction stage in the case of the walls is comparatively low. For the hybrid CLT wall, the $GWP_{fossil}$ of modules C1-4 accounts for approximately 25 % of the $GWP_{fossil}$ of modules A1-3.

Looking at the benefits and losses outside the system boundaries makes clear that the benefits for the CLT due to the thermal recovery of the wood are the highest, followed by the hybrid CLT wall due to the thermal recovery of the lamellas. The replacement of primary material with recycled concrete at the End of Live brings only a very small amount of benefits. This shows that even if module D is considered separately, it may influence decisions when taking Circular Economy principles into account.

The dominant $GWP_{fossil}$ as well as the considerations of module D point out the importance of enabling separability and hence ensuring a high-level recyclability of the products.

# 6 CONCLUSION

The LCA results for the full life cycle indicate that, dependent on the load level and the resulting thicknesses, the use of hybrid CLT walls can show less greenhouse gas emissions and can be a structurally reasonable alternative to concrete and CLT.

Regarding $GWP_{fossil}$ for the production stage, the reinforced concrete wall constantly shows the highest greenhouse-gas emissions. Under small loads, the CLT wall emits the lowest greenhouse gases. At 2600 kN, the CLT wall reaches its carrying capacity. At 2100 kN a tipping point is reached and the hybrid CLT wall shows

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the lowest global warming potential. At even higher load levels, the hybrid CLT wall shows less environmental impacts than the concrete wall. The change in the thickness of the UHPC lamella in the hybrid CLT wall, has a significant influence on the global warming potential. When the thickness of the UHPC lamella changes from 40 mm to 80 mm, the $GWP_{fossil}$ of the hybrid CLT wall differs only slightly from that of the reinforced concrete wall. However, with further increasing loads, this difference increases again until the hybrid CLT wall reaches its carrying capacity. Applying only the UHPC lamella where high loads are expected (alternating), may lead to a decrease of the environmental impacts of the wall.

A consideration of $GWP_{total}$ or $GWP_{biogenic}$ only for the production stage could be misleading. because of the negative accounting of the biogenic carbon in the wood when entering the product system. The production stage of the hybrid CLT as well as the CLT wall seems to be carbon neutral or even positive, but when accounting for the benefits and loads resulting from the processes and especially from the biogenic carbon leaving the system boundary at End-of-Life, all three construction methods lead to greenhouse gas emissions. Nevertheless, further investigations on long-term carbon storage in buildings and their components should be conducted to explore this possible potential.

These carbon emissions during the life cycle and the End-of-Life considerations for all three construction methods show the necessity to bring solutions into practice that enable high-level recycling, or even reuse of the walls for further cycles instead of final disposal or incineration.

To improve the LCA results, background data, other impact indicators, different End-of-Life options, and practical deconstruction and separation trials of the hybrid CLT wall must be further researched. Dependent on the load level, the thicknesses of the walls can differ from 10 mm to more than 100 mm. The wall thickness is directly related to the volume. This aspect must be further evaluated.

For the comparison of construction components, this study highlights the importance of defining a robust functional equivalent for LCA comparisons dependent on the main functions of the component and the goal of the study. Here, only the load-bearing capacity was considered. To improve the validity of the results, it is further necessary, to consider not only the load-bearing capacity. For the functional equivalence of inner walls especially fire safety and sound protection play an important role. These requirements will be further considered in the ongoing research project as the focus is on the building level. In addition, for the comparison of external walls, thermal behaviour should be considered.

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