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Case study

A comparative study between glulam and concrete columns in view of design, economy and environment

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ABSTRACT

In this paper, it is attempted to study possible sustainability solutions for building structures. In this context, comparisons are made between two load-bearing columns with different building materials – glued laminated timber and concrete – with regard to structural design, economic consequences and the emission of greenhouse gases. In terms of structural design, the results show that with small axial forces, glulam columns will result in smaller cross-sectional areas compared to concrete columns. However, at larger axial forces, concrete columns will result in smaller cross-sectional areas than glulam columns. An increased column length also means larger dimensions for glulam columns, but this does not always apply to concrete columns. With respect to environmental impact, it is shown that using glulam columns is the more environmentally friendly option. From an economic point of view, the cost estimates for glulam and concrete columns may vary depending on the country and the abundance of the construction material. In Sweden, a forest-rich country, it is shown that the costs for both column types are quite similar considering small axial loads. At higher axial loading, concrete is generally the cheaper alternative.

1. Introduction

Sustainable development is a concept that integrates economic, social and environmental developments with a view that human well-being should be improved in the long run. The aim is to find a balance between these elements. In this context, buildings have an enormous environmental and economic impact. For example, buildings represent approximately 32% of total final energy consumption [1]. Moreover, the building sector was responsible for 38% of carbon dioxide emissions globally in 2019 [2]. Subsequently, building construction can play an important role to achieve sustainable development goals. A sustainable built environment may require integrating the environmental and economic consequences of the building elements into the structural design [3]. By optimising and choosing the most suitable construction material, the sustainable design of the building can be improved.

This article attempts to study the sustainability of building in view of construction materials, specifically wood and concrete. Concrete, as a composed material, consists of cement, lime and aggregates. As a construction material in buildings, concrete can have many advantages. The material is inexpensive and has good workability and durability, high compressive strength and good fire and sound resistance, and can be moulded into any desired shape. However, from an environmental point of view, the production of

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cement is responsible for approximately 7% of total global carbon dioxide emissions in 2018 [4]. Other disadvantages of concrete include the need for formwork, the long curing time, the possibility of cracks and the requirement for reinforcing with steel due to its low tensile strength. The other construction material is wood, which is becoming increasingly common for the construction of houses in forest-rich countries. Gulam (glued laminated timber) is an engineered wood product with relatively high strength, and consists of multiple individual layers (45 mm thick laminates) that are glued together under controlled conditions. The material can be used in beams and columns. In comparison to a solid wooden beam, glulam has higher structural strength and the probability of defects (e.g. large knots) occurring in the same cross-section of glulam is relatively small. The disadvantages of glulam as a construction material include vulnerability to water damage, fire, decay and biotic deterioration (e.g. fungi). With respect to environmental consequences, a structure made of wood instead of concrete can show a significant reduction in carbon dioxide emissions, since the finished construction will continue storing carbon dioxide during its life cycle.

It is worth pointing out that the current Covid-19 pandemic has relatively changed the world economy. A study by the UN has shown that an average general drop in the Index of Industrial Production (IIP) across countries [5]. Consequently, investigating and developing cost-effective and eco-friendly construction materials will yield multiple economic and environmental benefits since the economic and environmental consequences of the two materials can be compared.

With respect to only environmental aspects, Guo et al. [6] compared reinforced concrete and cross-laminated timber (CLT) structures in China and concluded that CLT construction has a higher energy saving than reinforced concrete in the severe cold region of China. Hill and Dibdiakova [7] compared the environmental impact of wood to commonly used building materials. Nässén et al. [8] compared buildings with concrete frames and wooden frames with respect to carbon dioxide emissions and total material, energy and carbon dioxide costs. Glover et al. [9] assessed the life-cycle for wood versus concrete and steel in house construction, and concluded that wood houses will require less energy in their manufacture, assembly and operation. With respect to economic consequences, Schneider [10] suggested a cost model to evaluate the construction cost of a multi-family building constructed using six different construction materials in USA. It was concluded that the cost associated with using a concrete construction material was less than the lightweight conventional wood frame construction cost, as estimated in May 2017.

With respect to comparison studies between different building materials that combine structural design, cost estimate and environmental consequences, a number of studies have been reported. Nkem et al. [11] compared concrete and timber in residential buildings in Nigeria and concluded that timber is an excellent material for residential buildings and moderate sized buildings compared to concrete. Hassan and Johansson [12] studied glued-laminated timber beams and steel beams in view of structural design and economic and environmental consequences, and concluded that glulam beams can be the best choice, especially with respect to the environment. In the same context, Hassan et al. [3] investigated cross-laminated timber and concrete slabs with respect to their impact on design, the environment and economy, and found that, from a sustainability point of view, cross-laminated timber floor construction can be a suitable alternative to concrete floor construction.

This paper attempts to study potential sustainability solutions for building structures. In this context, comparisons are made between two load-bearing columns with different building materials – glued laminated timber and concrete – with regard to structural design, economic consequences and the emission of greenhouse gases.

This present study attempts to examine the following questions:

1. How does the axial loading affect the structural design dimensions for a glulam column in comparison with a concrete column?

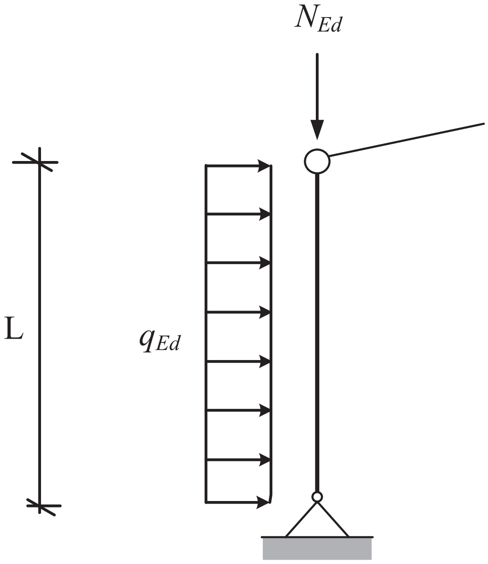

Fig. 1. Load-bearing column, simply supported at both ends.

2. What are the cost estimates of a glulam column in comparison with a concrete column?
3. With respect to environmental impact, what is the amount of the emissions of greenhouse gases, in terms of lifetime carbon dioxide equivalent emissions from the two columns?

2. Limitations

The structural design is analysed using Eurocode 2 [13] and Eurocode 5 [14]. In terms of structural design, the columns are simply supported loaded with the design wind load (q_{Ed}) and axial load (N_{Ed}) as shown in Fig. 1. The column lengths are taken as 3 m, 4 m and 5 m. The acting design axial loads on the columns are set at $N_{Ed} = 100$ kN, 500 kN and 1000 kN. The design moment occurs only around the strong axis (y-axis). Dynamic effects and design for fire will not be examined.

For the concrete column calculation, the concrete strength class (concrete grade) C30/37 is considered. The cement type is Portland cement and the water cement ratio (W/C) is 0.6. For the calculation of the second-order moment, only the stiffness method [13] is employed. For the reinforcing bars and stirrups, steel grade with K rating (K500C) is used. The exposure class of the concrete is XC1, and a service life of L50 is chosen. The effective creep ratio is set at $\varphi_{ef} = 2.0$. Moreover, links with diameter $\phi = 8$ mm and longitudinal steel bars with diameter $\phi = 12$ mm are used in accordance with the requirements of Eurocode 2 [13]. In the same context, the cover thickness is calculated as 28 mm (rounded to 30 mm) and the distance between bars in same layer and different layers is 20 mm. Ballast with a diameter (d_g) of 16 mm is assumed.

For wooden columns, a glulam with a typical strength class of GL30c is chosen with climate class 2.

The calculations for both column types are based only on the ultimate limit state (ULS) [13,14], which is required for the safety of the building. The serviceability limit state is not checked, since it is not often the decisive factor for the design of columns. Moreover, the loading on the two columns is chosen to represent typical action values in small to medium-sized residential buildings. Shear stresses are not explicitly controlled, as the shear forces due to wind loading are relatively small.

With respect to the environmental impact, the emission of greenhouse gases is only considered.

For the economic assessment, the material cost and the ready-to-assemble cost for each column type are based on the Swedish construction market. Logistics costs to the construction site are not covered in this study. For the concrete column, in-situ casting will be considered.

The comparison methodology involves analysing the effects of different axial loads and column lengths on the resulting structural design values, costs and lifetime carbon dioxide emissions.

3. Structural design

3.1. Loading actions

The columns are spaced at 6 m, centre to centre. The calculation of wind action is based on the requirements stated in Eurocode 1 [15]. The basic wind velocity is given as $v_b = 26$ m/s in an area with terrain category II. The characteristic value of the wind on the columns (kN/m.

^{2}) can be obtained as:

$$w_k = q_p(z)\bullet(\mathrm{c}_{\mathrm{pe},10} + \mathrm{c}_{\mathrm{pi},10}) \tag{1}$$

where q_p is the peak velocity pressure, z is the reference height for the pressure above the terrain (taken here as equal to column height), $c_{pe,10}$ is the pressure coefficient for the external pressure depending on the size of the loaded area (which is taken here as larger than 10 m^2) and $c_{pi,10}$ is the pressure coefficient for internal pressure. The peak velocity pressure q_p is calculated using the simplified table method as presented in Eurocode 1 [15]. The external and internal pressure coefficients are taken as $c_{pe,10} = 0.8$ and $c_{pi,10} = 0.3$ [15]. The design value of the wind load on the column may now be combined using the load combination, STR-B [15,16], and the partial safety factor, $\gamma_d = 1.0$, as:

$$q_{Ed} = 1.5W_k \tag{2}$$

For the column in Fig. 1, the design moment around the strong axis (y-axis) due to wind action, M_{Ed}, is consequently given by:

$$M_{Ed} = \frac{q_{Ed}L^2}{8} \tag{3}$$

3.2. Glulam column

All the following formulae are according to Eurocode 5 [14]. Columns subjected to combined bending and axial compression parallel to the grain (with risk of flexural buckling) can be controlled as:

$$\frac{M_{y,Ed}}{M_{y,Rd}} + k_m\frac{M_{z,Ed}}{M_{z,Rd}} + \frac{N_{c,Ed}}{N_{c,Rd,y}} \leq 1 \tag{4}$$

$$k_m\frac{M_{y,Ed}}{M_{y,Rd}}+\frac{M_{z,Ed}}{M_{z,Rd}}+\frac{N_{c,Ed}}{N_{c,Rd,z}}\leq 1 \tag{5}$$

where $M_{y,Ed}$ and $M_{z,Ed}$ are the maximum moments according to first-order theory about the principal y- and z-axes, respectively, k_m for rectangular section = 0.7, $M_{y,Ed}$ and $M_{z,Ed}$ are the design moment capacities about the principal y- and z-axes, respectively: $M_{y,Ed} = f_{m,y,d}W_y$ and.

$M_{z,Ed} = f_{m,z,d}W_z$, where $f_{m,y,d}$ and $f_{m,z,d}$ are the design bending strength about the principal y- and z-axes respectively and W is elastic bending stiffness. $N_{c,Ed}$ is the design normal force: $N_{c,Rd,y} = k_{c,y}Af_{c,0,d}$ and $N_{c,Rd,z} = k_{c,z}Af_{c,0,d}$, where $f_{c,0,d}$ is the design compressive strength along the grains and A is the cross-sectional area. Eq. (4) and Eq. (5) can be valid if $\lambda_{rel,y}$ and/or $\lambda_{rel,z} > 0.3$, where

$$\lambda_{rel,y}=\frac{\lambda_y}{\pi}\left(\frac{f_{c,0,k}}{E_{0,05}}\right)^{1/2};\lambda_{rel,z}=\frac{\lambda_z}{\pi}\left(\frac{f_{c,0,k}}{E_{0,05}}\right)^{1/2} \tag{6ab}$$

where $E_{0,05}$ is the modulus of elasticity parallel to the grain (5% value) of and $f_{c,0,k}$ is the characteristic compression strength along the grains.

The design compressive strength along the grains and the design bending strength can be expressed as:

$$f_{c,0,d}=\frac{k_{mod}f_{c,0,k}}{\gamma_M} \tag{7}$$

$$f_{m,d}=\frac{k_{mod}f_{m,k}k_h}{\gamma_M} \tag{8}$$

where γ_M is the partial factor for a material property (=1.25 for glulam), $f_{m,k}$ is the characteristic value of bending strength, k_{mod} is a modification factor taking into account the effect of the duration of load and moisture content, and k_h is a factor to take into account the volume effect, which can be expressed as:

$$k_h\leq\left\{\begin{matrix}(600/h)^{0.1}\\1.1\end{matrix}\right\} \tag{9}$$

where h is the depth of the bending member in mm and λ is the slenderness ratio expressed as:

$$\lambda_y=\frac{\beta L_y}{i_y};\lambda_z=\frac{\beta L_z}{i_z} \tag{10ab}$$

where i is the radius of gyration, L is column length and β is a factor which takes into account the support conditions, $\beta = 1$ for a simply supported column. The buckling reduction factors $k_{c,y}$ and $k_{c,z}$ can be expressed as:

$$k_{c,y}=\left[k_y+\sqrt{\left(k_y^2-\lambda_{rel,y}^2\right)}\right]^{-1};k_{c,z}=\left[k_z+\sqrt{\left(k_z^2-\lambda_{rel,z}^2\right)}\right]^{-1} \tag{11ab}$$

where

$$k_y=0.5\left(1+0.1\left(\lambda_{rel,y}-0.3\right)+\lambda_{rel,y}^2\right);\quad k_z=0.5\left(1+0.1\left(\lambda_{rel,z}-0.3\right)+\lambda_{rel,z}^2\right) \tag{12ab}$$

An additional control for the lateral-torsional stability [14] may be performed. In this case, the stresses may satisfy the following expression:

$$\frac{\sigma_{c,0,d}}{k_{c,z}f_{c,0,d}}+\left(\frac{\sigma_{m,y,d}}{k_{crit}f_{m,y,d}}\right)^2\leq 1 \tag{13}$$

where $\sigma_{m,d}$ is the design bending stress, $\sigma_{c,d}$ is the design compressive stress, $f_{c,0,d}$ is the design compressive strength parallel to grain, $k_{c,z}$ is given by Eq. (11b) and k_{crit} is a reduction factor due to lateral-torsional buckling. The relative slenderness for bending may be expressed as:

$$\lambda_{rel,m}=\sqrt{\frac{f_{mk}}{\sigma_{m,crit}}} \tag{14}$$

The critical bending stress, where $\sigma_{m,crit}$ for a rectangular section may be approximated as:

$$\sigma_{m,crit}\approx\frac{0.78b^2}{hl_{ef}}E_{0,05} \tag{15}$$

where l_{ef} is the effective length of the column, which may be taken here as approximately equal to actual column length. The quantity

k_{crit} can now be determined from the following expression:

$$k_{crit} = \left\{ \begin{array}{c} 1.0 \quad (\lambda_{rel,m} \leq 0.75) \\ 1.56 - 0.75\lambda_{rel,m} \quad (0.75 < \lambda_{rel,m} \leq 1.4) \\ \left(\lambda_{rel,m}^{2}\right)^{-1} (\lambda_{rel,m} > 1.4) \end{array} \right\} \tag{16}$$

3.3. *Concrete column*

All the following formulae are according to Eurocode [13]. The design strength values of the reinforced concrete can be written as:

$$f_{cd} = \frac{f_{ck}}{1.5}; \quad f_{yd} = \frac{f_{yk}}{1.15} \tag{17ab}$$

where f_{yk} is the characteristic yield strength of the steel bars and f_{ck} is the characteristic cylinder strength of the concrete. For concrete with strength class C30/37, $f_{cd} = 20$ MPa; the design modulus of the elasticity of concrete, E_{cd}, $= 27.5$ GPa. For steel grade K500C, $f_{yd} = 455$ MPa and the modulus of elasticity of reinforcement, $E_s = 200$ GPa.

The design criterion of a slender column can be simplified as:

$$M_{Rd} \geq M_{Ed}; M_{Rd} \geq N_{Ed}.e_0 \tag{18ab}$$

where M_{Ed} is the second-order moment, N_{Ed} is the ultimate design axial load and e_0 is the minimum eccentricity,

$$e_0 = h/30 \text{ but} \geq 20 \quad (mm) \tag{19}$$

where h is the height of the column cross-section, M_{Rd} is the design moment of resistance of the concrete column, which may be expressed as:

$$M_{Rd} = 0.8 \bullet f_{cd} \bullet \mathrm{x} \bullet \mathrm{b}(\mathrm{d} - 0.4\mathrm{x}) + \sigma_{\mathrm{s}}^{'} \bullet \mathrm{A}_{\mathrm{s}}^{'}(\mathrm{d} - \mathrm{d}^{'}) - \mathrm{N}_{\mathrm{Ed}}\left(\mathrm{d} - \frac{\mathrm{h}}{2}\right) \tag{20}$$

where x is the distance from the top of the column to the neutral axis, σ_s and $\sigma_s^{'}$ are the yield stress of the tension and compression steel, respectively, d and $d^{'}$ for a doubly reinforced rectangular section are the effective depth of the section, i.e. the distance from the top of the column to the centre of the area of the tension and compression steel, respectively, and b and h are the column (cross-section) height and width, respectively.

The yielding of tension steel can be controlled as:

$$\varepsilon_s = \frac{d - x}{x} \bullet \varepsilon_{\mathrm{cu}} \tag{21}$$

Accordingly σ_s can be obtained as:

$$\sigma_s = f_{yd}\ (\varepsilon_s \geq \varepsilon_{sy}) \text{ and } \sigma_s = E_s\varepsilon_s\ (\varepsilon_s < \varepsilon_{sy}) \tag{22}$$

where ε_{cu} is the ultimate strain of concrete $= 0.0035$ [13], ε_s is the steel strain in tension andε_{sy} is the design yield strain of the reinforcing steel in tension ($= f_{yd}/E_s$). The yielding of compression steel can be controlled as:

$$\varepsilon_s^{'} = \varepsilon_{cu}\frac{x - d'}{x} \tag{23}$$

Accordingly, $\sigma_s^{'}$ can be obtained as:

$$\sigma_s^{'} = f_{yd}\left(\varepsilon_s^{'} \geq \varepsilon_{sy}^{'}\right) \text{ and } \sigma_s^{'} = E_s\varepsilon_s^{'}(\varepsilon_s^{'} < \varepsilon_{sy}^{'}) \tag{24}$$

where $\varepsilon_s^{'}$ is the steel strain in compression and $\varepsilon_{sy}^{'}$ is the design yield strain of the reinforcing steel in compression ($= f_{yd}/E_s$). More basic details on the equilibrium equations (Eq. (20) to Eq. (24)) and diagrams of deformations and stresses can be found in Mosely et al. [17].

The minimum area of reinforcement for crack control may be expressed as:

$$A_s \geq 0.002A_c \tag{25}$$

where A_c is the area of concrete cross-section.

The effects of geometric imperfections on the load capacity of the concrete column must be considered. For isolated members at ULS, the effect of imperfections may be taken into account as:

$$e_i = \frac{l_0}{400} \tag{26}$$

where l_0 is the effective length, which for simplicity is taken as being equal to the actual length of the column. The first-order moment can be written as:

$$M_{0Ed} = M_{Ed} + N_{Ed} \bullet \mathrm{e_i} \tag{27}$$

The slenderness ratio can be expressed as:

$$\lambda = \frac{l_0}{i} \tag{28}$$

where i is the radius of gyration, $i = \sqrt{I_c/A_c}$, where I_c is moment of inertia and A_c is cross-sectional area of concrete. Allowable slenderness may be written as:

$$\lambda_{lim} = \frac{20 \bullet A \bullet B \bullet C}{\sqrt{n}} \tag{29}$$

where

$$A = \frac{1}{1 + 0.2\varphi_{ef}} \tag{30}$$

where φ_{ef} is the effective creep ratio.

$$B = \sqrt{1 + 2\omega} \tag{31}$$

where

$$\omega = \frac{A_s f_{yd}}{A_c f_{cd}} \tag{32}$$

If ω is unknown (as in the given case), $B = 1.1$ may be used.

$$C = 1.7 - r_m \tag{33}$$

where

$$r_m = \frac{M_{01}}{M_{02}} \tag{34}$$

where M_{01}, M_{02} are first-order end moments. As r_m is unknown, $C = 0.7$ may be used [13].

$$n = \frac{N_{Ed}}{A_c f_{cd}} \tag{35}$$

If $\lambda > \lambda_{lim}$, then the column is considered slender and so the second-order effects must be taken into account. It should be noted that in all the investigated cases, the columns are designed as slender. To account for second-order effects, the method based on nominal stiffness may be used [13]. The design second-order moment can thus be written as:

$$M_{Ed} = M_{0Ed} \left[1 + \frac{\beta}{(N_B/N_{Ed}) - 1}\right] \tag{36}$$

where

$$\beta = \frac{\pi^2}{c_0} \tag{37}$$

where c_0 is a coefficient related to the distribution of first-order moment. If the distribution is parabolic, as in the given case, then $c_0 = 9.6$ [13].

The buckling load may be calculated as:

$$N_B = \frac{\pi^2 EI}{{l_0}^2} \tag{38}$$

The nominal stiffness can be calculated as:

$$EI = K_c E_{cd} I_c + K_s E_s I_s \tag{39}$$

where

$$K_s = 0,\ K_c = \frac{0.3}{1 + 0.5\varphi_{ef}},\ \text{if}\ \rho = \frac{A_s}{A_c} \geq 0,01 \tag{40}$$

and

$$K_s = 1,\ K_c = \frac{k_1 k_2}{1 + \varphi_{ef}},\ \text{if}\ \rho \geq 0,002 \tag{41}$$

and

$$k_1 = \sqrt{\frac{f_{ck}}{20}} \tag{42}$$

$$k_2 = n\frac{\lambda}{170} \leq 0.2 \tag{43}$$

and

$$E_{cd} = \frac{E_{cm}}{1.2} \tag{44}$$

where E_{cm} is the mean value of elastic modulus. In Eq. (39), I_c and I_s are the moment inertia of the concrete and reinforcement, respectively. By calculating the second-order moment, the reinforcement area can be calculated using the column design charts as presented in Eurocode 2 [13].

The bending capacities of the concrete column may be evaluated by calculating the utilisation ratio (%):

$$\frac{M_{Ed}}{M_{Rd}} \leq 1.0 \tag{45}$$

4. Economy

The final cost of the two types of columns depends on the material design, logistics issues and employment rate. For the study, two cost estimates for the two types of column are considered: material cost and the ready-to-assemble cost (or labour cost), which includes the cost of assembly, formwork and mounting details. Tables 1 to 2 show the cost estimates of the two types of columns. Cost estimation for material and labour for concrete and glulam columns have been collected by contacting the local companies that manufacture and deliver these types of materials. The material and labour costs are estimated (average value) from the Swedish market in June 2021.

In general, there are a number of factors that can influence the price such as quantity, dimension, delivery and country. For instance, the price of constructing one column will not be the same if several columns are built in. Different dimensions mean different volumes, which means that the price for each dimension can be different. For example, the price of a glulam column with the dimensions 90×90×5000 is SEK 475; if, on the other hand, a column with dimensions 115×115×5000 is used, the cost will be SEK 815. The price is almost twice as much and can vary from supplier to supplier. The delivery of material to the required site also determines what the final price will be, as a longer distance means a higher price compared to a shorter distance.

5. Environment

The greenhouse effect occurs when a number of gases form a layer that prevents heat radiation from leaving the earth, leading to an increased average temperature. An increased greenhouse effect is a consequence of the fact that consumed goods and services emit more carbon dioxide, methane and nitrous oxide than nature can handle. To generalise the contribution of heating due to greenhouse gases, carbon dioxide equivalents will be used, i.e. each greenhouse gas has a global warming potential (GWP) for which the heating potential of carbon dioxide is used as a basis. Subsequently, the effect of greenhouse gases may be evaluated using CO_2 equivalents (CO_2e).

5.1. Glulam

Wood is a renewable material and plays an important role in all life on our planet, as it performs the chemical process of photosynthesis. It can capture and store carbon dioxide from the atmosphere. This process is called carbon sequestration and takes place

Table 1
Cost estimate of the glulam column.

	Unit	Material (SEK/unit)	Labour (SEK/unit)
Glulam	m^3	12,700	60
Mounting of the column base	Piece	1230	420
Underpinning	Piece	50	163

Table 2
Cost estimate of the concrete column.

	Unit	Material (SEK/unit)	Labour (SEK/unit)
Formwork	m^2	233	399
Concrete C30/37(pump/truck mixer)	m^3	1337	377
After treatment	m^2	5.5	42
Steel bars, ø12	m	22.5	26
Steel links, ø8	m	10	26
Triangular batten	m	12	21

while wooden constructions are in use, thereby creating what is called "negative emissions". When wood construction is completely used and needs to be demolished, the stored energy can be recovered. During energy recovery, wood is burned and the bound carbon dioxide that wood has stored during its lifetime is released into the air. Consequently, constructions built with timber products can effectively diminish the climate change caused by burning fossil fuels; see e.g. [18]. Glulam is an engineered wood product consisting of multiple laminates. The process of glulam production is energy efficient and does not result in much waste. The waste that occurs during the production of laminates can be chips and pellets, and these can be used for energy recovery, which in turn can reduce the need for fossil fuel. Subsequently, glulam will not have many negative environmental effects compared to other construction materials [19].

5.2. Input values

The quantity of CO_2e for the glulam column can be calculated as: [12].

$$CO_{2e} = X_g bhL\rho \quad (\text{kg}) \tag{46}$$

where ρ is the mean density of the glulam (kg/m^3) (expressed for the purposes of the study as $\rho = 480$ kg/m^3), b is the column width, h is its height (cross-section), L is the column length and X_g is the mean value of sequestration or emission (kg CO_2e/kg product). In this study, two values are considered: $X_g = -1.3$ [12], which is the average emission of carbon dioxide to the air from timber, including carbon storage, and $X_g = 0.43$ [12], which is the average emission of carbon dioxide to the air from timber, excluding carbon storage. These values can vary to some degree, depending on the production process. Emissions due to logistics will not be included here.

5.3. Concrete

The production of concrete results in large amounts of carbon dioxide emissions. During its lifetime, concrete absorbs carbon dioxide from the surroundings through a process called carbonation.

5.4. Input values

The quantity of CO_2e for the concrete column, the may be written as: [3].

$$CO_{2e} = X_c Lb\rho h \quad (\text{kg}) \tag{47}$$

where ρ is the mean density of concrete($\rho = 2400$ kg/m^3 for the study) and X_c is the mean value of emissions (kg CO_2e/kg product). In the same way as previously, two values are considered: $X_c = 0.2$ [3], which is the average emission of carbon dioxide to the air from concrete, including carbon storage, and $X_g = 0.22$ [3], which is the average emission of carbon dioxide to the air from concrete, excluding carbon storage. These values can vary slightly depending on the production process of concrete. As with glulam, emissions due to logistics will not be included.

6. Results

6.1. Structural design

Tables 3 to 4 present the design results for both columns, and Tables 5 to 6 present the utilisation ratios. Glulam and concrete have

Table 3
Dimensions of the concrete columns.

N_{Ed}	100 kN		500 kN		1000 kN	
L (m)	b x h (mm^2)	A_s (mm^2)	b x h (mm^2)	A_s (mm^2)	b x h (mm^2)	A_s(mm^2)
3	150 × 150	679	200 × 200	679	250 × 250	679
4	200 × 200	452	250 × 250	679	250 × 250	1810
5	200 × 200	905	250 × 250	1131	300 × 300	1131

Table 4
Dimensions of the glulam columns.

N_{Ed}	100 kN	500 kN	1000 kN
L (m)	b x h (mm^2)	b x h (mm^2)	b x h (mm^2)
3	115 × 180	190 × 225	215 × 360
4	140 × 225	215 × 270	215 × 405
5	165 × 225	215 × 315	215 × 540

Table 5
The utilisation ratios of the glulam columns.

$N_{Ed} = 100$ kN			
Length (m)	Eq. (13)	Eq. (4)	Eq. (5)
3	0.76	0.77	0.88
4	0.61	0.64	0.73
5	0.72	0.80	0.80
$N_{Ed} = 500$ kN			
Length (m)	Eq. (13)	Eq. (4)	Eq. (5)
3	0.78	0.88	0.87
4	0.66	0.73	0.75
5	0.77	0.70	0.87
NEd = 1000 kN			
Length (m)	Eq. (13)	Eq. (4)	Eq. (5)
3	0.8	0.81	0.84
4	0.84	0.76	0.89
5	0.84	0.58	0.89

Table 6
The utilisation ratios of the concrete columns, Eq. (45).

Length (m)	$N_{Ed} = 100$ kN	$N_{Ed} = 500$ kN	$N_{Ed} = 1000$ kN
3	0.64	0.63	0.61
4	0.93	0.58	0.57
5	0.81	0.94	0.91

completely different properties and are best suited to different purposes, so it was important in this comparison study to even out their differences and try to achieve a fair comparison by choosing appropriate dimensions. For reasons related to safety and cost-effectiveness, the utilisation rate (the ratio between current load and load-bearing capacity) is set in the study at 70–95%. To be closer to the safe side, a higher rate than 95% is not considered. A lower degree of utilisation means increased column dimensions, which in turn leads to unnecessary costs. Subsequently, the dimensions are optimised to maintain the utilisation ratio.

When designing concrete columns, reinforcement is an important factor that must be taken into account during the calculation so that no tensile forces will lead to a collapse or cracking of the concrete. Subsequently, it is also important to control the bending moment capacity, as this is crucial when designing concrete columns. However, compressive strength capacity alone is not as interesting as concrete is known for its high compressive strength, which is not the case for glulam columns. As shown in Table 1, an increased normal force and length of the column resulted in an increased column dimension in three out of nine cases. In the remaining six cases, the same column dimension could be used for different lengths and larger normal forces. Interestingly, the reinforcement area (A_s) of the column with $L = 3$ m is the same despite the different applied normal forces. This is because only the minimum area of

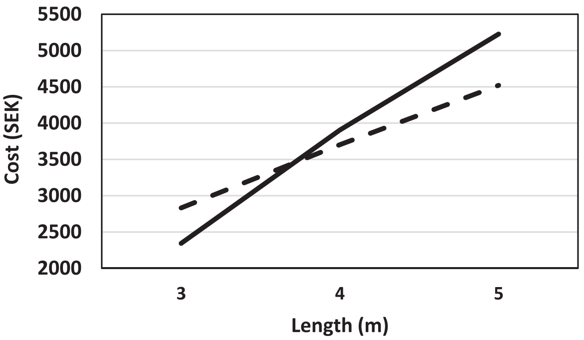

Fig. 2. Cost estimate for axial force, $N_{Ed} = 100$ kN. ▬ ▬ ▬, Glulam column; ▬▬▬▬, Concrete column.

reinforcement is required.

For glulam columns, an increased normal force leads to a relatively higher increase in the dimensions (Table 4) compared with the concrete column. In this context, the compressive force capacity plays a crucial role in the design compared to the bending moment capacity. Another important factor that should be considered when designing glulam columns is the later-torsional buckling. This phenomenon is not considered in the design of concrete columns, since in the latter case a typical concrete column resists the later-torsional forces. However, for the case investigated in this study, it is not observed that later-torsional buckling as inspected by Eq. (13) affects the dimensions of the glulam columns. Note that in some special cases, the effect of flexural-torsional buckling of timber columns may also be controlled for additional safety reasons [20].

6.2. Economy

The cost estimate (material costs and labour costs) for each material is presented in Fig. 2 to Fig. 4, where SEK is Swedish kroner. As can be seen in Fig. 2 and Fig. 3, the cost estimates for columns loaded with 100 and 500 kN do not deviate much. However, a glulam column is about SEK 400 more expensive than a concrete column with a length of 3 m. The cost estimate for the concrete column increases more than the cost of the glulam column with increasing length, and becomes more expensive at 4 m and 5 m. For columns loaded with 1000 kN, Fig. 4 shows that a concrete column is cheaper than a glulam column at 3 m in length, more expensive at 4 m and cheaper at 5 m. This is mainly due to the relatively large reinforcement area, which is required to satisfy the structural criteria for a cross-sectional area of 250 × 250, ultimately leading to an increased cost. Although concrete columns are cost-effective in this way, it should be noted though that a concrete column requires a longer production time than a glulam column. Additionally, a glulam column is lighter in weight than a concrete column and weighs about one sixth of a concrete column. This in turn affects the design of the building foundation and possibly the logistical costs. On the other hand, a typical concrete column may not require strict criteria to compensate for fire and acoustic issues compared with a glulam column. This in turn will reduce the total cost estimate for concrete.

6.3. Environment

The results are shown in Fig. 5 to Fig. 10. The emission of greenhouse gases as quantified by carbon dioxide equivalents are higher in the concrete than in the glulam. Glulam as a material for columns is a more environmentally friendly alternative than concrete columns under the same conditions, due to wood storing a lot of carbon dioxide, as indicated earlier. The difference between glulam and concrete columns can vary between 70 and 240 kg carbon dioxide equivalents (with carbon storage) at 3 m in length, and can be up to 570 kg at 5 m. However, it is worth pointing out that, from an environmental point of view, the concrete column has an advantage with respect to the reusability of the material. If a concrete column is demolished, the concrete can be reused as ballast and steel bars while the glulam column is rarely reused in practice. However, the wood residues can also be reused in energy recovery and the carbon dioxide that wood has stored then returns to the atmosphere, as shown in Fig. 5, Fig. 7 and Fig. 9, where carbon dioxide equivalent emissions are calculated excluding carbon dioxide uptake. By comparison, wood that excludes carbon storage is more environmentally friendly than concrete including carbon storage for the selected length ranges; emissions can vary between 20 and 50 kg of carbon dioxide at 3 m in length up to 110 kg at 5 m.

7. Concluding remarks

The sustainability of building structures is an increasingly an important issue to be considered in construction engineering. One way to achieve this is to integrate environmental and economic effects into the technical design of buildings.

Concrete can resist greater axial forces without the need to considerably increase the cross-sectional dimensions. On the other hand, the magnitude of axial forces affects the cross-sectional area of a glulam column more than a concrete column. Column length also plays a decisive role, as increased length will result in increased cross-sectional area for a glulam column, but this is not always the case for a concrete column. In this context, the glulam column is more sensitive to flexural buckling than the concrete column.

With respect to economic aspects, it is almost unfeasible to estimate the exact final cost for each column as factors such as delivery, quantity and supplier can mean different costs. Prices can differ significantly. The two columns do not vary much in price at axial loads of 100 kN and 500 kN. It is cheaper to build with concrete at a 3-metre column length, as the material cost is low compared to glulam. With columns of 4 or 5 m, it is cheaper to build with glulam as the labour cost for concrete will be high. As for the column, which is loaded with an axial load 1000 kN, it can be concluded that concrete is generally cheaper. Due to the short assembly time, a glulam column can, however, be efficient in the production, which in turn will have a positive impact on the construction economy and subsequently on society in terms of employment.

With respect to environmental consequences, it is found that glulam columns are the best choice regarding emissions of greenhouse gases. This is due to wood's ability to store carbon dioxide, and is thus more favourable when it stores more than what is emitted during the manufacture of a glulam column. The production of concrete (cement and steel) involves a lot of greenhouse gas emissions. Concrete stores carbon dioxide to some degree. However, concrete does not have the same carbon dioxide storage capacity as wood. Even if the glulam column is demolished and the wood is used for energy recovery, which leads to the stored carbon dioxide being released into the atmosphere again, the glulam will still be a more environmentally friendly alternative than concrete. On the other hand, as the concrete is dense and stores heat (high heat capacity), the energy consumption for the building can decrease with time. Unlike glulam, opportunities for reusing concrete are greater as the obsolete concrete can be reused either as aggregate or as a filler in the production of new concrete. This means that the use of obsolete concrete may also contribute to achieving environmental and

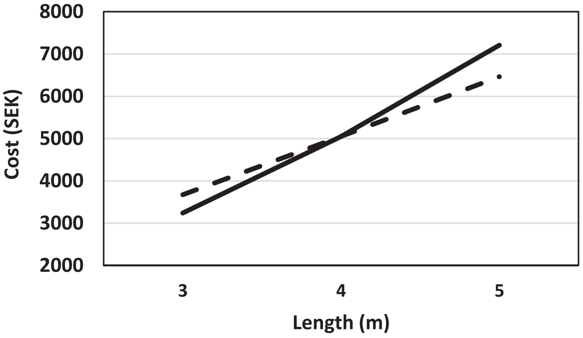

Fig. 3. Cost estimate for axial force, $N_{Ed} = 500$ kN. ▬ ▬ ▬, Glulam column; ▬▬▬▬▬, Concrete column.

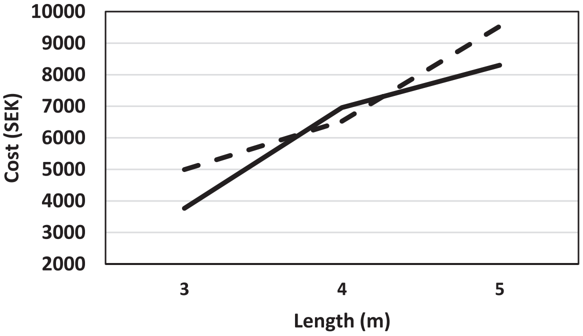

Fig. 4. Cost estimate for axial force, $N_{Ed} = 1000$ kN. ▬ ▬ ▬, Glulam column; ▬▬▬▬▬, Concrete column.

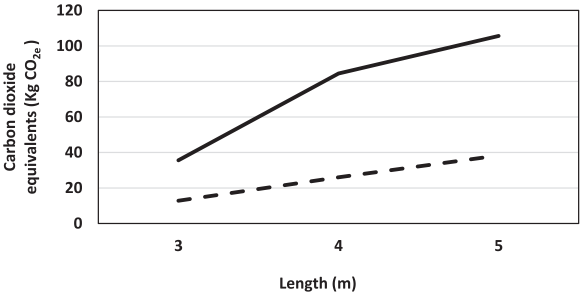

Fig. 5. Emission of carbon dioxide equivalents (without carbon storage) for axial force, $N_{Ed} = 100$ kN.▬ ▬ ▬, Glulam column; ▬▬▬▬▬, Concrete column.

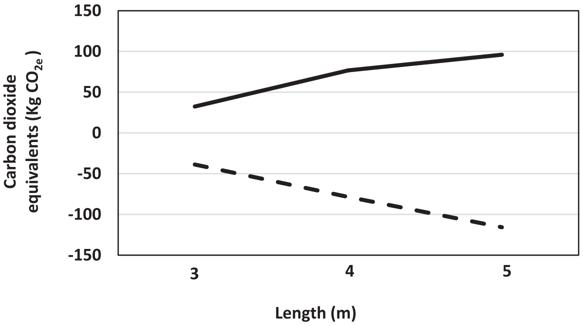

Fig. 6. Emission of carbon dioxide equivalents (with carbon storage) for axial force, $N_{Ed} = 100$ kN.▬ ▬ ▬, Glulam column; ▬▬▬▬▬, Concrete column.

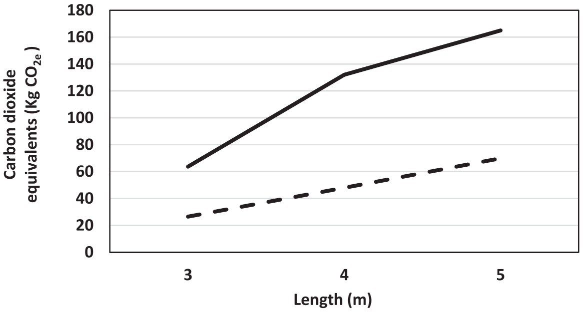

Fig. 7. Emission of carbon dioxide equivalents (without carbon storage) for axial force, $N_{Ed} = 500$ kN.■ ■ ■, Glulam column; ■■■■■, Concrete column.

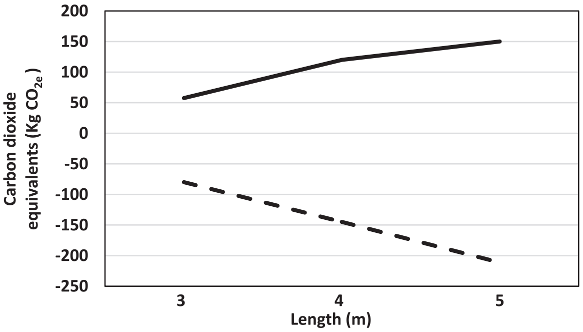

Fig. 8. Emission of carbon dioxide equivalents (with carbon storage) for axial force, $N_{Ed} = 500$ kN.■ ■ ■, Glulam column; ■■■■■, Concrete column.

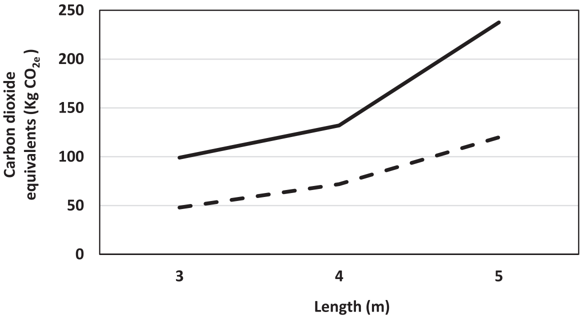

Fig. 9. Emission of carbon dioxide equivalents (without carbon storage) for axial force, $N_{Ed} = 1000$ kN.■ ■ ■, Glulam column; ■■■■■, Concrete column.

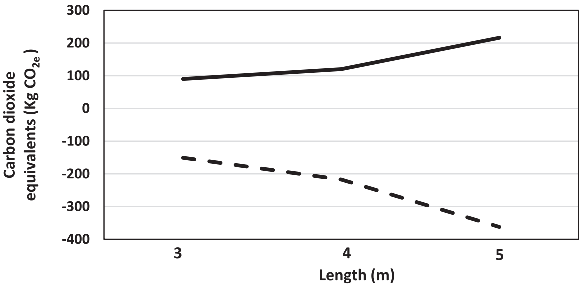

Fig. 10. Emission of carbon dioxide equivalents (with carbon storage) for axial force, $N_{Ed} = 1000$ kN.■ ■ ■, Glulam column; ■■■■■, Concrete column.

economic goals.

From a structural point of view, the glulam and concrete are usually used in wood structure and reinforced concrete structure respectively. They usually cannot replace each other in the design of a certain type of buildings. However, this study shows that wooden columns can effectively replace concrete columns in small to medium-sized residential buildings. In some cases, when there is a need for redesigning or renovating an existing building to provide better sustainable solutions, and the designers have the possibility to choose between the two materials, then the wood can be a better choice with regards to structural design, economic consequences and the emission of greenhouse gases.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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