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Optimum design of a welded steel box beam connected to timber floor parts

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Abstract

Buildings from steel frames and timber floors are innovative low cost structures. A welded steel box beam is connected to glued laminated timber (GLT) floor parts. In order to enable the smooth assembly, the box beam should be specially designed. Its bottom flange should be extended and 1/2V butt welds should be used between webs and flanges. The normal stresses and deflection of the simply supported composite beam are derived using the condition that the specific strains at the extreme fibre of the steel and timber parts should be equal. The dimensions of the box beam are optimized by using constraints on deflection, on local buckling of webs and on minimum cost.

Keywords: welded box beam, structural optimization, glued laminated timber floor, deflection constraint, welding cost

1 Introduction

The aim of the present study is to show the minimum cost design procedure for a welded steel box beam which is connected to structural timber parts. Such composite beams are used in buildings constructed with a steel frame and timber floors. Such buildings are used in some countries, since their innovative design can produce low cost structures.

In order to show the international research activity regarding timber structures, a short literature overview is given as follows.

Eurocode 5 [1] gives rules for the design of timber structures.

Harrington,J. et al. [2] have written a handbook as a good complement to Eurocode 5.

Mohammad et al. [3] have treated a seven-story CLT (Cross Laminated Timber) house investigated in a laboratory and an eight-story building under construction.

Van der Kuilen et al. [4] showed concepts for high-rise buildings with a concrete core and CLT floors and walls. A wall-floor-wall connection is realized with integrated tension bars.

Vilguts,A. et al. [5] treated design methods of CLT panels checked by experiments and FEM.

Glulam.co.uk [6] gives data for various GLT (Glued Laminated Timber) strength classes.

AS/NZ 1720 [7] New Zealand’s standard gives strength characteristics of GLT.

Firstly, the normal stresses and deflection of the simply supported composite beam are derived using the condition that the specific strains at the extreme fibre of the steel and timber parts should be equal.

Secondly, the dimensions of the box beam are determined by constraints on deflection, local buckling of webs and on minimization of the total cost. The cost function contents cost of material and welding.

2 Derivation of the formulae for the stresses and deflection of a composite beam

The maximum bending moment of a simply supported beam subject to a uniformly distributed normal load

$$M = \frac{pL^2}{8} \tag{1}$$

Considering also the self- mass of steel (index *s*) and timber (index *t*) part

$$p = \gamma p_0 + \left(A_w + 2A_f\right)\rho_s + A_t\rho_t \tag{2}$$

$$A_w = ht_w,\ A_f = b_1 t_{f1} = b_2 t_{f2} \tag{3}$$

are the cross-sectional areas of webs and flanges, resp. (Fig.1).
Normal stresses in steel and timber part

$$\sigma_s = \frac{M_s}{I_s}\frac{h}{2},\ \sigma_t = \frac{M_t}{I_t}\frac{h}{2} \tag{4}$$

Since the whole bending moment *M* has been divided by two parts

$$M = M_s + M_t \tag{5}$$

I_s and I_t are the moments of inertia, ρ_s and ρ_t are specific densities of the steel and timber beam parts.

The specific strains are equal for both beam parts

$$\varepsilon_s = \varepsilon_t\left(1 + \psi_f\right) \tag{6}$$

ψ_f is a coefficient of flexibility of the joint between steel beam and timber parts (Fig.1). For screwed joint this coefficient should be determined by experimental measurements.
Using the correlation between stresses and strains

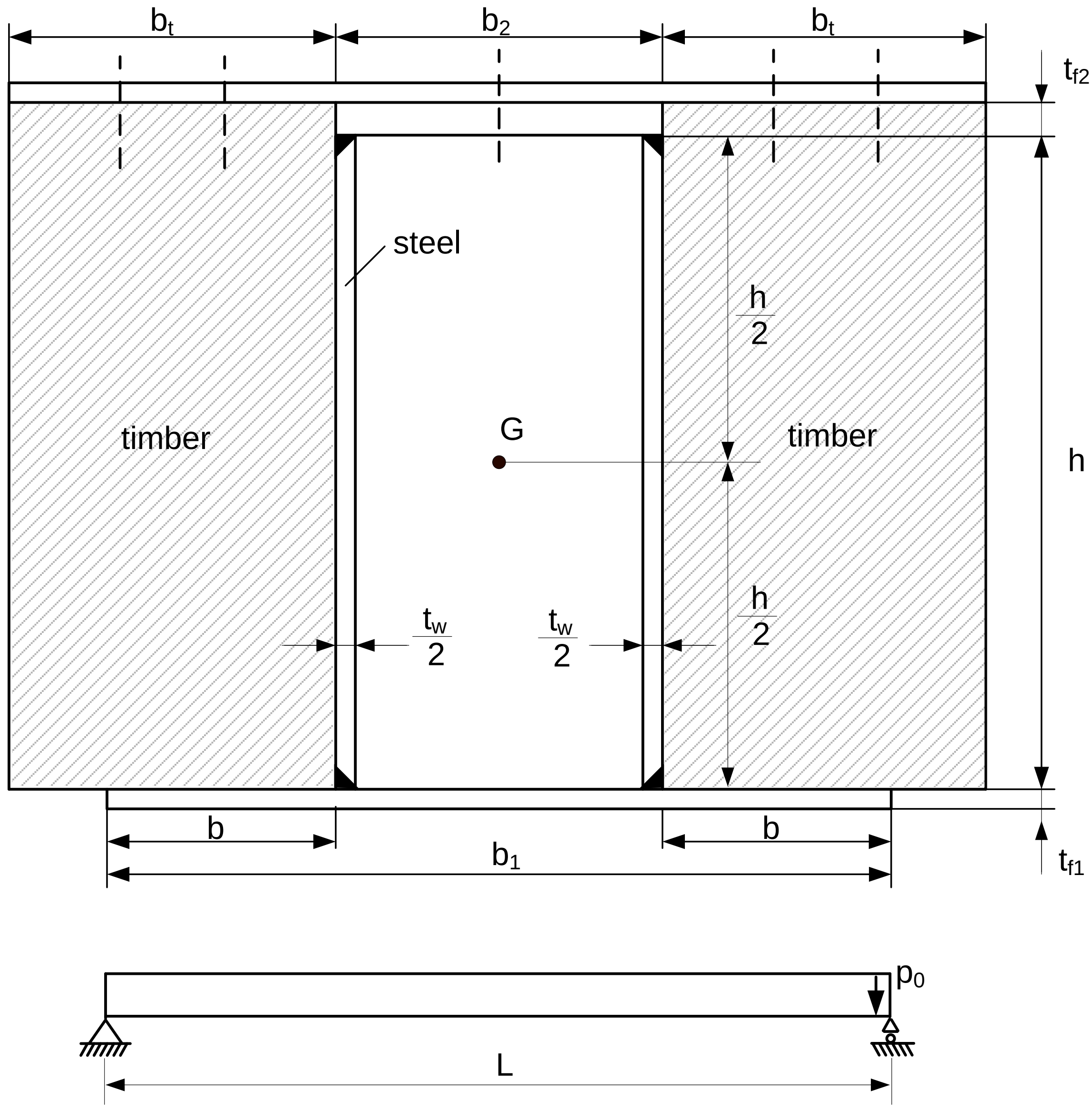

Figure 1. A simply supported beam of steel-timber composite cross-section

$$\varepsilon_s = \frac{\sigma_s}{E_s}, \;\; \varepsilon_t = \frac{\sigma_t}{E_t} \tag{7}$$

one obtains

$$\frac{M_s}{E_s I_s}\frac{h}{2} = \frac{M_t(1+\psi_f)}{E_t I_t}\frac{h}{2} \tag{8}$$

Using Eq.(5) we obtain

$$M_s = \frac{M(1+\psi_f)E_s I_s}{(1+\psi_f)E_s I_s + E_t I_t} \tag{9}$$

and

$$\sigma_s = \frac{M(1+\psi_f)E_s}{(1+\psi_f)E_sI_s+E_tI_t}\frac{h}{2}\,,\ \ \sigma_t = \frac{ME_t}{(1+\psi_f)E_sI_s+E_tI_t}\frac{h}{2} \tag{10}$$

and the maximum deflection considering only the live load

$$w_s = \frac{5p_0L^4}{48\left(E_sI_s+\frac{E_tI_t}{1+\psi_f}\right)} \tag{11}$$

3 Optimum design

3.1 Numerical data

Table 1 gives some data of GLT according to AS/NZ 1720 [7].

Table 1. Strength data for GLT in MPa

Class	Bending strength	Elastic modulus
GL 10	22	10000
GL 12	25	11500
GL 18	50	18500

Data for GLT (glued laminated timber) are taken from Table 1.

Class GL12 is selected for the calculation.

Admissible normal stresses

steel σ_{adms} = 355 MPa, timber σ_{admt} = 25 MPa

elastic moduli

steel E_s = 2.1x10^5 MPa, timber E_t = 1.15x10^4 MPa

specific densities

steel ρ_s = 7.85x10^{-6} N/mm^3, timber ρ_t = 0.8x10^{-5} N/mm^3

Dimensions of the composite beam (Fig.1) in mm

L = 4000, b = 150, b_t = 500, h = 600 (depends on the timber floor structure) intensity of the live load p_0 = 350 N/mm, safety factor γ = 1.5, coefficient of flexibility ψ_f = 0.1

3.2 Constraints

Stress constraints

$$\sigma_s \leq \sigma_{adms}\ ,\quad \sigma_t \leq \sigma_{admt} \tag{12}$$

Deflection constraint

$$w_s \leq w_{adm} = \frac{L}{200} = 20 \text{ mm} \tag{13}$$

Constraint on local buckling of the webs of the steel box beam according to Eurocode 3 (2009) [8]

$$\frac{t_w}{2} \leq \beta h\ ,\ \frac{1}{\beta} = 69\varepsilon\ ,\ \varepsilon = \sqrt{\frac{235}{\sigma_s}} \tag{14}$$

Since the local buckling constraint depends on σ_s , an iteration process is needed.

To calculate a symmetric box section the cross-section areas of the flanges should be equal

$$b_1 t_{f1} = b_2 t_{f2} \tag{15}$$

3.3 Unknowns to be optimized

$$t_w, b_1, t_{f1}, b_2, t_{f2} \tag{16}$$

In the calculation of w_s the cross-section areas of webs A_w=ht_w and flanges A_f = $b_1 t_{f1}$ are used, the moment of inertia with these areas

$$I_s = A_w \frac{h^2}{12} + A_f \frac{h^2}{2} \tag{17}$$

3.4 The cost function [9]

Cost of material

$$K_{Ms} = k_{Ms}\rho_{s1}A_s L\ ,\ k_{Ms} = 1.0\frac{€}{kg}\ ,\ \rho_{s1} = 7.85x10^{-5} \text{ kg/mm}^3 \tag{18}$$

$$A_s = A_w + 2A_f \tag{19}$$

Cost of welding using 4 SAW (submerged arc welding) 1/2V butt welds (Fig.2)

$$K_{ws} = k_{ws}\left(\Theta\sqrt{\kappa\rho_s A_s L} + 1.3x0.1559x10^{-3}a_w^2 4L\right) \quad (20)$$

Total cost to be minimized

$$K_s = K_{Ms} + K_{ws} \quad (21)$$

3.5 Optimum design procedure

The calculations show that the deflection constraint is active and the stress constraints are passive. Therefore the values of A_w and A_f are sought, which satisfy the deflection constraint.

The iteration begins with the selection of $\sigma_s = 355$ MPa. The iteration steps are shown in Table 2.

Table 2. Iteration steps to obtain t_w . Dimensions in mm and mm^2, stress in MPa

σ_s	β	t_w	$A_w = ht_w$	A_f	σ_s
355	0.018	21.375	12825	5250	143.3
143.3	0.011	13.581	8148	6050	143.0
143.0	0.011	13.567≈14	8400	6000	143.1

Note that the value of t_w does not change in the third step, therefore it is rounded to 14 mm.

The iteration process for t_w results in the following final values: t_w = 14, A_w = 8400, for this value to fulfill the deflection constraint A_f =6000, with these values w_s = 19.95 mm and $\sigma_s = 143.1$, from Eq.(14) t_w = 13.57, thus the final value is t_w =14 mm.

Finally, the value of b_2 is sought to minimize the total cost. In the present case four 1/2V butt welds are used between webs and flanges to enable the easy assembly of the timber parts. These welds minimize the cost, since the cost depends on a_w. In this case the total cost does not depend on the b_2. Thus, the following dimensions are used: b_2 = 300, t_{f2} = 20, b_1 = 600, t_{f1} = 10 mm.

The systematic search is performed using a MathCAD program.

Such optimum design process can be performed for other values of h depending on the floor structure.

4 Conclusions

The selection of the height of the GLT floor determines of the height of the welded steel box beam supporting the floor parts. The box beam's bottom flange should be extended, should have a sufficient thickness and the welds between webs and flanges should be 1/2V butt ones to enable the smooth assembly of the timber floor parts. To simplify the calculation the cross-sectional areas of the two flanges are taken to be equal.

In the optimization process the thickness of webs and four dimensions of the flanges should be optimized: The constraints on beam deflection, on local buckling of the webs and minimization of the beam total cost, which contains the material and welding cost.
The effect of the flexibility of the screwed joint between the steel and timber should be determined by experimental measurements.

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