Cost optimization of composite floors

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Abstract

The paper presents the cost optimization of composite floors. The composite structure consists of a reinforced concrete slab and welded steel Pratt trusses built up of hot rolled channel sections. The structural optimization is performed by the nonlinear programming (NLP) approach taking into account design constraints defined according to Eurocodes. A detailed objective function of the manufacturing material, power and labour costs is subjected to structural analysis constraints. In this way, the obtained optimal structural design satisfied the conditions of both the ultimate and the serviceability limit states. An example of the optimization of the composite truss floor system is presented at the end of the paper in order to show the applicability of the proposed approach.
Keywords: structural optimization, non-linear programming, composite structures, costs.

1 Introduction

The economy of construction is commonly handled in engineering practice by the time-consuming structural analysis of various design alternatives. In the conceptual design stage, the costs related with a change in the structural design are low. The possibilities of such a change to decrease (or increase) the costs in the construction stage are numerous. Since the significant cost savings may be obtained on account of effective conceptual design, the importance of accurate structural cost optimization cannot be overemphasized.

Over the last three decades, researches and engineers have mainly considered the cost optimization of composite structures from the viewpoint of the development and application of different optimization techniques [1–4]. Majority of the performed research works include simplified cost objective functions with fixed cost parameters.

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The paper presents the cost optimization of composite floor system. The composite structure consists of a reinforced concrete slab and welded steel Pratt trusses built up of hot rolled channel sections. The optimization is performed by the nonlinear programming approach, NLP. A detailed objective function of the manufacturing material, power and labour costs is defined for the optimization, Klanšek and Kravanja [5]. The cost objective function is subjected to structural analysis constraints. The design constraints are defined according to Eurocodes 1, 2, 3 and 4 [6–9] to satisfy the conditions of both the ultimate (ULS) and the serviceability (SLS) limit states. An example of the optimization of the composite truss floor is presented at the end of the paper in order to show the applicability of the proposed approach.

2 Composite trusses

The composite floor structure is constructed of a reinforced concrete slab and welded steel Pratt trusses consisting of hot rolled channel sections, see Figure 1.

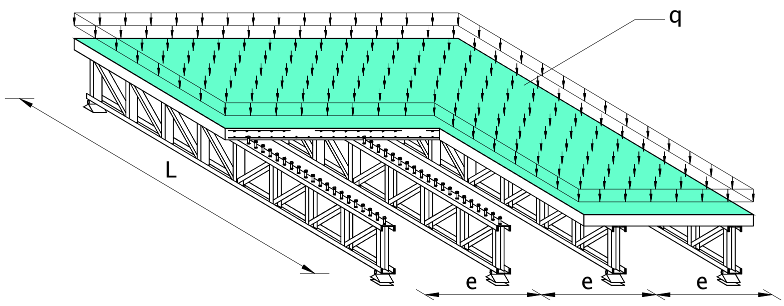

Figure 1: Composite trusses.

The full composite action between the concrete slab and the steel truss is achieved by the cylindrical shear studs, welded to the top chord of truss and embedded in concrete. The composite structure is designed according to Eurocode 4 [9] for both the ULS and the SLS conditions. The design loads are calculated with regard to Eurocode 1 [6]. The continuous spanning concrete slab is designed in view of Eurocode 2 [7]. The steel members are designed according to Eurocode 3 [8].

3 NLP optimization

3.1 NLP problem formulation

The structural optimization is performed by the nonlinear programming approach, NLP. The general NLP optimization problem is formulated as:

$$\text{Min } z = f(\boldsymbol{x})$$
$$\text{subjected to:}$$
$$\boldsymbol{h}(\boldsymbol{x}) = 0 \qquad \text{(NLP)}$$

$$\boldsymbol{g}(\boldsymbol{x}) \le 0$$
$$\boldsymbol{x} \in \boldsymbol{X} = \{\boldsymbol{x} \mid \boldsymbol{x} \in \boldsymbol{R}^n, \boldsymbol{x}^{LO} \le \boldsymbol{x} \le \boldsymbol{x}^{UP}\}$$

where $\boldsymbol{x}$ is the vector of the continuous variables, defined within the compact set $\boldsymbol{X}$. Functions $f(\boldsymbol{x})$, $\boldsymbol{h}(\boldsymbol{x})$ and $\boldsymbol{g}(\boldsymbol{x})$ are the (non)linear functions involved in the objective function z, the equality and inequality constraints, respectively. All the functions $f(\boldsymbol{x})$, $\boldsymbol{h}(\boldsymbol{x})$ and $\boldsymbol{g}(\boldsymbol{x})$ must be continuous and differentiable.

In view of the optimization of composite trusses, the continuous variables define dimensions, forces, stresses, strains, cost parameters, etc. The (in)equality constraints and the bounds of the variables represent a rigorous system of design, load, resistance and deflection functions known from the structural analysis. The objective function is proposed to minimize the structure's manufacturing costs.

3.2 Cost objective function

The optimal design of composite trusses is determined by the minimum of the manufacturing costs. In this way, the cost objective function is defined as:

$$\begin{aligned}\text{min: } Cost = \{ & C_{M,s,c,r} + C_{M,sc} + \sum_{i,j} C_{M,e_{i,j}} + \sum_{i,j} C_{M,ac,fp,tc_{i,j}} + C_{M,f} \\ & + \sum_{i,j} C_{P,c,hs_{i,j}} + \sum_{i,j} C_{P,c,gm_{i,j}} + \sum_{i,j} C_{P,w_{i,j}} + C_{P,sw} + C_{P,v} \\ & + \sum_{i,j} C_{L,c,hs_{i,j}} + \sum_{i,j} C_{L,g_{i,j}} + C_{L,p,a,t} + \sum_{i,j} C_{L,SMAW_{i,j}} + C_{L,sw} \\ & + \sum_{i,j} C_{L,spp_{i,j}} + C_{L,f} + C_{L,r} + C_{L,c} + C_{L,v} + C_{L,cc} \} / (e \cdot L)\end{aligned} \tag{1}$$

where $Cost$ [€/m^2] represents the manufacturing costs per m^2 of the useable surface; $C_{M,...}$, $C_{P,...}$ and $C_{L,...}$ are the material, power and labour cost items calculated in €; $\sum_{i,j}$ is the sum of all the truss element cost contributions; subscripts i, j are the end joints of a single truss member; e [m] is the intermediate distance between the trusses and L [m] is the span of the composite truss. The material, power and labour costs are defined in the next equations.

3.2.1 Material costs

Steel, concrete and reinforcement:

$$C_{M,s,c,r} = c_{M,s} \cdot \rho_s \cdot \sum_{i,j} A_{i,j} \cdot l_{i,j} + c_{M,c} \cdot d \cdot e \cdot L + c_{M,r} \cdot \rho_s \cdot A_s \cdot l_s \cdot L \tag{2}$$

where $c_{M,s}$ [€/kg], $c_{M,c}$ [€/m^3] and $c_{M,r}$ [€/kg] are the prices of the structural steel, the concrete and the reinforcement; ρ_s is the steel density 7850 kg/m^3; $A_{i,j}$ [m^2] and $l_{i,j}$ [m] are the cross-section area and the length of a single truss member; d [m] is the depth of the concrete slab; A_s [m^2/m^1] is the cross-section area of steel reinforcement per m^1 and l_s [m] is the length of the reinforcing steel.

Cylindrical shear studs:

$$C_{M,sc} = c_{M,sc} \cdot n_{sc} \tag{3}$$

where $c_{M,sc}$ [€/stud] and n_{sc} are the price and the number of cylindrical studs.

Electrode consumption, see Creese et al. [10]:

$$C_{M,e_{i,j}} = c_{M,e} \cdot \rho_s \cdot A_{w_{i,j}} \cdot l_{w_{i,j}} \big/ EMY \tag{4}$$

where $c_{M,e}$ [€/kg] is the price of the electrodes; $Aw_{i,j}$ [m^2] is the weld cross-section area; *EMY* is the electrode metal yield and $lw_{i,j}$ [m] is the weld length.

Anti-corrosion, fire protection and top coat paint:

$$C_{M,ac,fp,tc_{i,j}} = \left(c_{M,ac} + c_{M,fp} + c_{M,tc}\right) \cdot \left(1 + k_p \cdot k_{sur} \cdot k_{wc}\right) \cdot A_{ss_{i,j}} \tag{5}$$

where $c_{M,ac}$ [€/m^2], $c_{M,fp}$ [€/m^2] and $c_{M,tc}$ [€/m^2] are the prices of the anti-corrosion, the fire protection and the top coat paints per m^2 of painted surface; k_p, k_{sur} and k_{wc} are the paint loss factors which consider the painting technique, the complexity of the structure's surface and the weather conditions in which the structure is painted; $Ass_{i,j}$ [m^2] is the steel surface area of the truss member.

Formwork floor-slab panels:

$$C_{M,f} = c_{M,f} \cdot e \cdot L / n_{uc} \tag{6}$$

where $c_{M,f}$ [€/m^2] is the price of the formwork floor-slab panels per m^2 of the concrete slab panelling surface area and n_{uc} is the number, how many times the formwork panels may be used before they have to be replaced with the new ones.

3.2.2 Power costs

Sawing the steel section:

$$C_{P,c,hs_{i,j}} = c_P \cdot \left(P_{hs} / \eta_{hs}\right) \cdot k_{am} \cdot T_{c,hs} \cdot b_{i,j} \tag{7}$$

where c_P [€/kWh] is the electric power price; P_{hs} [kW] and η_{hs} are the machine power and the machine power efficiency of the hacksaw; k_{am} is the factor which considers the allowances to machining time; $T_{c,hs}$ [h/m] is the time for steel cutting and $b_{i,j}$ [m] is the overall web width of the truss member.

Edge grinding the steel section:

$$C_{P,c,gm_{i,j}} = c_P \cdot \left(P_{gm} / \eta_{gm}\right) \cdot k_{am} \cdot T_g \cdot l_{g\,i,j} \tag{8}$$

where P_{gm} [kW] and η_{gm} are the machine power and the machine power efficiency of the grinding machine; Tg [h/m] is the time of edge grinding and $lg_{i,j}$ [m] is the grinding length of the individual truss member.

Shielded metal arc welding, see Creese et al. [10]:

$$C_{P,w_{i,j}} = c_P \cdot \rho_s \cdot \left(I \cdot U / \eta_w\right) \cdot A_{w_{i,j}} \cdot l_{w_{i,j}} / DR \tag{9}$$

where I [kA] and U [V] are the welding current and the voltage; η_w is the machine power efficiency of the arc welding machine and DR [kg/h] is the deposition rate.

Stud arc welding:

$$C_{P,sw} = c_P \cdot \left(I_{sw} \cdot U_{sw} / \eta_w\right) \cdot n_{sc} \cdot T_{sw} \tag{10}$$

where I_{sw} [kA], U_{sw} [V] and T_{sw} [h/stud] are the current, the voltage and the time required for stud welding.

Vibrating the concrete:

$$C_{P,v} = c_P \cdot \left(P_v / \eta_v\right) \cdot T_v \cdot e \cdot L \tag{11}$$

where P_v [kW] and η_v are the power and the machine power efficiency of the concrete vibrator; T_v [h/m^2] is the time required for consolidation of the concrete.

3.2.3 Labour costs

Sawing the steel section:

$$C_{L,c,hs_{i,j}} = c_L \cdot k_{am} \cdot T_{c,hs} \cdot b_{i,j} \tag{12}$$

where c_L [€/h] denotes the labour cost per working hour.

Edge grinding of the steel section:

$$C_{L,g_{i,j}} = c_L \cdot k_{am} \cdot T_g \cdot l_{g_{i,j}} \tag{13}$$

Preparation, assembly and tacking of the steel structure to be welded:

$$C_{L,p,a,t} = c_L \cdot T_{p,a,t} \tag{14}$$

where $T_{p,a,t}$ [h] is the time for the preparation, assembling and tacking.

Manual shielded metal arc welding:

$$C_{L,SMAW_{i,j}} = c_L \cdot k_d \cdot k_{wp} \cdot k_{wd} \cdot k_{wl} \cdot k_r \cdot T_{SMAW} \cdot l_{w_{i,j}} \tag{15}$$

where k_d is the difficulty factor which reflects the local working conditions; k_{wp} is the factor which considers the welding position; k_{wd} considers the welding direction; k_{wl} considers the shape and the length of the weld; k_r considers the chamfering of the root of the weld; T_{SMAW} [h/m] is the time for manual shielded metal arc welding.

Semi-automatic stud arc welding:

$$C_{L,sw} = c_L \cdot T_{swp} \cdot n_{sc} \tag{16}$$

where T_{swp} [h/stud] denotes the time needed for stud welding, placing/removal of a ceramic ferrule and cleaning the connection.

Steel surface preparation and protection:

$$C_{L,spp_{i,j}} = c_L \cdot k_{dp} \cdot \left(T_{ss} + n_{ac} \cdot T_{ac} + n_{fp} \cdot T_{fp} + n_{tc} \cdot T_{tc}\right) \cdot A_{ss_{i,j}} \tag{17}$$

where k_{dp} is the difficulty factor related to the painting position; T_{ss} [h/m^2], T_{ac} [h/m^2], T_{fp} [h/m^2] and T_{tc} [h/m^2] are the times for the sand-spraying, the anti-corrosion resistant painting, the fire protection painting and the top coat painting of the steel surface, respectively; n_{ac}, n_{fp} and n_{tc} are the numbers of layers of the anti-corrosion resistant paint, the fire protection paint and the top coat paint.

Placing the formwork (panelling, levelling, disassembly and cleaning):

$$C_{L,f} = c_L \cdot T_f \cdot e \cdot L \tag{18}$$

where T_f [h/m^2] represents the time necessary for panelling, levelling, disassembly and cleaning a formwork.

Cutting, placing and connecting the reinforcement:

$$C_{L,r} = c_L \cdot \rho_s \cdot k_{rh} \cdot k_{ri} \cdot T_r \cdot A_s \cdot l_s \cdot L \tag{19}$$

where k_{rh} and k_{ri} are the difficulty factors related to the structural height and inclination of the concrete slab; T_r [h/kg] is the time required for the cutting, placing and connecting of the reinforcement.

Concreting the slab:

$$C_{L,c} = c_L \cdot T_c \cdot d \cdot e \cdot L \tag{20}$$

where T_c [h/m^3] represents the time for placement of the pumped concrete.

Concrete consolidation:

$$C_{L,v} = c_L \cdot T_v \cdot e \cdot L \tag{21}$$

Curing the concrete:

$$C_{L,cc} = c_L \cdot T_{cc} \cdot d \cdot e \cdot L \tag{22}$$

where T_{cc} [h/m^3] is the time required for the curing of the concrete.

For detailed interpretation and the values of the parameters see Reference [5].

3.3 Structural analysis constraints

The objective function is subjected to structural analysis constraints defined according to Eurocode 4 for both the ULS and the SLS conditions. The optimization model formulation and structural analysis constraints for the presented composite structure may be found in reference Klanšek et al. [11].

4 Numerical example

The paper presents the cost optimization of a 30 m long simply supported composite truss floor system, subjected to self-weight and the variable load of 3.5 kN/m^2, see Figure 2.

The material, power and labour cost parameters are shown in Table 1. The fabrication times and the approximation functions for the fabrication times are shown in Table 2 and Table 3. All other input data are listed in Table 4.

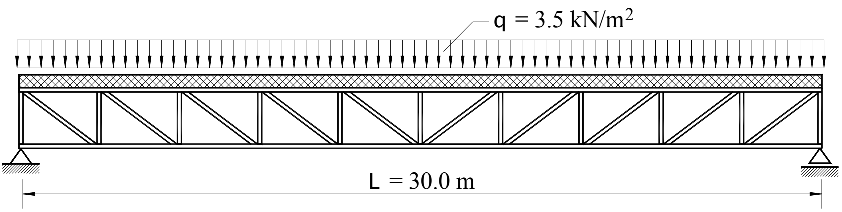

Figure 2: Composite truss system.

Table 1: Material, power and labour costs parameters.

$c_{M,s}$	Price of the structural steel S 235–S 355:	1.00–1.07	€/kg
$c_{M,c}$	Price of the concrete C 25/30–C 50/60:	85.00–120.00	€/m^3
$c_{M,r}$	Price of the reinforcing steel S 400:	0.70	€/kg
$c_{M,sc}$	Price of the cylindrical shear studs:	0.50	€/piece
$c_{M,e}$	Price of the electrodes:	1.70	€/kg
$c_{M,ac}$	Price of the anti-corrosion paint:	0.85	€/m^2
$c_{M,fp}$	Price of the fire protection paint (F 30):	9.00	€/m^2
$c_{M,tc}$	Price of top coat paint:	0.65	€/m^2
$c_{M,f}$	Price of the prefabricated floor-slab panels:	30.00	€/m^2
c_P	Electric power price:	0.10	€/kWh
c_L	Labour costs:	20.00	€/h

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Table 2: Fabrication times.

$T_{c,hs}$	Time for sawing the steel sections: 1.337 h/m
T_g	Time for edge grinding of the steel sections: 33.333×10^{-3} h/m
T_{sw}	Time for stud welding: 2.333×10^{-4} h/stud
T_v	Time for consolidation of the concrete: 0.200 h/m^2
T_{swp}	Time for welding/placing/removal of a ferrule/cleaning: 55.555×10^{-4} h/stud
T_{ss}	Time for sand-spraying: 0.050 h/m^2
T_{ac}	Time for anti-corrosion resistant painting: 0.050 h/m^2
T_{fp}	Time for fire protection painting: 0.050 h/m^2
T_{tc}	Time for top coat painting: 0.050 h/m^2
T_f	Time for panelling/levelling/disassembly/cleaning the formwork: 0.300 h/m^2
T_r	Time for cutting/placing/connecting the reinforcement: 0.024 h/kg
T_{cc}	Time for curing the concrete: 0.200 h/m^3

Table 3: Approximation functions for fabrication times.

$T_{p,a,t}$*	Time for preparation/assembling/tacking: $T_{p,a,t} = C_1 \cdot \Theta_d \cdot (\kappa \cdot \rho_s \cdot V_s)^{0.5}/60$ [h]; $C_1 = 1.0$ min/kg$^{0.5}$; $\Theta_d = 3.00$; $\kappa = 23$ elements; $\rho_s = 7850$ kg/m^3 and V_s [m^3]
T_{SMAW}	Time for manual shielded metal arc welding: Fillet welds: $T_{SMAW} = a_2 \cdot a_w^2 + a_1 \cdot a_w + a_0$ [h/m]; $a_2 = 1.2653\times10^{-2}$; $a_1 = 1.3773\times10^{-3}$; $a_0 = 1.6111\times10^{-2}$ and a_w [mm] ½ 60° V welds: $T_{SMAW} = b_6 \cdot a_w^6 + b_5 \cdot a_w^5 + b_4 \cdot a_w^4 + b_3 \cdot a_w^3 + b_2 \cdot a_w^2 + b_1 \cdot a_w + b_0$ [h/m]; $b_6 = -1.7138\times10^{-8}$; $b_5 = 1.7372\times10^{-6}$; $b_4 = -0.5576\times10^{-4}$; $b_3 = 4.1851\times10^{-4}$; $b_2 = 1.0805\times10^{-2}$; $b_1 = -0.7401\times10^{-1}$; $b_0 = 2.8286\times10^{-1}$ and a_w [mm]
T_c	Time for placement of pumped concrete: $T_c = c_2 \cdot d^2 + c_1 \cdot d + c_0$ [h/m^3]; $c_2 = 2.4000\times10^{-3}$; $c_1 = -5.4000\times10^{-2}$; $c_0 = 9.9500\times10^{-1}$ and d [cm]

* Fabrication time proposed by Jármai and Farkas [12].

The optimization was performed in two successive steps. The first step included the NLP optimization, where the continuous variables were calculated inside their upper and lower bounds. At this stage, the structure was fully exploited considering either ultimate or serviceability limit state conditions. In the second step, the calculation was repeated/checked for the fixed variables rounded up, from in the first stage obtained continuous values, to their nearest upper standard values. CONOPT (Generalized reduced-gradient method) was used for the optimization, Drud [13]. The obtained optimal structural design is presented in Figures 3 and 4.

The optimal result of 7329.57 € per single composite truss (or 87.26 €/m^2 of useable floor surface) was obtained in the second NLP stage. The optimal steel sections are listed as follows: top chord (UPE 270) bottom chord (UPE 270); diagonals D_1 (UPE 160), D_2 (UPE 140), D_3 (UPE 120), D_4 (UPE 100), D_5 (UPE 100); verticals V_1 (UPE 160), V_2 (UPE 160), V_3 (UPE 140), V_4 (UPE 120), V_5 (UPE 100), V_6 (UPE 100).

Table 4: Input data.

ρ_s	Steel density: 7850 kg/m^3
ρ_c	Concrete density: 2500 kg/m^3
EMY	Electrode metal yield: 0.60
k_p	Paint loss factor–painting technique: 0.05 brush painting
k_{sur}	Paint loss factor–complexity of the structure: 1.00 large surfaces
k_{wc}	Paint loss factor–weather conditions: 1.00 brush painting
n_{uc}	Number, how many times the formwork floor-slab panels may be used: 30
k_{am}	Factor–allowances to machining time: 1.09 machining process
P_{hs}	Power of the hacksaw: 2.20 kW
η_{hs}	Machine power efficiency: 0.85 hacksaw
P_{gm}	Power of the grinding machine: 1.10 kW
η_{gm}	Machine power efficiency: 0.85 grinding machine
I	Welding current: 230 A
U	Welding voltage: 25 V
η_w	Machine power efficiency: 0.90 arc welding machine
DR	Deposition rate: 3.7 kg/h
P_v	Power of the internal vibrator ø 48 mm: 3.10 kW
η_v	Machine power efficiency: 0.85 internal concrete vibrator
k_d	Difficulty factor–working conditions: 1.00 normal conditions
k_{wp}	Difficulty factor–welding position: 1.00 flat, 1.10 vertical and overhead
k_{wd}	Difficulty factor–welding direction: 1.00 flat position and vertical welds
k_{wl}	Difficulty factor–welding length: 1.00 long welds
k_r	Difficulty factor–root of the weld: 1.00 welds without treatment of root
k_{dp}	Difficulty factor–painting position: 1.00 horizontal painting
k_{rh}	Difficulty factor–structural height: 1.00 structural height less than 6 m
k_{ri}	Difficulty factor–inclination of the concrete slab: 1.00 horizontal slab

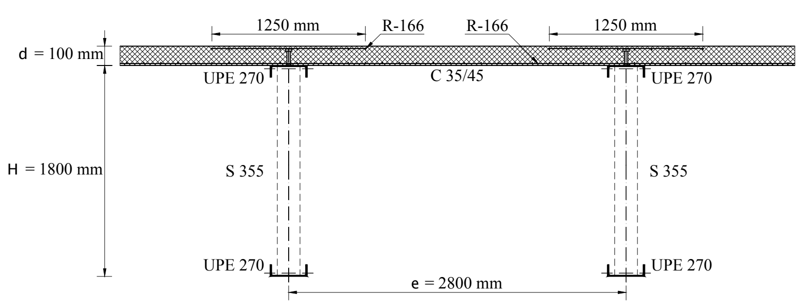

Figure 3: Optimal design of composite trusses.

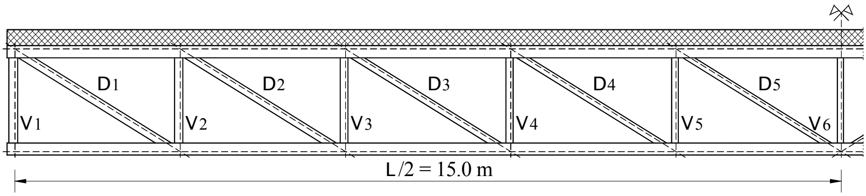

Figure 4: Arrangement of steel truss members.

5 Conclusions

The paper presents the cost optimization of composite floor system. The composite structure consists of a reinforced concrete slab and welded steel Pratt trusses built up of hot rolled channel sections. The optimization is performed by the nonlinear programming approach, NLP. A detailed objective function of the manufacturing material, power and labour costs is subjected to structural analysis constraints.

The use of modern optimization techniques essentially improves the economical efficiency of structural design of the composite floor systems.

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