UDC 338.58:519.8:624.016
Original scientific paper
Received: 20.07.2006.

Manufacturing cost optimization of composite floor trusses

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SUMMARY

This paper presents the manufacturing cost optimization of composite floor trusses. The composite floor trusses are designed to be built up of a reinforced concrete slab and steel trusses consisting of cold formed hollow sections. The optimization was performed by the nonlinear programming approach, NLP. An accurate objective function of the manufacturing material, power and labour costs was developed and applied for the optimization. Composite floor trusses were optimized according to Eurocode 4 for the conditions of both the ultimate and the serviceability limit states. A numerical example of the manufacturing cost optimization of a composite floor truss system, presented at the end of the paper, shows the applicability of the proposed approach.

Key words: *structural optimization, nonlinear programming, composite floor trusses, welded structures, manufacturing costs.*

1. INTRODUCTION

Traditional engineering methods for the cost effective structural design are based on trial-and-error procedure. This way, the economy of construction is achieved in 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. Alongside the structural design, the most important factors influencing the economical construction are the location conditions, construction technology and materials [1]. 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 [2–5]. Majority of the performed research works include simplified cost objective functions with fixed cost parameters. The cost optimization of cable-stayed bridges with composite superstructures is presented in Ref. [6]. The defined cost objective function includes concrete, structural steel, reinforcement, cable stays and formworks costs. The optimization of composite floors, presented in Ref. [7], was carried out by an employment the cost objective function, which contained the costs of concrete, steel beams and shear studs. The optimization based comparison between composite I beams and composite trusses, introduced in Ref. [8], was accomplished by using the fixed cost parameter based objective functions, which comprised the costs of concrete, structural steel, reinforcement, shear studs, anti-corrosion paint, fire protection paint F 30, sheet-steel cutting costs, welding costs and the costs of the formworks.

This paper presents an approach to the manufacturing cost optimization of composite floor trusses, built up of a reinforced concrete slab and steel trusses consisting of cold formed hollow sections. In this way, an accurate objective function of the structure's manufacturing costs was developed and applied. The proposed objective function is defined as a multitude of the material, power consumption and labour cost items, required to handle all the necessary manufacturing costs of the composite trusses. The proposed objective function provides the engineer a complete and detailed insight into the manufacturing cost distribution of the obtained optimal structural design. It should be noted that the engineering, amortisation, transportation, erection, overhead, and maintenance costs, the costs of scrap as well as other expenses are not considered in the scope of this paper. The structural optimization was performed by the nonlinear programming (NLP) approach taking into account design constraints defined according to Eurocodes [9–12]. A numerical example of the manufacturing cost optimization of a composite floor truss system with the span of *30 m* is presented at the end of the paper in order to show the applicability of the proposed approach.

2. COMPOSITE FLOOR TRUSSES

The composite floor truss system is proposed to be built up of the reinforced concrete slab of constant depth and steel Pratt trusses with tension diagonals, see Figure 1. The trusses consist of cold formed square and circular hollow sections, see Figure 2. The bracing members and chords are connected together by the fillet welds. The full composite action between the concrete and the steel parts of the cross-section is achieved by the cylindrical shear studs, welded to the top chord of truss and embedded in concrete.

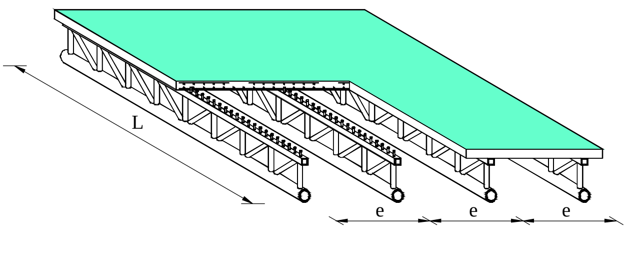

Fig. 1 Composite floor truss system

The composite trusses were designed according to Eurocode 4 [12] for the conditions of both the ultimate and the serviceability limit states. The design loads were defined considering the requirements of Eurocode 1 [9]. The concrete slab was designed as the continuous spanning slab, running over the steel trusses, with respect to Eurocode 2 [10]. The calculation of internal forces in bracing members of the composite trusses was executed by the method of joints regarding to the guidelines of British Standard 5950 [13]. The design of structural steel members was performed upon the Eurocode 3 [11] specifications.

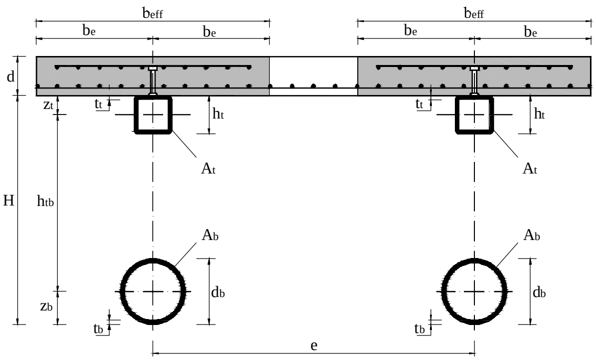

Fig. 2 Vertical cross-section of the composite floor truss system

The following conditions were checked at the ultimate limit state: plastic resistance to the bending moment of the effective composite cross-section; plastic resistance to the local bending moment of the truss top chord; tension resistance of the truss diagonals; compression/buckling resistance of the truss verticals; plastic resistance of the cylindrical shear studs; resistance of fillet welds; resistance of the hollow-section truss connections; plastic resistance to the bending moment of the concrete slab; and resistance of the concrete slab to longitudinal shear.

Considering the serviceability limit state conditions, the composite trusses were checked for vertical deflections. The vertical deflections were calculated by using the elastic method, considering the effective second moment of the cross-section area and the effects of the creep/shrinkage of concrete. Both, the total deflection δ_{max} subjected to the overall load and the deflection δ_2 subjected to the variable imposed load were calculated to be under the limited maximum values: *L/250* and *L/300*, respectively.

3. NLP OPTIMIZATION

3.1 NLP problem formulation

The optimization of the composite floor truss system was performed by the nonlinear programming approach, NLP. The general NLP optimization problem is formulated as:

$$Min\ z = f(\boldsymbol{x})$$

subjected to:

$$\boldsymbol{h}(\boldsymbol{x}) = \boldsymbol{0} \qquad \text{(NLP)}$$
$$\boldsymbol{g}(\boldsymbol{x}) \leq \boldsymbol{0}$$
$$\boldsymbol{x} \in \boldsymbol{X} = \{\boldsymbol{x} \mid \boldsymbol{x} \in \boldsymbol{R}^n, \boldsymbol{x}^{LO} \leq \boldsymbol{x} \leq \boldsymbol{x}^{UP}\}$$

where $\boldsymbol{x}$ is a vector of the continuous variables, defined within the compact set $\boldsymbol{X}$. Functions $f(\boldsymbol{x})$, $\boldsymbol{h}(\boldsymbol{x})$ and $\boldsymbol{g}(\mathbf{x})$ 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.

Considering the optimization of composite floor trusses, the vector of continuous variables defines dimensions, cross-section characteristics, forces, stresses, strains, cost parameters, etc. The system of equality and inequality constraints as well as the bounds on variables determines a design, load, stress, resistance and deflection conditions taken from the structural analysis. In this paper, a cost objective function is proposed to minimize the structure's manufacturing costs.

3.2 Cost objective function

The optimal design of composite floor trusses was determined by the minimum of the manufacturing costs. In this case, the manufacturing costs are defined as a sum of the material costs, power consumption costs and labour costs, required for the fabrication of the composite trusses. The fabrication times, the electrical power consumption and the material consumption are also included in the objective function, which gives the engineer a complete view into the distribution of the manufacturing costs. The proposed objective function of the manufacturing costs is defined in the following form:

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

where the variable *Cost* [€/m^2] represents the manufacturing costs per m^2 of the useable surface of the composite floor truss system; the denotations $C_{M,...}$, $C_{P,...}$ and $C_{L,...}$ represent the considered material, power and labour cost items calculated in €; $\Sigma i,j$ represent the sum of all the individual steel truss element cost contributions; subscripts i, j denote the end joints of the individual truss member; e [m] is the intermediate distance between the steel trusses and L [m] is the span of the composite truss. The considered material, power and labour costs are discussed in the following sections.

3.2.1 Material costs

Steel, concrete and reinforcement:

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

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

Cylindrical shear studs:

$$C_{M,sc} = c_{M,sc} \cdot n_{sc} \quad (3)$$

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

Electrode consumption [14]:

$$C_{M,e_{i,j}} = c_{M,e} \cdot \rho_s \cdot A_{w_{i,j}} \cdot l_{w_{i,j}} \Big/ EMY \quad (4)$$

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

Anti-corrosion, fire protection and top coat paint:

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

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 take into account the painting technique, the complexity of the structure's surface and the weather conditions in which the structure is painted, respectively; $A_{ssi,j}$ [m^2] is the steel surface area of the truss member.

Formwork floor-slab panels:

$$C_{M,f} = c_{M,f} \cdot e \cdot L \big/ n_{uc} \quad (6)$$

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, which defines how many times the formwork floor-slab panels may be used before they have to be replaced with the new ones.

3.2.2 Power costs

Sawing the steel section:

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

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 performed by the power hacksaw and $b_{i,j}$ [m] is the overall diameter of the truss member.

Edge grinding the steel section:

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

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

Shielded metal arc welding [14]:

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

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

Stud arc welding:

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

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:

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

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

3.2.3 Labour costs

Sawing the steel section:

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

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

Edge grinding of the steel section:

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

Preparation, assembly and tacking:

$$C_{L,p,a,t} = c_L \cdot T_{p,a,t} \qquad (14)$$

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

Manual shielded metal arc welding:

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

where k_d, k_{wp}, k_{wd}, k_{wl} and k_r represent the difficulty factors which consider the working conditions, the welding position, the welding direction, the length of the weld and the chamfering of the root of the weld, respectively; T_{SMAW} [h/m] is the time required for manual shielded metal arc welding.

Semi-automatic stud arc welding:

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

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:

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

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 required 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):

$$C_{L,f} = c_L \cdot T_f \cdot e \cdot L \qquad (18)$$

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

Cutting, placing and connecting the reinforcement:

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

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:

$$C_{L,c} = c_L \cdot T_c \cdot d \cdot e \cdot L \qquad (20)$$

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

Concrete consolidation:

$$C_{L,v} = c_L \cdot T_v \cdot e \cdot L \qquad (21)$$

Curing the concrete:

$$C_{L,cc} = c_L \cdot T_{cc} \cdot d \cdot e \cdot L \qquad (22)$$

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

3.3 The optimization

With reference to the given NLP optimization problem formulation, the optimization model COMTOPTH (COMposite Trusses OPTimization/ Hollow sections) was developed for the composite floor trusses made from cold formed hollow sections. A high level language GAMS (General Algebraic Modelling System) [15] was used for the mathematical modelling and for data inputs/outputs.

The proposed cost objective function was subjected to structural analysis constraints, checking for both the ultimate and the serviceability limit states according to Eurocodes. The task of the optimization was to find the optimal structural design and the optimal concrete/steel materials considering the defined criterion of the optimization, namely the minimum of the manufacturing costs.

4. NUMERICAL EXAMPLE

The paper shows the example of the manufacturing cost optimization of the simply supported composite floor truss system. The considered composite floor trusses are *30 m* long, subjected to combined effects of the self-weight and the variable imposed load of 5.*0 kN/m²*, see Figure 3.

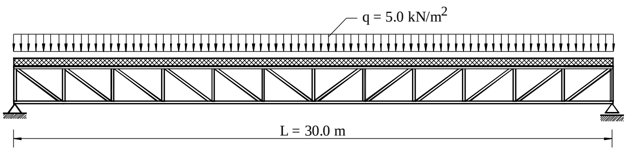

Fig. 3 Composite floor trusses

4.1 Input data

Trusses are proposed to be made from standard steel cold formed hollow sections. While the steel elements are cut by using a power hacksaw, their cross-sections are prepared to be welded by using the edge grinding machine. The bracing members and chords are connected together with the fillet welds. The welds are made manually by applying the shielded metal arc welding technology, SMAW. The full shear connection between the concrete slab and the steel trusses is finished by using the 19 *mm* cylindrical shear studs. The studs are connected to the top chord by performing the semi-automatic stud arc welding. The surfaces of truss members are cleaned by manual sand-spraying. Afterwards, the steel trusses are brushed over with a single coat of anti-corrosion paint, two coats of fire protection paint F 30 and a top coat.

The concrete slab is panelled by the fully prefabricated formwork. The formwork floor-slab panels may be used in 30 panelling cycles before they have to be replaced with new ones. The one-way spanning high bond steel-wire meshes S 400 are fastened together and concreted into slab. While the concrete is placed into slab by using a mobile concrete pump, the concrete consolidation is achieved by employing the internal vibrators. Finally, the concrete slab is cured by ponding the water for 3 days after the placement.

The input data for the cost optimization of composite floor truss system includes:

- material, power and labour cost parameters, listed in Table 1,
- fabrication times, listed in Table 2,
- approximation functions for fabrication times, listed in Table 3,
- material, power and technology factors, listed in Table 4.

Table 1 Material, power and labour cost parameters

$c_{M,s}^{(a)}$	*Price of the structural steel S 235 – S 355:*	*1.50–1.62 €/kg*
$c_{M,c}^{(b)}$	*Price of the concrete C 25/30 – C 50/60:*	*85.00–120.00 €/m³*
$c_{M,r}$	*Price of the reinforcing steel S 400:*	*0.70 €/kg*
$c_{M,sc}$	*Price of the cylindrical shear studs:*	*0.50 €/stud*
$c_{M,e}$	*Price of the electrodes:*	*1.70 €/kg*
$c_{M,ac}$	*Price of the anti-corrosion paint:*	*0.85 €/m²*
$c_{M,fp}$	*Price of the fire protection paint (F 30):*	*13.50 €/m²*
$c_{M,tc}$	*Price of top coat paint:*	*0.65 €/m²*
$c_{M,f}$	*Price of the prefabricated floor-slab panels:*	*30.00 €/m²*
c_P	*Electric power price:*	*0.10 €/kWh*
c_L	*Labour costs:*	*20.00 €/h*

(a) *Price of the structural steel is calculated by using the approximation function:*

$c_{M,s} = c_S \cdot (j_2 \cdot f_y^2 + j_1 \cdot f_y + j_0)$ [€/kg]; *where:*

$c_S = 1.50$ €/kg; $j_2 = -3.7202\times10^{-4}$; $j_1 = 2.7902\times10^{-2}$; $j_0 = 5.4976\times10^{-1}$ *and* f_y [kN/cm²]

(b) *Price of the concrete is calculated by using the approximation function:*

$c_{M,c} = c_C \cdot (k_2 \cdot f_{ck}^2 + k_1 \cdot f_{ck} + k_0)$ [€/kg]; *where:*

$c_C = 85.00$ €/kg; $k_2 = -3.2220\times10^{-2}$; $k_1 = 4.0571\times10^{-1}$; $k_0 = 1.8829\times10^{-1}$ *and* f_{ck} [kN/cm²]

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 arc welding:* 2.433×10^{-4} *h/stud*
T_v	*Time for consolidation of the concrete: 0.200 h/m²*
T_{swp}	*Time for welding, placing/removal of a ferrule and cleaning:* 55.555×10^{-4} *h/stud*
T_{ss}	*Time for sand-spraying: 0.050 h/m²*
T_{ac}	*Time for anti-corrosion resistant painting: 0.050 h/m²*
T_{fp}	*Time for fire protection painting: 0.050 h/m²*
T_{tc}	*Time for top coat painting: 0.050 h/m²*
T_f	*Time for panelling, levelling, disassembly and cleaning the formwork: 0.300 h/m²*
T_r	*Time for cutting, placing and connecting the reinforcement: 0.024 h/kg*
T_{cc}	*Time for curing the concrete: 0.200 h/m³*

Table 3 Approximation functions for fabrication times

$T_{p,a,t}$ [(a)]	*Time for preparation, assembling and tacking of welded elements:* $T_{p,a,t} = C_1 \cdot \Theta_d \cdot (\kappa \cdot \rho_s \cdot V_s)^{0.5}/60$ [h]; $C_1 = 1.0$ min/kg$^{0.5}$; $\Theta_d = 3.00$; $\kappa = 27$ elements; $\rho_s = 7850$ kg/m^3 and V_s [m^3]
T_{SMAW} [(b)]	*Time for manual shielded metal arc welding of fillet welds:* $T_{SMAW,F} = f_2 \cdot a_w^2 + f_1 \cdot a_w + f_0$ [h/m]; $f_2 = 1.2653\times10^{-2}$; $f_1 = 1.3773\times10^{-3}$; $f_0 = 1.6111\times10^{-2}$ and a_w [mm]
T_c [(c)]	*Time for placement of pumped concrete:* $T_c = i_2 \cdot d^2 + i_1 \cdot d + i_0$ [h/m^3]; $i_2 = 2.4000\times10^{-3}$; $i_1 = -5.4000\times10^{-2}$; $i_0 = 9.9500\times10^{-1}$ and d [cm]

[(a)] *Fabrication time proposed in Ref.* [16]

[(b)] *Approximation functions developed on the basis of data given by company Metalna for sizes of fillet weld 3–28 mm, see Refs.* [17–19]

[(c)] *Approximation function developed on the basis of data given in Ref.* [20]

Table 4 Material, power and technology factors

ρ_s	*Steel density: 7850 kg/m^3*
ρ_c	*Concrete density: 2500 kg/m^3*
EMY	*Electrode metal yield: 0.60*
k_p [(a)]	*Paint loss factor – painting technique: 0.05 for brush painting*
k_{sur} [(b)]	*Paint loss factor – complexity of the structure: 1.00 for large surfaces*
k_{wc} [(b)]	*Paint loss factor – weather conditions: 1.00 for 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 for the machining process*
P_{hs}	*Power of the hacksaw: 2.20 kW*
η_{hs}	*Machine power efficiency: 0.85 for the hacksaw*
P_{gm}	*Power of the grinding machine: 1.10 kW*
η_{gm}	*Machine power efficiency: 0.85 for the grinding machine*
I	*Welding current: 230 A*
I_{sw}	*Welding current for stud arc welding: 1409 A*
U	*Welding voltage: 25 V*
U_{sw}	*Welding voltage for stud arc welding: 20 V*
η_w	*Machine power efficiency: 0.90 for the 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 for the internal concrete vibrator*
k_d	*Difficulty factor – working conditions: 1.00 for normal conditions*
k_{wp}	*Difficulty factor – welding position: 1.10 for vertical and overhead position*
k_{wd}	*Difficulty factor – welding direction: 1.00 for flat position and vertical welds*
k_{wl}	*Difficulty factor – welding length: 1.00 for long welds*
k_r	*Difficulty factor – root of the weld: 1.00 for welds without treatment of root*
k_{dp}	*Difficulty factor – painting position: 1.00 for horizontal painting*
k_{rh}	*Difficulty factor – structural height: 1.00 for structural height less than 6 m*
k_{ri}	*Difficulty factor – inclination of the concrete slab: 1.00 for horizontal slab*

[(a)] $k_p = 0.05$ *denotes that 5 % paint loss is accounted for with respect to manual brush painting*

[(b)] $k_{sur} = 1.00$ *and* $k_{wc} = 1.00$ *denotes that no additional paint loss is accounted for regarding the complexity of the steel structure and weather conditions in which the structure is being painted*

4.2 Optimization

The aim of the optimization was to find the cross-section dimensions as well as steel and concrete grades for the considered composite floor system with respect to the minimum of the manufacturing costs, checking for both the ultimate and the serviceability limit constraints, defined according to the Eurocodes.

The standard structural steel grades S 235, S 275 and S 355 as well as the standard concrete strengths from C 25/30 to C 50/60 were included in the optimization. While the prices of the structural steel S 235 and the concrete C 25/30 were defined to be the input data, the prices of higher steel grades and concrete strengths were calculated as functions of the input grades throughout the optimization process.

The variable load was defined in the input data and it remained constant during the optimization process. As the self-weight of the structure depends on the obtained dimensions, it was simultaneously calculated for each alternative structural design throughout the optimization.

The structural optimization was carried out by the application of the developed optimization model COMTOPTH. The optimization of the composite floor truss was performed in two successive steps. In the first step, the ordinary NLP optimization was performed to calculate the optimal continuous variables (dimensions, materials) 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 and rounded variables (from in the first stage obtained continuous values to their nearest upper standard/discrete values). CONOPT (Generalized reduced-gradient method) [21] was used for the optimization.

4.3 Results

The optimal structural design of the considered composite floor truss system was obtained in the second step of the NLP optimization, see Figures 4, 5 and 6. The gained minimum of the manufacturing costs was found to be 8502.11 € or 119.08 € per m^2 of the useable surface of the composite truss system. The obtained optimal results include the optimal steel grade, the concrete strength, the intermediate distance between trusses, the overall depth of the composite truss, the depth of the slab, the cross-section area of the steel-wire mesh reinforcement and the optimal structural steel sections of all truss members (chords, diagonals and verticals), see Table 5.

The example also shows the distribution of the obtained minimal manufacturing costs of the composite floor truss for the given economical data. The material costs represent 78.7%, the labour costs 21.2% and the power consumption costs 0.1% of the obtained minimal manufacturing costs, see Table 6 and Figure 7.

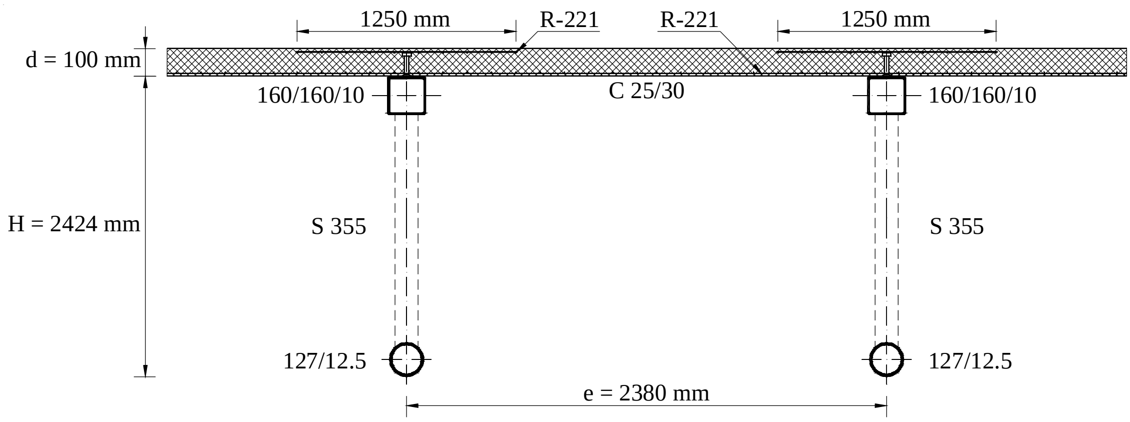

Fig. 4 Optimal cross-section design of the composite floor trusses

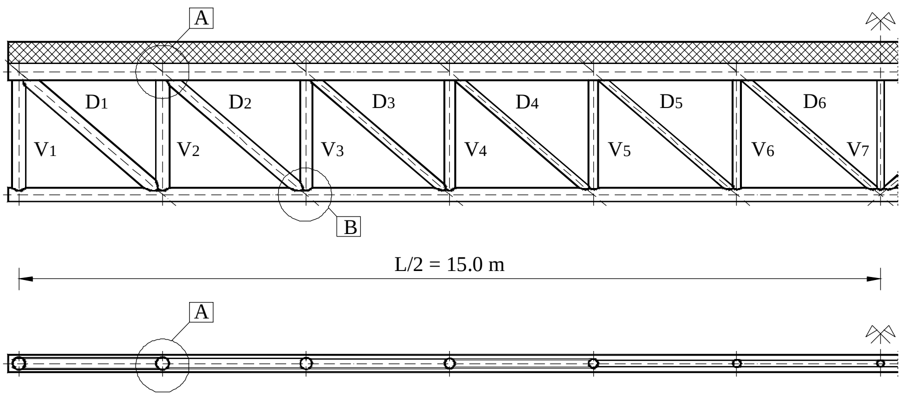

Fig. 5 Arrangement of bracing members

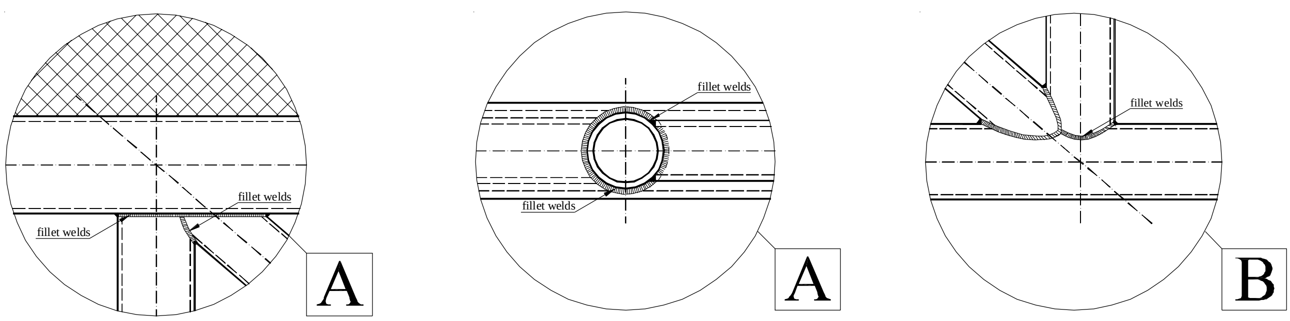

Fig. 6 Design of welded joints

Table 5 Obtained optimal design parameters of the composite floor truss

Top chord – square hollow section (height/width/thickness [mm]): 160/160/10
Bottom chord – circular hollow section (outer diameter/thickness [mm]): 127/12.5
Diagonals – circular hollow sections (outer diameter/thickness [mm]):
D_1: 127/4.5; D_2: 108/4.5; D_3: 82.5/4.5; D_4: 70/4.5; D_5: 70/3; D_6:70/3
Verticals – circular hollow sections (outer diameter/thickness [mm]):
V_1: 127/4.5; V_2: 121/4; V_3: 114.3/4; V_4: 101.6/4; V_5: 88.9/3.5; V_6: 76.1/3.5; V_7: 70/3
Depth of the concrete slab: d = 10.0 cm
Overall depth of the steel truss: H = 242.4 cm
Intermediate distance between the steel trusses: e = 238.0 cm
Cross-section area of the steel-wire mesh reinforcement (R–221): $A_s = 2.21\ cm^2/m^1$
Yield strength of the structural steel (S 355): $f_y = 35.5\ kN/cm^2$
Characteristic cylinder strength of the concrete (C 25/30): $f_{ck} = 2.5\ kN/cm^2$
Manufacturing costs of the composite floor truss per m^2*: Cost = 119.08 €/*m^2

* *for denotations of bracing members, see Figure 5*

Table 6 Recapitulation of the optimal manufacturing costs

Material costs:		
$C_{M,s}$	*Structural steel S 355*	*4979.11 €*
$C_{M,c}$	*Concrete C 25/30*	*607.62 €*
$C_{M,r}$	*Steel-wire mesh reinforcement R–221 S 400*	*162.17 €*
$C_{M,sc}$	*Cylindrical shear studs*	*38.00 €*
$C_{M,e}$	*Electrodes*	*12.85 €*
$C_{M,ac,fp,tc}$	*Anti-corrosion paint, fire protection paint and top coat paint*	*817.34 €*
$C_{M,f}$	*Floor-slab panels*	*71.40 €*
	Total material costs:	*6688.49 €*
Power costs:		
$C_{P,c,hs}$	*Sawing process*	*1.80 €*
$C_{P,gm}$	*Edge grinding process*	*0.08 €*
$C_{P,w}$	*Welding process*	*0.78 €*
$C_{P,sw}$	*Arc stud welding process*	*0.06 €*
$C_{P,v}$	*Vibrating the concrete*	*5.21 €*
	Total power consumption costs:	*7.93 €*
Labour costs:		
$C_{L,c,hs}$	*Sawing*	*138.90 €*
$C_{L,g}$	*Edge grinding*	*1.30 €*
$C_{L,p,a,t}$	*Preparation, assembly and tacking of the elements*	*289.22 €*
$C_{L,SMAW}$	*Welding process performed by SMAW technology*	*155.35 €*
$C_{L,sw}$	*Semi-automatic arc stud welding process*	*8.44 €*
$C_{L,spp}$	*Sand-spraying, anti-corrosion, fire resistant and top coat painting*	*259.47 €*
$C_{L,f}$	*Placing the formwork*	*428.40 €*
$C_{L,r}$	*Cutting, placing and connecting the reinforcement*	*111.20 €*
$C_{L,c}$	*Concreting the reinforced concrete slab*	*99.25 €*
$C_{L,v}$	*Consolidating the concrete by internal vibrators*	*285.60 €*
$C_{L,cc}$	*Curing the concrete*	*28.56 €*
	Total labour costs:	*1805.69 €*
Total manufacturing costs per 1 composite truss:		*8502.11 €*
Manufacturing costs per m^2 *of useable surface of the composite floor:*		*119.08 €/*m^2

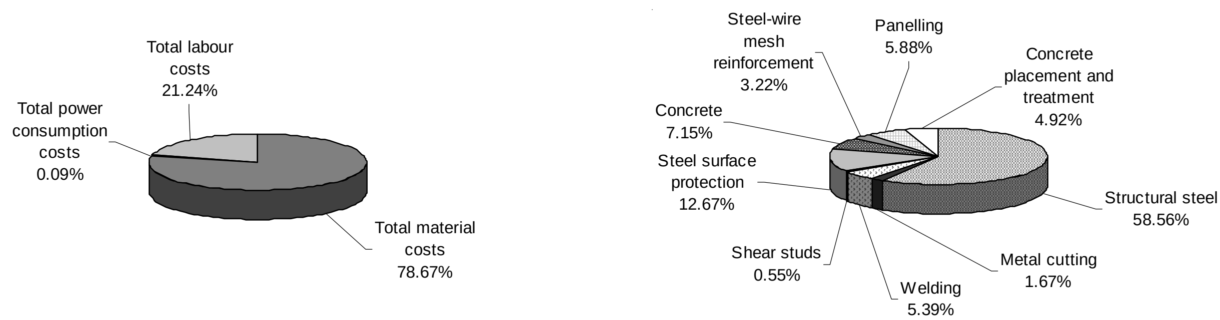

Fig. 7 The distribution of the optimal manufacturing costs of the composite truss system

5. CONCLUSIONS

The paper presents the manufacturing cost optimization of composite floor trusses built up of a reinforced concrete slab and steel trusses consisting of cold formed hollow sections. The structural optimization was performed by the nonlinear programming approach, NLP. For this purpose, an NLP optimization model was developed. The objective function was subjected to the defined system of structural analysis and design (in)equality constraints. Composite floor trusses were optimized according to Eurocode 4 for the conditions of both the ultimate and the serviceability limit states.

An extensive and accurate objective function of the manufacturing material, power and labour costs was developed and applied for the optimization. The material costs include the structural steel, the concrete, the reinforcement, the shear connectors, the electrodes, the anti-corrosion, fire protection and top coat painting and the formwork floor-slab panels. The defined power consumption costs comprise the costs of sawing the steel sections, of edge grinding, welding, stud welding and vibrating the concrete. The labour costs comprehend the costs of sawing, edge grinding, preparation, assembling and tacking, welding, welding of shear connectors, steel surface preparation and protection, placing the formwork, cutting, placing and connecting the reinforcement, concreting, consolidating and curing the concrete.

Beside the costs, the proposed objective function also included the fabrication times, electrical power and material consumption. The objective function is formulated in an open manner to be easily adopted and used for any specific data in different economical and technological conditions. It also provides a detailed insight into the manufacturing costs distribution which enables the engineer to objectively value the obtained optimal design already at conceptual design level. A numerical example of the manufacturing cost optimization of the composite floor truss system is presented at the end of the paper in order to show the applicability of the proposed approach.

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OPTIMIZACIJA PROIZVODNIH TROŠKOVA SPREGNUTIH REŠETKASTIH PODNIH NOSAČA

SAŽETAK

U radu je prikazana optimizacija proizvodnih troškova spregnutih rešetkastih podnih nosača. Spregnuti rešetkasti podni nosači su sastavljeni od armiranobetonske ploče i čelične rešetke iz hladno oblikovanih šupljih profila. Optimizacija konstrukcije je provedena pristupom nelinearnog programiranja, NLP. Za optimizaciju je razvijena i upotrijebljena precizna ciljna funkcija proizvodnih troškova materijala, energije i rada. Spregnuti rešetkasti podni nosači su optimizirani prema Eurocode 4 za krajnja granična stanja i granična stanja uporabivosti. Na kraju rada je pokazan računski primjer optimizacije proizvodnih troškova sustava spregnutog rešetkastog podnog nosača koji prikazuje uporabivost predlaganog pristupa.

Ključne riječi: *optimizacija konstrukcija, nelinearno programiranje, spregnuti rešetkasti podni nosači, zavarene konstrukcije, proizvodni troškovi.*