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Cost optimization of composite floor trusses

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Abstract. The paper presents the cost optimization of composite floor trusses composed from a reinforced concrete slab of constant depth and steel trusses consisting of hot rolled channel sections. The optimization was performed by the nonlinear programming approach, NLP. Accordingly, a NLP optimization model for composite floor trusses was developed. An accurate objective function of the manufacturing material, power and labour costs was proposed to be defined for the optimization. Alongside the costs, the objective function also considers the fabrication times, and the electrical power and material consumption. Composite trusses were optimized according to Eurocode 4 for the conditions of both the ultimate and the serviceability limit states. A numerical example of the optimization of the composite truss system presented at the end of the paper demonstrates the applicability of the proposed approach.

Keywords: structural optimization; nonlinear programming; NLP; composite trusses; composite floor trusses; welded structures.

1. Introduction

Constant demand for lighter and cheaper structures has in the last three decades encouraged structural engineers and researchers to develop various optimization techniques applicable also in the field of composite structures. For this purpose, Surtees and Tordoff (1977) described an automated procedure for the cost and mass optimization of a composite box girder bridge. Bhatti and Al-Gahtani (1995) introduced the optimization of a highway bridge composite welded plate girder. In his following research, Bhatti (1996) performed the cost optimization of partially composite beams using the symbolic algebra program Mathematica (1991). Cohn and Werner (1996) performed optimization of composite bridges throughout an exhaustive search with recursive analysis. Long *et al.* (1999) investigated nonlinear programming based optimization of cable-stayed bridges with a composite superstructure using the Newton-Raphson iteration procedure.

Considering the cost optimization of composite I beams, Kravanja and Šilih (1999) and Šilih and Kravanja (2000) applied the non-linear programming (NLP) techniques. Adeli and Kim (2001) proposed the mixed integer-discrete nonlinear programming approach using the branch and bound method and the simulated annealing method for the optimization of composite floors. The mixed integer nonlinear programming approach to discrete/continuous optimization of composite I beams was introduced by

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Kravanja and Šilih (2001). Foley and Lucas (2004) applied the genetic algorithm to obtain the optimal cost design of a composite wide-flange beam floor system.

Some efforts were also presented in the field on the optimal design of composite trusses. El-Sheikh (1999) introduced optimization of composite space trusses and discussed the optimal design in a view of the span/depth ratio and the number of chord panels. Šilih and Kravanja (2002) and Kravanja and Šilih (2003) performed an NLP optimization based comparison between composite welded I beams and composite trusses consisting of cold formed hollow sections.

This paper presents the minimization of the manufacturing costs of composite floor trusses composed from a reinforced concrete slab of constant depth and steel trusses produced from hot rolled channel sections. The optimization was performed by the nonlinear programming (NLP) approach. The research, dealt within this paper, presents a natural continuation of the work introduced by Kravanja and Šilih (2003), where the optimization of composite I beams and composite trusses consisting of cold formed hollow sections was performed by using a simplified cost objective functions with fixed cost parameters. In a view of previous research, a new extensive and accurate objective function of the structure's manufacturing costs was developed and applied. The objective function comprehended all the necessary material, power and labour manufacturing costs resulting from the structure's direct production. In addition, the fabrication times, and the electrical power and material consumption were also calculated which provides the engineer with a complete and detailed insight into the manufacturing costs distribution. It should be noted that the engineering, amortisation, transportation, erection, overhead, and maintenance costs, the costs of scrap and other expenses are not considered in this paper.

The composite trusses were proposed to be designed according to Eurocode specifications (Eurocode 1 1995, Eurocode 2 1992, Eurocode 3 1995, Eurocode 4 1992). A numerical example of the optimization of a composite truss system with the span of 30 m is presented at the end of the paper to demonstrate the applicability of the proposed approach.

2. Composite floor trusses

The considered composite floor truss system is composed from a reinforced concrete slab of constant depth and steel Pratt trusses with tension diagonals, see Fig. 1. The truss members are proposed to be designed from hot rolled channel sections. The bracing members and chords are connected together by using a combination of fillet and full penetration welds. The concrete slab and the top chord of the steel truss (see Fig. 2) are connected together by cylindrical shear studs, welded to the web of the chord's section and embedded in concrete. The full shear connection between the slab and the steel section is considered here.

The dimensioning of the composite trusses was proposed to be performed in accordance with Eurocode 4 (1992) for the conditions of both the ultimate and the serviceability limit states. The design loads were calculated with regard to Eurocode 1 (1995). The concrete slab was separately designed in accordance with Eurocode 2 (1992) as a one way spanning slab, running continuously over the steel trusses. As Eurocodes do not provide any directions for the calculation of internal forces in members of the composite trusses, they were determined according to the British Standard 5950 (1990). The optimization of structural steel members was performed on the basis of Eurocode 3 (1995) specifications.

The composite trusses were subjected to the combined effect of the dead-weight and the uniformly distributed variable imposed load. While the variable load was constant throughout the optimization, the dead-weight was simultaneously calculated for each structural design.

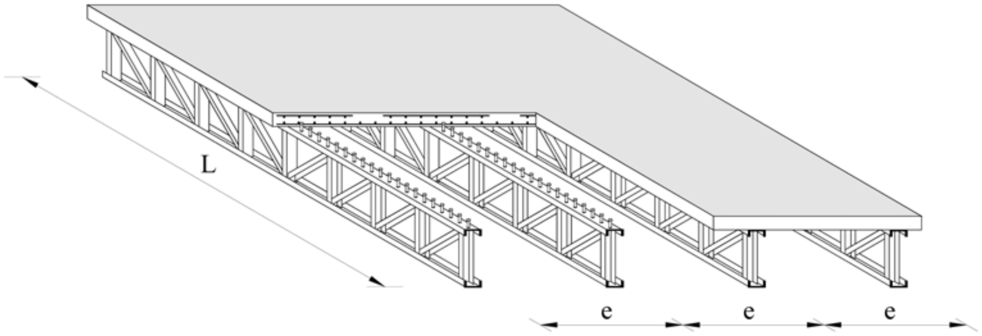

Fig. 1 Composite floor truss system

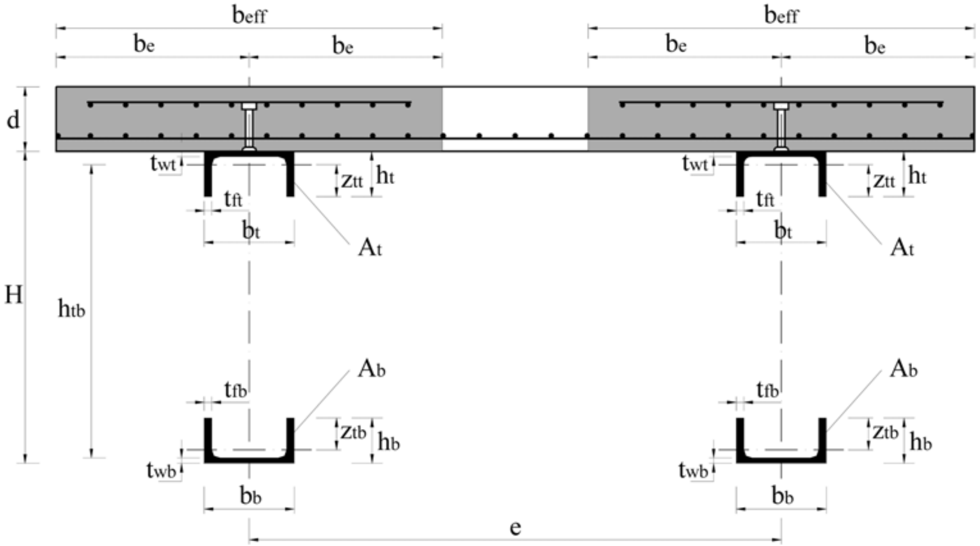

Fig. 2 Vertical cross-section of the composite floor truss system

When the ultimate limit state was considered, the composite trusses were checked for the bending moment, vertical shear force and the longitudinal shear force between the concrete slab and the top chord of the steel truss. The ultimate moment capacity was calculated by the plastic method. It was assumed that structural steel was fully yielded and the effective concrete slab cross-section stressed to 85% of its compressive strength. The ultimate moment capacity was determined by the tensile resistance of the bottom steel chord and the compressive resistance of the concrete slab, neglecting the contribution of the top chord of the steel truss. The contribution of the top steel chord was neglected because of concern about the amount of strain in the bottom chord necessary before the full compressive action of the top chord is developed. The vertical load is transferred via axial forces into the bracing members. Since the steel truss is statically determinate, the design axial forces in the bracing members are calculated by using the method of joints. All the joints of the steel truss were assumed to be pinned. Consequently, the shear resistance of the composite truss system was evaluated by considering the tensile and the compression/buckling capacity of the bracing members. A proper longitudinal shear transfer was achieved by the sufficient design bearing/shear resistance of the shear studs and a design resistance of the surfaces of the potential shear failure in the concrete slab. The shear connectors were designed via the plastic method.

When the serviceability limit state was accounted for, 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 problem of the composite floor system is non-linear, since the objective function and the inequality constraints defined are non-linear. The non-linear programming (NLP) optimization approach was thus applied. The general NLP optimization problem can be formulated as follows:

$$\begin{gathered} \text{Min } z = f(\boldsymbol{x}) \\ \text{subjected to:} \\ \boldsymbol{h}(\boldsymbol{x}) = \boldsymbol{0} \\ \boldsymbol{g}(\boldsymbol{x}) \le \boldsymbol{0} \\ \boldsymbol{x} \in \boldsymbol{X} = \{\boldsymbol{x} \mid \boldsymbol{x} \in \boldsymbol{R}^n, \boldsymbol{x}^{LO} \le \boldsymbol{x} \le \boldsymbol{x}^{UP}\} \end{gathered} \qquad \text{(NLP)}$$

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 $\boldsymbol{g}(\boldsymbol{x})$ are the nonlinear 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 the context of structural optimization, variables include dimensions, cross-section characteristics, forces, stresses, strains, economic parameters, etc. Equality and inequality constraints and the bounds on the variables represent a system of a design, load, stress, resistance and deflection functions taken from the structural analysis. The optimization of the structures may include various objectives worthy of consideration. The most popular criterion used today is the minimization of mass. In this paper, an economic objective function is proposed to minimize the structure's manufacturing costs.

3.2. NLP optimization model for composite floor trusses

The NLP optimization model COMPFT (COMPosite Floor Trusses) for the optimization of composite floor trusses composed from a concrete slab and steel channel-section trusses has been developed with relating to the above NLP problem formulation. The high-level language GAMS (General Algebraic Modelling System) (Brooke 1988) was used for the modelling and for data inputs/outputs. The proposed optimization model includes the input data (constants), the variables, the structure's objective function and the structural analysis constraints, see the optimization model formulation in Fig. 3.

The objective function is subjected to structural analysis constraints. The structural analysis inequality constraints and the bounds of the variables represent a rigorous system of design, load, resistance and deflection functions known from the structural analysis. Since these constraints are

OPTIMIZATION MODEL FORMULATION FOR COMPOSITE FLOOR TRUSSES
Cost objective function: min $Cost = f(\boldsymbol{x})$
subjected to: *Structural analysis constraints* ($\boldsymbol{h}(\boldsymbol{x}) = \boldsymbol{0}, \boldsymbol{g}(\boldsymbol{x}) \leq \boldsymbol{0}$): *Ultimate limit state constrains (ULS):* - calculation of the internal forces, - resistance to the bending moment of the composite cross-section, - local bending moment resistance of the top chord cross-section, - tension resistance of the truss diagonals, - compression/buckling resistance of the truss verticals, - resistance of the shear connectors-cylindrical shear studs, - resistance of the fillet welds, - resistance to the longitudinal shear in concrete slab, - bending moment resistance of the concrete slab. *Serviceability limit state constrains (SLS):* - calculation of the deflections, - checking the vertical deflections of the composite truss, - checking the vertical deflections of the concrete slab.
Input data (constants): - span, number of truss members, variable load, partial safety coefficients, elastic modules, difficulty labour coefficients, material and labour costs coefficients etc. *Variables:* ($\boldsymbol{x} \in \boldsymbol{R}^n$) - Independent: dimensions of the cross-sections, yield strength of the structural steel, characteristic cylinder strength of the concrete, etc. - Dependent: geometrical characteristics of the cross-sections, self-weight, design loads, internal forces, resistances, deflections, etc.

Fig. 3 Optimization model formulation for composite floor trusses

defined in accordance with Eurocode 4 in order to satisfy the requirements of both the ultimate and the serviceability limit states, they are divided into two subsets: ultimate limit state constraints (ULS) and serviceability limit state constraints (SLS), see Fig. 3. Because the developed optimization model is relatively comprehensive, only the objective function and some basic structural analysis constraints are described in following sections of the paper.

3.3. The cost objective function

In this paper, minimization of the manufacturing costs of composite floor trusses is set as the criterion of the optimization. The objective function of the manufacturing costs is formulated as a complex system of cost items, i.e., nonlinear expressions. 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. Moreover, the fabrication times, the electrical power consumption and the material consumption are also calculated giving the engineer a complete view of the distribution of the manufacturing costs.

The labour costs for the preparation, assembly and tacking of the welded parts of the composite structure were calculated according to the fabrication times reported by Jármai and Farkas (1999) and Jármai (2003). In the context of shielded metal arc welding, the electrode and power consumption costs were calculated by applying the expressions given by Creese *et al.* (1992). Some parameters in connection with the welding costs (electrode metal yield, welding voltage etc.) were used as suggested by Cary (1995, 2002). In the work of Kravanja *et al.* (1995, 1998) and Kravanja (2002), an estimation of the manufacturing costs, partially based on the normative of the Slovenian company Metalna, was applied for the optimization of hydraulic steel gates. In this paper, the labour costs of the welding process were calculated using the same data. The stud welding current and time were established on the basis of the data introduced by Stud Welding Associates (2005). The material costs of the anti-corrosion, fire protection and top coat paint consumption for structural steel members were calculated in accordance with the guidelines proposed by International Protective Coatings (2005). The expressions for calculation of the fabrication times related to concrete works e.g. panelling, reinforcing, concreting and curing of the concrete slab were developed on the basis of data presented by Bučar (1999).

The proposed objective function of the manufacturing costs is derived in the following form:

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

where the variable *Cost* [€/m^2] represents the manufacturing costs per m^2 of the useable surface of the composite floor truss system; $C_{M,s,c,r}$ are the material costs of the structural steel, concrete and the reinforcement; $C_{M,sc}$ are the material costs of the cylindrical shear studs; $C_{M,e}$ are the material costs of the electrode consumption; $C_{M,ac,fp,tc}$ are the material costs of the anti-corrosion, fire protection and top coat paints; $C_{M,f}$ are the material costs of the formwork floor-slab panels; $C_{P,c,hs}$ are the power consumption costs for sawing the steel section; $C_{P,c,gm}$ are the power consumption costs for the edge grinding of the structural steel section; $C_{P,w}$ are the power consumption costs for welding; $C_{P,sw}$ are the power consumption costs for the stud welding; $C_{P,v}$ are the power consumption costs for vibrating the concrete; $C_{L,c,hs}$ are the labour costs for sawing the steel section; $C_{L,g}$ are the labour costs for edge grinding of the structural steel section; $C_{L,p,a,t}$ are the labour costs for the preparation, assembling and tacking of the welded structure; $C_{L,SMAW}$ are the labour costs for shielded metal arc welding; $C_{L,sw}$ are the labour costs for welding the shear connectors; $C_{L,spp}$ are the labour costs for steel surface preparation and protection; $C_{L,f}$ are the labour costs for the panelling, levelling, disassembly and cleaning a formwork; $C_{L,r}$ are the labour costs for cutting, placing and connecting the reinforcement; $C_{L,c}$ are the labour costs for concreting the reinforced concrete slab; $C_{L,v}$ are the labour costs for vibrating the concrete; $C_{L,cc}$ are the labour costs for curing the concrete; $\Sigma_{i,j}$ represents 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.

3.3.1. 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 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; A_s [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:

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

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

Electrode consumption:

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

where $c_{M,e}$ [€/kg] is the price of the electrodes; $A_{w_{i,j}}$ [m^2] is the cross-section area of the weld; EMY is the electrode metal yield and $l_{w_{i,j}}$ [m] is the length of the weld. The ranges of the electrode metal yield were proposed by Cary (2002): a typical value for shielded metal arc welding process is $EMY = 0.6$.

Anti-corrosion, fire protection and top coat paint:

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

where $c_{M,ac}$ [€/m^2], $c_{M,fp}$ [€/m^2] and $c_{M,tc}$ [€/m^2] are the prices of the anti-corrosion (ground paint), 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; $A_{ss_{i,j}}$ [m^2] is the steel surface area of the truss member. For a skilled worker k_p is 0.20 in the case of airless and conventional spraying, while k_p is 0.05 in the case of brush and roller painting. Factor k_{sur} is 1.00 for structures consisting of flat and large surface elements, while k_{sur} is between 2.00 and 3.00 for structures consisting of small surface elements. Factor k_{wc} is 1.00 for brush and roller painting. The k_{wc} for sprayed surfaces is 1.05 for spraying in confined space, 1.10 for spraying outdoors in windless conditions and 1.20 for spraying outdoors in windy conditions, respectively.

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 floor-slab panels may be used before they have to be replaced with the new ones. The n_{uc} varies considerably from company to company, namely from 10 to 100.

3.3.2. Power costs

Sawing the steel section:

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

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 performed by the power hacksaw and $b_{i,j}$ [m] is the overall web width of the truss member. For the purpose of the power consumption cost estimation in this paper, the 85 percent machine power efficiency is proposed to be a typical value for machining processes (η_{hs} is 0.85). The typical value $k_{am} = 1.09$ proposed by Creese *et al.* (1992) may be used for machining processes. In the Slovenian company Metalna (Kravanja *et al.* 1995, 1998 and Kravanja 2002), the proposed approximate cutting time $T_{c,hs} = 1.337$ h/m was used for standard open structural steel sections with the depth up to 700 mm. The times for the hand cutting and machine grinding of the strut ends in tubular structures may be found in the work of Jármai (2003).

Edge grinding the steel section:

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

where P_{gm} [kW] and η_{gm} are the machine power and the machine power efficiency of the grinding machine; T_g [h/m] is the time of edge grinding and $l_{g_{i,j}}$ [m] is the grinding length of the individual truss member. The proposed value η_{gm} is 0.85. The basic edge grinding times T_g for the steel plates and the flat open structural sections 22.2×10^{-3} h/m, 33.3×10^{-3} h/m, 44.4×10^{-3} h/m and 55.6×10^{-3} h/m have been suggested for steel plate thickness 10, 20, 30 and 40 mm, respectively, by Metalna's normatives (defined on the basis of their own measurements and research).

Shielded metal arc welding:

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

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. The electric power price is constant, but at different technologies both current and voltage can be different. Most arc welding power supplies are approximately 90 percent efficient (η_w is 0.9), see Creese *et al.* (1992). In Metalna's normatives, the deposition rate for the welding current of 230 A and the voltage of 25 V is claimed to be 3.7 kg/h.

Stud arc welding:

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

where I_{sw} [kA], U_{sw} [V] and T_{sw} [h/stud] are the current, the voltage and the time required for stud welding. Under normal welding conditions, the output voltage ranges between 20 and 40 V, see Cary (1995). In catalogues of different producers, the welding currents are generally valued between 0.2 and 2500 kA and the welding times between 0.1 and 2 s. Some guidelines for the stud welding current and time in dependence with the stud base diameter have been proposed by the Stud Welding Associates (2005).

Vibrating the concrete:

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

where P_v [kW] and η_v are the power and the machine power efficiency of the internal concrete vibrator, respectively; T_v [h/m^2] is the time required for consolidation of the concrete. The proposed value η_v is 0.85. In cases when the diameters of the vibrating head range from ø30 to ø48 mm and the depths of concrete slab are between 10 and 25 cm, the required vibration time T_v can be according to Bučar (1999) between 0.2 and 0.4 h/m^2.

3.3.3. 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:

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

where $T_{p,a,t}$ [h] denotes the time for the preparation, assembling and tacking of the welded structure. The calculation of $T_{p,a,t}$ can be performed by using the expression proposed by Jármai and Farkas (1999).

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_d can be defined between 0.8 and 1.2 for a skilled welder; in normal conditions k_d is 1.0), k_{wp} is the factor which considers the welding position (k_{wp} is 1.0 for flat positions, k_{wp} is 1.1 for vertical and overhead positions), k_{wd} is the factor which considers the welding direction (for flat positions: k_{wd} is 1.0, for vertical and overhead positions: k_{wd} is 1.0 for vertical welds and k_{wd} is 1.4 for horizontal welds), k_{wl} considers the shape and the length of the weld (k_{wl} is 1.0 for continuous welds and welds longer than 0.5 m and k_{wl} is 1.2 for discontinuous welds and for welds shorter than 0.5 m), k_r considers the chamfering of the root of the weld (k_r is 1.2 for a chamfered root, otherwise k_r is 1.0); T_{SMAW} [h/m] is the time required for manual shielded metal arc welding. The welding time T_{SMAW} may be determined by using the approximation functions proposed in Table 4 and also by using the expressions introduced by Jármai and Farkas (1999).

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 (in the case of the flat welding position, T_{swp} is 55.55×10^{-4} h/stud).

Steel surface preparation and protection:

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

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. Jármai and Farkas (1999) proposed k_{dp} to be 1, 2, 3 for horizontal, vertical and overhead painting (and sand-spraying), respectively. Times T_{ss}, T_{ac}, T_{fp} and T_{tc} are approximately 0.050 h/m^2. In most of the cases n_{ac} and n_{tc} are 1. The n_{fp} significantly varied in dependence with the intumescent paint properties and the cross-sectional characteristics of the individual structural section. For fire class R30: the n_{fp} was between 1 and 3 for the standard open sections, while n_{fp} was between 2 and 6 for the standard hollow sections.

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

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

where T_f [h/m^2] represents the time necessary for panelling, levelling, disassembly and cleaning a formwork. The time T_f for fully prefabricated formwork systems and for skilled workers in common building constructions ranges between 0.20 and 0.30 h/m^2, see Bučar (1999).

Cutting, placing and connecting the reinforcement:

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

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. Factor k_{rh} is 1.00 for structural heights of less than 6 m and k_{rh} is 1.20 for structural heights of over 6 m. The k_{ri} is 1.00 for a concrete slab inclined less than 30º and k_{ri} is 1.10 for a concrete slab inclined more than 30º. Bučar (1999) has proposed the time T_r to be between 0.0355 h/kg and 0.0090 h/kg for the consumption of steel-wire mesh reinforcement within the range of 2.0 and 10.0 kg on m^2 of useable slab surface.

Concreting the slab:

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

where T_c [h/m^3] represents the time required for placement of the pumped concrete. According to data given by Bučar (1999) for the average mobile concrete pump with the effective vertical range of 20 m and the depth of the concrete slab between 10 and 25 cm the time T_c is between 0.70 and 1.14 h/m^3.

Concrete consolidation:

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

Curing the concrete:

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

where T_{cc} [h/m^3] is the time required for the curing of the concrete. When concrete is placed in a concrete slab of the depth between 10 and 25 cm at a temperature between +2° and +20°C, the curing time T_{cc} is 0.20 h/m^3, see Bučar (1999).

3.4. Structural analysis constraints

The objective function is subjected to structural analysis constraints. The structural analysis inequality constraints and the bounds of the variables represent a rigorous system of design, load, resistance and deflection functions known from the structural analysis. Only the basic constraints are presented in the paper, see Table 1. Since these constraints are defined in accordance with Eurocode 4 in order to satisfy the requirements of both the ultimate and the serviceability limit states, they are divided into two subsets:

- Ultimate limit state constraints (ULS),
- Serviceability limit state constraints (SLS).

The listed ultimate limit state constraints are defined by Eqs. (23) - (44). Eqs. (23) - (25) present the condition for the bending moment resistance of the composite truss cross-section, where $M_{Sd,ct}$ in Eq. (24) represents the design bending moment and $M_{pl,Rd,ct}$ given by Eq. (24) denotes the plastic bending moment resistance. The following group of expressions, Eqs. (26) - (28), introduce the necessary condition for the local bending moment resistance of the top chord cross-section. While $M_{Sd,tc}$ assigned in Eq. (27) is the design bending moment imposed to top chord, $M_{pl,Rd,tc}$ shown in Eq. (28) denotes the top chord's plastic bending moment resistance. The condition for the tension resistance of the truss diagonals is indicated in Eqs. (29) - (30), where $N_{Sd_{i,j}}$ denotes the design axial force and $N_{pl,Rd_{i,j}}$ represents the plastic tension resistance of the individual bracing member. The requirement for the compression/buckling resistances of each truss vertical $N_{b,Rd_{i,j}}$ is handled by the constraints in Eqs. (31) - (32). The proper transfer of the design longitudinal shear force V_l between the concrete slab and top chord of the steel truss is assured with the condition for the resistance of the shear connector P_{Rd}, see Eqs. (33) - (35). Eqs. (36) - (38) represent the condition for the design resistance of the fillet weld, where $F_{w,Sd}$ in Eq. (37) represents the design force which is transmitted by the weld and $F_{w,Rd}$ given by Eq. (38) designates the design resistance of the weld. The inequality in Eq. (39) is the condition for resistance to the longitudinal shear in the concrete slab. While the design longitudinal shear per unit length v_{Sd} is calculated using Eq. (40), the design resistance of the surfaces of the potential longitudinal shear failure v_{Rd} is defined by Eq. (41). The condition for the bending moment resistance of the concrete slab is introduced by Eqs. (42) - (44), where $M_{Sd,cs}$ and $M_{ult,cs}$ denote the design bending moment and the ultimate moment capacity of the concrete slab, respectively.

The presented serviceability limit state constraints comprise Eqs. (45) - (55). The vertical deflections of the composite truss are checked by the conditions handled in Eqs. (45) - (50), where δ_2 is the deflection of the composite truss subjected to a variable imposed load, $\delta_{\max}$ is the deflection of the composite truss subjected to the overall load, δ_{cr} is the deflection of the composite truss subjected to a permanent load and a creep of concrete and δ_{sh} is the deflection of the composite truss subjected to shrinkage of concrete. The condition for vertical deflections of the concrete slab is defined by Eqs. (51) - (55). The total deflection of the reinforced concrete slab subjected to the overall load δ_{∞}, the deflection of a cracked reinforced concrete slab subjected to the overall load $\delta_{c,\infty}$ and the deflection of an uncracked reinforced concrete slab subjected to the overall load $\delta_{u,\infty}$ are calculated by using the expressions given in Eqs. (52), (54) and (55), respectively. All the denotations used in the equations are explained in the Notations at the end of the paper.

Table 1 Structural analysis constraints

Structural analysis constraints	
Ultimate limit state constraints (ULS):	
- resistance to the bending moment of the composite truss cross-section:	
$M_{Sd,ct} \leq M_{pl,Rd,ct}$	(23)
$M_{Sd,ct} = q_{sd,ct} \cdot L^2 / 8$ where $q_{sd,ct} = (\gamma_g \cdot g + \gamma_q \cdot q \cdot e)$	(24)
$M_{pl,Rd,ct} = [h_{tb} + (h_t - z_{tt}) + d - (A_b \cdot f_y \cdot \gamma_c) / (4 \cdot b_e \cdot \alpha_c \cdot f_{ck} \cdot \gamma_a)] \cdot A_b \cdot f_y / \gamma_a$	(25)
- local bending moment resistance of the top chord cross-section:	
$M_{Sd,tc} \leq M_{pl,Rd,tc}$	(26)
$M_{Sd,tc} = q_{sd,ct} \cdot (L / n_{ip})^2 / 11.67$	(27)
$M_{pl,Rd,tc} = W_{pl,tc} \cdot f_y / \gamma_{M0}$	(28)
- tension resistance of the truss diagonals[(a)]:	
$N_{Sd_{i,j}} \leq N_{pl,Rd_{i,j}}$	(29)
$N_{pl,Rd_{i,j}} = A_{i,j} \cdot f_y / \gamma_{M0}$	(30)
- compression/buckling resistance of the truss verticals[(a)]:	
$N_{Sd_{i,j}} \leq N_{b,Rd_{i,j}}$	(31)
$N_{b,Rd_{i,j}} = \chi z_{i,j} \cdot A_{i,j} \cdot f_y / \gamma_{M1}$	(32)
- resistance of the shear connectors – cylindrical shear studs:	
$V_l \leq ½ \cdot n_{sc} \cdot P_{Rd}$	(33)
$V_l = \min \{A_b \cdot f_y / \gamma_a; 2 \cdot b_e \cdot \alpha_c \cdot f_{ck} / \gamma c\}$	(34)
$P_{Rd} = \min \{0.29 \cdot \alpha \cdot d_{sc}^2 \cdot (f_{ck} \cdot E_{cm})^{½} / \gamma_v; 0.8 \cdot fu \cdot \pi \cdot d_{sc}^2 / (4 \cdot \gamma_v)\}$	(35)
- resistance of the fillet welds:	
$F_{w,Sd_{i,j}} \leq F_{w,Rd_{i,j}}$	(36)
$F_{w,Sd_{i,j}} = N_{Sd_{i,j}}$	(37)
$F_{w,Rd_{i,j}} = a_{w_{i,j}} \cdot f_{uw} \cdot l_{w_{i,j}} / (3^{½} \cdot \beta_w \cdot \gamma_{Mw})$	(38)
- resistance to the longitudinal shear in the concrete slab:	
$v_{Sd} \leq v_{Rd}$	(39)
$v_{Sd} = 2 \cdot V_l / L$	(40)
$v_{Rd} = \min \{2.5 \cdot A_{cv} \cdot \eta \cdot \tau_{Rd} + A_e \cdot f_{ya} / \gamma_s; 0.2 \cdot \eta \cdot A_{cv} \cdot f_{ck} / \gamma_c\}$	(41)
- bending moment resistance of the concrete slab:	
$M_{Sd,cs} \leq M_{ult,cs}$	(42)
$M_{Sd,cs} = q_{sd,cs} \cdot e^2 / 16$ where $q_{sd,cs} = (\gamma_g \cdot \rho_c \cdot b_{cu} \cdot d + \gamma_q \cdot q \cdot b_{cu})$	(43)
$M_{ult,cs} = 0.48 \cdot \alpha_c \cdot f_{ck} \cdot b_{cu} \cdot x_p^2 / \gamma_c + A_s \cdot b_{cu} \cdot (d - x_p) \cdot f_{ya} / \gamma_s$	(44)
Serviceability limit state constraints (SLS):	
- checking the vertical deflections of the composite truss	
$\delta_2 \leq L / 300$	(45)
$\delta_2 = 5 \cdot q \cdot e \cdot L^4 / (384 \cdot E_a \cdot I_i)$	(46)
$\delta_{\max} \leq L / 250$	(47)
$\delta_{\max} = \delta_2 + \delta_{cr} + \delta_{sh}$	(48)
$\delta_{cr} = 5 \cdot q \cdot e \cdot L^4 / (384 \cdot E_a \cdot I_{cr})$	(49)
$\delta_{sh} = M_{sh} \cdot L^2 / (8 \cdot E_a \cdot I_{sh})$	(50)
- checking the vertical deflections of the concrete slab in the span between the steel trusses	
$\delta_\infty \leq L / 250$	(51)
$\delta_\infty = \zeta \cdot \delta_{c,\infty} + (1 - \zeta) \cdot \delta_{u,\infty}$	(52)
$\zeta = 1 - 0.5 \cdot (\sigma_{sr} / \sigma_s)$	(53)
$\delta_{c,\infty} = k \cdot [\rho_c \cdot b_{cu} \cdot d \cdot e^4 / (E_{c,eff} \cdot I_c) + q \cdot b_{cu} \cdot e^4 / (E_{cm} \cdot I_c)]$	(54)
$\delta_{u,\infty} = k \cdot [\rho_c \cdot b_{cu} \cdot d \cdot e^4 / (E_{c,eff} \cdot I_u) + q \cdot b_{cu} \cdot e^4 / (E_{cm} \cdot I_u)]$	(55)

[(a)]the design axial forces in the bracing members are calculated using the method of joints

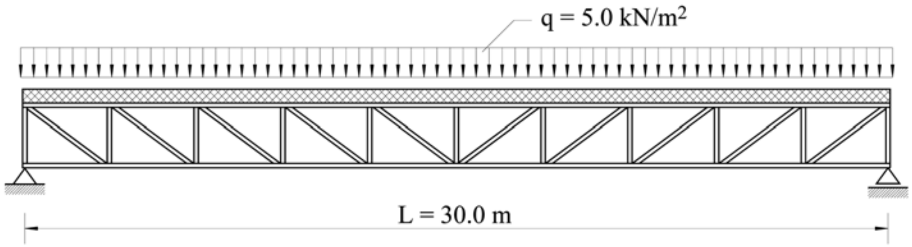

Fig. 4 Composite truss system

4. Numerical example

In order to present the applicability of the proposed approach, the paper presents an example of the cost optimization of a simply supported composite floor truss system, shown in Fig. 4. The considered composite trusses are 30 m long, subjected to self-weight and the variable imposed load of 5.0 kN/m^2.

4.1. Input data

Truss members are proposed to be designed from the European channel sections, i.e., UPE sections. They are cut by means of a power hacksaw and prepared to be welded by using an edge grinding machine. The bracing members are manually welded together with a combination of fillet welds and full penetration ½ 60°V welds, see Fig. 6. The shielded metal arc welding technology (SMAW) is used. The trusses and the concrete slab are connected together by cylindrical shear studs with a 19 mm wide base diameter. Cylindrical studs are welded semi-automatically to the top chord of the steel truss by using the stud arc welder. The steel surfaces are manually sand-sprayed and brushed over with a single coat of anti-corrosion paint, two coats of fire protection paint F 30 and a top coat.

With the assembling of the fully prefabricated formwork the panelling of the concrete slab is complete. It is assumed that formwork floor-slab panels can be used 30 times before they have to be replaced with new ones. The slab is reinforced with the one-way spanning high bond steel-wire mesh reinforcement S 400. The placement and consolidation of the concrete is achieved by using a mobile

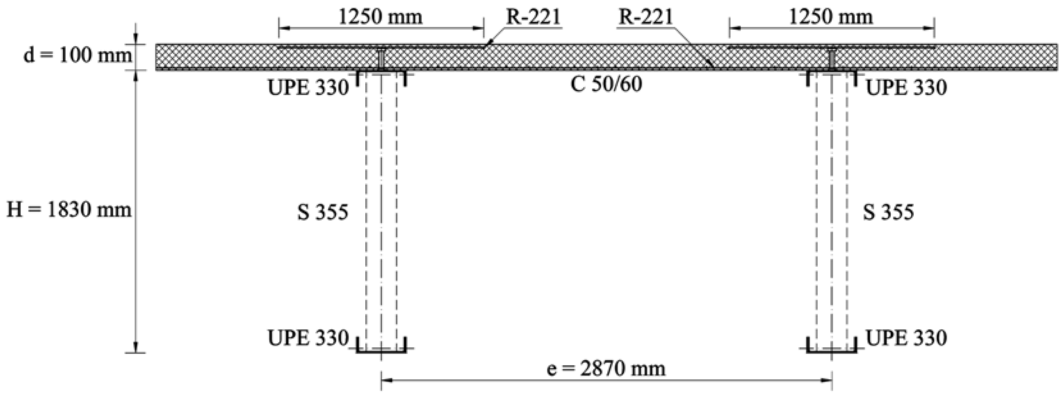

Fig. 5 Optimum cross-section design of the composite floor trusses

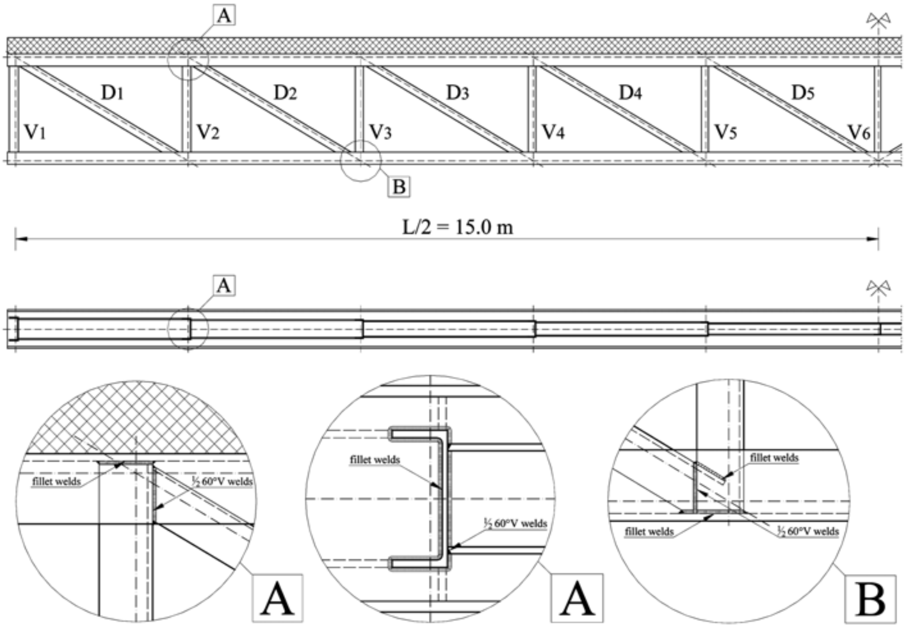

Fig. 6 Arrangement of bracing members and design of welded joints

Table 2 Material, power and labour cost parameters

$c_{M,s}$[(a)]	Price of the structural steel S 235 – S 355:	1.00 – 1.07	€/kg
$c_{M,c}$[(b)]	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

[(a)] Price of the structural steel is calculated by using the following approximation function:
$c_{M,s} = -3.7202\times10^{-4}\cdot f_y^2 + 2.7902\times10^{-2}\cdot f_y + 5.4976\times10^{-1}$ [€/kg] and f_y [kN/cm^2].
[(b)] Price of the concrete is calculated by using the following approximation function:
$c_{M,c} = -2.7387\cdot f_{ck}^2 + 34.4850\cdot f_{ck} + 16.0050$ [€/kg] and f_{ck} [kN/cm^2].

concrete pump and the internal vibrators. The concrete is cured by ponding the water for 3 days after the placement.

The material, power and labour cost parameters used in the optimization are shown in Table 2. The fabrication times and the approximation functions for the fabrication times are shown in Tables 3 and 4. All other input data are listed in Table 5.

Table 3 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 and 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 paneling, leveling, disassembly and cleaning the formwork: 0.300 h/m^2
T_r	Time for cutting, placing and connecting the reinforcement: 0.024 h/kg
T_{cc}	Time for curing the concrete: 0.200 h/m^3

Table 4 Approximation functions for fabrication times

$T_{p,a,t}$[(a)]	Time for preparation, assembling and 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}[(b)]	Time for manual shielded metal arc welding: <u>Fillet welds:</u> $T_{SMAW} = a_2 \cdot a_w^2 + a_1 \cdot a_w + a_0$ [h/m]; $a_2 = 1.2653 \times 10^{-2}$; $a_1 = 1.3773 \times 10^{-3}$; $a_0 = 1.6111 \times 10^{-2}$ and a_w [mm]. <u>½ 60° V welds:</u> $T_{SMAW} = b_6 \cdot a_w^6 + b_5 \cdot a_w^5 + b_4 \cdot a_w^4 + b_3 \cdot a_w^3 + b_2 \cdot a_w^2 + b_1 \cdot a_w + b_0$ [h/m]; $b_6 = -1.7138 \times 10^{-8}$; $b_5 = 1.7372 \times 10^{-6}$; $b_4 = -0.5576 \times 10^{-4}$; $b_3 = 4.1851 \times 10^{-4}$; $b_2 = 1.0805 \times 10^{-2}$; $b_1 = -0.7401 \times 10^{-1}$; $b_0 = 2.8286 \times 10^{-1}$ and a_w [mm].
T_c[(c)]	Time for placement of pumped concrete: $T_c = c_2 \cdot d^2 + c_1 \cdot d + c_0$ [h/m^3]; $c_2 = 2.4000 \times 10^{-3}$; $c_1 = -5.4000 \times 10^{-2}$; $c_0 = 9.9500 \times 10^{-1}$ and d [cm].

[(a)] Fabrication time proposed by Jármai and Farkas (1999) and Jármai (2003).
[(b)] Approximation functions developed on the basis of data given by company Metalna, see Kravanja *et al.* (1995, 1998, 2002), for sizes of fillet welds 3-28 mm and for sizes of full penetration ½ 60°V welds 3-40 mm.
[(c)] Approximation function developed on the basis of data given by Bučar (1999).

4.2. Optimization

The purpose of the optimization was to find the optimal cross-section sizes, the optimal concrete strength and the steel grade of the considered composite floor truss with respect to the minimum of manufacturing costs, subjected to the design, load, resistance and deflection constraints, defined in accordance with the Eurocodes.

The proposed optimization model COMPFT was applied. A variety of concrete strengths from 25 to 50 MPa (C 25/30 to C 50/60) and three different structural steels S 235, S 275 and S 355 were proposed to be included in the optimization. While the material costs of the structural steel S 235 and the concrete C 25/30 were considered to be the input data, the costs of higher steel grades and concrete strengths were calculated by means of the approximation functions throughout the optimization process.

The optimization of the composite floor truss was executed in two successive steps. The first step represents the ordinary NLP optimization, where the continuous variables (dimensions, materials) were calculated inside their upper and lower bounds. At this stage, the structure is fully exploited considering either ultimate or serviceability limit state conditions. In the second step, the calculation was repeated/

Table 5 Input data

ρ_s	Steel density: 7850 kg/m^3
ρ_c	Concrete density: 2500 kg/m^3
EMY	Electrode metal yield: 0.60
$k_p^{(a)}$	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
U	Welding voltage: 25 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 normal conditions
k_{wp}	Difficulty factor – welding position: 1.00 for flat 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.

Table 6 Obtained optimal design parameters of the composite floor truss

Top and bottom chords: UPE 330
Diagonals D_1: UPE 180, D_2: UPE 160, D_3: UPE 140, D_4: UPE 120, D_5: UPE 100
Verticals V_1: UPE 200, V_2: UPE 180, V_3: UPE 160, V_4: UPE 140, V_5: UPE 120, V_6: UPE 100
Depth of the concrete slab: d = 10.0 cm
Overall depth of the steel truss: H = 183.0 cm
Intermediate distance between the steel trusses: e = 287.0 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 50/60): f_{ck} = 50.0 kN/cm^2
Manufacturing costs of the composite floor truss per m^2: *Cost* = 103.63 €/m^2

*for denotations of bracing members, see Fig 6.

Table 7 Recapitulation of the optimal manufacturing costs

MATERIAL COSTS:		
$C_{M,s}$	Structural steel S 355	4253.08 €
$C_{M,c}$	Concrete C 50/60	1032.88 €
$C_{M,r}$	Steel-wire mesh reinforcement R-221 S 400	196.40 €
$C_{M,sc}$	Cylindrical shear studs	38.00 €
$C_{M,e}$	Electrodes	13.17 €
$C_{M,ac,fp,tc}$	Anti-corrosion paint, fire protection paint and top coat paint	1029.10 €
$C_{M,f}$	Floor-slab panels	86.10 €
	Total material costs:	6648.73 €
POWER COSTS:		
$C_{P,c,hs}$	Sawing	2.34 €
$C_{P,c,gm}$	Edge grinding process	0.02 €
$C_{P,w}$	Welding process	0.80 €
$C_{P,sw}$	Arc stud welding process	0.06 €
$C_{P,v}$	Vibrating the concrete	6.28 €
	Total power consumption costs:	9.50 €
LABOUR COSTS:		
$C_{L,c,hs}$	Sawing	180.71 €
$C_{L,g}$	Edge grinding	2.21 €
$C_{L,p,a,t}$	Preparation, assembly and tacking of the elements	302.16 €
$C_{L,SMAW}$	Welding process performed by SMAW technology	167.52 €
$C_{L,sw}$	Arc stud welding process	8.44 €
$C_{L,spp}$	Sand-spraying, anti-corrosion, fire resistant and top coat painting	468.43 €
$C_{L,f}$	Placing the formwork	516.60 €
$C_{L,r}$	Cutting, placing and connecting the reinforcement	120.45 €
$C_{L,c}$	Concreting the reinforced concrete slab	119.68 €
$C_{L,v}$	Consolidating the concrete by internal vibrators	344.40 €
$C_{L,cc}$	Curing the concrete	34.44 €
	Total labour costs:	2265.04 €
TOTAL MANUFACTURING COSTS per 1 composite truss:		**8923.27 €**
Manufacturing costs per m^2 of useable surface of the composite floor:		103.63 €/m^2

checked for the fixed variables rounded up, from in the first stage obtained continuous values, to their nearest upper standard/discrete values. CONOPT (Generalized reduced-gradient method) (Drud 1994) was used for the optimization.

4.3. Results

The obtained optimal design of the considered composite floor truss is presented in Figs. 5 and 6. The optimal result of 8923.27 € per single composite truss (or 103.63 € per m^2 of useable surface of the composite floor system) was obtained in the second NLP stage. Alongside the optimal manufacturing

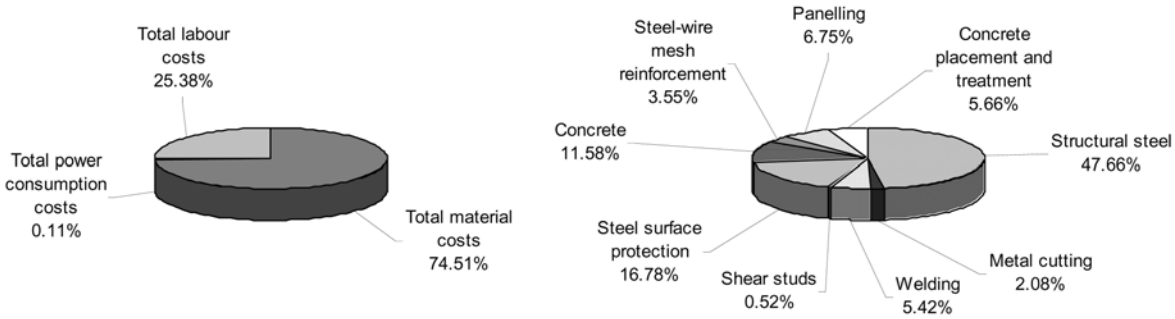

Fig. 7 The distribution of the optimal manufacturing costs of the composite truss system

costs, there were also obtained: the optimal steel grade S 355, the concrete strength C50/60, the intermediate distance between trusses, the overall depth of the composite truss, the depth of the slab, the cross-section area of the wire mesh reinforcement and the optimal structural steel sections of all truss members (chords, diagonals and verticals), see Table 6.

The example also demonstrates the distribution of the manufacturing costs of the composite floor truss for the given economical data. In this case, the material costs represent approximately 75% and the labour costs 25% of the obtained manufacturing costs. The power consumption costs were found to be a negligible quantity, see Table 7 and Fig. 7.

5. Conclusions

The paper presents the cost optimization of the composite floor trusses composed from a reinforced concrete slab of constant depth and from steel trusses made from hot rolled channel sections. The optimization was performed by the nonlinear programming (NLP) approach. A NLP optimization model for composite floor trusses was thus developed. The economic objective function of the structure's manufacturing costs is subjected to a rigorous system of design, load, resistance and deflections inequality constraints, defined in accordance with Eurocode 4 to satisfied both the ultimate and the serviceability limit states.

An accurate objective function of the manufacturing material, power and labour costs was defined for the optimization. The material costs included 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 comprised the costs of sawing the steel sections, of edge grinding, welding, stud welding and vibrating the concrete. The labour costs (times) included 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.

Alongside the costs, the objective function also includes the fabrication times, electrical power and material consumption which provides the engineer with a detailed insight in the manufacturing costs distribution of the obtained optimal design. Since the cost function is detailed and formulated in an open manner, it can be easily adopted and used for any specific data in different economical and technological conditions. The numerical example presented at the end of the paper demonstrates the applicability of the proposed approach.

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Notations

A : cross-section area of the structural steel section
A_b : cross-section area of the bottom chord of the steel truss
A_{cv} : mean cross-section area per unit of truss length of the concrete shear surface under consideration
A_e : sum of the cross-section areas of transverse reinforcement per unit of truss length crossing the concrete shear surface under consideration
A_s : cross-section area of tension steel reinforcement per m^1
A_{ss} : steel surface area of the truss member
A_w : cross-section area of the weld
a_w : weld size
b : overall web width of the truss member
b_{cu} : unit width of the concrete slab
b_e : half of the effective width of the concrete slab
c_L : labour cost per working hour
$C_{L,c}$: labour costs for concreting the reinforced concrete slab
$C_{L,cc}$: labour costs for curing the concrete
$C_{L,c,hs}$: labour costs for sawing the steel section
$C_{L,f}$: labour costs for panelling, levelling, disassembly and cleaning a formwork
$C_{L,g}$: labour costs for edge grinding of the structural steel sections
$C_{L,p,a,t}$: labour costs for preparation, assembling and tacking of the welded structure
$C_{L,r}$: labour costs for cutting, placing and connecting the reinforcement
$C_{L,SMAW}$: labour costs for shielded metal arc welding
$C_{L,spp}$: labour costs for steel surface preparation and protection
$C_{L,sw}$: labour costs for welding the shear connectors
$C_{L,v}$: labour costs for vibrating the concrete
$C_{M,ac,fp,tc}$: material costs of anti-corrosion, fire protection and top coat paints
$c_{M,ac}$: price of anti-corrosion paint per m^2 of painted surface
$c_{M,c}$: price of concrete per m^3
$C_{M,e}$: material costs of electrode consumption
$c_{M,e}$: price of electrodes per kg
$C_{M,f}$: material costs of formwork floor-slab panels
$c_{M,f}$: material costs of the formwork floor-slab panels per m^2 of concrete slab panelling surface area
$c_{M,fp}$: price of fire protection paint per m^2 of painted surface
$c_{M,r}$: price of reinforcing steel per kg
$c_{M,s}$: price of structural steel per kg
$C_{M,sc}$: material costs of the cylindrical shear studs
$c_{M,sc}$: price of cylindrical shear studs per piece
$C_{M,s,c,r}$: material costs of the structural steel, concrete and reinforcement
$c_{M,tc}$: price of top coat paint per m^2 of painted surface
$Cost$: represents the self-manufacturing costs per m^2 of use surface of the composite truss system
c_p : electric power price
$C_{P,c,gm}$: power consumption costs for edge grinding of the structural steel section
$C_{P,c,hs}$: power consumption costs for sawing the steel section
$C_{P,sw}$: power consumption costs for stud welding
$C_{P,v}$: power consumption costs for vibrating the concrete
$C_{P,w}$: power consumption costs for welding

d : depth of the concrete slab
DR : deposition rate
d_{sc} : diameter of the shank of the cylindrical shear stud
e : intermediate distance between the trusses
E_a : elastic modulus of structural steel
E_{cm} : secant elastic modulus of normal weight concrete
$E_{c,eff}$: effective elastic modulus of concrete
EMY : electrode metal yield
f_{ck} : characteristic cylinder strength of concrete
f_u : ultimate tensile strength of the cylindrical shear studs
f_{uw} : nominal ultimate tensile strength of the welded steel material
$F_{w,Rd}$: design resistance of a weld
$F_{w,Sd}$: design force transmitted by the weld
f_y : yield strength of structural steel
f_{ya} : yield strength of reinforcing steel
g : self-weight of the composite truss
h_t : overall flange width of the top chord of the steel truss
h_{tb} : distance between the centroids of the chords of the steel truss
I : welding current
I_i : second moment of the area about the y-y axis of the equivalent transformed composite truss cross-section
I_c : second moment of the unit cross-section area of a cracked concrete slab about the y-y axis
I_{cr} : second moment of the area about the y-y axis of the equivalent transformed composite truss cross-section related to creep of the concrete
I_{sh} : second moment of the area about the y-y axis of the equivalent transformed composite truss cross-section regarding to shrinkage of the concrete
I_{sw} : stud welding current
I_u : second moment of the unit cross-section area of an uncracked concrete slab about the y-y axis
k : coefficient which depends on the number of spans of the continuous concrete slab
k_{am} : factor which considers the allowances to machining time
k_d : difficulty factor related to working conditions
k_{dp} : difficulty factor related to the painting position
k_p : paint loss factor related to the painting technique
k_{rh} : difficulty factor related to the structural height
k_r : factor which considers chamfering the root of the weld
k_{ri} : difficulty factor related to the inclination of the slab
k_{sur} : paint loss factor related to the complexity of structure's surface
k_{wc} : paint loss factor related to the weather conditions in which the structure is painted
k_{wd} : factor which considers the welding direction
k_{wl} : factor which considers the length of the weld
k_{wp} : factor which considers the welding position
L : span of the composite truss
l : length of the structural steel section
l_g : grinding length of the truss member
l_s : length of the reinforcing steel
l_w : length of the weld
$M_{pl,Rd,ct}$: plastic bending moment resistance of the composite truss cross-section
$M_{pl,Rd,tc}$: local plastic bending moment resistance of the top chord of the steel truss
$M_{Sd,cs}$: design bending moment of the concrete slab
$M_{Sd,ct}$: design bending moment of the composite truss
$M_{Sd,tc}$: design local bending moment of the top chord of the steel truss
M_{sh} : bending moment on account of the shrinkage of concrete

$M_{ult,cs}$: ultimate moment capacity of the concrete slab
n_{ac} : number of layers of anti-corrosion resistant paint
n_{fp} : number of layers of fire protection paint
n_{ip} : even topology constant-number of truss panels
$N_{b,Rd}$: compressive/buckling resistance of truss verticals
$N_{pl,Rd}$: tension resistance of truss diagonals
N_{Sd} : design axial (tensile or compressive) force in the individual bracing member
n_{sc} : number of cylindrical shear studs
n_{tc} : number of layers of top coat paint
n_{uc} : number, how many times the formwork floor-slab panels may be used before they have to be replaced with the new ones
P_{gm} : machine power of the grinding machine
P_{hs} : machine power of the hacksaw
P_{Rd} : shear resistance of the cylindrical studs
P_v : power of the internal concrete vibrator
q : variable imposed load per m^2 of the concrete slab use surface
$q_{sd,cs}$: design uniformly distributed load imposed on the concrete slab
$q_{sd,ct}$: design uniformly distributed load imposed on the composite truss
T_{ac} : time required for anti-corrosion resistant painting
T_c : time required for placement of pumped concrete
T_{cc} : time required for curing of concrete
$T_{c,hs}$: time required for steel cutting performed by the power hacksaw
T_f : time required for panelling, levelling, disassembly and cleaning a formwork
T_{fp} : time required for fire protection painting
T_g : time required for edge grinding of steel sections
$T_{p,a,t}$: time required for preparation, assembling and tacking of the welded structure
T_r : time required for cutting, placing and connecting the reinforcement
T_{SMAW} : time required for manual shielded metal arc welding
T_{ss} : time required for sand-spraying
T_{sw} : time required for stud welding
T_{swp} : time required for stud welding, placing/removal of a ceramic ferrule and cleaning the connection
T_{tc} : time required for top coat painting
T_v : time required for consolidation of the concrete
U : welding voltage
U_{sw} : stud welding voltage
V_l : design longitudinal shear force
v_{Rd} : design resistance of surfaces of potential longitudinal shear failure
v_{Sd} : design longitudinal shear per unit length of truss
$W_{pl,tc}$: plastic section modulus of the top chord of the steel truss
$\boldsymbol{X}$: compact set
$\boldsymbol{x}$: vector of continuous variables
x_p : vertical position of the plastic neutral axis of the concrete slab from the top edge
z : objective function
z_{tt} : vertical position of the centroid of the top chord of the steel truss

Greeks

α : coefficient related to slenderness of the cylindrical shear stud
α_c : coefficient which accounts for the long-term effects on the compressive strength of concrete and for the unfavourable effects resulting from the way in which the load is applied
β_w : correlation factor
γ_a : partial safety coefficient for structural steel
γ_c : partial safety coefficient for concrete

γ_g : partial safety coefficient for a permanent load
γ_{M0} : partial safety coefficient for Class 1, 2 and 3 cross-sections
γ_{M1} : partial safety coefficient for element instability
γ_{Mw} : partial safety coefficient for welds
γ_q : partial safety coefficient for the variable imposed load
γ_s : partial safety coefficient for the reinforcing steel
γ_v : partial safety coefficient for cylindrical shear studs
δ_{cr} : deflection of the composite truss subjected to a permanent load and creep of concrete
$\delta_{c,\infty}$: deflection of a cracked reinforced concrete slab subjected to the overall load
$\delta_{u,\infty}$: deflection of an uncracked reinforced concrete slab subjected to the overall load
$\delta_{\max}$: deflection of a composite truss subjected to the overall load
δ_{sh} : deflection of a composite truss subjected to shrinkage of concrete
δ_2 : deflection of a composite truss subjected to a variable imposed load
δ_∞ : total deflection of the reinforced concrete slab subjected to the overall load
ζ : distribution coefficient
η : coefficient related to weight characteristics of the concrete slab
η_{gm} : machine power efficiency of the grinding machine
η_{hs} : machine power efficiency of the hacksaw
η_v : machine power efficiency of the internal concrete vibrator
η_w : machine power efficiency of the arc welding machine
π : Ludolf's number
ρ_c : concrete density
ρ_s : steel density
σ_s : stress in tension steel reinforcement calculated on the basis of a cracked concrete section
σ_{sr} : stress in tension steel reinforcement calculated on the basis of a cracked concrete section under the loading which will just cause cracking
τ_{Rd} : basic shear strength of concrete
χ_z : reduction factor for the relevant buckling mode about the z-z axis

Subscripts

i : first end joint of the truss element
j : second end joint of the truss element

Superscripts

LO : lower bound
UP : upper bound

CC