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*Research Article*

# Sizing optimization of the protected steel components at elevated temperature

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**Abstract:** In this paper, the metaheuristic algorithms such as Flower pollination and Harmony search algorithms are proposed to optimize the sizes of the steel components at the elevated temperature dealing with EN 1993 1-2. The purpose of these algorithms inspired by nature is to obtain the appropriate cross-section properties of the welded I sections. Numerical examples from the literature consisting of the protected steel structural components have been resized under different fire situations such as 30-, 60- and 90-minutes fire time. Based on the results from the numerical examples, the effect of the fire protection materials on the objective function (total weight of the steel structures) is quite high and the reduction of the total cost is almost 30% compared with the other studies. In addition, one of the most important duties of civil engineers, ensuring the balance between economic efficiency and safety, is fulfilled in a short time with the aid of the metaheuristic algorithms

**Keywords:** Eurocode 3, fire design, metaheuristic algorithms, optimization, steel structures.

## 1. Introduction

In civil engineering, some optimization methods, which are responsible to determine the optimal value of the design variables and objective function, instead of a trial-and-error based procedure of engineers are developed in order to ensure safety and economical design in complex problems. Among these optimization methods (stochastic search techniques), the most important advantage of the metaheuristic algorithms is to obtain the effective engineering solutions in a much shorter time considering the limitations described by regulations. Whale optimization algorithm (WOA) (Mirjalili and Lewis, 2016), Harmony search (HS) (Geem et al., 2001), Flower pollination algorithm (FPA) (Yang, 2012), Jaya algorithm (Rao, 2016) Imperialist competitive algorithm (ICA) (Atashpaz-Gargari and Lucas, 2007), Particle Swarm Optimization (PSO) (Kennedy and Eberhart, 1995), Evolutionary algorithms (EA) (Vikhar, 2016), Bat algorithm (BA) (Yang, 2010), Firefly algorithm (FA) (Fister et al., 2013), Artificial bee colony (ABC) (Karaboga and Basturk, 2008), Teaching-learning based Optimization (TLBO) (Rao et al., 2011), Farmland Fertility (FF) (Shayanfar and Gharehchopogh , 2018) Archimedes optimization algorithm (AOA) (Hashim et al., 2021), the gannet optimization algorithm (GOA) (Pan et al.,2022) and War Strategy Optimization (WSO) (Ayyarao et al., 2022) are used the most metaheuristic algorithms for optimal design in engineering problems. The common feature of these metaheuristic algorithms, which have different properties in their mathematical expressions, is the random selection of design variables and the selection of the best target function.

There are many studies in the literature in which an optimal design of steel structures is carried out using existing, new, and modified or hybrid generation metaheuristic algorithms. For examples, a new hybrid algorithms consisting of a combination of PSO and charged system search (CSS) has been introduced to optimally design the space steel frame (Kaveh and Talatahari, 2012). The optimal cross sections of the different structures (unbraced steel frame, industrial steel structure and high-rise braced steel frame) are calculated using heuristic algorithm (Ky et al., 2015) such as BA (Hasancebi and Carbas, 2014), TLBO (Togan, 2012) and School based optimization algorithm (SBO) (Farshchin et al, 2018). The optimum design of the nonlinear steel frame structures and time-cost- quality for construction projects are done via Genetic Algortihm GA (Pezeshk et al., 2000; Akcay and Isıkyıldız, 2020).

Also, the effect of the connection and geometrical nonlinearity on the steel structures design is demonstrated with the help of GA (Kameshki and Saka, 2001) and HS with a multi-comparison technique (MCT) (Truong and Kim, 2018). A new optimal design procedure technique including PSO is proposed for steel structures subjected to earthquake (Gholizadeh and Salajegheh, 2009). In addition, optimum PSO design of simple steel frame against the seismic loads is done considering the fabrication costs and the selection of the connection type (Jarmai et al., 2006). To investigate the influence of soil structure interaction effect (SSI), the metaheuristic based optimization design such as HS and GA are presented for the steel space frame (Daloglu et al, 2016). The optimum cross sections of moment steel frame for performance based seismic design is selected using a neural network model with modified firefly algorithm (MFA) (Gholizadeh, 2015), the newly proposed algorithm Newton Metaheuristic Algorithm (NMA) (Gholizadeh et al., 2020) and School based optimization algorithm (Degertekin et al., 2021). The different metaheuristic algorithms, FPA , HS and FA are applied to minimize the total weights of various truss structures made of steel (Bekdas et al., 2015; Miguel, 2012). All these studies indicate that the proposed metaheuristic algorithms are proved better robustness and effectiveness than the other optimization methods.

There are some investigations in the literature about the behavior of steel structures in case of fire. The material properties such as stiffness retention, temperature development, thermal properties and strength of the stainless and carbon steel are compared based on the numerical analytical and experimental results (Gardner, 2007). To demonstrate the behavior of the stainless steel I section at the elevated temperature, shell finite element models are created to compare it with the experimental results (Xing et al., 2021). The unprotected stainless steel beams and columns are experimentally tested to develop the design of steel structures at elevated temperature (Gardner and Baddoo, 2006). The performance of the steel circular hollow section components subjected to compression is examined at the elevated temperature using normal (S235 S275 and S355) and high strength (S460 and S690) steel material (Kucukler, 2020). The material behavior, the stability and cross- sectional capacity of the carbon steel with different section typs such as H-section (HEA), rectangular and square hollow section are studied in fire (Gardner and Nethercot, 2004).

The structural optimization of steel structures has been made generally at the room temperature in recent years. However, fire resistance optimization techniques for these structures have received little attention. In this paper, two metaheuristic algorithms such as FPA and HS are proposed to calculate the optimum cross section of the steel structures with and without protection materials in case of 30, 60 and 90 minutes fire. The design of these structures is done according to EN 1993 1-2 (Eurocode 3: Design of Steel structures - Part 1- 2 General structural fire design, 2004).

## 2. Materials and methods

### 2.1. *Design of steel structures in case of fire*

Structural fire protection is an essential factor for the economical design of the structures. Therefore, the possible fire protection solutions such as fire protection materials for 60- and 90-minutes fire or the appropriate cross-section for 30 minutes fire should be taken into account in the planning phase. Thus, the robustness of the steel structures due to rapid loss of strength at temperatures of more than 500 degrees can be guaranteed. Two design methods (simplified and advanced design models) are permitted to detect the fire resistance of the steel members according to EN 1993 1-2. It is generally proven that the mechanical actions can be absorbed by a steel component or a steel structure after the expiration of the prescribed fire time. The equation of the mechanic actions according to EN 1990:2002 (Eurocode: Basis of structural design, 2002) and EN 1993 1-2 is given in Eq. (1). $A_d(t)$ is the design value of indirect actions and is equal to 0 if, for example, a statically determined system is involved. $\psi_{1,1}$ and $\psi_{2,i}$ are the combination factors for the frequent value and quasi-permanent value of the variable actions ( $Q_{k,1}$ , $Q_{k,i}$ ), respectively. $G_k$ is the characteristic value of the permanent action. $\gamma_{GA}$ is the partial factor for the permanent actions. Also, the actions in fire can obtained like Eq. (2) with a simplification from the actions at normal temperature. $E_d$ is the design value at normal temperature, $E_{d,fi}$ is the design value at the elevated temperature, and $\eta_{fi}$ is reduction factor for design load. The critical steel temperature $\theta_{a,cr}$ is calculated as follows:

$$E_{d,fi} = \sum \gamma_{GA} * G_k + \psi_{1,1} * Q_{k,1} + \sum \psi_{2,i} * Q_{k,i} + \sum A_d(t) \quad (1)$$

$$E_{d,fi} = \eta_{fi} * E_d \quad (2)$$

$$\eta_{fi} = \frac{G_k + \psi_{1,1} Q_{k,1}}{\gamma_G G_k + \gamma_{Q,1} Q_{k,1}} \quad (3)$$

$$\theta_{a,cr} = 39.13 \, ln \left[ \frac{1}{0.9674 \, u_0^{3,833}} - 1 \right] + 482 \;\; with \; u_0 = n_{fi} \quad (4)$$

The material values of the steel vary in case of fire. For instance, the modulus of elasticity begins to decrease from around 100 degree or the effective yield strength begins to reduce after 400 degree or the behavior of steel in fire is not linearly elastic to the yield stress like at normal temperature. For this reason, the reduction factors for effective yield strength $k_{y,\theta}$, proportional limit $k_{p,\theta}$ and the slope of linear elastic range $k_{E,\theta}$ at the elevated temperature presented in Table 1 should be taken into account to determine the resistances to compression, tension shear or moment. Also, the specific heat $c_a$ [J/kgK] of steel components changes at the elevated temperature. The equations of the change of the specific heat of steel are given in Eqs (5), (6) and (7).

For 20°C ≤ $\theta_a$ < 600°C:

$$c_a = 425 + 7{,}73 * 10^{-1}\theta_a - 1{,}69 * 10^{-3}\theta_a^2 + 2{,}2 * 10^{-6}\theta_a^3 \quad (5)$$

For 600°C ≤ $\theta_a$ < 735°C:

$$c_a = 666 + \frac{13002}{738 - \theta_a} \quad (6)$$

For 735°C ≤ $\theta_a$ < 900°C:

$$c_a = 545 + \frac{17820}{\theta_a - 731} \quad (7)$$

For 900°C ≤ $\theta_a$ ≤ 1200°C:

$$c_a = 650$$

The development of the steel temperature according to EN 1993-1-2 (simplified design models) can be calculated for two cases such as unprotected internal steelwork and internal steelwork with fire protection material depending on the fire exposure over time. In both cases, the temperature is evenly distributed over the steel cross-section due to the high thermal conductivity and the time step method is used to determine the ambient gas temperature $\theta_{g,t}$ and steel temperature $\theta_{a,t}$ at time t. The rise of temperature $\Delta\theta_{a,t}$ in a steel member without protection materials during a time interval $\Delta t$ is calculated as follows:

$$k_{sh} = 0{,}9 \frac{(A_m/V)_b}{(A_m/V)} \quad \text{for I section} \quad (9)$$

$$k_{sh} = \frac{(A_m/V)_b}{(A_m/V)} \quad \text{for all other cases} \quad (10)$$

$$\dot{h}_{net} = \dot{h}_c + \dot{h}_r \tag{11}$$

$$\dot{h}_c = \alpha_c(\theta_g - \theta_a) \tag{12}$$

$$\theta_g = 20 + 345\, log_{10}(8t + 1) \tag{13}$$

$$\dot{h}_r = \phi.\, \mathcal{E}_s.\, \mathcal{E}_f.\, \sigma \left[ \left(\theta_g + 273\right)^4 - \left(\theta_a + 273\right)^4 \right] \tag{14}$$

where $k_{sh}$ represents the correction factor for the shadow effect, $A_m$ is the surface area of the component for unit length [$m^2$/m], V is the volume of a component for unit length [$m^3$/m], $A_m/V$ is the section factor for unprotected steel components [1/m] defined in Table 3, $[Am/V]_b$ is box value of the section factor defined in Table 3, $\rho_a$ is the unit mass of steel [kg/$m^3$], $h_{net}$ is the design value of the net heat flux for unit area [W/$m^2$], $h_c$ is the rate of heat flux from convention, $h_r$ is the rate of heat flux from radiation, $\alpha_c$ is the convective heat transfer coefficient [W/$m^2$K], t is the time in fire exposure, ϕ is the configuration factor, $\mathcal{E}_s$ is the emissivity of steel, $\mathcal{E}_f$ is the emissivity of a flame and σ is the Stefan Boltzmann constant [W/$m^2K^4$].

**Table 1.** The reduction factors considering the strain stress relationship of the carbon steel in case of fire.

| Steel Temperature [°C] | Reduction Factors at $\theta_a$°C relating to the value of $f_y$ or $E_a$ at 20° | | |
|---|---|---|---|
| | Reduction factor (relating to $f_y$) for effective yield strength | Reduction factor (relating to $f_y$) for proportional limit | Reduction factor (relating to $f_y$) for the slope of the linear elastic range |
| | $k_{y,\theta}=f_{y,\theta}/f_y$ | $k_{p,\theta}=f_{p,\theta}/f_y$ | $k_{E,\theta}=E_{a,\theta}/E_a$ |
| 20-100 | 1.00 | 1.00 | 1.00 |
| 200 | 1.00 | 0.81 | 0.90 |
| 300 | 1.00 | 0.61 | 0.80 |
| 400 | 1.00 | 0.42 | 0.70 |
| 500 | 0.78 | 0.36 | 0.60 |
| 600 | 0.47 | 0.18 | 0.31 |
| 700 | 0.23 | 0.08 | 0.13 |
| 800 | 0.11 | 0.05 | 0.09 |
| 900 | 0.06 | 0.038 | 0.068 |
| 1000 | 0.04 | 0.025 | 0.045 |
| 1100 | 0.02 | 0.013 | 0.023 |

Note: linear interpolation may be used for intermediate values of the steel temperature,

There are different fire protection systems to limit the temperature rise of steel components in the event of a fire. These are cladding with fire rated boards, a hollow column with water and cooling a steel structure with sprinklers. In this study, plate cladding boards are used to protect the steel components against warming. The thermal properties of the different plate cladding boards are given in Table 3. The increase of temperature $\Delta\theta_{a,t}$ in an protected steel member during a time interval Δt is calculated as follows:

$$\Delta\theta_{a,t} = \frac{\lambda_p A_p/V}{d_p c_a \rho_a} \frac{(\theta_{g,t} - \theta_{a,t})}{(1+\phi/3)} \Delta t - \left(e^{\frac{\phi}{10}} - 1\right) \Delta\theta_{g,t} \quad \text{but } \Delta\theta_{g,t} \geq 0 \text{ if } \Delta\theta_{g,t} > 0 \tag{15}$$

$$\text{With } \phi = \frac{c_p \rho_p}{c_a \rho_a} d_p A_p/V \tag{16}$$

$A_p$ is the convenient area of the fire protection material for the unit length of the member [$m^2$/m], $A_p/V$ is section factor for protected steel member defined in Table 4, $\lambda_p$, $c_p$, $d_p$ and $\rho_p$ are the thermal conductivity, temperature independent specific heat, thickness and unit mass of the fire protection materials, respectively.

**Table 2.** Section factor and box value of the section factor for unprotected steel member.

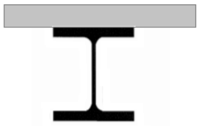
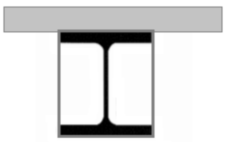
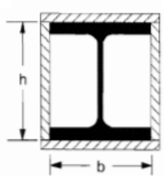
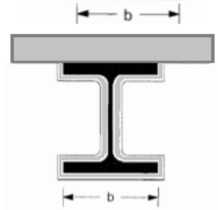
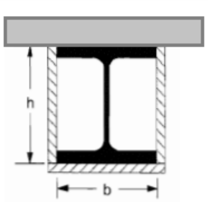
| Sketch | Description | Section factor $A_m/V$ |
|---|---|---|
|  | Open section with four sided fire | $\frac{\text{Steel perimeter}}{\text{Steel cross section area}}$ |
|  | Open section with three sided fire | $\frac{\text{Steel surface exposed to fire}}{\text{Steel cross section area}}$ |
|  | Box value of section factor | $\frac{\text{Box perimeter}}{\text{Steel cross section area}}$ |
|  | Box value of section factor | $\frac{\text{Box surface exposed to fire}}{\text{Steel cross section area}}$ |

**Table 3.** The thermal properties of the different plate cladding boards.

| Plate cladding boards | Thermal conductivity [W/mK] | Specific heat [J/kgK] | Unit mass [kg/m$^3$] |
|---|---|---|---|
| plasterboard suitable for fire-resistant types | 0.20 | 1700 | 800 |
| Silicate boards | 0.15 | 1200 | 800 |

**Table 4.** Section factor for protected steel member.

| Sketch | Description | Section factor $A_p/V$ |
|---|---|---|
|  | Contour encasement of constant thickness with four sided fire | $\frac{\text{Steel perimeter}}{\text{Steel cross section area}}$ |
|   | Hollow encasement of constant thickness with three sided fire | $\frac{2(b+h)}{\text{Steel cross section area}}$ |
|   | Contour encasement of constant thickness with four sided fire | $\frac{\text{Steel perimeter} - b}{\text{Steel cross section area}}$ |
|   | Hollow encasement of constant thickness with three sided fire | $\frac{2h+b}{\text{Steel cross section area}}$ |

The cross- sections of the steel components can be graded as for the normal temperature design with the material parameter ε reduced by 15% due to greater expansions. After the determination of the class of cross-sections in case of fire, the design value of the buckling resistance $N_{b,fi,t,Rd}$, lateral torsional buckling resistance moment $M_{b,fi,t,Rd}$, the moment resistance $M_{fi,t,Rd}$ as well as the tension resistance $N_{fi,\theta,Rd}$ are calculated using the Eq. (18). $F_y$ is yield strength, $N_{Rd}$ and $M_{Rd}$ are tension an moment resistance of the cross section at normal temperature, A is elemental area of the cross-section, $\gamma_{M,fi}$ and $\gamma_{M,0}$ are the partial factor for elevated and normal temperature, $\chi_{fi}$ is reduction factor for flexural buckling in case of fire, $\Phi_\theta$ is the value to determine the reduction factor in case of fire $\chi_{fi}$, α is the imperfection factor, $\bar{\lambda}$ and $\bar{\lambda}_\theta$ is the non-dimensional slenderness for normal and elevated temperature, $W_{pl,y}$ is the section modulus about y axis, $\chi_{LT,fi}$ is the reduction factor for lateral-torsional buckling, $\Phi_{LT,\theta}$ value to determine the reduction factor $\chi_{LT,fi}$, $\bar{\lambda}_{LT,\theta}$ is the non-dimensional slenderness for lateral torsional buckling in case of fire, $\kappa_1$ and $\kappa_2$ are the adaption factors given in Table 5.

$$\varepsilon = 0.85\sqrt{\frac{235}{f_y}} \tag{17}$$

$$N_{fi,\theta,Rd} = k_{y,\theta} N_{Rd}\left(\gamma_{M,0}/\gamma_{M,fi}\right) \tag{18}$$

$$N_{b,fi,t,Rd} = \chi_{fi} A\, k_{y,\theta}\, f_y/\gamma_{M,fi} \tag{19}$$

$$\chi_{fi} = \frac{1}{\Phi_\theta + \sqrt{\Phi_\theta^2 - \bar{\lambda}_\theta^2}} \tag{20}$$

$$\Phi_\theta = 0{,}5(1 + \alpha\, \bar{\lambda}_\theta + \bar{\lambda}_\theta^2) \tag{21}$$

$$\alpha = 0{,}65\sqrt{235/f_y} \tag{22}$$

$$\bar{\lambda}_\theta = \bar{\lambda}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}} \tag{23}$$

$$M_{fi,\theta,Rd} = k_{y,\theta}\left(\frac{\gamma_{M,0}}{\gamma_{M,fi}}\right) M_{Rd} \tag{24}$$

$$M_{fi,t,Rd} = \frac{M_{fi,\theta,Rd}}{\kappa_1 \kappa_2} \tag{25}$$

$$M_{b,fi,t,Rd} = \chi_{LT,fi}\, W_{pl,y}\, k_{y,\theta}\, f_y/\gamma_{M,fi} \tag{26}$$

$$\chi_{LT,fi} = \frac{1}{\Phi_{LT,\theta} + \sqrt{\Phi_{LT,\theta}^2 - \bar{\lambda}_{LT,\theta}^2}} \tag{27}$$

$$\Phi_{LT,\theta} = 0{,}5(1 + \alpha\, \bar{\lambda}_{LT,\theta} + \bar{\lambda}_{LT,\theta}^2) \tag{28}$$

$$\bar{\lambda}_{LT,\theta} = \bar{\lambda}_{LT}\sqrt{k_{y,\theta}/k_{E,\theta}} \tag{29}$$

**Table 5.** The adaption factors ($\kappa_1$ and $\kappa_2$) for non-uniform temperature distribution.

| The adaptation factor over a cross-section | $\kappa_1$ |
|---|---|
| a beam with four sided fire | 1.0 |
| an unprotected beam with three sided fire | 0.70 |
| an protected beam with three sided fire | 0.85 |
| The adaptation factor along a beam | $\kappa_2$ |
| at the bearings of a statically indeterminate beam | 0.85 |
| In every other situation | 1.0 |

### 2.2. *Metaheuristic algorithms*

#### 2.2.1. Flower pollination algorithm

Flower pollination algorithm, whose formulation is based on the pollination transfer process of flowering plants. There are two kinds of optimization process in its structure called local and global optimization. In the global optimization, the optimization process imitated the global pollination and is done by pollinators (insect, bee and other animals) among the different plant flowers while the local optimization process is done with the help of diffusion and wind among different flowers of the same plants. One of the important key factors of both types of optimization process is the constant repetition of visits to the same flower from the pollinator to put the pollen into the most precise flower. A random flight known the Levy flight should be considered because of a long direction in global optimization. In addition, the relationship between local and global optimization process can be controlled with a switch probability which tolerates the local pollination. The Pseudo Code of Flower Pollination Algorithm is presented in Figure 1. The equations of the global and local pollination are as follows:

$$x_i^{t+1} = x_i^t + L\,(x_i^t - g^*) \tag{30}$$

$$x_i^{t+1} = x_i^t + \varepsilon(x_j^t - x_k^t) \tag{31}$$

```
Start
% Writing whole design variables, limitations and constants
% Defining the iteration and population number
% Calculating the value of the internal forces
% Finding randomly the weight of the steel components
    -   Finding the weight of the steel components under normal temperature according to EC 3
    -   Finding the weight of the steel components under fire according to EC 3
    -   Comparing both weights of the steel components to select more optimal cross-sections
    -   Generating the initial solution matrix paying attention to the limitations
The step of Flower Pollination Algorithm
% Finding exiting, best value and two randomly values of initial solution matrix
% Finding a switch probability
% Generating the variables using levy or linear distribution
% Finding randomly the weight of the steel components
    -   Finding the weight of the steel components under normal temperature according to EC 3
    -   Finding the weight of the steel components under fire according to EC 3
    -   Comparing both weights of the steel components to select more optimal cross-sections
    -   Generating the initial solution matrix paying attention to the limitations
% Comparing the initial and new matrix, and choosing best one.
End
```

**Figure 1.** The pseudo code of flower pollination algorithm.

$x_i^{t+1}$ is the newly generated i$^{th}$ solution for (t+1)$^{th}$ iteration, L is Levy distribution, $x_i^t$ is the existing solution for i$^{th}$ iteration, g* is the best existing solution, ε is the linear distribution, $x_j^t$ and $x_k^t$ are randomly chosen existing solutions.

#### 2.2.2. Harmony search algorithm

Harmony Search Algorithm whose mathematical expression is based on the musical performance of musicians. Harmony of the notes is constantly improved by a musician to achieve the best musical work and to please the audience. For this purpose, the various efforts such as playing different notes or notes of the popular music in memory or new notes similar to the notes of a known music are performed by musicians. In optimization process, the values range of two important parameters harmony memory considering rate (HMCR) that is responsible for the probability of calculating a new value close to the old values and the pitch adjusting rate (PAR) defined the shrinking solution range to the entire solution range should be determined. These value ranges for both parameters vary between 0 and 1. The Pseudo Code of Harmony Search Algorithm is presented in Figure 2. The mathematical expressions of HS are presented in Eq. (32).

$$x_i^{t+1} = \begin{cases} x_{min} + rand(1) * (x_{max} - x_{min}) & \text{if HMCR} > \text{rand (1)} \\ x_k^t + rand\left(-\frac{1}{2}, \frac{1}{2}\right) * PAR * (x_{max} - x_{min}) & \text{if HMCR} < \text{rand (1)} \end{cases} \quad (32)$$

```
Start
% Writing whole design variables, limitations and constants
% Defining the iteration and population number
% Calculating the value of the internal forces
% Finding randomly the weight of the steel components
    -   Finding the weight of the steel components under normal temperature according to EC 3
    -   Finding the weight of the steel components under fire according to EC 3
    -   Comparing both weights of the steel components to select more optimal cross- sections
    -   Generating the initial solution matrix paying attention to the limitations
The step of Harmony Search Algorithm
% Finding harmony memory considering rate (HMCR) and pitch adjusting rate (PAR)
% Finding min, max limit of design variables and a randomly chosen exiting solution
% Generating the variables
% Finding randomly the weight of the steel components
    -   Finding the weight of the steel components under normal temperature according to EC 3
    -   Finding the weight of the steel components under fire according to EC 3
    -   Comparing both weights of the steel components to select more optimal cross-sections
    -   Generating the initial solution matrix paying attention to the limitations
% Comparing the initial and new matrix, and choosing best one.
End
```

**Figure 2.** The pseudo code of harmony search algorithm.

$x_i^{t+1}$ is the newly generated i[th] solution for (t+1)[th] iteration, $x_{max}$ and $x_{min}$ are max and min limit of design variables, $x_k^t$ is randomly chosen existing solutions and rand(1) is a random value between 0-1.

## 3. Numerical example and analysis

The 5-strorey steel structure shown in Figure 3 is used as numerical example and taken from the book 'Brandschutz in Europa – Bemessung nach Eurocodes' (Dietmar, 2012). All steel structural members are numbered from 1 to 19 and are examined under different cases by considering various fire durations and with or without protective materials. The cases are summarized in Table 6. The steel grade is S235 for all steel members. The permanent and live load actions for floor are $g_k$= 26 KN/m and $p_k$= 10 KN/m, respectively. These values for roof are $g_k$ = 4 KN/m and $s_k$ =3,5 KN/m. Also, In the continuous columns that extend over several floors and where each floor forms its own fire compartment with adequate fire resistance, the buckling length are accepted as in Figure 4.

**Table 6.** The protected and unprotected steel components under different cases.

| Cases | Fire Duration (min.) | Protective Material and Thickness (mm) |
|---|---|---|
| Case 1 | 30 | No protective Material |
| Case 2 | 30 | Plaster or Silicate boards, 15 |
| Case 3 | 60 | Silicate boards, 15 |
| Case 4 | 60 | Plaster boards, 15 |
| Case 5 | 90 | Silicate boards, 15 |
| Case 6 | 90 | Silicate boards, 20 |

The design variables, design constraints of the steel components in case of fire and the analysis process with HS and FPA are summarized in this section. Firstly, the design variable boundaries, design constraints with a penalty function presented in Table 7-8 and design constant of the steel component in case of fire such as the unit mass (7850 kg/m$^3$), the initial ambient gas temperature and the initial steel temperature (Room Temperature 20 C) should be determined. After the determination of these values, the first solution set with a defined population numbers are generated randomly. The optimization process is either stopped or new solution set (cross-sections and its associated objective functions) are produced within the framework of the specified algorithm rules by evaluating whether this solution set is sufficient or not to prevent the destruction of the steel components under fire. If a new solution set is created, the last step is applied and at this stage, the new solution set and the existing solution set are compared in terms of objective function (construction cost) defined in Eq. (33) and a more successful solution set updates constantly until the number of iterations is complete and the best results is achieved. $V_T$ is the vo lume of the steel component. The optimum cross-sections of I section in mm and the objective function w in kg (weight of the structure) obtained after 4000000 iterations with 10 Population numbers are presented in Tables 9-10 for the various case s according to HS and FPA.

$$\text{Min } F(x) = \rho_a V_t \tag{33}$$

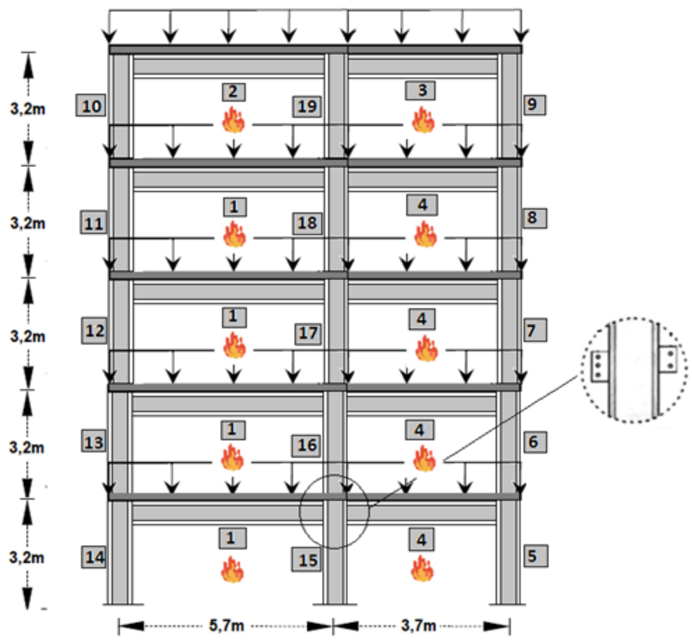



**Figure 3.** The 5-storey steel structure.

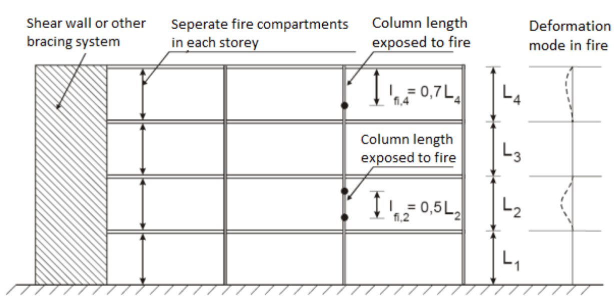



**Figure 4.** The buckling length of columns in case of fire.

**Table 7.** Design variable boundaries of the steel component with or without protection materials in fire.

| Structural components | Description | Design variables in mm |
|---|---|---|
| Column and beams | the width of the steel I cross-section b | $120 \leq b \leq 300$ |
| | the height of the steel I cross-section h | $150 \leq h \leq 1000$ |
| | the thickness of the flange $t_f$ | $8 \leq t_f \leq 40$ |
| | the thickness of the web $t_w$ | $6 \leq t_w \leq 20$ |

**Table 8.** Design Constraints of the steel components with or without protection materials in fire.

| Structural components | Description | Design constraints |
|---|---|---|
| Column and beams | Safety in buckling resistance design | See the Eq. (19) |
| | Safety in moment resistance design | See the Eq. (25) |
| | Safety in lateral torsional buckling resistance moment design | See the Eq. (26) |

In the numerical example taken from the book, the critical beam and column are the steel components numbered 1 and 15 shown in Figure 4, respectively. When the critical column in the book is examined under 5$^{th}$ case in Table 6, the appropriate cross-section is obtained as HEA 200. Likewise, when the critical beam examined under the 6th case, HEA 300 is selected as the appropriate section. Likewise, when the critical beam examined under the 6$^{th}$ case, HEA 300 is selected as the appropriate section. The time-temperature curves of the critical components with optimal cross-sections using HS and FPA for the cases 5 and 6 are given in Figures 5 and 6. The utilization factors of the normal stress in the event of fire or at normal temperature for the beam numbered 1 are 1.00 and 0.99, respectively.

For the column numbered 15, the utilization factors of buckling in the event of fire or at normal temperature are 1.00. If cross-section values are compared for the critical beam and column from the literature example and the proposed method, the weight of the critical beam and column is reduced by about 38% and 23%, respectively. The utilization factors of the normal stress and buckling in the event of fire are below 1.00 for all cases except case 1. In this case, the critical temperature is exceeded for any candidate cross-section shown in Figure 7. Therefore, it is not possible to design column without protective material. The cross-section size only has an effect on the time to exceed the critical temperature. For example, when the maximum cross-sectional value is taken, the critical temperature is exceeded in 22.82 minutes. As the cross-section values get smaller, the time to exceed the critical temperature decreases.

When the protective material is used in the fire of 30 minutes, the temperature of the steel components drops below the critical temperature shown in Figure 8. However, the optimum cross section is calculated considering the normal temperature in this case. For this reason, the material properties or thickness have no effect on the optimum section calculation. On the other hand, if the fire duration is 60 or 90 minutes, the characteristic properties of the protective material and the thickness of the protective material are a factor that ensures optimum design. Exemplary different objective function (building weights) are achieved due to the protective material, although the steel structural components are exposed to the same fire duration such as in cases 3 and 4. Another example, the building weights for cases 3 and 4 are 1780 and 2132 kg, respectively. The time-temperature curves show similarity to the Figures 6 and 6 except fire duration.

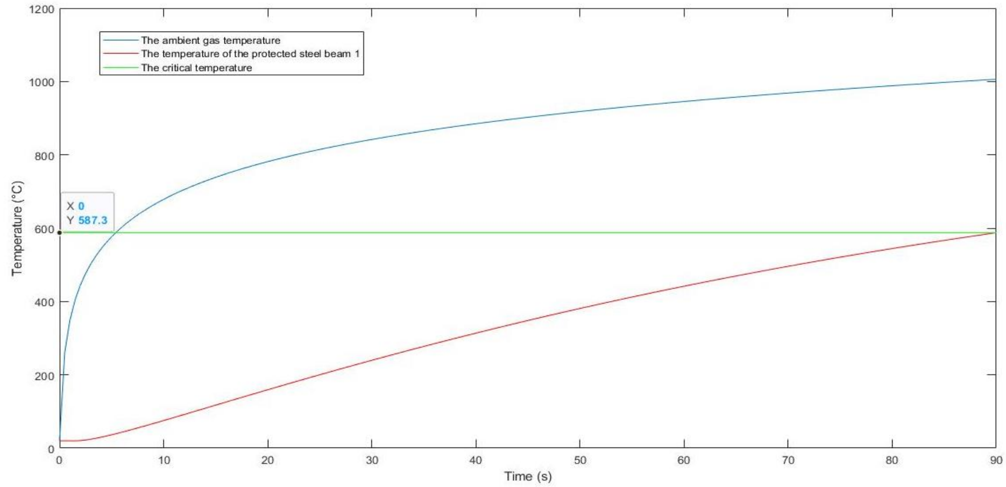



**Figure 5.** The time-temperature curves of the protected steel beam with optimal cross-sections for Case 5.

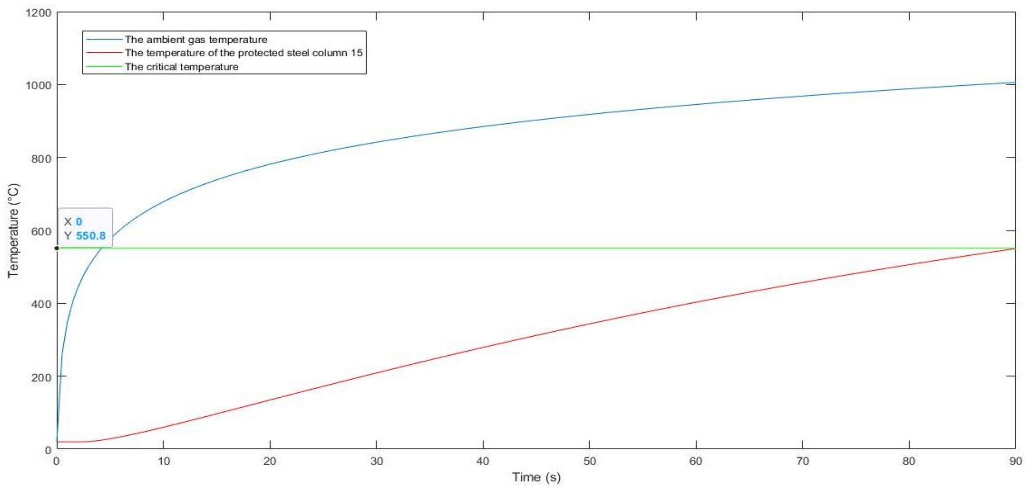



**Figure 6.** The time-temperature curves of the protected steel column with optimal cross-sections for case 6.

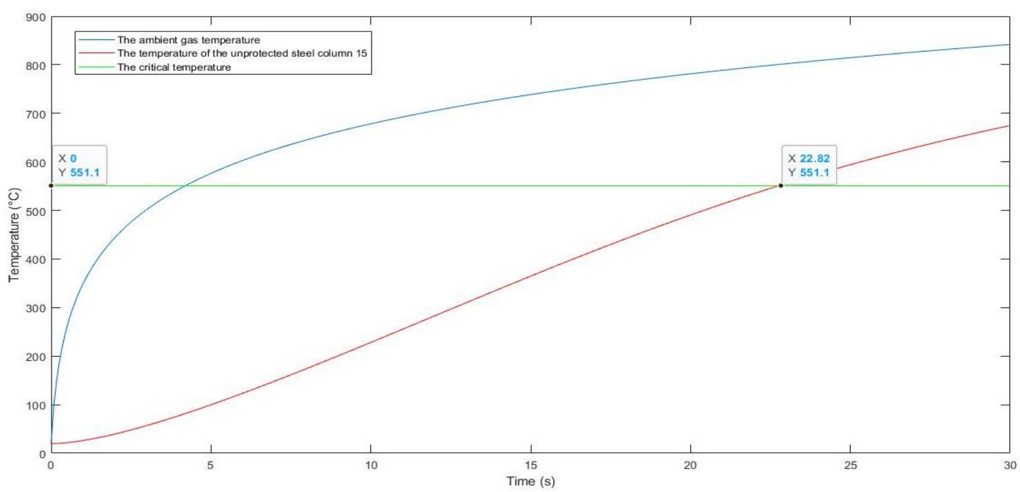



**Figure 7.** The time-temperature curves of the unprotected steel column with maximums values of cross-section.

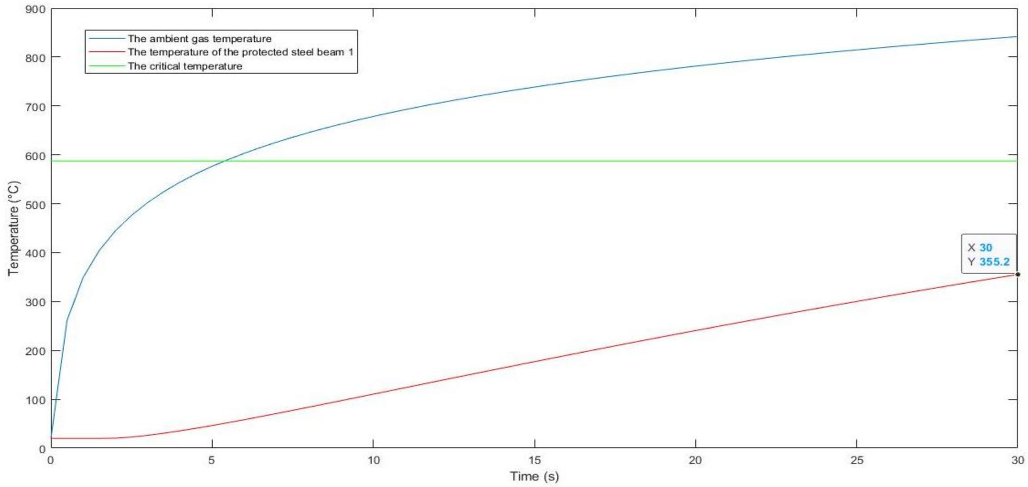



**Figure 8.** The time-temperature curves of the protected steel beam with optimal cross-section for case 2.

**Table 9.** The optimal cross-section of the steel components for cases 1, 2 and 3 according to HS and FPA.

| No | Case 1 | | | | | Case 2 | | | | | Case 3 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HS and FPA | B (mm) | H (mm) | $t_w$ (mm) | $t_f$ (mm) | W (kg) | B (mm) | H (mm) | $t_w$ (mm) | $t_f$ (mm) | W (kg) | B (mm) | H (mm) | $t_w$ (mm) | $t_f$ (mm) | W (kg) |
| 1 | 147 | 184 | 6 | 40 | 556 | 120 | 490 | 7 | 8 | 236 | 120 | 455 | 6 | 11 | 236 |
| 2 | 120 | 150 | 10 | 33 | 393 | 120 | 164 | 6 | 8 | 127 | 120 | 164 | 6 | 8 | 127 |
| 3 | 120 | 150 | 20 | 29 | 257 | 120 | 150 | 6 | 8 | 80 | 120 | 150 | 6 | 8 | 80 |
| 4 | 120 | 150 | 7 | 40 | 294 | 120 | 277 | 6 | 8 | 102 | 120 | 277 | 6 | 8 | 102 |
| 5,6,7,8,11,12,13,17,18 | | | | | | 120 | 150 | 6 | 8 | 69 | 120 | 150 | 6 | 10 | 81 |
| 9,10,19 | The Critical temperature is exceeded for any candidat e cross-section. Therefore, it is not possible to design column without protective material. | | | | | 120 | 150 | 6 | 8 | 69 | 120 | 150 | 6 | 8 | 69 |
| 14 | | | | | | 154 | 150 | 6 | 8 | 82 | 120 | 150 | 6 | 11 | 87 |
| 15 | | | | | | 239 | 150 | 6 | 8 | 117 | 233 | 150 | 7 | 8 | 119 |
| 16 | | | | | | 171 | 150 | 6 | 8 | 90 | 159 | 150 | 6 | 9 | 93 |
| | | | | | | | | | | 1662 kg | | | | | 1780 kg |

**Table 10.** The optimal cross-section of the steel components for cases 4, 5 and 6 according to HS and FPA.

| No | Case 4 | | | | | Case 5 | | | | | Case 6 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HS and FPA | B (mm) | H (mm) | $t_w$ (mm) | $t_f$ (mm) | W (kg) | B (mm) | H (mm) | $t_w$ (mm) | $t_f$ (mm) | W (kg) | B (mm) | H (mm) | $t_w$ (mm) | $t_f$ (mm) | W (kg) |
| 1 | 120 | 379 | 6 | 15.5 | 262 | 120 | 304 | 6 | 22.5 | 313 | 120 | 386 | 6 | 15 | 258 |
| 2 | 120 | 164 | 6 | 8 | 127 | 120 | 150 | 6 | 11.5 | 159 | 120 | 164 | 6 | 8 | 127 |
| 3 | 120 | 150 | 6 | 8 | 80 | 120 | 150 | 6 | 11.5 | 103 | 120 | 150 | 6 | 8 | 80 |
| 4 | 120 | 234 | 6 | 11 | 115 | 120 | 186 | 6 | 16 | 139 | 120 | 240 | 6 | 10.5 | 112 |
| 5,6,7,8,11,12,13,17,18 | 120 | 150 | 6 | 14.5 | 107 | 120 | 150 | 6 | 22.5 | 152 | 120 | 150 | 6 | 13.5 | 101 |
| 9,10,19 | 120 | 150 | 6 | 10 | 81 | 120 | 150 | 6 | 17.5 | 124 | 120 | 150 | 6 | 10 | 81 |
| 14 | 120 | 150 | 6 | 14.5 | 107 | 120 | 150 | 6 | 22.5 | 152 | 120 | 150 | 6 | 13.5 | 101 |
| 15 | 172 | 150 | 6 | 12.5 | 128 | 120 | 150 | 6 | 22.5 | 152 | 182 | 150 | 6 | 11.5 | 124 |
| 16 | 120 | 150 | 6 | 14.5 | 107 | 120 | 150 | 6 | 22.5 | 152 | 120 | 150 | 6 | 13.5 | 101 |
| | | | | | 2132 kg | | | | | 2910 kg | | | | | 2055kg |

## 4. Conclusions and comments

In this study, metaheuristic algorithms such as FPA and HS are presented for the optimal design of the protected steel structures at elevated temperature using EN 1993 1-2. The conclusions about this study are as follows:

1. If cross-section values are compared only for the critical beam and column from the literature example and the proposed method, the weight of the critical beam and column is reduced by about 38% and 23%, respectively.
2. The critical temperature in columns without protection material is exceeded for all possible cross-sections in case of fire. The cross-section size only has an effect on the time to exceed the critical temperature.
3. For the 30-minute fire design, the thickness or type of protective material such as Case 2 (15 mm thick Plaster or Silicate boards) does not change the optimum cross-section because the normal temperature design is decisive here.
4. The type of protective material in case of 60 and 90 fire duration plays a key role to optimally design. For example, when cases 3 and 4 are compared, the total weight of the structure decreases from 2132 kg to 1780 kg.
5. The thickness of protective material in case of 60 and 90 fire duration is also an important factor to obtain the optimum cross-section because there is an 855 kg difference between cases 5 and 6.

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