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OPTIMIZATION OF STEEL FRAMES WITH RELIABILITY CONSTRAINT UNDER THE EFFECT OF FIRE LOAD USING COLLIDING BODIES OPTIMIZATION ALGORITHM

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ABSTRACT

In recent decades, steel was used more than other materials in structural engineering. However, the safety of high-heat steel structures dramatically decreased, due to steel mechanical properties. Therefore, the design process should be done in a way that the structure has the required resistance at high temperatures and during the fire, according to the effect of heat on the performance of steel structures. In this study, the optimal design process of steel structures is considered under the fire load. In the optimal design process, the failure risk of the structure members is considered as a constraint. Therefore, the optimization process requires thermal and structural reliability analysis. A parametric model has been used to analyse the reliability of the structure in the fire limit state. The optimization process is also performed based on the Colliding Bodies Optimization (CBO) algorithm. In order to evaluate the optimal design process, 3 and 6-floors frames have been investigated. The results showed that the members' condition is effective in the structural resistance for the thermal loading. On the contrary, the structure design based on the reliability under the fire load provides a proper prediction from the behaviour of the structure and satisfies the requirements for the common state of design.

Keywords: fire load; reliability; frame structures; colliding bodies optimization (CBO).

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1. INTRODUCTION

Fire is one of the environmental factors that are likely to occur in structural systems. Therefore, considering the fire load in the design process is an important and effective step

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for the structures safe design. The first step in the fire process is to restrict and prevent the fire spread, which is generally seen in the layout of building spaces. But, the basic issue of designing structure against fire is based on reducing the risks by increasing the required time for the building discharge (in proportion to the user of structure). This idea involves considering the thermal load in the design process [1]. In recent decades, the widespread use of steel structures has increased to concrete structures in construction engineering, due to its high strength and uniformity, high installation speed, run in high-rise openings, aesthetics, etc. However, the main problem with steel structures is its weakness against fire. The mechanical and thermal properties of steel in the fire process have changed considerably, and produce different levels of temperature stresses in the structure. Steel is a material with a high coefficient of thermal expansion, and also is sensitive to high temperatures. These properties will reduce the resistance and elasticity module of steel at high temperatures. These reasons caused by the effect of fire load on steel structures, more than concrete structures. Therefore, it is important to consider the fire load in the steel structures designing process.

In this regard, due to the widespread use of steel structures as well as their inescapable weakness against fire, significant researches have been focused on this matter by laboratory and numerical methods around the world. But most of the studies are numerical methods, and laboratory studies have been carried out at small levels generally and for instrumental elements mostly. This is because of the high costs for creating laboratory conditions and the assumptions complexity about fire scenarios. Based on this, various parametric models are presented in order to evaluate the temperature effects on the firing process. Models such as the standard fire model, natural fire model are based on the combustible material amount in the closed space; parametric fire model, etc. And they are amongst the various models for assessing the thermal load effects. On the contrary, various studies have been carried out about the fire effect on the behavior of structures [2-3]. These part results of the research are presented as learning standards in some cases, such as ASTM, BS, ISO, as well as European standards [2-6]. In other cases, research is also available in various researches and science papers or reports. In this regard, the Standard National Association of America presented a report entitled "Fire protection of steel buildings" in 2004. This report includes some studies about the potential for fire occurrence in existing structures, the type of material behavior against the fire, and the methods of refining steel structures against fire. In this report, different levels of fire were studied, and the results indicated the design process importance based on increasing the resistance against fire. Consequently, three general suggestions were presented including improving design methods against fire, improving test methods of materials against fire, and accepting the responsibility for the construction, operation and maintenance of fire protection systems throughout the structure life [7]. In another study by Della Corte et al., 2005, numerical models were developed in order to evaluate the moment frames resistance performance to fire after an earthquake. In this research, the effect of earthquake on the structure is considered as a permanent deformation, and failure as a decrease in the modulus of elasticity and reduction in the yield stress is considered in certain points of the structure. The results of the research showed that observing the principles of seismic design has a remarkable effect on the moment frames performance in post-earthquake fire [8]. In a study by Kim et al. in 2008, the capacity resistance to progressive failure arising from fire was investigated in steel moment frames. In this research, the comparison between the linear and nonlinear static and dynamic analysis methods is presented in accordance with various regulations. This study results showed that nonlinear dynamic analysis is a more accurate tool for assessing the potential of progressive failure in construction structures [9]. Hoang examined the effect of members and joints of structure in fire situations in 2010. The results indicated that the amount of member stress, continuity, and structural integrity are important factors for the structure stability in the fire [10]. Faggiano et al. performed a nonlinear static analysis and thermal analysis in 2011, in order to evaluate the performance of metal frames under lateral and fire loads following an earthquake. This research results showed that if the system does not violate the level of service performance, the structure has the required resistance to fallout mechanism of frame after the earthquake and also against fire [11]. Another research was carried out by Braxtan and Pessiki in order to assess resistance to fire by testing the beam-to-column joint in 2011. This study demonstrated that failure at the beam wing is visible at a certain level of relative variation in the floor. In addition, the results of numerical analysis indicated that failure in resistant joint against fire load is due to excessive heat penetration and a rise in the temperature of the surrounding columns [12]. In 2011, Pucinotti et al. evaluated the performance of composite beams with high-resistance joints to the fire following an earthquake under an experimental and numerical analysis series. The results indicated that joints based on PGA equal 0.4g are resistant to damages arising from fire [13]. In 2012, Keller et al. examined the fire effect on resistant to fire material (by anti-spray) that have failure arising from earthquake using numerical methods. For achieving to this goal, they assessed the beam-to-column joint behavior for high temperatures. The study results showed that the round stiffness and moment capacity of the beam-to-column joint under fire load, which has damages from the earthquake, has remarkably decreased [14]. Eamon and Jensen, conducted a research on reliability analysis on reinforced concrete beams and columns under thermal load from 2012 till 2013. The research results showed that reliability index is decreased by considering the different armatures percentage and loading type as a nonlinear function with time [15-16]. Memari et al. also surveyed the post-earthquake fire process for a moment frame resistance with RBS joint in 2014. In this research, thermal-mechanical analysis was used for thermal loading, and the dynamics analysis of time history with near-field records was used for seismic loading [17]. In 2015, Geo evaluated the reliability of structures under fire load. In this survey, a probabilistic framework was presented in order to evaluate the reliability of the structure according to the existing uncertainties and proposed different methods for the reliability of the structure under fire load. Also, the importance of different parameters based on the sensitivity of the response and it was also based on the finite difference method has been investigated [18]. In 2016, Balogh et al. proposed a method for calculating the structures reliability under fire load. This study results showed that the proposed method results in more precise reliability index than the methods in the regulation [19].

As presented above, the research carried out has investigated the effect of fire load on the structure or structural elements in different situations generally, and the process of optimal design of the structure under thermal loading has been less considered. One of the reasons for this issue is the thermal loading random nature, which generally requires thermal analysis based on structural reliability. Accordingly, in this study, we have investigated and also presented the steel structures optimal design process under the fire load. For this purpose, the efficient algorithm of colliding body optimization (CBO) has been used for optimization process. During the process of optimizing the level of structural members and the weight of the structure, the design variables and the objective function are the goal of optimization problem, respectively. On the other hand, the constraints of the optimization problem are defined rendering to the reliability constraint of the members of the structure. Therefore, the chance of failure of the structural members is considered as a problem constraint. Assumed structures are under the fire load and for example under common loads of design and fire load concurrently. Therefore, the optimal design process requires thermal analysis and structural reliability analysis, according to the nature of the loading and the constraint of problem. In order to achieve this goal, a parametric fire model has been used in design based on the reliability of the structure in the limit state of fire. The design process has been investigated with different structural requirements and different loading conditions for two frames. The research results indicate that the structure resistance and members of structure against the fire are depending on various factors like the membership position and condition in the structure. On the contrary, the optimal design satisfies the requirements of the design rules in a common loading state based on the reliability constraint under the fire load.

2. STRUCTURAL RELIABILITY IN FIRE LOAD STATE

Using the reliability theory and considering the structural parameters such as yield stress of materials, loads applied to the structure and etc., as random variables would make the designing process of the structures more accurate. Because generally these quantities have lack of the certain values in reality, and in some cases, there are differences with the hypothetical values in the design process conventional state. In other word, commonly, for simplicity in the normal state of design, many design parameters are assumed to be fixed at a certain value. While in real situation, these values are not constant. However, in design based on reliability, the variables values can be assumed randomly. So the design based on reliability will lead to more realistic simulation, because it is based on assuming random values for the parameters. Accordingly, logical models or appropriate functions are required to make the analysis process meaningful, in order to analyse reliability. This is an important point in the issues of the fire load. In other words, in the case of reliability analysis with thermal loading (fire), the selected fire model is effective in the reliability of reliability analysis. The use of nominal fire models, like the standard time-temperature curve, is not allowed to determine the structural member reliability. Because the standard time-temperature curves are not based on the physical behavior of the fire, so the design method is not acceptable on this basis [18]. Parametric temperature-time curves with a set of analytic equations attempt to describe the actual behavior of fire in terms of maximum time as following [6].

$$\theta_g = \theta_{\max} - 625\left(t^* - t^*_{\max}.x\right) \quad ; \quad t^*_{\max} \le 0.5 \tag{1}$$

$$\theta_g = \theta_{\max} - 250\left(3 - t^*_{\max}\right)\left(t^* - t^*_{\max}.x\right) \quad ; \quad 0.5 < t^*_{\max} < 2 \tag{2}$$

$$\theta_g = \theta_{\max} - 250\left(t^* - t^*_{\max}.x\right) \quad ; \quad t^*_{\max} \geq 0.5 \tag{3}$$

In the above equations, θ_g is the temperature in the fire section, $\theta_{\max}$ is the maximum temperature, t^* is the desired time, and $t^*_{\max}$ is the maximum time (fire interval), which were determined by the following equation.

$$t^*_{\max} = (0.0002\frac{q_{t,d}}{O}).\Gamma \tag{4}$$

In Eq. (4), $q_{t,d}$ is the fire load density design value; Γ is the gamma probability distribution function, and O is the opening coefficient calculated on the basis of different variables of the fire distribution [20]. On the other hand, in Eqs. (1) to (3), x is also a variable determined by the maximum limit time and maximal time values as follows [6].

$$x = 1 \quad if \quad t_{\max} \geq t_{\lim} \tag{5}$$

$$\theta_g = \theta_{\max} - 250\left(3 - t^*_{\max}\right)\left(t^* - t^*_{\max}.x\right) \quad ; \quad 0.5 < t^*_{\max} < 2 \tag{6}$$

In the above equations, $t_{\lim}$ is the temperature maximum limit time in the fire process. Consequently, the design process is performed with the assumption of the reliability of the structure in the fire limit state based on the parametric fire model [18-20]. The limit state of the fire load is a random limit state defined by considering all the states leading to failure at a high indefinite level. On the contrary, the failure probability of a structure member is also the random quantities function that is allowed in the design process based on the reliability theory of alternative stress. In other words, the member failure probability is used as design constraints. The member failure state occurs when the internal parameters of the member arising from the loads applied violates the member's capacity. If R indicates resistance and S indicates the load effect, then a function or limit state function can be defined as follows [21].

$$g(R,S) = R - S \tag{7}$$

The limit state is the boundary between the desired and undesired performance, and also is defined as $g(R,S) = 0$. If $g(R,S) > 0$, the structure is safe (desired performance), and if $g(R,S) < 0$, structure is unsafe (undesired performance). Therefore, the probability of failure of the structure can be defined as the probability of undesired performance.

$$P_f = P(R - S < 0) = P(g(R,S) < 0) = P(g < 0) = \int_{-\infty}^{0} f_g(z)dz \tag{8}$$

On the other hand, the desired performance probability of the structure is defined as following.

$$P_s = P(g > 0) = \int_0^{\infty} f_g(z)dz \tag{9}$$

Thus, according to Eqs. (8) and (9), the safe behavior probability of the structure (structural reliability) can be shown as following.

$$P_s = 1 - P_f \tag{10}$$

In Eq. (10), P_f is the failure probability and P_s is the safe behavior probability (desired performance) of the structure. In this research, the log-normal distribution function has been used in order to calculate the failure probability as the following equation [22].

$$P_f = \varphi(u) = \varphi\left(\frac{Ln(X) - \mu_{Ln}}{\sigma_{Ln}}\right) \tag{11}$$

In Eq. (11), X is a random variable; u is the standard normal, μ_{Ln} mean values, and σ_{Ln} is the standard deviation of values. On the other hand, the standardized cumulative distribution function F_U for log-normal distribution function can be considered as follows [22].

$$F_U(u) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}(u)^2\right] \tag{12}$$

3. PROBABILISTIC OPTIMIZATION OF STRUCTURES

In probabilistic optimization of structures, various structural parameters like load, structural strength, and etc. are considered as random variables. Thus, it is possible to consider the failure probability of the structures in the safety calculations, and by examining the member's behavior and its interaction in the structural systems, in addition to the lowest weight, obtained the highest reliability for the members and then for structure. In order to obtain this purpose, the probability of failure as an objective function or part of the objective function is assumed in the process of optimization, or in some cases, it will be considered as a constraint [23]. For this purpose, generally, in structures probabilistic optimization based on reliability, one of the following states will be considered.

- Minimizing the structure weight under the reliability constraint of structural members
- Minimizing the structure weight under the reliability constraint of the structural system
- Minimizing the failure probability under the weight constraint of structure

In this study, minimizing the weight of the structure under the structural members reliability constraint has been considered. In other words, the goal is to find the minimum structure weight, so that the failure probability of each structure member is not greater than the permitted value (design problem constraint). In order to achieve this goal, in the process of optimizing the design variables, the members' section level and the problem constraint are defined based on the failure probability of the members.

3.1 Objective function

As stated before, the goal in optimization problems of structure is usually to find the structure least weight with the condition of establishing constraints. This is happened while the structure weight is determined by the level of the structure members. Therefore, design variables in structural weight optimization issues are the section level of structure members. On the contrary, in the optimization process, the problem constraints are one of the important factors during the process. These constraints in the reliability-based optimization problems are considered as the failure probability of each structure member. Consequently, the problem of optimizing the structure weight is defined under the reliability constraints of the structure members as follows.

$$\begin{aligned} &\mathit{Minimize}\ W = \sum_{i=1}^{ne} \rho_i L_i a_i \\ &\mathit{Subject\,to}\ \ P_f = \int_{-\infty}^{+\infty} \left[1 - P_s\left(x\right)\right] P_R\left(x\right) dx = 0 \end{aligned} \tag{13}$$

In Eq. (13), W is the structure weight that must be minimized. ne is the number of structural members, ρ_i is the unit weight of materials, L_i is length, a_i is sectional level, and ith is member of the structure. On the other hand, in order to evaluate each design (jth structure) in the search space, the extent of violation of the constraints for the jth design is determined as follows.

$$C_j = \sum_{i=1}^{ne} \max\left[\left(\left(\frac{P_{f,i}}{P_{f,a}}\right) - 1\right), 0\right] \tag{14}$$

In Eq. (14), C_j is the violation extent of reliability constraints by the j structure. $P_{f,a}$ and $P_{f,i}$ represent the probability of allowed failure and the probability of failure for the ith member of the jth design (structure) in the search space, respectively. By determining the violation extent of the constraints for any proposed proposal in the search space, the suitability function value for each design will be determined as following.

$$\phi_j = W_j(1 + C_j) \tag{15}$$

In Eq. (15), ϕ_j indicates the suitability of jth design in the search space. Accordingly, each design more violates the problem constraints, the ϕ function corresponding to it is greater, and thus it will have less suitability, and any design with less ϕ will have more suitability.

On the other hand, hypotheses have been considered to apply the fire load to the structure, considering the loading conditions in this research. Based on this, it is assumed that the thermal load (fire) for each member affects separately, and only on the each member failure, due to applied loads (fire load, static loads, etc.) it is effective in the structural system and the thermal load of each member has no effect on the other members. In other words, if the thermal loading system (fire load) is assumed to be general, all of the structures should be considered as a whole system in order to calculate the probability of failure. In this situation, the system reliability should be considered as a design constrain. However, if insulation is sufficient to prevent the fire spread, the assumption of failure for each member can be investigated individually. Accordingly, the member reliability constraint for optimal design is defined and the assumption of large deformations will not cause a defect in the thermal loading. In order to achieve this goal, safe design requirements against fire should be considered for buildings with steel frames [24]. It should be noted that in the presumed state, the structural members' failure during the fire can lead to the failure. For this reason, the failure probability in a fire state must be defined less than the failure probability for design at natural temperature in the final limit state.

3.2. CBO

The CBO algorithm is one of the meta-algorithms, which invented by Kaveh in 2015 using physical laws [25]. This algorithm is formulated based on the particles one-dimensional collision. In this algorithm, each structure is considered as a mass particle, which can be considered as a solution for the optimization problem. Each particle has mass and initial velocity before colliding with another particle. After collision of two particles, each particle will be separated from other particles at a certain speed, and moves from its original position to the secondary position. The secondary position can be better than the initial position or it also can be less suitable. This algorithm process is summarized as follows [26].

In this algorithm, the design variables number in the search space is equal to the structure members' number and each particle signifies a structure. Thus, at first, some particles are generated with some random values for the design variables. Then, based on the suitability, each mass particle is assigned, and the particles are sorted according to the suitability and in descending order. Afterward, the particles are divided into two different groups. In the way that the first group is constant particles and the second group are moving particles. Moving particles are less suitable than constant particles. Moving particles crash constant particles and their position change in the search space. The moving and constant particles velocity is determined as follows.

$$\begin{cases} V_i = 0 \qquad i = 1, 2, 3, ..., \dfrac{np}{2} \\ V_i = X_{i-\frac{np}{2}} - X_i \qquad i = \dfrac{np}{2} + 1, \dfrac{np}{2} + 2, ..., np \end{cases} \tag{16}$$

In Eq. (16) *np* is the particles number, X_i is the position of the particle *i*th, and V_i is the particle speed of *i*th. Then, due to the collision between two objects in accordance with the laws of physics, the size motion of all the particles before the collision is equal to the motion size of all particles after the collision. Therefore, by equating the kinetic energy before and after the collision, the velocity of the constant and moving particles after collision ($V_i^{'}$) is obtained as the following equations.

$$\begin{cases} V_i^{'} = \dfrac{\left(mp_{i+\frac{np}{2}} + (\mu)\left(mp_{i+\frac{np}{2}}\right)\right)V_{i+\frac{np}{2}}}{mp_i + mp_{i+\frac{n}{2}}} & i = 1,2,3,....,\dfrac{np}{2} \\ V_i^{'} = \dfrac{\left(mp_i - (\mu)\left(mp_{i-\frac{np}{2}}\right)\right)V_i}{mp_i + mp_{i-\frac{np}{2}}} & i = \dfrac{np}{2}+1, \dfrac{np}{2}+2, ..., np \end{cases} \tag{17}$$

In Eq. (17), mp_i is the mass of *i*th particle, defined as Eq. (18).

$$mp_i = \frac{\frac{1}{\phi_i}}{\sum_{k=1}^{np} \frac{1}{\phi_k}} \qquad i = 1,2,3,....,np \tag{18}$$

In Eq. (18), ϕ_i is the suitability function value of the particle *i*th. For better search of search space, the coefficient μ is considered as Eq. (19) in Eq. (17).

$$\mu = 1 - \frac{iter}{iter_{\max}} \tag{19}$$

In Eq. (19), $iter$ is the current repetition number, and $iter_{\max}$ is the total number of repetitions in the optimization process. Finally, each particle new position is obtained by considering the velocity after the collision in Eq. (20).

$$\mu = 1 - \frac{iter}{iter_{\max}} \tag{20}$$

In Eq. (20), $rand$ is a random number in range of zero and one, and X_i^{new} is the new position of *i*th particle after the collision.

4. NUMERICAL EXAMPLES

In order to examine the proposed process efficiency of optimizing structures with reliability constraint, and under the thermal loading (fire load), two examples have been investigated with different structural conditions. In this process, static and thermal analyses of the structure are performed with the help of the OPENSEES software. Based on this, in the thermal analysis of the modelling process for steel material behavioral model, Steel01Thermal is used, and for the members behavioral model of beam and column, a nonlinear element of DispbeamColumnThermal is used. Thus, the process of optimization with reliability constraint under the static and the thermal load is provided in the flowchart of Fig. 1.

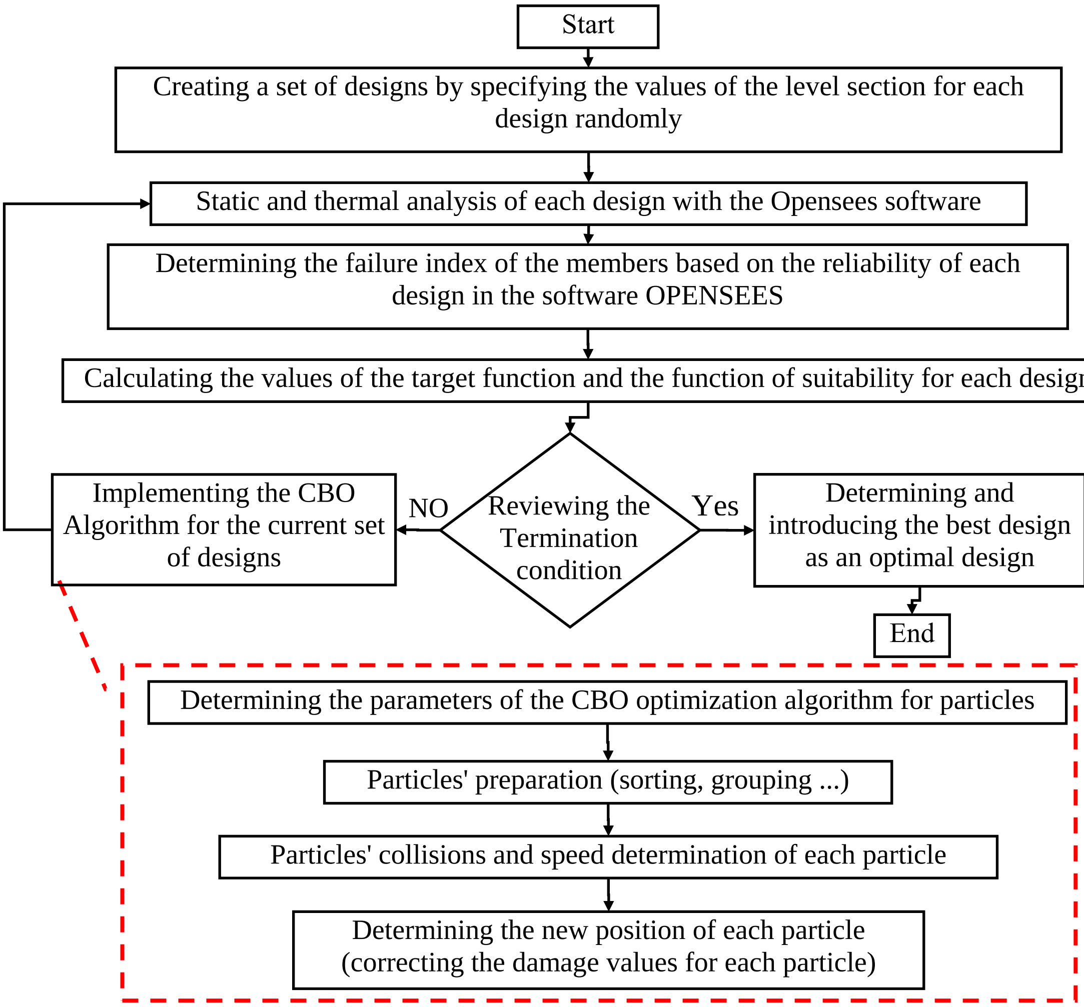

Figure 1. Reliability-based optimization of structures under fire load

4.1 A two bay three-story frame structure

In order to evaluate the method performance and optimization algorithm, the two-dimensional 15-bar frame is evaluated according to Fig. 2. E and ρ for all members are considered 2.06×10^6 kg/cm^2 and 7850 kg/m^3, respectively. The members' grouping is also indicated in Fig. 2 with abbreviation G. It should be noted that for this frame, only the thermal load is considered in the optimal design process.

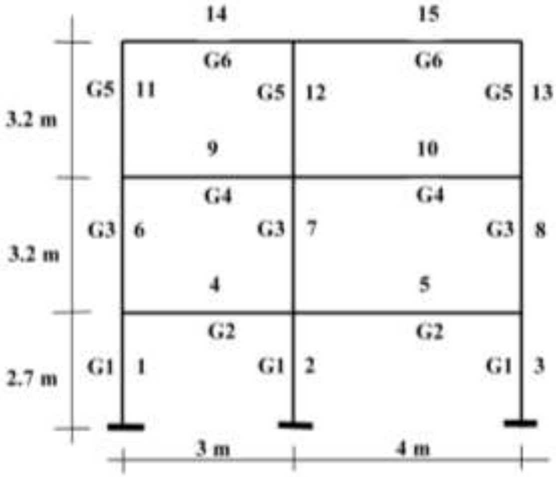

Figure 2. A two-bay three-story frame structure

The list set of existing sections (*S*) is also categorized as following for an optimal design process

S= {IPB140, IPB160, IPB180, IPB200, IPB220, IPB240, IPB260, IPB280, IPB300, IPB320, IPB340, IPB360}.

For thermal loading it was assumed that the heat changes uniformly throughout the member section is 1000° C. Consequently, the optimal design process is done according to the flowchart shown in Fig. 1, so that the failure probability of each member is less than 0.0002. In order to achieve this goal, the designs number for each repetition in the optimization process is equal to 14, and also the repetitions number of the optimization process is assumed equal to 100. After the optimization process, the optimal sections and members' failure probability are obtained in Table 1.

Table 1: The results of optimal design for the two-bay, three-story frame

No. Element	Optimal sections	Probability of failure	No. Element	Optimal sections	Probability of failure
1	IPB 280	2.123×10^{-5}	9	IPB 140	5.735×10^{-5}
2	IPB 280	1.612×10^{-5}	10	IPB 140	2.876×10^{-4}
3	IPB 280	1.23×10^{-4}	11	IPB 140	5.398×10^{-5}
4	IPB 140	2.546×10^{-5}	12	IPB 140	2.123×10^{-5}
5	IPB 140	3.762×10^{-4}	13	IPB 140	1.322×10^{-4}
6	IPB 200	4.349×10^{-5}	14	IPB 160	4.546×10^{-5}
7	IPB 200	2.041×10^{-5}	15	IPB 160	7.654×10^{-5}
8	IPB 200	1.786×10^{-4}	***Weight***	**2481 *kg***	

The convergence for the optimization process is also presented in Fig. 3. As shown in this figure, the optimization process in reaching the optimal point according to the search space has a suitable velocity.

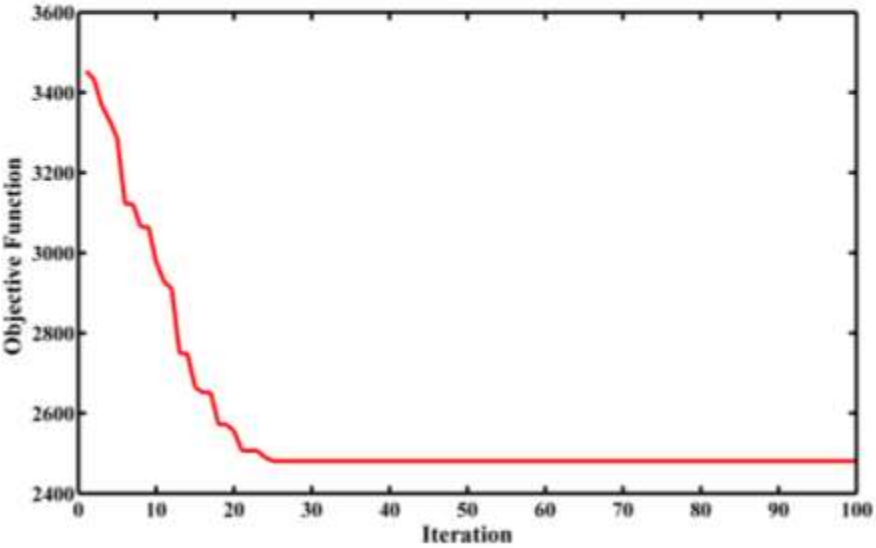

Figure 3. The convergence history of the optimization process for the two-bay, three-story frame

It should be noted that this example was also reviewed by reference [27]. But in this reference, instead of the thermal load, the optimal design has been investigated under the reliability constraint of the member in static loading state. This reference represents the optimum weight of the present structure under a static load equal to 3048 *kg*, and the final sections have differences with the present optimal design (in the fire load state). However, according to the optimal design conditions inadequacy (uneven loading, etc.), the optimal design results of reference [27] are not comparable with this study results. However, the study of the differences between the optimal sections of the present study and the reference [27] shows that the process of optimization under the fire load, on the first floor, has obtained larger sections than the static load state, but in the higher floors, these values are smaller than static state. Therefore, it can be concluded that in the up floors, design based on static loads also provides acceptable results for the thermal load. But the adequacy of the sections should be controlled under the fire load, in the lower floors in design state based on the static load. In other words, in design state based on the static load (conventional state of design), it can be assured that the upper floors sections in the fire process have a good performance, but the lower floors (especially the first floor) need to be strengthened.

4.2 A Three-bay, six-story frame structure

For the first time in the present paper, to evaluate the proposed process in optimal design, two-dimensional steel frame is investigated in Fig. 4. In this example, the values of E and ρ for all members are assumed to be 2.06×10^6 kg/cm^2 and 7850 kg/m^3, respectively. The members' arrangement and also their grouping are indicated in Fig. 4.

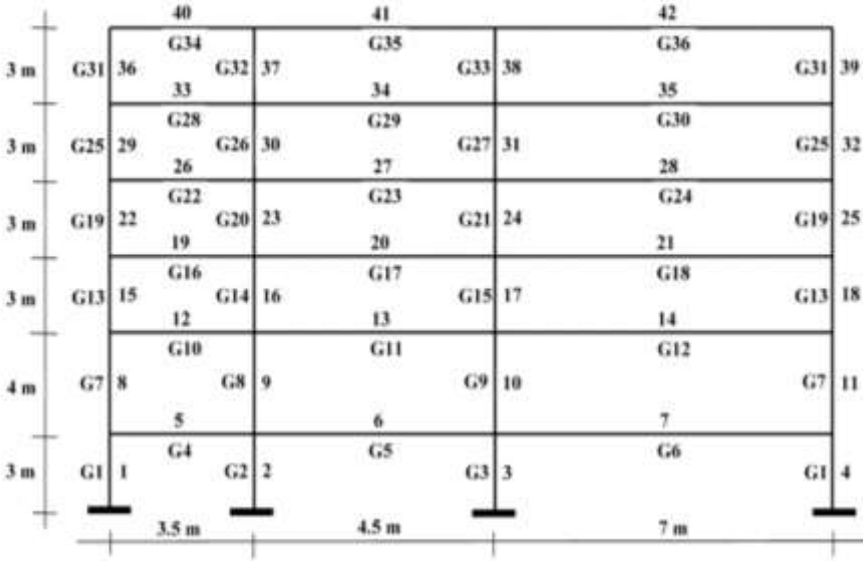

Figure 4. A three-bay, six-story frame structure

On the other hand, static loading is also considered in the optimal design process in this example. Therefore, a wide gravity load of 600 *kg*/*m* for all structural beams is considered in the optimal design process. Therefore, the yield stress values of members and the failure probability of members are considered to be 2400 *kg*/*cm*^{2}, and 0.0002, respectively. For loading the fire assumed that the heat changes uniformly throughout the section are equal to 1200° C. The list of sections for optimal design is also as follows.

S= {IPB140, IPB160, IPB180, IPB200, IPB220, IPB240, IPB260, IPB280, IPB300, IPB320, IPB340, IPB360, IPB400, IPB450, IPB500}.

After optimization process implementation, the optimal design sections and the failure probability of members are obtained in Table 2. It should be noted that in this example, as in the previous example, for the optimization process based on the CBO algorithm, the number of designs for each repetition is equal to 14 and the repetitions number of the optimization process is considered equal to 100.

Table 2: The results of optimal design for the three-bay, six-story frame

No. Element	Sections	Probability of failure	No. Element	Sections	Probability of failure
1	IPB 140	2.543×10^{-4}	22	IPB 160	7.32×10^{-4}
2	IPB 160	3.11×10^{-4}	23	IPB 140	6.795×10^{-5}
3	IPB 140	6.43×10^{-2}	24	IPB 200	2.301×10^{-4}
4	IPB 140	5.843×10^{-4}	25	IPB 180	2.716×10^{-4}
5	IPB 140	6.213×10^{-5}	26	IPB 140	3.666×10^{-5}
6	IPB 140	4.54×10^{-4}	27	IPB 240	4.398×10^{-5}
7	IPB 140	1.267×10^{-3}	28	IPB 160	7.876×10^{-5}
8	IPB 200	2.987×10^{-5}	29	IPB 140	3.876×10^{-4}
9	IPB 180	7.543×10^{-3}	30	IPB 160	2.548×10^{-4}

10	IPB 140	2.768 x 10^{-4}	31	IPB 140	5.943 x 10^{-4}
11	IPB 200	8.453 x 10^{-4}	32	IPB 140	8.453 x 10^{-4}
12	IPB 300	6.254 x 10^{-4}	33	IPB 160	7.778 x 10^{-4}
13	IPB 180	6.148 x 10^{-4}	34	IPB 140	6.639 x 10^{-4}
14	IPB 140	3.923 x 10^{-4}	35	IPB 140	2.215 x 10^{-4}
15	IPB 240	1.023 x 10^{-4}	36	IPB 160	4.545 x 10^{-4}
16	IPB 140	5.004 x 10^{-4}	37	IPB 180	1.19 x 10^{-4}
17	IPB 160	3.987 x 10^{-5}	38	IPB 180	1.14 x 10^{-4}
18	IPB 240	4.894 x 10^{-4}	39	IPB 160	4.679 x 10^{-4}
19	IPB 160	3.365 x 10^{-4}	40	IPB 180	3.548 x 10^{-4}
20	IPB 220	2.143 x 10^{-4}	41	IPB 140	4.612 x 10^{-4}
21	IPB 140	2.675 x 10^{-4}	42	IPB 140	4.056 x 10^{-4}

According to the optimal design results, and as indicated in Table 2, the structure weight is obtained as 7560 *kg*. The value convergence process of the objective function of optimization problem is also as in Fig. 5. And it showed that the optimization process is converged according to search space in last repetitions in a constant amount for weight.

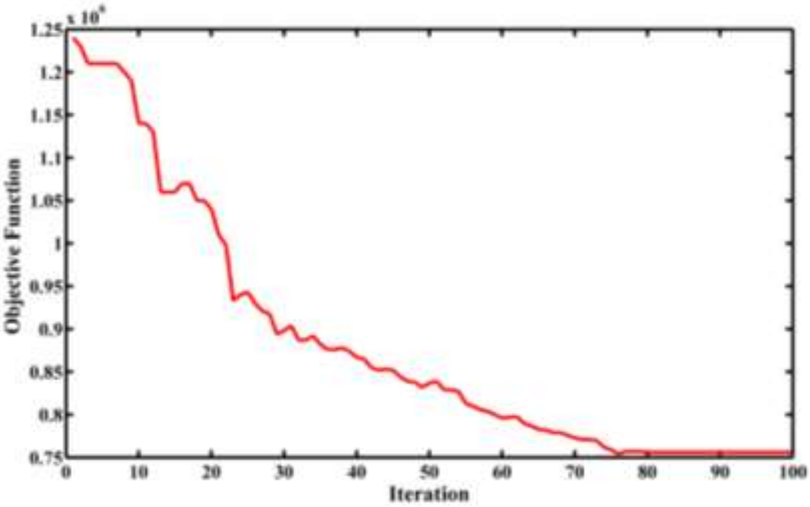

Figure 5. The convergence history of the optimization process for the three-bay, six-story frame

5. CONCLUSION

In order to the optimal design of steel structures under the thermal load (fire load), a method based on reliability formulation is proposed to perform the optimization process. In this formulation, the failure probability of members is assumed as a constraint instead of considering the stress of the members as design constraints. Therefore, the objective in this problem is to optimize the structure weight under the members' reliability constraint. In this regard, for the first time in this study, thermal loading (fire load) is also included in the optimal design process. For this purpose, the OPENSEES software is used for thermal analysis. The colliding bodies optimization (CBO) algorithm is also used for the optimization process. The optimization process in two frames has been evaluated with various structural conditions and different loading. The results of the research show that the structure stability and resistance to the fire depend on various factors like the position and condition of the member in the structure. Accordingly, if the structure is designed under static and dynamic loads correctly, the members in the upper floors have adequate resistance against fire. However, for some members of the lower floors, especially the first floor, investigations of the thermal loading (fire) is required. On the contrary, the optimal design satisfies the design rules requirements in a common loading state based on the reliability constraint under the fire load. In other words, it can be stated that structural design based on reliability provides an accurate prediction from structural behavior, and it is a good basis for estimating the members' failure and structures. Accordingly, reliability analysis is a logical step in optimizing structures under the fire load. Therefore, it is recommended that the design process of structures to be carried out under the reliability constraint, especially steel structures with thermal load acquisition (fire load).

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