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COST-OPTIMIZATION BASED TARGET RELIABILITY FOR FIRE DESIGN OF INSULATED STEEL COLUMNS

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Abstract.

Adequacy of a structural fire design can in theory be demonstrated through a probabilistic risk assessment (PRA) where the compliance with tolerability limits and the ALARP requirement are explicitly ascertained. However, explicit assessment of ALARP requirement is challenging and impractical for day-to-day designs, due to the burden of estimating uncertain future costs and current safety investment costs. For normal design conditions, the use of target reliability indices has been recommended instead. These target reliability indices however have not been defined for structural design under fire events. To address this gap, the current study demonstrates a method to derive target reliability indices for a fire-exposed structure. As a case study, an insulated steel column (with varying levels of ISO fire rating) exposed to parametric natural fires is considered. The target reliability indices are derived for the steel column for varying fire exposure scenarios, considering different fire load densities and opening factor, relating to the building occupancies. This study thus investigates the important issue of adopting target reliability indices in fire design that are cost-optimized from quantitative analyses considering natural fire exposures, which has significant implications for fire safety and rational use of resources in the construction industry.

Keywords: Life-time cost optimization, probabilistic risk assessment, reliability, reliability indices, steel columns.

1. Introduction

Traditionally, structures are assumed to perform adequately in the event of fire if designed based on prescriptive guidelines. These prescriptive guidelines rely on the experience of the profession, gained over time in response to the fire disasters. However, given the variety of structures and development of new materials and systems, prescriptive designs can be inefficient in certain situations and unconservative in others [1]. This observation led to an increased use of performance-based design (PBD), where the structural design is tailored to meet the specific objectives of a building.

Within a PBD approach, a probabilistic structural fire design can be adopted to consider explicitly the effects of the uncertainties associated with the structural system [2]. The probabilistic structural design should be compliant with the As Low as Reasonably Practicable (ALARP) requirement [3]. The evaluation of ALARP requirement involves balancing the cost of safety investment and the cost of benefits associated with the safety investment [4]. Yet, a project specific evaluation of these costs to assess the ALARP requirement is time and resource expensive. For ambient structural design, this challenge is generally avoided by the specification of a target reliability index (β_t) [5–7], which is underpinned by cost-benefit considerations. For example, EN 1990:2002 [5] recommends a target reliability index of 3.8 for a reference period of 50 years (incorporated in partial safety factors) for a building with medium failure consequences. EN 1990 [5] further specifies the target reliabilities considering different level of structural failure consequences. A more detailed recommendation for the target reliability can be found in [7], where target reliabilities have been proposed considering relative cost of safety measure in addition to the consequences of structural failure. Van Coile et al. [8] argue that these reliability targets derived for normal design cannot be directly transposed for structural design under fire. However, the cost optimization approach to derive these target safety levels remains applicable [9].

In this study, the concept of cost optimization to develop target reliabilities is revisited in the context of structural fire design. As a case study, a fire protected steel column is considered, similar to the steel beam investigations presented by [10]. The cost of the insulation material serves as the safety investment cost for fire exposure, while the structural failure cost is evaluated considering the ultimate limit state. The minimization of the life-time cost allows achieving an optimum insulation and thus determining the reliability target. The reliability target is derived considering natural fire scenarios with varying fire load density and compartment opening factors.

2. Reliability targets for fire exposed structures

In [7, 8], the target reliabilities are derived by balancing the cost of the added safety measure and expected failure consequences. This concept of lifetime cost-optimization to derive target reliabilities relies on works by [11]. The lifetime cost optimization in general is done through the maximization of the life-time utility [11, 12], Y, which is given by:

$$Y = B - C - A - D = B - K \tag{1}$$

where, B is the benefit associated with the structure's existence, C is the total cost of the structure, A is the obsolescence cost, and D is the damage cost associated with the structural failure. Since the expected benefit B over the structural life-time is assumed independent of the safety investments, the maximization of life-time utility Y reduces to the minimization of lifetime costs K. The components of K are further elaborated in Equation 2. The evaluations are done considering an infinite time horizon.

$$\begin{aligned} C &= C_0 + C_1 \\ A &= C\,\frac{\omega}{\gamma} = (C_0 + C_1)\,\frac{\omega}{\gamma} \end{aligned} \tag{2}$$

where, C_0 is the cost of structure, C_1 is the added cost of the safety measure, ω is the obsolescence rate (0.02/ year adopted as in [12]), γ is the discounting factor (0.02/year adopted for societal decision-maker). D is the structural failure cost associated with the limit state $Z = R - E$ taking negative values (where R is resistance effect and E is the load effect).

The structural failure cost directly relates to the consequences of structural failure and mostly comprises cost of structural reconstruction, cost relating to loss of building functionality, societal costs related to injuries and fatalities, and cost related to environmental effects. These costs depend on many societal parameters, making the evaluation of structural failure cost challenging and subject to a significant uncertainty. The available studies generally simplify the structural failure cost by considering the different levels of structural failure consequences expressed as factor of initial structural cost ($\xi\, C_0$ considered here as in [12]). This structural failure cost for an adverse event such as fire is evaluated as the expected failure cost for the entire life-time of the structure [12, 13]. Equation 3 gives the failure cost during life-time structure and is evaluated as the present net value of the future expected annual failure costs over life-time (infinite time horizon). In Equation 3, $\xi\, C_0$ is the average structural failure cost and λ is the annual probability of fire event occurrence.

$$E\,[D] = \frac{\lambda\, P_f\,(p)}{\gamma}\,\xi\, C_0 \tag{3}$$

where, $P_f\,(p)$ is the structural failure probability considering the occurrence of a fire event (evaluated as $P_f\,(p) = \mathrm{P}\,[R - E < 0]$), p is the design parameter. On substituting the components of lifetime cost from Equations 2 and 3 in Equation 1, the minimization of the life-time cost can be achieved through Equation 4:

$$\min\nolimits_p \left[K = C_0\,(1 + \varepsilon(p))\left(1 + \frac{\omega}{\gamma}\right) + \frac{\lambda\, P_f\,(p)}{\gamma}\,\xi\, C_0\right] \tag{4}$$

where, $\varepsilon(p) = C_1/C_0$ investment cost factor for the design. Since, C_0 is constant and thus has no effect in the minimization of K, Equation 5 further results in:

$$\min_p \left[K = C_0\,\varepsilon(p)\left(1 + \frac{\omega}{\gamma}\right) + \frac{\lambda\, P_f\,(p)}{\gamma}\,\xi\, C_0\right] \tag{5}$$

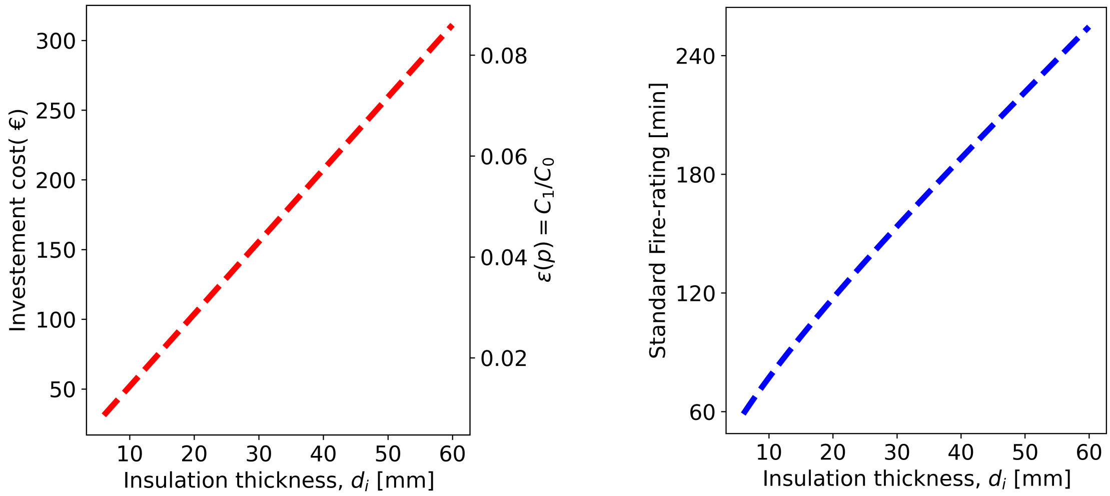
3. Case study: Fire protected steel columns

A fire protected steel column is considered as a case study to derive target reliabilities for a fire exposed structure. For fire protection of the steel column, spray applied fire resistant (SFRM) material is used. The sub-sections below discuss the application of the concept of cost-optimization to derive reliability targets for the steel column.

3.1. Structural model

A steel column (W14 × 109) of height 5.486 m is considered. The column is from the first story of a nine-story office building designed based on US guidelines [16, 18]. The column is considered here as a reference section for further study, while the structural loads are re-calculated considering safety factors from Eurocode [5]. This is done to meet the ambient design criteria as in Eurocode (e.g., β of 3.70 is obtained). The characteristic permanent load on the column is estimated as 2903 kN, while the imposed load is estimated as 1244 kN (considering a load factor of 0.3 and structural buckling resistance at ambient temperature). The column is exposed to the fire from three sides (i.e., assuming a peripheral column with wall along one of the flanges). The thermal properties for the steel are taken from [19]. The steel yield strength (characteristic) is 345 MPa with temperature-dependent retention factors for yield strength and elastic modulus from the probabilistic model by [15]. The temperature-dependent thermal properties of SFRM can be found in Table 1 and are in accordance with those adopted in [18].

The temperature distribution is assumed to be uniform in the steel cross-section. It is determined based on the lumped mass model from [19]. The column is assumed to be in pure compression and is not susceptible to local buckling. The global buckling resistance thus governs the compression resistance of such column and is calculated as:



(a) (b)

Figure 1. (a) Cost of SFRM insulation of steel column. (b) Relationship between SFRM insulation thickness and standard fire-rating of the steel column (based on ISO 834 criteria)

Stochastic variables	Distribution	Mean	COV
Material properties, SFRM [14]			
Thickness, d_i	Lognormal	Nominal + 1.6 mm	0.2
Quantile parameter, e	Normal	Standard normal distribution ($\mu = 0$ and $\sigma = 1$)	
Density, ρ_i		$\rho_i = \exp(-2.028 + 7.83\,T^{-0.0065} + 0.122e)$	
Specific heat, c_i		$c_i = 1700 - \exp(6.81 - 1.61.10^{-3}T + 0.44.10^{-6}\,T^2 + 0.213e)$	
Conductivity, k_i		$k_i = \exp(-2.72 + 1.89.10^{-3}T - 0.195.10^{-6}\,T^2 + 0.209e)$	
Material properties, Steel [15]			
Retention factor for steel yield strength, k_{fy}	Logistic model	Temperature-dependent	Temperature-dependent
Mechanical loading [16]			
Permanent load	Normal	2903 kN	0.1
Imposed load	Gamma	0.2 × 1244 kN	0.95
Fire loading [17]			
Fire load density, q_f (EN 1991-1-2:2002)	Gumbel	Nominal ($100 - 1600$ MJ/m^2)	0.3
Opening factor, O	Normal	Nominal ($0.04 - 0.20$ m$^{1/2}$)	0.1
Model uncertainties [16]			
Resistance estimation, K_R	Lognormal	1.1	0.1
Load estimation, K_E	Lognormal	1.0	0.1

Table 1. Stochastic parameters for the probabilistic analysis of steel columns.

$$N_{bR} = \varkappa_T A_{col}\, f_{y,T} \tag{6}$$

where, $\varkappa_T$ is the temperature dependent buckling resistance factor, A_{col} is the cross-sectional area of column and $f_{y,T} = k_{y,T}\, f_y$ is temperature-dependent yield strength of steel, in which $k_{y,T}$ is the yield strength retention factor. The buckling resistance factor, $\varkappa_T$ is evaluated based on EN 1993-1-2:2005.

3.2. Life-time cost optimization

The life-time cost optimization for the steel column involves determining the cost of the SFRM protection and the cost of structural failure for the fire event. The cost optimization is carried out considering SFRM thickness, d_i varying between 6-60 mm. A factor of $\xi = 3.0$ is considered for the relative cost of structural failure due to fire event (indicates minor failure consequence as reported in [13]. The reliability targets are later derived in Section 4 for failure costs with both a factor of 3 and 20 to assess the sensitivity to this assumption.

Investment cost

The investment cost is the cost of SFRM protection of the steel column. It is obtained from the RSMeans (2019) database [20], which is a database comprising cost of structural building materials. SFRM costs \$132 / inch /m^2. Figure 1(a) plots the cost of SFRM application for the steel column as a function of the thickness, which is the determining factor for fire performance. Based on RSMeans (2019), the cost of the steel column is determined as \$3618. The cost of the steel column represents the structural cost, C_O. Figure 1(a) also shows the marginal safety investment cost, $\varepsilon(p)$, which can directly be implemented in Equation 5 for cost optimization.

Commonly, prescriptive guidelines report the fire protection of steel members in terms of standard fire-rating (e.g., ISO834, ASTM E119). Figure 1(b) plots the ISO834 fire-rating for the considered thicknesses of SFRM protection, where the critical temperature is determined based on the column's buckling resistance (here, $T_{b,cr} = 536°$C as defined by the accidental limit state for fire design).

Failure cost

The failure cost in Equation 3 involves determining the failure probability, P_f, of the steel column, considering occurrence of a fire event. The limit state for the column here relates to the exceedance of buckling resistance (assuming the column is in pure compression). The failure probability of the column is represented as:

$$P_f = \mathrm{P}\left[K_R\, N_{bR} - K_E\, N_E < 0\right] \tag{7}$$

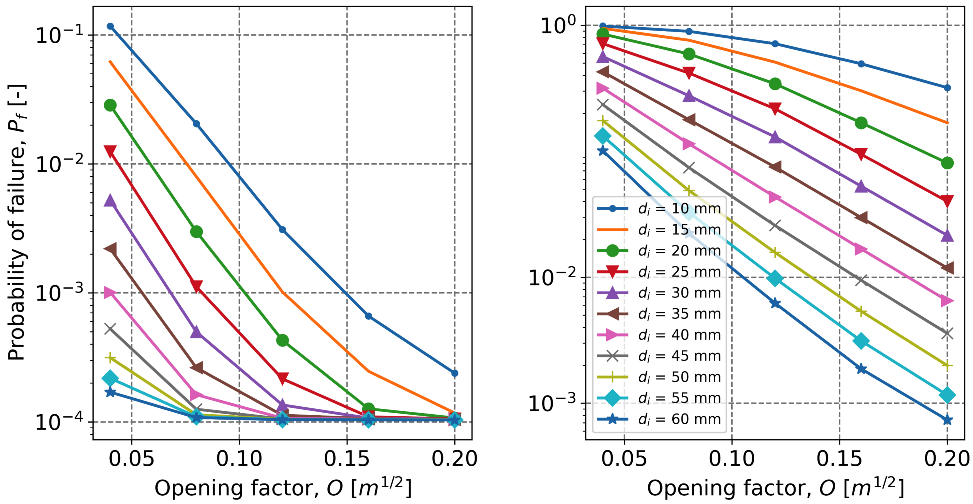
where, N_{bR} is the column's buckling resistance, N_E is the load on column and K_R and K_E are the model uncertainties for resistance and load estimation. The estimation of N_{bR} for fire exposure scenario comprises two steps: (i) calculating the maximum temperature reached in the steel section under the considered fire scenario, and (ii) estimating the buckling resistance for this maximum temperature using Equation 6. Table 1 lists the stochastic parameters identified for the probabilistic analysis of the steel column. The failure probability is estimated considering d_i of SFRM varying from $6 - 60$ mm at increment of 1 mm. The application of SFRM with $d_i < 6$ mm is assumed to be difficult in application. Thus, the cost optimization approach evaluates an optimum value of d_i within the range of $6 - 60$ mm.

The Eurocode parametric fire curve is adopted here to define the fire scenarios for the steel column [17]. A wide range of fire scenarios is considered by varying the fire load density (100-1600 MJ/m^2) and the compartment opening factor (0.04, 0.08, 0.12,0.16 and 0.20 m$^{1/2}$). The target reliabilities for fire design are then derived for each of these fire scenarios. The considered fire load densities can be related to the building occupancies as discussed in Annex E of [17]. Considering 80 cases of fire scenarios and 54 cases of d_i, the probabilistic analysis involving 10^5 Monte Carlo (MC) simulations each to determine the maximum steel temperatures is computationally demanding (approximately 120,000 core hours needed). To reduce the computational expense, a Neural Network (NN) based surrogate model is adopted [21]. The optimum NN model has 4 hidden layers with 300 neurons each and has a R^2 of 0.99 (3000 samples used for training and 500 as test data set).

To carry out the probabilistic analysis, 10^5 MC samples are applied. NN model gives the maximum temperature of the steel section, while Equation 6 evaluates the buckling resistance of the column for the samples. Since the model to evaluate the mechanical response is less computationally expensive than that for the thermal response, 10^8 MC samples are developed for the load and model uncertainties. A higher number of samples allows developing more precise fragility curves. Figure 2 presents a sample of fragility curves for the steel column for the considered scenarios of parametric fire exposures. The opening factor is selected as the intensity measure. For illustration, only the cases with fire load density of 500 and 1500 MJ/m^2 are presented. In the figure, the P_f is 0.12 for a steel column with 10 mm SFRM in case of fire with a fire load of 500 MJ/m^2 and opening factor of 0.04 m$^{1/2}$. This P_f is reduced to 1.7×10^{-4} with 60 mm SFRM. Similarly, the P_f is reduced from 0.99 to 0.10 for fire load density of 1500 MJ/m^2 as shown in Figure 2b. Thus, SFRM is observed to decrease the failure probability of steel column significantly for given fire inputs. Failure costs are evaluated from the computed probability of failure using Equation 3.

Life-time cost

Figure 3 demonstrates the life-time cost optimization procedure to determine the optimum insulation thickness of the steel column for a particular case of fire exposure ($q_f = 800\,\mathrm{MJ/m^2}$ and $O = 0.04m^{1/2}$). The annual probability of fire occurrence is assumed to be 2.5×10^{-3}. This value corresponds to the mean yearly ignition frequency in office buildings (in Finland estimated for year 1995 as studied by [22]). This fire frequency (λ) is adopted considering that building relies only on insulation thickness for fire safety and that there are no fire suppression systems or nearby fire brigades. This value can be considered high and is thus considered to result in a high estimation of the



(a) q_f = 500 MJ/m² (b) q_f = 1500 MJ/m²

FIGURE 2. Fragility curves for steel columns with varying SFRM thickness under parametric fire exposure.

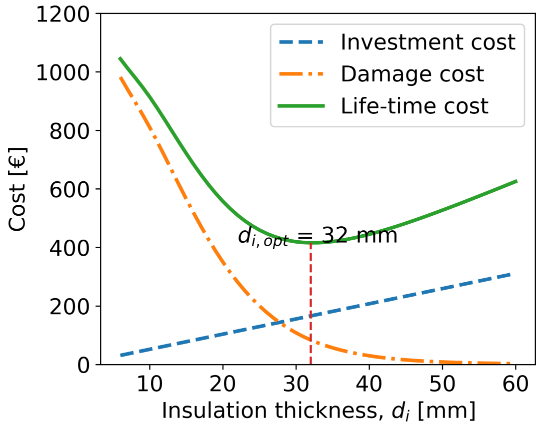


FIGURE 3. Investment, failure and life-time cost for a specific fire scenario case of steel column (qf = 800 MJ/m^2 and O = 0.04 m$^{1/2}$). Optimum SFRM thickness, $d_{i,opt}$ of 32 mm obtained for the case.

benefit of fire protection. In absence of data on the failure cost factor for fire hazard, a factor of 3.0 representing the minor failure consequences for ambient structural design [6, 7] has been considered here. For this case, an optimum insulation thickness of 32 mm is obtained.

Figure 4(a) shows the optimum thicknesses of insulation determined based on life-time cost optimization for all the considered cases of parametric fire exposure. The optimum SFRM thickness required for a mean fire load of 420 MJ/m^2 (average value for office buildings) can be interpolated from the Figure and is found to be 8 mm for O of 0.04 m$^{1/2}$. A 6 mm insulation is the lowest practical SFRM insulation as mentioned above. However, the optimum d_i in case of higher consequences of structural failure ($\xi > 3.0$) will be higher. Similarly, if the building is used as residential (i.e., $q_f = 780\,\text{MJ/m}^2$), the optimum insulation thickness required is 31 mm for an opening factor of 0.04 m$^{1/2}$. Based on Figure 1(b), the SFRM thickness of 31 mm corresponds to 158 min of ISO fire rating. In other words, the optimum fire protection for steel column in a residential building needs to be designed for a fire rating of 158 min (practical values are 120 min and 180 min). The cost optimization approach thus enable recommending an optimum design parameter, demonstrating a cost-effective and a reliable structural design. Figure 4b shows the optimum failure probability corresponding to the optimum insulation thicknesses of the steel column, as a function of the fire load density. As the fire load density increases, it is more cost-efficient to allow a higher probability of failure should a fire occur, compared with occupancies with lower fire load densities. Indeed, it is costly to reduce P_f in buildings with large fire loads, while it is assumed here that neither the probability of occurrence of a fire nor the cost of the failure depend on the fire load. The evaluation of optimum failure probability allows further generalization of the concept of cost optimization. In the Figure 4b, the optimum failure probability for the steel column considering office building with compartment opening factor of 0.04 m$^{1/2}$ is 0.053. The optimum failure probability can easily be interpolated for all other parametric

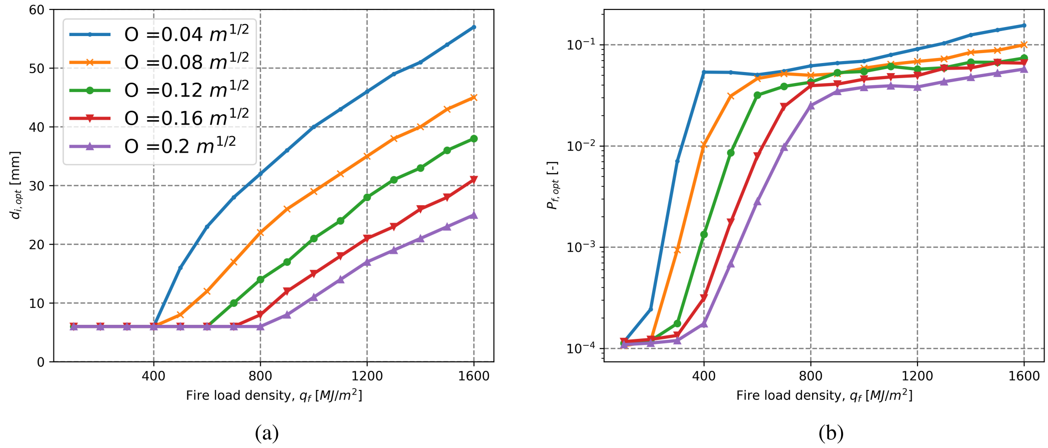


FIGURE 4. Optimum (a) SFRM thicknesses and (b) failure probability for considered cases of fire scenarios of steel column.

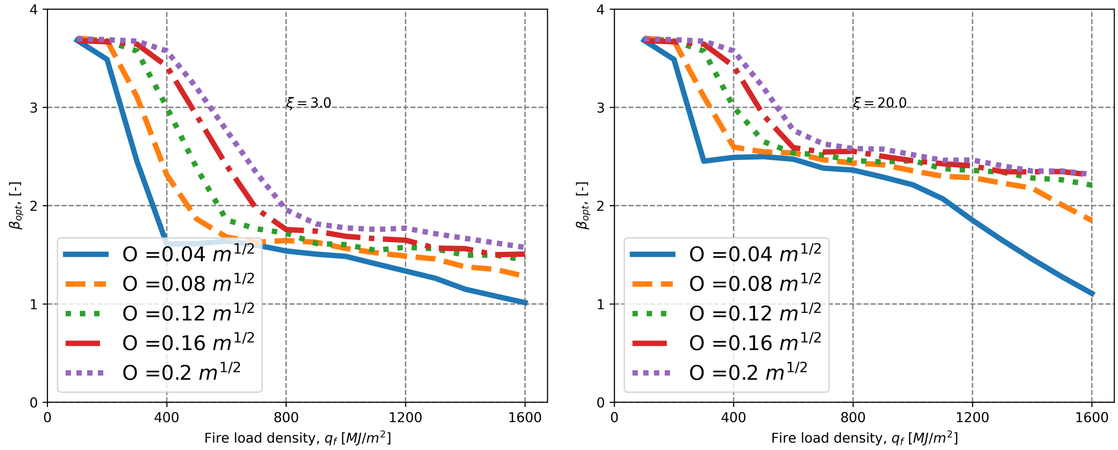


FIGURE 5. Reliability targets for steel column for parametric fire exposure of steel column (constant annual fire probability of 2.5×10^{-3} and, two cases of relative failure costs, $\xi = 3.0$ and 20.0 considered).

natural fire scenarios.

4. RELIABILITY TARGETS FOR FIRE PROTECTED STEEL COLUMNS

The optimum failure probability in Figure 4(b) can be translated into optimum reliability index by evaluating the inverse standard normal cumulative density function (Φ) and is given by:

$$\beta = -\Phi^{-1}(P_f) \tag{8}$$

These evaluated optimum reliability indices represent the target reliabilities for the structure. In this study, the target reliabilities are developed for natural fire exposure of steel column. Figure 5 presents the target reliabilities for the steel column for natural fire exposure ($\xi = 3.0$ and 20.0). The target fire reliability for steel column (part of office building i.e., $q_f = 420\,\mathrm{MJ/m^2}$) is 1.65, 2.15, 2.83, 3.36, and 3.53 for compartment opening factors of 0.04, 0.08, 0.16, 0.20 $\mathrm{m}^{1/2}$, respectively, considering $\xi = 3.0$. For the structure considering higher relative failure cost, i.e., $\xi = 20.0$ the target reliabilities are 2.47, 2.64, 2.96, 3.36 and 3.48. Similarly, the target reliabilities for other possible fire scenarios can be obtained from Figure 5. The benefit of deriving such target reliability is the possibility of generalizing the reliability value as a target for similar design situations. The structural fire design based on these derived target reliabilities allows a prompt and economical structural design without a need of re-applying the cost-optimization approach developed in this study. The target reliabilities however depends on the considered structural models and the probabilistic modeling assumptions, which one should be cautious about while reapplying for structural fire designs. This will be considered as part of follow up research targeting the generalization described above.

5. CONCLUSIONS

In this study, reliability targets based on life-time cost optimizations are derived for fire-exposed steel columns. In the first part of the study, optimum thickness of insulation are determined through life-time cost optimization as a function of the fire inputs, which are found in standards and codes based on building occupancies. For example, considering a mean fire load of 420 MJ/m^2 as recommended in Eurocode for office buildings and an opening factor of 0.04 m$^{1/2}$, an optimum insulation thickness of 8 mm is found. The methodology proposed in the first part of the paper can serve to evaluate the optimum of a design parameter (e.g., insulation thickness) for a specific project. However, application of such methodology is inconvenient and time consuming for practical applications. Therefore, in the second part, the study describes how to evaluate general reliability targets based on the obtained optimum values of the design parameter. Design based on such pre-derived reliability targets for a fire-exposed structure allows a prompt, economical, and reliable structural fire design. The method was illustrated on the case study of a protected steel column, but the method will be applied in the future to other and more general configurations. The study thus constitutes a next step toward proposing target reliability values for the fire design of structures.

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