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EXPLORATORY STUDY INTO A SAFETY FORMAT FOR COMPOSITE COLUMNS EXPOSED TO FIRE

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Abstract

Current performance based structural fire engineering approaches evaluate structural behaviour under prescribed fire scenarios. The mechanical properties of the materials, the load conditions and geometric parameters are all however fraught with uncertainty, and there is currently no clear safety format ensuring the reliability of the design solution. In this contribution, a safety format is explored for evaluating the fire resistance of composite columns, following results obtained in earlier studies on uncertainty quantification. Using the safety format, a single nonlinear finite element evaluation of the fire resistance time is combined with a global safety factor, defining its design value. Under the assumptions derived from earlier work, the safety format works well, but additional parameter studies indicate that good performance is limited to relatively low ambient design utilization ratios. The results thus highlight the importance of uncertainty quantification and the limitations of basing a safety format for structural fire design on limited studies. It is concluded that detailed studies into the probabilistic description of the response of composite columns exposed to fire are required to generalize the results to a broadly applicable design rule.

Keywords: composite column, design, global safety factor, reliability, fire safety

1 INTRODUCTION

Structural fire design is commonly based on an evaluation of structural performance under a specified fire scenario, without consideration of the uncertainties associated with the loading and model parameters (Lange et al., 2019). As such, the safety level achieved by a design is not explicitly evaluated. This hampers communication with stakeholders and poses the potential for missed expectations. Application of a full probabilistic design methodology can alleviate this problem, but these approaches are in general too computationally expensive for design applications.

For normal (ambient) design situations, these problems are avoided through a safety factor format calibrated by full probabilistic background calculations, e.g. EN 1990 (CEN, 2002). For structural fire design such a calibrated safety factor format is currently absent, with any existing formats in guidance documents based on experience and consensus instead. It is noteworthy that this lack of reliability-based foundation also holds true for the prescriptive approach currently in use.

In the following, the results of an exploratory study into a safety format for the structural fire design of composite columns is presented, building on results presented in (Gernay et al., 2019). The format allows the design of a composite column for fire resistance at a given reliability level, based on a single (finite element) evaluation of fire performance and the application of a global safety factor. The methodology is introduced step-wise, giving insight into the research process and the assumptions underlying the safety format. The developed format is found to be accurate at the low load ratios for which it was originally developed, but the accuracy is reduced when applying the concept to higher load ratios. Overall, the paper presents a roadmap for further studies and can be a starting point for similar evaluations for other structural fire design cases and materials.

2 COMPOSITE COLUMN EXPOSED TO FIRE

In Gernay et al. (2019), the application of an efficient uncertainty quantification method to advanced structural fire engineering applications has been demonstrated. One validation case related to the fire resistance time of the composite column illustrated in Fig. 1, was evaluated using the dedicated finite element package SAFIR (Franssen & Gernay, 2017). Due to the many uncertainties associated with the load and resistance effects, also the fire resistance time t_R achieved by the column is uncertain. The analyses in (Gernay et al., 2019) indicated that, for the case under consideration (see input data Table 1), t_R could be described by a lognormal distribution (Fig. 2), with mean μ_{tR} of 135 minutes and coefficient of variation V_{tR} equal to 0.15.

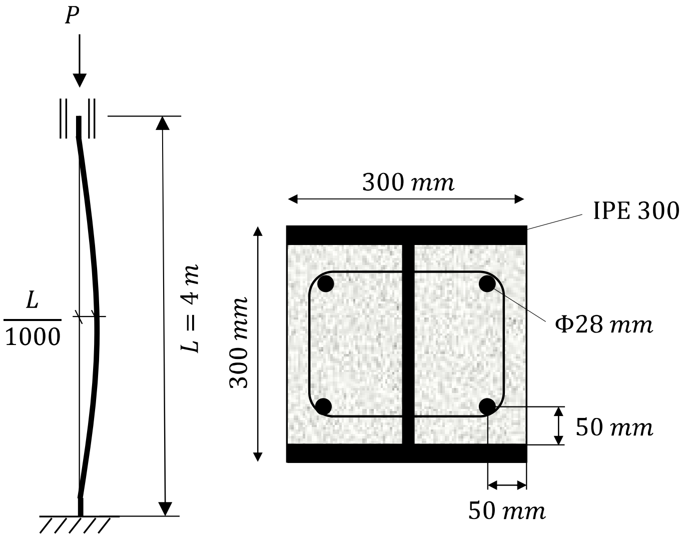

Fig. 1 Composite steel-concrete column (Gernay et al., 2019): (a) elevation; (b) cross-section

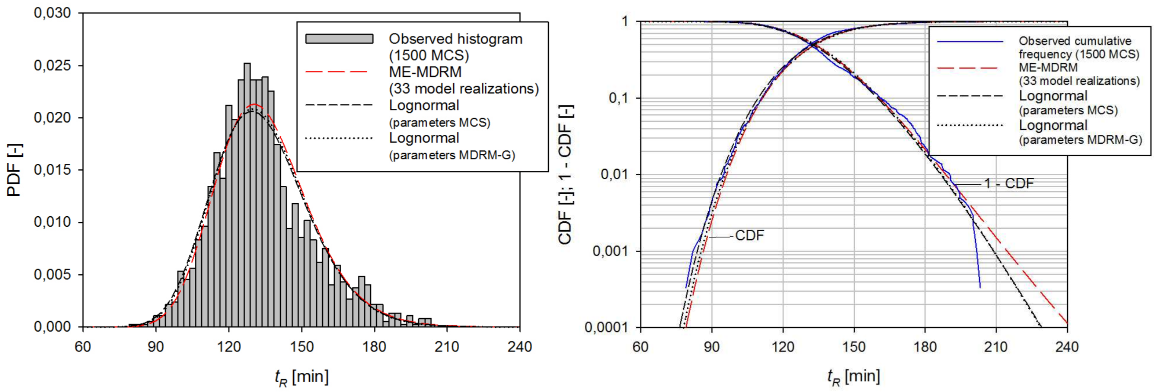

Fig. 2 Fire resistance time t_R for composite column (Gernay et al., 2019): Comparison of 1500 crude Monte Carlo Simulations with distribution descriptions (a) PDF; (b) CDF and complementary CDF

3 SAFETY FACTOR FORMAT

3.1 Initial considerations

The above observation of Fig. 2 has prompted follow up studies into a safety factor format for the numerical evaluation of fire resistance using advanced calculation tools. Currently, the safety format to be applied when numerically assessing the fire resistance of a structural element is unclear. Should the input values (e.g., material strength) correspond to characteristic values as for normal design conditions? Should a safety factor be applied to the material properties? Should the element maintain stability for a certain time beyond the nominal prescribed fire resistance (or even until burnout), or is it sufficient to maintain stability up to the nominal standard fire duration?

Importantly, the above questions cannot be decoupled from underlying considerations on the reliability targeted by the design evaluation. In other words, with what confidence level should the prescribed fire resistance be achieved?

For normal (ambient) design, e.g. EN 1990 (CEN, 2002), the target reliability levels have been derived through calibration and cost-optimization considerations (Van Coile et al., 2017). These target reliability levels consider both the costs of investing in increased safety, as well as the costs incurred in case of structural failure. For structural fire design, the costs of increasing fire resistance, as well as the consequences of a fire-induced structural failure, are currently not fully explored and likely depend to a very large degree on the situation under consideration (e.g. industrial storage of bulk goods vs. high-rise residential buildings). Therefore, a proposed safety format needs to be flexible to allow for local considerations on target reliability levels.

Furthermore, the safety format should ideally allow users to assess the adequacy of the design using a single nonlinear finite element calculation.

Table 1 List of stochastic variables, based on (Holicky and Sykora, 2010), see (Gernay et al., 2019)

Parameter	**Distribution**
Normal design concrete compressive strength, f_{ck} [MPa]	LN, $\mu = \frac{f_{ck}}{1-2V_{fck}}$, $V_{fk,b} = 0.15$
Normal design yield strength of the steel profile, fy,b [MPa]	LN, $\mu = \frac{f_{yk,b}}{1-2V_{fyk,b}}$, $V_{fy,b} = 0.07$
Normal design yield strength of the reinforcement, fy,r [MPa]	LN, $\mu = f_{yk,r} + 2\sigma_{fy,r}$, $\sigma_{fy,r} = 30$ MPa
Equivalent load P [kN] , taking into account the total model uncertainty K_T, and relating the characteristic values of the permanent loads G and imposed loads Q by $\chi = \frac{Q_k}{Q_k + G_k}$	LN, $\mu_{P_{eq}} = \mu_{K_T}\left(\mu_G + \mu_Q\right)$; $\sigma_{P_{eq}} = \sqrt{\sigma_{K_T}^2\left(\mu_G+\mu_Q\right)^2 + \mu_{K_T}^2\left(\sigma_G^2+\sigma_Q^2\right)}$
Temperature dependent retention factors for concrete compressive strength and steel yield strength	Logistic, see (Elhami Khorasani et al., 2015) and (Gernay et al., 2019)
Geometric imperfection	Normal, $\mu = 0$, $\sigma = h/1000$ with h the column height

3.2 A global safety factor for fire resistance

Based on the evaluation by Gernay et al. (2019), i.e. Fig. 2, the fire resistance t_R of the composite column can be described by a lognormal distribution. Considering a prescribed fire severity given by an equivalent standard fire duration t_E (deterministic limit), the probability P_f of the design reaching its fire resistance before t_E is:

$$P_f = P\left[t_R < t_E\right] = \Phi\left(\frac{\ln\left(t_E\right) - \mu_{\ln t_R}}{\sigma_{\ln t_R}}\right) \tag{1}$$

with σ_{lntR} and μ_{lntR} the parameters of the lognormal distribution, as defined in general terms by Eqs. (2) for a lognormally distributed variable X with mean μ_X and coefficient of variation V_X.

$$\sigma_{\ln X} = \sqrt{\ln\left(1+V_X^2\right)} \text{ and } \mu_{\ln X} = \ln\left(\mu_X\right) - \frac{1}{2}\sigma_{\ln X}^2 \tag{2}$$

A possible design criterion is given by Eq. (3), stating that the design is accepted when the design value t_{Rd} of the fire resistance time exceeds the prescribed equivalent fire duration t_E. In this formulation, the uncertainty with respect to t_R is considered in the design value t_{Rd}. Thus, t_{Rd} should be defined in a way that the probability of t_R being lower then t_{Rd}, $P[t_R < t_{Rd}]$, is limited to a maximum allowable (target) failure probability $P_{f,t}$, or an equivalent target reliability β_t, i.e. Eq. (4). Combining Eqs. (4) and (2), the ratio of t_{Rd} to μ_{tR} is given by Eq. (5). Opportunistically choosing to define t_{Rd} as μ_{tR} / γ_R, with γ_R a global resistance (safety) factor and μ_{tR} the mean fire resistance time, reveals an equation for the required safety factor in function of the coefficient of variation V_{tR} and target reliability index β_t, Eq. (6), with the approximation holding for $V_{tR} \leq 0.2$.

$$t_{Rd} \geq t_E \tag{3}$$

$$P\left[t_R < t_{Rd}\right] = P_{f,t} = \Phi\left(-\beta_t\right) = \Phi\left(\frac{\ln\left(t_{Rd}\right) - \mu_{\ln t_R}}{\sigma_{\ln t_R}}\right) \tag{4}$$

$$\exp\left(-\beta_t \sigma_{\ln t_R} + \frac{1}{2}\sigma^2_{\ln tR}\right) = \frac{t_{Rd}}{\mu_{tR}} \tag{5}$$

$$\gamma_R = \exp\left(\beta_t \sigma_{\ln t_R} - \frac{1}{2}\sigma^2_{\ln tR}\right) \approx \exp\left(\beta_t V_{tR}\right) \text{ for } t_{Rd} = \frac{\mu_{tR}}{\gamma_R} \tag{6}$$

Nomograms for the above derived global resistance factor are given in Fig. 3 as a function of the target failure probability $P_{f,t}$ – or equivalently β_t – for different V_{tR}. Both the exact formulation and the approximate formulation of Eq. (6) are depicted, confirming the approximation.

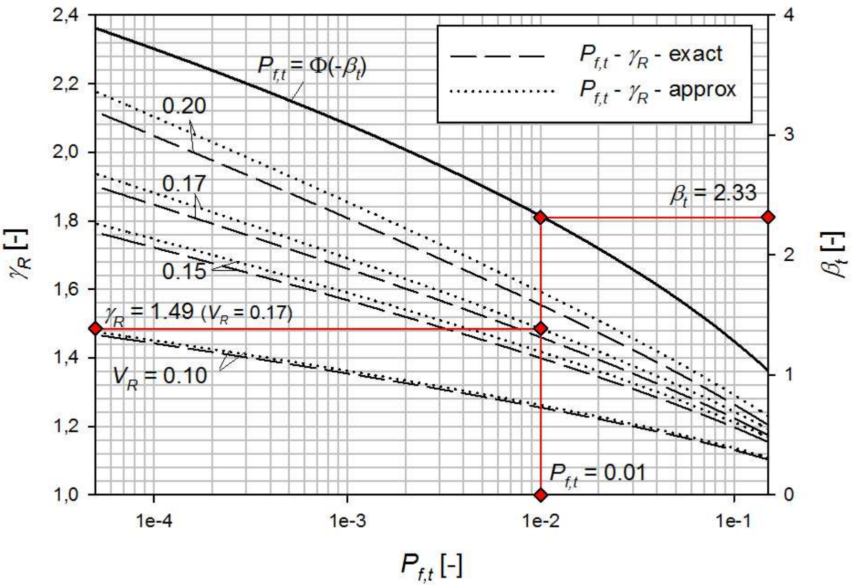

Fig. 3 Global resistance safety factor γ_R for different coefficient of variation V_{tR} (general notation: V_R), in function of the maximum (target) probability of failure $P_{f,t}$. Relationship between $P_{f,t}$ and the target reliability index β_t. Visualization of application example Section 3.3.

3.3 Concept demonstration

For a first demonstration of applying the safety format, consider the composite column specified in Fig. 1. The fire resistance requirement has in hypothesis been specified through a maximum (target) failure probability of 0.01 for an equivalent ISO 834 standard fire exposure of 90 minutes. Assume that V_{tR} for this type of column is – based on experience and assuming the results of Section 2 are unknown since the objective is to avoid a full probabilistic evaluation – conservatively set at 0.17 (see Section 4). In order to demonstrate that the column achieves the specified target reliability, a single nonlinear finite element calculation is performed, using mean values for all stochastic variables as listed in Table 1. The fire resistance time of 135 minutes obtained with this single evaluation is a first order Taylor approximation for the true mean of t_R (and corresponds well with the value listed by Gernay et al. (2019), see Section 2). For an assumed COV of 0.17 and $P_{f,t}$ of 0.01, Fig. 3 indicates $\gamma_R = 1.49 \approx 1.50$. Thus, t_{Rd} = 135 min / 1.50 = 90 min $\geq t_E$ = 90 min, and the composite column passes the criterion of Eq. (3). In other words, based on the single finite element calculation, the column is considered to have a probability of no more than 0.01 of not maintaining its load bearing capacity up to 90 minutes of standard fire exposure. The detailed uncertainty quantification in Fig. 2 indicates that the threshold probability of 0.01 is exceeded only for approximately 96 minutes of exposure, confirming for this specific case the conservative nature of the safety format.

In situations where the design itself is open to modification (or optimization), the safety format equivalently requires $\mu_{tR} \geq \gamma_{tR} \cdot t_E$. For the situation described above, this implies that the design can be optimized, under the constraint that the column – considering mean values for the input variables – maintains its load bearing capacity for at least 135 min ISO 834 exposure (135 = 1.50 x 90).

Table 2 – List of cases investigated: nominal input values, ambient utilization u, observed V_{tR} and appropriateness of LN approximation: ok, conservative (C), non-conservative (NC) and inappropriate (OFF).

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Test series	REF	S1	S1	S1	S1	S1	S1	S1	S1	S2	S2	S2
f_{ck} [MPa]	25	45	45	25	25	25	25	25	25	30	35	40
f_{ykb} [MPa]	235	235	355	355	235	235	235	235	235	235	355	355
f_{ykr} [MPa]	500	500	500	500	420	500	500	500	500	420	500	420
P_k [kN]	1700	1700	1700	1700	1700	1700	2000	2000	1400	1400	2100	1600
χ [-]	0.25	0.25	0.25	0.25	0.25	0.40	0.40	0.25	0.25	0.30	0.40	0.35
u [-]	0.45	0.45	0.45	0.45	0.45	0.45	0.53	0.52	0.37	0.37	0.56	0.42
V_{tR} [-]	0.15	0.17	0.16	0.15	0.15	0.17	0.15	0.15	0.16	0.17	0.17	0.16
LN*	ok	ok	ok	C	ok	C	ok	ok	C	ok	C	NC
Case	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Test series	S2	S2	S2	S2	S2	S2	S2	S3	S3	S3	S3	S3
f_{ck} [MPa]	25	40	40	40	40	25	25	25	25	25	25	25
f_{ykb} [MPa]	235	355	235	355	235	355	235	235	235	235	235	235
f_{ykr} [MPa]	420	420	420	420	420	420	500	500	500	500	500	500
P_k [kN]	1800	2000	1600	1600	1800	1800	4500	3056	2674	3438	3820	2292
χ [-]	0.20	0.35	0.35	0.20	0.35	0.4	0.25	0.25	0.25	0.25	0.25	0.25
u [-]	0.47	0.53	0.42	0.42	0.48	0.48	1.18	0.80	0.70	0.90	1.00	0.60
V_{tR} [-]	0.15	0.17	0.17	0.17	0.17	0.16	0.30	0.18	0.16	0.20	0.23	0.15
LN*	ok	ok	NC	ok	ok	C	OFF	OFF	NC	OFF	OFF	NC

4 GENERALIZATION AND VALIDATION STUDY

The proposed safety format has been developed with the composite column of Fig. 1 in mind, assuming a lognormal distribution for t_R as indicated by Fig. 2. To generalize the results, a first parameter study (S1) was performed with the goal to: (i) confirm that t_R can be (conservatively) described by a lognormal distribution, and (ii) evaluate any variation in V_{tR} and to propose a single conservative value which is generally applicable. A list of the performed calculations is given in Table 2, together with the appropriateness of the lognormality assumption (based on the procedure described in Gernay et al. (2019)), as well as V_{tR}, both evaluated using the procedure described in

(Gernay et al., 2019). Based on the results of S1, lognormality was tentatively accepted and V_{tR} = 0.17 postulated as a default value. A second validation series (S2) was performed. Issues with the lognormality assumption where observed for cases 12 and 15, but the safety format could be maintained for these cases subject to V_{tR} being set equal to 0.18. For case 19 however a major issue was observed. While the ambient utilization u (i.e. E_d / R_d, with R_d assessed considering design values for the material properties and perfect axial compression) was smaller than 0.60 for all cases 1 to 18, the much higher load in case 19 resulted in the lognormal distribution being inappropriate and the safety format inadequate. A further parameter study (S3) at load ratios ranging from 0.6 to 1 confirmed the observed limitation of both the lognormality assumption and the developed safety format. Additional calculation series using columns with an IPE160 profile confirmed these observations (not listed here). Overall, the parameter study in Table 2 suggests that the developed safety format may be appropriate for utilizations $u \leq 0.60$ but cannot be applied for higher ambient load ratios. To improve the safety format of Section 3 and to generalize its applicability, detailed studies into the probabilistic description of t_R for composite columns are necessary. The results highlight the pit-falls involved with accepting a common probability distribution type (e.g. a lognormal distribution) based on limited data.

5 CONCLUSIONS

Considering results from earlier uncertainty quantification studies where the fire resistance time was found to follow a lognormal distribution, a safety format for the fire resistance time of composite columns was developed. The derived safety format combines a single nonlinear finite element calculation with a global resistance factor to determine a design value of the fire resistance time, to be compared with requirements of equivalent standard fire exposure. The safety format ensures that reliability considerations are duly considered, without increasing the computational expense for design studies. Validation studies however highlight that a lognormal approximation is only appropriate at ambient design utilization ratios up to 60%. Consequently, for higher utilization ratios the safety format considered here was found inappropriate. The study stands as a warning to duly take into account the uncertainties inherent in structural fire engineering, and against generalizing probabilistic descriptions from limited validation studies only. It is concluded that an improvement of the derived safety format is needed before it can find application, and that this necessitates detailed studies into the probabilistic description of the fire resistance time of composite columns also at high utilization ratios.

REFERENCES

CEN. 2002. EN 1990: Eurocode 0: Basis of Structural Design. *European Standard*. European Committee for Standardization.

Elhami Khorasani, N., Gardoni, P., Garlock, M. (2015). Probabilistic fire analysis: evaluation of steel structural members. *Journal of Structural Engineering*, 141(12).

Franssen, J.-M., Gernay, T. 2017. Modeling structures in fire with SAFIR®: Theoretical background and capabilities. *Journal of Structural Fire Engineering*, 8(3). P. 300-323.

Gernay, T., Van Coile, R., Elhami Khorasani, N., Hopkin, D. 2019. Efficient Uncertainty Quantification Method Applied to Structural Fire Engineering Computations. *Engineering Structures*, 183, 1-17.

Holicky, M., Sykora, M., 2010. Stochastic models in analysis of structural reliability. In: *International symposium on stochastic models in reliability engineering, life sciences and operation management*, 8-11 February 2010, Beer Sheva, Israel.

Lange, D., Hopkin, D., Van Coile, R., Elhami Khorasani, N. 2019. *Uncertainty in Structural Fire Design. In: Structural Fire Engineering Handbook, Springer, New York.*

Van Coile, R., Hopkin, D., Bisby, L., Caspeele, R. 2017. The meaning of Beta: background and applicability of the target reliability index for normal conditions to structural fire engineering. *Procedia engineering*, 210, p. 528-536.