Addressing the pitfalls of risk-based methods for fire safety design of structures

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ABSTRACT: Risk-based design and assessment methods are gaining popularity in the context of performance-based structural fire engineering. Nevertheless, they often ignore that there exists a strong dependency between the combustion process and the structural features, impacting the structural safety assessment outcomes. This paper compares a conventional risk-based design approach with a methodology named the Maximum Allowable Consequence (MAC) approach proposed by the authors to address such a limitation. An illustrative example concerning the fire safety design of a bridge is presented. It is shown that the considered risk-based approach yields coefficients of variation on the consequence metric one order of magnitude larger than the MAC approach. Finally, this approach enables the explicit selection of the design variables that make the bridge compliant with the desired performance objectives.

1. INTRODUCTION

Risk-based design and assessment approaches developed for natural hazards such as earthquakes and wind have been increasingly applied in performance-based structural fire engineering. These approaches span from analytical/numerical methodologies (e.g. first-order reliability method (Guo and Jeffers, 2015)), as well as simulation-based approaches (e.g. Monte Carlo sampling (Hopkin et al., 2021)) from structural reliability analysis to procedures based on the Pacific Earthquake Engineering Research centre (PEER)'s performance-based earthquake engineering (PBEE) framework (e.g., (Porter, 2003)), reviewed by Shrivastava et al. (2019). All these approaches start from the definition of fire (hazard) scenarios. Then, they compute fire-induced structural response and use the structural analysis results to estimate a probabilistic demand model (i.e., structural response in terms of an engineering demand parameter vs hazard intensity measure) and derive statistics of the resulting hazard-induced consequences (e.g., damage levels, repair costs, downtimes, and casualties). The selected consequence metrics are then appraised against a set of pre-defined design objectives. Finally, the design variables are updated until an objective-compliant (or optimal) solution is attained.

From a fire safety *design* perspective, however, these methodologies need to be revised to deliver more optimised design solutions. Indeed, such approaches ignore the coupling between a fire and the surrounding structure(s) (Torero, 2006, 2013). Specifically, while the fire releases thermal energy and species that deteriorates structural properties, the heated environment, in turn, affects the combustion process through radiative feedback, ventilation constraints and geometric effects on the buoyant fluxes. Additionally, heat and species release triggers people's response and activate fire safety measures to control fire grown and spread. Due to this coupling, approaches that estimate consequences based on a set of preliminarily defined hazard scenarios cannot identify the conditions which maximise fire impacts. Furthermore, they cannot exploit the beneficial influence that design decisions (structural layout, cross-sectional properties and shape, materials) can have on fire intensity and other fire characteristics. In this sense, the fire scenario should be an analysis output and becomes an additional design variable as opposed to being considered a design/assessment input.

The Maximum Allowable Damage methodology by Cadena et al. (2022) partially embraces this unique fire feature by suggesting that scenario assumptions should be updated during the assessment. Nevertheless, this method does not compute the fire scenario yielding maximum consequences nor quantifies uncertainty propagation to consequence metrics of interest. Such quantification is instead an advantage of risk-based approaches. However, their reliance on preliminary fixed fire scenarios raises concerns about the result's significance and hampers their capacity to deliver robust optimal solutions (i.e., insensitive to small changes in uncertain input quantities (Zang, 2002)).

The dynamic coupling between structures and fire also makes the Markovian-dependence assumption (Baker et al., 2021) for the variables/distribution/calculation steps involved in the PEER-PBEE framework (e.g., intensity measure, engineering demand parameter, damage measure) ill-founded. In particular, non-efficient and non-sufficient (Padgett et al., 2008) intensity measures are considered (e.g., fuel load density, maximum fire temperature, fire duration). Additionally, the strong dependence of the combustion process on the surrounding environment (including its structures) hinders the accuracy of hazard occurrence models calibrated on empirical data from past events.

To cope with these limitations, Franchini et al. (2023) have recently developed an alternative methodology to fire safety design named the Maximum Allowable Consequence (MAC) approach. This paper aims to compare a risk-based approach and the MAC approach, highlighting their differences and the potential benefits of the latter.

2. CONSIDERED METHODS

Figure 1 compares a general risk-based (RB) and the MAC design methodologies. Both considered approaches start by defining performance objectives regarding life safety and serviceability limit states or property protection. Then, the selected objectives guide the choice of consequence metrics of interest. In this regard, RB methods generally refer to distributions (or statistics) of the considered consequence or annual exceedance rates (i.e., risk curve). Differently, the MAC approach focuses on a consequence potential model from which the maximum consequence a fire can cause is derived and compared to a threshold (the MAC) set by end users. This threshold might refer to life safety, property protection or continuity of operation performance objectives.

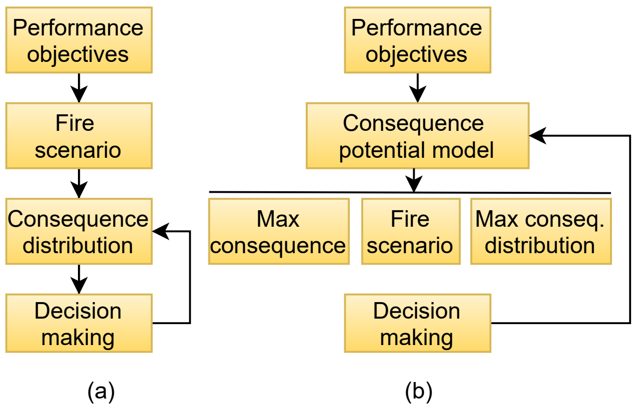

Figure 1: Fire safety design: (a) Risk-based approach; (b) MAC approach.

In the second step (Figure 1a), a typical RB approach probabilistically characterises the features and likelihood of fire scenarios that might threaten the structure under investigation. Most of the literature refers to post-flashover temperature curves developed through random sampling of fuel load density, ventilation factors, room geometry and surface materials (Shrivastava et al., 2019). These factors exhibit large building-to-building variability. Additionally, they should be designed to influence the fire's growth and spread so that consequences are limited to a tolerable level. This goal is achieved in combination with appropriate detailing of structural capacities. In contrast, handling these parameters as random variables limits the designer's ability to positively affect the combustion process and results in unnecessarily uncertain consequence distributions.

The scenarios' probabilities of occurrence are calculated based on statistical data from previous events in buildings of the same occupancy category as the considered one (e.g., (Sleich et al., 2002)). Nevertheless, such data cannot consider an individual structure's peculiarities which strongly impact the fire characteristics. In this respect, Torero (2019) discussed that each fire scenario is unique and, therefore, should not be assigned a probability of occurrence. The result is a fire occurrence model affected by significant uncertainty, which propagates to the consequence estimates and entails potentially misleading results. Similarly, for structures other than buildings in which flashover fires are not representative (e.g., bridges), the fuel bed location is required for scenario definition. Yet, previous studies (e.g., (Ma et al., 2019; Zhu et al., 2023)) assigned an equal probability of occurrence to different possible ignition locations. Following the scenario definition, an RB approach computes consequences based on structural analysis and eventually uses them to inform decision-making (third and fourth steps in Figure 1a).

Figure 1b illustrates the proposed MAC methodology. Instead of analysing the structural response to a set of pre-defined scenarios, the approach builds a consequence potential model which captures the relationship between the structural features and the fire phenomenon (second step). Afterwards, in the third step, numerical optimisation is applied to identify fire scenario characteristics that maximise consequences in the considered structural context. Such information is somehow "masked" by the large result dispersions when using RB methods.

Once the scenario maximising consequences is found, Monte Carlo sampling (MCS) propagates uncertainties due to the considered random variables (e.g., material properties, initial temperature) to consequence estimates. This analysis outputs the probability $Pr\left[\overline{MC} > MAC\right]$ that realisations of the maximum consequence potential random variable $\overline{MC}$ are larger than the maximum allowable threshold (MAC). Furthermore, the coefficient of variation of $\overline{MC}$ (named CoV_{MC}) measures the solution's robustness to input variability. Importantly, the designer is called to choose which sources of uncertainty are significant for the considered problem. Thus, $Pr\left[\overline{MC} > MAC\right]$ and CoV_{MC} only appraise the effect of those selected sources.

Comparing how uncertainty propagation techniques are used in RB and MAC approaches is possible. Specifically, the former aims to estimate a consequence distribution that accounts for all the relevant uncertainty sources (including but not limited to those considered in the MAC approach). Then, based on these results, it calculates statistics of those distributions or consequence occurrence rates for performance assessment. Differently, the MAC approach first uses deterministic scenario analysis to identify the fire scenario yielding the most severe effects on the structure. Afterwards, it quantifies such a calculation's robustness to uncertainty.

A final comparison regards the design updating effect (see Figure 1). In the MAC approach, updating the design variables (through comparative assessment or optimisation) modifies the consequence potential model, thereby allowing the designing of fire scenarios whose maximum consequences and robustness are tolerable. In contrast, RB approaches modify the design variables until the response to the pre-set scenarios is acceptable.

The following sections compare the RB and the MAC approach through the fire safety design of a case-study bridge.

3. ILLUSTRATIVE EXAMPLE

3.1. Case-study description

This section performs the fire safety design of the single-span bridge studied by Peris-Sayol et al.

(2015), which (in the initial configuration) consists of five W36x300 steel girders supporting a concrete slab. The performance objective is for the bridge to resist a car fire for twenty minutes without collapsing. Therefore, the time to collapse (t_c) is the consequence metric of interest. In the context of the MAC approach, the twenty-minute threshold represents the maximum allowable consequence ($t_{c,MAC} = 20min$).

Figure 2 shows the problem geometry. Only one girder is considered and studied in the 2-D x-y plane. Furthermore, the left-hand side of the beam is fixed to demonstrate the MAC approach's ability to find worst-case conditions that are not obvious just based on judgement. The girder is subject to a uniformly distributed load $q = 42.17kN/m$, which accounts for dead and traffic loads. Following the Load Model 1 from EN (1991b), the traffic effect is also represented through a tandem system of two concentrated loads located at $x_{ts} = \alpha_{ts}L_{gir}$. Here, $L_{gir} = 21.34m$ is the length of the girder and $\alpha_{ts} \in [0,1]$ a scaling factor. The design variables are the scaling factors of the bridge clearance (X_H), the girder depth (X_{Hgir}) and the girder width (X_{bf}). Such factors are collected in the vector $\mathbf{X}$.

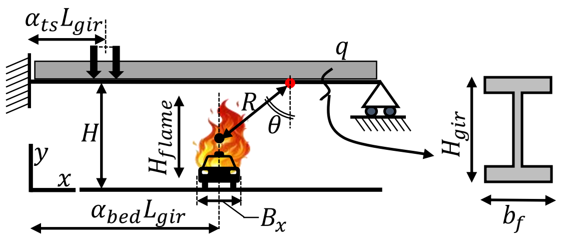

Figure 2: Case study bridge.

The bridge is subject to a localised car fire with the fuel bed positioned at $x_{bed} = \alpha_{bed}L_{gir}$. As for the fire model, the heat release rate (HRR) curve grows linearly and reaches the peak hrr_{max} at a time t_{max}. Then, it remains constant until the burnout time t_{bo}. HRR parameters and energy released values representative of natural fires were obtained from the experimental data reported by Tohir et al. (2013).

The use of these data is different for the RB and MAC design approaches. More precisely, the probabilistic distributions for peak HRR, time to peak and energy released (ER) suggested in the reference and summarised in Table 1 are adopted for the RB design. The same table shows that the fuel bed and the tandem system locations are assumed uniformly distributed, recognising that they might be at any longitudinal position when the fire ignites. Other uncertainty sources included in the analysis are the steel material properties. Their distributions were obtained from the work of Devaney (2015) and are listed in Table 1.

Table 1: Random variables considered in the example.

Parameter	Distributon
Heat release rate (RB only)	
Peak HRR [kW]	Weibull(5256, 2.03)
Time to peak [min]	Weibull(31.3, 2.12)
Energy released [MJ]	Weibull(5233, 3.23)
Fuel bed location [-]	Uniform(0.035, 0.965)
Tandem location [-]	Uniform(0.028, 0.972)
Steel material (RB and MAC)	
Yielding stress [MPa]	Lognormal(281, 0.07)
Elastic modulus [GPa]	Lognormal(210, 0.03)
Density [kg/m^3]	Normal(7850, 0.01)

When applying the MAC approach, the experimental data on vehicle fires inform the selection of boundary conditions for scenario optimisation. First, ER is fixed to a conservative value of $7GJ$. Then, an HRR curve characterised by $hrr_{max,ref} = 5000kW$ and $t_{max,ref} = 10min$ as per NFPA-502 (2011) is taken as the reference curve. Finally, scaling factors $\alpha_{hrr,max} \in [0.4, 1.6]$ and $\alpha_{t_{max}} \in [0.6, 1.4]$ are selected based on the experimental data. Eventually, the vector $\alpha = [\alpha_{bed}, \alpha_{hrr,max}, \alpha_{t_{max}}, \alpha_{ts}]$ identifies a fire scenario. Then, the bridge's thermomechanical response is computed for each scenario through the procedure described in the next section.

3.2. *Thermomechanical response calculation*

3.2.1. *Heat transfer and thermal analysis*

The heat flux from the fire to the girder is required to define boundary conditions for thermal response analysis. To that end, the girder is discretised into 0.5 m-long elements, and it is assumed that the heat flux to each of them is constant at a given time step.

The calculation combines several heat transfer models from localised fires. At each time step, the mean flame height (defined as the distance above the fire source where the intermittency has declined to 0.5) is calculated as per Hurley et al. (2015) and compared to the bridge clearance. This comparison distinguishes the two cases of flames not impinging or impinging on the deck. In the first case, a smoke layer forms at the deck level and transfers radiative and convective heat to the deck elements above the fuel bed footprint (B_x in Figure 2). The smoke temperature is obtained through Hasemi's localised fire model for flames not impinging the ceiling, reported in EN (1991a). On the other hand, only radiative heat transfer is considered for girder elements positioned outside the boundaries of the fuel bed. This flux is calculated using the point source model (Hurley et al., 2015).

In the second case, the flame impinges on the bridge deck, turns and spreads horizontally. When this happens, Heskestad and Hamada (1993) observed that the mean horizontal flame length is approximately equal to the difference between the free flame height and the height of the obstructing surface. Thus, the heat flux to girder elements in contact with the flames is taken as $85kW/m^2$. This value is representative of objects immersed in flames (Hurley et al., 2015). Conversely, only radiative heat transfer computed through the point source model is considered for the other elements.

The obtained heat flux is used as the boundary condition for the thermal response analysis, aiming to compute the temperature's time history in the girder. Assuming a constant temperature distribution across the section is acceptable for this calculation. Thus, under this hypothesis, the temperature development in the girder is obtained through the lumped thermal mass approach described by Quiel et al. (2015).

3.2.2. *Structural response and consequence analysis*

The temperature's time histories are used to calculate the bridge's structural response through the OpenSees for fire software (Jiang et al., 2015). In this process, the displacement of each girder node is recorded. Then, the time to collapse t_c is detected when any of the conditions described by Hu et al. (2021) occurs: i) runaway behaviour of girder deflection; ii) reversal of horizontal displacement at the free-end support; iii) excessive vertical deflection. This procedure calculates the time to collapse $t_c(\mathbf{X}, \alpha)$ for a given fire scenario and design variable configuration.

When applying the considered RB approach, calculating t_c for one of the pre-set scenarios described in Section 3.1 estimates a realisation of the random variable $\bar{t}_c$. Differently, in the MAC approach, $t_c(\mathbf{X}, \alpha)$ represents the consequence potential model (see Figure 1). At first, it is used to compute the fire scenario properties α_{MC} yielding the minimum time to collapse $t_{c,MC}$ for a given design variable configuration $\mathbf{X}'$:

$$t_{c,MC}, \alpha_{MC} = min\left\{t_c\left(\mathbf{X}', \alpha\right)\right\} \tag{1}$$

Next, the consequence potential model is applied to investigate the uncertainty effect on $t_{c,MC}$ through MCS. The analysis estimates the distribution of the random variable $\bar{t}_{c,MC}$, its coefficient of variation $CoV_{t_{c,MC}}$, and the probability that the time to collapse is lower than the MAC threshold (i.e., the failure probability $Pr\left[\bar{t}_{c,MC} < t_{c,MAC}\right]$). Among them, the $CoV_{t_{c,MC}}$ quantifies the robustness (i.e., limited variability) of the computed solution to input uncertainties. In this study, only the uncertainty of steel material properties is considered and represented through the distributions of Table 1.

4. RESULTS

The initial bridge design configuration is named "Design A" and is characterised by a design variable vector $\mathbf{X}_A = [1, 1, 1]$. When applying the RB approach, MCS for hazard scenario generation provides the light-grey curves in Figure 3. In addition, experimental HRR curve envelopes from Tohir et al. (2013) are reported. Comparing them to the curves generated through MCS, it is noted that a large number of samples exhibit a growth rate higher than the observed ones. For safety assessment, this is a conservative condition when paired with high energy released. In addition, several samples reach the peak HRR at a time significantly larger than the 20 min threshold. Each of these

HRR curves is associated with a random location of the fuel bed and tandem system as presented in Figure 4. As shown in Table 2, the resulting $\bar{t}_c$ distribution is characterised by a mean of 29.60 min, a mode of 23.70 min and a CoV equal to 0.351. Furthermore, the probability that the time to collapse is lower than the 20 min threshold is 0.041. This probability might be acceptable considering the short time required to evacuate the bridge in the case of a fire so that collapse does not threaten life safety. Hence, according to the RB method, Design A complies with the performance objectives and does not require updating.

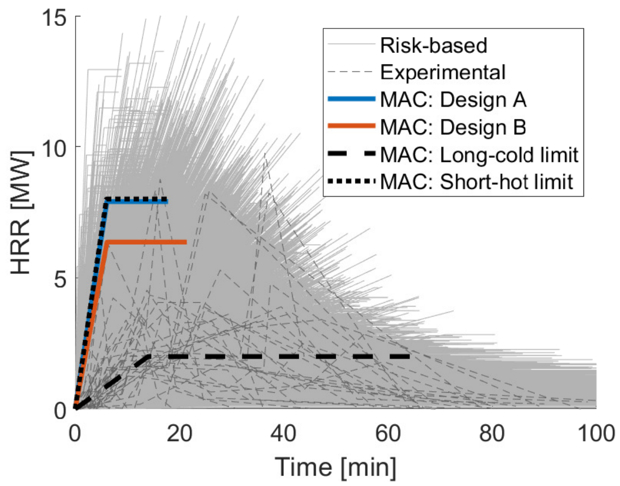

Figure 3: Heat release rate curve comparison.

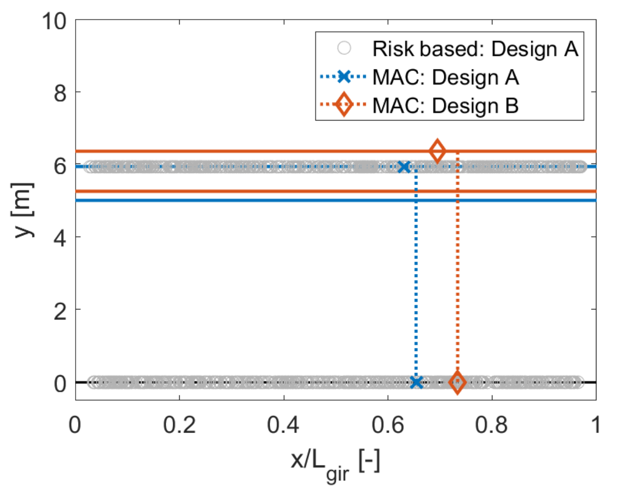

Figure 4: Fuel bed and tandem system location comparison.

Table 2: Design method comparison.

Design	A		B
Method	Risk-based	MAC	MAC
X_H [-]	1.00	1.00	1.05
X_{Hgir} [-]	1.00	1.00	1.20
X_{bf} [-]	1.00	1.00	1.15
α_{bed} [-]	Random	0.654	0.734
α_{hrrmax} [-]	Random	1.580	1.272
α_{tmax} [-]	Random	0.608	0.612
α_{ts} [-]	Random	0.631	0.696
t_c [min]	Random	11.47	20.23
$\bar{t}_c$ mean [min]	29.60	12.32	20.79
$\bar{t}_c$ mode [min]	23.70	12.23	21.33
$CoV_{t_{c,MC}}$ [-]	0.351	0.040	0.021
$Pr[t_c < t_{c,MAC}]$	0.041	1.000	0.026

Consider now the MAC approach. Figure 3 presents the long-cold and short-hot limits constituting the boundaries for scenario optimisation. Solving Eq. 1 for Design A provides the scenario vector α_A listed in the third column of Table 2 and plotted in Figure 3-4. The corresponding time to collapse is $t_{c,MC,A} = 11.47min$. Because this time is significantly lower than the MAC threshold, a sensitivity study is conducted for design variable updating. Consistently, Design B in Table 2 is selected. This configuration requires a 5% increase in bridge clearance, a 20% increase in the girder depth and a 15% increase in the flange width. The resulting time to collapse is $t_{c,MC,B} = 20.23min$.

The observation of Table 2 and Figure 3-4 reveals that the fire scenarios yielding $t_{c,MC}$ are noticeably different from each other. In particular, maximum consequences are structure-specific and do not derive from boundary values. Therefore, selecting fire scenarios *a-priori* and neglecting this dependency undermines achieving life safety objectives. Indeed, judgement and/or random sampling do not ensure capturing the information on the maximum consequence. Even when captured, such information is hidden behind the large result dispersion (light-grey curves in Figure 3 and circles in Figure 4).

A large and misleading dispersion can also be observed in the results of MCS in Figure 5. In particular, the figure plots the distribution of $\bar{t}_{c,A}$ from the RB approach and those of $\bar{t}_{c,MC,A}$ and $\bar{t}_{c,MC,B}$ from the MAC approach. Here, the large uncertainty propagated through the RB approach is visually apparent. Consistently, when comparing the coefficients of variation in Table 2, the one corresponding to the RB approach is one order of magnitude larger than that resulting from the MAC-based design (0.351 vs 0.040 and 0.021). Hence, these data emphasise again the excessive result uncertainty deriving from the RB design approach.

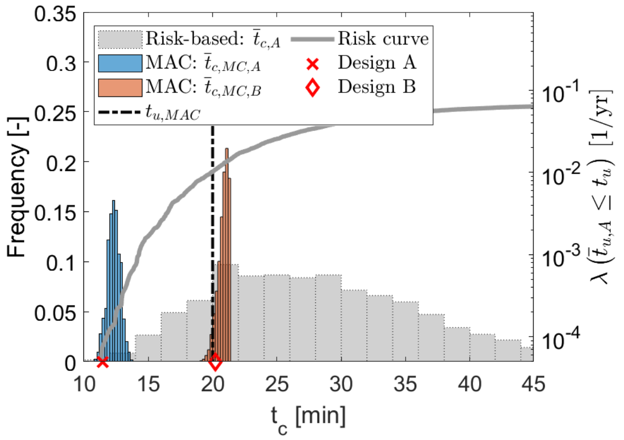

Figure 5: Distributions of the time to collapse from the RB design and MAC approaches.

Figure 5 shows that the $\bar{t}_{c,MAC}$ threshold belongs to the tail of the $\bar{t}_{c,MC,A}$ distribution and is approximately fifteen standard deviations far from the median. Thus, for this case, a sample size of 10^4 was considered, and $Pr[\bar{t}_{c,MC,A} < t_{c,MAC}]$ was conservatively assumed equal to 1. Differently, Design B presents a failure probability equal to 0.026, estimated through $5x10^4$ simulations. As discussed above for $\bar{t}_{c,MC,A}$, such a value is tolerable for life safety.

Figure 5 also plots the risk curve from the RB design approach. Such a curve shows the mean annual probability that the time to collapse is lower than the value on the horizontal axis. For its calculation, the car fire's occurrence frequency was assumed equal to 0.0684 fires/year as per Ma et al. (2019). As expected, the results of the MAC approach overlap with those from the RB design approach in the high-consequence (i.e., low t_c) low-probability region. Therefore, a performance *assessment* based on the RB approach in that region provides similar conclusions to those of MAC. Nevertheless, when considering *design updating*, the RB method cannot detect which variables are more effective in diminishing maximum consequences. Indeed, even neglecting the computational burden of an MCS-based design update, the RB design approach searches variables that improve the response to the preliminarily selected scenarios. Hence, it ignores the set of solutions that diminish fire intensity. In contrast, the MAC approach focuses on such solutions and optimises the balance between diminishing fire intensity and increasing structural capacity. This objective is achieved simultaneously with an assessment of the solution's robustness to selected sources of uncertainty.

5. CONCLUSIONS

In the context of fire safety design under uncertainties, this paper compared a risk-based design approach with a novel methodology recently proposed by the authors (Maximum Allowable Consequence approach), yielding the following conclusions:

- Most RB design approaches consider fire hazard scenarios as additional uncertainty sources and set them as analysis inputs. Such an assumption ignores that a strong coupling between the fire phenomenon and the structure exists enabling an ad-hoc design variable selection to decrease fire intensity. Instead, relying on preliminarily selected scenarios does not allow for exploiting such a relationship. Furthermore, the information on maximum consequences might be lost or hidden behind large uncertainty propagation.
- In contrast, the MAC approach determines fire scenarios maximising consequences as analysis outputs. Then, it uses MCS to investigate the impact of selected uncertainty sources on the solution robustness. In this way, the design update exploits the dynamic coupling described above without losing information on the uncertainty effect.
- For the fire safety design of a case-study bridge, the RB design approach entailed coef-

ficients of variation on the estimated time to collapse one order of magnitude larger than MAC (0.351 vs 0.040). Furthermore, according to the RB design approach, the initial design configuration complied with the performance objectives within a tolerable failure probability (0.041). However, the maximum consequences entailed by this configuration exceeded the allowable threshold. Eventually, the MAC approach provided a solution with higher robustness to uncertainty ($CoV = 0.021$) and maximum consequence level complying with the selected objective.

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7. REFERENCES

Baker, J., Bradley, B., and Stafford, P. (2021). "Seismic hazard and risk analysis.

Cadena, J. E., McLaggan, M., Osorio, A. F., Torero, J. L., and Lange, D. (2022). "Maximum allowable damage approach to fire safety performance quantification." *Fire safety journal*, 128, 103537.

Devaney, S. (2015). "Development of software for reliability based design of steel framed structures in fire." Ph.D. thesis, University of Edinburgh, University of Edinburgh.

EN, B. (1991a). "1-2: 2002 eurocode 1: Actions on structures—part 1-2: General actions—actions on structures exposed to fire." *British Standards*.

EN, B. (1991b). "2: 2003, eurocode 1: Actions on structures-part 2: Traffic loads on bridges." *ICS*, Vol. 91, 93–040.

Franchini, A., Galasso, C., and Torero, J. L. (2023). "Mac for fire safety under uncertainty." *Paper under review*.

Guo, Q. and Jeffers, A. E. (2015). "Finite-element reliability analysis of structures subjected to fire." *Journal of Structural Engineering*, 141(4), 04014129.

Heskestad, G. and Hamada, T. (1993). "Ceiling jets of strong fire plumes." *Fire Safety Journal*, 21(1), 69–82.

Hopkin, D., Fu, I., and Van Coile, R. (2021). "Adequate fire safety for structural steel elements based upon life-time cost optimization." *Fire Safety Journal*, 120, 103095.

Hu, J., Carvel, R., and Usmani, A. (2021). "Bridge fires in the 21st century: A literature review." *Fire safety journal*, 126, 103487.

Hurley, M. J., Gottuk, D. T., Hall Jr, J. R., Harada, K., Kuligowski, E. D., Puchovsky, M., Watts Jr, J. M., WIECZOREK, C. J., et al. (2015). *SFPE handbook of fire protection engineering*. Springer.

Jiang, J., Jiang, L., Kotsovinos, P., Zhang, J., Usmani, A., McKenna, F., and Li, G.-Q. (2015). "Opensees software architecture for the analysis of structures in fire." *Journal of Computing in Civil Engineering*, 29(1), 04014030.

Ma, R., Cui, C., Ma, M., and Chen, A. (2019). "Performance-based design of bridge structures under vehicle-induced fire accidents: basic framework and a case study." *Engineering Structures*, 197, 109390.

NFPA-502 (2011). *Standard for road tunnels, bridges, and other limited access highways*. NFPA.

Padgett, J. E., Nielson, B. G., and DesRoches, R. (2008). "Selection of optimal intensity measures in probabilistic seismic demand models of highway bridge portfolios." *Earthquake engineering & structural dynamics*, 37(5), 711–725.

Peris-Sayol, G., Paya-Zaforteza, I., Alos-Moya, J., and Hospitaler, A. (2015). "Analysis of the influence of structural models in fire responses of steel girder bridges." *Structures Congress 2015*, 160–171.

Porter, K. A. (2003). "An overview of peer's performance-based earthquake engineering methodology." *Proceedings of ninth international conference on applications of statistics and probability in civil engineering*, Citeseer, 1–8.

Quiel, S. E., Yokoyama, T., Bregman, L. S., Mueller, K. A., and Marjanishvili, S. M. (2015). "A streamlined framework for calculating the response of steel-supported bridges to open-air tanker truck fires." *Fire Safety Journal*, 73, 63–75.

Shrivastava, M., Abu, A., Dhakal, R., and Moss, P. (2019). “State-of-the-art of probabilistic performance based structural fire engineering.” *Journal of Structural Fire Engineering*.

Sleich, J.-B., Cajot, L.-G., Pierre, M., Joyeux, D., Aurtenetxe, G., Unanua, J., Pustorino, S., Heise, F.-J., Salomon, R., Twilt, L., et al. (2002). “Competitive steel buildings through natural fire safety concepts.” *EUR*, (20360), 1–740.

Tohir, M., Zahirasri, M., and Spearpoint, M. (2013). “Distribution analysis of the fire severity characteristics of single passenger road vehicles using heat release rate data.” *Fire science reviews*, 2(1), 1–26.

Torero, J. (2013). “Structures in fire or fires in structures? assessing the true performance of structures in fire.” *Proceedings of the 5th International Conference on Structural Engineering*, 1919–1923.

Torero, J. L. (2006). “The risk imposed by fire to buildings and how to address it.” *Protection of civilian infrastructure from acts of terrorism*, Springer, 41–57.

Torero, J. L. (2019). “Fire safety of historical buildings: principles and methodological approach.” *International Journal of Architectural Heritage*, 13(7), 926–940.

Zang, T. A. (2002). *Needs and opportunities for uncertainty-based multidisciplinary design methods for aerospace vehicles*. National Aeronautics and Space Administration, Langley Research Center.

Zhu, Z., Quiel, S. E., and Khorasani, N. E. (2023). “Bivariate structural-fire fragility curves for simple-span overpass bridges with composite steel plate girders.” *Structural Safety*, 100, 102294.