14th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP14
Dublin, Ireland, July 9-13, 2023

Combined Strategies to Achieve Robust Structures

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ABSTRACT: The rules for ensuring robustness reflect the increasing complexity and opacity characterizing structural design codes. While the practical importance of designing and building robust structures is universally acknowledged, the codes presently in place are often vague or confusing. At the same time, however, that lack of clarity may afford opportunities for innovative solutions by building items that ensure robustness into the conceptual design of a structure. Building on that premise, a practical approach to design robust structures is summarized in the paper. The proposal generally envisages the conceptual design of continuous, ductile structural systems due to their inherent advantages for identified design situations. To avoid progressive collapse given the occurrence of local failure due to unidentified accidental situations, either alternative load paths or predefined collapse mechanisms should be built into such systems. The proposal includes a procedure to achieve correspondence between assumed and real mechanisms in case of failure of any member on which the strength and stability of the system or subsystem depends. For the design or assessment of such key members, risk-based target reliability indices are developed for both, persistent and identified accidental situations, and considerations are made about the target reliability for the remaining system left standing after key member failure.

1. INTRODUCTION

The partial factor format, which is currently being used in practice in conjunction with limit state design to verify structural compliance with resistance and stability requirements, according to codes such as prEN 1990 (2020), was established to calculate action effects and structural response separately and to verify structural safety on the cross-sectional or member scale. However, structural collapse occurs if a full failure mechanism develops and, as discussed in the literature, e.g. Melchers (1987), depends on the system considered, and the behaviour of its members, ductile or brittle, among other parameters such as the load arrangement and intensity for relevant hazard scenarios and, of course, the load-bearing capacity of cross-sections and members. Since today's design criteria focus on local failure, the results for overall or system structural reliability cannot be uniform. Consequently, depending on the case, any change in the static system due to the failure of one structural component with the subsequent redistribution of internal forces and moments may lead to the successive collapse of other components. As pointed out by Starossek (2018), current procedures may provide unsafe designs, even if the required level of reliability is provided to the individual members constituting a structure.

Structural damage may be the outcome of a variety of circumstances such as accidents, overloading, deterioration or malevolence. Proper design should deliver structures able to withstand such damage to some extent, for example, to save lives by allowing time to evacuate a building or infrastructure, or prevent the interruption of lifeline functions. To avoid progressive collapse, modern codes as for example prEN 1990 (2020) stipulate, for instance, that the consequences of structural damage attributable to an unforeseen adverse event must not be disproportionate to the respective cause. Although this feature is generally acknowledged to be justified, codes and standards often do not contain broader provisions intended to ensure its implementation or, where they exist, specifications are often vague or not generally applicable, as explained by Starossek (2018), André and Faber (2019), and other authors. The lack of operational rules for the design and construction of robust structures may be attributable, among others, to the non-existence, to date, of a practical metric of robustness, in turn due to the complexity of the problem. The adoption of a specific design strategy to achieve the robustness of a given structure may well yield a conceptual solution in which some features may mitigate certain hazard scenarios but worsen others, depending on the structural system, the abnormal trigger, the magnitude and location of the initial failure or the type of collapse, according to Starossek (2018).

Given that the possible propagation of damage ensuing from local failure in a load-bearing system depends heavily on the underlying structural solution, conceptual design is of utmost importance to ensure a structure will be sufficiently robust, as well as compliant with all other design goals. Robustness must consequently be addressed early in the design process and more specifically in the conceptual design stage. Insofar as any given conceptual solution for increased robustness may compromise safety in some scenarios, even seemingly robust solutions must be analysed to unequivocally identify and take all significant hazards and hazard scenarios into due consideration in structural design. More specific operational rules are also needed to ensure structural robustness, above and beyond the general strategies set out in the existing codes, EN 1991-1-7 (2006), prEN 1990 (2020). Such new rules should establish quantitative criteria for determining the acceptability of a given structure in terms of robustness.

2. OPERATING PROCEDURE

In order not only to meet all the requirements for serviceability and structural safety but also for robustness, in an environmentally and economically efficient manner, a combination of design strategies should be called into play. Although the Eurocode prEN 1990 (2020) suggests the possibility of a combined approach, no specific rules are provided for the practical implementation of that recommendation. Further to the general strategies listed in prEN 1990 (2020), two combinations appear to be particularly promising in this regard:

- ensuring redundancy and an adequate structural design for the remaining system standing after key member failure;
- stopping collapse and suitably designing key members.

In this context by key members is meant those on which structural system or subsystem strength and stability depend. They may be identified, then, as members in whose absence a planned load-bearing mechanism will develop only if suitable measures are adopted, i.e., if the corresponding structural behaviour can be verified with sufficient reliability.

Structural design of any load-bearing system is a multi-step process. As illustrated for bridges in Tanner and Hingorani (2021), iteration taking into account case-specific constraints is usually required to develop an engineering structure. This applies in particular to the design for robustness based on the combined strategies recommended in this paper, since key members and the risks associated with their possible collapse, for whatever reason, depend on the system and its behaviour. In that respect, the decisive phase is the conceptual structural design, consisting of the selection of the type, layout and main dimensions of the load-bearing system, individual members and most prominent details, as well as the appropriate materials. The discussion of the structural design process, emphasizing the importance of the conceptual phase, has been covered in previous papers such as the one mentioned above and is omitted here. In addition, the principles underlying the actual deployment of the proposed combined robustness strategies are summarized in Tanner, Hingorani, et al. (2022), and case studies are included in both articles for illustration of the approach. The present contribution therefore focuses on specifying the level of reliability sought when applying these strategies.

3. RISK-BASED ACCEPTANCE CRITERIA

3.1. Overview

Although according to the international standard about general principles on reliability of structures, ISO 2394 (2015), there is no need to define acceptable levels of risk to persons, in the opinion of the social scientists consulted by the authors it is unlikely that the public would accept higher failure rates than those associated with current best practice, even if they are based on rational acceptance criteria such as the Marginal Life Saving Cost (MLSC) principle. Indeed, the aforementioned standard states that "an activity which is found acceptable should be assessed in regard to the corresponding absolute level of life safety risk", and that the practical implementation of the MLSC principle by using the Life Quality Index (LQI) could result in higher levels of risk compared to current practice and might therefore require the specification of "absolute values of the acceptable life safety risks".

On these grounds, the reliability requirements for the purpose of the robustness design according to the proposed procedure are based on engineering structure-related risks for persons, in compliance with accepted current practice. Section 3.2 summarizes annual target reliabilities, derived from implicitly acceptable life safety risks, for the ultimate limit state design of key members, respectively in permanent and identified accidental situations. Design requirements for weak components or fuses and the remaining system in all relevant situations during and after a key member failure are discussed in section 3.3. Both sections, 3.2 and 3.3, relate to the design of new structures, since target reliability indices are based on average values of implicitly accepted risks and are intended for calibration procedures, for example for partial factors. As an inherent feature of any calibration process, a certain proportion of structures correctly designed using the partial factors thus obtained achieve a reliability below the target value used. This raises the question at what level a minimum reliability requirement should be set. Answering this question is particularly important in the context of assessing existing structures, where reliability requirements can often be lower than for new structures due to economic, social and sustainability considerations, CEN/TC250/SC10/AHG (2021). The impact of lower requirements for existing structures on life safety risks is therefore discussed in section 3.4.

3.2. Key members

3.2.1. Persistent situations

In daily practice, the question of the acceptability of civil engineering structures is assessed using prescribed, codified rules. Such design rules have been developed based on calibration to a long experience of building tradition, CEN/TC250/SC10/AHG (2021), and result in a level of structural performance that reflects what is often referred to as Best Current Practice, BCP. Risk levels associated with structures designed and built in accordance with these rules are perceived as reasonable and generally acceptable to the public, Calgaro and Gulvanessian (2001).

Based on this postulate, the level of risk associated with structures that strictly comply with the design rules specified in existing structural codes, such as the Eurocode EN 1990 (2002), can be defined as acceptable. Such acceptable risks are therefore directly related to the level of reliability implicitly required of the considered codes, which may differ fundamentally from the nominal target ceilings set in the same codes, as found by the authors, Tanner (2016), and also by Baravalle (2017) or Meinen and Steenbergen (2018).

Under an operational criterion suggested in an earlier study, Tanner and Hingorani (2015), reliability requirements for human safety, $\beta_{t,LR}$, were inferred from current practice and represented for a reference period of one year, varying with the area affected by the considered collapse, A_{col}, and the respective consequence class as defined in the Eurocode, prEN 1990

(2020). Although developed for building structures, those target reliabilities can be applied to the design of other load-bearing systems, provided the number of persons at risk per unit area is of the same order of magnitude. These requirements have been improved more recently, Hingorani and Tanner (2020). It was further acknowledged that since the previous studies assumed statistically independent failure events in subsequent years of the considered reference period of 50 years, the annual reliability index targets may be lowered. In view of time-invariant influences (e.g., strength variables in the absence of deterioration, self-weight, etc.) on the failure probabilities, failure events are indeed partially correlated over the years of the planned service life of a structure. The simplifying assumption of statistical independence therefore leads to an underestimation of the implicitly acceptable annual risks and, with the approach chosen in the previous studies, to overly conservative (i.e., comparatively high) estimates of the required annual reliability.

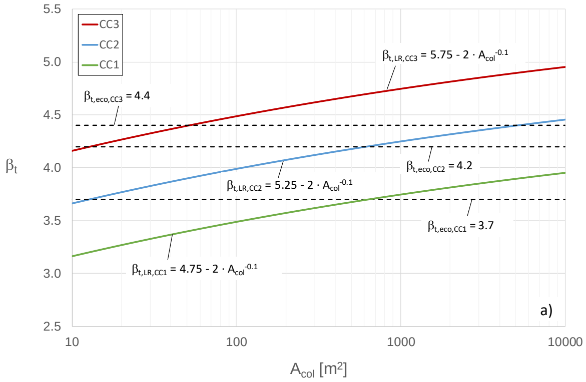

Figure 1: Annual reliability requirements for human safety, $\beta_{t,LR}$, depending on the collapse area, A_{col}, and the consequence class, CC, prEN 1990 (2020), recommended for the design of key members; $\beta_{t,eco}$ JCSS (2001): tentative target reliabilities based on economic optimisation for medium relative cost of safety measures and different consequence classes, CC.

The recalculation of the results obtained in the previous studies mentioned above, taking into account the correlation effect between failure events in subsequent years of the intended service life of the structures under consideration, shows a significant influence on the implicitly acceptable risks and thus on the proposed reliability requirements. The results obtained are presented in Figure 1, where they are compared with values based on monetary optimization, JCSS (2001). Both types of requirements appear to be generally compatible, provided that the expected consequences and safety costs refer to the same failure event, taking into account the possibility of a (sub)system collapse following a key member failure.

3.2.2. Identified accidental situations

Key members should meet reliability requirements for both persistent and identified accidental situations to give a structure adequate robustness. According to ISO 2394 (2015), an appropriate level of reliability should be chosen considering the possible consequences of a failure, the expense involved and the effort required to reduce the risks. This can be achieved by considering target reliability indices conditional on the occurrence of the accidental situation, taking into account the corresponding hazard occurrence rate.

For example, Hingorani, Tanner, et al. (2019) refer to structures in buildings where gases are burned, regulated, transported or stored, establishing life safety risk-based requirements, given a gas explosion and the subsequent member exposure to the pressure wave generated. For this purpose, the total failure probability, $p_{f,tot}$, stemming from the sum of the failure probabilities associated with the relevant persistent and explosion hazard scenarios, respectively $p_{f,per}$ and $p_{f,exp}$, is limited to a target value, $p_{ft,tot}$, as expressed by Eq. (1):

$$p_{f,tot} = p_{f,per} + p_{f,exp} \leq p_{ft,tot} \tag{1}$$

In analogy to the derivation of target values for persistent situations only, Tanner and Hingorani (2015), target values $p_{ft,tot}$ are derived from the implicitly accepted life safety risk levels associated with the structures considered, Hingorani, Tanner, et al. (2019). Taking into account the gas explosion probability of occurrence, $p(exp)$, Eq. (1) is converted into the following requirement for the conditional (under the condition that a gas explosion occurs and the affected member is exposed to the pressure wave generated) member failure probability due to the applied accidental load, $p_{f|exp}$:

$$p_{f|exp} \leq p_{ft|exp} = \frac{p_{ft,tot} - p_{f,per}}{p(exp)} \qquad (2)$$

According to Eq. (2), the conditional target failure probability $p_{ft|exp}$ for a potentially explosion-exposed member increases as the contribution of the failure probability for persistent situations, $p_{f,per}$, to the overall member failure probability, $p_{f,tot}$, decreases. This observation is fundamentally plausible and consistent with the statement that the requirement for higher reliability levels in the case of large uncertainties could be associated with prohibitive costs, JCSS (2001). In fact, Eq. (2) leads to lower safety requirements if the highly uncertain explosion-induced loads dominate the reliability level associated with a particular member failure mode, Hingorani, Tanner, et al. (2019).

For the sake of simplicity, it is proposed to establish target values, $p_{ft|exp}$, for the verification of structural member reliability in the event of an explosion, by limiting the contribution of the persistent situations to the overall failure probability to the corresponding target value, $p_{ft,per}$. Factoring the analytical functions developed for $p_{ft,per}$, represented in the previous section in terms of reliability indices, and $p_{ft,tot}$ from Hingorani, Tanner, et al. (2019) into Eq. (2), along with an assumed hazard occurrence probability of $p(exp) = 10^{-5}$ explosions per year and gas-supplied building, delivers the conditional target failure probabilities, $p_{ft|exp}$. After conversion to annual reliability indices, the conditional life safety risk-based requirement for the design of key members in building structures of consequence class CC2, prEN 1990 (2020), for accidental situations due to gas explosions, $\beta_{t,LR|exp}$, is as follows:

$$\beta_{t,LR|exp} = 3 - 7.75(A_{col})^{-0.4} \qquad (3)$$

As in Figure 1, A_{col} is the area, in m^2, affected by the collapse of the key member. If A_{col} is less than a minimum value, $A_{col,min}$, no explosion-specific reliability requirements need to be considered for member design, as the derived target value according to Eq. (2) would be $p_{ft|exp} = 1$, Hingorani, Tanner, et al. (2019). Given their importance within a structural system, failure of any key member as described in section 2 would normally affect collapse areas beyond these minimum values.

3.3. Remaining system

Similar to the requirements for key members subject to identified accidental situations, the target reliabilities for remaining systems, $\beta_{t,rs}$, are also conditional, as mentioned in Tanner and Hingorani (2021). Depending on the design strategy used, i.e. including built-in fuses, the intended failure mode should be verified for the same requirement. Both verifications, respectively fuse failure and non-failure of the remaining system, are to be carried out for situations after key member failure and thus conditional target reliabilities can be derived from Eq. (4), based on work by Ellingwood and Dusenberry (2005) and Ellingwood (2006):

$$P(F_{rs}) = P(F_{rs}|F_{km}) \cdot P(F_{km}|H_i) \cdot P(H_i) \qquad (4)$$

The equation expresses the probability of failure of the remaining system, $P(F_{rs})$, that develops from an abnormal, disregarded hazard, H_i. In addition to the probability of this hazard occurring, $P(H_i)$, it factors in two conditional probabilities, namely that of the failure of a key member given the occurrence of H_i, $P(F_{km} | H_i)$, and that the remaining system will collapse given the failure of this key member, $P(F_{rs} | F_{km})$. When estimating values for these probabilities, a reference period of one year seems more appropriate than the lifetime or 50 year reference period often used in structural design codes such as the Eurocode, EN 1990 (2002).

Ellingwood and Dusenberry (2005) and Ellingwood (2006) propose to limit the remaining system failure probability, $P(F_{rs})$, to a value corresponding to a threshold below which life safety risk is of no "legal concern" as suggested by Pate-Cornell (1994) based on a review of accepted risk levels for the management of industrial facilities. The metric of the so-called *de minimis* risk of 10^{-7} per year established by the same authors, Ellingwood and Dusenberry (2005) and Ellingwood (2006), measured in probabilities, implying a conditional probability of death of a person present in case of failure of 1. The latter is of course a conservative assumption, as can also be shown by comparison with statistical estimates of this conditional probability, Hingorani, Tanner, et al. (2020). An annual fatality rate from structural failure of 10^{-7} per year is also broadly consistent with the implicitly acceptable notional life-safety risk associated with building structures designed to current best practices, Tanner and Hingorani (2015). Hence, the value given provides a reasonable criterion for determining $P(F_{rs})$ in the context of the present study.

The conditional probability $P(F_{km} \mid H_i)$ can be conservatively assumed to reach 1.0, arguing that failure of the key member, F_{km}, is very likely if, as assumed here, the hazard H_i is not considered in the design process, Ellingwood and Dusenberry (2005). This assumption is compatible with the results of a study by Hingorani (2017) which shows that the failure probabilities of RC members subjected to the effects of a gas explosion can increase significantly if the accidental action is not taken into account in the design and instead member resistance is only provided for persistent situations.

Factoring $P(F_{rs}) = 10^{-7}$/year and $P(F_{km} \mid H_i) = 1.0$ into Eq. (4), the conditional probability that the remaining system will collapse given key member failure, $P(F_{rs} \mid F_{km})$, is defined as a function of the annual hazard occurrence probability, $P(H_i)$. The corresponding target reliability, $\beta_{t,rs}$, then results from Eq. (5), where Φ represents the standard normal distribution:

$$\beta_{t,rs} = \Phi^{-1}\big(P(F_{rs}|F_{km})\big) = \Phi^{-1}\left(\frac{10^{-7}}{P(H_i)}\right) \quad (5)$$

Empirical estimates of the probability of occurrence of certain accidental and man-made hazards, $P(H_i)$, can be found in the literature, e.g. Ellingwood (2006), Stewart (2008), Vrouwenvelder, et al. (2012), Hingorani (2017). In the present context, it is recalled that H_i refers to hazards that are not considered in structural design, nor at a later stage, either because they are not identified or because they are ignored, e.g. a terrorist attack. $P(H_i)$ can therefore also cover potential hazards which, although identified at the design stage, are intentionally not considered in structural analysis and verification. According to Ellingwood (2006), the probability of such unconsidered hazards that can ultimately lead to the failure of a key member, $P(H_i)$, is typically of the order of 10^{-4} per year, or less. For a probability $P(H_i) = 2\cdot10^{-7}$ per year, Eq. (5) yields a reliability target of $\beta_{t,rs} = 0$, suggesting that for such extremely rare hazards no remaining system verification would be required. Although the context is different since risk-based cost optimisation is addressed, it is interesting to note that Beck, et al. (2022) obtain similar values for plane frames subjected to anomalous events, concluding that a target reliability value of zero indicates a transition from situations where adding reinforcement is cost effective to situations where it is not. However, in the absence of more accurate data on $P(H_i)$, it seems prudent to assume a 10^{-5} per year probability for unidentified hazards that could evolve into key member failures. This value would cover most abnormal hazards and result in an annual reliability target of the order of $\beta_{t,rs} = 2.3$ for remaining systems.

3.4. Key members in existing structures

3.4.1. General

To improve structural performance in terms of robustness, most known strategies require the adoption of measures in the conceptual design phase. Such measures cannot usually be implemented in existing structures without constructional interventions. Therefore, the availability of operational rules to check structural robustness, going beyond a list of general strategies, is particularly important for existing structures and these should include quantitative criteria for decision-making. As already emphasized, human safety verifications are particularly relevant in a context where the failure of key members could lead to the partial or total collapse of the structure concerned.

For the reasons given in section 3.1, the required reliability levels for new structures can be considered conservative in most cases when used for the assessment of existing structures. This reasoning can also be extended to human safety if it is ensured that the structure under consideration meets a minimum level of reliability.

3.4.2. Persistent situations

For the ultimate limit state assessment of key members in persistent situations, the draft Model Code fib MC2020 (2022) recommends a reduction of the annual reliability requirements for human safety specified in Figure 1 by $\Delta\beta_{t,LR}$ = 0.5. While the target reliability indices for the design are determined based on the average values of the implicitly accepted risks, as explained in section 3.1, the minimum reliability requirements for the assessment proposed in fib MC2020 (2022) correspond to the 98% fractile values of these risks. Regarding the implicitly accepted annual fatality rate from structural failure of key members, the target reliability requirements for design and the minimum requirements for assessment correspond to values of 10^{-6} per year and 10^{-5} per year, respectively. So, the impact of lowering the reliability requirements by $\Delta\beta_{t,LR}$ = 0.5 for existing structures, as proposed in fib MC2020 (2022), is of an order of magnitude in terms of life safety risks.

3.4.3. Identified accidental situations

Lower reliability requirements are also indicated for the ultimate limit state assessment of key members in existing structures that are exposed to identified accidental situations. Such requirements can be derived as shown in section 3.2.2 for the design of key members, but using upper fractiles instead of average values for the implicitly accepted risks. Therefore, in case of exposure to pressure waves generated by gas explosions, the draft of the model code fib MC2020 (2022) recommends a reduction of the conditional annual target reliability index according to Eq. (3) by $\Delta\beta_{t,LR|exp}$ = 1.0. No specific guidance is available for the assessment of existing key members exposed to other identified accidental situations.

4. CONCLUSIONS

Specialisation and increasingly extensive and opaque standardisation and control systems come at the expense of structural engineers' creativity and other skills necessary to successfully translate the many conditioning factors into solutions that meet all performance requirements while also addressing considerations such as environmental and economic efficiency or elegance. Rules for robust design can be cited as representative of increasing code opacity. That lack of clarity for robust structural design, an outcome of the complexity of the problem itself, may spur careful or even innovative solutions if suitable mechanisms are built into the load-bearing system already in the conceptual design phase. Building on this premise, this paper proposes a practical approach to robust structural design. Deployment of this procedure afford reasonable certainty that the actual load-bearing mechanism called into play after local failure in the wake of unidentified accidental situations would be as assumed. It would also ensure that possible failure of members on which structural system strength and stability depend entails no higher risk to persons than implicitly consented in present practice. But more than complex calculations, the conceptual structural design is decisive in this context. Achieving all design goals, including robustness, therefore requires counteracting the impoverishment of the profession, e.g., by attributing sufficient importance to conceptual and creative thinking in both engineering education and engineering practice.

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