Robustness design made easy

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ABSTRACT

A practical approach for a risk-based design of robust structures is suggested in the present contribution. The proposal generally envisages continuous, ductile structural systems due to their inherent advantages for persistent and identified accidental design situations. In order to avoid progressive collapse, either alternative load paths or predefined collapse mechanisms should be built into such systems. A procedure is proposed to achieve coincidence between assumed and real mechanisms in case of key member failure. For the design or assessment of such key members, risk-based target reliability indices are provided considering both, persistent and identified accidental situations.

KEYWORDS: Risk, System reliability, Robustness, Key element, Alternative load paths, Segmentation.

1. Introduction

The partial factor method, in conjunction with the limit state design which is currently being used in practice for the verification of the requirements regarding the resistance and stability of structures, has been established for separate calculations of action effects and structural response, respectively, and for the verification of structural safety at a cross-section or member level. In reality, structural collapse occurs if a full mechanism develops, depending on the system considered and its behaviour [1], among other parameters. Since the current design approach focuses on local failure, the results obtained in terms of structural reliability at a global or system level cannot be uniform. If the change in the static system due to the failure of one structural component and the subsequent redistribution of internal forces and moments leads to a successive collapse of other components, current procedures may produce unsafe designs, even if the required level of safety is provided to the individual elements constituting a structure [2].

Structural damage may result from a variety of circumstances such as accidents, overloading, deterioration or malevolence. Therefore, a good design should result in structures which are able to sustain such damage to a certain degree, e.g. in order to save lives by evacuating a building or infrastructure in due time, or avoid interruption of lifeline functions [3]. For this purpose, most modern structural design codes require that the consequence of damage to structures should not be disproportionate to the original cause [3]. Such requirements are usually not developed further, however, despite the importance of robustness for structural design and assessment. Or, if available, standardized methods for checking robustness are not generally applicable [2]. Among other reasons, the lack of operational rules may be due to the fact that up to now no widely accepted, practical metric exists to facilitate robustness quantification. This, in turn, is related to the complexity of the problem at hand. Indeed, the adoption of a particular strategy for designing a given structure for robustness will lead to a conceptual solution with structural features which may be beneficial for some hazard scenarios and detrimental for others, depending on the structural system, the abnormal triggering-event, the magnitude and location of the initial failure or the type of collapse [2].

According to all the foregoing, a pragmatic approach is urgently needed for the evaluation of the robustness of structures with a view to prevent possible events of progressive collapse. Discussion of the most common strategies for designing robust structures and their associated problems (Section 2) serves as a starting point for a proposal of an operational design procedure enabling to adequately address disproportionate collapse problems (Section 3). The pragmatic approach concretizes in practical rules the general strategies for designing robust structures, as established in the current [4, 5] and future [6] Eurocodes. The approach includes a proposal for the establishment of reliability requirements for key elements (Section 4), upon which the stability of the remainder of a load bearing system depends, according to the definition in [5, 6]. The main conclusions of this paper are summarized in Section 5, including some guidance on the further development of the proposed approach.

2. Common design strategies

The reliability of a structure, built to fulfil a specific function and exposed to particular conditions, depends on numerous inherent features, among which the structural system and its behaviour, ductile or brittle, are particularly important. For persistent and identified accidental situations, it can be shown that the failure probability for a statically determinate solution considerably exceeds that obtained for an equivalent, statically indeterminate system. Furthermore, the failure probability calculated for the latter system assuming brittle behaviour would be much larger than the probability for the same structure if presumed to be governed by ductile behaviour [1, 7]. To account for robustness considerations in structural design, in addition to the traditional design procedures based on the fulfillment of structural safety and serviceability requirements for individual elements constituting a structure, various strategies can be selected according to literature and current regulations [2, 5, 6, 8], among them:

- Design of key elements;
- Creation of alternative load paths;
- Segmentation.

Mostly, robustness strategies are focussing on measures which need to be adopted at the conceptual design stage. A careful analysis of such strategies shows that a particular conceptual solution used to enhance robustness may improve the structural performance for some hazard scenarios and worsen it for others. For example, progressive collapse is possible even in carefully conceived, statically indeterminate, ductile structures, in case of unexpected failure of vertical elements, see for instance [9]. For this reason, even in supposedly robust structures, the goal must be pursued to identify and take into account all relevant hazards and hazard scenarios. In addition, more operational rules are needed for providing structural robustness, beyond a list of general strategies, such as those included in current codes [5, 6].

In existing structures, measures associated with the conceptual layout cannot normally be put into practice without structural intervention. Unequivocal identification of all relevant hazards and hazard scenarios is therefore particularly important for assessing the robustness of existing structures [10]. Quantitative criteria should also be available for decision-making regarding the acceptance of the robustness of such structures. This need is in contrast to the statement included in the available Eurocode draft [6] in the sense that the methods given for enhancing robustness are not associated with a particular target level of reliability.

3. Operational approach

3.1 General

The most accurate strategy for the design of robust structures depends on each individual project. The current Eurocode [5] establishes parameters to be considered when choosing a strategy for the design of structures exposed to identified accidental actions. Similar parameters should also be taken into account for unidentified accidental actions, since they are relevant for the design of the remaining structure after key member failure due to such actions:

- Measures taken for preventing or mitigating other hazards (e.g. those associated with persistent or identified accidental actions);
- The probability of occurrence of other hazards;
- The consequences of failure of the remaining structure;
- The acceptable level of risks.

The most appropriate way for economically meeting all structural safety and robustness requirements should be based on a combination of design strategies. Such an approach is indeed suggested in the future Eurocode [6], without further substantiation, however. Based on the previously mentioned strategies for robustness (Section 2), the following two possibilities for merger seem particularly advantageous:

- Enhanced redundancy in combination with design of key elements;
- Collapse stop in combination with design of key elements.

Hints are given in the following for the practical application of both combined strategies. For the sake of clarity, the operational approach concentrates on the design for robustness of new structures. However, the method can also be adapted to assess the robustness of existing structures, taking into account their actual conditions [10].

Multiple steps are required to develop a detailed structural design of any load bearing system [1]. An iterative procedure must often be deployed before a structural idea, in keeping with case-specific constraints, may be materialised. This is particularly the case when designing structures for robustness according to the combined strategies advocated in this section.

The conceptual design of a structure consists primarily in choosing the type, layout and main dimensions of the load bearing system, individual elements and main details, as well as in selecting the appropriate materials. This stage should also address the identification of the most important elements upon which system stability depends and the choice of the type of resisting mechanism after their possible failure. In the subsequent design steps –which include exact definition of the geometric properties, structural analysis, verification and optimization–, the fulfillment of this assumption must be ensured, i.e. coincidence of the assumed and the actual resisting mechanisms must be achieved.

3.2 Redundancy and key element design

The goal of this strategy is to build alternative load paths into a continuous structural system for the event of key element collapse due to unidentified accidental actions. In turn, for persistent and identified accidental situations, these elements should reach a level of reliability that depends on the expected consequences of their possible collapse. As well the members which are decisive for the stability of the remainder of a structure, i.e. key elements, as the consequences of their collapse, depend on the conceptual layout of the load bearing system and its structural behaviour, among other parameters. Achieving the above design goal therefore requires iteration.

The procedure for structural design according to this strategy involves the following main steps:

1. Conceptual design of a continuous structural system with a ductile behavior.
2. Identification of key elements and choice of a load bearing mechanism after their failure.
3. If necessary, adaptation of the conceptual design to the chosen mechanism.
4. Structural analysis and verification of structural reliability for ultimate and serviceability limit states related to persistent, transient and (identified) accidental design situations [6].
5. Assumption of key element failure (one by one) due to an unidentified accidental action, analysis of the modified structural system according to the previously chosen mechanism and verification of structural reliability for ultimate limit states. To this end, the combinations of actions to be considered for the establishment of the design action effects E_d refer to situations after the unidentified accidental event (no explicit accidental action: $A = 0$; frequent or quasi-permanent values for variable actions, depending on the situation). However, dynamic effects due to sudden key element collapse must be taken into account when redistributing internal forces and moments to the remaining part of the structure, $\Delta E_{d,col}$. Figure 1 shows schematically such a redistribution due to catenary behaviour of beams after column failure in a frame-type building structure. When determining the design value of the corresponding resistance, R_d, reduced values for partial factors can be taken into account for material properties and resistance model uncertainties, associated with accidental design situations according to the material-specific Eurocodes (e.g. [11]).
6. Determination of reliability requirements for key elements associated with, respectively, persistent and identified accidental design situations. The risk-based target reliability indices developed for this purpose (Section 4) depend on the expected consequences of the failure of the key element considered, according to the chosen load bearing mechanism, and may be more demanding than the reliability requirements under current code rules [4, 6], as applied in Step 4 of the iterative design procedure.
7. Adjustment of the key element design according to the risk-based reliability requirements for ultimate limit states related to persistent and (identified) accidental design situations [6].

The main difference between the combined strategy proposed in this section and the conventional creation of alternative load paths, as mentioned in Section 2, is the consideration of rational, risk-based requirements for the design of key elements. Advantages and disadvantages are similar for both approaches. Among the former, the favourable structural behaviour for all kind of design situations –persistent, transient and accidental, identified or otherwise– may be cited. Also, consequences in case of key element failure are minimized. In contrast, disadvantages include uneconomic structural design for other than unidentified accidental situations. This problem could be mitigated by using a risk-based approach to the design of the remaining structure, factoring into the reliability verifications the likelihood of key element collapse. Of course, estimation of the latter is far from straightforward. In this regard, open questions also include the estimation of the likelihood of a simultaneous collapse of more than one key element, e.g. because of deliberate malevolence of knowledgeable terrorists. Should such a possibility be considered when providing alternative load paths? Where should the limit be set?

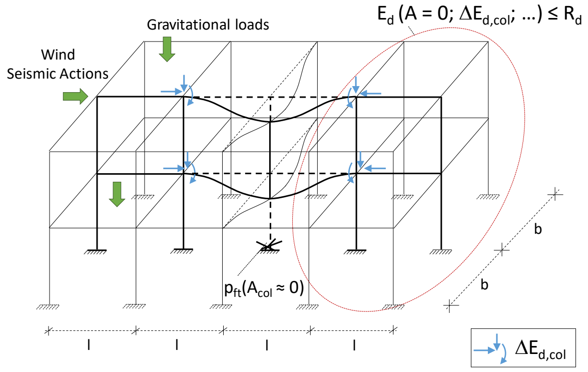

Figure 1. Schematic representation of the verifications to be carried out according to the combined strategy based on catenary behaviour of beams and key element design ($\Delta E_{d,col}$: design value of internal forces and moments transferred to the remaining structure due to local failure).

3.3 Collapse stop and key element design

By building weak components into a system, a structure can be separated into distinct parts which, in the event of key element failure due to unidentified accidental actions, are able to collapse independently without pulling the other parts down. Simultaneously, such weak components or fuses are to be designed for sufficient strength and stiffness for persistent, transient and identified accidental situations. In turn, the remaining parts of the structure must be able to withstand the additional internal forces and moments, $\Delta E_{d,col}$, generated when reaching the ultimate strength of the fuses after key element failure. As in the previously discussed strategy (Section 3.2), for persistent and identified accidental situations, the key elements should reach a sufficient level of reliability, depending on the expected consequences of their possible collapse.

In order to comply with the aforementioned objective of the strategy outlined in this section, it is of the utmost importance that for all identified and unidentified situations, the actual behaviour of the structure conforms to the assumptions. Also in this case, iteration is needed in structural design. The main steps are basically equivalent to those established in Section 3.2. However, in order to achieve collapse-stop rather than enhanced redundancy, as sought by the previous strategy, some differences should be observed:

- After the conceptual design of a redundant structure with a ductile behavior has been carried out (Step 1) and the key elements have been identified, fuses are to be introduced to the system for the case of failure of the latter (Step 2). These fuses are best chosen in a way to minimize the additional internal forces and moments, $\Delta E_{d,col}$, which are acting on the remaining parts of the structure after key element failure. For this purpose, the weakest elements, cross-sections or joints might be a good choice. It may also be necessary to adapt the conceptual design depending on the selected fuses (Step 3).
- Once individual elements constituting a structure have been provided with sufficient reliability considering persistent, transient and (identified) accidental situations (Step 4), specific robustness verifications are to be carried out. For a frame-type building

structure, Figure 2 shows schematically the verifications to be performed for achieving collapse stop after column failure. Assuming key element collapse (Step 5), fuse failure must be verified. For the relevant situations after the unidentified accidental event (Section 3.2: $A = 0$; frequent or quasi-permanent values for variable actions; dynamic effects due to sudden key element collapse), the design value of the action effects in the assumed fuses, $E_{d,fuse}$, should exceed the upper design value of the corresponding resistance, $R_{d,sup,fuse}$. Further to that and considering the same situations, structural reliability of the remaining parts of the structure needs to be verified with regard to ultimate limit states. For this purpose, the additional internal forces and moments, $\Delta E_{d,col}$, should conservatively be established based on the upper design value of the fuse strength, $R_{d,sup,fuse}$. Finally, the design value of the resistance of the remaining structure, R_d, may be obtained on the basis of reduced partial factors for accidental design situations (Section 3.2).

- Compared to the strategy described in Section 3.2, basically there is no difference regarding the determination of target reliabilities for key elements (Step 6) as well as the adjustment of their design (Step 7). The expected consequences of key element failure, thus the risk-based target reliability indices, depend on the in-built collapse stop mechanisms.

In contrast to the conventional robustness design by means of segmentation (Section 2), the proposed combined strategy leads to an adequate structural behaviour for all kind of design situations and key elements are designed to rational, risk-based criteria (Section 4). All requirements for the whole structural system as well as individual members, with regard to their safety, serviceability and robustness, may be fulfilled simultaneously. An additional advantage is that a collapse stop is possible even if more than one key element fails at the same time.

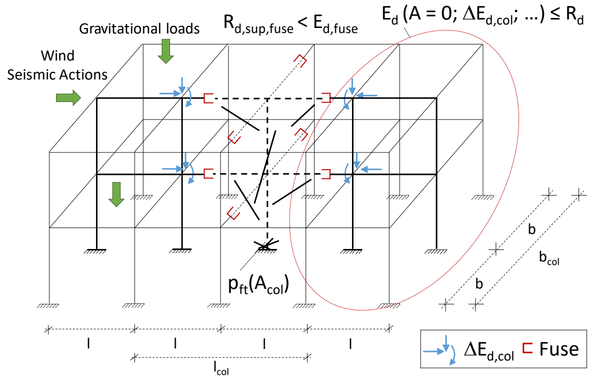

Figure 2. Schematic representation of the verifications to be carried out according to the combined strategy based on collapse stop by means of fuses and key element design ($\Delta E_{d,col}$: design value of internal forces and moments transferred to the remaining structure after local and fuse failure; $E_{d,fuse}$: design value of the action effects in the fuse; $R_{d,sup,fuse}$: upper design value of fuse strength).

In return, this strategy can lead to uneconomic solutions for transient, persistent and identified accidental situations, since the design of the remaining structure after key element failure (due to unidentified accidental actions) may be fuse strength driven ($\Delta E_{d,col}$ is dependent upon $R_{d,sup,fuse}$). As stated in the previous section, a risk-based approach to the design of the remaining structure could be helpful in this context. Other disadvantages are that normally the optimal fuse arrangement is not obvious and the procedure therefore requires important design and computation efforts.

4. Reliability requirements for key elements

4.1 Persistent situations

In a prior study conducted by the authors [12, 13], a procedure for determining the implicitly accepted life safety risks associated with building structures was defined, based on the probability of structural collapse and the consequences of such a collapse in terms of loss of human life. The procedure was applied to a representative set of structures that are strictly compliant with the safety requirements set out in the Eurocodes [4], which in turn reflect current best practice. Acceptance criteria for, respectively, structural design and assessment were deduced from the findings. In particular, consequence-dependant target failure probabilities for structural key members, $p_{ft,PER}$, were proposed, where subscript *PER* refers to persistent situations, associated with normal use conditions as considered in [12, 13].

4.2 Accidental situations

In a recent study [14, 15], the scope of the analysis was enhanced to building structures where, in addition to the normal load conditions, the possibility of accidental situations caused by gas explosions was considered. For key members of such structures a performance criterion was established, which limits the total failure probability $p_{f,TOT}$, stemming from the sum of the relevant persistent (*PER*)- and explosion hazard scenarios (*EX*), $p_{f,PER}$ and $p_{f,EX}$, respectively, to a target value $p_{ft,TOT}$, as expressed by equation (1). In analogy to [12, 13], the target failure probabilities $p_{ft,TOT}$ were deduced from implicitly acceptable life safety risk levels associated with the structures analysed [14].

$$p_{f,TOT} = p_{f,PER} + p_{f,EX} \leq p_{ft,TOT} \quad (1)$$

Under the consideration of gas explosion occurrence probability $p(EX)$, criterion (1) was translated into the following requirement for the conditional member failure probability due to the accidental load acting on the member in question, $p_{f|EX}$ (given that a gas explosion occurs and the member in question is exposed to the generated pressure wave):

$$p_{f|EX} \leq p_{ft|EX} = \frac{p_{ft,TOT} - p_{f,PER}}{p(EX)} \quad (2)$$

According to (2), the conditional target failure probability $p_{ft|EX}$ for a potentially explosion-exposed member increases with diminishing contribution of the persistent situations $p_{f,PER}$ to the total member failure probability $p_{f,TOT}$. This is generally plausible and in line with the statement that the demand of higher safety levels might involve prohibitive costs in case of large uncertainties [16]. Indeed, equation (2) suggests lower safety requirements in case the highly uncertain, explosion-induced loads dominate the reliability level associated with a specific member failure mode [14].

For sake of simplicity, and since it is a conservative approach, it is finally suggested to establish target value $p_{ft|EX}$ for verification of structural member safety in relation with a potential explosion exposure by limiting the contribution of the persistent load arrangements $p_{f,PER}$ in any case to target value $p_{ft,PER}$, adopted from [13]. Factoring the analytical functions developed for $p_{ft,PER}$ [13] and $p_{ft,TOT}$ [14] into (2), along with an assumed hazard occurrence probability of $p(EX) = 10^{-5}$ explosions per year and gas-supplied dwelling, delivers the conditional target failure probabilities $p_{ft|EX}$ shown in Figure 3 as a function of the area affected by the collapse of the member in question, A_{col}. Two functions based on, respectively, the 5% fractile and the mean value of the implicitly accepted risks are distinguished. As a result of an analysis of the associated annual fatality rates of building users, the 5% fractile is recommended for key member design, whereas for assessment of existing members, the less demanding mean value criteria could be adopted [14]. The mean value criterion applies for members whose collapse would affect an area of at least $A_{col,min,m} \approx 100$ m^2 (areas below $A_{col,min,m}$ deliver

$p_{ft|EX} > 1$). When the 5% fractile value is referred to, $A_{col,min,5\%}$ decreases to 15 m^2. Below these minimum areas, key member design can be based on $p_{ft,PER}$ (Section 4.1), without any further provisions for the explosion loading. Beyond these threshold areas, diminishing $p_{ft|EX}$ with increasing A_{col} account for aversion to collapse events with larger consequences to personal integrity [14].

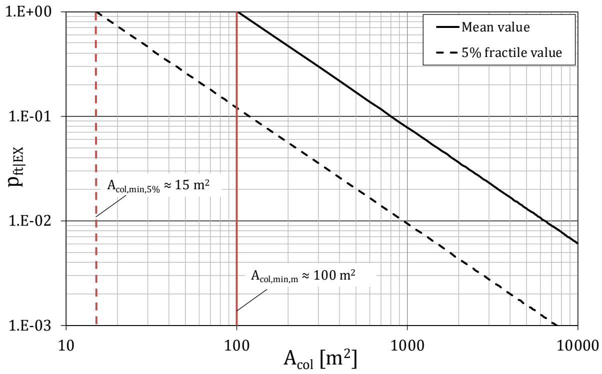

Figure 3. Conditional target failure probability $p_{ft|EX}$ as a function of the area affected by the key member collapse A_{col}.

4.3 Estimation of collapse areas

An estimation of the area affected by potential collapse of a particular key member, A_{col}, is required for establishment of the proposed target reliabilities. Particularly, this applies to the design strategy described in Section 3.3, where segmentation by means of structural fuses is foreseen in order to limit the collapse propagation. In this case, area A_{col} should be conservatively based on the dimensions covering the entire span of the part of the building that is directly affected by the key member collapse (see collapse length l_{col} and width b_{col} in Figure 2). On the contrary, if a redundant structural system is considered, as in Section 3.2, the loads can be redistributed to adjacent members in case of a key member collapse and hence no significant building area will be affected ($A_{col} \approx 0$). In this case, the expected consequences to persons are minimized and key member design shall be based on minimum reliability requirements according to [13].

5. Conclusions

In current practice, several strategies exist for the design of robust structures. General aspects of such strategies are also reflected in codes and standards. Depending on the circumstances of each individual case, they might imply significant disadvantages either leading to unfavourable structural behaviour for other than unidentified accidental situations, including undesirable collapse mechanisms with major consequences in the event of local failure, inefficient solutions, or a combination thereof. The present paper therefore proposes a pragmatic approach with the aim of economically meeting all structural performance requirements, including robustness. It is based on a suitable combination of different design strategies:

- Adoption of continuous structural systems with a ductile behavior.
- Provision of either alternative load paths or predefined collapse mechanisms for the event of local failure of selected structural components due to unidentified accidental actions.
- Realization of specific verifications to ensure consistency between assumed and real mechanisms in case of local failure.
- Provision of reliability levels to selected structural components (i.e. key elements), depending on the expected consequences in case of failure due to persistent or identified accidental situations.

It should be emphasized that when designing structures for robustness, the solutions may be uneconomic from the point of view of transient, persistent and (identified) accidental situations. Future work therefore includes the refinement of the verification criteria for the remaining structure after key element collapse. A risk-based approach seems appropriate for this purpose, factoring into the reliability verifications the likelihood of key element collapse.

References

[1] Tanner P., Bellod J.L., and Sanz D. Paper and Pencil in the Age of BIM, Structural Engineering International. 2018; 28(4):396-407

[2] Starossek U. Progressive Collapse of Structures. London: ICE Publishing; 2018.

[3] JCSS and IABSE. Robustness of structures – Workshop, BRE, Watford. Zürich: Joint Committee on Structural Safety and International Association for Bridge and Structural Engineering; 2005; http://www.jcss.ethz.ch

[4] EN 1990. Eurocode: Basis of structural design. Brussels: European Committee for Standardisation; 2002.

[5] EN 1991-1-7. Eurocode 1 – Actions on structures – Part 1-7: General actions – Accidental actions. Brussels: European Committee for Standardisation; 2006.

[6] prEN 1990. Eurocode: Basis of structural and geotechnical design. Second revised draft from Management Group 2019-05-06. Brussels: CEN/TC 250/SC 10; European Committee for Standardisation; 2019.

[7] Tanner P. Requisitos de seguridad estructural basados en los riesgos para las personas. Madrid: Universidad Politécnica de Madrid; 2016.

[8] Adam J.M., Parisi F., Sagaseta J., and Lu X. Research and practice on progressive collapse and robustness of building structures in the 21st century, Engineering Structures. 2018; 173: 122-149

[9] Corres H., Romero E. Reconstrucción "Módulo D" Aparcamiento Madrid Barajas T-4. IV Congreso de ACHE (Asociación Científico-Técnica del Hormigón Estructural). Valencia; 2008.

[10] prCEN/TS. Technical Specification – Assessment of existing structures. Brussels: European Committee for Standardisation; 2019.

[11] prEN 1992-1-1. Eurocode 2 – Design of concrete structures – Part 1-1: General rules, rules for buildings, bridges and civil engineering structures. 6th Revision 2019-10-25. Brussels: European Committee for Standardisation; 2019.

[12] Tanner P., Hingorani R. Acceptable risks to persons associated with building structures. Structural Concrete. 2015; 16(3):314-22.

[13] Hingorani R., Tanner P. Risk-informed requirements for design and assessment of structures under temporary use. Risk Analysis. 2019; Published online, 06 May 2019.

[14] Hingorani R, Tanner P, Zanuy C. Life safety risk-based requirements for concrete structures in accidental situations caused by gas explosions. Structural Safety. 2019; 76:184-96.

[15] Hingorani R. Acceptable life safety risks associated with the effects of gas explosions on reinforced concrete structures: Universidad Politecnica de Madrid (UPM). https://doi.org/10.20868/UPM.thesis.47772; 2017.

[16] JCSS. Probabilistic Model Code, Part 1 - Basis of design. Joint Committee on Structural Safety 2000.