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Life safety risk-based requirements for concrete structures in accidental situations caused by gas explosions

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ABSTRACT

Accidental hazards are associated with large uncertainties regarding their occurrence probability, their effects on a structure and the possible consequences these effects might entail in case of failure. Consequently, decision-making related to safety accounting for such hazards is difficult and prone to be based on irrational grounds. Gas explosions in buildings are a good example therefore. Although dealt with in many codes, they are seldom accounted for in design of building structures. As a consequence, the associated risks are often ignored or sometimes consciously accepted. If this is a justified practice cannot be easily judged however, since under the implicit approach adopted in practice for assuring structural safety the risks are not quantified nor are the acceptable risk levels established.

On this background, the paper explores methods and tools for the practical application of explicit risk analysis in connection with the effects of gas explosions on RC structures. A procedure is established to determine structure-related risks to persons and applied to a representative set of structures designed according to current best practice. Target reliabilities for the design of key elements are deduced from the findings. Such target values facilitate rational decisions on both, the need and the appropriate choice of risk-reduction measures to counteract the effects of gas explosions in buildings.

1. Introduction

In a technical context, risks are understood as a mathematical expectation of the consequences of an undesired event [55]. While not totally avoidable, risks can be analysed, assessed and, if required, reduced by appropriate measures. In daily structural design practice, the treatment of risks is generally implicit, i.e. they are not explicitly quantified and the question of their acceptability is judged on the base of prescriptive, codified rules. These rules are mainly based on experience and knowledge gained in the past. They approximately represent the state of best practice and provide reasonable grounds for the design of most structures under normal loading, operational and environmental conditions [22,55].

In addition to the normal use conditions, structures might be exposed to abnormal or accidental actions, which are among the most common causes of structural failure [56]. Accidental actions may be characterized as low probability – high consequence hazards [15]. Hence, their occurrence during the envisaged design working-life of a structure is unlikely, but if it happens, and if not appropriately accounted for, the corresponding effects might entail significant consequences. Due to the high uncertainties involved, decision-making related to structural safety accounting for such actions is generally complex and prone to be based on irrational grounds. Explicit risk analysis might offer substantial advantages in this regard. In such an analysis, the specific characteristics inherent to accidental actions, such as their low occurrence probabilities, on one hand, and the potentially high failure consequences, on the other, can be judged in a rational manner in terms of risk [16,56].

Among the possible accidental hazards in buildings, gas explosions account for a substantial number [58]. Despite the continuous modernization of gas installations and appliances, available statistics from different western countries show that the occurrence rate of such explosions still does not decrease in a significant way. Among the possible reasons is the fact that a certain proportion of the incidents is not attributable to technical shortcomings but to suicide attempts. Given their well-known hazard potential to structural safety, gas explosions are dealt with in many structural design codes. In Eurocode EN 1991-1-7 [20], for instance, they are demanded to be accounted for "in the design of all parts of the building (or other engineering works) where gas is burnt or regulated…". Specific guidance on practical implementation of

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associated design measures is provided e.g. in [57].

In spite of their consideration in codes and guidelines, gas explosions are only seldom accounted for in layout and design of building structures. Among possible reasons therefore, one might quote the reluctance to allocate funds to mitigate such kind of low-probability future events [15]. The question that rises is if "doing nothing" is a justified practice, or if certain risk reduction measures would be appropriate. Providing a knowledgeable answer to these questions calls for an explicit analysis and assessment of structure-related risks, what was addressed in the context of the PhD thesis of the first author [26]. The research presented in the present paper has been the subject of this thesis. Models for estimation of both the probabilities and the consequences to persons of a gas explosion-induced collapse in reinforced concrete (RC) building structures are presented. Following the general approach developed in previous studies [50,51], these models are subsequently employed to determine the implicitly accepted life safety risks associated with such structures. Rational acceptance criteria for structural safety verifications of potentially explosion-exposed structural members are deduced from the findings. They could be employed in the framework of a performance-based reliability design or assessment. Moreover, they may serve as a basis for the calibration of semi-probabilistic models for applications in daily practice, following current developments for structure-related explosion hazards due to terrorist attacks [2,48].

2. Methodology

2.1. Assumptions for the inference of acceptable risks

Decision-making related to technical facilities in general, and structures in particular, unavoidably requires addressing life safety risks in order to assure that persons are safeguarded from undue threats to their life to the highest affordable level [23]. According to the Marginal Life Saving Cost (MLSC) principle established in the international standard on the reliability of structures [34], this level is closely related to the societal willingness to pay for saving one statistical individual and can be quantified by means of the Life Quality Index (LQI). However, the standard also states that "an activity which is found to be acceptable should be assessed in regard to the corresponding absolute level of life safety risk". Moreover, it specifies that the practical implementation of the MLSC principle by using the LQI might require the specification of "absolute values of the acceptable life safety risks". Indeed, in the opinion of social scientists the public at large would be unlikely to accept higher failure rates than associated with current *best practice* [51], even if they are based on rational acceptance criteria such as the MLSC principle. For these reasons, the present study explores life safety risk-related acceptance criteria associated with building structures compliant with current best practice, in turn reflected by the structural design codes in force. Risk acceptability therefore depends on the *degree of reliability implicitly required by these codes*. This degree is unknown and, as previous studies show, might differ fundamentally from nominal target ceilings established in the codes [30,50].

Structural design codes such as [20] offer a variety of possible measures to counteract the effects of accidental actions in building structures [16,31], based on the general performance requirement, that "*the structure shall be designed and executed in a way that it will not be damaged to an extent disproportionate to the original cause*". Among those measures, one might quote prescriptive design and detailing rules foreseen to enhance structural redundancy and/or robustness. Other strategies are related to the mitigation of consequences such as tolerating local member failure, provided alternative load paths might develop which ensure the overall stability of the structural system. Although it might not be an attractive solution from an economical point of view, design of structural members to withstand the effects of an accidental action constitutes another possible risk-reduction measure. For this purpose, the codes offer specific accidental design rules. Hence, in analogy to the persistent design situations, the failure probabilities associated with cross-sections or members designed for the accidental situation, might be referred to as intrinsically acceptable by the current legislation. This applies as well to the corresponding structure-related risks. The inference of requirements for structural safety is based on this appreciation. The effect of prescriptive code rules for enhancing redundancy and/or robustness on structure-related risks is not investigated in the present study.

2.2. Mathematical framework

A mathematical framework for the quantification of structure-related risks is defined in line with the main principles established in prior studies [50,51]. These principles are based on the state of knowledge regarding explicit approaches for the analysis and assessment of risks associated with technical systems. In the present context, such a system is described by a particular building structure. Each of the n_j hazard scenarios associated with this structure is represented by a specific collapse scenario triggered by failure of one of its n_m principle loadbearing members. Such a failure, in turn, is characterized by a specific failure mode that is induced by a particular load arrangement. The n_j hazard scenarios are mathematically described by their occurrence probabilities p_j and the associated consequences to persons, in terms of the expected number of collapse-induced fatalities, N_j. Assuming statistical independency between the $j = 1, 2, \ldots, n_j$ hazard scenarios, these can be represented in a so-called risk profile (Fig. 1). In such a risk profile, the n_j hazard scenarios are arranged according to the magnitude of the consequences N_j, represented on the axis of abscissa. The axis of ordinates represents the occurrence probabilities p_j of the scenarios. The integral of the risk profile (Eq. (1)) corresponds to the risk R associated with the structure in question. The occurrence probabilities p_j, and hence the risks R, are associated with a specific reference period.

$$R = \sum_{j=1}^{n_j} p_j \cdot N_j \tag{1}$$

2.3. Procedure

A procedure has been established that comprises the definition of the tasks to be addressed in the present study (Fig. 2). The procedure initially requires the definition of the general context, scope and objectives of the study (step 1), addressed before in Sections 1 and 2.1. The necessary mathematical framework for the estimation of structure-related risks (step 2) was briefly described in Section 2.2.

With the principle aim to cover the majority of the cases encountered in practice, step 3 subsequently involves selecting representative sets of hypothetical but realistic building structures and

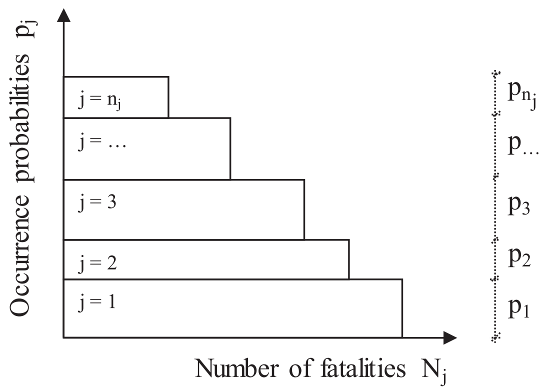

Fig. 1. Schematic representation of a probability-consequence diagram (risk profile).

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