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Setting structural safety requirement for controlling earthquake mortality risk

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ABSTRACT

Structural engineers design buildings according to the earthquake action (demand) specified in code of practice, whilst the rationale behind such requirement is commonly untold. In fact, even if a structure is designed strictly in accordance to the best standard and practice in the world, there is still a (small) chance of failure or collapse in an extreme earthquake event, due to the uncertainties in material properties and actual ground motions characteristics. This is the residual risk, which is unavoidable, and should be taken as a governing parameter for determining the performance goals of seismic design. This study attempts to establish the required (target) collapse risk limits for designing different types of ordinary buildings based on a well-accepted tolerable level of mortality risk and estimates of fatality rates in buildings. The proposed limits are compared with the target risk of collapse stipulated in the 2012 edition of the International Building Code (IBC). The risk-based approach presented in this paper should also be applicable for setting performance objectives for structural design of buildings and infrastructure against other natural, human-caused and technological hazards.

1. Introduction

Structural design codes and standards for buildings aim at protecting life or limb, health, property, and public welfare. From a layman's perspective, collapse of structures and the associated fatalities must be unacceptable, and should be avoided by all means. However, enormous uncertainties exist in the characterisations of loadings, material properties, design and construction process, this is in fact impossible for engineers to guarantee "zero-risk" for all the structures that are designed and constructed.

Hence, when a design standard or code is to be written, the first question to ask should be "what are the performance requirements?", or in layman's term "how safe is safe enough?" On one hand, the safety of occupancy/user of the engineered facility must be ensured, whilst on the other hand, engineers have the responsibility to design and construct a facility in an economical way. The two goals are always contradicting and there is a trade-off between safety and costs (Starr, 1972; Porter et al., 1998; Liel and Deierlein, 2013).

This is particularly true for earthquake-resistant design, as it is clearly possible that the actual level of ground motions significantly exceeds the design ground motions and the actual material properties (e.g. strength) can be poorer than expected, even if buildings are designed and built in accordance to all the necessary requirements. Hence, it is not practical to design 100% "earthquake-proof" structures, and there are still a small percentage of code-conforming buildings that could suffer from partial or even complete collapse which may lead to casualties. It should be logical and appropriate if the performance requirements in seismic codes of practice and earthquake safety policy are defined with the consideration of the residual risk of structural collapse and casualty (Wiggins, 1972; Liel and Deierlein, 2012; Porter, 2014; Dolšek, 2015).

The 2012 edition of the International Building Code (IBC) (ICC, 2012) and the 2010 edition of the structural design standard ASCE/SEI 7 (ASCE, 2010) have firstly set out risk-targeted performance requirements for seismic design. However, the implications of the requirements for life safety have not been explicitly considered. This study addresses exactly this gap by evaluating whether the stipulated requirements are adequate for mortality control or not. *On what basis should we set the tolerable levels of mortality and collapse risk?* To answer this question, the residual risk (of collapse and casualty in building) has firstly been discussed in the context of earthquake-resistant structural design and a brief description of the design performance requirements has been given in Section 2. This is followed by a multi-disciplinary review

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of major studies and guidelines about the tolerable level of mortality risk (Section 3). A rational limit of tolerable earthquake fatality risk has then been recommended. Based on an analysis of casualty data collected from past earthquakes around the world, the required (target) collapse risk limits for structural design can be established (Section 4).

This issue concerns not only civil and structural engineers, but all the stakeholders in the community, including architects, surveyors, builders, policy makers and the general public (i.e. owners and users). Also, the recommendations provided in this paper should be of interest to readers in any countries, although the exact values of the results could be different.

2. Residual risk of collapse and casualty

The current set of performance objectives for earthquake resistant design has firstly been established in the 1968 edition of the document titled "Recommended Lateral Force Requirements and Commentary" (SEAOC, 1968) (commonly known as the SEAOC Blue Book), published by the Structural Engineers Association of California (SEAOC). This has been passed onto later editions and the recent editions state that "structures designed in conformance should, in general, be able to:

> Level 1: resist a minor level of earthquake ground motion without damage;
> Level 2: resist a moderate level of earthquake ground motion without severe structural damage, but possibly experience some non-structural damage;
> Level 3: resist a major level of earthquake ground motion having an *intensity equal to the strongest either experienced or forecast* for the building site, without collapse, but possibly with some structural as well as non-structural damage".

Similar set of design objectives has also been adopted in other major codes and standards all around the world, including but not limited to Australian Standard (AS 1170.4) (SA, 2007), Eurocode 8 (EN 1998-1) (CEN, 2004), Chinese Code for Seismic Design of Buildings (GB 50011) (CABP, 2010), National Building Code of Canada (NBCC) (NRCC, 2010), and New Zealand Standard (NZS 1170.5) (SNZ, 2004). These performance requirements at various levels of seismic actions have further been expanded and developed into the performance-based earthquake engineering framework since the 1990s (SEAOC, 1995; EERC, 1996; ATC, 1997, 2006; Porter, 2003; Moehle and Deierlein, 2004; PEER, 2010).

For collapse prevention level (i.e. Level 3), as it is difficult to reliably forecast the intensity level of the strongest earthquake ground motion, an intensity level associated with a reference probability of exceedance (*PE*) in a notional design life of 50 years, or the corresponding reference return period (*RP*) is typically adopted. Such intensity level is regarded as maximum *considered* earthquake (MCE) ground motion. It recognises that no design code or standard can provide 100% confidence of life safety: "The protection of life is reasonably provided, but not with complete assurance", as stated in the SEAOC Blue Book. In other words, there exists certain level of residual risk in our structures.

"Residual risk" is defined by the United Nations International Strategy for Disaster Reduction (UNISDR, 2009) as "the risk that remains in unmanaged form, even when effective disaster risk reduction measures are in place, and for which emergency response and recovery capacities must be maintained". In the context of seismic design, standards and codes of practice are considered as effective disaster risk reduction measures, whilst unexpected earthquake ground motions and substandard performance of structures can be considered as "unmanaged" as they are intended not to be "considered" in the codes. However, the target level of residual risk is typically not stated explicitly in structural design standards or codes of practice.

Recently, the requirements of collapse prevention (i.e. Level 3) in IBC-2012 and ASCE/SEI 7-10 were re-defined in terms of "*risk-targeted*" maximum considered earthquake (MCE_R) ground motion (as described in FEMA P-750 report, prepared by BSSC, 2009), which requires ordinary buildings to be designed to have equal (uniform) collapse risk of 1% in 50 years (i.e. annual *PE* of 2×10^{-4}). Meanwhile, the probability of collapse should be limited to 10% under the MCE_R action. Risk-based performance objectives are currently under development in other parts of the world for potential incorporation into future editions of codes and standards (e.g. Dolšek, 2015).

The rationale behind such requirements is actually not clear, and there has been inadequate formal discussion over such an important issue (Porter, 2014). In fact, the newly-defined MCE_R ground motion levels and the previous MCE ground motion levels at various locations in the U.S. are broadly consistent (within plus or minus 15%, except very few locations such as around the New Madrid Seismic Zone). Also, the collapse risk of 1% in 50 years is about what had been achieved in the western U.S. with the previous requirements (Luco et al., 2012). In other words, the overall seismic performance of building stock designed (or upgraded) according to the new requirements has not been enhanced at the national level. Anyhow, such change has highlighted the need of considering the residual risk of structure in the design process. However, for a rational discussion about the adequacy of the current requirements and for setting a more desirable level of protection, the first question should be "*how much residual risk might be considered tolerable?*" Also, *is it consistent with the risk levels of other causes?*

3. Basis of the tolerable mortality risk limit

3.1. Historical empirical approach

Starr (1969) has published a seminal paper on the acceptable level of technological risks, which has guided the research in the field of risk acceptance since then. It was suggested that the level of acceptable risk of an event depends if an individual participates voluntarily or involuntarily. Whilst the risks associated with "voluntary" activities could be evaluated based on the individual value system and past experiences, the acceptable risk levels of "involuntary" activities are usually determined by a controlling body, such as government agency or a group of policy makers. The safety standard for building structures falls into the latter category, as the residence in a building is a necessity that there is no choice of not taking the risk of structural failure. Meanwhile, the public usually does not have a channel to provide opinions or feedback into the decision process. Even if such a communication channel exists, the feedback mechanism is usually a slow and ineffective process.

In such situation, the historical data and trends related to the risk of those involuntary activities are the more significant indicators of the social acceptability. Amongst all the events, it was suggested in Starr et al. (1976) that the mortality caused by natural hazards, such as lightning, flood and earthquake, could be taken as the lowest level of reference, because such risk has historically been treated by the public as "acts of God".

Starr (1969) cited the annual mortality rates of 2.2×10^{-6} and 7×10^{-7}, respectively, due to floods and major storms in the U.S., 1.66×10^{-6} due to California earthquakes and 2.2×10^{-6} due to tornadoes in the mid-west U.S. These values indicated a base guide level of mortality rate of 10^{-6}, i.e. one death per year per million population (Starr, 1972). This has been taken as the acceptable or