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RESIDUAL FATALITY RISK ESTIMATES FOR SETTING EARTHQUAKE SAFETY REQUIREMENT

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Abstract

Structures designed strictly in accordance with the required code of practice could still have a small probability of collapse in a major earthquake. This is the residual risk, which should be lower than the level that is acceptable or tolerable by the public and stakeholders. The 2012 edition of the International Building Code (IBC) has 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 this gap by evaluating whether the stipulated requirements are adequate for mortality control or not. The annual individual fatality risk in different categories of buildings is first estimated and benchmarked against the tolerable level of mortality risk. A rational collapse risk limit is then proposed for structural design of different types of buildings. The paper also looks at some of the uncertainties associated with fatality estimation and the use of annualized mortality risk for design purposes.

Keywords: building structure; performance objectives; tolerable; earthquake fatality; target collapse risk

1. Introduction

Structural engineers design buildings according to the earthquake action (demand) specified in codes of practice, whilst the rationale behind such requirement is not commonly stated. In fact, even if a structure is designed strictly in accordance with 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 motion characteristics. It should be logical and appropriate that the performance requirements in seismic codes of practice and earthquake safety policy are defined along with the consideration of the residual risk of structural collapse and casualty [1–4].

"Residual risk" is defined by the United Nations International Strategy for Disaster Reduction (UNISDR, [5]) 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 not intended 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.

The 2012 edition of the International Building Code (IBC) (2012) [6] and the 2010 edition of the structural design standard ASCE/SEI 7 [7] 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 this gap by evaluating whether the stipulated requirements are adequate for mortality control or not.

To answer this question, the residual risk (of collapse and casualty in building) is firstly discussed in the context of earthquake-resistant structural design and a brief description of the design performance requirements is given in Section 2. Based on an analysis of casualty data in Hazus, the annual individual fatality risk in different categories of buildings designed in conformance to IBC-2012 is then estimated in Section 3, and benchmarked against the tolerable level of mortality risk. This is followed by a summary of the proposed target collapse risk limits for structural design in Section 4. The mortality risk is then examined in a global context as to the acceptability and uncertainties associated with fatality-based estimation (Section 5). The discussion and the recommendations provided in this paper should be of interest to readers in any countries.

2. Residual Risk in Seismic Design

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", published by the Structural Engineers Association of California (SEAOC) (commonly known as the SEAOC Blue Book) [8]. This has been passed onto later editions and those performance requirements at various levels of seismic actions have been expanded further and developed into the performance-based earthquake engineering framework since the 1990s.

The recent editions of the SEAOC Blue Book state that structures designed in conformance should be able to 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. 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 in a notional design life of 50 years, or the corresponding reference return period, is typically adopted. Such intensity level is regarded as maximum considered earthquake (MCE) ground motion. It recognizes that there exists certain level of residual risk in our structures.

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 [9]), which requires ordinary buildings to be designed to have equal (uniform) collapse risk, P(C), of 1% in 50 years (i.e. annual probability of exceedance of 2×10^{-4}). Meanwhile, the probability of collapse should be limited to 10% under the MCE_R action. Such change has highlighted the need for consideration of the residual risk of structure in the design process. New generation performance requirements in building codes should ideally be specified based on the residual risk. 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. [4]). Hence, it is essential to have a discussion about a tolerable level of residual fatality risk in seismic design, which is the objective of this paper.

3. Earthquake Fatality Risk in Buildings

In this section, the annual individual fatality risk, P(D), in buildings designed in conformance to IBC-2012 and ASCE/SEI 7-10 will be estimated based on the fatality risk due to structural collapse, P(D|C), using Eq. (1). The estimates will then be benchmarked against a tolerable (or acceptable) risk level.

$$P(D) = P(C) \times P(D|C) \tag{1}$$

3.1 Basis of tolerable level of fatality risk

A tolerable level of individual annual fatality risk of 10^{-6} has been recommended by various organizations, as listed below. This has been well supported by historical mortality data caused by natural hazards [10,11]. A brief review of the relevant documents has been given in Tsang and Wenzel [12].

- ISO 2394:1998 "General Principles on Reliability for Structures" [13]
- Eurocode – Basis of Structural Design EN 1990:2002 [14]
- The Ministry of Housing, Spatial Planning and the Environment (VROM) of the Netherlands [15]
- The Long Beach City Council, California, U.S. [1]

Nevertheless, the level of tolerable fatality risk depends on the public awareness and perception of the associated risk as well as the risks from other hazards and events. In terms of earthquake protection, it may also depend on the level of seismicity in the area of interest, advancement of seismic design technologies, or the level of economic and social development. In view of this, an individual annual fatality risk limit of 10^{-6} is considered reasonable at least for developed countries. This issue will be discussed further in a global context in Section 5.

Using the CATDAT Damaging Earthquakes Database and event deaths vs. population per year, and distributing the average annual mortality rate in the unit of micromorts (i.e. annual mortality rate of 10^{-6}) (see Fig. 1), it can be seen that such a limit was exceeded in many countries historically. The historical implications of this limit are discussed in the accompanying paper, Paper No. 170 [16].

3.2 Estimates of fatality risk based on Hazus data

It is clear that when a one-storey timber frame dwelling and a 10-storey concrete building collapse together, their fatality risks are likely to be very different. In other words, the probability of dying due to structural collapse, P(D|C), should vary between structural types and number of storeys. For estimating fatality risk due to structural collapse, P(D|C), Hazus (https://www.fema.gov/hazus/) has provided an authoritative and comprehensive set of background data for estimating earthquake-related casualties. The estimates provided by Hazus have been made based on extensive databases of casualties induced by past earthquakes.

Estimates of fatalities due to various levels of damages of different types of structures in past earthquakes have been summarized in the Hazus Technical Manual [17]. Undoubtedly, there is a high level of variability in the estimated losses between individual buildings in the same category. Each estimate is considered as the average for a group of buildings with similar characteristics (e.g. structural form, construction material, number of storeys), which can fulfil the need for planning and policy-making, i.e. the purpose of this study.

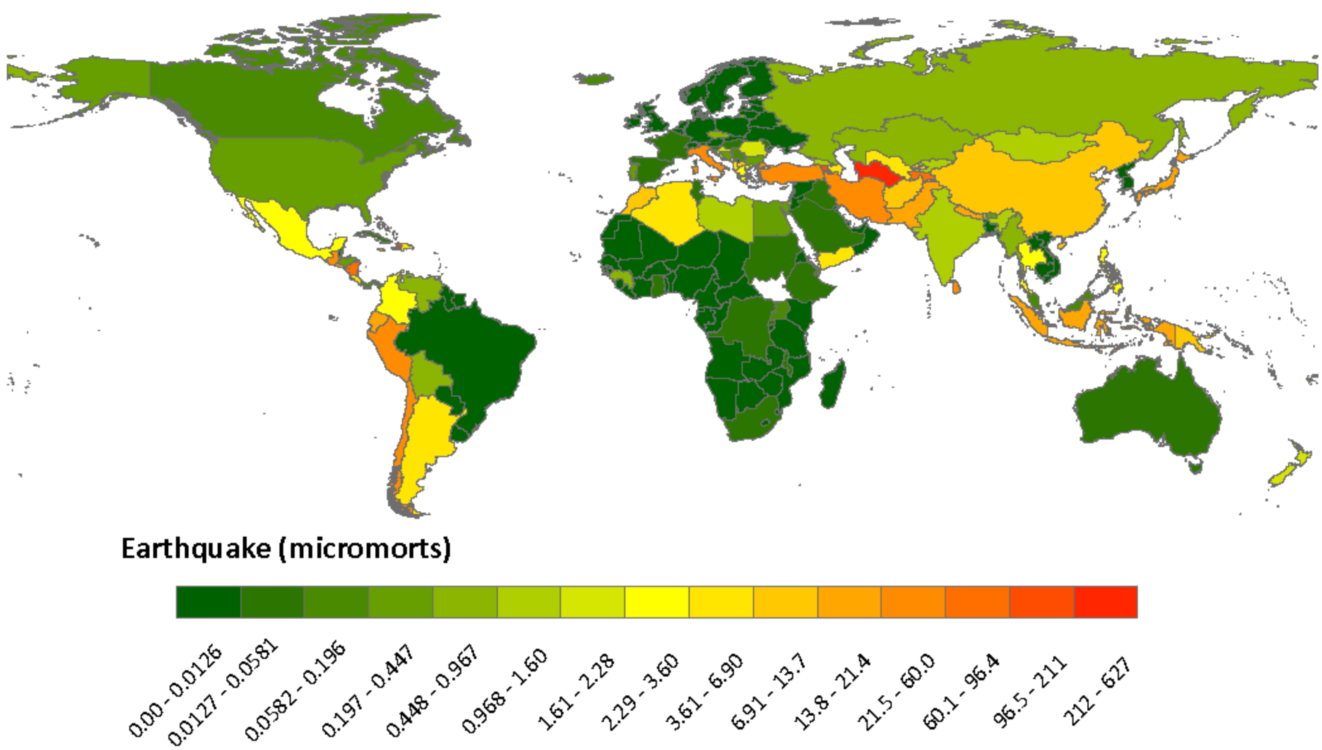

Fig. 1 – Global view of average annual earthquake mortality rate in micromorts (i.e. mortality rate of 10^{-6}) [16] based on CATDAT Damaging Earthquakes Database.

3.2.1 Definition of structural collapse

For this purpose, an appropriate definition of structural collapse, consistent with the usual practice of structural design, is required for reliable and representative calculations. "Collapse" is typically defined as dynamic instability due to excessive lateral deformations of certain components or the estimated demands exceeding a pre-defined limit. When a structure reaches either of these conditions, nearly complete damages with low residual lateral strength and stiffness must be anticipated. However, wholesale collapse rarely occurs, and the degree or proportion of collapse depends on the robustness of the structure and the intrinsic properties of the construction materials.

In fact, the true collapse risk of a structure is very hard to be estimated accurately in practice through structural analysis, despite the advancement of modelling techniques. Hence, collapse is defined as the state of structural damage that could lead to instantaneous deaths and immediate life-threatening injuries, which could result when a structure has suffered from the most severe damage state of "Complete Structural Damage (*CSD*)" in Hazus. This definition is essentially consistent with the "Collapse Prevention" level as defined in the FEMA Publication 273 [18], or the "Near Collapse" level in the Vision 2000 performance-based seismic design framework [19] and the Eurocode 8 – Part 3 (EN 1998-3:2005) [20] that has life-threatening risk [21].

The structural system is on the verge of experiencing partial or total collapse at this level of damage. Technically, there could be excessive permanent lateral deformation or brittle failure of certain critical structural components, or loss of stability of part of the structure. However, only a certain percentage of floor area of buildings with *CSD* is expected to collapse. The damage state of *CSD* is analogous to damage grades D4 (very heavy damage, partial collapse) and D5 (total or near total collapse) combined [22] under the classification scheme used in the European Macroseismic Scale 1998 (EMS-98) [23]. Actually, the second most severe damage state of "Extensive Structural Damage" in Hazus could also lead to life-threatening casualties, but it does not have a significant contribution to the overall fatality risk.

3.2.2 Hazus fatality data

Hazus has adopted a systematic framework for estimating fatality rate, which takes into account occupancy rate at different times of earthquake occurrence, collapse vulnerability of different building categories, and so forth. In this study, only fatalities directly due to structural damage have been considered. The latter could be caused by the failure of parapet walls or the fall of non-structural wall panels. However, the estimates exclude those caused by co-existing events like fires, tsunami and landslides, or indirect causes including heart attacks, power failure and the release of hazardous materials.

The most commonly adopted construction materials for engineered structures around the world are concrete, steel and timber. Hence, the relevant building categories in Hazus have been considered in this study and the fatality data for these building types have been analysed. Unreinforced masonry (URM) infill walls are sometimes used for enhancing the lateral stiffness of structures. They are usually the more vulnerable components which have a higher risk of collapse than the primary frame structure. Hence, buildings with such components could kill more people in an earthquake, and have to be treated separately.

Hazus has provided an estimate of the indoor and outdoor population at three scenario times. A sensitivity study has revealed that the results are not sensitive to the assumed proportion of outdoor population. Hence, a time-independent outdoor population of 10% has been considered in the calculation. Also, the manual has recommended the proportions of the population in buildings of different groups of functions, namely, residential, commercial, education, industrial, and so forth. However, the function of structure is not considered in this study, with an assumption that the level of fatality risk is taken as the same for occupants in all types of structures.

3.2.3 Calculation of annual fatality risk

The overall conditional fatality risks, P(D|C), for different categories of buildings have been presented in Tsang and Wenzel [12]. Given the "collapse" of structure (i.e. *CSD*), the fatality risk ranges from 0.23% (for steel light frame) to 1.95% (for low-rise concrete structure with URM infill walls). These values might be considered low generally, which illustrates the life-safety objective of the existing structural design philosophy that a completely damaged (near collapse) structure is still capable of supporting gravity loads with its residual strength and stiffness.

Next, assuming that all the buildings are designed in conformance to IBC-2012 and ASCE/SEI 7-10, with a (uniform) collapse risk, P(C), of 1% in 50 years or an annual probability of exceedance of 2×10^{-4}, the annual individual fatality risk, P(D), in buildings can be calculated using Eq. (1). The results are presented in Fig. 2, in which the tolerable level of individual annual fatality risk of 10^{-6} has been included as a benchmark. It can be observed that lighter structures, including timber and steel light frame, generally lead to fatality risk lower (i.e. safer) than the benchmark risk level, while heavy concrete structures can lead to more fatalities. The individual annual fatality risk in steel buildings is estimated to be around 1×10^{-6} to 2×10^{-6}, whereas the risk in concrete buildings is around 1.5×10^{-6} to 4×10^{-6}, which is higher than the benchmark level.

Collapse risk assessment for buildings has been conducted by Haselton and Deierlein [24] and Liel and Deierlein [25]. These studies provide an updated understanding of the expected level of safety and the residual risk of both ductile (code-conformed) and non-ductile (pre-code) concrete frame buildings in California, U.S. The number of fatalities has also been estimated [25]. As shown in Fig. 3, the individual annual fatality risk in ductile structures is estimated to be around 2×10^{-6} to 18×10^{-6}, whereas the risk in non-ductile structures is around 30×10^{-6} to 420×10^{-6}, which is significantly higher than the tolerable level of 1×10^{-6}.

Similar collapse risk studies have also been conducted for typical soft-storey buildings with precast [26] or in-situ [27] reinforced concrete columns under a low axial load ratio located in the low-to-moderate seismicity Melbourne, Australia. The individual annual fatality risk is estimated to be around 0.1×10^{-6} to 3×10^{-6} for a wide range of site conditions, which is generally below or around the tolerable level.

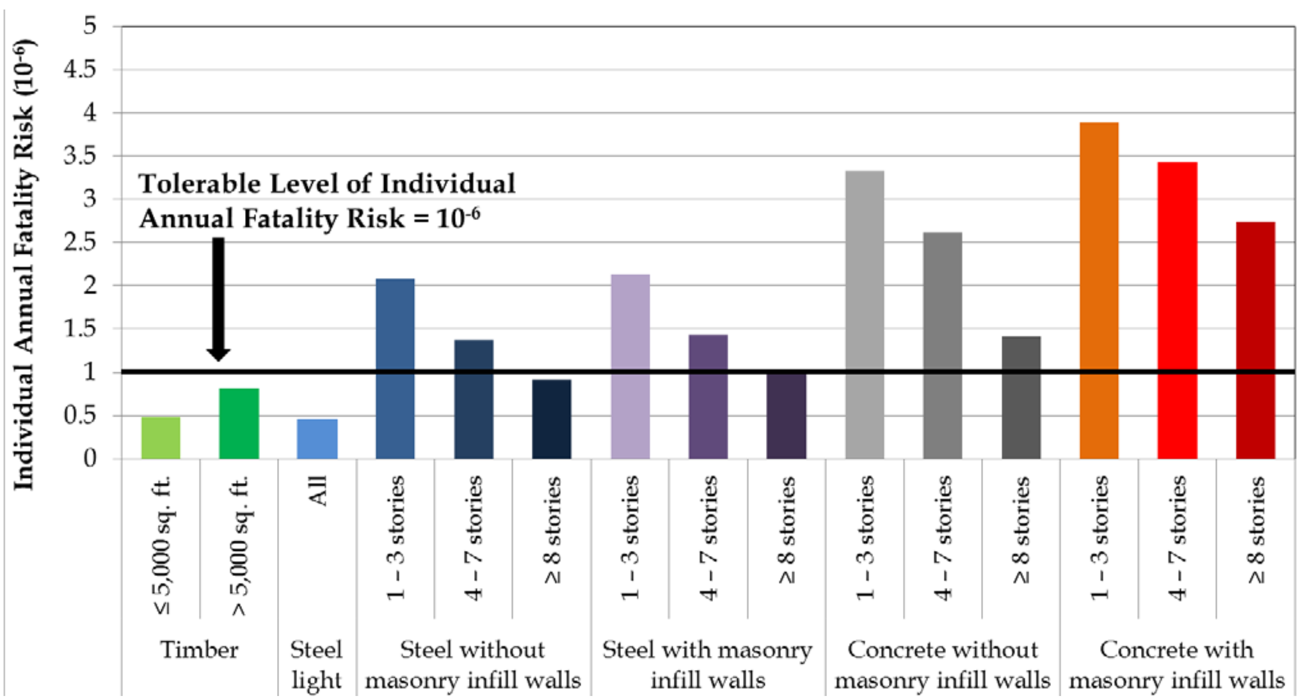

Fig. 2 – The estimated annual individual fatality risk in different Hazus categories of buildings that are designed in conformance with the collapse risk requirement in IBC-2012 and ASCE/SEI 7-10.

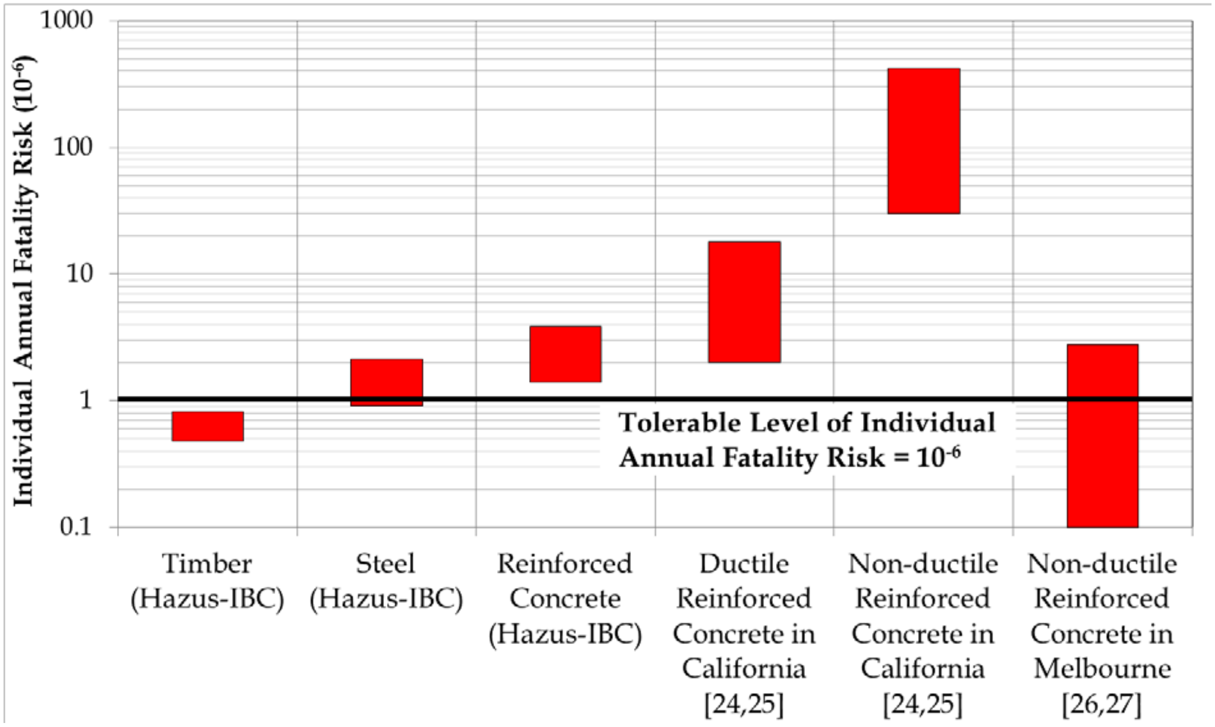

Fig. 3 – The estimated annual individual fatality risk in different broad Hazus categories of buildings that are designed in conformance with the collapse risk requirement in IBC-2012, in comparison with the estimates from the seismic performance assessment studies for California, U.S. [24,25], and Melbourne, Australia [26,27].

4. Proposed Target Collapse Risk Limits

In order to control the fatality risk in all categories of buildings to the same tolerable level (i.e. 10^{-6}), the target collapse risk limit, $P_L(C)$, for the structural design of (ordinary) buildings can be established through Eq. (2). As the conditional probability of dying due to structural "collapse", $P(D|C)$, varies between structural types and number of storeys, the target collapse risk limit, $P(C)$, also varies between different categories of structures. The results have been presented in Tsang and Wenzel [12] and are reproduced as Fig. 4. These limits can serve as a guide for setting the minimum requirements in the structural design of different categories of ordinary buildings.

$$P_L(C) = 10^{-6} \div P(D|C) \tag{2}$$

The proposed annual collapse risk limit ranges from 0.5×10^{-4} to 4.5×10^{-4}. The required risk limit for structural design could be more lenient for timber and steel light frame construction, as the collapse of these light-weight structures poses a lower risk of killing the occupants. However, more stringent requirement should be specified for heavier buildings, in particular concrete structures.

The proposed design risk limits for different categories of ordinary buildings can be compared with the requirement that has been stipulated in IBC-2012. The latter requires that all ordinary buildings have to be designed (and properly constructed) such that the annual risk of total or partial collapse is less than 2×10^{-4}. Based on the findings of this study, such a requirement is adequate for controlling fatality risks in light-weight steel and timber construction, as well as high-rise ($\geq$ 8 stories) steel structures. However, the fatality risk in low-to-medium-rise steel buildings is about a double, whilst the fatality risk in concrete buildings could be up to four times higher than the requirements deduced in this study.

It is noted that a lower design requirement is sometimes stipulated for low-rise residential houses in current codes of practice. This could indeed lead to a smaller safety margin for timber and steel light frame structures, and further increase the fatality risk in low-rise steel and concrete buildings.

Ideally, different risk limit requirements could be stipulated for different categories of buildings in the design standard, in order to achieve a uniform level of fatality risk. However, it may be viewed as overly meticulous given the generally high level of uncertainties involved in structural design and construction practice. Nevertheless, it is clear from the results (see Fig. 4) that the requirement in the current design standard is insufficient in terms of mortality control. If a uniform target has to be recommended, an annual collapse risk of not higher than 1×10^{-4} can be proposed based on the findings in this study.

Referring back to the aforementioned collapse risk studies [24–27], the predicted mean annual collapse probability for buildings with modern seismic design in California, U.S., varies from 0.7×10^{-4} to 7.0×10^{-4} (i.e. 0.35% to 3.4% in 50 years), which is generally higher than the target level of 2×10^{-4} in IBC-2012 (i.e. 1% in 50 years) or 1×10^{-4} proposed in this study (i.e. 0.5% in 50 years). For buildings that were designed before the mid-1970s without modern seismic design consideration, the predicted mean annual collapse probability varies from 16×10^{-4} to 223×10^{-4} (i.e. 8% to 67% in 50 years). Such values for Melbourne, Australia, are generally below the target limit of 2×10^{-4} stipulated in IBC-2012.

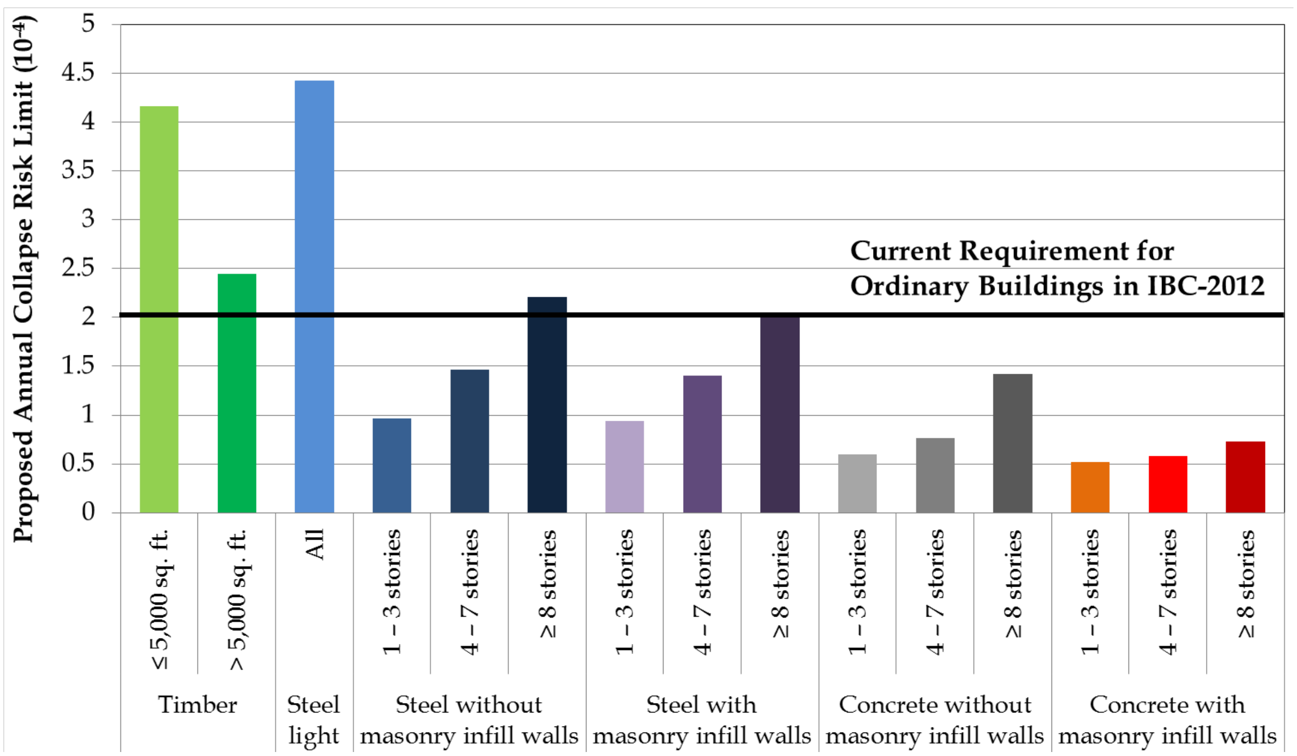

Fig. 4 – The proposed annual collapse risk limit for structural design of different categories of ordinary buildings [12], in comparison with the requirement in IBC-2012. The majority of building categories require a more stringent (i.e. lower) risk limit for adequate mortality control.

5. Where Would Annual Limits Be Applicable?

A set of annual collapse risk limits with an evaluation of the fatality rates could be universally applicable to the design of new buildings. However, for assessing existing structures, two main factors need to be considered as different countries are at different stages of earthquake protection.

5.1 Building age and seismic code implementation

Not all countries have seismic codes, whilst documentation does not exist on a global scale to see which countries have seismic codes and whether they are part of law, enforced or ignored. Given the disparity across a country of where seismic code is implemented, the application of those limits may require further regulatory analysis based on a country-wide study. In order to determine the factors by which damage level is changing, a significant review and analysis has been undertaken [28] to create a harmonized up-to-date list of locations where seismic codes have been considered.

There were several early initiatives which attempted to undertake this by looking at only some of the countries worldwide with seismic codes, including the “World List” initiative by the International Association for Earthquake Engineering (IAEE) which includes details as to some seismic codes in various countries [29–31]. In addition, there have been some countries which have some form of seismic codes as listed in “The Practice of Earthquake Hazard Assessment” (covering 92 countries) [32]. The “Seismic Code Evaluation” work in Central America as well as South America has been collected and implemented in the database [33]. 166 nations out of 244 nations have some form of seismic code, as of 2013 (see Fig. 5), but they are usually not implemented for all types of buildings (see Fig. 6), given the large number of non-engineered building types worldwide and over 510 versions of codes and updates that have occurred formally worldwide since 1900 [34].

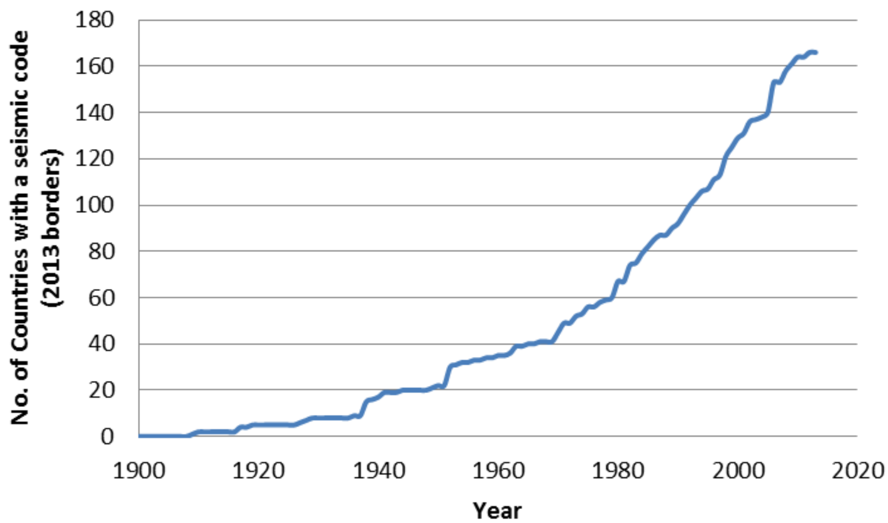

Fig. 5 – The number of countries with a seismic resistant code/zonation, as of 2013 [34].

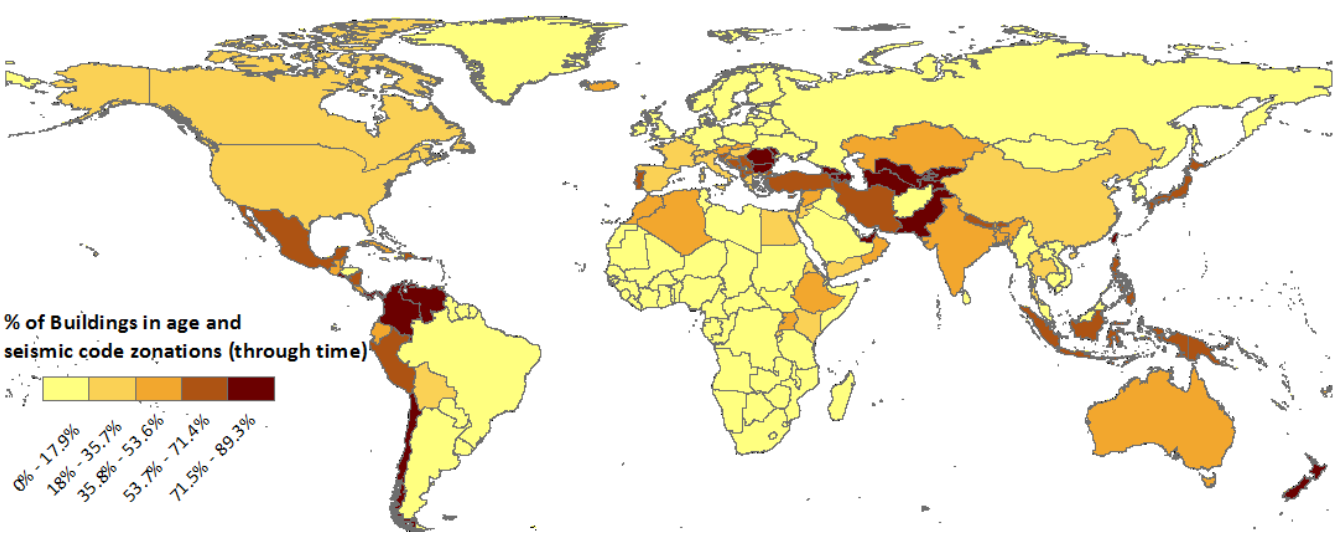

Fig. 6 – The percentage of buildings in each country that should have been built under a seismic code [34].

5.2 Structural typology vs. fatality rate

The calculation of fatality rates vs. structural typology has inherent difficulties, with a lack of data globally on earthquake fatality rates associated with various structural building types.

A review of fatality estimation models globally [35] shows over 200 casualty estimation methodologies. The uncertainty within these models is very large; however, when moving towards a structural based methodology for application of annual rate of fatalities, some key methodologies exist, with quantification of structural collapse vs. fatality rate. The semi-empirical model of PAGER [36] combines data from WHE-PAGER to produce fragility functions for the 89 building typologies. This is the best model for use for base vulnerability as it uses expert opinion from various nations. Tiedemann [37] provides a useful view of a very coarse death rate law depending upon MMI and building type. Coburn et al. [38] have a percentage of people trapped as a typology for masonry, i.e. intensity VII (5%), VIII (30%), IX (60%), X (70%), and concrete buildings (50-75%), depending on the collapse mechanism. This translates to death rates for masonry of around VII (3.2%), VIII (19%), IX (39%), X (45%). For concrete, it depends on collapse mechanism and frequency content, with near-field short period ground motion giving a death rate of 57%, and 41% for long period distant motion.

Survival space is a key element to earthquake casualties, and has been studied over a number of years by authors such as Okada and Takai [39], Hengjian et al. [40] for Japan, and more recently global collapse rates have been calculated by So and Spence [41] using superclasses and investigating the relationship of occupancy and lethality. The amount of injury distribution also differs, with a greater number of deaths coming from concrete buildings as compared to masonry. The intensity with which the collapse occurs causes a difference often in terms of the collapse volume, but also the speed with which occupants can vacate the premises due to sensing the earthquake; hence, the fatality rate changes with increasing intensity due to this correlation.

The difficulty and variation in the definition of collapse (e.g. softening, complete catastrophic collapse, ultimate limit) often lead to great uncertainties in the application of a fatality rate in buildings [42]; thus, the uncertainties need to be taken into any residual risk analysis.

6. Aggregated Risk in Society

One-in-a-million seems to be a very small value as an individual risk of death, or the collapse probability of 1% in 50 years for a single building, which the property owner or the tenant has to bear throughout the whole design life, is considered very low. Such "low" level of individual risk is synonymous with "no" risk for most people. However, the aggregated risk for the whole society could become significant.

The 1% collapse risk in 50 years may still be tolerable to a society when such damaging earthquake strikes a remote area, but it is clearly not manageable if it strikes a metropolitan city like Melbourne (the capital city in the state of Victoria, Australia). As a simple illustration, if it is assumed that all building structures were designed conforming to modern seismic code, or have been retrofitted to the level that is comparable to the code requirements as for new buildings, then the annual fatality risk is the same for every individual, i.e. 10^{-6}. With a total population of 4.4 million in Melbourne, the Potential Loss of Life (*PLL*) due to structural failures in earthquakes would be 4.4 each year or 44 every decade. Furthermore, a higher amount of *PLL* could be anticipated if seismic action has not been taken into account in the design process.

In fact, the tolerable level of risk has been found to decrease with an increasing number of exposed persons [10]. In other words, the tolerable level should be lower in a densely populated region, as the number of people being affected at the same time is enormous, and there might be a lack of emergency response capacity in the society for coping with the potential disaster. UNISDR [5] defines it as an "intensive risk", as it is "associated with the exposure of large concentrations of people and economic activities to intense hazard events, which can lead to potentially catastrophic disaster impacts involving high mortality and asset loss". In principle, a lower tolerable level of risk, i.e. $P(D) < 10^{-6}$, should be adopted for such metropolitan areas.

The return period of the associated risk also plays a role in the fatality rate that can be applied. An average annual probability of the risk can consist of long return period events with high numbers of fatalities and frequent small events with very few losses. Thus, a risk acceptability curve or F-N curve (return period vs. number of fatalities) and risk aversion need to be taken into account in addition to the annualized risk. One may accept the risk of a 10,000-year event killing 100,000 people in a city, as the probability of it happening in the lifetime of the occupants is very low; however, the same annualized risk may be unacceptable when looking at 100 people being killed in 10 years.

7. Conclusions and Closing Remarks

Residual risk is inevitable in the face of earthquake hazards and the associated uncertainties. An ideal building code should indicate the target levels of collapse and fatality risk since it is a legal document that sets forth structural design requirements for protecting life and property. However, very few stakeholders would query whether the requirements stipulated in a code are adequately safe or not.

An individual annual fatality risk of 10^{-6} due to structural failure in earthquakes has been adopted as the maximum tolerable risk level. This has then been used for deducing the required collapse risk limits for the design of different types of building structures. The results have been compared with the target risk limit that is stipulated in the 2012 edition of the International Building Code (IBC), which is found to be insufficient from the perspective of mortality control. Based on the dataset adopted in this study, a maximum value of 10^{-4} is recommended as the target annual collapse risk for an ordinary building.

In fact, a higher safety standard can be achieved by better understanding of the weakest links of structures, encouraging the use of best practices, as well as more stringent monitoring and quality control during construction. These measures will undoubtedly enhance structural robustness, and reduce gross errors and the chance of premature or unexpected failure, which can fundamentally reduce the uncertainties and risk levels.

A few different factors need to be considered for assessing existing buildings, however, when looking at the uncertainty associated with collapse and fatality rates, including building age and quality, the location of the building, the structural typology and its fatality rate and the return period associated with the risk. In addition, the acceptability of annualized fatality risk differs between countries, and the risk aversion of high loss events needs to be integrated into potential code safety level changes.

Thus, determination of an appropriate safety level is not a purely scientific issue. The acceptability of risk can also be very different throughout the world. As the consequences of structural failure concern life safety and economic losses, the responsibility of decision-making should be shared amongst relevant government authorities, property developers, code writers, insurance companies, engineers and builders, as well as the general public, in order to minimize the residual risk to a tolerable level.

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