Derivation of Globally Applicable Casualty Rates for use in Earthquake Loss Estimation Models

E.K.M. So
Department of Architecture, University of Cambridge, UK

A. Pomonis
Cambridge Architectural Research Ltd., UK

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SUMMARY

Under the auspices of USGS's PAGER, empirical fatality data related to the predominant structural classes, the population, the time of occurrence and to well-documented collapses of buildings from 25 significant earthquakes since 1970 have been examined. The aim of this research is to supplement current earthquake loss estimation with fatality rates (% of occupants killed) for use in models which are based on empirical information on deaths from earthquakes. This paper specifically explores the lethality potential of occupants in collapsed masonry structures as witnessed in recent events. Whilst earthquake casualty modelling has admittedly suffered from a lack of post-earthquake collection of data and rigour in assessing these data, earthquakes such as 2001 Bhuj (India) and 2009 L'Aquila (Italy) have brought to light some important findings. In the development of globally applicable fatality rates, we demonstrate the fundamental importance of empirical data in improving earthquake casualty estimation models.

Keywords: earthquake, casualties, loss, estimation, model

1. INTRODUCTION

Tremendous progress has been made in earthquake science and engineering in the past decades. However, fatalities and injuries due to earthquakes continue to dominate recent headlines, and the mitigation of these losses remains a challenge. In order to provide appropriate response and mitigation plans for the future, realistic estimates of risk to life from earthquakes anywhere in the world are necessary. In spite of this, there are currently no globally applicable casualty rates for use in earthquake loss estimation models, although there are some regional casualty rate models (e.g., HAZUS (NIBS-FEMA, 2006) predicts loss of life from earthquakes in the U.S.).

The U.S. Geological Survey's Prompt Assessment for Global Earthquakes Response (PAGER) system provides an alert for users to gauge the number of deaths due to ground shaking following an earthquake. The current operational system uses an empirical approach developed from observations of fatalities in past events (Jaiswal et al., 2009a). However, population and buildings are ever changing and for some countries, due to a lack of earthquakes in the past 40 years, PAGER has relied on neighbouring countries to estimate likely lethality. In order to provide realistic estimates to mobilise disaster relief, there is a need to replace this methodology with an approach that uses our knowledge acquired from past events on the built environment to capture fundamental elements that dominate risk to life, as the majority of deaths are caused by building collapses (Marano et al., 2009).

Concurrently, PAGER has a semi-empirical approach (Jaiswal and Wald, 2010) where estimates of fatalities are made using local building inventory, their vulnerability to ground shaking and subsequent collapses of buildings.

This paper sets out a process for estimating fatalities in collapsed buildings during ground shaking in an earthquake. Empirical data related to deaths from building collapse from earthquakes in the past 40 years have been thoroughly examined. Through detailed investigations of the volume reductions within collapsed buildings, important clues related to the lethality potential of different failure mechanisms of global modern and older construction types were found. The aim is to supplement PAGER with fatality rates (% of occupants killed) for different types of buildings and collapse mechanisms. In particular, the present study focuses on the lethality potential of collapsed masonry structures. The gathered evidence forms the basis of the derivation of a set of fatality rates for masonry buildings. The resolutions and quality of available data, the important assumptions made in the derivation of fatality rates are also discussed in this paper.

2. STRATEGY FOR DERIVING FATALITY RATES

2.1. Data and Definitions

One of the main issues of casualty modelling has been a lack of good empirical data from past events from which to derive realistic fatality rates. Therefore, the main element of this research was a concerted effort to obtain and assemble global casualty information from recent earthquakes. The levels of resolution of data found were as follows:

- 1st level: global data on the overall fatality count per event, some with secondary information on the causes of the deaths (building collapse, slope failure, tsunami, fire following). The information for this comes directly from USGS' PAGER-CAT (Allen et al., 2009).
- 2nd level: fatality numbers over population at particular geographical units that contain several population centres (i.e. county, district).
- 3rd level: damaged building types per city/village/neighbourhood and number of people killed overall in each building type (often paired with an approximation of population per building) that can be linked to the level of ground shaking intensity and exclude life losses due to secondary hazards. Such data are rare. Although for some events we know that almost all the deaths were related to a particular type of structure, e.g., adobe in Bam 2003; rubble stone in Maharashtra 1993; RC frame (pre-1984) in Athens 1999, and so on.
- 4th level: actual building-by-building survey of structure types and damage levels corresponding with the number killed (and injured) amongst the known number of occupants at the time of an event. There were only three surveys used in this study (So, 2009).

Globally, most fatalities are caused by building collapse. This is supported by field observations and other studies (Coburn and Spence 2002; Marano et al., 2009). Fatality rate as defined in PAGER is the percentage of occupants killed in a building unit. It should be noted that the PAGER methodology readily acknowledges that fatalities from landslides, tsunamis and fire following could also be the main or an important cause of fatalities in an event.

Since the PAGER semi-empirical model is used as a basis for this study, only building collapses are considered and the amount of data is therefore reduced by filtering to 3rd and 4th levels. However, some inferences were made to information from levels 1 and 2, as these set the scene for earthquake fatalities and give the numbers' vital relevance and background, especially in terms of other contributory factors, like time of day.

In thoroughly reviewing earthquake casualty information from the past 40 years, the 25 events shown in Table 2.1 were evaluated in detail. It is important to note that these earthquakes account for more than 30% of global life loss due to building collapses from ground shaking since 1970.

Table 2.1. List of studies considered in the fatality assessment

	Event name	Country	Year	Month	Day	Time (local)	Mag	No. of fatalities	Dominant building type(s)
1	Karnaveh	IRAN	1970	7	30	4:52	6.8	200	Adobe mud brick
2	Ghir	IRAN	1972	4	10	5:37	7.1	5,374	Adobe mud brick
3	Guatemala	GUATEMALA	1976	2	4	3:05	7.5	22,868	Adobe mud brick
4	Friuli	ITALY	1976	5	6	21:06	6.9	989	Stone masonry
5	Tabas	IRAN	1978	9	16	19:36	7.4	20,500	Adobe mud brick
6	Irpinia	ITALY	1980	11	23	19:34	6.9	3,000+	Stone masonry with wooden diaphragms
7	Spitak	ARMENIA	1988	12	7	11:41	6.9	25,000	Precast RC frame; mid-rise stone masonry
8	Latur	INDIA	1993	9	30	3:55	6.2	9,748	Mud mortar stone masonry
9	Northridge	USA	1994	1	17	4:31	6.7	72	Northridge Meadows (3-storey timber and RC)
10	Kobe	JAPAN	1995	1	17	5:46	6.8	6,434	Old wooden housing with heavy tiled roofs
11	Neftegorsk	RUSSIA	1995	5	29	0:10	7.6	2,035	17 mid-rise RC collapses
12	Aegion	GREECE	1995	6	15	3:16	6.4	26	2 mid-rise RC MRF collapses
13	Kocaeli	TURKEY	1999	8	17	3:02	7.4	17,479+	Mid-rise RC with soft storey
14	Athens	GREECE	1999	9	7	14:56	6.0	143	low to mid-rise RC MRF with URM infill
15	Chi Chi	TAIWAN	1999	9	20	1:47	7.6	2,539	Mud brick/ High-rise RC buildings
16	Bhuj	INDIA	2001	1	26	8:46	7.6	13,830	Adobe mud brick; RC frame
17	Bam	IRAN	2003	12	26	5:26	6.6	26,796	Mud mortar adobe
18	Niigata	JAPAN	2004	10	23	17:56	6.8	48	Timber frame housing
19	Kashmir	PAKISTAN	2005	10	8	8:50	7.6	75,150	Stone (katcha)
20	Yogyakarta	INDONESIA	2006	5	27	5:54	6.3	6,234	Stone; timber frame with truss roofs
21	Pisco	PERU	2007	8	15	18:40	8.0	913	Adobe, quincha roofs
22	Wenchuan	CHINA	2008	5	12	14:28	7.9	87,476	Stone masonry. Mixed concrete
23	L'Aquila	ITALY	2009	4	6	3:32	6.3	308	Stone masonry, 1 major RC collapse
24	Chile	CHILE	2010	2	27	3:34	8.8	550	1 high-rise RC collapse; adobe
25	Canterbury	NEW ZEALAND	2011	2	22	12:54	6.3	181	Collapse of 2 mid-rise RC frame, falling debris

2.1.1 Definition of collapse

An important assumption of this loss estimation approach is that fatalities are caused by building collapses; therefore the definition of collapse is crucial. Assessing damage to a building and what constitutes a collapse is subjective and the definition is further complicated by the end users' needs. For example, an assessment carried out rapidly after an event to give an indication for temporary housing needs will yield different results to an engineering survey of a building's integrity.

The survivability of occupants in buildings primarily depends on its collapse mechanism and the internal volume loss to the structure (Okada, 1996), as well as other factors such as characteristics of the ground motion, evasive action and site conditions. These latter aspects are all very difficult to quantify but this reflects the reality of post-earthquake data collection and the added complexity of assessing casualty data.

However using data collected with loose definitions of collapse does pose problems. If the definition of complete collapse (D5) of "more than one wall collapsed or more than half of a roof dislodged or failure of structure members to allow fall of roof or slab" was used, as taken from Coburn et al. (1992), the actual volume reduction and therefore lethality potential would vary dramatically. For example, for load-bearing masonry, 'collapsed' buildings can have volumetric reduction ranges from 10% to 100% as illustrated in Figure 2.1.

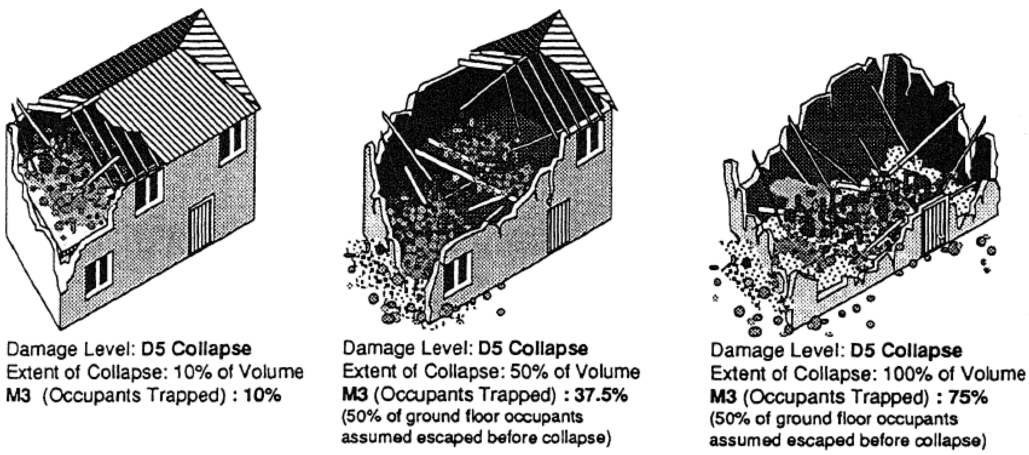

Figure 2.1. Sketches showing the differences in volumetric reduction of a single collapsed load-bearing masonry building with implications on survivability of its occupants (from Coburn et al., 1992)

Given this variation and its implications on casualties and search and rescue (SAR) requirements, an assessment of possible collapse forms of buildings is necessary and formed an important component of the study. For example after the 1995 Kobe earthquake, Okada (1996) revised damage categorisation to reflect the different failure mechanisms and associated volume reductions of collapsed wooden dwellings and its impact on the survival of occupants.

Common failure mechanisms of different building typologies collected from recent earthquakes are used to evaluate and describe the lethality potential of buildings. A study of the failure mechanisms is of significant value as victims are generally killed by:

a) crushing or suffocation under collapsed structural elements, or
b) asphyxiation by the volume of dust generated by the collapse or
c) delay in being rescued.

The amount of space (volume) available for surviving but trapped occupants in a collapsed structure and of course the speed and ability for search and rescue determine survivability. It is worth noting that an increased fatality rate due to collapse is likely when the number of collapsed structures exceeds a certain threshold, to account for limitations of search and rescue capabilities. These latter factors are much harder to quantify and therefore we concentrate on assessing the failure mechanisms to help understand the lethality potential of buildings.

Based on an evaluation of possible collapse mechanisms, the definition used in this paper for deriving fatality rates from a collapsed building is as follows:

At least 10% volume reduction from whatever cause or mechanism of failure.

The collapse mechanisms would depend on building typologies and the characteristics of the ground motions. Future developments into assessing damage states may call for separate definitions of the term "collapse", according to its lethality potential associated with the mechanism of failure. A review and proposal for a fatality-centric damage categorisation is currently being undertaken by the Global Earthquake Model, GEM (Rossetto et al., 2012).

2.2 A Review of Fatalities in Masonry Buildings

In the subsequent sections, the process for deriving a set of judgment based fatality rates for masonry buildings is presented. The building class is first described, followed by an assessment of possible failure mechanisms as witnessed in recent events. Based on an assessment of the 25 earthquakes in Table 2.1, evidence of collapses from past events and how they relate to the lethality potential are reviewed. An in-depth study of other building classes in PAGER –STR[1] using the described strategy is currently under way in collaboration with the USGS.

For the generic building class of masonry, there are three main types namely *weak*, *load bearing* and *structural masonry*. Further divisions have been added to account for the variability of masonry structures around the world, adapting for local cultural and climatic factors. Through recent field surveys and studies, it was found that these changes to the buildings' attributes play an important role in the failure mechanism and therefore the survivability of occupants. A thorough assessment of this class of structures has been made possible as observations from several recent earthquakes from Bhuj, India in 2001 to the 2009 event in L'Aquila, Italy have helped improve our understanding of fatalities in masonry buildings.

2.2.1. Weak masonry

Weak masonry consists of adobe and irregular rubble stone structures, usually set in mud or lime mortar. These houses are typically single to two storey high and house on average of 4-7 people (So, 2009) in countries of the developing world, while in Europe their occupancy is often quite low (e.g., less than 1.1 person per building in the case of Greece). The types of weak masonry have been further divided by roof type. Recent surveys in Peru and Pakistan have shown that the influences of roofing material and its weight are significant (So, 2009).

The actual constitution of the masonry and the type of roof played a part as apparent in 2003 Bam (Iran), where people not only died as a result of the weight of the falling walls and roofs but many more did not survive due to asphyxiation (Kuwata et al., 2006). This could help explain the difference between the 10% fatality rate evident in completely destroyed adobe housing in the 2007 Pisco (Peru) earthquake where the roofs consisted of lightweight matted bamboo and the 40-60% fatality rates witnessed in Iranian earthquakes of the 1970s (e.g., 1972 Ghir, 1978 Tabas earthquakes) and also the high lethality in the 1970 Ancash (Peru) event. In Peru, although in both regions adobe houses were dominant, in the Ancash earthquake much of the affected region was in the Andes Mountains and the roofs were covered with heavy tiles; while in Pisco which is by the sea and in a desert area, the typical roofing was much lighter. In the 1970 event, the coastal city of Chimbote experienced shaking of intensity VIII and most of its adobe buildings were destroyed (Berg and Husid, 1971) with the city

[1] PAGER-STR is the building taxonomy developed for use in USGS's PAGER.

losing 0.6% of its 117,500 people (Plafker et al., 1971). In Huaraz (at an altitude of 3,050m) the shaking intensity was VII-VIII but almost all the adobe houses in the southern half of the city were destroyed and the city lost 26% of its 65,300 people (Plafker et al., 1971). It is worth noting that amongst this devastation, none of the well-constructed RC buildings suffered more than moderate damage due to shaking (Berg and Husid, 1971). The photos below show the differences in roofing between weak masonry houses in Pisco and Ancash in Peru.

Figure 2.2. Single storey adobe residence with woven bamboo roof cover found in the coastal regions of southern Peru (L) and adobe houses with heavier roofs found in the Andean regions of Peru (R)

Earthquakes in China, Indonesia, India and Pakistan have been the main references for the suggested fatality rates for irregular rubble stone houses shown in Table 2.2. Once again, these are mostly residential houses of one to two storeys, made with locally found stones. These may be irregular in shape and size and can be very poorly joined with weak mortar. The percentage of occupants killed due to collapse of these structures was found to depend on the material and shape of the roofs. In China (Wenchuan, 2008), the pitched tile roofs were supported by a wooden truss. These types of structures were found to be less lethal and the fatality rate ranged from 10-15% in the casualty data as attained from the Yogyakarta earthquake (So, 2009), although still failing at low intensities. In the Wenchuan earthquake, some buildings failed completely at intensities as low as VII due to the poorly connected stone walls (Sun and Zhang, 2010).

By contrast, the Kashmir (Pakistan) event of 2005 revealed mixed material construction where stone masonry was used to support flat concrete slab roofs. As the walls failed, the heavy roofing structure proved much more lethal. The proportion of occupants killed in these types of housing from the earthquake was found to range from 18-27% (So, 2009). A summary of the suggested rates for weak masonry are shown in Table 2.2.

Table 2.2. Suggested fatality rates for collapsed weak masonry

Weak Masonry	Typical volume loss (%)	Fatality rates (% of occupants)	Reference earthquakes
Adobe light roof	<50%	10%	Pisco 2007
Adobe heavy roof	>75%	40-60%	Iran 1970-2003, Ancash, 1970
Irregular stone with wooden pitched roofs (low-rise)	40-60%	10-15%	Wenchuan 2008, Yogyakarta 2006
Irregular stone low-rise concrete slab roofs	>70%	15-30%	Kashmir 2005

2.2.2. Load bearing masonry

Load bearing masonry can be divided into two categories, representing the different lethality potential of buildings, i.e. with wooden and concrete flooring. The data supporting the derivation of these fatality rates are from Europe, where wooden floors are common (e.g., Italy) and Asia (Indonesia, Taiwan and China), where concrete floors are more typical.

Unlike weak masonry structures, load bearing masonry structures can be up to seven storeys and the height of the building does affect its lethality potential (De Bruycker, et al., 1985). Figure 2.3 shows two typical examples.

Figure 2.3. Partial collapse of load bearing brick masonry buildings (LBM) low rise in 2006 Yogyakarta, Indonesia (L) and mid-rise in 2009 L'Aquila, Italy earthquakes (EEFIT, 2009)

Although two walls have completely collapsed, the support system of the other walls and the light weight wooden truss and tiles provided life safety for the inhabitants in the left hand picture. By contrast, the load bearing walls of a three storey building in Onna, Italy, again losing two walls proved more lethal as the failed floors fell on the inhabitants on the ground floor (EEFIT, 2009). Examining collapses of low to mid-rise masonry buildings with wooden floors in Italian earthquakes revealed typical volume losses of completely damaged buildings of >30%, with a fatality rate of 9-12%.

As for masonry buildings with concrete flooring, evidence from the 2008 Wenchuan earthquake where precast hollow-core planks were used for the floor systems, were examined. Observations of the damage suggest that there were no connections between the precast panels and the supporting brick walls. Typically out-of-plane failures of top storeys due to inadequate lateral restraint were found as shown in Figure 2.4.

Figure 2.4. A 4-storey load bearing masonry failure in Hehuachi District, 2008 Wenchuan. (Zhang and Jin, 2008)

The fatality rate amongst these collapsed structures ranged from 10-18% with volume reductions greater than 50%, as inferred from damage studies carried out after the Wenchuan event.

Table 2.3. Suggested fatality rates for load bearing masonry

Load Bearing Masonry	Typical volume loss (%)	Fatality rates (% of occupants)	Reference earthquakes
European (wooden floors)	>30%	9-12%	Italy 1970s-1990s
Asia (concrete floors)	>50%	10-18%	Chi Chi 1999, Wenchuan 2008

2.2.3 Structural masonry

Structural masonry class has a very broad definition that encompasses a range of structural types including confined masonry, dual masonry wall with metal or reinforced concrete frame system with timber or concrete as well as metal deck floor diaphragms. The information used for the derivation of fatality rates has been obtained from detailed studies in Italy, taken from a mixture of load bearing and structural masonry buildings in the De Bruycker et al. (1985) study of seven villages in the Irpinia, 1980 earthquake epicentral area, as well as informed by observations in Chile, China and Haiti.

An inference has been made that the majority of load bearing masonry buildings in Italy have wooden floors. This is based on a analyses of 115,000 masonry buildings from the Italian post-earthquake damage database showing that 64% had wooden and 36% had RC floors (Rota et al., 2008).

Confined masonry

Over the last 30 years, confined masonry construction has been practiced in many regions, among others in Mediterranean Europe (Italy, Slovenia, Serbia), Latin America (Mexico, Chile, Peru, Argentina, and other countries), the Middle East (Iran), south Asia (Indonesia), and the Far East (China). In confined masonry construction, the masonry walls carry the seismic loads and the concrete is used to confine the walls.

By and large, confined masonry buildings performed very well in providing life safety in the 2010 Maule (Chile) earthquake. Most one and two-storey single-family dwellings did not experience any damage, except for a few buildings which suffered moderate damage. There were as noted by Brzev et al. (2010), two 3-storey confined masonry buildings collapses in Constitución and Santa Cruz. Most damage in these two buildings was concentrated to the ground floor, with a complete soft storey failure noted in Santa Cruz as shown in Figure 2.5. In each block there were 12 units, so at least 20 people were inside the collapsed building at the time of the earthquake. With two deaths, the fatality rate in this building was less than 10%. The building was assessed by EERI engineers concluding that the failure was attributed to poor quality of construction for both brick and concrete block masonry and the low wall density (less than 1% per floor); though out of the 28 identical 3-storey confined masonry buildings in the complex, only one collapsed (Yadlin, 2011).

Figure 2.5. Collapse of a 3-storey confined masonry building in Santa Cruz (2010 Maule, Chile) earthquake

By contrast, confined masonry buildings which were widespread in Port-au-Prince, Haiti did not conform to code specifications and did not perform well in the January 12, 2010 earthquake.

Tragically as noted by the EEFIT team, the Haitian version had the outward appearance of confined masonry but had been built without the seismic detailing to provide confinement of the masonry walls, resulting in thousands of catastrophic failures (EEFIT, 2010). The confined masonry construction witnessed in Haiti, used in some cases for multi-storey buildings performed no better than its weaker unreinforced masonry counterpart.

In terms of assessing the lethality potential of collapsed confined masonry buildings, as demonstrated in comparing the 2010 Haiti and Chile earthquakes, realising the quality of construction is vital.

Figure 2.6. Typical failure mechanism of three-storey confined masonry buildings in Port-au-Prince; and widespread poor "confinement", witnessed after the 2010 Haiti earthquake

Table 2.4. Suggested fatality rates for structural masonry

	Typical volume loss (%)	Fatality rates (% of occupants)	Reference earthquakes
Structural masonry (low-rise)	-	6-8%	Italy 1970-1990s
Structural masonry (4-7 floors)	-	13-16%	Italy 1970-1990s
Confined masonry (to code)	20%	2%	Chile 2011
Low quality confined masonry	>60%	30%	Haiti 2010

4. LIMITATIONS AND POTENTIAL FOR DEVELOPMENT IN PAGER

Although every effort was made in collecting detailed fatality information from past events in the presented study, it was found that in most cases, the data were scarce and incomplete for allowing the derivation of fatality rates with high confidence. The hope is that with the advent of GEM from hereon in, a more systematic effort will be made to collect standardised casualty information to be used in future loss estimation models.

There already exists a set of fatality rates for 12 buildings types in the PAGER semi-empirical model (Spence, 2007) and together with the HAZUS (NIBS-FEMA, 2006) casualty rates for the US; these parameters provide fatality estimations for this approach. The LessLoss rates (Spence, 2007) were collated based on observations and expert judgment from past studies. The work described in this paper forms part of a USGS open file report and supersedes the LessLoss effort in providing relevant discussions and the underlying empirical data to support the judgments on lethality potentials of collapsed buildings. The proposed fatality rates will be tested in the background PAGER semi-empirical model with past and future events before implementation, although a concerted effort on improving the collapse probabilities of buildings in the model is also necessary. Further work will include assessments of more global building types but also examination of volumetric reduction of collapses to inform building types where little empirical data are available.

The paper presents a snapshot of the work being done at the University of Cambridge, Cambridge

Architectural Research and at USGS PAGER to improve the underlying input to casualty loss estimation models. In the development of globally applicable fatality rates, we demonstrate the necessity for empirical data in improving global earthquake casualty estimation models.

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