# ESTIMATING SHAKING-INDUCED CASUALTIES AND BUILDING DAMAGE FOR GLOBAL EARTHQUAKE EVENTS

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# ABSTRACT

Recent earthquakes such as the Kashmir earthquake on 8th October, 2005 and the Java earthquake of 27th May 2006 have highlighted the importance of estimating casualty as both these events resulted in surprisingly high death tolls, casualties and survivors made homeless. In the Mw = 7.9 Kashmir earthquake in Pakistan, over 70,000 people perished with over 200,000 reported injuries and over 2 million homeless. Although a much smaller Mw = 6.5 earthquake by comparison, the event in Yogyakarta resulted in over 6,000 deaths with a further 40,000 people with serious or moderate injuries and over 1.5 million people were left homeless. The team at Cambridge Architectural Research have in the past year designed and carried out surveys in both these areas and these questionnaires have been aimed at answering the questions of why, where and how injuries were caused in these events. In total, over 1000 questionnaires were completed which represents over 4500 surviving individuals from these events.

These interviews have provided an important insight into a survivor's history and how different aspects of a natural hazard and environment affect the eventual rescue, treatment and resulting injury of a survivor. But they now need to be incorporated into usable and accessible tools for casualty estimation. One of the goals set out in the national priorities set out by USGS is to "develop new products and procedures allowing USGS to deliver rapid and/ or more accurate post-earthquake information for emergency response purposes. The desired focus is on global earthquake shaking-induced casualty and losses for events, as well as impacts from secondary effect (including landslide, liquefaction, and likelihood of surface rupture potential)." There is thus clear synergy between what is the aim of the USGS Earthquake Hazards Program and the data and understanding recently acquired by the Cambridge Research team.

The objective of this project is to contribute to ongoing global and US efforts to develop a way to make an estimate of probable earthquake casualty rates very rapidly after an earthquake has taken place similar to that used in USGS's PAGER (Prompt Assessment of Global Earthquakes for Response). A purely empirical approach to this task is to correlate earthquake casualties directly with ground shaking intensity and population, but this involves making gross assumptions, and eliminates many of the explanatory variables. A semi-empirical approach would estimate damage rates for different classes of buildings present in the local building stock, and then relate casualty rates (death and injury) to the damage rates of each class of buildings. Using this approach makes it possible to take account of the effect of the very different types of buildings (by climatic zone, urban/rural location, culture, income level etc), and their mix, and also to factor in local characteristics of search and rescue and post-rescue treatment capability.

The project was split into 3 phases: Phase 1 concentrated on data assembly and development of ground motion estimates. The team concentrated on case studies for which Shakemaps had already been prepared e.g Kashmir and Kocaeli. This phase began with a definition of the scope of the project based on available

ground-motion mapping. The 2$^{nd}$ phase is the data analysis stage where the assembled data was analyzed by event and also across events to test the relationships of casualty distributions (deaths and other classes of injury) to the main explanatory variables of building type, building damage level, earthquake intensity etc where parallels would be drawn for each country/ region. The final phase, phase 3, concentrated on the development of a prototype global casualty estimation model. The resulting casualty parameters were tested against the overall casualty data from several historical earthquakes.

The findings of this project will be discussed and disseminated to Federal and international agencies and aims to improve the accuracy of their current assessment and develop real-time systems to estimate damage and human impact immediately following global earthquakes.

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# 1 INTRODUCTION

## 1.1 Project Objectives

The objective of this project is to contribute to ongoing global and US efforts to develop a way to make an estimate of probable earthquake casualty rates very rapidly after an earthquake has taken place similar to USGS's PAGER programme (Prompt Assessment of Global Earthquakes for Response). There are three common approaches to estimating casualties from earthquakes. The first is purely empirical approach and consist mainly of simple correlations of the exposed population to earthquake casualties and estimated ground shaking intensity. However this involves making gross assumptions, and eliminates many of the explanatory variables and cannot satisfactorily take into account casualties due to secondary hazards. A semi-empirical approach would estimate damage rates for different classes of buildings present in the local building stock, and then relate casualty rates (death and injury) to the damage rates of each class of buildings. Using this approach makes it possible to take account of the effect of the very different types of buildings (by climatic zone, urban/rural location, culture, income level etc), and their mix, and also to factor in local characteristics of search and rescue and post-rescue treatment capability. The third uses purely analytical methods to predict behaviour of buildings in earthquakes and therefore the effects on people inside these structures. This method has its limitations mainly in that it does not address satisfactorily the behaviour of the numerous non-engineered buildings in earthquake-prone parts of the world where the impacts on humans are greatest, but also it cannot take into account the huge variety of existing building types around the world where in some cases so-called engineered structures have been seen to perform much worse than expected (e.g. 1988 Armenia, 1995 Neftegorsk, 1999 Izmit, 2003 Boumerdes etc.). In light of these reasons, the authors have chosen in this project to concentrate on examining the empirical and semi-empirical methods of building damage and casualty estimation for global earthquake events. The aim is to derive a method where a broad brush death estimate using basic data can be obtained but also improved on if and when more crucial geographical, cultural and correction factors affecting casualties in the region are available.

The project has been split into three phases. The first phase concentrates on data assembly and development of ground motion estimates. The next chapter concentrates on case studies for which Shakemaps have already been prepared by the USGS. This phase began with a definition of the scope of the project based on available ground-motion mapping. The second phase is the data analysis stage where the assembled data would be analyzed by event and also across events to test the relationships of casualty distributions (deaths and other classes of injury) to the main explanatory variables of building type, building damage level, earthquake intensity etc where parallels would be drawn for each country or region. The final phase, phase three concentrates on the development of a prototype global casualty estimation model. The resulting casualty parameters are tested against the overall casualty data obtained from several historical earthquakes.

The work carried out during the project period is detailed in this report including conclusions and recommendations for further work.

As an introduction to the subject, the next section examines the current state of earthquake casualty estimation.

### 1.2 Current state of the assessment of casualties in earthquake loss estimation

Earthquake loss estimation programs and models are commonly used within civil protection groups, emergency planning agencies and the insurance industries for different reasons. The first two groups use loss estimation models to predict likely losses, in terms of buildings and infrastructure and human losses to guide mitigation policies but also for emergency management to allocate resources when an event occurs. Insurance industries use loss estimation models to project insurance payouts for their building portfolios should an event occur; this helps determine the pricing of insurance. In all of these models, a casualty module is needed to predict the number of fatalities and injuries that may occur.

The quantity and quality of information and progress in casualty modelling varies between earthquake-prone countries. In Japan and USA, past national events resulting in casualties have been used to form empirical relationships and models to postulate casualty numbers. In areas where there is little historic data, for example in Portugal, casualty models from other regions of the world have been used and modified to their building environment. The following key findings were drawn from a review of the availability and the quality of casualty information in these models as well as data from recent events including other disciplines (Noji, 1997; Aroni, 1988; Petal, 2004; So, 2009):

1. Collection of casualty data is rare and often uncoordinated.
2. Where efforts have been made, these have been examined from the viewpoint of a single discipline; therefore the complete experience of survivors and what contributed to their survival have not been recorded. In the same way, deaths have not been truly explored, although increasingly in recent decades some events have been studied more thoroughly than in the past.
3. There has been no standardised method of recording casualty data and there is currently no global casualty repository storing available data.
4. Models in the past have been based on earthquakes from the 1970s and 1980s and are mainly from Japan, USA and Turkey. Due to a lack of data and available models, published casualty rates related to building types have been at times applied in an ad-hoc fashion to other areas of the world than intended.
5. Where there have been investigations into casualties after earthquakes these have shown that there are more factors than those accounted for in the models affecting the number of casualties in an

earthquake.

All of these findings prompted a further examination in this study into the causes of deaths and injuries. This study has placed a focus on emergency management, because not only is accounting for casualty numbers important but also an understanding of where, what and how casualties are caused is key to their operations.

Before embarking on data assembly and analysing building damage and casualty data from past earthquakes, it is important to first establish what the main causes of building damage and deaths and injuries are. This is essential to improve casualty estimation modelling in earthquakes. This may seem obvious but one of the problems discovered whilst researching the topic is that a loss modeller's perception of what causes injuries and deaths is often skewed by numbers generated for other countries with different building stock, climate and cultural influences. Secondly, as cities develop in more hazardous areas and building stocks change and evolve, it is important to see what effect these changes have on current thinking. In short, are we at higher or lower risk now with modern building stock and what factors affect mortality and morbidity in reality?

The next section draws on conclusions from a thorough review of available models and literature carried out for this project and presents the key established hypotheses in casualty estimation. The chapter then continues to examine 11 recent events in detail to draw out information on building damage and casualties and to see if these events have confirmed or challenged these theories. The chapter concludes with a summary of the lessons learnt from recent events and identifies the gaps that need to be filled in this research area in the future.

### 1.2.1 Exploring the key hypotheses of casualty estimation

The following sets of hypotheses have been formed from current literature and models and are used here to provide a basis for evaluating casualty information collected from recent events. This set of hypotheses is historically held though some have been disproved in the past, and they are not all believed to be true. They have been developed to test and assure that the data collected in the database developed in this project is sufficiently complete to address the types of questions that are of potential importance to emergency planning and relief. This alignment of data collection to needs is absolutely crucial. From previous estimation models, assumptions have been made on what contributes towards the casualty rates, but there are no explanations of:

1. What the key factors contributing to deaths are or,
2. How the types and severity of injuries vary with building damage and buildings types?

One other reason for listing out the hypotheses below is to challenge the use of 'regionalised' loss models where casualty rates for one region is used in another without really considering the factors determining the estimates. Can one really apply what is commercially available for a specific building stock and seismicity to another? Do the assumptions on causes of deaths and injuries hold true in all cases? If not, why not?

To explore these questions, we first examine the common hypotheses concerning deaths.

***Hypotheses concerning Deaths***

*For those inside buildings at the time of the earthquake:*

1. The primary cause of death is injury (trauma) directly caused by building collapse. As suggested in the Cambridge Model (Coburn and Spence, 2002)
   - Some survive but are trapped by the collapse
   - Those in buildings which do not collapse have a much lower risk of death
   - For a collapsed building, the proportion of occupants at the time of collapse who are either killed or trapped depends on the form of construction
2. Research (Macintyre et al., 2005) demonstrates that structural collapses from earthquakes generate trapped victims who infrequently may survive for 5–6 days. Under special, ideal conditions (with food and water), survival may extend to two weeks.
3. The rescue rate of those trapped depends on the effectiveness of search and rescue (SAR). SAR effectiveness depends on:
   - The proportion of buildings that collapse
   - Availability of organised SAR to supplement local community capability
   - Distance travelled by rescue teams
   - Transportation disruption
4. Death rates are higher for the most vulnerable: the aged and children.

*For those outside buildings:*

5. Deaths are rare.

***Hypotheses concerning Injuries***

In terms of hypotheses concerning injuries, these can be summarised as follows:

*For those in buildings:*

6. All or most severe injuries are caused by structural collapses.
7. Some injuries are caused by failure of non-structural elements or contents: these are mostly in buildings which do not collapse.
8. Where a building does not collapse, injury levels are lower if people take evasive action. People do take these evasive actions when:
   - They are awake
   - They are adults, but not elderly

- They have had some recent earthquake experience

9. Moderate injuries occur from both structural collapse and from non-structural hazards
10. Injury rates do not vary across building types for lesser damage states as these are mainly due to non-structural components as assumed in HAZUS.
11. Light injuries mostly occur from non-structural hazards.

*For those outside buildings:*

12. Injuries are mostly light or moderate, and occur from falling debris and from falls

The statements above are considered common hypotheses in published literature but there are other questions one should try and answer when examining information from recent events.

For example, is the time of day the only factor which determines the distribution of people inside buildings? Are the time brackets[1] proposed by HAZUS generally useful? In addition, could a maximum death rate associated with the complete collapse of a building realistically be as low as 10% (as suggested in HAZUS Table 13.7)? Could using specific casualty rates for the United States in other countries be justified based on findings from recent events? What other factors determine casualty rates in buildings? Are there other contributing factors emerging from recent events that we should include and consider when estimating casualties in the future? When assessing what should be included in casualty estimation models, examining how different factors have contributed to the final casualty number in real earthquakes and what other causes are significant is an important process.

### 1.3 Lessons Learnt from Recent Events

In the past 10 years, there have been significant events which have informed us of the ways earthquake motions have affected their local inhabitants. Each event has its own characteristics in terms of epicentral location, magnitude, focal depth, source mechanism, severity and direction of ground motion, time of day, day of the week, season, proximity to centres of population, proportions of vulnerable building stock and human behaviour characteristics. Although there are many variables changing the scale and therefore impact on humans, it is nonetheless essential to learn from these earthquakes in order to understand the causal pathways of injuries and deaths and the degree in which each of the parameters aforementioned affect the final casualty toll.

A table from the Mallet Milne lecture 2007 (Spence, 2007) has been adapted and shown below which summarises main causes of deaths, types of injuries, collapsed building types and significant secondary hazards for the deadliest earthquakes since 1960.

[1] 2am- night time scenario; 2pm- day time scenario; 5pm commute (FEMA, 1999)

**Table 1.1** Table showing main causes of deaths for the 10 deadliest earthquakes of the past 50 years (adapted from Spence, 2007)

| Event | Date | Fatalities (injuries)* | Cause of Deaths | Injury Types | Collapse Building Types | Secondary Hazards |
|---|---|---|---|---|---|---|
| Ancash | 31/05/1970 | 66,794 (143,331) | Vulnerable Housing, Avalanche turning into mudslide | | Adobe | Flooding, Avalanche |
| Guatemala | 04/02/1976 | 22,778 (76,504) | Vulnerable Housing | | Adobe | |
| Tangshan | 28/07/1976 | 242,800 (7,086) | Vulnerable Housing | | 78% of industrial buildings, 93% of residential buildings | City lies on unstable alluvial soil |
| Armenia | 07/12/1988 | 25,000 (20,000) | Structural collapse of 9 storey buildings- 40 times more likely to be killed | 24.9% minor trauma, 20.3% minor fractures, 12.2% closed head injuries | Failure of precast concrete frames | |
| Manjil | 21/06/1990 | 45,000 (60,000) | Vulnerable housing | | Collapse of traditional heavy masonry dwellings | landslides |
| Kocaeli | 17/08/1999 | 17,439 (43,953) | 66.6% structural, 26% non-structural | 36% suffered injuries to the leg, | | |

| Event | Date | Fatalities (injuries)* | Cause of Deaths | Injury Types | Collapse Building Types | Secondary Hazards |
|---|---|---|---|---|---|---|
| | | | | knee, feet and toes | | |
| Bhuj | 26/01/2001 | 13,805 (166,836) | Vulnerable housing | | Rubble masonry building collapse | |
| Bam | 26/12/2003 | 26,271 (30,000) | Vulnerable housing | | Extreme weakness of adobe housing | |
| Indian Ocean | 26/12/2004 | 227,898 | Drowning; debris | | Wave impact | Tsunami |
| Kashmir | 08/10/2005 | 87,351 (75,266) | Vulnerable housing, site effects | Lower extremities, most head/ crush injuries died | Masonry buildings | Unstable slopes |
| Wenchuan | 12/05/2008 | 69,195 (374,177) | Site effects, vulnerable housing, slope failures leading to massive landslides | | RC and URM buildings | Rock slides |

* from PDE (USGS, 2009)

As shown in Table 1.1, most high-fatality earthquakes have been in low-income, developing countries. Since 1960, of events with over 1,000 deaths, only the Kobe earthquake in 1995 (5,500 deaths), the Irpinia earthquake in 1980 (3,000 deaths) and the Friuli earthquake in 1976 (1,000 deaths) occurred in developed, industrialised countries. The total death toll from these three events only accounts for 1.2% of the 800,000 deaths which occurred during that time (USGS, 2009). The table show clearly that vulnerable housing is the main cause of mass casualties in these events but what have they taught us about the injuries? Where were these major injuries caused and how?

The section below attempts to address this by exploring 11 recent events in both developed and developing countries in the past decade in greater detail. These earthquakes have been selected as in each of these events, researchers around the world have collected additional field data to explore the causes of deaths and injuries supplementing published statistics. Some of this work has been done by public health specialists and others by engineers. Four of the most recent events are reviewed in more detail as the authors have carried field studies in each of these locations. The aim of this review is to draw important lessons and special characteristics from each of these events focusing on casualties. An in-depth examination of these earthquakes will help develop a better understanding of the factors contributing to deaths and injuries and how failures and damage to local building types have contributed to these casualties.

***Northridge Earthquake, 17th January, 1994***

On 17 January, 1994, a 6.7Mw earthquake struck the area of Los Angeles at 4:30am local time, originating from a previously unknown thrust fault which brought extensive damage to buildings, utilities and infrastructure. Extensive damage was caused to parking structures and freeway overpasses. For example, a section of the Antelope Valley Freeway collapsed onto the Golden State Freeway south of Newhall resulting in the death of 1 motorist and a 2,500 capacity car park at the California State University, which was 3km away from the epicentre at Northridge, collapsed, resulting in the serious injury of its night guard. In addition 16 people died due to the partial collapse of the Northridge Meadows 3-storey wood frame apartment building, where 27 were rescued by the Los Angeles Fire Department (8 in serious or critical condition). Though there were no other significant life threatening structural collapses, 12,000 buildings sustained substantial structural damage and property damage was over $US 40 billion according to the California Department of Finance and reached $US 57.7 billion according to a more detailed assessment (Seligson and Eguchi, 2004). It was one of the worst natural disasters in the history of the United States, on par with Hurricane Andrew in 1992 in terms of financial loss.

A total of 171 hospitalised earthquake-related injuries were identified in Los Angeles County, 33 of which were fatal and 138 required hospital admission. According to a study carried out by Peek-Asa et al (2003), injury rates were approximately equal by gender but increased significantly with increasing age.

According to her study, most of the fatalities were due to building collapse, and most of the hospital-admitted injuries were caused by falls or being hit by objects. Head and chest injuries were common among fatalities, and extremity injuries were the most common among those admitted to a hospital. Burns and injuries related to traffic accidents were also common causes of injury. The injury pyramid below is taken from the paper and shows the different levels of earthquake-related injuries.

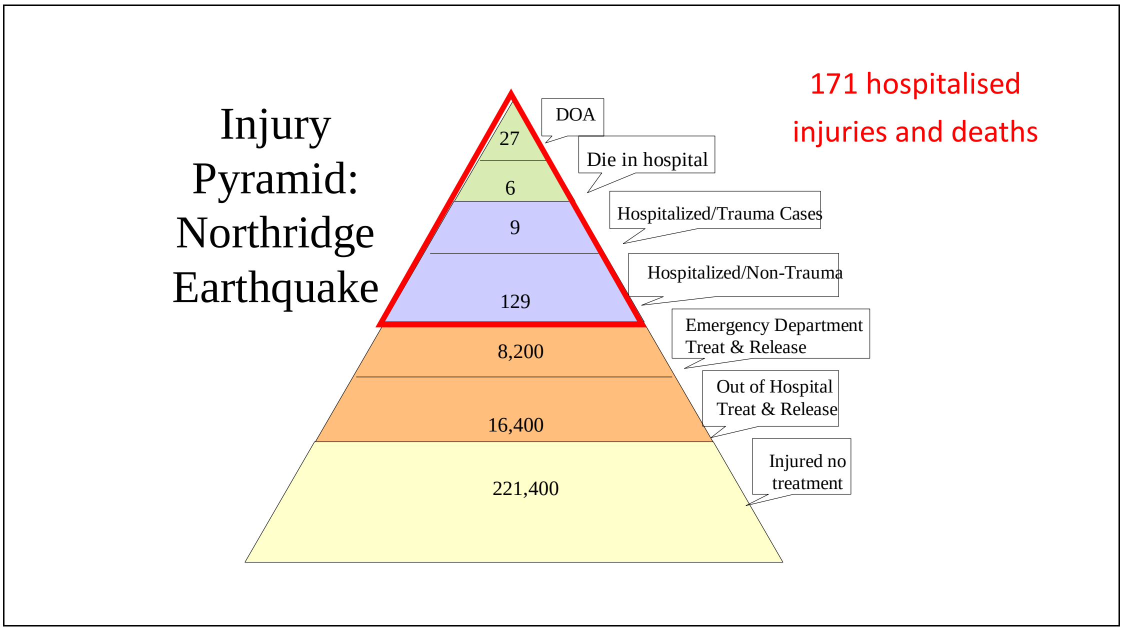



**Figure 1.1** Injury Pyramid for the Northridge Earthquake, 1994 (Peek-Asa et al., 2003)

For the Northridge earthquake, an injury pyramid has been applied as shown in Figure 1.1, which shows increasing numbers of casualties as the severity reduces. However, we also learnt that an unprecedented number of injuries classified as earthquake related were later found not to be so (Shoaf, 1999). This highlights the need to be cautious when using official statistics from earthquakes.

The Northridge earthquake was a modern day event occurring in a developed country on the northern suburbs of a major metropolitan centre. The death toll was low and as expected, the timber frame residential buildings housing the majority of the population performed well. This event has underlined the importance of time of day as if the earthquake had occurred at rush hour, the situation could be much worse as there would have been many more vehicles on the failed infrastructures.

***Kobe Earthquake, 17th January, 1995***

On 17 January 1995, at 5:46am local time, an earthquake measuring 6.9Mw struck the Hanshin district of Japan with an observed maximum seismic intensity of 7 on the JMA scale (highest intensity). The epicentre was located on Awaji Island, some 30km away from the centre of Kobe City. The earthquake caused extensive damage in the urban areas with more than 104,000 completely collapsed houses and 136,952 houses moderately damaged (Nishimura, 1997). Traditional Japanese wooden houses suffered the greatest damage. Most collapsed houses were buildings with one or two storeys, and the first floor or both floors were completely destroyed. In this region, roofs of traditional houses are especially heavy to protect against typhoons. Since the earthquake occurred early in the morning when most residents were sleeping, the majority of fatalities happened in the residential areas, particularly in densely populated ones. The earthquake resulted in 6,432 fatalities, 10,494 people with severe injuries and 29,598 people with slight injuries as reported on 27 December 2000 by the Japan Fire Defence Agency (2001). Around 90%

of direct[2] fatalities were caused due to collapsed buildings (Nishimura, 1997) and 80% were estimated to die within the first 14 minutes (Ueno et al., 1998). In general, aged people slept on the first floor of wooden houses and accounted for 45% of the deaths as failures of these timber houses occurred on the first (ground) floor. 5,502 died directly due to the earthquake (4,823 due to house collapse and (or) fall of furniture; 550 were burned; 34 died due to a landslide in Nishinomiya, 17 due to collapse of expressways and traffic accidents and 4 due to gas poisoning. An additional 930 deaths were registered as indirectly related to the earthquake in the one year period following the event and were due to accidents during reconstruction, fatal diseases occurring in the post-earthquake shelters, suicides and the decreased ability of the medical care system in the recovery period.

**Figure 1.2**: Rescue efforts after the Kobe earthquake in 1995 through narrow streets. Picture also shows the typical timber housing with the heavy tiled roofs of Japan

After the earthquake, a medical team composed of medical investigators of the Hyogo Prefecture, forensic doctors of the Medico-Legal Society of Japan and other clinical doctors investigated 3,660 certifications of fatalities, corresponding to 95% of all direct fatalities (Mizuno, 1995). The causes of fatalities were classified into five groups:

(1) traumatic asphyxia due to crushing and relatively sustained pressure on the torso,

(2) head, cervical spinal cord and organ injury, traumatic and psychological shock,

(3) burns due to fires,

(4) deterioration due to a lack of food and very cold temperatures and

(5) others.

Above all, traumatic asphyxia due to collapsed houses and falling furniture was shown to be the major cause of death, at around 75.8%.

[2] Direct fatalities are directly caused by the ground motion and are separate from those people who died from fires as a result of the earthquake.

Examining in detail the types of injuries reported by people in areas of different levels of damage, people who were in severely damaged areas reported many cut wounds, whilst those in moderately or slightly damaged area had mainly contusions. Reported number of cuts by pieces of glasses and debris were high because these injuries occurred both during shaking as well as cleaning up and rescue operations. In the lesser damaged areas, falling furniture and objects increased the number of contusion injuries. The highest lethality rates were 0.69% of the population in Higashi Nada and Nada wards, 0.58% in Nagata ward and 0.48% in Ashiya town. For Kobe city as a whole the lethality rate was 0.26% with the wards that experienced shaking of 7 in the JMA intensity scale reaching 0.35%. In terms of injury rate the highest rates were in Ashiya town and Chuo ward (3.7% of the population injured). In the event as a whole the injury to death ratio was 7.5 to 1, which is in line with the overall injury to death ratio in Japan in the period 1946-2008, but in the wards that suffered JMA7 intensity it was 3.2 to 1 and in Nagata ward that was raged by fires it was just 0.74 to 1. In the moderately damaged areas (JMA6 or less) there were 280 injuries for each of the 55 deaths that occurred there (these areas are: Kita, Nishi and Tarumi wards of Kobe, as well as Amagasaki, Kawanishi, Itami and Akashi towns). On the northern part of Awaji Island despite its epicentral location and surface fault rupture, the lethality rate was just 0.08% and there were 21 injured for every fatality. This was because on Awaji Island the timber dwellings were newer and more spacious (Murakami et al., 2004)

The earthquake in Kobe resulted in a large number of medical science studies published in the international literature addressing issues such as mortality, morbidity, ability to rescue, crush syndrome, chest and spinal injuries. There are ample data that allow the estimation of the fatality and injury distribution inside the collapsed old timber frame houses characteristic of this part of Japan as well as in the so-called tenement houses-typical Japanese town housing of small timber framed apartment buildings (Murakami, 1996 and Murakami et al., 2004).

This earthquake was a wake-up call for Japanese earthquake engineers as the degree of damage and number of casualties was unexpected. Japanese researchers have for many years led and still lead in seismic research and disaster preparedness, the scale of damage was considered an embarrassment too. The main contributor was the 2-storey traditional wooden residences but there were also deaths related to fire and injuries related to falling debris (signs and glass blow outs). The time of day was also critical since most deaths were related to the failure of old residential timber houses. The demographics of casualties might have been very different had the earthquake happened during work hours when fewer people would be home. More injuries might have been caused by falling debris but possible more deaths would be incurred on the failed infrastructure (expressway and railway bridges) and the numerous collapsed non-residential buildings.

The Kobe earthquake reminds us how even with improved technology and building designs, a substantial percentage of the city's building stock, especially in historic cities could be highly vulnerable to collapse as well as to secondary hazards such as fires. The earthquake brought about policy and code changes as well as generated funding into earthquake research (Ohta, 2007), especially in gathering data from the field in improving loss estimation models and mitigation programmes.

***Kocaeli Earthquake, 17th August, 1999***

The 17 August 1999 7.4Mw Kocaeli earthquake occurred midweek at 3:02am local time affecting an urban industrial centre, 60km from Istanbul. The earthquake's epicentre was located about 11 km southeast of the city of Izmit, on the northernmost strand of the North Anatolian fault system. The earthquake originated at a depth of 17 kilometers and caused right-lateral strike-slip movement on the fault. Field reports confirmed this type of motion on the fault, and field observations indicated that the earthquake produced at least 60 kilometers of surface rupture and right-lateral offsets as large as 2.7 meters. The earthquake caused extensive damage. According to Youd et al. (2000), an estimated 60,000 to 115,000 buildings collapsed or were damaged beyond repair, most of which were 5 to 7 storey apartment blocks built within the last 30 years. The total death toll was 17,118 and over 43,000 injuries were reported. However doubts have been raised as to whether all the deaths have been accounted for with the suggested death toll for this event being as much as 45,000 (Marza, 2004). Erdik in his analysis of the damages of Kocaeli and Duzce eaqs reports that 40% of the injured will be permanently disabled. He also reports that the number of totally collapsed buildings (pancake type) reached 3,000 to 3,500. One can easily imagine that it would be impossible to carry SAR operations in such a large number of sites. The number of live rescues by formal Turkish SAR operations was just 207 (unknown how many were saved by the 21 international SAR teams that started work more than 48 hours after the event)

Detailed damage studies (D'Ayala et al., 2003) suggest that the most recent buildings (built since 1980) performed worse; and that there was a much higher collapse rate among buildings higher than 4 storeys compared with those of 1-3 storeys. The high failure rate of these apartment buildings has been attributed mainly to a failure to follow the code both in design and construction, and a failure of code enforcement through building control (Gülkan, 2005).

**Figure 1.3**: Typical reinforced concrete 'pancake' collapse of apartment buildings in Turkey (Erdik, 1999)

In addition to ground shaking, many land instabilities took place, including a major coastal landslip near Degirmendere, and liquefaction also occurred in some urban areas, notably Adapazari; and many buildings were directly affected by the surface fault rupture (Youd et al., 2000). At the time of day that the earthquake struck however, most people were at home, and the huge death toll was caused by the collapse of a very large number of multi-storey reinforced concrete apartment buildings.

In the worst affected Yalova province based on the officially reported casualty statistics the lethality rate was 1.54%, while the morbidity was 2.76% of the population. However Petal's study of a geospatially-stratified population sample at Gölcük town found that about 3.7% of the population was killed and 3.8% were hospitalised with injuries (Petal, 2004). In Kocaeli province based on the officially reported casualty statistics the lethality rate was 0.75%, while the morbidity was 0.79% of the population. The rate of all injuries was approximately 13.5% of the population, with 47.2% in the minor category, 45.2% moderate and 7.7% severe. Uniquely, the study also looks at the causes of the injury, and finds that while 91% of severe injuries have a structural cause, only 51% of moderate and 32% of light injuries have a wholly or partly structural origin, indicating that non-structural hazards such as displaced partition walls, furniture and light-fittings can be responsible for many injuries.

Shiono and his associates (Shiono et al, 2000) proposed a macro model to estimate human fatalities based on magnitude and the distribution of housing stock. Murakami and her colleagues (JSCE, 2001) during their reconnaissance to Kocaeli used this equation to examine the human losses in the area. The resulting fatalities demonstrated that the deaths were heavily influenced by building types in the affected area. Moreover, comparing these values to the 1967 Adapazari earthquake which only caused 86 deaths demonstrates how the increase of poorly built reinforced concrete frame construction in the 32 years in between had contributed to the large 17,000 death toll. In 1967, the majority of residential buildings were wooden frame dwellings of very good quality called bagdadi or half timber structures with stone and adobe bricks (Ohashi et al., 1982).

The Kocaeli event has brought about questions on building control and quality of construction. 6 years after this event, a local engineer was brought to a criminal court and was convicted of negligence. As rapid urbanisation takes place in many parts of the world, some in seismically active regions, one must be wary of what defects are hidden behind seemingly well- engineered buildings.

***Athens Earthquake, 7th September, 1999***

The 5.9Mw earthquake of 7 September 1999 occurred 18 kilometres north-west of the city centre of Athens at 14:57 local time and despite its moderate magnitude, caused the total or partial collapse of more than 50 buildings, in 31 of which people were trapped under the rubble. Search and rescue activities started promptly aided by the time of day and proximity of the affected zone and it was eventually possible to pull out alive from the rubble 85 trapped victims in 27 collapse sites, all within the first 72 hours (Rozakis, 2005). The number of fatalities reached 143 (established 6 days after the event, when the last victim was pulled out of the rubble) and the number of reported injuries reached 2,006. Around 500 of the injured were admitted to hospitals, with around half of them staying more than a day with 25 having life threatening injuries (Ta Nea 9/9, 1999) which would imply that a quarter of all injuries were in the serious and above categories. This was the most costly natural disaster Greece had ever experienced with the direct and indirect losses reaching around 3% of Greece's GDP. The number of collapsed reinforced concrete buildings was unprecedented partly because past strong earthquakes were further away from Athens and because there were fewer buildings falling inside a zone of intensity MMI VIII or higher in the past (Pomonis, 2002).

It has been established that 127 of the 143 fatalities in the earthquake were due to building collapse while 16 were due to other causes such as heart attacks (at least 6), falling building debris at street level (at least 1) as well as panic jumps and falls. Table 1.2 summarises where these deaths took place in terms of building use.

**Table 1.2** Fatalities due to Building Collapse by Occupancy Type

| Building Use | No. of Buildings | No. of Fatalities | % of total Fatalities |
|---|---|---|---|
| Industrial | 7 | 64 | 45% |
| Commercial/Public | 3 | 3 | 2% |
| Residential | 21 | 60 | 42% |
| Total from Building Collapse | 31 | 127 | 89% |

Detailed autopsy analysis for 111 of the victims has been published, containing information such as cause of death, location of death, time of extrication from the rubble, injury severity score etc. (Papadopoulos et al., 2004).

The Athens earthquake is a very good case study demonstrating the quality of casualty information that can be attained through diligent research and data collection. Since the fatality and injury rates were low and all of the 31 buildings which completely collapsed were accountable along with the people inside, this makes the work of comparing injury and deaths rates to published sources easier. In this earthquake, 31 buildings required the assistance of local and international search and rescue teams and exceptionally, there are records of the survival rates in this earthquake, which is not recorded in Macintyre's paper of entrapment and time-to-rescue (Macintyre et al., 2005). This was obtained from research by local engineers interviewing and collecting information from regional authorities.

***Chi-Chi Earthquake, 21st September, 1999***

The Chi-Chi earthquake of 21 September 1999 with a moment magnitude of 7.6 struck central Taiwan at 1:47am local time. The epicentre of the earthquake was in a mountainous area near the small country town of Chi-Chi, where a ground rupture along the Chelungpu fault that slipped for more than 80km in the north-south direction was mapped in detail. The earthquake severely affected an estimated population of over two million in Nantou and Taichung Counties. Subsequent damage assessments showed that 51,753 houses completely collapsed and 54,406 houses were damaged. In addition 138 multi-storey apartment buildings (housing 11,284 families) also collapsed, as did 508 public buildings. Most of the damage was concentrated along or near the line of fault rupture and was mainly to residential and civil infrastructures. Although many public buildings collapsed (schools, fire departments etc.), the time of the event meant that there were extremely few deaths in these buildings. The total number of deaths reported was 2,492 and 47 missing with 11,306 injured during the earthquake according to the Department of Health, Republic of China (2000). The highest lethality rate (0.98% of the population) was in Tsungliao township (Nantou county), the next worst affected township was Tungshih (Taichung county) where the lethality rate reached 0.54% of the population (Han and Chen, 2000).

In Tien's study of casualties (Tien et al., 2001), it was noted that out of the 2,360 investigated victims of the earthquake, 41% died in mud-brick residences; 17% in reinforced concrete buildings below 6 storeys and another 17% were inside 10-15 storey reinforced concrete buildings and 6% due to landslides. Most of the lower level reinforced concrete buildings were built of the same open ground floor design resulting in many soft storey collapses. One interesting finding from this event was that protective lattice bars fixed to windows and entrances, typical of residential buildings in Taiwan were found to hamper abilities to evacuate and actually contributed to entrapment and injuries (Kuwata, 2004).

The Chi Chi earthquake brought about collapses of many public buildings which if occupied could have been catastrophic. This event also serves as a reminder that there are cultural factors to consider when assessing casualties globally. The living environments in Taiwan where, in urban centres, most of the population reside in large apartment buildings of 30 storeys or more is not typical in other seismic countries like Indonesia. In Japan, as part of their earthquake preparedness education, if possible, residents are advised to open their front doors during the earthquake so that there is a way of escape. Their recent earthquake experiences have shown that many people are trapped in houses as the windows and front doors are twisted during the ground motion (Kuwata, 2007).

The casualty data of the Chi-Chi earthquake are quite detailed and in combination with Taiwan's dense strong motion observation network allowed spatial analysis of lethality in relation to ground motion and the proportion of dwellings that collapsed in the worst affected Nantou and Taichung counties (Tsai et al., 2001). A more recent study (Pai et al., 2007) has further investigated the human casualty aspects of this earthquake, by identifying the location of more than 80% of the fatal incidents. A victim attribute database has been compiled that includes the GPS coordinates of the positioned victims as well as other attribute data associated with the victims. The human-fatality rates in the near-fault regions have been analyzed with regard to distance from the Chelungpu fault, the hanging-wall and footwall areas, as well as building type. The lethality rate within a 30 metres distance from the Chelungpu fault was 1.43%, falling to 0.73% in the 0-100 metres zone and 0.33% in the 0-300 metres zone.

***Bhuj Earthquake, 26th January, 2001***

On 26 January 2001 at 8:46am local time, a 7.7Mw earthquake occurred in the Kachchh District of Gujarat State in India causing widespread damage to the regions' buildings and infrastructure. The earthquake's epicentre was located approximately 70 km east of the historic city of Bhuj but no surface fault rupture was evident. Approximately 339,000 buildings were destroyed including several hundred reinforced concrete frame buildings while 783,000 were damaged in the Bhuj-Ahmadabad-Rajkot area and other parts of Gujarat. There were about 13,800 deaths (although 20,000 deaths were initially estimated) in the earthquake, a very high level of mortality in a natural disaster. About 166,000 people were injured, out of which more than 20,000 had serious injuries (Vatsa, 2002). This earthquake was India's most severe in more than 60 years causing damage in over 20 districts in the Gujarat Province. The initial estimate of deaths in the district Kachchh was close to 18,500. It seems a large number of missing people were also included in the category of dead. When the government checked these details later at the household level for the purpose of providing assistance to families of the dead, the number of deaths was revised downwards to 12,221. though still significantly 89% of the total. Other seriously affected districts were Ahmedabad and Rajkot with 751 and 433 fatalities respectively (98% of the fatalities occurred in these 3 districts). In the worst affected Kachchh district the lethality rate was 1.20% and the morbidity rate exceeded 3%,

Pawar et al. (2005) published an analysis of casualties in 144 villages in the Bhuj block and immediate vicinity where 541 lives were lost among a total population of 170,056 (lethality of 0.32%), while the number injured reached 1,412 (morbidity 0.83%). They report a lethality rate of just 1.00% and morbidity of 3.37% for the 17 villages that are situated within a 10-km radius from the epicentre.

The 2001 Bhuj earthquake is considered to be a relatively low mortality event even though it resulted in a high fatality count where the circumscribed analysis area encompassed a high total population of nearly 40 million people. A possible explanation is cited in the report of the Disaster Mitigation Institute of India (2001) "26th January was Republic Day and parades were due to take place at 9am. When the earthquake happened, fourteen minutes earlier, many children and onlookers were out in the open getting ready for the celebrations and so escaped the collapse of walls and roofs. If the earthquake had occurred at night when people were asleep in their houses the mortality would have been very much higher". The main cause of death was due to crushing by the complete failure of masonry buildings in the region. The magnitude of the death toll was a reflection of the very wide area over which heavy ground shaking was observed, combined with the extreme weakness of the masonry buildings. Building construction quality was the most important factor governing earthquake vulnerability. Most buildings in rural areas were traditional houses and constructed from local materials like stone, mud and timber. These vernacular structures offered almost no resistance to ground shaking. Random rubble stone walls with mud mortar or weakly-bonded cement mortar suffered maximum damage. In the Kachchh district, many buildings constructed of large block masonry were bonded with mud or low-strength cement mortar not only made them more vulnerable to damage, but the weight of the blocks increased human casualties. In multi-storied buildings damage was observed typically in three to four storeys reinforced concrete structures with no infill walls on the ground floor.

**Figure 1.4**: Typical weak masonry buildings in the area of Bhuj (EERI, 2001)

A survey carried out by the EEFIT team of damaged buildings in Bhuj and neighbouring villages (Madabhushi et al, 2005) showed that rubble masonry buildings performed worst with over 30% collapse rate while masonry with reinforced concrete slabs and frame apartment buildings performed better (7% and 3% collapse rates respectively). The deep alluvial deposits which underlie much of the town of Ahmedabad, 20km away from the epicentre amplified ground motions significantly and coupled with poor design and construction, caused the collapses and failure of several dozen multi-storey reinforced concrete frames buildings. Despite a comprehensive Indian Building Code (ISI, 1970) it is often ignored as it is not binding on private builders.

The nature of injuries ranged from orthopaedic and head injuries to tissue losses, abdominal and thoracic trauma and fractures resulting in amputations. Many children were killed, and there were more adult female than male deaths. The scarcity of water was also cited as a serious problem throughout Gujarat after the event and the widespread damage to water supply only aggravated the issues faced by the Government of India, with unaccountable consequent health effects (Murty et al., 2005).

For Bhuj, the overwhelming number of deaths was attributed to vulnerable housing, due to weak materials and badly controlled building practice.

***Bam Earthquake, 26th December, 2003***

On the 26 December, 2003, a devastating earthquake measuring 6.6Mw struck at 5:26am local time in southeastern Iran. The earthquake caused catastrophic damage, especially to the historic city of Bam in the Kerman province. Damage statistics were provided by the Iranian government following the earthquake which shows that out of 25,700 buildings in Bam and 7,200 buildings in Baravat, 92% of them collapsed in Bam and 61% in Baravat.

The death toll published by the government in February 2004 was estimated at 43,200 but in late March 2004, the Iranian government corrected the number of deaths to 26,271 and 525 missing and the number of injured to 14,300. The huge difference was claimed mainly due to the double counting of bodies and the chaos caused by the disaster (IFRC Bam earthquake operations update of April 8, 2004). A census had been conducted to determine the exact number killed and covered the city of Bam as well as its surrounding areas and districts, where a total of 142,376 people were living (BBC, March 29, 2004), which means that around 19% of the population in the affected region perished in this one event, while in Bam the lethality rate reached 28.3% of the population.

The response to this disaster was tremendous both from the Iranian government and the international aid agencies. Only hours after the earthquake search and rescue (SAR) teams from the region started to work in Bam. During the first days after the earthquake, the Iranian Government evacuated 10,000 injured to hospitals in other parts of the country, because almost all the health facilities in the affected region were devastated. The Iranian Red Crescent Society (IRCS) mobilized 8,500 relief workers and distributed 108,000 tents 380,000 blankets, 65,000 plastic sheets. The international community's response was also very swift. Within two days of the Iranian government's request for helo some 34 urban search and rescue (USAR) teams from 27 countries arrived in Bam. A total of 13 international field hospitals (with 560 doctors and nurses) were dispatched. Five days after the earthquake approximately 1,600 international staff from 44 countries was operating in the affected area (UNDAC Mission Report, January 2004). However as usually the success of the international USAR effort was limited since they were not able to arrive sooner than 24 hours after the event.

The main reason for the high death toll was that the fault attributed to this earthquake ran directly under the city of Bam (Berberian, 2005). Of the injuries, 9,477 were reported to be serious and were treated in hospitals in Kerman and elsewhere as all the hospitals in Bam were severely damaged: abdominal trauma, pneumothorax, bladder rupture and head injuries constituted most of the emergency surgery cases.

The massive death toll in Bam is attributed to the extreme weaknesses of the adobe houses which housed the majority of the affected population. According to a field survey carried out by Iranian researchers only 2% of those who died were in buildings which did not collapse (Ghafory-Ashtiany, 2005). These houses have been created as a response to the climate of Southern Iran, with high diurnal temperature swings, and also from the lack of timber due to deforestation in the area for construction (Maheri et al, 2005). Under earthquake motions however, the buildings simply disintegrated leaving behind heaps of rubble and dust. Asphyxiation resulting from the huge amount of dust was suggested as a further cause of many deaths (Movahedi, 2005).

The chances of survival were further diminished by the close spacing of these dwellings, leaving little opportunity for escape, and inhibiting search and rescue. The death toll was further increased by the lack of immediate response capability. Local emergency response units were completely destroyed by the earthquake, and for the first crucial hours the only rescue was being performed by locals who had survived the earthquake. The loss of electricity and therefore light meant that rescue stopped at nightfall, and freezing temperatures reduced the chances of overnight survival under the rubble (Movahedi, 2005).

In Bam, two characteristics were found to play key roles in determining the magnitude of casualties: vulnerable housing producing dust but also close spacing of these dwellings.

***Kashmir Earthquake, 8th October, 2005***

This 7.6Mw magnitude earthquake occurred at 8:50am during Ramadan affecting the mountainous areas of Pakistan and India. It was the deadliest earthquake in the recent history of the sub-continent resulting in more than 73,000 officially reported deaths and over 69,000 people seriously injured officially

(WHO, 2006), with several thousand still reported as missing. Casualties reported by DfID in November 2005 showed that in addition to serious injuries, in Pakistan there were 6,823 injured in the Northwest Frontier Province (NWFP) and 51,912 injured in the Azad Jammu Kashmir (AJK). Therefore the total number of injuries in Pakistan amounts to 127,322. The devastation was immense, affecting an area of over 30,000km² and between 3.2 and 3.5 million people (IFRC, 2005) approximately 2.2% of whom have been killed and 3.8% injured. In total, 272,000 buildings (including 455 health facilities) were destroyed and 183,000 damaged (EEFIT, 2008a). Many witnesses reported scenes resembling a bomb site and cited intensities of X+ at the city of Balakot. The earthquake's epicentre was 19 km northeast of Muzaffarabad and both the provinces of AJK and NWFP were severely affected. Worst affected were 4 districts of AJK province (Neelum, Muzaffarabad, Bagh and Poonch) and 5 districts of the NWF province (Mansehra, Kohistan, Shangla, Batagram and Abbottabad). In Muzaffarabad and Mansehra districts respectively around 5% and 2% of the population was killed. The largest recorded lethality rate was in Muzaffarabad city where 29% of the city's population was killed (EEFIT, 2008a). More than 1,200 aftershocks were recorded in the region, some reaching close to 6.0Mw.

**Figure 1.5**: Photograph showing the extent of damage of housing by the Jhelum River in Muzaffarabad

The major cities and towns affected were Muzaffarabad, Bagh and Rawalakot in Kashmir and Balakot and Batagram in NWFP in Pakistan. Most buildings in the affected area had poor earthquake resistance. Of the total housing stock, 84% was damaged or destroyed in AJK and 36% was damaged or destroyed in NWFP. Figure 1.6 presents a map showing the extent of damage in the affected area of Pakistan (JRC, 2005).

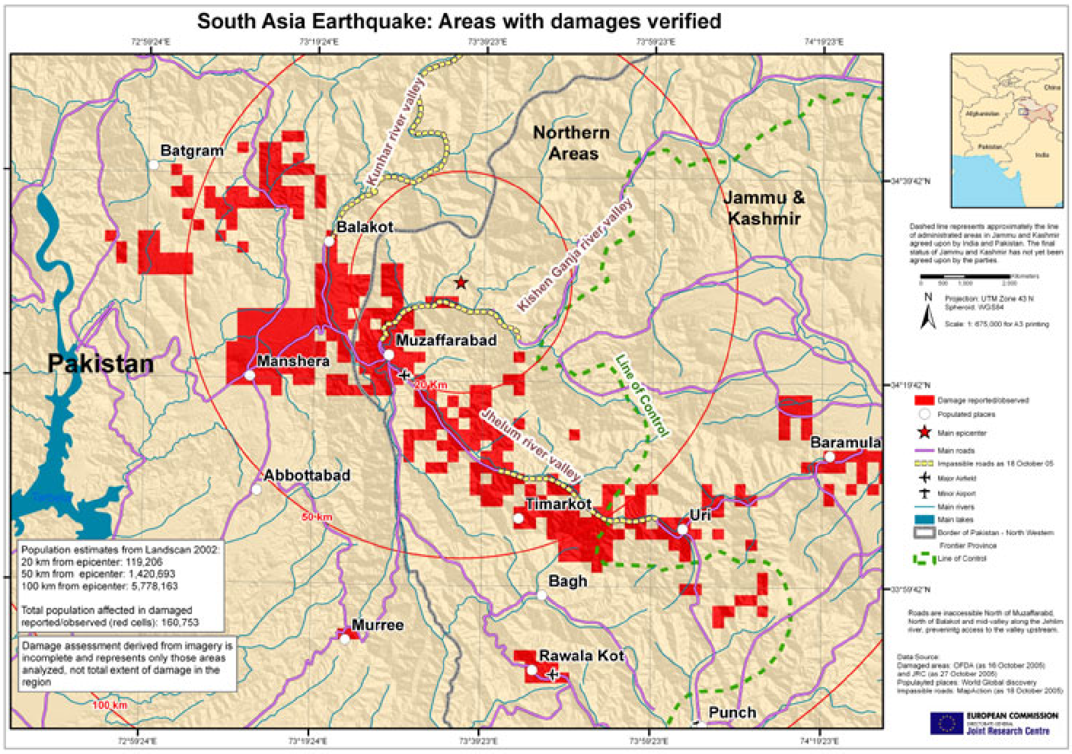



**Figure 1.6:** Map showing the major damage areas in Pakistan after the Kashmir Earthquake of 2005 (JRC, 2005)

In the worst damage regions of Pakistan, over 80% of the districts were seriously damaged due the earthquake as surveyed by ERRA (Earthquake Reconstruction and Rehabilitation Authority).

Virtually all major public buildings in the main cities of Balakot and Muzaffarbad were partially damaged or completely destroyed (EERI, 2005). Electricity and water supply in the towns and villages were severely affected. Huge landslides also occurred at various locations in the affected area including this slip opposite the town of Chella Bandi, north of Muzaffarabad shown in Figure 1.7.

**Figure 1.7**: A massive landslide dominating the landscape with Chella Bandi, one of the surveyed villages in the foreground (courtesy of Navin Peiris)

A significant number of casualties and injuries in the affected region were associated with the complete collapse of single storey unreinforced stone masonry buildings (So, 2007). Almost all the buildings, mainly of stone and block masonry in cement sand mortar with reinforced concrete slab or galvanised iron sheet roofing, collapsed in the areas close to the epicentre. The stone masonry walls consisted of irregularly placed undressed stones which were laid in cement sand or mud mortar. Stone masonry buildings were more common in the rural villages (75% of the building stock) than in the cities (15% of the building stock) (EERI, 2005). The quality of mortar and stones used and the level of workmanship were very poor due to the economic situation of the people living in these parts The most commonly used mortars consisted of 1 part cement to 10 part sand but there were incidences where dry walls were observed as well as mud mortars (So, 2007). Often river stones which are locally available would be used and these rounded and smooth stones in addition to the poor quality of mortar rendered a very loose bond between the stones which made the structures extremely vulnerable to earthquake forces. There was very little evidence of horizontal bond beams provided at the levels of plinth, or roof in these Katcha dwellings (traditional rubble stone masonry house with mud mortar, see Figure 1.8).

**Figure 1.8**: Typical rural residences made of river pebble stones stacked-up and loosely bonded with mud mortar (Katcha Houses)

In urban areas, concrete block masonry buildings were dominant (about 60% of the buildings). The collapse of these block masonry buildings, as shown in Figure 1.9 was reported to be responsible for the major portion (over 60%) of deaths and injuries in the cities (EERI, 2005). The most probable reasons for failure were observed to be poor quality of concrete and mortar, inadequate thicknesses of walls to provide main shear-resisting elements and the lack of connections at corners.

For the past 15 years, reinforced concrete frame buildings have been increasingly used for the construction of public buildings including government offices, colleges, hospitals, hotels, markets, as well as some affluent residential buildings.

**Figure 1.9**: Pancake collapse of one storey concrete block building with flat concrete slab roof in Balakot, Pakistan

However, many reinforced concrete buildings completely collapsed and many more were seriously damaged by this earthquake. The main reason for these failures was weak beam connections. As observed on the reconnaissance mission, there was simply inadequate reinforcement or ties resulting in rotation and plastic hinging at the beam to column connections. The EERI team of engineers suggested that primary factors contributing to the failure of reinforced concrete frame structures include deficient design for seismic forces; improper length and location of column splices; improper spacing and anchorage of lateral ties in columns and poor quality of concrete (EERI, 2005).

The type of building which performed best was brick masonry as shown in Figure 1.10. These single and two storey brick and confined brick masonry buildings, with RC slabs as roofing, comprised 25% of the total building stock of the cities near the epicentre. It was observed that only 30% of these buildings collapsed, whilst the rest suffered only slight damage. The brick masonry buildings were only constructed by more affluent people because the unit cost of brick masonry is higher than that of other forms of masonry in the area. It was observed that along with better workmanship, good quality mortar was used in the construction of brick masonry buildings (EERI, 2005).

**Figure 1.10**: A confined brick masonry building which survived relatively undamaged the earthquake in Muzaffarabad despite its extremely precarious position by the Jhelum River

The typical failure mode from damage surveys in the area was collapse of walls due to the lack lateral support leading to a subsequent roof collapse. There was also evidence of column failures in 2-storey reinforced concrete buildings. However, another major contributor to damage and casualties was geohazard. Many houses in the Kaghan Valley and in Muzaffarabad were built on steep and unstable slopes and toppled with the sliding of these slopes. Landslides and vulnerable infrastructure also hampered rescue and medical efforts and the media reported at the time that many of the injured were carried for days by relatives down the mountains to seek help. Over 3,000 schools collapsed, many were on steep unstable slopes in the Kaghan Valley and given the earthquake occurred in school hours, many children died. Figure 1.11 shows the typical topography into the Kaghan Valley.

**Figure 1.11:** Schools and houses at the tops of steep slopes along the Kaghan Valley had little chance of survival

Apart from the general casualty statistics stated in Table 1.3 below, there has been limited amount of published work on casualties relating to the 2005 Kashmir earthquake. Mulvey et al. (2008) analysed the condition of 1,502 injured people that arrived in one of the few surviving health facilities in the epicentral region during the first 72 hours from the earthquake. They report than 31.1% of these patients were admitted and that only 9.9% required a procedure under general anaesthesia. The most common type of injuries were: superficial lacerations (64.9%); fractures (22.2%); and soft tissue contusions/sprains (5.9%). Ahmad (2008) and Rathore et al. (2007) report on the treatment of spinal cord and other injuries in hospitals of Pakistan (around 670 spinal cord injuries in total). The health implications of this earthquake can be followed through the 38 Situation Reports published by the World Health Organization (http://www.who.int/hac/crises/international/pakistan_earthquake/sitrep/en/). .

**Table 1.3** Casualties in the affected districts of NWFP and AJK provinces (Source: www.ajk.gov.pk, ADB-WB (2005), data at Nov 12, 2005)

| District | Deaths | Injuries |
|---|---|---|
| *North West Frontier Province (NWFP)* | | |
| Shangla | 423 | 957 |
| Mansehra | 24,511 | 30,585 |
| Kohistan | 661 | 639 |
| Abbottabad | 515 | 1,730 |
| Batagram | 3,232 | 3,279 |
| **Sub Total** | **29,342** | **37,190** |
| *Azad Jammu Kashmir (AJK)* | | |
| Neelum | 447 | 1,013 |
| Muzaffarabad | 33,724 | 21,374 |
| Bagh | 8,157 | 6,644 |
| Rawalakot | 1,025 | 1,909 |
| Sudhnoti | 4 | 16 |
| Mirpur | 6 | 11 |
| **Sub-Total** | 43,363 | 30,967 |
| **Total** | **72,705** | **68,157** |

According to studies by WHO (World Health Organisation) and HANDICAP, out of the 69,000 serious injuries, just over 1,450 cases (2%) would be classified as critical injuries requiring rehabilitation. This statistic contradicts early reports of the mass of amputations performed which resulted in an oversupply of the wrong medical provisions and relief to the area (Mallick, 2006). According to WHO, over 2,000 prosthetic limbs were sent to the area but were never used.

For Kashmir, the high level of serious injuries reminds of the need to assess deaths and injuries in loss estimation and the need to ensure transport links are in operation after an event to get to the affected before injuries are further complicated.

***Yogyakarta Earthquake, 27th May, 2006***

Centred in the Yogyakarta region of Java, the 6.4Mw earthquake occurred at 5:53am local time killing nearly 6,000 people whilst the injury list was reported to have exceeded 78,000 (CRED, 2006). An area of 200km$^2$ of intense shaking (over intensity IX) gave rise to the complete or partial collapse of 156,700 houses and other structures and the damage to another 202,000. Given the destruction, it is fortunate that not more people died. The earthquake hit Central Java, is one of the most densely populated rural areas in the world. Had the earthquake occurred during school or work hours, the number of fatalities might have been greater. However, there is sizeable number of injuries and therefore why so many people survived given the heavy damage to dwellings is an interesting question.

The impact of the disaster was highly concentrated in the districts of Bantul in Yogyakarta province and Klaten in Central Java province, constituting more than 70% of the total damage and losses (World Bank, 2006). In Bantul district the lethality and injury rates were 0.50% and 1.50% of the estimated district's population respectively. In Klaten district the lethality and injury rates were 0.10% and 1.60% of the estimated district's population respectively. The other major damaged areas included the City of Yogyakarta and three other rural districts in the province of Yogyakarta (Sleman, Kulonprogo and Gunung Kidul). In the city of Yogyakarta damage was lighter and the lethality and injury rates were 0.05% and 0.08% of the estimated population in the city.

**Figure 1.12**: Aerial photograph showing extent of damage and the density of buildings in this rural area of Bantul (World Bank, 2006)

The six districts most affected by the earthquake have a combined population of about 4.5 million. The districts of Bantul and Klaten both have an average population density of over 1,700 people/km$^2$ and are ranked among the top fifteen most densely populated non-municipal districts of Indonesia. The municipality of Yogyakarta is Indonesia's seventh most densely populated municipality.

The shallowness of the hypocentre (less than 15 km) was a possible reason for the widespread structural damage in the affected area. Another proposed reason for the extensive damage was that the thick lahar deposits underlying the worst affected areas amplified the ground motion (Walter et al., 2008). Based on a 3-month aftershock observation period it was established that the Yogyakarta earthquake occurred at 10–20 km distance east of the worst affected areas which lied within a narrow topographic and structural depression along the Opak River and its tributary Code River. This area is underlain by thick volcaniclastic deposits commonly derived in the form of lahars from Mt. Merapi Volcano (Walter et al., 2008).

Large-scale damage to buildings was also evidence of a lack of adherence to safe building standards and basic earthquake resistant construction methods. Most of the private homes were constructed with low-quality building materials and lacked supporting structural frames and columns which collapsed easily as a result of the earthquake ground motions. The typical house in the affected rural areas is a one-story unreinforced clay brick/block masonry in cement or lime mortar. The main load-carrying components are unreinforced clay brick masonry walls on which a timber roof system is supported. The roofs are covered by slate, metal asbestos-cement or plastic corrugated tiles. The loads are transferred to rubble stone strip or isolated footing through concrete or wood ring beams. There is no special connection system between the timber roof system and the masonry walls. During the past 30 years, reinforced concrete framing systems with half brick masonry infill walls have been also used both in rural and urban areas (MAEC, 2007). The damage and losses were predominantly in the private sector (91% Private; 9% Public, UNDP).

According to a preliminary damage and loss assessment report (World Bank, 2006), more than 90% of the total damage to housing occurred in the four rural districts of Bantul, Klaten, Sleman, and Gunung Kidul (see Figure 1.13). The frequently used brick masonry is brittle and has low compressive strength of 2-6 MPa. Since clay bricks are produced in large numbers and at a low cost without any standard, their quality is very much dependent on the local conditions and circumstances. Therefore it was not surprising that damage distribution also varied greatly, even from street to street due to inconsistent quality of materials and construction.

The typical house in the affected rural areas is a single storey unburnt clay brick/block masonry in cement or lime mortar also known as katcha house, same as the Pakistan traditional dwelling. The main load-carrying components are the clay brick masonry walls on which a timber truss roof system is supported. It was observed during the damage survey that in many cases, there were no connections evident between the timber trusses and the masonry walls (So, 2006).

**Figure 1.13**: A typical katcha house in Indonesia (Photo courtesy of Fumio Yamazaki)

Due to poor anchoring of the roofs to the walls and of the walls to the foundations, the houses simply collapsed under the induced lateral loads. In some cases, the timber roof had slid off the masonry wall.

Over the past 30 years, reinforced concrete framing systems with brick masonry infill walls have also been used both in rural and urban areas (MAE, 2006). Many public buildings of this form also collapsed due to poor construction standards, in particular schools, many of which were built in the 1970s and 1980s with special government grant funds. Most of the commercial buildings in the cities damaged in the affected areas were engineered multi-storey reinforced concrete structures. Although the Indonesian building code includes seismic design provisions, a number of buildings surveyed by the author and other reconnaissance teams (MAEC, JICE) revealed poor detailing at joints and connections resulting in soft storey and column failures.

**Figure 1.14**: A combination of soft storey and failure of joints and connections due to poor detailing of RC buildings in the city of Yogyakarta after the earthquake (Photo courtesy of Yusuke Ono)

*Reported Casualties*

Figure 1.15 shows a breakdown of reported casualties from the 9 affected regions. Of the total death toll, 4,121 victims resided in Bantul, while 1,041 died in Klaten district (World Bank, 2006). As most of the rural and urban infrastructure remained intact and suffered little damage, the local emergency rescue teams including volunteers supported by government and the community had most of those trapped rescued within an hour of the event (OCHA, 2006).

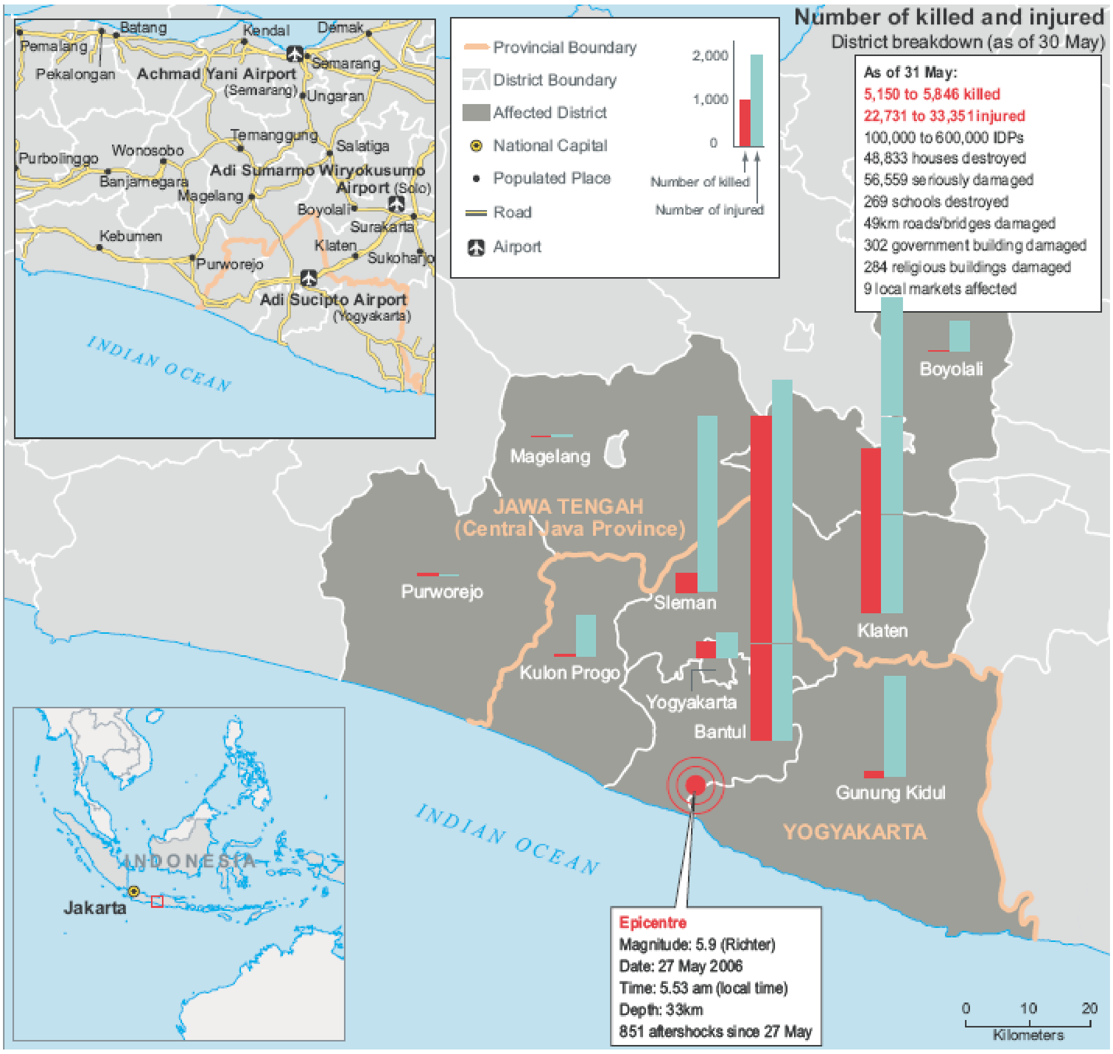



**Figure 1.15:** District breakdown of casualties after the Yogyakarta Earthquake (OCHA, 2006)

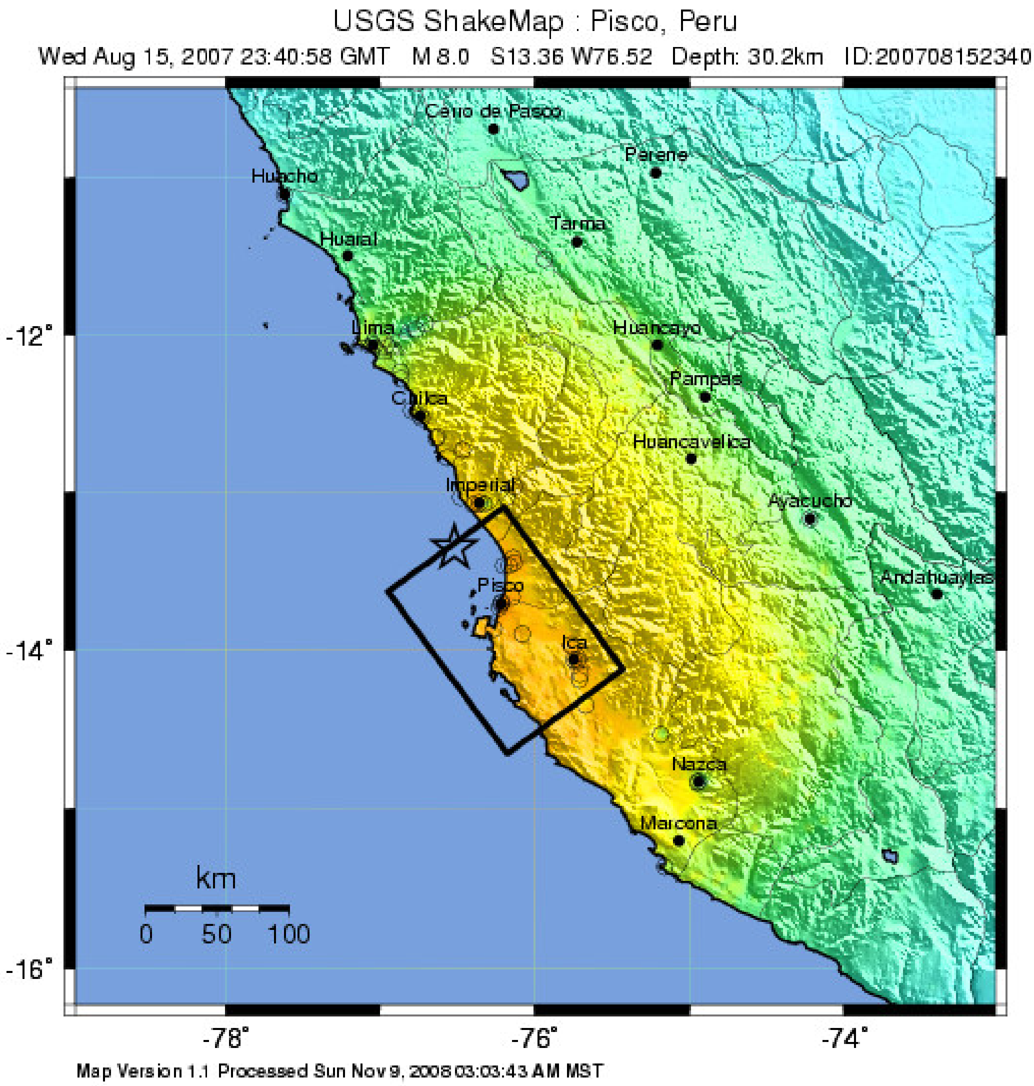
Also working in the area were WHO and HANDICAP volunteers helping the regions' PWDs (persons with disability). There was a marked increase of PWDs in the area of Bantul. This also gives an indication of the severity of injuries sustained by the people affected by the earthquake. Especially in the rural setting, aftercare and rehabilitation are crucial to enable inhabitants to become part of the community again.

The Yogyakarta earthquake highlights the need to examine cultural and other contributory factors to casualties as the heavy damage to the region from this event would suggest many more deaths which did not happen perhaps due to housing type and evasive action of the affected population.

### *Pisco Earthquake, 15th August, 2007*

At 6:40 pm local time on 15 August 2007, an earthquake measuring 8.0Mw struck offshore of the region of Ica, 25 miles west-northwest of Chincha Alta on the coast of southern Peru. Figure 1.16 is the earthquake shake map published by USGS after the event which shows seismic intensities of MMI VI to

VII in the most affected regions in the rectangular box. This is also an interesting earthquake as all time history recordings in the area show a total duration of shaking of approximately 160 seconds with three sequences of motion with a period of 20-30s of smaller amplitude in between the two stronger parts. This calmer interval may have allowed people to escape from their low-rise houses.




| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <.17 | .17-1.4 | 1.4-3.9 | 3.9-9.2 | 9.2-18 | 18-34 | 34-65 | 65-124 | >124 |
| PEAK VEL.(cm/s) | <0.1 | 0.1-1.1 | 1.1-3.4 | 3.4-8.1 | 8.1-16 | 16-31 | 31-60 | 60-116 | >116 |
| INSTRUMENTAL INTENSITY | I | II-III | IV | V | VI | VII | VIII | IX | X+ |

**Figure 1.16:** Map showing intensity distributions in the affected region (source: USGS)

The final death toll was reported as 595 plus 318 missing (INEI Peru, October 2, 2007) while the number of injured stood at 2,615 (EERI Newsletter, October 2007, quoting lead physician of Peru's Ministry of

Health). More than three quarters of the fatalities (463) were in Pisco, a town of 54,000 people. Of those killed in Pisco town, 150 perished when the roof of the San Clemente church in Pisco collapsed during a funeral service. Another 15 died at the Embassy Hotel, where the bottom two stories of the 5-storey reinforced concrete structure collapsed. Search and rescue operations lasted more than 5 days in this site. This means that half of the deaths in Pisco town occurred in non-residential buildings.

Almost 320,000 people lived in houses that were destroyed or deteriorated as a result of the substantial spread of damage in the affected area where 76,000 houses will need to be rebuilt (INEI Peru, October 2, 2007). There was mass devastation throughout, especially in and around the town of Pisco where 80% of the town's adobe housing had collapsed or sustained heavy damage.

There were several reasons why there was such widespread damage. First and foremost, the quality of the building stock in this area was poor. Traditional earth structures, in particular those of adobe construction, designed without the inclusion of any kind of reinforcement, and without consideration of earthquake resistant concepts were susceptible to collapse in a sudden, brittle way. Apparently, the adobe blocks and mortar in the Pisco and surrounding areas were made with sandy soil, which did not have sufficient clay to provide good adhesion between mortar and adobe blocks (EERI Newsletter, October 2007). .This was the cause of most of the deaths and injuries of their occupants. However, earth structures (one storey adobe or combined with *quincha* at the second storey) designed for earthquake resistance and built by NGO's present in Peru prior to the earthquake event were found to perform satisfactorily; an example of which is shown in Figure 1.17.

**Figure 1.17**: Photo showing a reinforced adobe house which survived the earthquake in Lunahuana

Despite this devastation just 0.65% of Pisco's population was killed in residential buildings and 2.50% injured. This may have to do with the aforementioned specific characteristics of the ground motion, but also due to the time of occurrence (6:40 pm), as well as the extent of collapse of the local buildings related to the weight and type of roofs.

Structures built according to current standards of earthquake resistant design, such as 1-6 storeys confined masonry buildings also performed satisfactory with minimum levels of damage in the affected area, with the exception of the Embassy hotel in Pisco (EEFIT, 2007). Schools and hospitals built prior to current standards of earthquake resistant design sustained high levels of damage, due a combination of factors including inappropriate detailing, unfavourable global geometries (soft storeys and short columns) as well as low quality construction materials (Taucer et al., 2008).

The location of some of the building structures were found to be on poor quality soils susceptible to liquefaction and to ground failure, as well as in areas exposed to tsunami (in the town of Tambo de Mora). In the inland mountainous areas, rural houses constructed on or near slopes without proper consideration of the risk associated to landslides and rock falls were evident. These resulted in severe damage.

Most of the attention in emergency relief was focused on the large cities (Ica, Pisco and Chincha Alta), while rural, remote areas, especially along the valleys running up the Andes faced delays in receiving emergency relief. As the reconstruction process led by Governmental Institutions had not started at the time of the field mission, part of the affected population had already started reconstruction, in general without qualified assistance. In rural areas with higher levels of poverty, the adobe bricks from the fallen houses were being reused without any guidance, thus re-establishing the same level of high risk that existed prior to the earthquake event. Informal interviews (Taucer et al., 2008) showed that the affected population were concerned and expressed a desire to reconstruct earthquake safe houses, different from the existing ones that collapsed. It is important to mention a general awareness of the good performance of earthquake resistant adobe houses built before the earthquake event amongst the affected population.

The Pisco earthquake is one of only 4 out of the 11 events which happened during waking hours. The combination of low occupancy and the nature of the terrain and roofing material of the numerous collapsed buildings are key factors in the casualty number in this event. This event also highlights the benefits of retrofitting traditional houses.

***Wenchuan Earthquake, 12th May, 2008***

A magnitude 7.9Mw earthquake struck the Sichuan Province of China on 12 May 2008 at 14:28. This was the strongest earthquake to occur in China in over 50 years, and caused the largest loss of life since the Tangshan earthquake killed an estimated 242,000 people in 1976. The earthquake occurred in Wenchuan County, a rural and mountainous but densely inhabited region in eastern Sichuan Province, around 50 miles (80 km) west-northwest of Chengdu city. The damage statistics are enormous and unprecedented: the number of destroyed buildings may be greater than 5 million, with another 21 million buildings damaged, 15 million people were evacuated for fear of landslides and further damage from aftershocks, at least 5 million people were rendered homeless (USGS Significant Earthquakes of 2008). The official death toll published on the first anniversary of the earthquake indicates that 69,712 people died, 17,921 are still missing, and almost 375,000 were injured during the earthquake. An additional 2.6 million people suffered at least a minor injury (China News Agency, June 24, 2008) among an effected population that reached 45.5 million people. The school pupil and student population was particularly hard affected with 5,355 dead or missing and 546 handicapped by their injuries.

This earthquake also generated a great number of aftershocks. As of September 8th 2008, more than 28,000 aftershocks were recorded, of which 39 of M5 or greater, and 8 greater than M6, with the largest aftershock (Mw6.5) occurring on Sunday, May 25. These strong aftershocks contributed to the collapse of many of the buildings damaged during the main shock, causing further loss of life. The earthquake had occurred early afternoon on a Monday, a time when the majority of adults were at work and children were at school.

The Wenchuan earthquake will also be remembered for its tremendous landslides. The damage caused by these landslides occurred on numerous levels: firstly, the environmental damage as these landslides have permanently changed the landscape, damaging or possibly even destroying vulnerable ecological networks and waterways. Secondly, the landslides caused significant damage to buildings and infrastructure—including road networks, communications equipment, and power stations, severely affecting communications. The toll on humans was evident as many people were buried or simply crushed by the landslides (for example at least 700 people were buried by a landslide in Qingchuan). Blocked and damaged roads also severely disrupted transportation to affected areas, isolating communities, hampering relief efforts and cutting off much needed supplies. Due to the mountainous terrain, blocked access to the affected region made search and rescue efforts painstakingly slow. The slow progress of search and rescue efforts compounded the death toll, as many people were trapped beneath collapsed buildings with no access to medical aid, food, or water. In many places, including Beichuan, a town 60km from the epicentre but lying directly on the northern end of the ruptured fault, it took more than 10 days for the rescuers to reach the inhabitants.

Based on field reports (WCEE, 2008), the epicentral region experienced extreme shaking of intensity IX–XI on the Chinese Intensity Scale, capable of causing heavy to very heavy damage. Many of the buildings collapsed because they were of soft story configuration—reinforced concrete moment resisting frames with masonry infill, where the ground floor is cleared of walls to make space for commercial purposes or car parking. It has also been reported that the peak ground accelerations at these affected towns and villages were near to 3 times the design levels in the current Chinese earthquake design code, although there have been no official release of strong motion data to date (EEFIT, 2008b).

The main cause of deaths was due to collapses of buildings but many and possibly more were buried by land and rockslides. In Beichuan, 15,000 out of 22,000 inhabitants perished with the entire downtown area inundated by a massive landslide (see Figure 1.18).


**Figure 1.18:** View of Beichuan after the Wenchuan earthquake of May 12th 2008. The downtown area is completely buried by the landslide marked on the left side of the picture

The main types of serious injuries were crushing injuries to upper and lower limbs. A number have resulted in amputation due to the delays in rescue efforts as all of those injured had to be airlifted to hospitals outside the affected region. The emergency response centres in the affected mountainous areas were completely out of action. Since it was a workday, many of those who survived were outside at the time, working in markets or in commute, survivors also mentioned being lucky as they had run out of buildings before collapse. (So, 2008)

Two characteristics in particular were found to play key roles during this earthquake: location, which affects the level of shaking, and building age, which can be closely correlated to resistance to shaking offered by the seismic design level. Large devastating events such as these remind us of the challenges we face due to rapid growth and urbanisation in hazardous regions around the world.

## 1.4 Conclusions from the overview of recent earthquakes

What then can we conclude from this review of recent earthquakes and what have we learnt from each of these events? One overriding conclusion from the summary is that the major cause of death is building collapse, therefore testing our first hypothesis that structural collapses are the main cause of deaths. In general, unreinforced masonry buildings (URM) have historically been shown to be the greatest danger to their inhabitants, and the weaker the masonry, the higher the death toll in the event of a strong earthquake, as evidenced by the high loss of life in the moderate sized Bam (2003) earthquake. Deforestation has been blamed for the lack of timber which had traditionally been used to provide the tension capacity in these rural housing. In many areas of the world including Turkey, Iran and Peru, there have been changes to traditional building techniques and modern materials such as concrete have been introduced when regenerating building stocks. When built without proper building codes and guidance by trained builders, the vulnerability of these structures are expected to be high. Recent earthquakes like Kocaeli (1999) have demonstrated the potential dangers from reinforced concrete buildings when built without codes, or proper consideration of potential earthquake loading. Without proper building control, the rapid urbanisation in cities like Istanbul, Tehran and Lima, more numerous reinforced concrete failures and associated deaths in the future are sadly conceivable. Other lessons and factors which have had a major impact on the final casualty number in the 11 illustrated earthquakes are summarised in Table 1.4 below:

**Table 1.4** Important lessons learnt from 11 recent events

| Event | Date (local time) | Important lessons |
|---|---|---|
| Northridge, Mw 6.7 | 17th January, 1994, 04:30 | The earthquake affected one of the new suburbs of the Los Angeles Metropolitan region, where the number of old buildings was limited. What if the earthquake had occurred during rush hour and closer to Los Angeles? Portions of Interstate 10 (the Santa Monica Freeway), Interstate 5 (the Golden State Freeway) and State Route 14 (the Antelope Valley Freeway) all collapsed and had to be rebuilt, many casualties would have been generated should these be carrying traffic. Severe damage to hitherto deemed safe moment resistant steel frame structures. Confusion about the actual number of injured people. Excellent studies of the human casualty and medical implications. |
| Kobe (Great Hanshin), Mw 6.9 | 17th January, 1995, 05:46 | Review of old vulnerable timber housing (shinkabe and okabe) which is still quite common in parts of Japan affected by strong winds especially in western Honshu Island; collapse of multi-storey steel-reinforced concrete composite structures at mid-level, collapse of motorway and railway overpasses, failure of rapid search and rescue mobilization, huge traffic jams and road collapses hampered access to Kobe city from Osaka for days, fire |

| Event | Date (local time) | Important lessons |
|---|---|---|
| | | following earthquake continues to be a huge problem in densely inhabited wards of Japanese cities, wake-up call for Japanese earthquake design. Excellent studies of the human casualty and medical implications. |
| Kocaeli, Mw 7.4 | 17th August, 1999, 03:01 | Building control called into question in Turkey, corruption in the building construction industry is endemic, vulnerability of Istanbul to forthcoming Marmara Sea earthquake is enormous, new reinforced concrete apartment buildings performed worse than older and traditional buildings (such and bagdadi and himis). Serious doubts as to whether the official death toll is realistic. |
| Athens, Mw 5.9 | 7th September, 1999, 14:56 | Even a small earthquake (Mw5.9) can cause significant damage if it centred near urban centres. All collapsed buildings were either pre-code or low-code structures. Transportation networks were operational and time of day and proximity of the affected area enabled rapid rescue of 85 people in 25 out of 31 collapsed buildings where victims were trapped. Some of the collapsed buildings has been damaged in the 1981 Corinth bay earthquake. 45% of the fatalities were in industrial buildings of inferior quality and hazardous location. Useful data on search and rescue and the lethality of collapsed RC frame buildings |
| Chi Chi, Mw 7.6 | 21st September, 1999, 01:47 | Collapse of 138 multi-storey buildings (many high-rises) and 508 public buildings; deaths tolls could potentially be greater if the earthquake was during working hours. Excellent studies of the human casualty and medical implications. There were 4.5 injuries per fatality. |
| Bhuj, Mw 7.7 | 26th January, 2001, 08:46 | Extremely weak rubble masonry housing suffered the most but site effects were also significant. Considered to be a low mortality event but more investigation is necessary to obtain casualty figures at the individual city level (Bhuj, Anjar, Gandhidham etc.). Time of occurrence (8:46 am) on a day of celebrations (Republic Day) may have helped to reduce the loss of life. Injuries though were widespread amounting to 8 per fatality. |

| Event | Date (local time) | Important lessons |
|---|---|---|
| Bam, Mw 6.6 | 26th December, 2003, 05:26 | Close spacing hampering escape and access for search and rescue. Extremely vulnerable dry mud brick buildings in the medieval citadel of Bam. Below freezing temperatures at night. Extremely high lethality event (19% of the population in Bam and surrounding towns and villages waere killed; in Bam city the lethality reached 28.5%). However this is not unprecedented in Iran (e.g. 85% of the population of Tabas was killed in the September 16, 1978 Tabas earthquake (Mw7.4). Tremendous international SAR mobilization but with limited success. The reported injury to death ratio in this event was very low (0.54). |
| Kashmir, Mw 7.6 | 8th October, 2005, 08:50 | The poor roads in this mountainous region hampered rescue and bad siting of towns and schools killed many. The extremely steep Himalayan terrain makes access very difficult, thus rendering the populations on the isolated slopes and valleys extremely vulnerable to strong earthquakes. Helicopters had to be used to air lift the injured and homeless in evacuation operations that lasted more than a month. In the city of Muzaffarabad the lethality was the same as in Bam (29%). The reported injury to death ratio in this event was very low (1.79). Some doubt about the final number of fatalities in Pakistan (73,000 and 86,000 have been proposed). |
| Yogyakarta, Mw 6.4 | 27th May, 2006, 05:53 | Though the damage to buildings was extensive, this early morning earthquake did not 'kill' as expected, possibly due to evasive action but also because of better quality construction (unreinforced brick masonry was the most common type for housing). In the worst affected Bantul district lethality did not exceed 0.50% and injury rate was also low (1.50%). This event because of its smaller magnitude caused extreme damage in localized areas perhaps due to motion amplification of the deep lahar deposits.. In the worst affected area (5 districts in Yogyakarta province and 1 district in Central Java) there were 1 million dwellings and only 15% of these has |

| Event | Date (local time) | Important lessons |
|---|---|---|
| | | been classified as destroyed (many of these though did not collapse entirely, but were damaged beyond repair). Some doubt about the number of injured (78,000 or 130,000?). |
| Pisco, Mw 8.0 | 15th August, 2007, 18:40 | The terrain and time of day meant many were outside or were awake and able to move to safety. In worst affected town of Pisco, 80% of the adobe houses were destroyed but lethality was only 0.65% of the population. It is not clear what proportion of the town's population lived in adobe houses, but it is believed to be the majority. Therefore in this day-time event we have similarly low lethality as in the 2001 Gujarat event. In addition this was a double shock event with a calmer interval of 20-30 seconds in between the strong shaking that may have allowed the alert residents to run outside. More data need to be collected with damage and casualty statistics in each affected location to better interpret this event. The tremendous death toll in the Pisco church is unfortunately not unusual for earthquakes in Central and South America where many churches have often collapsed in catastrophic manner (e.g. Popayan 1983, Callao 1966). |
| Wenchuan, Mw 8.0 | 12th May, 2008, 14:28 | A combination of unexpectedly high seismic motions, unstable steep slopes and vulnerable buildings led to a very high death toll. Breakdown of casualties by cause (building collapse, landslide) is needed. Damage and casualty statistics per location must be collected. |

The table highlights particular key factors contributing to deaths that must be considered in casualty modelling and this has been an important exercise in drawing these parameters out. However, despite significant progress in the accuracy of the casualty reporting, data on the precise causes of death and injury is in most cases not available. It seems evident though that most of the deaths are the result of injuries sustained when buildings collapse with roofs or walls falling on the occupants. In some earthquakes like Bam, there is evidence that asphyxiation resulting from the dust and fine material released when buildings collapsed has contributed to deaths of its occupants (Hatamizadeh et al., 2006). Critical injuries, which would include internal organ failure, limb amputations or spinal injuries leading to permanent disability are comparatively small in number when compared with death tolls. In consulting with emergency physicians who have worked in the immediate aftermath of earthquakes, it appears that most people would die from critical injuries. Therefore resulting critical injuries are likely to be generated from complications to serious injuries for example delays in search and rescue though there is no concrete evidence to support this hypothesis.

With the exception of Northridge 1994, Kobe 1995, Athens 1999 and Chi-Chi 1999 earthquakes, the other events that have occurred in Turkey (Kocaeli 1999), India (Bhuj 2001), Iran (Bam 2003), Pakistan (Kashmir 2005), Indonesia (Yogyakarta 2006) and Peru (Pisco2007) are not so well documented with discrepancies or uncertainties about the number of fatalities or injuries in 4 of the 6 events (Kocaeli, Bam, Kashmir for the fatalities and Yogyakarta for the injuries). The lessons from the 2008 earthquake in Wenchuan are yet to be fully explored as literature is still being reviewed. What is lacking most are casualty statistics for each individual affected location and their respective damage survey data. When these data are available then correlations start to become reasonable and trends clearer to see, otherwise confusion can arise as to why in some events lethality or morbidity is very different than expected. Even in well restrained and quite uniform locations in terms of building inventory and shaking severity we see that lethality rates can be an order of magnitude different (e.g. Awaji Island versus Nada ward) because of nuances about the age of the buildings or other characteristics (e.g. the age profile of the population).

Detailed epidemiological studies of places affected are also quite rare. The study of a Guatemalan village struck by the deadly 1976 earthquake (Glass et al., 1977) is considered to be the seminal work in this field. It was followed by the study of 7 unnamed villages in the epicentral zone of the 1980 Irpinia earthquake in Italy by de Bruycker et al. (1983 and 1985) and the studies of the Northridge, Kobe and Taiwan earthquakes. The literature in the last 15 years is increasing exponentially, but few works can tackle the problem in its entirety, because of the complexity of the problem which requires multi-disciplinary collaborations between state bodies that carry-out the damage and population census in the affected areas, the fire departments and the various other SAR groups that carry-out the victim extrications, the medical staff that treat the injured and do the autopsies of the deceased, the social scientists that study the many social aspects of disasters and most of all the people who lived through the experience and who usually have extricated and saved many of their relatives and neighbours during the first 12 to 24 hours.

An additional problem is that the definition of a destroyed building is quite different depending on its type and location. Increasing wealth and safety standards mean that in some cases the assignment of a building to the destroyed category may be nowadays more lenient than 2 decades ago. Furthermore a destroyed building does not always mean that it has collapsed trapping its occupants. Often most of the destroyed buildings (except in areas where buildings are known to be extremely vulnerable) have either been extensively damaged (unrepairable) but are still standing or have fallen partly (with limited volume loss) or their walls have fallen out-of-plane but roofs are still standing etc. The physiognomy of destroyed buildings is therefore a key factor (Schweier and Markus, 2006; Okada and Takai, 2000; Hengjian et al., 2003) and this relates also to the structural type of the building (its redundancy or lack of it). Given a collapsed building the chances of survival are also quite different depending on the type of structure (e.g. a rubble stone masonry house without mortar and a heavy roof will kill a much larger proportion of its occupants than a house made of timber that has collapsed). Reinforced concrete buildings will kill more occupants if they lack redundancy and collapse in a pancake manner, and the more floors they have the larger will be the proportion of those killed among the occupants. Mid-level collapses or top-down collapses such as those seen in Mexico city and Kobe will kill a much smaller proportion of their occupants.

Injuries and in particular severe injuries also result from building collapses and failures though such injuries may also occur in smaller proportions even when the building damage level is moderate as shown in some in-depth studies (Murakami, 2001; Petal, 2004). Despite relatively large differences in the number of injuries and types of wounds in each of these events, the body parts of injured samples from surveys seem to present similar characteristics: lower extremities injuries dominate in general, followed by head and neck, and then upper extremities. Wounds in the central parts like the abdomen were not reported as much. This may be because most chest wound victims die as a result of crushing and the compression of the lungs (CMD, 2006). It could also be explained by the fact that when earthquakes happen during night time (5 out of the 11 events examined here), people who are asleep in bed would have wounds on parts of the body close to surrounding objects and furniture (Okada, 2007). Understanding these reasons and applying them to emergency planning would improve the efficiency of disaster medical teams.

In some cases, improvement of emergency services, and the speed at which they can be deployed, could have saved lives. For example, narrative accounts from the UK Fire Services Search and Rescue Team diaries have stated that the delays in deployment and failures of infrastructure on which the emergency services rely on are critical to the number of lives saved (UKFSSART, 2005). But the precise proportion of deaths and injuries attributed to these delays are unknown as there are no comparative analyses possible, therefore one can only infer from the information collected.

It is also evident that injuries cannot be accounted for solely by the damage to buildings. Density of population, infrastructure and the locations and connections of vulnerable areas strongly affect the ability of a region to cope with the immediate aftermath of an event and therefore complications in injuries. However, these parameters and their exact effect on the final casualty estimate cannot be derived from casualty statistics. This information has to be captured another way.

### 1.4.1 Testing Hypotheses

So what of these hypotheses from established models? Have these been tested with findings from recent earthquakes? What can one test from gathered information and what have we had to infer? The table below reviews these statements in turn:

**Table 1.5** Table assessing the validity of established hypotheses against information gathered from recent events

| | Established Hypotheses | Tested by recent events? | Ability to test with published findings? |
|---|---|---|---|
| **DEATHS** | | | |
| D1 | For those inside buildings at the time of the earthquake, the primary cause of death is injury (trauma) directly caused by building collapse | Crushing in collapsed buildings has been cited as causes of deaths in most events. Dust inhalation is also a major cause of death in collapsed buildings. | There have been autopsy reports of deaths in Northridge, Athens and Kobe but for all other earthquakes of mass casualties, this hypothesis have been inferred from search and rescue reports. |
| D2 | As suggested in the original Cambridge University Casualty Model:<br>1. some survive but are trapped by the collapse<br>2. Those in buildings which do not collapse have a much lower risk of death | There are certainly survivors from collapsed buildings as witnessed in all of these earthquakes. | The precise risk of death and percentage of trapped and non-trapped people is unknown. It has been established that it varies by structural type, building height, building footprint, volume loss, age and gender of the occupants, time of day, season, duration and severity of shaking, frequency characteristics of ground motion and the duration of the collapse. |
| D3 | For a collapsed building, the proportion of occupants at the time of collapse who are either killed or trapped depends of the form of construction | This can only be done by looking at casualty distribution in completely collapsed buildings. | Percentage breakdowns of fatalities attributed to building types like that carried out by Pomonis for Athens are rare and should be encouraged. Death rates can be established |

| Established Hypotheses | | Tested by recent events? | Ability to test with published findings? |
|---|---|---|---|
| | | | for collapsed buildings by structural type (RC frame by volume loss; rubble stone, adobe, bahareque/tapial/quincha, Kobe-type timber frame, California-type timber frame etc.) |
| D4 | The rescue rate of those trapped depends on the effectiveness of search and rescue (SAR). SAR effectiveness depends on<br>1. The proportion of buildings which collapse<br>2. Availability of organised SAR to supplement local community capability<br>3. Distance travelled by rescue teams<br>4. Transportation disruption | There are some reports and statistics gathered on search and rescue and comparisons made by Kuwata (2006) for Kobe and Chi Chi highlighting factors contributing to effectiveness of SAR, commenting on transportation disruptions and distance travelled but not on capability limits. | Not immediately obvious what proportion of deaths would be preventable deaths. Autopsies estimating the time of death of the victims in Kobe showed that 12.8% died more than 6 hours after the event. For the Athens earthquake it was established based on their low injury severity score (ISS) that 10.5% of the victims trapped under rubble were potentially preventable had the victims been extricated soon enough. Also all that died from asphyxia (29.5%) had low ISS. |
| D5 | Death rates are higher for the most vulnerable: the aged and children. | Individuals over age 65 had 2.9 times the risk of injury as younger people (95% confidence interval (CI) 1.2 to 7.4) and women had a 2.4 times greater risk than men (95% CI 1.2 to 5.1) according | Not enough evidence to generalise as a dominant factor. |

| | Established Hypotheses | Tested by recent events? | Ability to test with published findings? |
|---|---|---|---|
| | | to Peek-Asa (2003) for Northridge. The aged were certainly more at risk in Kobe though this was due to living habits in the most vulnerable of houses. Liao et al. (2003) and Chou et al. (2004) on Chi Chi, Taiwan found that those 65 and over were over-represented in the fatalities. | |
| D6 | For those outside, deaths are rare. | Rock and mudslides as shown in Kashmir and Wenchuan are indiscriminate. | There is knowledge about the breakdown of the causes of death (building collapse, ground shaking, landslide, tsunami, fire following, etc.) which can be broken down by geographic region. |
| **INJURIES** | | | |
| I1 | All or most severe injuries are caused by structural collapses. | Petal's survey found that 91% of severe injuries have structural causes. In Kobe, cut wounds were associated with more damaged areas. Non-structural hazards such as displaced partition walls, furniture and light-fittings can be responsible for many | Investigations into severity of injuries with the damage states of dwelling should be possible after events. This is not always published and field surveys are necessary to extract this information especially for lesser damaged houses and less severe injuries not requiring hospitalisation. |
| I2 | Some injuries are caused by failure of non-structural elements or contents: these are mostly in buildings which do not collapse. | | |

| Established Hypotheses | | Tested by recent events? | Ability to test with published findings? |
|---|---|---|---|
| | | injuries, including serious injuries as discovered in Kocaeli. | |
| I3 | Where a building does not collapse, injury levels are less if people take evasive action and people would take these evasive actions when:<br>● They are awake<br>● They are adults, but not elderly<br>● They have had some recent earthquake experience | Not tested in gathered statistics. | It is the author's belief that this information can only be gathered through talking directly to survivors of earthquakes. |
| I4 | Moderate injuries occur from both structural collapse and from non-structural elements<br><br>Injury rates do not vary across building types for lesser damage states as these are mainly due to non-structural components as assumed in HAZUS. | Little work has been done in comparing injury rates across building types. Murakami and Petal's work on Kobe and Kocaeli respectively do show injury rates varying with damage levels, above those proposed by HAZUS. | General casualty information collected from government and aid agencies offer very little in the form of causes of different severity of injuries |
| I5 | Light injuries mostly occur from non-structural hazards, contents | Petal's work show moderate to serious injuries associated with non-structural hazards too (Petal, 2004) | |
| I6 | For those outside buildings:<br>Injuries are mostly light or moderate, and occur from falling debris and from falls | Not captured in information gathered from these events. | |

As presented in Table 1.5, there are knowledge gaps, especially on injuries that we need to comprehend in formulating a realistic casualty estimation model. There has been very little published data about the precise processes leading to these injuries. In particular, would the types of injuries change with different building types? What is the influence of regional factors on the distribution of injuries? Would the same distribution apply in developed and developing countries? We have already seen from this sample of earthquakes that the injury pyramids apply to industrialised countries but may become top heavy in an event where there is widespread building collapse like that seen in Bhuj.

It is evident that a crucial part of improving casualty modelling has to start with data collection and designing a method which is aimed at filling these gaps to better our understanding of casualties from earthquakes. It is important to collect the relevant information from actual events to answer the questions that would inform us of the influence of the certain parameters in a loss estimation model. The next section looks at collating this casualty information and building damage information into a central database for public use.

# 2 CAMBRIDGE UNIVERSITY EARTHQUAKE DAMAGE AND CASUALTY DATABASE

During and as part of this project, the beginnings of the Cambridge University Earthquake Damage Database, a web-accessible archive of quantitative building damage and casualty data has been developed. It is designed to improve understanding of building vulnerability and to contribute to earthquake risk assessment and mitigation studies. It has been compiled from damage studies and reports carried out following major damaging earthquakes worldwide, and assembled over 25 years at the Martin Centre, Cambridge University. The database provides a reference and support for the empirical derivation of earthquake vulnerabilities across many countries and a wide range of building types.

The Database is freely accessible to all users, and uses a simple xml format suitable for data mining. Location maps and images of damage are provided for each earthquake event. The Database links to the USGS Shakemap archive to add data on local intensities and on measured ground shaking. Analytical tools are provided to enable user-defined cross event comparisons by ground shaking intensity and by building class. Currently the database contains damage data from more than 53 earthquakes and damage data on over 1.3 million individual buildings. Table 2.1 shows the list of events included in the database to date. In addition to this damage database, where available casualty information have also been added to catalogue.

**Table 2.1** List of events for which some damage data is currently on the damage database

| Date | Country |
|---|---|
| 18/04/1906 | United States (San Francisco) |
| 28/06/1925 | United States (Santa Barbara) |
| 10/03/1933 | United States (Long Beach) |
| 28/06/1948 | Japan (Fukui) |
| 21/07/1952 | United States (Kern County) |
| 16/06/1964 | Japan (Niigata) |
| 29/04/1965 | United States (Puget Sound) |
| 09/02/1971 | United States (San Fernando) |
| 27/07/1976 | China (Tangshan) |
| 12/06/1978 | Japan (Miyagi-ken) |
| 15/04/1979 | Yugoslavia (Montenegro) |
| 23/11/1980 | Italy (Irpinia) |
| 02/05/1983 | United States (Coalinga) |
| 13/09/1986 | Greece (Kalamata) |
| 07/12/1988 | Armenia (Spitak) |

| Date | Country |
|---|---|
| 29/10/1989 | Algeria (Tipaza) |
| 27/12/1989 | Australia (Newcastle) |
| 30/05/1989 | Romania (Vrancea) |
| 20/06/1990 | Iran (Manjil) |
| 16/07/1990 | Philippines (Luzon) |
| 13/12/1990 | Italy (Eastern Sicily) |
| 13/03/1992 | Turkey (Erzincan) |
| 13/04/1992 | Germany (Roermond) |
| 12/10/1992 | Egypt (Dahshur) |
| 15/01/1993 | Japan (Kushiro-oki) |
| 12/07/1993 | Japan (Hokkaido-Nansei-oki) |
| 30/09/1993 | India (Latur) |
| 17/01/1994 | United States (Northridge) |
| 28/12/1994 | Japan (Sanriku-Haruka-Oki) |
| 16/01/1995 | Japan (Kobe) |
| 15/06/1995 | Greece (Aighion) |
| 26/09/1997 | Italy (Umbria-Marche) |
| 26/03/1998 | Italy (Umbria) |
| 09/09/1998 | Italy (Pollino) |
| 17/08/1999 | Turkey (Kocaeli) |
| 07/09/1999 | Greece (Athens) |
| 20/09/1999 | Taiwan (Chi-Chi) |
| 06/10/2000 | Japan (Tottori-ken Seibu) |
| 26/01/2001 | India (Gujarat) |
| 24/03/2001 | Japan (Geiyo) |
| 25/07/2001 | Japan (Miyagi-ken Hokubu) |
| 21/05/2003 | Algeria (Boumerdes) |
| 14/08/2003 | Lefkada |
| 23/10/2004 | Japan (Chuetsu) |
| 20/03/2005 | Japan (Fukuoka-ken Seiho-oki) |
| 08/10/2005 | Pakistan (Kashmir) |
| 26/05/2006 | Indonesia (Yogyakarta) |
| 15/08/2007 | Peru (Pisco) |
| 12/05/2008 | China (Wenchuan) |

The website uses Google maps. The homepage (Figure 2.1) shows a global map indicating epicentres of all earthquakes for which data is available, and lists the earthquakes by country and date.

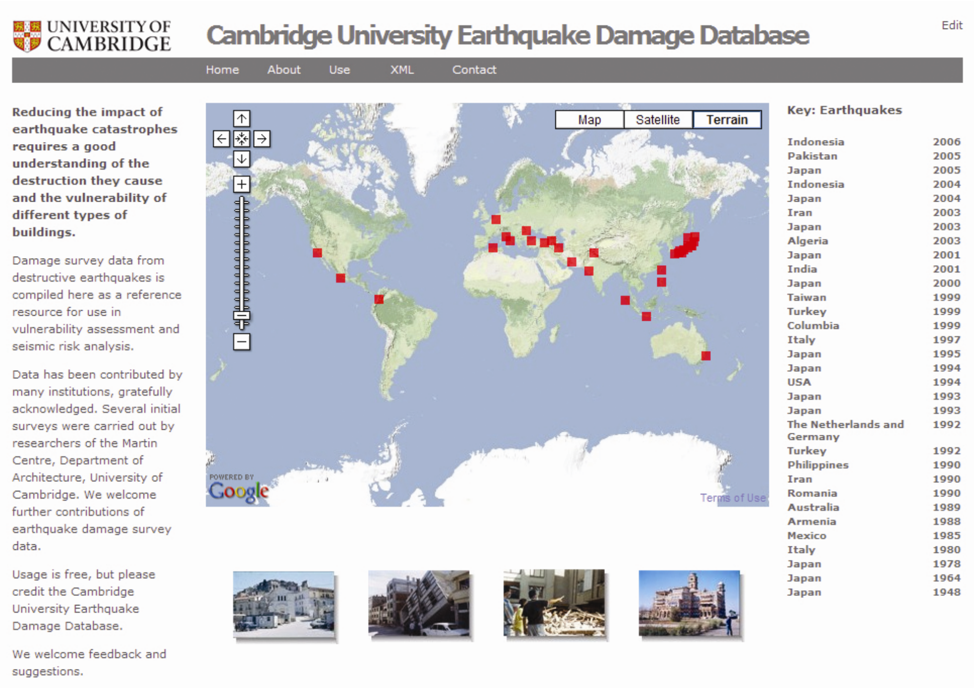



**Figure 2.1:** CUEDD Homepage

Clicking on the name or location brings up the primary event data for that earthquake (Figure 2.2). This includes date, time, magnitude and epicentral location. It also records the estimate of the number of casualties caused. It identifies the separate damage studies carried out for that earthquake for which the database contains data.

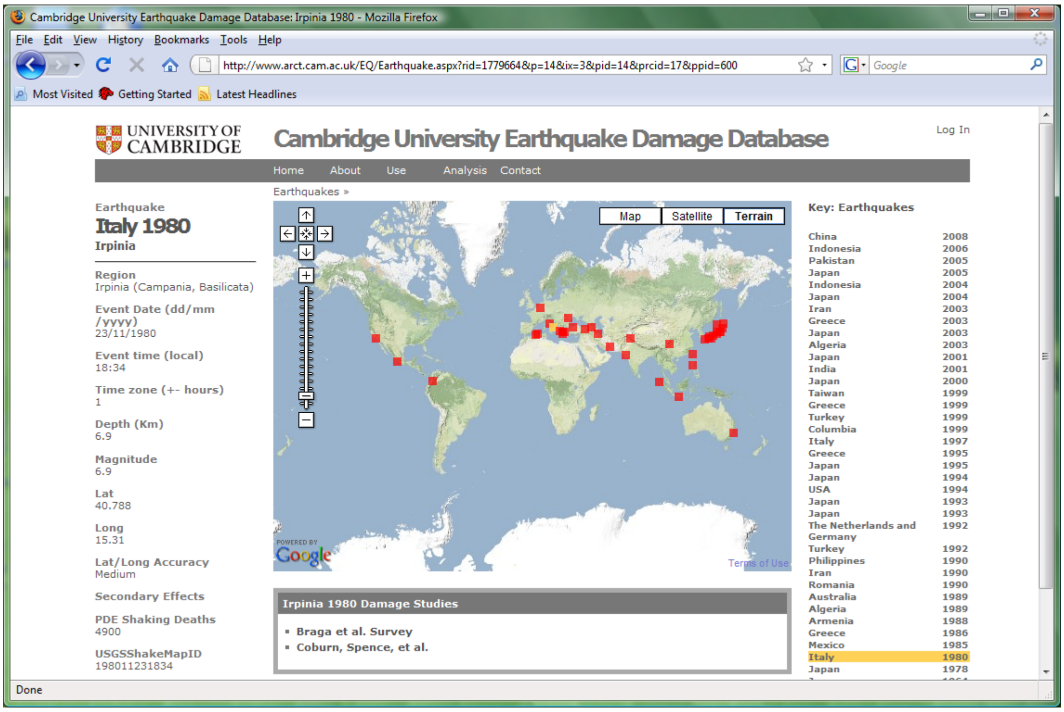



**Figure 2.2**: Damage database - event main page giving overall event characteristics

For each study a map (Figure 2.3) shows the locations of surveys carried out within that study, and gives details of the damage level and building typology classification systems used (Fig 2.5). The survey locations are listed.

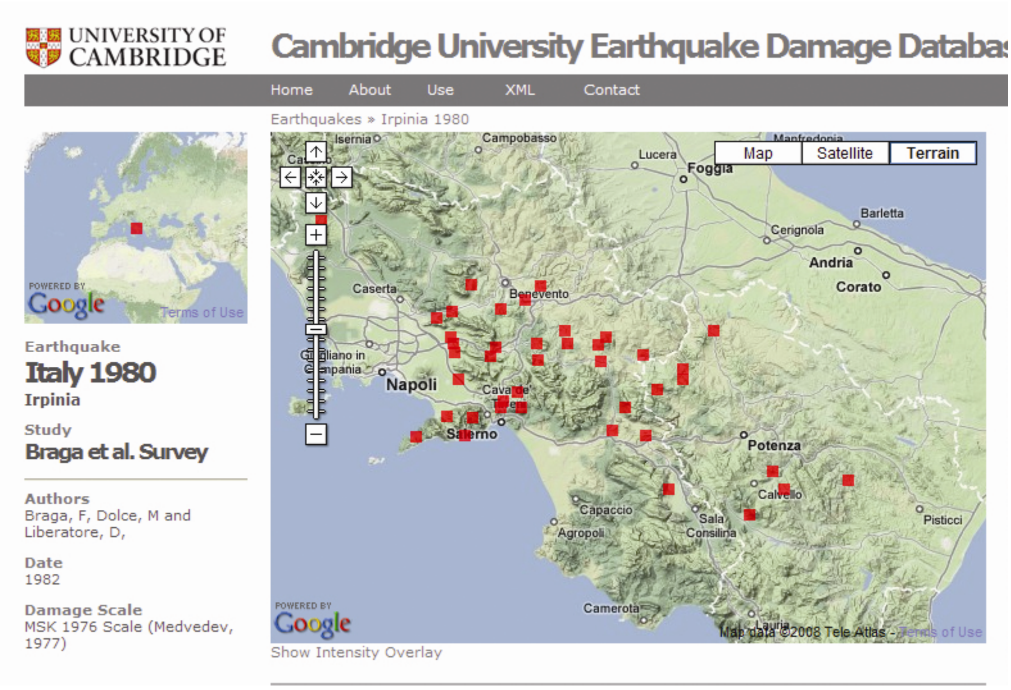



**Figure 2.3**: Typical map for a particular study, giving reference information, and map of study locations

An overlay is available showing the USGS Shakemap, (Fig 2.4) which can be chosen to be contoured according to various measures of ground shaking intensity. A set of photos giving typical damage for that event are displayed. Links are available to strong ground motion locations and recordings for each event. Documentation and reference material for the study are given. Clicking on a survey location brings up the survey data for that location.

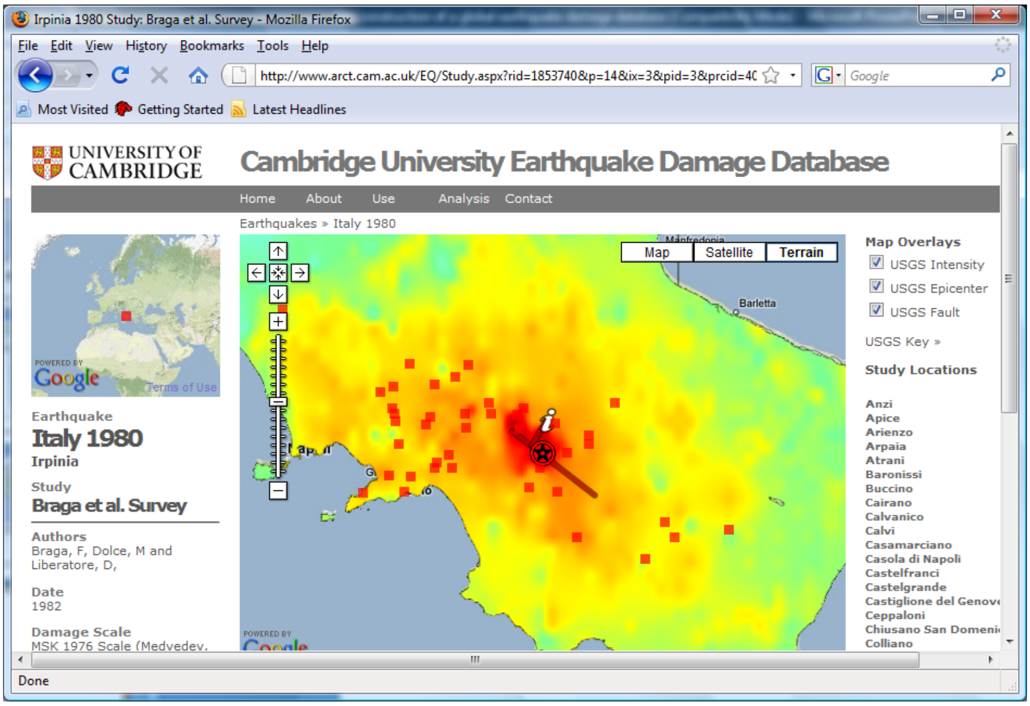



**Figure 2.4**: USGS Shakemap overlay for the event shown in Figure 2.3.

Image Gallery | Data | Documentation

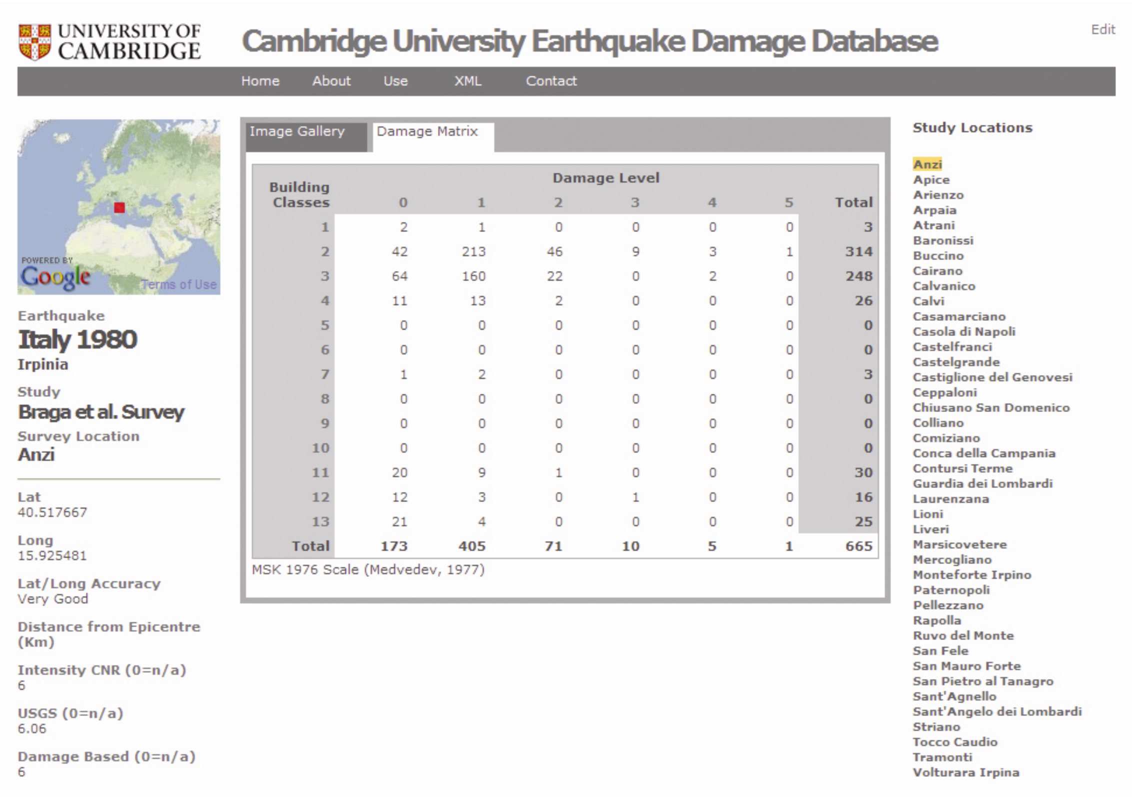
| Damage Levels | | | Master Damage Level |
|---|---|---|---|
| D0 | Undamaged | No visible damage | D0 |
| D1 | Negligable to slight damage | Hairline cracks | D1 |
| D2 | Moderate damage | Cracks 5-20mm | D2 |
| D3 | Substantial to heavy damage | Cracks 20mm or wall material dislodged | D3 |
| D4 | Very heavy damage, partial collapse | Complete collapse of individual wall or roof support | D4 |
| D5 | Total or near total collapse | More than one wall collapsed or more than half of roof | D5 |

| ID | Building Classes | |
|---|---|---|
| 18 | Residential Masonry built before 1920 | Loadbearing masonry, chiefly residential, 2-3 storeys, built before 1920. Some built 18th century and before. |
| 19 | Residential Masonry built between 1920 and 1960 | Load bearing masonry, chiefly residential, 2 - 3 storeys, built between 1920 and 1960. Mostly post-war, c. 1950s, some 1930s. No chimneys. |
| 20 | Residential Masonry built since 1960 | Modern loadbearing masonry, chiefly residential. Some cavity wall construction. |

**Figure 2.5**: Typical damage levels and typical building class definitions

## 2.1 The Damage Survey Data

Each survey is defined by a particular location, by a number of separate building classes and by the number of buildings suffering different levels of damage. Data is presented in tabular form (Figure 2.6), and can be presented by numbers of buildings or as percentages. The lat-long location and the observed or calculated ground shaking at that location are shown. A small map provides a link to the location. The survey data is accompanied by a strip of captioned images showing examples of the damage at that location. These can be expanded full screen.




| Building Classes | Damage Level 0 | 1 | 2 | 3 | 4 | 5 | Total |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 1 | 0 | 0 | 0 | 0 | 3 |
| 2 | 42 | 213 | 46 | 9 | 3 | 1 | 314 |
| 3 | 64 | 160 | 22 | 0 | 2 | 0 | 248 |
| 4 | 11 | 13 | 2 | 0 | 0 | 0 | 26 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 1 | 2 | 0 | 0 | 0 | 0 | 3 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 20 | 9 | 1 | 0 | 0 | 0 | 30 |
| 12 | 12 | 3 | 0 | 1 | 0 | 0 | 16 |
| 13 | 21 | 4 | 0 | 0 | 0 | 0 | 25 |
| Total | 173 | 405 | 71 | 10 | 5 | 1 | 665 |

MSK 1976 Scale (Medvedev, 1977)

**Figure 2.6:** The damage data for a typical earthquake, study and location

### 2.2 The Casualty Survey Data

In addition to physical damage surveys from past earthquakes, the database also houses casualty information for some events. The difficulties in finding useful and dependable data from past research and literature have prompted the development of this casualty database which would promote:

- sharing of knowledge on earthquake casualty from previous events
- translations of research in the local language into a common language whether mathematical or prose in English
- peer review of posted information
- development of global casualty estimation models
- development of guidelines in collecting this information post earthquakes amongst disciplines
- standardisation of injury definitions.

Despite the differences in the nature of events and the difficulty in conforming individual events to averages, there have been significant recent events which have informed us of the ways earthquake motions have affected their local inhabitants. Each event has its own characteristics in terms of level and direction of motion, time of day, proximity of population and vulnerable housing stock and human behaviour. Although there are many factors changing the scale and therefore impact on humans, it is nonetheless essential to learn from these earthquakes in order to understand the degree in which each variable affect the final casualty toll.

In the same format as shown for the damage data, casualty studies for events appear in the main page (Figure 2.7). At the most basic level, casualty data will be presented in the form of regional information, where fatalities and injuries are given for affected districts, towns and villages. The locations of these individual studies are shown as the population centres of the study areas with corresponding intensities taken again from the USGS Shake maps. Figure 2.7 below shows regional casualty data from a historic event.

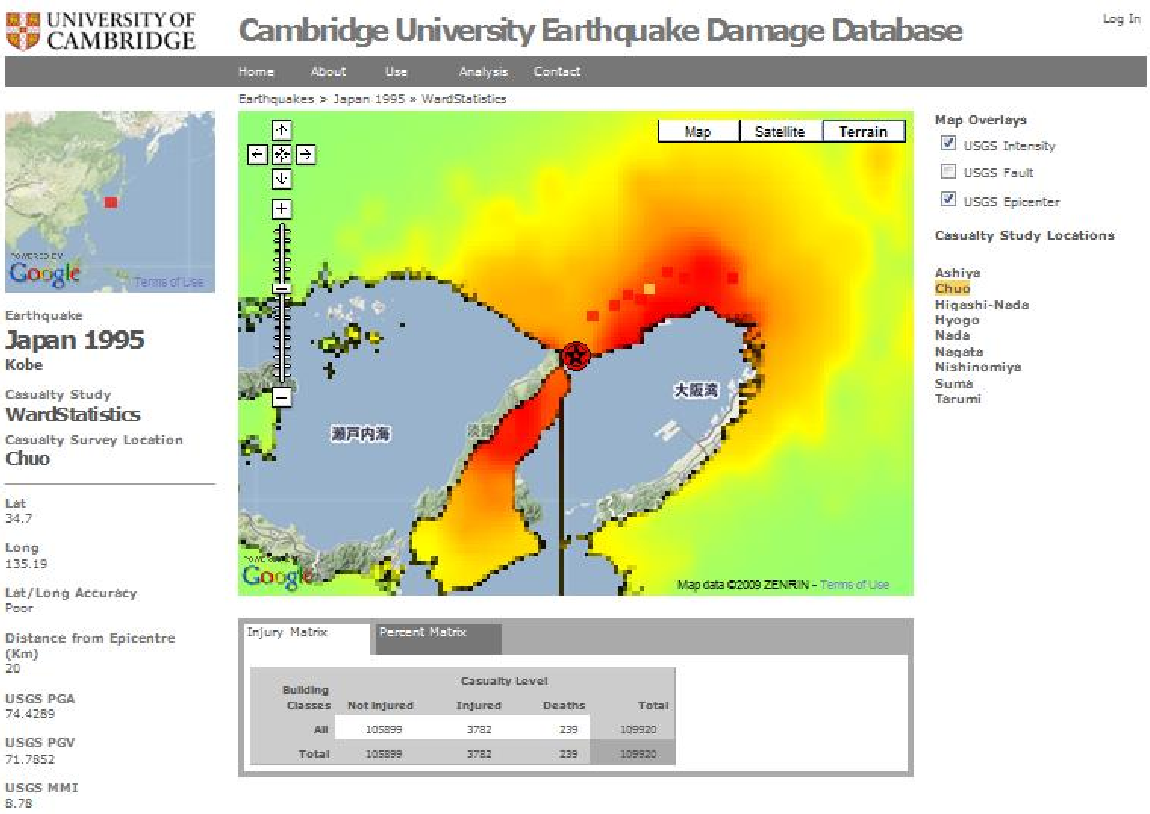



**Figure 2.7:** Regional casualty data for a typical earthquake, study and location

If casualty surveys are available, where fatalities and injuries are related to housing types and damage to housing types, the matrix is further divided into rows according to injury levels, as shown in Figure 2.8 below:

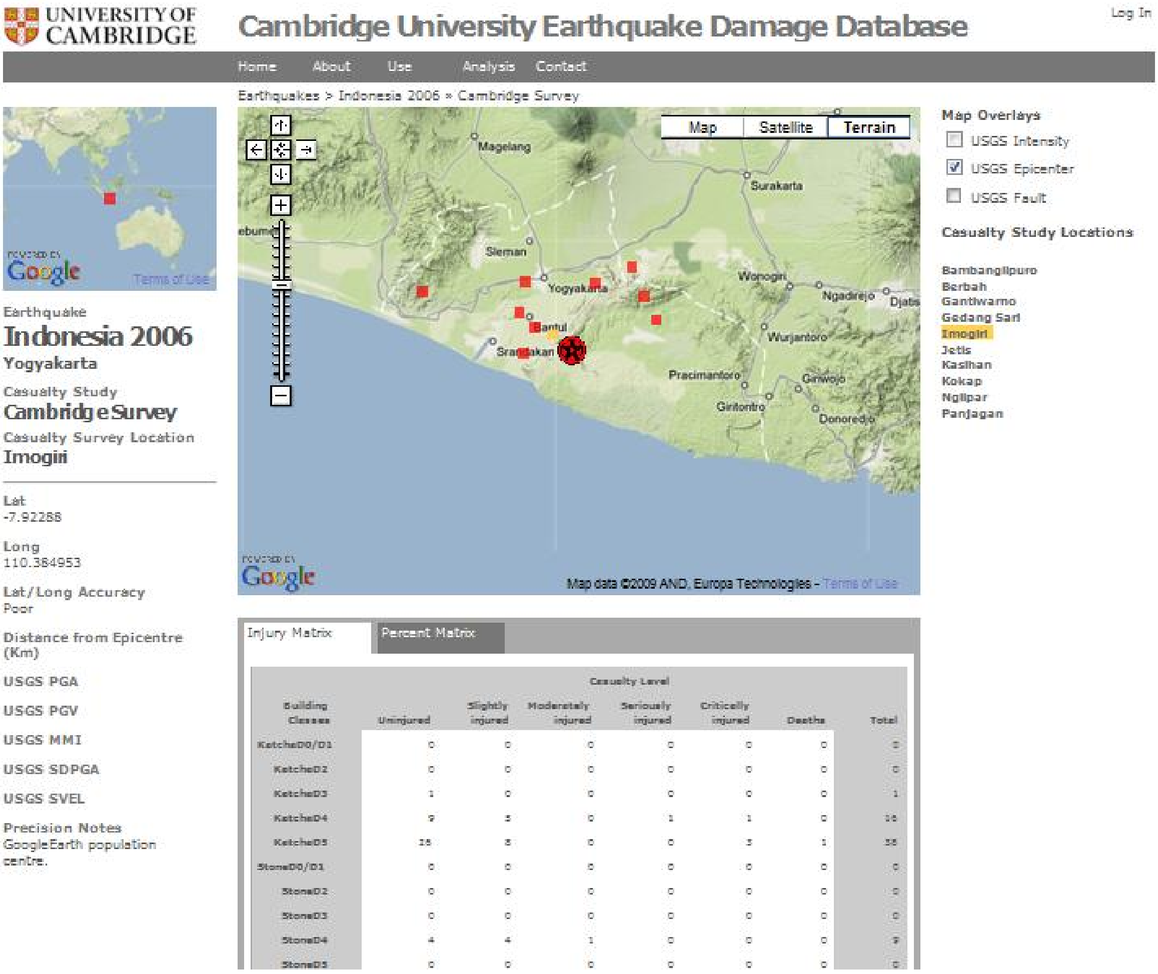



**Figure 2.8:** Detailed casualty data for an earthquake, split into construction type and damage

For each event, the database also houses miscellaneous information such as published casualty literature which includes casualty models for the country or region and published fatality functions and casualty relationships. Since published models hypothesise deaths and most injuries are related to damage to buildings, this forms the focus of the database. In most loss estimation models, casualty rates are presented as a percentage of occupants in a particular building at the time of the earthquake. However, when evaluating the available literature, it was found that many studies do not necessary have statistics in this form. A decision was therefore made to present the data in two forms. The original data will be kept in its entirety but where there can be inferences made on population and occupancy rates based on supplementary local knowledge of the earthquake, a postulated set of casualty rates can also be calculated for comparison purposes. An example of this is shown in Figure 2.9 for the 1999 Kocaeli event where the data attained from Petal's field study are compared against published rates from HAZUS (FEMA, 1999), ATC-13 and Erdik et al., (2000).

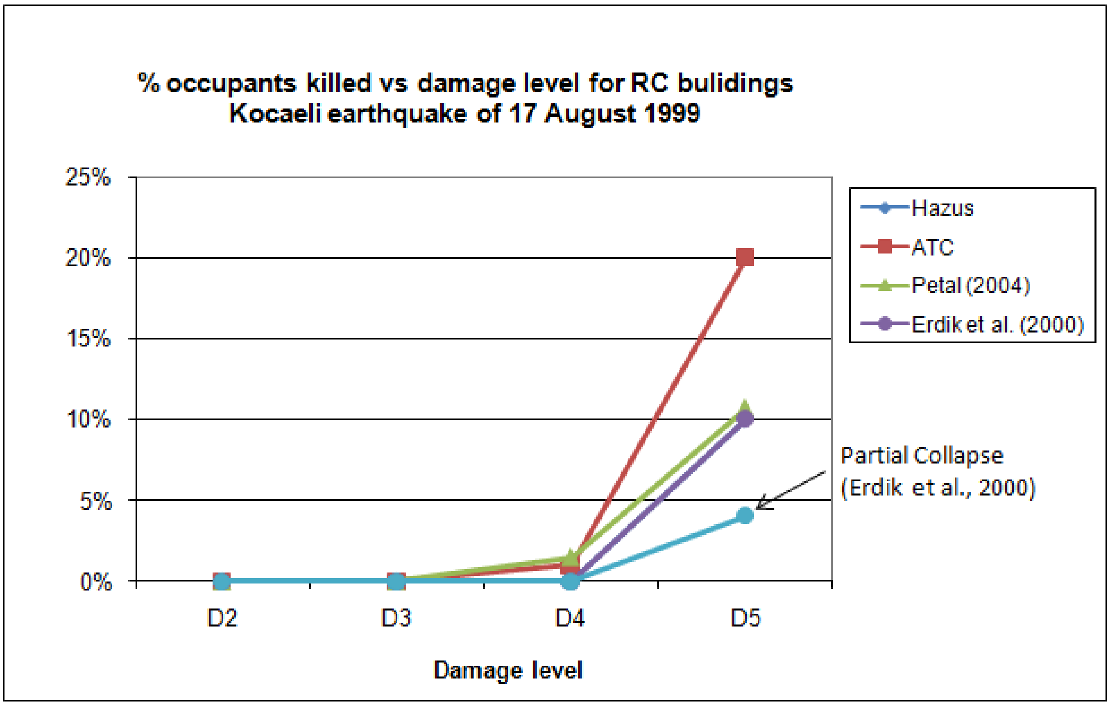



**Figure 2.9:** Graph comparing percentage of occupants killed in reinforced concrete housing from a survey in Gölcük and rates published by various sources

One of the aims of this casualty component of the CUEDD is to bring together practitioners from different disciplines involved in earthquake emergency management. In line with this, the database also houses medical and public health information from past earthquakes including studies on medical causes of deaths and injuries. A critique of this information may tell us more about the types of injuries associated with different housing, climatic and cultural environments. For example, none of the 1,502 patients received at the Pakistani military hospital surveyed by Mulvey et al. (2008) were identified as having either crush injuries or acute renal failure in the first 72 hours after the Kashmir earthquake. This compares to 17% of instances found in the Kocaeli earthquake (Bulut et al., 2005) and 2-5% suggested for major earthquakes (Sheng et al., 1987). The lack of crush injury cases may be due to the high mortality rate from the heavy masonry structures or an indication of the failure of the road network bringing rescuers into the affected area of Kashmir. In addition, only 73% of the surveyed patients reviewed continued with medical follow-ups which the authors say could be an indication of cultural beliefs. These pieces of information could be invaluable for international medical units in training for international disaster deployments.

As more information is gathered from future earthquakes, the casualty database will provide a good reference for comparative studies, such as that described in Chapter 5. Differences in the casualty ratios from one event to another may be explained by variations in building quality but also other hazards and causes.

## 2.3 Conclusions

Naturally, individual events do not conform to averages as each earthquake is different and there are many parameters governing likely damage probabilities and casualty rates. However, these earthquake damage and casualty statistics and correlations developed for specific events provide a basis for probabilistic reporting of the likelihood of damage and casualties in specific regions. A collation of available field data will help validate predictions in loss estimation models. Collecting information including observational field data on the sustained damage levels at various ground motions and the associated casualties will help form prediction relationships in the future especially in developing regions where there is little known of the structural properties and seismic resistance of local building types.

A careful study of earthquake damage and casualty statistics and field surveys over the past 30 years has allowed this compilation of information. In an attempt to standardise the method of recording and collating all publicly available damage and casualty information, a global database of earthquake field data has been outlined in this chapter. It is hoped that the Cambridge University Earthquake Damage Database (CUEDD) will add significant value to earthquake estimation models in the future. The next chapter will outline some potential analyses that can be carried out with information from this repository which will help with future global loss estimation in earthquakes.

# 3 ANALYSIS OF ASSEMBLED DATA

## 3.1 Analysis of Damage data in the CU Database

Data collected in the database is in XML format and can be downloaded using specified URLs and read into Excel or used directly in software applications. The following 6 datafiles are available:

- List of earthquakes and their characteristics
- List of separate studies and their key data
- List of survey locations and their characteristics
- List of all damage levels defined and equivalent master damage levels assumed
- List of all building classes defined
- Raw damage data

Using these XML files, survey data can be selected across events by building class, ground shaking level, and damage level., and criteria such as "greater than" a given damage level selected

"Superclasses" can be user-defined to assemble damage data across studies using different classifications, as shown in Table 3.1. Damage data from particular regions or time-periods can be selected.

**Table 3.1** Example of user-defined "superclasses" .

| | Construction typology | Superclass category | |
|---|---|---|---|
| M | Masonry | M1 | Weak masonry |
| | | M2 | Brick and block masonry, no rc slab |
| | | M3 | Brick and block masonry with rc slab |
| | | M4 | Reinforced or confined masonry |
| RC | Reinforced concrete | RC1L | RC pre code, low rise |
| | | RC1M | RC precode, mid or high rise |
| | | RC2L | RC early code, low rise |
| | | RC2M | RC early code, mid or high rise |
| | | RC3L | RC advanced code, low rise |
| | | RC3M | RC advanced code, mid or highrise |
| | | RCSW | RC shearwall |
| T | Timber | TH | Heavy timber frame |
| | | TL | Light timber frame |
| S | Steel | SMF | Steel moment frame |
| | | SBF | Steel braced frame |

| | Construction typology | Superclass category | |
|---|---|---|---|
| | | SLF | Light steel frame |

Two examples of analytical results are given, from the damage and casualty parts of the database. The first example is a cross-event damage analysis to derive empirical vulnerability curves for load-bearing masonry (Superclass M2), damage states vs MMI. Curves are based on data from 199 worldwide damage surveys, including 40,000 buildings. Since the dataset chosen for analysis is worldwide a high level of uncertainty can be expected. However, there was still insufficient data at MMI=5 or MMI=10 for values to be found for these intensity levels. For intensities MMI=6 to 9, Figure 3.1 shows average values of % exceeding each damage level D1 to D5, and regression curves assuming a cumulative normal distribution. Figure 3.2 shows a box and whiskers plot of mean damage ratio (MDR) vs MMI. Such plots can be drawn for any chosen measure of ground motion.

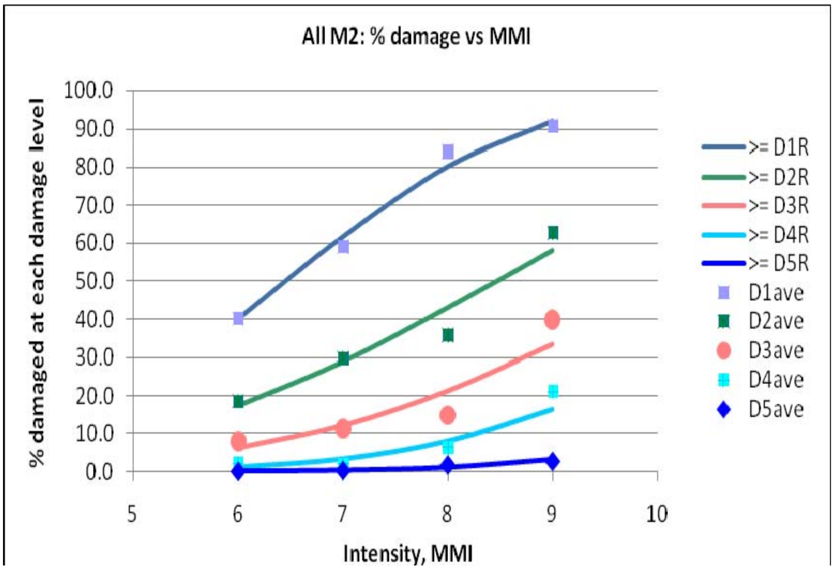



**Figure 3.1**: Percentage exceedence curves vs MMI for M2 superclass

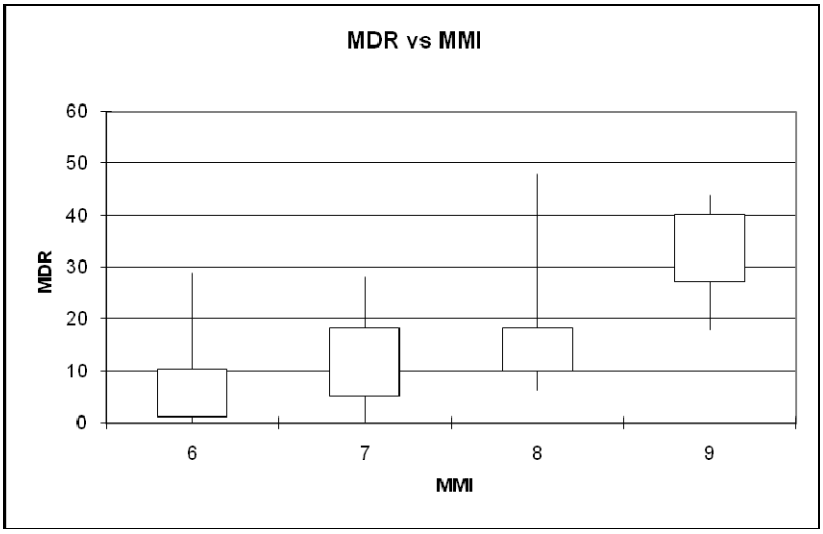



**Figure3.2:** Mean and range of MDR vs MMI for M2 superclass

Figure 3.3 shows a comparison between the mean value of MDR derived from this analysis with the mean value derived from an earlier analysis done as part of the GEVES project which includes vulnerability curves derived from a variety of sources (Spence et al. 2008).

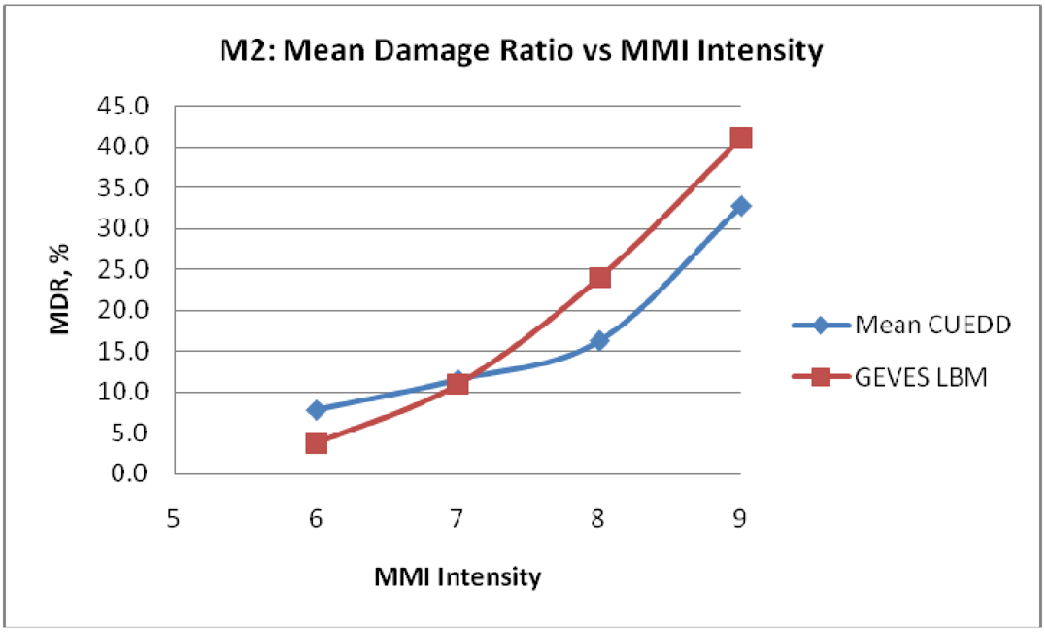



**Figure 3.3:** Comparison of empirical with GEVES vulnerability curves for class M2

### 3.2 Analysis of Cambridge Casualty Survey Data in the Database

In addition to collecting regional casualty data from the field, this piece of research is original because casualty information on two recent events have been collected and analysed in the same way by means of questionnaire surveys. What this means is that cross event analysis and comparisons can be made without assumptions on the precise definitions of the casualty information. One of the problems when attempting to assemble a casualty database and analysing findings from other earthquakes is firstly ensuring data quality and second being sure that one is comparing like with like. The main advantage when looking at two events concurrently is that important characteristics of each event can be drawn out. By comparing the contributing features of casualties of one event against another and using special local knowledge e.g. time of day and cultural factors about the events, one can derive possible factors affecting as well as trends within casualty distributions.

From the survey data, the physical damage to buildings and the relationship between damage states of buildings to deaths and injuries of occupants in these structures are investigated. Derived casualty distributions from these surveys are then compared to published sources, for example HAZUS (1999) and Coburn and Spence (2002). A discussion will follow to conclude what we have learnt from these two events and their implications on general earthquake casualty estimation.

*3.2.1 Examining the relationship between killed and injured and damage levels of dwellings*

In both HAZUS (1999) and Coburn and Spence (2002), casualty rates are given as a percentage of occupants who are likely to be injured and killed in different damage states and housing types. Since in the two events structural factors are still shown to be a leading cause of injuries and deaths, this measure is also used for these analyses.

The graph shown in Figure 3.4 is a plot of the percentage of occupants killed in buildings with different damage levels during the 2005 Kashmir and 2006 Yogyakarta earthquakes. The variation of the fatality rates attained from the surveys grouped by districts are also shown. The majority of people surveyed were in single storey rubble stone masonry dwellings in Pakistan whereas in Indonesia, most were in brick masonry houses with lighter timber truss roofs. This has been included to illustrate the possible ranges of results that can be collected from the same event, even at the same damage level. There were 5 districts surveyed in Yogyakarta, namely Klaten, Kulonprogo, Gunungkidul, Sleman and Bantul. In Pakistan the three districts surveyed were Muzaffarabad, Mansehra and Bagh. As shown in Figure 3.4, the deaths were only recorded in the districts of Bantul and Gunungkidul and though they seem much higher than the weighted average line, they only account for 3 deaths out of 9 occupants in buildings in damage state D3. In Muzaffarabad where dwellings of lower damage levels were reported, lethality rates were found at D2 and D3 to be around the 10-20% range, though again these account for only 9 deaths out of 150 victims. The sample sizes from the surveys at each of these locations are as follows:

**Table 3.2** Responses from collected surveys in Kashmir and Yogyakarta

| | Damage State | no, of deaths | % of occupants killed |
|---|---|---|---|
| **Pakistan** | | | |
| Muzaffarabad | D0/D1 | 5 | 71% |
| | D2 | 1 | 33% |
| | D3 | 2 | 50% |
| | D4 | 6 | 40% |
| | D5 | 136 | 56% |
| | Total | 150 | |
| Mansehra | D2 | 0 | 0% |
| | D4 | 0 | 0% |
| | D5 | 159 | 63% |
| | Total | 159 | |
| Bagh | D0/D1 | 1 | |
| | D3 | 0 | |
| | D4 | 9 | 36% |
| | D5 | 63 | 44% |
| | Total | | |
| **Indonesia** | | | |
| Klaten | D0/D1 | 0 | 0% |
| | D2 | 0 | 0% |
| | D4 | 0 | 0% |
| | D5 | 0 | 0% |
| | Total | 0 | |
| Kulonprogo | D0/D1 | 0 | 0% |
| | D2 | 0 | 0% |
| | D5 | 0 | 0% |
| | Total | 0 | |
| Gunungkidul | D0/D1 | 0 | 0% |
| | D2 | 0 | 0% |
| | D3 | 2 | 33% |
| | D4 | 2 | 6% |
| | D5 | 5 | 4% |
| | Total | 9 | |
| Sleman | D0/D1 | 0 | |
| | D2 | 0 | 0% |
| | D3 | 0 | 0% |
| | D4 | 0 | 0% |
| | D5 | 0 | 0% |
| | Total | 0 | |
| Bantul | D0/D1 | 0 | |
| | D2 | 0 | 0% |
| | D3 | 1 | 33% |
| | D4 | 2 | 4% |
| | D5 | 48 | 25% |
| | Total | 51 | |

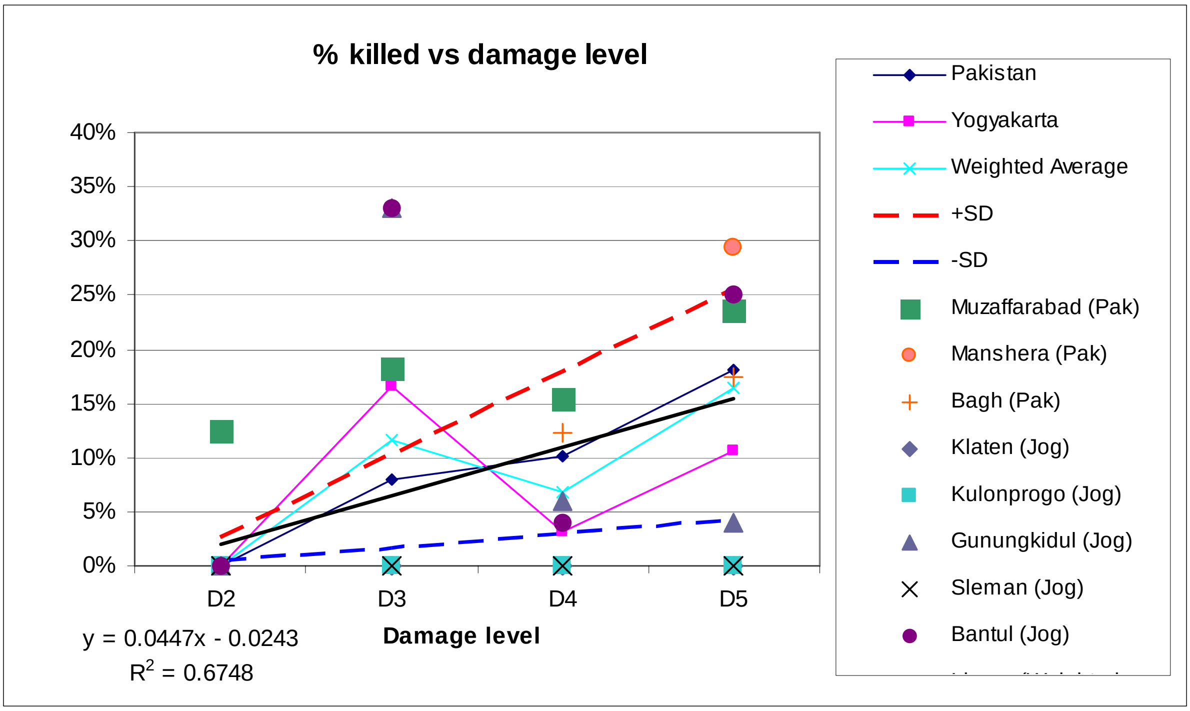



**Figure 3.4**: Graph showing relationship of percentage of occupants killed in the two surveys vs. building damage levels

No and slight damage data have not been included in this analysis as casualties in these damage states accounted for less than 0.3% of the total occupants injured in these dwellings. A weighted average line has been plotted which takes into account the differences in sample sizes between the two earthquakes. By including the additional information provided by respondents on other injured and killed within their party, the sample in Kashmir under consideration is now 2,082 individuals whereas in Yogyakarta there were 692. The resulting linear regression relationship has been drawn to capture the relationship between building damage level and percentage of people killed in these two earthquakes. This was found to be a linear relationship:

$$\% \text{ of occupants killed} = 0.0447x - 0.0243$$

x is a damage level increment for $D_{(N-1)}$, i.e. x =1 for $D_2$ with $R^2$ of 0.6748.

The $R^2$ would suggest the weighted average data fit reasonably well around the proposed linear relationship between building damage level and percentage of occupants killed in these damaged buildings. The mean ± standard deviation (σ) lines are also plotted in the graph shown in Figure 3.4. Since there is a large variation in the sample sizes at each damage level, a weighted σ to the sample size was first considered. This however produced insignificant variations about the mean at the less damaged levels as the relative number in the samples were so small. For example, there are only 24 responses in the sample for D2 as compared to 1,169 at D5. Therefore, the standard deviation at D5 was used to extrapolate to the lower damage levels, as shown.

In the same way, regression relationships have been obtained to capture the correlation between damage level and the proportion of occupants who were seriously injured (including fractures and organ and soft tissue damage) plus those killed in these two events in Figures 3.5 and 3.6.

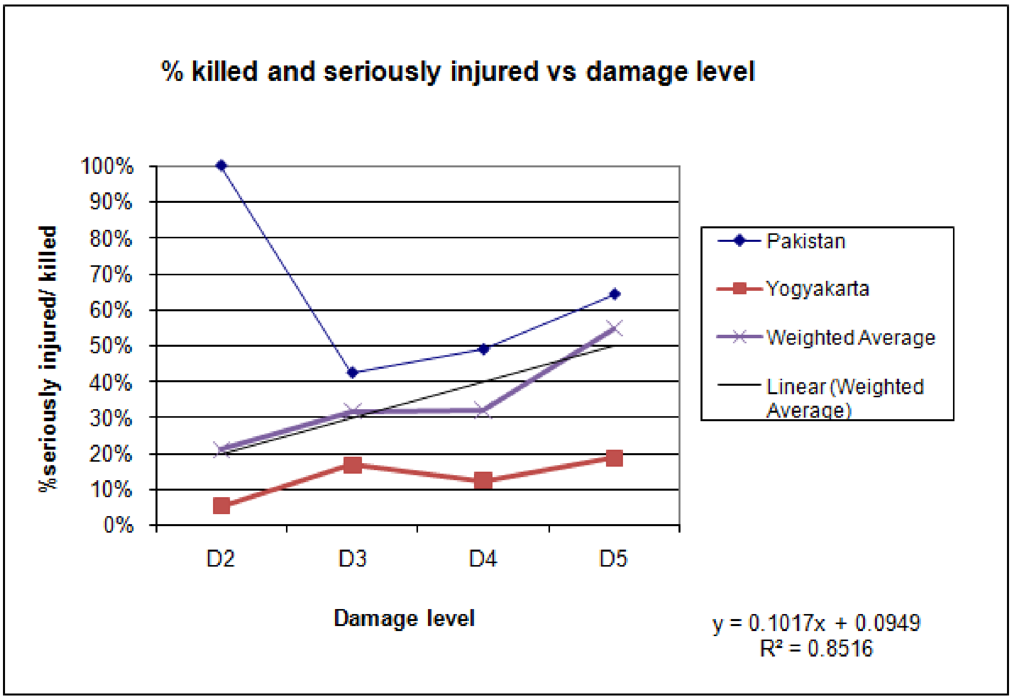



**Figure 3.5**: Graph showing relationship of percentage of occupants seriously injured and killed in the two surveys vs building damage levels

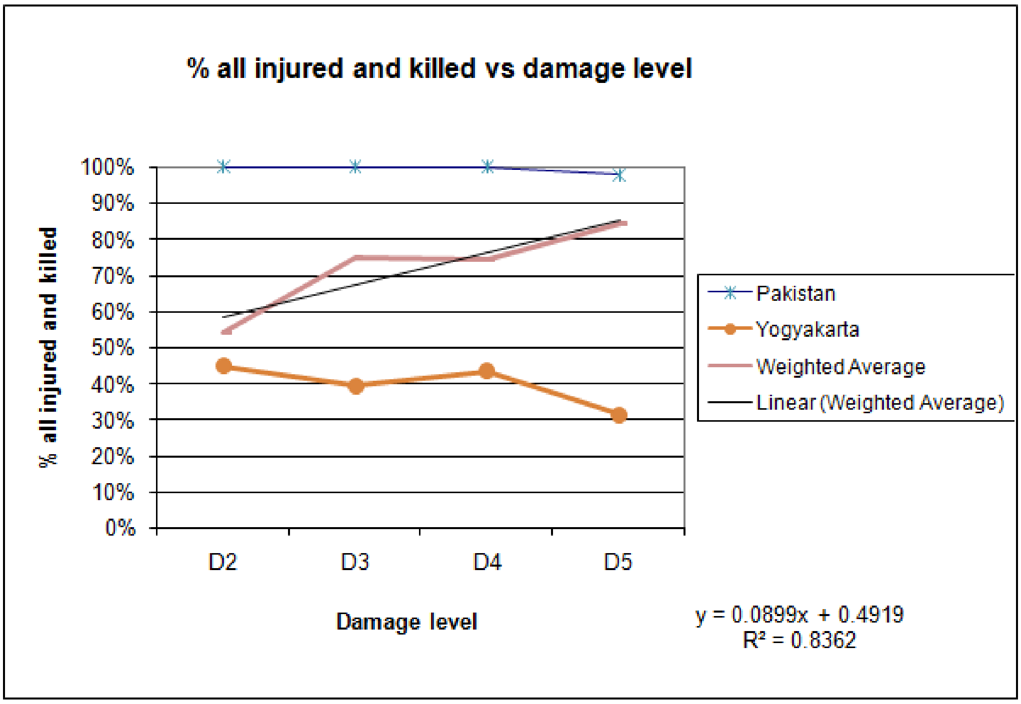


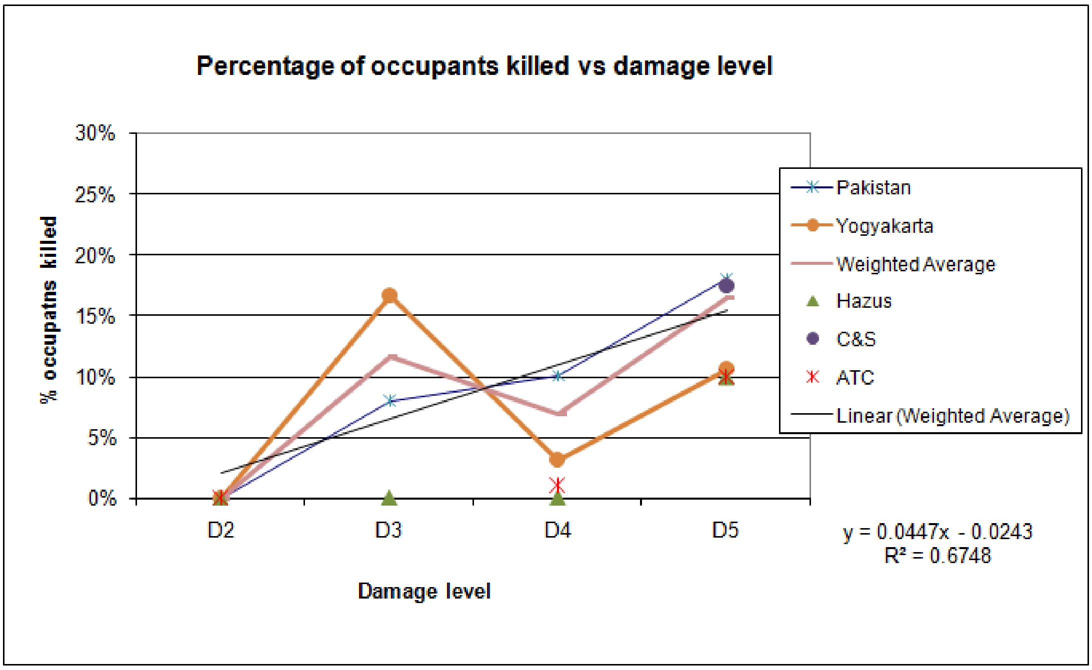

**Figure 3.6**: Graph showing relationship of percentage of all occupants who were injured and killed in the two surveys vs building damage levels

These graphs clearly illustrate the high injury and death rates in Pakistan as compared to Yogyakarta as 98% occupants surveyed in Pakistan were injured in some way at all building damage levels. Both sets of data can again be encapsulated with linear regressions relationships as shown in the Figures 3.5 and 3.6, the fit of the weighted average data to the linear relationships are shown to be very good ($R^2 > 0.83$).

The differences in casualty rates between the two earthquakes-regions are much more prominent in these two graphs, especially when all casualties are counted. This is because of the high injury rate evident in the dataset from Pakistan, which has also been reported in situational reports published by OCHA (OCHA, 2005). Averaging such different casualty levels may be questioned but given the extremes of the two events, this is considered reasonable at this early stage of the model development. These two event surveys are typical in so far as they portray what happens in reality. There are events like the Kashmir earthquake which was a large magnitude earthquake (7.6Mw) affecting a rural, mountainous area, destroying 263,000 dwellings that resulted in an immense death toll of 73,000 (in Pakistan). Whereas in Yogyakarta, an earthquake of moderate magnitude (6.4Mw) affecting a densely populated rural region, destroying 157,000 dwellings only resulted in 6,000 deaths. This would suggest that there are other factors to building damage causing such deviations about the derived weighted average line. In using these relationships, one must therefore assess how local factors may augment or diminish casualty rates by introducing corrections factors to account for their influence.

*3.2.2 Comparison with Published Models*

Whilst the individual analysis of the earthquakes and the analyses of variances across events have revealed other significant contributing factors to casualty distributions, it is also important to see how these earthquakes fare against published loss estimation models. In Figure 3.7, the percentage of occupants killed at different damage levels have been plotted against the results from the Kashmir and Yogyakarta event. Since the majority of building stock represented in these surveys is unreinforced masonry, casualty rates from HAZUS02, ATC-13 and Coburn and Spence (C&S) have been plotted for this category.




*URM casualty rates assumed for HAZUS, ATC and Coburn and Spence, since majority of affected building stock in both events is URM*

**Figure 3.7**: Graph showing relationship of percentage of occupants killed in the two surveys at different damage levels and those from published sources

It is very clearly illustrated in this graph that in current models, the assumption is that there will be negligible percentages of people killed in lower damage levels (only 0.2% of occupants in D4 in HAZUS), but the derived weighted average line shows significant difference in D3 and D4, which could be important.

Furthermore, if we look at overall casualties including people who are injured in these buildings, at D5 the three models are all within the range of the two events assessed. But for the lower damage levels, Figure 3.8 would suggest that the models are underestimating the number of people injured in these less damaged buildings.

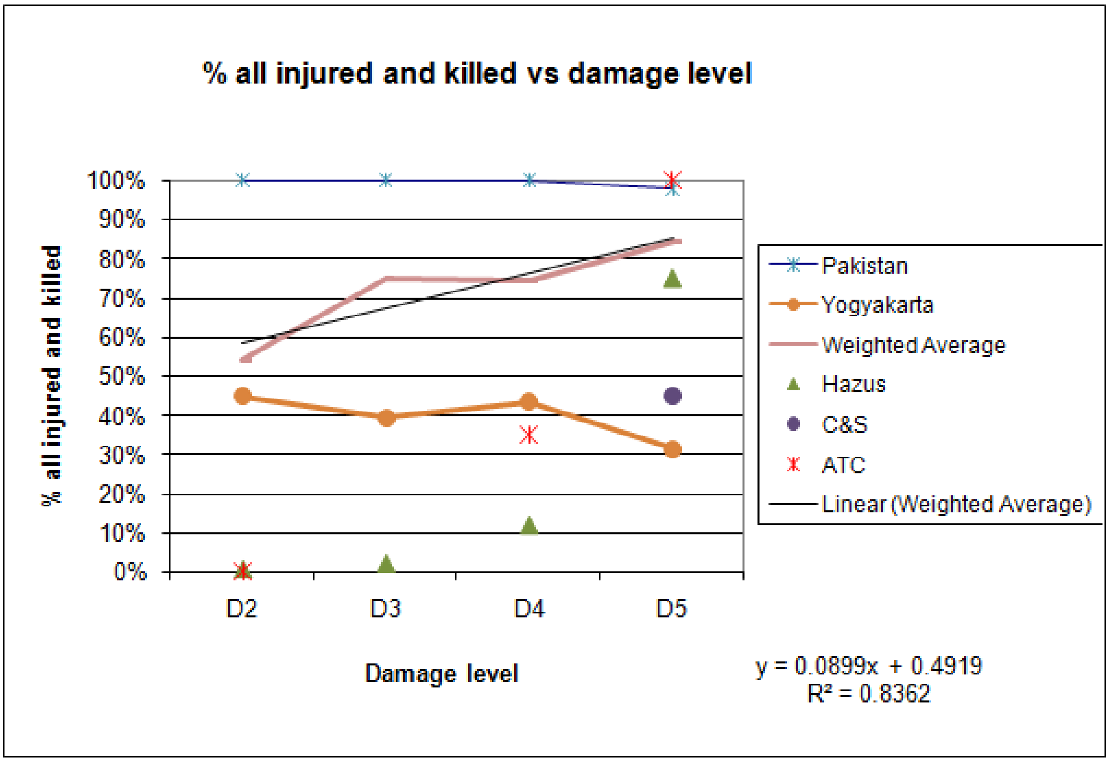



**Figure 3.8**: Graph showing relationship of percentage of occupants injured and killed in the two surveys at different damage levels and those from published sources

This is certainly an area where more research of this kind can help in evaluating current casualty estimation modelling by providing evidence of deaths and injuries in dwellings at lower damage levels.

At this stage, an assessment can be made to see whether these derived relationships can accurately estimate casualties from actual events. Nevertheless this is a crude evaluation as it only compares the casualties generated from building damage and URM rates are specific to local building stocks. One can argue that these assumptions are reasonable as, in current models, very few casualties are attributed to other causes like landslides; and lethality rates for URM are the highest amongst all published categories (Tables 13.3-Table 13.7 in HAZUS). This will provide a good indication of whether any improvements have been made through collecting field data and subsequent analyses in estimating casualties. Table 3.3 below compares the actual numbers of deaths and injuries collected in the surveys against what would be predicted with the derived linear weighted average equations and the published models of HAZUS, ATC-13 and Coburn and Spence.

**Table 3.3** Comparison of actual and estimated deaths on the surveyed sample in the Kashmir and Yogyakarta events

| | Actual reported | Estimation Model results | | | |
|---|---|---|---|---|---|
| | | **Cambridge** | **HAZUS** | **ATC-13** | **Coburn and Spence*** |
| **Kashmir Earthquake** | | | | | |
| Deaths | **362** | 311 (-14%) | 190 (-48%) | 191 (-47%) | 332 (-11%) |
| All Casualties | **1886** | 1752 (-7%) | 1442 (-24%) | 1950 (+3%) | 854 (-55%) |
| **Yogyakarta Earthquake** | | | | | |
| Deaths | **53** | 92 (+73%) | 50 (-6%) | 51 (-4%) | 87 (+64%) |
| All Casualties | **241** | 561(+133%) | 389 (+61%) | 542 (+125%) | 223 (-7%) |

*This has been taken from Table in 9.10 *Earthquake Protection* (Coburn and Spence, 2002) which refers to a study in Wellington in New Zealand and has a lethality rate for D5 buildings only.

This comparison has proved a very valuable exercise as it shows that using the proposed relationships, for earthquakes where building damage is the main cause of casualties as in the case of Pakistan, the predictions for deaths and injuries are both within 15% of the actual values, although this is to be expected since the linear fit is closely related to the Pakistan survey and complete collapses.. On the other hand, the estimates derived from current models, which are based on building collapses have wider ranges. For Kashmir, HAZUS estimates are between 24-48%, ATC estimates vary between 3 and 47% and Coburn and Spence offers predictions which are 11-55% outside the actual values.

For the Yogyakarta earthquake however, the proposed regression relationships do not provide good estimates and overestimates by up to 133%. As discussed in Chapter 2, there were other contributing factors to survival which helped lower injury rates in the Yogyakarta event. In this case, factors such as evasive action, the collapse mechanism of the vulnerable housing and therefore entrapment both played a part in reducing the final casualty number. For the Yogyakarta earthquake, the current models offer closer estimates than those calculated using the proposed relationships. The estimated deaths seem to correspond well with the actual number of people killed using HAZUS and ATC-13, however the number of total casualties predicted are up to 60- 120% outside the actual values. The lack of consistency in the predictions of deaths and the total number of casualties may suggest that the fit is coincidental.

In order to provide a viable casualty estimation model, it is therefore essential to determine what would control the final casualty number. In environments where there will be substantial building damage and little in terms of other influential factors making a significant impact on reducing or increasing casualties, then this regression relationship may be appropriate. Where other contributing factors may have an effect, the relationships should be used together with local knowledge to form correction factors. For example in the case of accounting for evasive action taken by the occupants, it may be appropriate to apply a reduction factor of 0.5 times the standard deviation. These correction factors will have to be fine tuned with field data and local studies but are an essential part of forming realistic casualty estimation models.

When presenting regression relationships, it is important to assess possible deviations by introducing upper and lower bounds. A proposed ±σ (standard deviation) seems appropriate as plotted in Figure 3.4, given the validation presented in Table 3.2. Though this will need to be tested with information from other earthquakes where the original data have not been used to generate the regression line. Figure 3.9 below shows the inclusion of these deviations plotted with the postulated regression relationship.

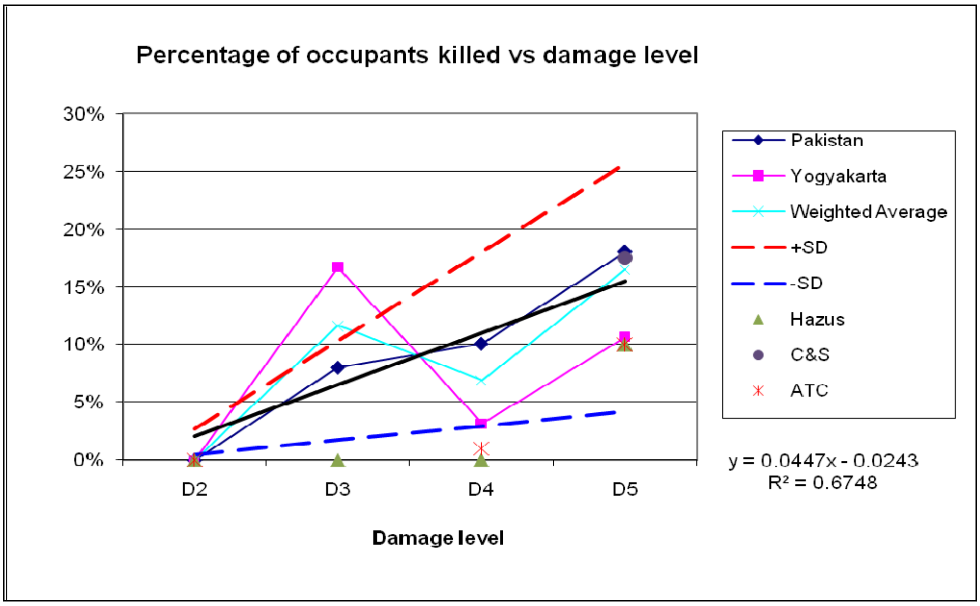



**Figure 3.9**: Graph showing the regression relationship for % of occupants killed at different building damage states with proposed error bands

***Discussion of Findings***

Using the data from the two surveys, relationships were postulated between percentage of occupants who were killed and injured in these events and the corresponding damage level of the building these people were in at the time of the earthquake and these are presented in Figures 3.5 – 3.7. Linear regression relationships were obtained with reasonable fit to the average weighted data ($0.67 < R^2 < 0.85$) which provide a good basis for comparing with published data and other earthquakes. Moreover, since this is the first time information has been collected in this manner in rural areas of developing countries, these relationships could be used with suitable allowance for uncertainties to postulate preliminary casualty numbers in loss estimation models for these regions.

When comparing the observed data with published casualty models, assuming the building type URM (unreinforced masonry), it has been shown that both the ATC-13 and HAZUS models fall within the range of observed lethality rates for building level D5 but both notably underestimate the number of injuries and deaths attributed to less damaged buildings. This is an area which needs more work in the future.

The proposed linear regression relationships were found to provide good estimates (within 14%) for the Kashmir earthquake where casualties were dominated by building collapse. In this case, the other models' predictions had larger errors. However, when calculating the expected deaths and injuries in Yogyakarta, the ATC-13, HAZUS and Coburn and Spence all fared better as shown in Table 3.2. This would suggest that the relationships produced should be used in conjunction with other correction factors to account for contributing factors which serve to reduce or augment number of casualties.

### 3.3 Conclusions from the Analyses of Building and Casualty Data

The analyses of these earthquakes have provided an insight into the complexity of estimating casualties due to the specific characteristics of each event and the possible scenarios associated with each respondent. For example, a survivor could have survived suffering only minor injuries in a collapsed unreinforced masonry house in Yogyakarta because he was by the door at the time and his knowledge of earthquake made him move outside where there is sufficient space. By contrast, when congregated with hundreds of other people in a equally vulnerable school building in Pakistan, there may be little time to react and take evasive action as a wall caves in, especially if the building is situated on a failing slope. These datasets have provided invaluable information for the investigation of causal factors of injuries and deaths. This work is unique as it has provided the opportunity to compare events based on data collected in the same manner and in doing so, relationships of damage and casualties have been derived for the two events.

What these earthquakes have taught us is that many of the common hypotheses still hold true but there are also others that cannot be tested directly and for which assumptions must be made or data have to be collected by other means. The findings from the surveys can guide us in making educated guesses on the influence of certain aspects, for example of search and rescue. Though not directly deduced from the data, the difference in waiting times to the arrival of medical aid certainly was affected by transportation disruption and efficiency of rescue teams.

The applicability of these lessons and conclusions may be questioned and one may ask whether these two events are typical of experiences that will be repeated in future events around the world? The simple answer is 'yes'. Although building techniques may differ around the world, these two earthquakes are both typical of developing countries where large number of casualties is most likely. These are countries where site locations, density of housing and populations are not controlled and most houses are built by local builders and owners who do not need to adhere to seismic codes. Furthermore the housing stock is what can be described as 'second generation' housing where traditional techniques and materials are mixed with new materials, such as reinforced concrete. This new breed of housing could also be called 'vernacular' housing of urbanising countries since it is not just a lack of funds but lack of understanding of earthquake resistant techniques that are making these houses vulnerable. It is important to examine information related to people living in these buildings and their behaviour under earthquake loading as there are no fragility data available for this building inventory which is common in these parts of the world. Couple this with poor siting due to lack of available land or proximity to steep slopes, and it is clear that the problem of casualty estimation becomes a complex matrix of contributing factors, many of which are not present in current casualty models. The findings from these datasets have also highlighted areas which may affect developed countries as well. Issues like mass gathering in cultural, educational or sporting events, bringing a group of people to one location could, if there is an unforeseen structural failure, generate mass hysteria and casualties similar to the stampedes at religious events. The casualty distribution may also change due to the unusual occupancy rates.

Unfortunately, in most cases, detailed damage and casualty surveys have not been carried out after events and it is necessary to produce realistic estimates for many regions of the world where earthquakes have not occurred recently. From the review of these surveys and previous literature on recent earthquake, the next chapter presents a prototype methodology of estimating casualties using information from the database and other published sources. The contributory factors, postulated relationships and the conclusions from this chapter and chapter 2 are used in formulating the arguments towards the methodology.

# 4 DEVELOPING A PROTOTYPE GLOBAL CASUALTY ESTIMATION MODEL

This Chapter describes a novel approach to rapid estimation of earthquake casualties, derived from the casualty data described in earlier Chapters, and also from work done on earthquake vulnerability done previously at Cambridge Architectural Research Ltd.

The aim was to produce a simplified semi-empirical approach by which earthquake casualties would be a derived from estimates of the collapse rates of buildings affected by the ground shaking, and would be suitable for application with PAGER.
There are four components to the approach.

- First, the building stock in any location is defined in terms of its distribution among 5 vulnerability classes (Classes A to E). The distribution is assumed to follow a binomial distribution, which allows a single parameter, $p_B$, to be used to define the entire distribution.
- For each vulnerability class, empirical data have been used to estimate the expected proportion of the buildings in that class to collapse (damage state D5) or partially collapse (D4), at increasing levels of ground motion intensity, measured by the Modified Mercalli intensity scale (MMI). From these collapse and partial collapse rates for individual vulnerability classes, a composite collapse rate has been determined for each value of $p_B$.
- Using an assumed occupancy rate for the area (depending on the time of day of the event and other factors), and assumed lethality rates for the building classes, an estimated death rate for the combined building stock is calculated at the given intensity.
- The number of deaths in any zone affected by a given intensity is then determined based on the total estimated population of that zone. The total number of deaths caused by the event is calculated by summing over all settlements with significant population and potentially destructive ground shaking.

The approach is designed to be incorporated within the PAGER alert system, in which the distribution of ground shaking in MMI and the estimated population at a given intensity is already calculated. The additional information needed to produce a casualty estimate is simply the $p_B$ value (or values) attributable to the building stock of the area, and the occupancy and lethality parameters to be used.

The following sections discuss how this approach has been applied, and its testing against geographically distributed casualty data available for 8 of the earthquakes in the Cambridge Earthquake Damage Database.

### 4.1 Building stock distributions

Given the large uncertainties inherent in earthquake vulnerability assessment, it was considered for the present purpose that a distribution of the building stock among 5 separate classes of structures would be sufficient. In previous projects, CAR have proposed, based on empirical data, vulnerability curves for Mean Damage Ratio in terms of MMI intensity for a range of building classes found worldwide (Spence et al., 2008); and empirical data have also been used to assess the proportion of the building stock falling into any level of damage (eg Damage Ratio >90%) given a value of MDR.

In this study, the main classes of building have been regrouped into 5 "super-classes" A to E[3], as shown in Table 4.1.

**Table 4.1**: Superclasses and building typology descriptions

| Superclass | Building typologies |
|---|---|
| A | Weak Masonry |
| B | Load-bearing masonry |
| C | Structural masonry, pre-code RC frame |
| D | Timber frame, concrete shear wall or moderate code RC frame |
| E | Steel structures, high-code concrete frame |

The collapse rates determined have also been compared with the expected collapse rates for European buildings classes A to F defined in the European Macroseismic Scale (Grunthal) by and Lagomarsino Giovinazzi (2006) It was found that at lower intensities there were significant differences, with generally significantly higher collapse rates proposed by Spence et al. (2008)

Given the 5 superclasses proposed, for any location a knowledge of the breakdown of the building stock into these classes enables a best-fit value of $p_B$ to be determined for that location. The evidence that building stock distributions are binomial in form, or close to it, is not very strong, but it can be shown that the error in estimating damage based on the assumed binomial distribution rather than the actual distribution is relatively small compared with the error already inherent in the estimate. For those events for which an actual distribution of the building stock has been obtained from a damage survey, the error in estimating the collapse rate at MMI=8 or 9 using the best-fit binomial rather than the actual distribution has been calculated. The errors range from 2% to 60% with an average error of 29%, as shown in Table 4.6. By contrast, the average ratio of collapse rate from one class to another is 4.3 at

[3] Not the same as the superclasses described in chapter 3

intensity 8 and 3.3 at intensity 9, implying that collapse rates are being estimated to within a factor of 2 at best, and that the additional error from using the binomial distribution is small.

Table 4.2 shows the standard distributions of the 5 classes of A to E which correspond to $p_B$ values from 0.1 to 0.9. A value of $p_B$ <0.1 indicates a building stock consisting virtually entirely of adobe or rubble masonry buildings, while a value of $p_B$ >0.7 indicates a relatively modern building stock with a high proportion of well-built earthquake-resistant construction.

**Table 4.2** The building stock distributions corresponding to each value of $p_B$

| Class | A | B | C | D | E |
|---|---|---|---|---|---|
| $p_B$ | (1-$p_B$)^4 | 4*$p_B$*(1-$p_B$)^3 | 6*$p_B$^2*(1-$p_B$)^2 | 4*$p_B$^3*(1-$p_B$) | $p_B$^4 |
| 0.1 | 0.6561 | 0.2916 | 0.0486 | 0.0036 | 0.0001 |
| 0.2 | 0.4096 | 0.4096 | 0.1536 | 0.0256 | 0.0016 |
| 0.3 | 0.2401 | 0.4116 | 0.2646 | 0.0756 | 0.0081 |
| 0.4 | 0.1296 | 0.3456 | 0.3456 | 0.1536 | 0.0256 |
| 0.5 | 0.0625 | 0.25 | 0.375 | 0.25 | 0.0625 |
| 0.6 | 0.0256 | 0.1536 | 0.3456 | 0.3456 | 0.1296 |
| 0.7 | 0.0081 | 0.0756 | 0.2646 | 0.4116 | 0.2401 |
| 0.8 | 0.0016 | 0.0256 | 0.1536 | 0.4096 | 0.4096 |
| 0.9 | 0.0001 | 0.0036 | 0.0486 | 0.2916 | 0.6561 |

Table 4.3 shows a number of best-fit values of $p_B$ which have been determined based on the building damage surveys in the CU Damage Database, including those locations where casualty survey data are available. It should be noted though that these values are based on the building typology descriptions only, not on the actual observed damage.

**Table 4.3** Estimated best-fit values of $p_B$ from various surveys

| | Source | no of buildings | Best fit $p_B$ value | Error in collapse rate at I=8 | Error in collapse rate at I=9 | Basis of survey |
|---|---|---|---|---|---|---|
| Kobe, Japan | EEFIT | 214 | 0.73 | 1.30 | 1.38 | post eq surveys |
| | BRI | 1036 | 0.78 | 0.70 | 0.74 | |
| | DPRI | 239 | 0.66 | 1.17 | 1.30 | |
| Kocaeli, Turkey | AIJ N Golcuk | 809 | 0.5 | 0.67 | 0.78 | AIJ post eq surveys |
| | AIJ S Golcuk | 952 | 0.5 | 0.70 | 0.80 | |

| | Source | no of buildings | Best fit $p_B$ value | Error in collapse rate at I=8 | Error in collapse rate at I=9 | Basis of survey |
|---|---|---|---|---|---|---|
| Athens, Greece | Elena paper | 6844 | 0.35 | 0.53 | 0.70 | Ano Liosia area at time of event |
| Chi-Chi, Taiwan | NCREE | 6275 | 0.46 | 0.46 | 0.64 | NCREE post earthquake surveys - all areas |
| Bhuj, India | | 86 | 0.44 | 1.59 | 1.43 | Damage study in West Bhuj |
| Bam, Iran | | 34531 | 0.15 | 1.03 | 1.03 | EERI special report |
| Niigata, Japan | | 2790 | 0.67 | 0.88 | 0.96 | AIJ Study in Ojiya city |
| Kashmir, Pakistan | | 503 | 0.1 | 1.00 | 1.01 | Cambridge Casualty survey |
| Yogyakarta, | | 497 | 0.11 | 0.93 | 0.92 | Cambridge Casualty survey |
| Pisco, Peru | | 107 | 0.04 | 0.98 | 0.98 | Cambridge Casualty survey |
| Irpinia | Balvano (rural) | 1813 | 0.05 | 0.93 | 0.93 | Braga et al |

### 4.2 Determining collapse rates as a function of $p_B$

Using previously assembled empirical data, estimated average collapse rates (D5) and partial collapse rates (D4) for each class have then been determined as a function of intensity (Figure 4.1 and Tables 4.4 and 4.5).

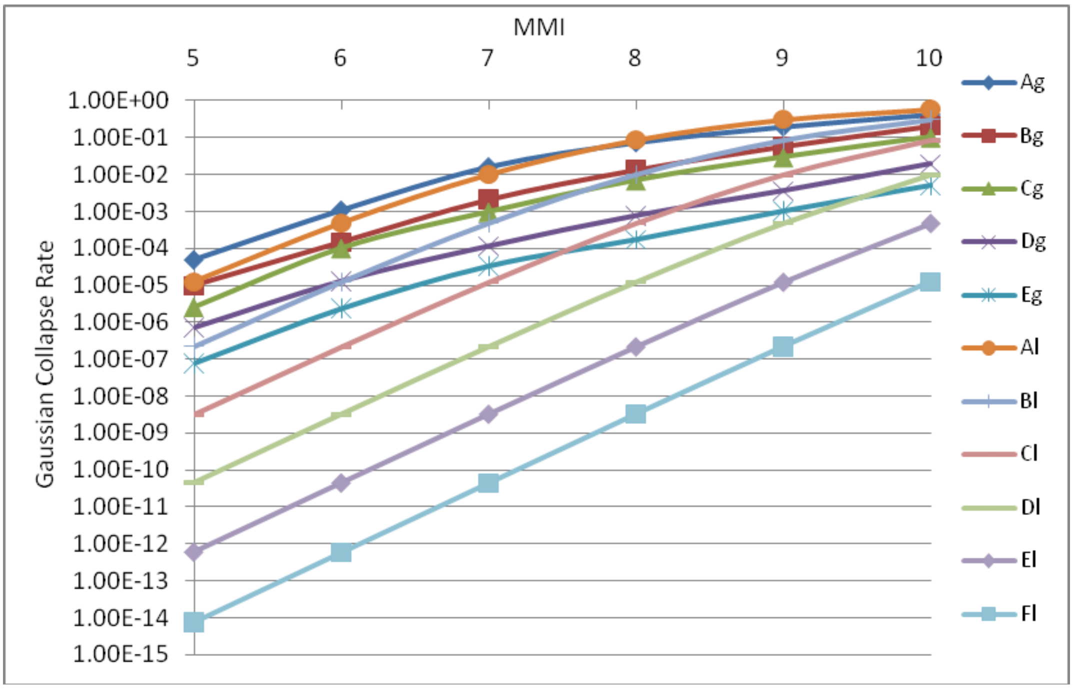



**Figure 4.1**: Collapse rates from GEVES study (Ag-Eg), Spence et al 2008, assuming that D5=MDR>90% and D4=MDR>70%; and European collapse rates from Lagomarsino and Giovanazzi (2006) (Al – Fl)

**Table 4.4** Average empirical collapse rates (D5) for each of the 5 superclasses

| Intensity, MMI | A | B | C | D | E |
|---|---|---|---|---|---|
| 5 | 4.93E-05 | 9.68E-06 | 3E-06 | 7E-07 | 8E-08 |
| 6 | 1.08E-03 | 1.47E-04 | 0.0001 | 1E-05 | 2E-06 |
| 7 | 0.0160 | 0.0021 | 0.001 | 0.0001 | 3E-05 |
| 8 | 0.0723 | 0.0132 | 0.007 | 0.0008 | 0.0002 |
| 9 | 0.1924 | 0.0579 | 0.0296 | 0.0036 | 0.001 |
| 10 | 0.4124 | 0.2071 | 0.1033 | 0.0192 | 0.005 |

**Table 4.5** Average empirical partial collapse rates (D4) for each of the 5 superclasses

| Intensity, MMI | A | B | C | D | E |
|---|---|---|---|---|---|
| 5 | 0.0009 | 0.0002 | 4E-05 | 3E-05 | 4E-06 |
| 6 | 0.0104 | 0.0021 | 0.001 | 0.0003 | 7E-05 |
| 7 | 0.0825 | 0.0174 | 0.0066 | 0.0018 | 0.0006 |
| 8 | 0.2413 | 0.0719 | 0.033 | 0.0082 | 0.0025 |
| 9 | 0.4554 | 0.2073 | 0.1027 | 0.0277 | 0.0103 |

| | | | | | |
|---|---|---|---|---|---|
| 10 | 0.7040 | 0.4764 | 0.2604 | 0.097 | 0.0357 |

Using the collapse rates and partial collapse rates shown in Tables 4.4 and 4.5, composite collapse rates and partial collapse rates as a function of $p_B$ were determined using Table 4.4 and it was found empirically that the following equations produce collapse rate curves as a function of $p_B$ and intensity MMI:

$$RD5= \Phi(C7+SL(MMI-7)) \quad (1)$$

Where RD5 is the collapse rate, Φ is the standard normal distribution and C7 and SL are functions of $p_B$ as follows:

$$C7= -1.72.\ p_B - 2.08 \quad (2)$$

$$SL= -0.135.\ p_B + 0.636 \quad (3)$$

and

$$RD4 = \Phi(C74+SL4(MMI-7)) \quad (4)$$

Where RD4 is the partial collapse rate, Φ is the standard normal distribution and C74 and SL4 are functions of $p_B$ as follows:

$$C74 = -1.79.\ p_B - 1.37 \quad (5)$$

$$SL4 = -0.138.\ p_B + 0.628 \quad (6)$$

### 4.3 Occupancy and lethality rates

In most events, deaths are caused largely by the collapse or partial collapse of residential buildings. Occupancy rates in the buildings can be expected to depend on time of day. There may also be an unexpectedly low occupancy at the time of the main shock if the earthquake occurs in daytime and there is either a precursory shock, or a larger shock following a short period of lower intensity ground shaking as happened in the Pisco 2008 event. The seismological data available immediately after the earthquake may make it possible to estimate plausible values. Here we have used an occupant rate of 0.9 except for one event in Yogyakarta for which there was evidence of people leaving their homes before the main shock struck (So, 2009).

Many different figures are given for lethality rates, partly depending on what is understood to be a collapsed building. For the purpose of this study, a lethality rate of 20% for D5, and 5% for D4 have been assumed based on previous studies (LessLoss, 2006). These are consistent with our understanding of the meaning of damage states D5 and D4. Most of the building classes in the areas studied are of unreinforced masonry. For Kobe a different lethality rate of 0.07 (based on Japanese data) have been applied to the assessment to reflect the different in lethality to their dominant vulnerable building stock of Okabe.

### 4.4 Testing against reported casualty data

The approach described above was tested against data on reported deaths in 8 earthquakes. For all of these events, fatality data was available on a geographically distributed basis, by village or district and is currently mounted in the Cambridge Damage Database. In most cases this data was collected and published by national studies, and it is difficult to know how accurate it is. For each event a USGS Shakemap was available, providing the opportunity to obtain ground shaking data for each location. And for each location a total population affected was available, enabling a fatality rate to be determined for each location, and aggregated across all locations.

For each event, the reported fatality rate for each location was plotted against USGS Shakemap intensity, as determined from the lat-long coordinates at that location; and on the same graph, the estimated fatality rate was also plotted as a continuous function of intensity, using the process described above, with values of $p_B$ taken from Table 4.3, and using assumed values of occupancy rate and lethality rate at D4 and D5 as shown in Table 4.6.

**Table 4.6** Events and assumed parameters used in testing.

| Event | $p_B$ | Occupancy | Lethality D5 | Lethality D4 | Ratio of estimated to reported death rate | Reason for discrepancy between estimated and reported death rate | Best fit value of $p_B$ |
|---|---|---|---|---|---|---|---|
| Kobe | 0.7 | 0.9 | 0.07 | 0.05 | 0.56 | Lethality rate from Japanese government may be based on retrofitted okabes since Kobe | 0.56 |
| Yogyakarta | 0.11 | 0.3 | 0.1 | 0.025 | 2.25 | People moved out of doors | 0.37 |
| Kocaeli | 0.5 | 0.9 | 0.2 | 0.05 | 1.03 | OK | 0.51 |
| Irpinia | 0.08 | 0.9 | 0.2 | 0.05 | 0.88 | OK | 0.05 |
| Kashmir | 0.1 | 0.9 | 0.2 | 0.05 | 0.40 | Reported death rate much enhanced by ground failures. | 0.03 |
| Chi-Chi | 0.46 | 0.9 | 0.2 | 0.05 | 5.20 | Building stock less vulnerable than assumed | 0.83 |
| Bhuj | 0.44 | 0.9 | 0.2 | 0.05 | 0.21 | Building stock more vulnerable than assumed | 0.03 |
| Latur | 0.1 | 0.9 | 0.2 | 0.05 | 0.16 | No good information on intensity levels | 0.00 |

Examples of the comparative plots are shown in Figures 4.2 to 4.9. These plots indicate that there is a wide scatter of fatality rates, but nevertheless for all events there is a tendency to higher fatality rates at higher intensities, as would be expected. The correlation coefficient for death rates vs intensity is positive and greater than 48% in all events except Chichi (-5%) and Latur (22%). Moreover, for all the events plotted, the estimated fatality rates fell within the extreme plotted data points.

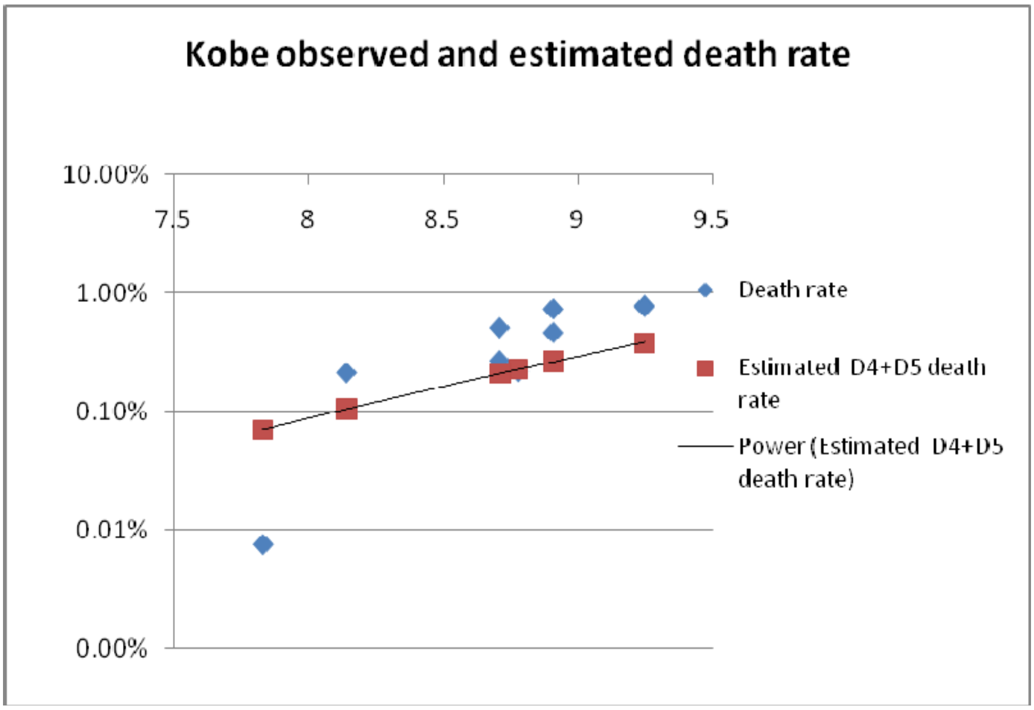



**Figure 4.2:** Observed and estimated deaths rates for 9 districts in the Kobe 1995 earthquake.

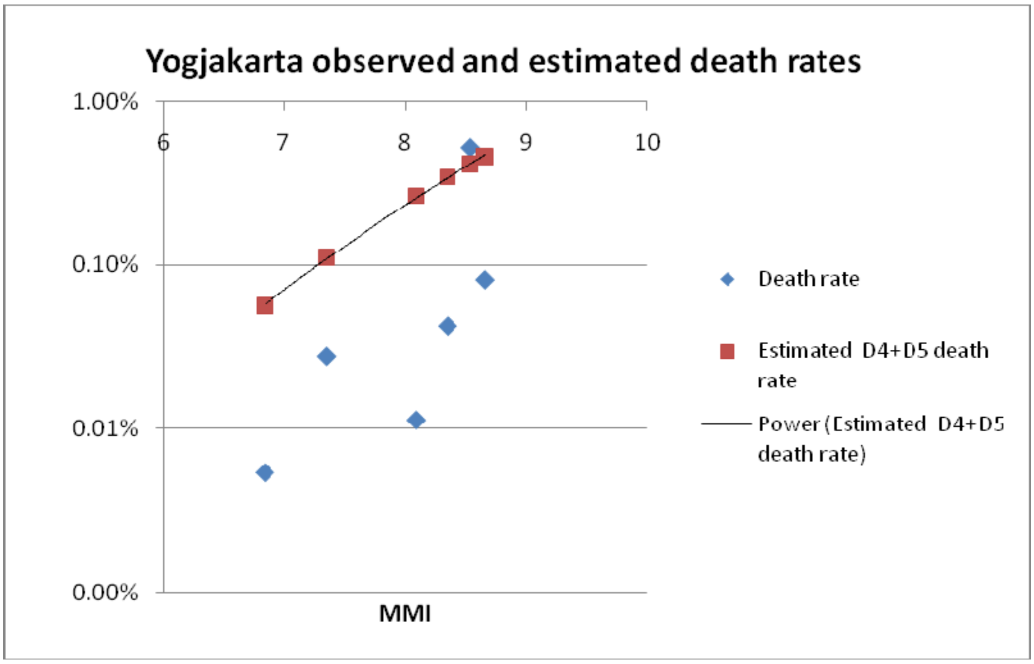


**Figure 4.3**: Observed and estimated death rates for 6 districts in the Yogyakarta 2006 earthquake

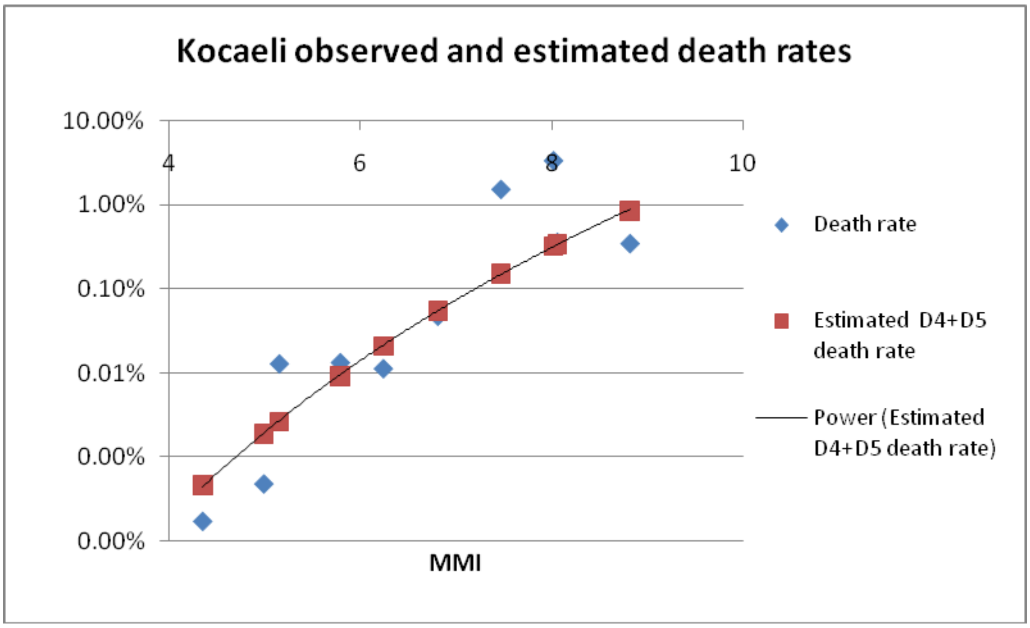



**Figure 4.4**: Observed and estimated death rates for 10 municipalities in the Kocaeli 1999 earthquake

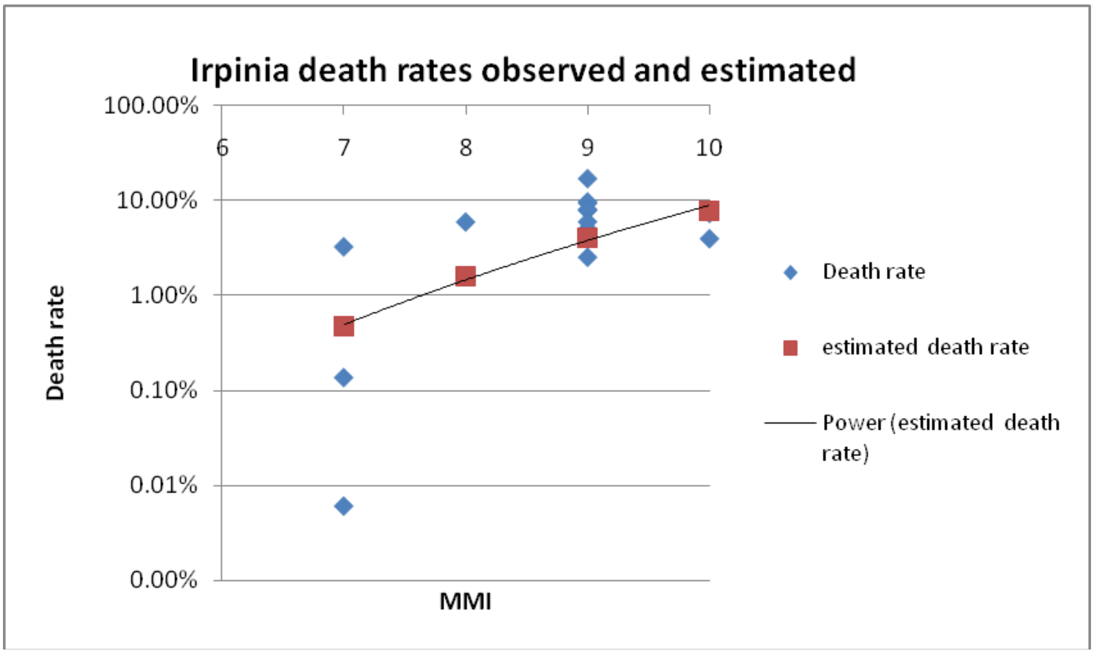



**Figure 4.5**: Observed and estimated deaths in 14 municipalities in the Irpinia 1980 earthquake

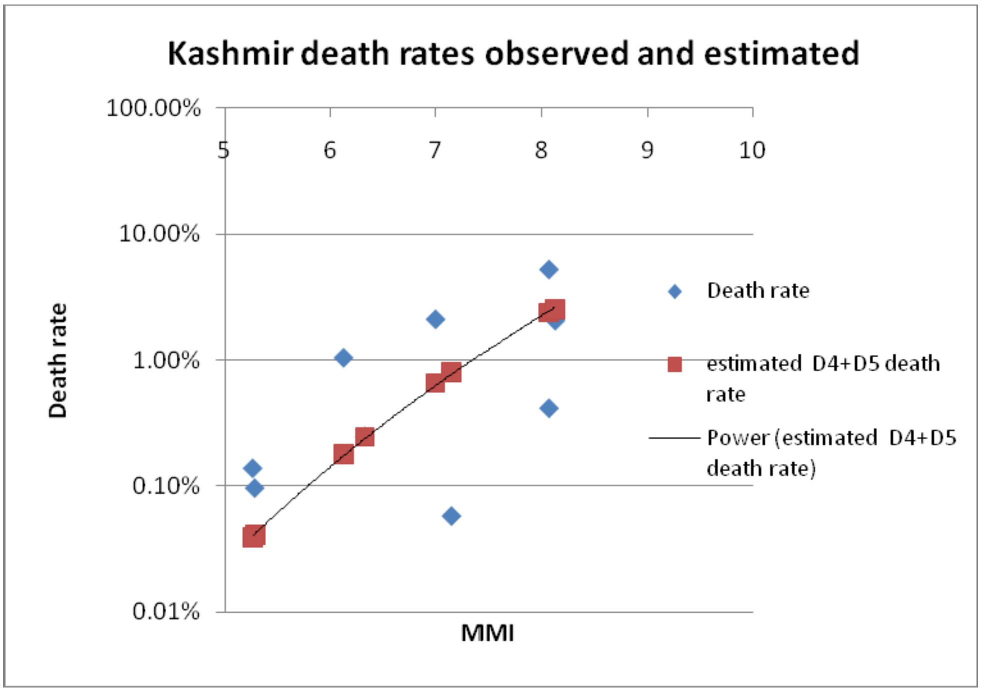



**Figure 4.6**: Observed and estimated deaths in 9 districts in the Kashmir 2005 earthquake

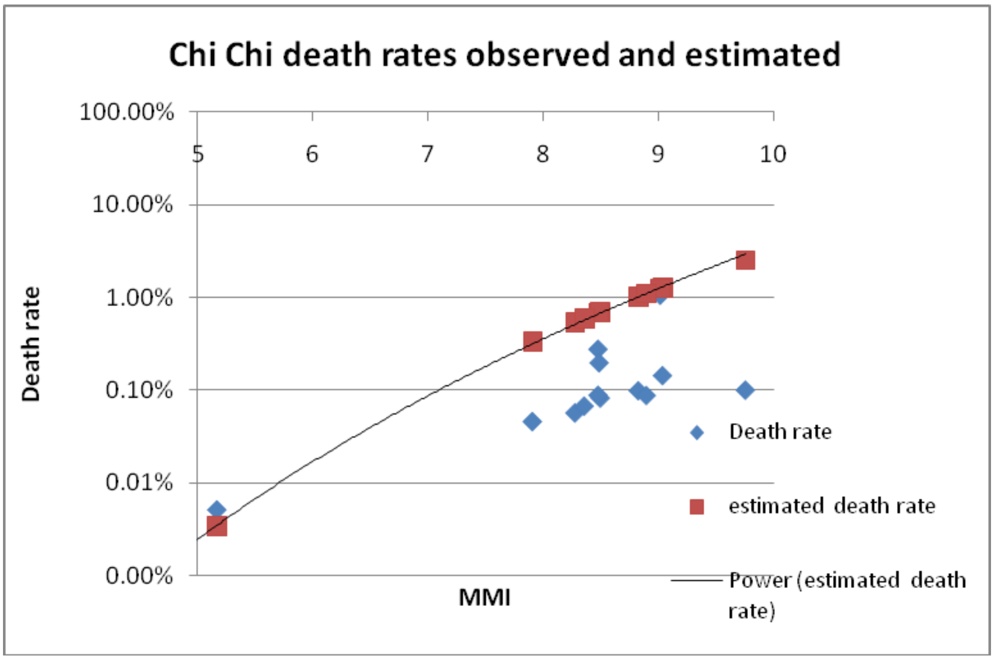



**Figure 4.7**: Observed and estimated deaths in 15 provinces in the Chi Chi 1999 earthquake

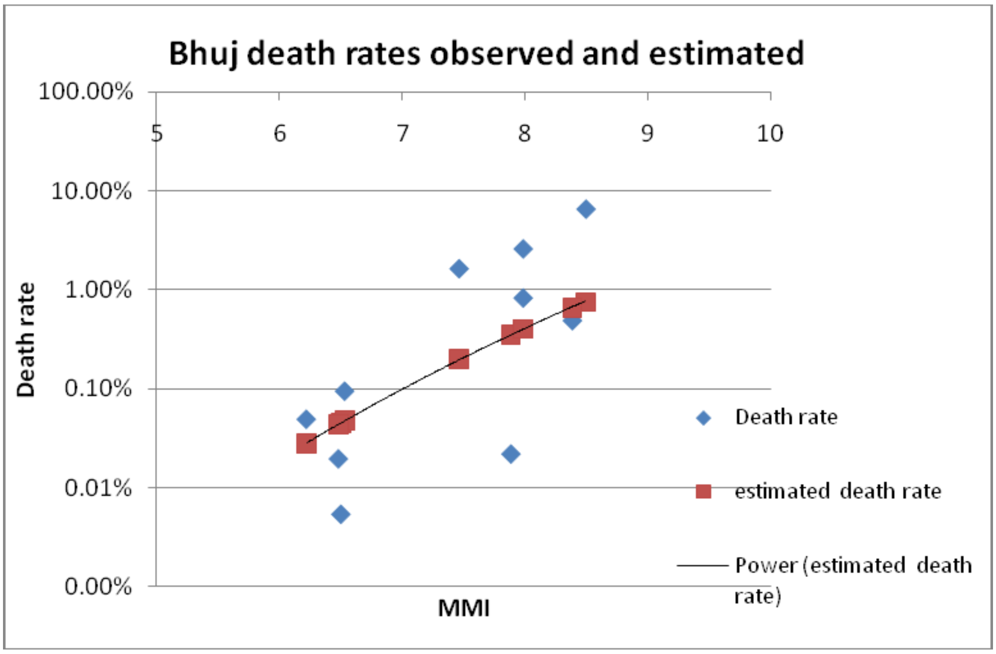



**Figure 4.8**: Observed and estimated deaths in 10 districts in the Bhuj 2001 earthquake

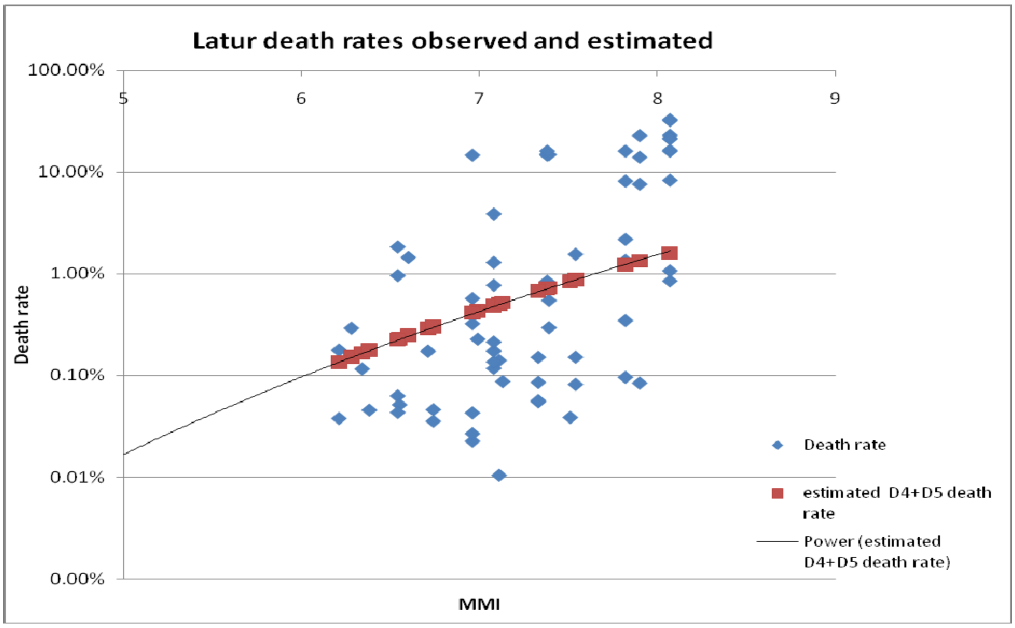



**Figure 4.9**: Observed and estimated deaths in 69 settlements in the Latur 1993 earthquake

For each event, the total number of deaths estimated and reported across all the locations has been calculated, and the ratio of estimated overall deaths to reported deaths for the event has been determined. This ratio is some measure of the overall error in the estimation procedure. Table 4.6 shows these ratios. A better fit could of course be obtained by making adjustments to the assumed $p_B$ values used or the assumed lethality rates. Table 4.6 shows the best fit value of $p_B$ assuming no change in the occupancy and lethality.

For two of the events (Kocaeli, Irpinia) the estimated overall number of deaths was within 15% of the reported values. For three others (Kobe, Chi-Chi and Bhuj) plausible modifications in $p_B$ and lethality rate could bring the estimated and reported deaths within 50%. For two further events additional explanations for the differences can be identified. In the Yogyakarta earthquake it is clear that many of the occupants had moved outside their homes at the moment of the main shock as demonstrated in the Cambridge survey, over 70% of 523 respondents moved outside, leading to a lower than expected fatality rate (So, 2009). While in the Kashmir, Pakistan event, the higher than expected fatality rate can possibly be attributed to the extensive ground failures which greatly enhanced building collapse rates in many of the locations worst affected. In Latur, the very large spread of reported death rates suggests that the data may be at fault.

### 4.5 Limitations to Method

The method proposed is simplistic and approximate, intended to provide an estimate of deaths from ground shaking to within about a factor of 3 or 4 in most situations, using only crude information about the quality of the building stock affected. Deaths and injuries from collateral hazards such as landslides, fires and tsunamis are not included. The estimates of ground shaking intensity are subject to all the limitations of the Shakemap intensity estimates as discussed by Wald et al (USGS Open File Report), with additional errors from the assignment of a single intensity value to district sized areas. Likewise the Landscan-based population estimates have the limitations inherent in that dataset. Assuming building stock can be classified with 5 classes and follows a binomial distribution introduces further uncertainty and error, as discussed in 4.2. Collapse rates for the given classes at each intensity level are based on extensive earlier damage data analysis, but in this collapse analysis, intensities have not been reassessed using USGS shakemap. Lethality rates used do not take account of all the data available, and have used a single rate across all building classes in each location: a more detailed assessment of lethality rates needs to be made. Occupancy rates are assumed, again, based on limited data. A systematic study of the uncertainties in this procedure has yet to be carried out, and this will be a key aspect of future planned improvements.

### 4.6 Conclusions

A wide scatter of fatality rates has been observed when plotted for individual events against intensity, but there is in all cases a tendency for fatality rates to increase with increasing ground shaking. In most cases the estimated fatalities summed across the affected area are within a factor of 2 of those reported; in several cases where there is a larger discrepancy this can be accounted for by particular factors affecting collapse rates or occupancy at the time of the event.

Much remains to be done to build an operationally robust casualty estimation method from the approach adopted, but this initial study suggests that the approach has potential value, in enabling the quality of the local building stock, its expected lethality rates, as well as expected building occupancy at the time of the event to be included in an empirical casualty estimation model.

Mapping of the parameter $p_B$ for national and local building stocks will be an essential element of the process. This can be done using building survey data as has been done here, or based on the USGS inventory data (Jaiswal et al., 2008); or it could be done based on damage survey data derived from the CUEDD for different localities, taking into account actual earthquake performance.

# 5 CONCLUSIONS

Global earthquake risk is growing as people are living in more concentrated and uncontrolled new settlements of high seismic hazard than in previous decades. These rapidly urbanising hubs consist of millions of densely populated houses, apartment blocks and commercial buildings, some of which have been built without awareness of the earthquake threat they are under. Recent tragic events killing tens of thousands of people in Iran in 2003, Pakistan in 2005 and China in 2008 have demonstrated just how dangerous earthquakes are.

As engineers, we know that though the event itself is inevitable, the consequences and the deaths can be mitigated. Such recent earthquakes have been the motivation behind this piece of research which focuses on accounting for the lives at risk in an earthquake. Compared to other areas of earthquake loss estimation, relatively little has been done on the subject of casualty modelling. Despite the importance of saving lives in earthquakes, the information on casualties obtained from events is often poor. As a result of this, the reasons behind what contributes to fatalities and casualties in earthquakes are not well understood.

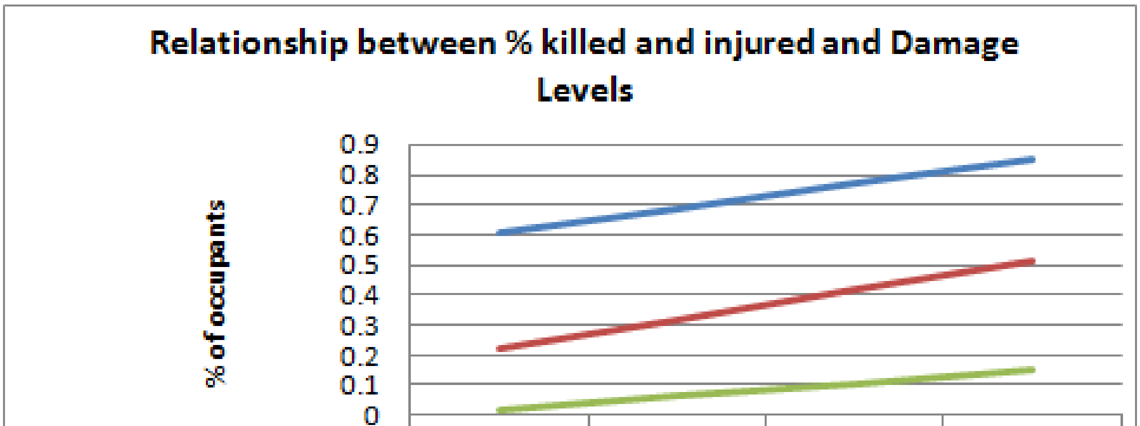
The aim of this study was to develop viable methods of estimating shaking–induced casualties related to building failure for global earthquake events. By seeking out relationships linking past events, the environment they affect and other factors contributing to deaths and also survivals, it is hoped that our understanding of casualties and therefore estimates will improve. This has been accomplished by a thorough investigation of the key components and methods of current casualty loss estimation modelling.

An exploration of the contributing factors to casualties has been carried out by examining 11 recent earthquakes in detail. The findings from each of the earthquakes were presented and analysed, systematically in the same way. The characteristics of the earthquakes were first addressed, followed by the time of day and likely occupancy patterns. Any variances associated with location were examined and then where possible the main causes of deaths and injuries were sought. The reviews also included additional research in the form of post mortems or hospital surveys, which supplemented generic information. These findings were tested against a set of common hypotheses and most importantly, an assessment of the underlying reasons for the variation in casualties between events was investigated.

Though the analysis revealed that most of the accepted wisdom within the field holds true as shown in Table 1.4, for example that deaths are mainly related to structural failure of buildings, other factors have emerged from the study. The remainder of the report describes work that was designed to improve our understanding of casualties in earthquakes. Two original outputs have been derived from this systematic evaluation of the causes of injuries and deaths based on field observations and data analyses. The first is a set of casualty functions that have been developed using regional building vulnerability data and casualty information from past events. As shown in most cases the estimated fatalities summed across the affected area are within a factor of 2 of those reported; in several cases where there is a larger discrepancy this can be accounted for by particular factors affecting collapse rates or occupancy at the time of the event.

Much remains to be done to build an operationally robust casualty estimation method from the approach adopted, but this initial study suggests that the approach has potential value, in enabling the quality of the local building stock, occupancy factors and lethality rates to be specifically included in an empirical casualty estimation model.

The second output is a set of casualty ratio curves which have been derived from the Cambridge questionnaire surveys. It is believed that where building collapses are the dominant factor of casualties, these relationships would encapsulate the likely percentage of injured and killed in dwellings of different damage states as shown in Figure 5.1 which is a summary of Figures 3.5 and 3.6




| | D2 | D3 | D4 | D5 |
|---|---|---|---|---|
| All Injuries | 0.60 | 0.69 | 0.77 | 0.85 |
| Seriously injured and killed | 0.22 | 0.32 | 0.42 | 0.51 |
| Killed | 0.02 | 0.06 | 0.10 | 0.15 |

**Figure 5.1**: Graph derived from casualty surveys in Pakistan, Indonesia and Peru on the relationships between percentage of occupants killed and injured in buildings of varying levels of damage (unreinforced masonry buildings using data collected from Cambridge casualty surveys)

From examining past events, to derive a realistic casualty loss estimation model, variations in environmental and cultural settings around the world must be taken into consideration as shown in the review of recent events in Chapter 2. Figure 5.2 presents a scenario which may be typical of an earthquake affecting an urban commercial district. Factors which may amplify casualties, especially injury numbers, are highlighted in red. This scenario postulates a long period ground motion resonating with tall buildings founded on soft alluvial basin. As shown, the main factor to consider first is the time of day. Are these classes of buildings fully occupied at the time of the postulated event? The second consideration is how many buildings fall in this natural period band and their properties, such as location, occupancy rates, number of floors and distance from hospitals. In this case, buildings are assumed to be built under stringent seismic codes and therefore the building quality option is not highlighted as a factor in the diagram. The main hazard for this scenario is likely to be non-structural in the form of toppling of furniture and false ceilings.

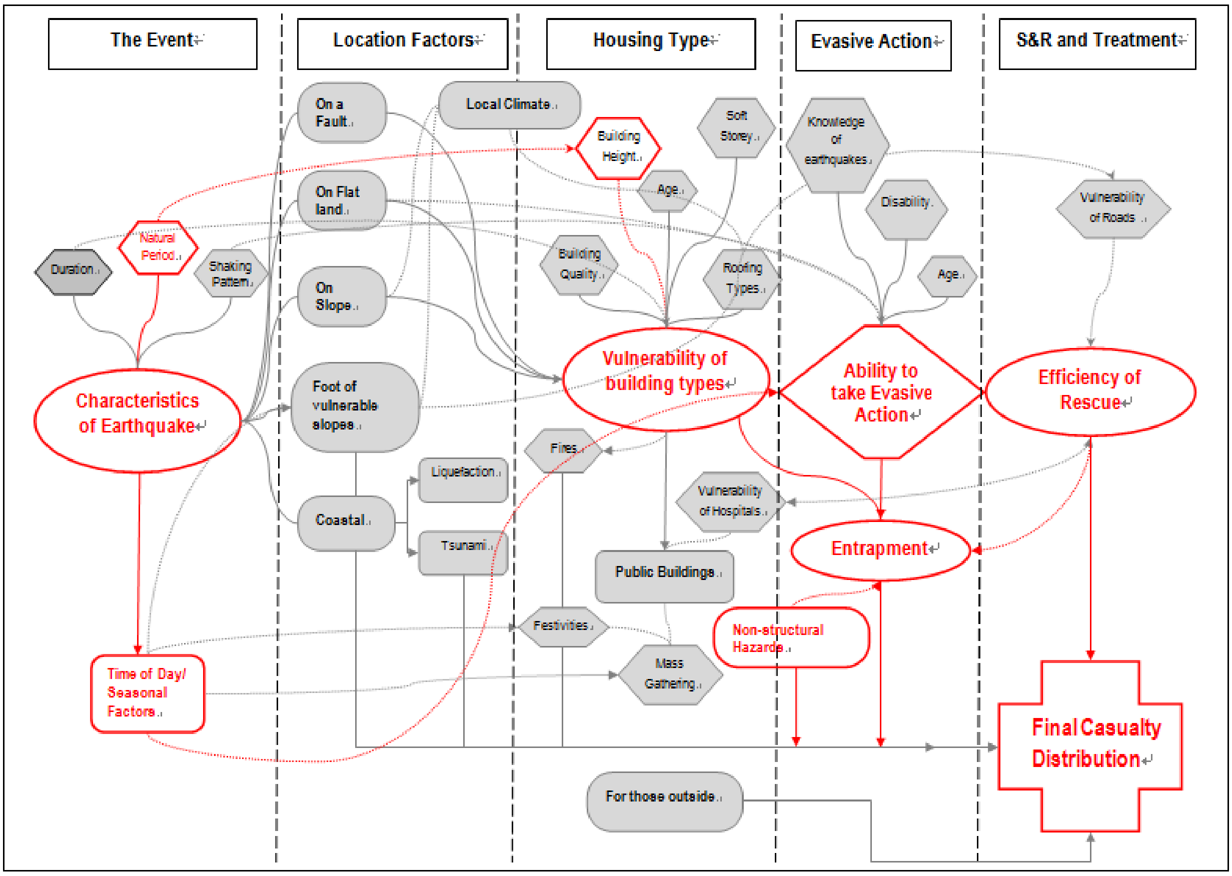



**Figure 5.2:** The factors contributing to casualty numbers in a long period ground motion earthquake amplifying motions for high rise buildings on soft soils

The picture in Figure 5.3 shows this scenario as a still photograph taken from a video of a full-scale experiment in Miki, Japan (Miyano, 2007). As shown, non-structural hazards such as furniture can be disturbed by the sway of tall buildings and injuries within these spaces depend on the ability of its occupants to take evasive action, for example, shielding under a table. The efficiency of search and rescue is also highlighted in the diagram. During work hours, each of these city high-rise buildings could house more than 2,000 employees and the rescue services could be completely overstretched if many occupants are trapped by heavy pieces of equipment and book shelves within these commercial units.


**Figure 5.3:** A still photograph captured in the video of an experiment focusing on injuries caused by furniture displacement (Miyano, 2007)

This diagram provides a good tool for the assessment of contributing factors to casualties. Assessment of uncertainties in these probabilistic models can be made with a logic tree approach where confidence levels are assigned to each input factor. When data becomes available to support and enhance the confidence of estimates, these levels can be refined.

### 5.1 Further research

There are still questions that need to be addressed. For example, how can the generated death estimates translate to account for the injured and displaced? In this analysis, only the death rates are used as these are most likely to be reliable since regional injury records are often patchy. In this analysis, only damage states D4 and D5 have been used as these would contribute to most of the deaths. However, as shown, there is also a need to add-in correction factors to account for human behaviour and secondary effects. These two components have been found to be significant in changing the casualty estimate.

This assessment has been possible as data has been collected from literature and from the field to investigate what truly contributes to casualties in a real event. The casualty questionnaire form and the developed collection method are robust and can be applied to future events. The authors are in the process of setting up a survey in Sichuan, China following the 12 May 2008 Wenchuan earthquake. The questionnaire has been translated to Chinese and in addition, photographs of housing and its setting will be incorporated under the direction of the local collaborator at Beijing Normal University. The next phase of this research will be to adapt these forms to capture information on general building stock of the local area, medical treatments and fade-away rates of different housing types.

As shown in the analysis of the survey results, there were bias and limitations to the collection method as well as the answers obtained. The questionnaire needs to be improved to address more issues, for example, a section exclusively asking survivors for their knowledge on causes of deaths of those who died. In addition, there are important relationships and information that cannot be answered by survivors of events. Their responses must be supplemented by other information from hospitals, personnel working in urban SAR teams and aid personnel. One component which has not been implemented fully during this research is an end user assessment. As the intention of this piece of work was to form part of a loss estimation application for rapid risk and aid assessment, USAID requirements and the needs of a possible application to the PAGER programme were explored. It would have been invaluable however to interview end users from the studied events. Such a study would form three parts: what casualty estimates were quoted at the outset of the event; what information on casualties was made available to them during their operations and also what information they lacked to plan relief and medical aid?

There are further pieces of information and correlations which can be extracted from the survey datasets and examined, depending on the focus of the study. These should and will be investigated in the future but this study was deliberately taken from an earthquake engineering viewpoint. The objectives were to test whether structural factors play a key part in casualty modelling and whether estimation models are realistically portraying what happens to people in real events. Other beneficiaries such as the Red Cross may be interested in exploring the relationship between severity of injuries and distance travelled for medical help. This would involve using data from the survey and from other sources such as road network situation reports and actual capacities of the medical facilities.

In terms of the collection of casualty information from the field in future, it is necessary to coordinate efforts with damage surveys. Although the surveys in this study were constrained by time and resources, more information on the buildings housing the survivors and the environment they were in could have been recorded. One assumption was that data relating to location and intensities could be obtained after the survey was completed and correlated with responses. However, it was found that local seismic intensity maps of the affected areas are rare. This is one of the reasons why Murakami devised a format of questions to assess micro intensity of regions (Murakami, 1999).

Involving medics in standardising casualty information is an important step for the future. A uniform, systematic approach, in line with emergency medicine, is required so that the information collected can be used across disciplines. It is recognised that this will be a huge undertaking. What is required is a simple collection method which could be implemented under physical survey constraints without compromising quality of results.

The casualty database presented in this study is an alpha version of what could be developed in the future. There is no doubt that there are many more research papers and nationally published data that need to be incorporated from past and future earthquakes. It is hoped that as this database progresses and is disseminated; the quantity and quality of this repository will be enhanced.

### 5.2 Where to next?

Within earthquake engineering and architecture, there is a need for increased effort in gathering data on the performance of buildings and other structures in earthquakes. Although for most of the recent large events, field surveys have been carried out and papers published, in many cases, the data collection often only skims the surface of the actual situation. Short reconnaissance visits are useful in providing an impression of the overall damage but are unlikely to include systematic building-by-building studies as these take time and require trained personnel. Very often, such reconnaissance missions overemphasise what has been damaged rather than what has survived and the reasons behind the survivals.

To truly take advantage of actual earthquakes, damage surveys would need better coordination of international and national reconnaissance teams to collect data across a larger proportion of the affected zone, examining areas of high and lower intensities rather than just concentrating on some newsworthy damaged sites. At the same time, casualty data collection could involve engineers, public health and medical practitioners working together. Research is needed to find methods to achieve consistent and practical ways of collecting and modelling casualties in earthquakes and international collaboration will be necessary to transfer expertise and resources to the communities in the cities which most need it.

Coupling the theories and findings from the field surveys with experiments would also be advantageous. It will not always be possible to validate theories and models with actual earthquakes. Computer simulations and advances in testing methods familiar to engineers need to be introduced to colleagues in other disciplines. As engineers we also have a responsibility to do much better in communicating what we know to the general public, disseminating knowledge in simpler forms. One of the aspirations of this research is to ensure that the costs and consequences of losses from earthquakes are more realistically portrayed in human terms. It is hoped that surveys and findings in this research would not only help improve casualty modelling for emergency management but also strengthen the case for mitigation.

One way of improving communication and dissemination is to ensure greater transparency in loss modelling to enable better understanding of inputs and uncertainties associated with the results. This has been encouraged by groups such as Alliance for Global Open Risk Analysis (AGORA, 2008) and more recently, by a global initiative called Global Earthquake Model (GEM, 2008). The key goal of GEM is to raise earthquake risk awareness by adopting a uniform and comprehensive approach to addressing hazard and risk modelling and dissemination. It promotes an open environment for international researchers to create an independent and scientifically advanced set of software, standards and datasets which is accessible and understandable to everyone. GEM cites building vulnerability and inventories to be central issues and urges scientists in earthquake-prone countries to develop national models to capture this information. As a group, researchers in the area of casualty modelling must ensure social impact studies are brought to the forefront in GEM.

Future collaborations with USGS, GEM and other civil protection groups in Europe and abroad would encourage more work to be done internationally in collecting and analysing casualty data.

*In closing*

One of the central conclusions to be drawn is that there is no universal rule to casualty modelling nor are there casualty rates that can be generically applied. Though the major contributing factors to casualties are consistent, the variation and priorities depend very much on the location and on causes beyond engineering and architecture. For example, in San Francisco and Tokyo, the emphasis has to be on earthquake drills as well as on dangers of non-structural hazards. Whereas in Nepal and Pakistan, perhaps public awareness programmes have to go a stage further to actually teach fundamental methods of earthquake engineering so that local building techniques can be adapted to incorporate these rather than prescribing a set method of construction. As witnessed in Peru, there is a willingness to learn by the affected people straight after the earthquake. As they have seen what has survived the event, they are receptive to the differences. Engineers and architects must capitalise on this and raise awareness.

Earthquake casualties, like many areas of public health (Spence, 2007), are entirely avoidable with the technical means at our disposal. The aim of this research is to provide current casualty estimation models with a viable method and recommendations to gauge the number of dead, injured and displaced following an earthquake. The work described in this research is intended to make a contribution towards the USGS PAGER programme and therefore decision making in the areas of emergency response and disaster management in mobilising medical personnel, supplies and relief efforts related to the likely types of injuries and exposure immediately after an earthquake.

By means of a thorough review of research in earthquake engineering and other disciplines, a global casualty database has been developed. The standardised datasets from the authors' own research and also from the database enabled detailed cross event analyses and a set of casualty rates and relationships have been examined and developed. A methodology for estimation global casualties, based on historic data has been proposed in this study. Through this research grant, an increased understanding of what contributes to casualties in earthquakes has been attained and significant steps have been made to move towards coordinating efforts to strive for a global casualty estimation model.

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