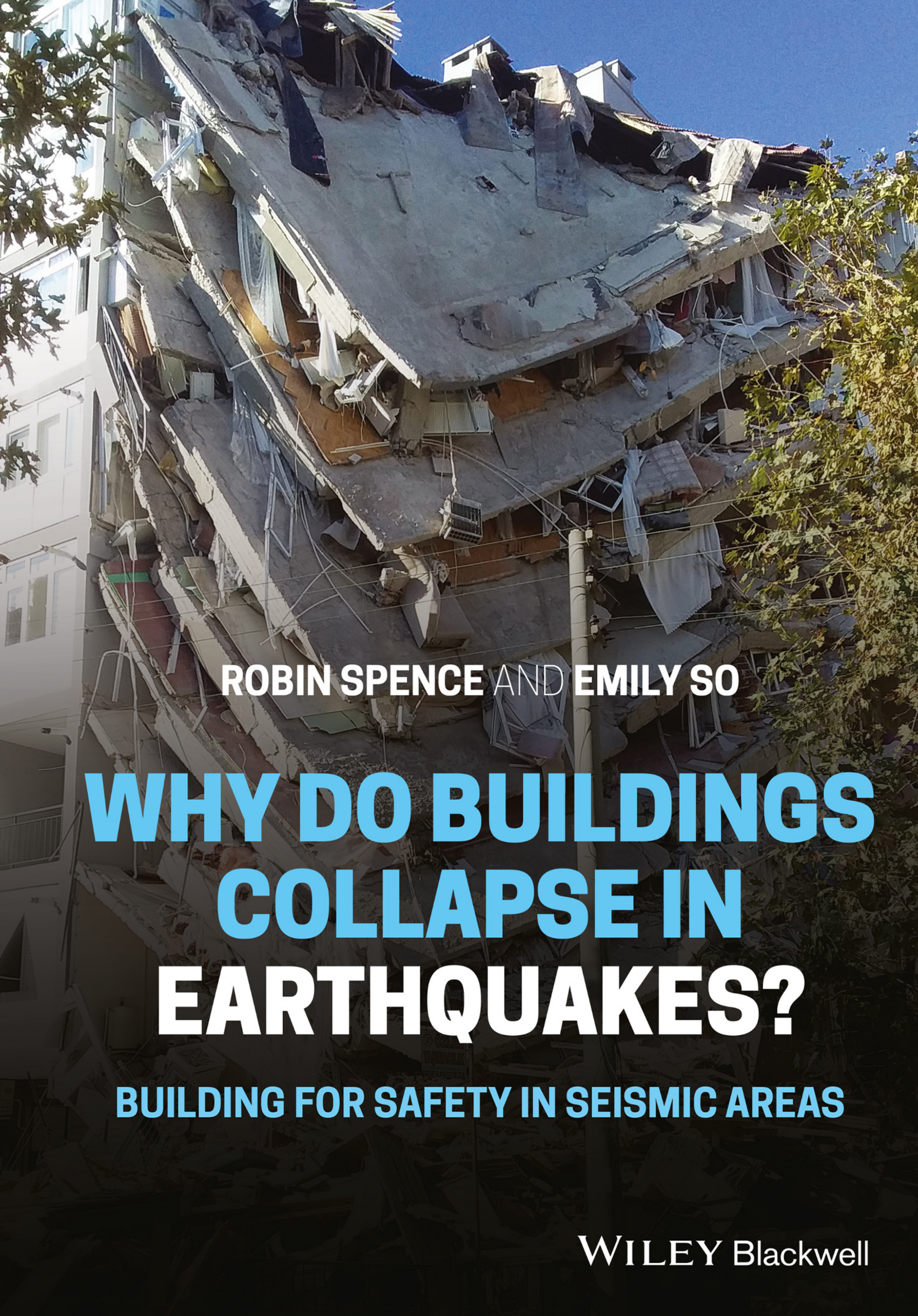

ROBIN SPENCE AND EMILY SO

WHY DO BUILDINGS COLLAPSE IN EARTHQUAKES?

BUILDING FOR SAFETY IN SEISMIC AREAS

WILEY Blackwell

Why Do Buildings Collapse in Earthquakes?

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Building for Safety in Seismic Areas

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Contents

5 How Do Different Forms of Construction Behave in Earthquakes? *97*

6 How is the Population Affected? *135*

7 How Can Buildings Be Improved? *173*

8 Successes and Failures in Earthquake Protection: A Country Comparison *205*

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1

Introduction: Why This Book

1.1 Earthquakes – An Underrated Hazard

Earthquakes have been a threat to human habitation throughout history, but until relatively recently, their causes were poorly understood. In the pre-scientific era, they were commonly ascribed to divine intervention. By the time of the Lisbon earthquake in 1755, there were many who understood that earthquakes had natural causes, but the mechanism remained unexplained, and the supernatural explanation was widely proclaimed, especially from church pulpits (Udias and Lopez Arroyo 2009). And over 150 years later, according to observer Axel Munthe (1929), the inhabitants of Messina, destroyed by a massive M7 earthquake in 1908, cried ‘Castigo di Dio’ (‘punishment from God’).

Only with the development of plate tectonics in the twentieth century has it become understood that earthquakes are associated with active faults in the earth’s crust, with most of the largest occurring at the boundaries of the tectonic plates as they interact with each other (as explained in Chapter 4). We can now identify with some precision whereabouts on the earth’s surface large earthquakes will occur. From measurements of the movements at plate boundaries, and from the historical record, we can make estimates of the largest magnitude event which can occur on a fault section, and approximately, the frequency with which events of different magnitude will occur. But the largest events commonly have return periods of several centuries or more (Bilham 2009), and science is still unable to predict, even to within a few decades, when the next large earthquake on any fault section will occur.

There is some evidence that the global earthquake mortality rate (deaths per 100 000 of the world’s population) has been rather gradually reducing over the last century or so. But it is a very slow rate of improvement, and the variation from decade to decade is very large. The first decade of the twenty-first century was a bad one, with several earthquakes resulting in more than 50 000 deaths. Yet, over the same timescale, death rates from many other causes, such as infectious diseases and road accidents, have been very significantly reduced (ourworldindata.org/causes-of-death 2020). This has been made possible with the introduction of public health programmes and protection measures, backed by government legislation and action programmes, but supported and implemented by the general public. Such programmes could similarly be applied to reduce earthquake risk, but in many countries most at risk, this has not so far happened. Why is this?

Why Do Buildings Collapse in Earthquakes?: Building for Safety in Seismic Areas,
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The greatest impact from earthquakes is nearly always the damage to buildings (and other built artefacts – roads, buildings, dams) from the ground shaking caused by the propagation of the earthquakes' waves through the earth's crust, which can result in destruction over a wide area. Over the twentieth century, understanding the nature of ground motion and the way in which this is transmitted through structures has enabled engineers to develop ways to build buildings which are able to withstand the expected ground shaking with limited damage. This understanding, gradually increasing through the development of structural engineering theory and practice, combined with detailed field investigation of the effects of successive earthquakes has enabled codes of practice for building design to be developed, and these are nowadays mandatory for new construction in most cities of the world.

But, as the world's population grows, and urbanisation increases in pace, there are many places where new buildings are being constructed without any reference to good engineering practice for earthquake resistance.

This is partly because those responsible for constructing the new buildings are unaware or possibly unconcerned that a large earthquake may occur any time soon, and building controls are lax. It is also due to lack of education, information, skill and sense of urgency on the part of builders and building owners (Bilham 2009; Moullier and Krimgold 2015).

In rural areas of many poor countries, buildings are largely constructed using highly vulnerable materials such as adobe and unreinforced masonry. Poverty and lack of understanding, combined with a vast demand for new dwelling places, are thus fuelling the creation of a series of future disaster scenarios (Musson 2012).

In order to understand why buildings collapse in earthquakes and to find out what we can do about it, we must look at each of the three ingredients of the problem: earthquakes, buildings and people.

1.2 Earthquakes, Buildings, People

One of the reasons why earthquake risk does not get acted on is because it is not well understood by the public. Although the likely locations of large earthquakes are now known, the timescale of their recurrence is very long, and for most people at risk the last occurrence of 'the big one' for which they need to be prepared is many centuries ago, often before the present cities existed. People may be aware that they are living in an earthquake zone but fail to appreciate the possibility of events much larger than recent experience. In 2008, a modelling exercise, the California Shakeout, was done to support earthquake protection action for Southern California, which is threatened by a large earthquake on the San Andreas Fault (Jones and Benthian 2011). Lucy Jones, who led the modelling team speaks of the 'normalisation bias, the human inability to see beyond ourselves, so that what we experience now or in our recent memory becomes our definition of what is possible'. Seismologists had identified much greater earthquakes in the past than those in recent memory, but the last great earthquake on that section of the San Andreas Fault was in 1688. The modelling exercise, based on a plausible, but by no means worst-case scenario magnitude 7.8 earthquake on the southern section of the San Andreas Fault, showed that around 1500 buildings would collapse, and 300 000 would be severely damaged, causing around

1800 deaths and $213 billion losses. Fires would break out and could become uncontrollable. And the disruption caused to roads and pipelines would cause massive disruption to business, lasting for months. This modelling exercise led to a huge public awareness and preparation programme which has resulted in much reduced risks in California over the past decade.

But considerably more devastating consequences face many of the growing cities in other earthquake zones, particularly in Asia. The southern edge of the Eurasian Plate, stretching from the Mediterranean to China, and including Myanmar and Indonesia, is responsible for 85% of the world's historic earthquake deaths. And this is a region in which cities are today growing rapidly both in size and in number, fuelled by global population rise and urbanisation. Seismologist Roger Musson points to the risk in Tehran, today a city of 12 million people. The last major earthquake on the North Tehran Fault, passing close to the city centre, was in 1834 at a time when Tehran was a small town: an earthquake of $M > 7$ hitting Tehran today could cause as many as 1.4 million deaths. And seismologist Roger Bilham (2009) has estimated that a direct hit on a megacity (>10 million population) somewhere in the world once a century is now statistically probable, with a possible death toll exceeding one million, because of the combination of hazardous locations and structural vulnerability. The World Bank estimates that three billion people will live in substandard housing by 2030. By 2050, the UN projects that two-thirds of the world's population, around 7 billion people, will live in urban areas.

Unfortunately, because the threat to each city is seen as remote, protection from earthquakes is given a lower priority than other issues. Few households prioritise spending on safety from future earthquakes above pressing immediate concerns, like providing extra space or better comfort, unless required to do so by regulation. And elected governments tend to look for expenditure programmes and new regulations which will give returns within their current tenure of office, despite evidence that money spent on disaster mitigation often avoids much greater losses over time. For this reason, general development expenditure is given priority over disaster risk mitigation. And even within that part of government budgets devoted to natural disasters, those from other natural hazards are often given priority. Windstorm and flood damage are more immediate risks, particularly as these are becoming worse as a result of climate change.

Optimistically and opportunistically, the climate change agenda has provided a global focus on resilience of communities to natural threats. It is recognised that especially in developing countries, cycles of disasters have depleted decades of progress made in development. The deaths and destruction from earthquakes are preventable. Whilst the hazard itself is natural, the disasters are largely man-made, and completely preventable with proactive interventions.

1.3 The Authors' Experience of Earthquake Risk Assessment

The overall aim of our work over four decades at the University of Cambridge's Department of Architecture and at Cambridge Architectural Research Ltd has been to understand the vulnerability of buildings to earthquakes globally, in order to estimate the damage which is likely to occur from future earthquakes. This knowledge can be used to provide a sound basis to improve the building stock, and reduce damage, loss of life and disruption from future earthquakes. We have developed our knowledge of building vulnerability through a series of collaborative research projects, supported by the European Union and the UK Government and Research Councils, and through work for individual cities, companies managing portfolios of buildings and insurance companies. But the primary source of our knowledge and experience of buildings' behaviour in earthquakes has been post-earthquake field missions. We have been involved in EEFIT, the UK's Earthquake Engineering Field Investigation team, since it was founded in 1982, and have between us participated in field missions in Japan, Italy, Turkey, India, Pakistan, Peru, Indonesia, China, New Zealand and the South Pacific. The detailed nature and aims of these field missions are discussed in Chapter 2: but an essential element in all cases is to describe and document the types of building affected and the types of damage observed.

Successive projects have examined in detail the problems of particular regions. In the 1980s, we examined the traditional stone-masonry construction of rural Eastern Turkey and conducted shake-table tests in Ankara to investigate simple ways to reduce their vulnerability, the cause of many deaths in earthquakes of the previous decade. In the 1990s, we investigated the options for protecting historic European cities such as Lisbon and Naples from likely future earthquake damage, and we looked at the performance of buildings which had been strengthened following previous earthquake damage. We also developed a method for assessing human casualties from earthquakes based on the level of building damage, and with colleagues in New Zealand applied this to the city of Wellington.

Since 2000 we have worked with others to develop loss modelling approaches to estimating damage and casualties, on a city-scale (in EU collaborative projects), for insurance companies, or with the US Geological Survey, for rapid post-disaster damage assessment. And we have applied our knowledge to assist organisations with large portfolios of buildings to identify those which should be upgraded.

We have also worked with teams developing new ways to assess earthquake damage using remote sensing, and led the team developing the Earthquake Consequences Database (So et al. 2012) for the Global Earthquake Model (GEM). And we have applied similar approaches to assessing vulnerability and damage to buildings from other natural hazards such as windstorms and volcanic eruptions. All this work is described in detail in technical project reports and published papers, referred to in the chapters which follow.

1.4 Aims of This Book

The title of this book asks a question: Why do buildings collapse in earthquakes? In exploring the many layers of the answer to this question, and the many answers in differing contexts across the world, we want to demonstrate that this is not just, not even primarily, a technical question, but also a social, organisational and even political question. In this book, we look at buildings not only as assemblages of materials and components put together to achieve certain functional ends, but also as products of a society and a culture. We aim to explain the physical reasons why buildings fail to withstand earthquakes, but also to attempt to understand the social, economic and political reasons why earthquake disasters continue to happen. And through this combined understanding, we want to point to the actions that can be taken to improve seismic safety, and identify who should be taking them.

With this aim, we hope to reach a wider audience than those interested in the purely technical aspects of earthquake protection, who would prefer a non-mathematical approach to the subject, with limited technical detail. Thus, the book is designed to be read by all those interested in the consequences of earthquakes, or concerned for their own safety as occupants of buildings in earthquake areas. It is also intended for those who have responsibility for ensuring the safety of others in earthquakes, whether as government officials, political representatives, building owners or managers of businesses. The book is written for a non-technical readership, but will also be of interest to all those professionally involved in disaster preparedness and earthquake engineering, as well as to students and practitioners of architecture and engineering seeking a broad overview of the consequences of earthquakes for buildings.

Some readers of the book will live in an earthquake zone, in which case they will want to know if their homes or workplaces are vulnerable, and what they can do to protect themselves from an earthquake, in advance or when it happens. Other readers may own or manage buildings in earthquake zones, or be responsible for the safety of those who occupy them; they will want to know what steps they as owners might be able to take to provide adequate safety. Other readers may be responsible, as architects and engineers, for the design of new buildings or the refurbishment of older ones in earthquake zones and will want to know what the essential steps in building for safety in such areas are. Yet, others may have a more general interest in natural disasters and need an informed but largely non-technical account of how buildings have performed and of how the way today's buildings are constructed has been influenced by past earthquakes. The book aims to provide useful and accessible answers for all of these groups of readers.

1.5 Outline of the Book

The remainder of the book is divided into eight chapters. Chapter 2 presents field evidence of how buildings behave in earthquakes. It discusses how post-earthquake field investigations have contributed to our understanding of building behaviour. It gives brief accounts of 10 of the most significant earthquakes of the past 20 years. It concludes with an assessment of the overall trends of earthquake damage and casualties over time, and their distribution between richer and poorer countries.

Chapter 3 looks at how buildings are constructed in the world's most earthquake-prone regions. It considers first how the local climate affects local patterns and traditions of building, and shows how those traditional building forms affect earthquake performance. The world's areas of the greatest earthquake risk are then subdivided into 10 separate zones, and the patterns of building typical of each are described and illustrated, distinguishing rural and urban types.

Chapter 4 explains what causes earthquakes, and shows how the ground motions caused by them are felt by buildings and how buildings respond. It also considers other ways in which earthquakes can affect buildings through ground deformation, landslides, tsunamis and fire outbreaks, and points to the growing risk of compound disasters triggered by earthquakes.

Chapter 5 considers how buildings of different types of construction respond to the principal earthquake hazard of ground shaking. It classifies buildings into their different types and subtypes according to the main material of the load-resisting system – masonry, reinforced concrete, timber and steel. For each main type, it describes the typical behaviour in an earthquake from the onset of damage to collapse, based on field observations. And it suggests cost-effective ways in which each type of building could be made more earthquake-resistant. Chapter 5 also compares the earthquake vulnerability of different building types, showing the wide disparities that exist within the global building stock.

Chapter 6 looks at human casualties caused by earthquakes. It identifies the main causes of casualties, and how these relate both to building performance and to occupant behaviours. It shows how the expected number of casualties from a particular earthquake can be estimated for loss modelling, using either statistical or engineering approaches.

Chapter 7 considers different routes by which the earthquake resistance of buildings can be improved. It looks first at the engineering design of buildings and how codes of practice are used to achieve acceptable safety levels, both in the construction of new buildings and in the strengthening of existing buildings, and discusses associated costs. It also considers limitations in the effectiveness of building control regulations and implementation of codes of practice, and describes how building for safety programmes have been used to improve the construction of non-engineered building in poorer countries.

Chapter 8 reports on a global survey of the successes and failures of earthquake protection, country by country, based on responses from 39 experts in 28 different countries. For each responding country, the identified successes and failures are examined, and the countries are divided into three groups 'high achievers', 'limited achievers' and those with 'continuing and growing risks', indicating the wide disparity of performance across the world.

What is technically possible will only be achieved by the action of individuals and society as a whole, and its institutions. Thus, Chapter 9 concludes the book with an examination of what part different organisations and groups of people can play in meeting the overall challenge of earthquake protection. The separate roles of governments (national and local), non-government organisations (NGOs), the scientific and professional community, businesses, homeowners and individual citizens and the insurance industry are considered, and suggestions are made for ways in which each group could act more effectively.

Emphasising the message that it is ultimately the action of individuals that counts, the book contains a series of profiles (located as boxes within the appropriate chapters) of some individuals – 'game-changers' – whose actions have made a notable contribution to earthquake protection in their particular situation. These advocates show what we can do with the knowledge to build safe buildings before an earthquake strikes and to stop preventable deaths. Earthquakes are an underrated hazard: but by ensuring safe buildings and earthquake awareness before the earthquakes strike, we can make the threat unremarkable.

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2

How Do Buildings Behave in Earthquakes?

2.1 Learning from Earthquakes

When a large earthquake occurs, it causes human casualties, damages buildings and infrastructure, and affects livelihoods, society and the wider economy. It also sets in motion a process of relief and recovery, damage assessment and then rebuilding, carried out by governments, NGOs, commercial firms and individual households. It is important that the experience of each earthquake is recorded in detail, and that the lessons learnt are identified and passed on, both for the benefit of the affected country in its attempt to improve preparation for subsequent earthquakes, and also for the international community. Much of the damage caused by an earthquake is visible only for a short time, because demolition and rebuilding often start within a few days, so it is important that damage investigations start rapidly after an event. But it is equally important that, if they are to be useful for international comparison, such investigations should be done in a systematic way.

The need for speedy but systematic post-earthquake investigations has led to the formation of a number of international earthquake reconnaissance teams whose aim is to be available for rapid deployment after an earthquake. They are composed of earthquake specialists from different disciplines, and generally include team members from the affected country. Each team conducts a survey whose exact scope depends on the scale and type of damage. But the study generally includes investigations of the seismological and geotechnical aspects of the event, the damage to buildings and to infrastructure, and the way in which relief and rescue has been conducted. On return, the team produces a report which is available to all who are interested, and is commonly made available on openly accessible websites. The team also communicates the findings through various technical meetings.

The Learning from Earthquakes programme of the California-based Earthquake Engineering Research Institute (EERI) has the most experience of such field reconnaissance missions, and has conducted more than 150 investigations since it began after the 1971 San Fernando, California earthquake. In the United Kingdom, the Earthquake Engineering Field Investigation Team (EEFIT), working in conjunction with the UK's Institution of Structural Engineers, has conducted more than 30 investigations since its

Why Do Buildings Collapse in Earthquakes?: Building for Safety in Seismic Areas,
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formation in 1982 following the Irpinia (Italy) earthquake of 1980. Similar organisations exist in several other countries (Spence 2014). The cumulative findings of the missions have been very influential in formulating research programmes which have studied aspects of the physical damage, response and recovery from multiple events. And these research programmes in turn have led to steady improvements of national and international codes of practice for building, as well as assisting in understanding the vulnerability of different types of affected facilities and in developing ways to enhance earthquake safety internationally (EERI 1986; Spence 2014).

Both authors have been involved with several EEFIT post-earthquake reconnaissance missions. Our direct knowledge of the types of buildings affected in earthquakes, and our understanding of their behaviour, is largely derived from these earthquake missions, as well as from some more detailed field investigations and household surveys carried out independently. The following sections give brief accounts of 10 of the most significant earthquakes of the last 20 years, partly based on our own observations, but also making use of the field reports of our colleagues in the EERI and EEFIT teams and other reports. As we are concerned in this book primarily with buildings, these brief accounts emphasise in particular the range of building types which were affected and the levels and types of damage caused, topics which we will return to look at in more detail later in the book. They also touch, where appropriate, on the methods of damage investigation used.

Table 2.1 lists the most significant events of the twenty-first century up to 2018. It includes all those events which, according to the EM-DAT database, killed more than 4000 people, and also all those which had a damage cost exceeding US$3.9bn. The 10 events briefly described here include the 9 events with the highest casualty tolls of the last 20 years, and one other event, the New Zealand Christchurch event of 2011. This was particularly significant not for its casualties, which were relatively low, but for the very high financial cost of the damage caused, and for its particular impact on the historic masonry buildings of the city of Christchurch.

The chapter concludes with some general observations about earthquake damage, an assessment of global damage trends and the distribution of damage between different regions and country groups. In this way, we aim to approach an assessment of the question: how well are we, as an international community, doing in trying to limit the effects of earthquakes for this and future generations?

2.2 Significant Earthquakes Since 2000

2.2.1 The 26.1.2001 Bhuj Earthquake: Mw7.7, 13 481 Deaths

At 8.46 a.m. on 26 January 2001, India's 52nd Republic Day, one of the most devastating earthquakes ever to strike India occurred in the Kutch Region of Gujarat State. The earthquake of moment magnitude Mw7.7 and focal depth 23 km was located approximately 70 km east of the historic city of Bhuj. Heavy ground shaking affected an area of tens of thousands of square kilometres, although there was no surface fault rupture observed. The isoseismal map prepared by the EERI team indicates that the area subject to shaking at a level exceeding MM Intensity VIII ('heavily damaging') was over 30 000 km^2 (Jain et al. 2002).

Table 2.1 Significant earthquakes worldwide since 2000, ordered by number of deaths.

Date	Country	World Bank Income Group	Event	Magnitude (Mw)	Total deaths	Total damage (US$bn)	Insured losses (US$bn)	Percent insured
26/12/2004	Indonesia, Thailand, Sri Lanka, India	UM, LM	Indian Ocean earthquake and tsunami	9.1	225 841	7.8	0.48	6.2
12/01/2010	Haiti	L	Haiti	7.0	222 570	8	0.2	2.5
12/05/2008	China	UM	Wenchuan	7.9	87 476	85	0.37	0.4
08/10/2005	Pakistan	LM	Kashmir	7.6	73 338	5.2	0	0
26/12/2003	Iran	UM	Bam	6.6	26 796	0.5	0	0
26/01/2001	India	LM	Bhuj	7.7	13 481	2.6	0.1	3.8
11/03/2011	Japan	H	Great Tohoku[a]	9.1	>18000	210	37.5	18
25/04/2015	Nepal	L	Gorkha	7.8	8 831	7.1	0.1	1.4
26/05/2006	Indonesia	UM	Yogyakarta	6.3	5 778	3.1	0.04	1.3
28/09/2018	Indonesia	UM	Sulawesi[a]	7.5	4 340	1.5	0	0
21/05/2003	Algeria	UM	Boumerdes	6.8	2 266	5	0	0
03/08/2014	China	UM	Yunnan	6.2	731	5	0	0
27/02/2010	Chile	H	Maule[a]	8.8	562	22	8	36
19/09/2017	Mexico	UM	Puebla	7.1	369	2.9	1.3	45
24/08/2016	Italy	H	Amatrice	6.2	296	7.9	0.12	2
20/04/2013	China	UM	Lushan	6.6	198	6.8	0.023	0
22/02/2011	New Zealand	H	Christchurch	6.1	181	15	12	80
16/04/2016	Japan	H	Kumamoto	7.0	49	20	5	25

(*Continued*)

Table 2.1 (Continued)

Date	Country	World Bank Income Group	Event	Magnitude (Mw)	Total deaths	Total damage (US$bn)	Insured losses (US$bn)	Percent insured
23/10/2004	Japan	H	Niigata	6.6	40	28	0.76	3
16/07/2007	Japan	H	Niigata	6.6	9	12.5	0.34	3
20/05/2012	Italy	H	Emilia-Romagna	6.0	7	15.8	1.3	8
14/11/2016	New Zealand	H	Kaikoura[a]	7.8	2	3.9	2.1	54
04/09/2010	New Zealand	H	Darfield	7.0	0	6.5	5	77%

Income groups are from World Bank data (High, H; Upper-middle, UM; Lower-middle, LM; Low, L). See also Table 2.2. Dates are given in DDMMYYYY format. Some casualty and loss data are amended based on more recent estimates (Pomonis 2020).

[a] Events with significant tsunami impacts are shown.

Sources: CRED (2020); Pomonis, A., 2020. Personal communication.

The area has experienced a previous large earthquake (Mw about 8.0) in 1819, and a moderate Mw6.1 one in 1956, and is in the zone with the highest earthquake loading requirements in the Indian code of practice for the design of buildings.

Load-bearing masonry is the predominant way of building throughout the affected area, but methods have changed over time. The most common masonry technique is a single-storey house with walls of random rubble stone masonry set in a mud mortar, with a clay tile roof: these buildings are found everywhere, both in the main towns and in the villages (Figure 2.1). More substantial dwellings use dressed or semi-dressed stone or sometimes clay brick walls; these are commonly two-storey buildings. In recent years, the use of reinforced concrete (RC) slabs for floors and roofs, with coursed masonry walls, has become common in the wealthier parts of Kutch (Figure 2.2). The main towns have also significant numbers of multistorey apartment blocks in RC (Figure 2.3). None of these forms of building were spared by the intense and widespread ground shaking.

The major city of Gandhidham, and four large towns Bhuj, Anjar, Bhachau and Rapar, all in the Kutch district, were devastated, as was every village within a wide area. Over 230 000 one- and two-storey masonry buildings and several hundred concrete frame buildings collapsed. However, as pointed out by Sudhir Jain (2016), the collapse rate of buildings in the zone of highest intensity was much lower in this earthquake than in the 1993 Mw6.2 Latur earthquake in India's Maharashtra province where rubble stone walls with heavy mud roof are typical.

In Ahmedabad, about 200 km from the epicentre, severe shaking was experienced and over 100 multistorey RC frame buildings collapsed. A survey of damaged buildings in Bhuj and neighbouring villages by EEFIT (2005), including the author's team, showed that the rubble masonry buildings performed worst (over 30% collapse rate) while masonry with RC slabs and RC frame apartment buildings performed better (7 and 3% collapse rates). The collapse of buildings in Ahmedabad, all of which were of multistorey RC frames, can be

Figure 2.1 Stone masonry building in the Kutch district damaged in the Bhuj earthquake.

Figure 2.2 Brick masonry building with reinforced concrete floors damaged in the Bhuj earthquake.

Figure 2.3 Reinforced concrete building in the Kutch district and typical damage patterns. Notice ground floor failure.

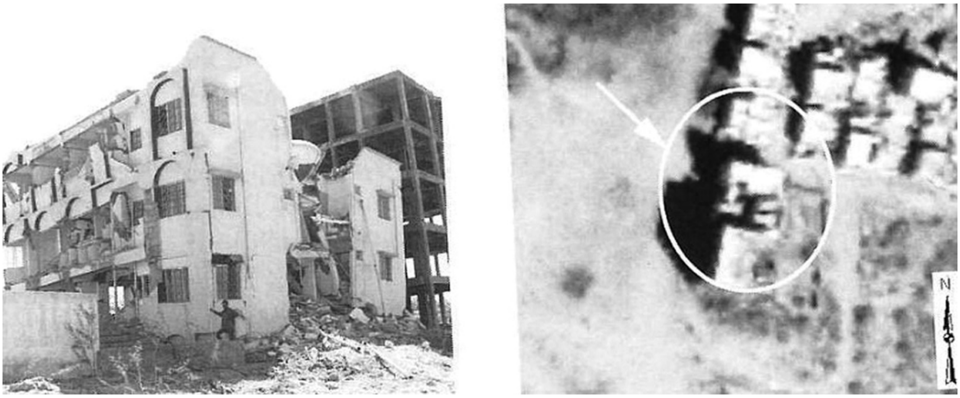

Figure 2.4 Damage to a reinforced concrete building in Bhuj, and view of the same building in satellite image, arrow showing viewing direction. *Source:* Saito et al. (2004).

attributed to amplification of the ground motion through the deep alluvial deposits on which Ahmedabad stands, coupled with poor design and construction – soft-storey apartment blocks were common. The Indian earthquake design code in use at the time is well-written and comprehensive, but it was not binding on private builders, and was largely ignored (see Chapter 8).

This earthquake was one of the first in which available high-resolution satellite imagery could be used to identify the damage to individual buildings, and this resulted in several studies to develop this technology (Saito et al. 2004) (Figure 2.4).

The final toll of dead and injured shows that altogether 13 481 people were killed in the earthquake (Jain et al. 2002). There were more than 166 000 injured, 20 000 of them seriously. From medical reports, it is clear that both death and injury were mainly the result of traumas associated with the collapse of buildings. Over 1000 school students and teachers were killed, though because it was a public holiday many schools were closed. There were also more adult female than male deaths (Murty 2005). There can be little doubt, though, that failure of weak masonry walls and the resulting collapse of dwellings was the main cause of death, and the magnitude of the death toll is a reflection of the very wide area over which heavy ground shaking was observed, combined with the weakness of the typical masonry buildings.

2.2.2 The 26.12.2003 Bam Earthquake: Mw6.6, about 27 000 Deaths

This earthquake occurred at 5.26 a.m. local time, on a hitherto unidentified fault passing under the historic city of Bam (Berberian 2005). Surface ruptures were identified along this fault south of Bam, and extending northwards towards the centre of the city. The area as a whole is one with a well-known history of active seismicity (nine earthquakes have been felt in Bam since the beginning of twentieth century). The earthquake was catastrophic in the city of Bam itself (far more than would be expected for an earthquake of this magnitude), as well as in the nearby town of Bharavat and neighbouring villages of Kerman Province. The intensity map, produced by IEES, indicated heavily damaging shaking intensity over an area of about 1000 km^2. The degree of damage in the city was clearly visible in high-resolution satellite images (Figure 2.5).

The massive death toll in Bam has been attributed to the extreme weakness of the adobe houses which are inhabited by the majority of the population. This method of building has been documented in the World Housing Encyclopedia (Maheri et al. 2005).

Adobe construction is an appropriate response to the climate of Southern Iran, given high day–night temperature swings, and also the lack of timber available for construction. At the time of the earthquake, this was still the predominant way of building in Bam. But in the event of an earthquake its weakness is extreme. The problems include (Maheri et al. 2005):

- Thick heavy walls, which attract large lateral seismic forces.
- Lack of connections between perpendicular walls.
- Heavy domed or vaulted mud roofs, exerting lateral pressure on walls.
- Poor quality of the adobe units (local sun-dried mud).
- Poor quality of mortar and bonding.
- Lack of foundations.
- Limited maintenance.

Architectural conservator Randolph Langenbach who made his own study in Bam following the earthquake (Langenbach 2015) has suggested that the use of straw reinforcement in adobe construction may have allowed termite attack, which could have reduced the inherent cohesion of the material. Certainly, many of Bam's adobe buildings simply disintegrated as a result of the ground shaking, leaving only heaps of dried mud brick rubble (Figure 2.6). The danger to occupants was increased by their close spacing, leaving little opportunity for escape, and this also inhibited search and rescue. Since the earthquake attempts have been made to develop a way of building dwellings which conforms to the climatic and space requirements, and uses local materials, but which is able to resist earthquakes (Maheri et al. 2005).

The huge death toll of nearly 27 000 was about 25% of the population of Bam at that time. It was undoubtedly the result of the collapse of very large numbers of adobe dwellings,

Figure 2.5 High-resolution satellite imagery of the centre of Bam taken (left) before and (right) after earthquake, clearly indicating the extent of the damage. *Source:* Satellite image ©2021 Maxar Technologies.

Figure 2.6 Failure of adobe dwelling in the Bam earthquake. *Source:* World Housing Encyclopedia. Reproduced with permission of EERI.

coupled with the early morning time of day, when most people were sleeping. It has been reported that only 2% of those who died were in buildings which did not collapse (Ghafory-Ashtiany and Mousavi 2005). Of the 23 600 injuries, 9477 were serious, and had to be treated in hospitals in Kerman and elsewhere as all the hospitals in Bam were severely damaged. Building collapse-related traumas constituted most emergency surgery cases. However, it has been suggested that a further very significant contribution to the death toll was the lack of immediate response capability (Movahedi 2005). The local emergency response capability was totally destroyed by the earthquake, and for the crucial first 24 hours the only rescue was being carried out by the local survivors using their bare hands. The loss of electricity meant that rescue stopped at nightfall, and freezing temperatures reduced the chances of overnight survival under the rubble. Asphyxiation resulting from the huge amount of dust was suggested as a further cause of many deaths (Movahedi 2005).

2.2.3 The 26.12.2004 Indian Ocean Earthquake and Tsunami: Mw = 9.1, 225 841 Deaths

At 7.59 a.m. on 26 December 2004, one of the largest earthquakes of the last 100 years anywhere in the world occurred in the Sunda trench in the Indian Ocean. At Mw9.1, the earthquake was one of the largest ever recorded, and had the longest duration of faulting ever recorded (between 8 and 10 minutes), with a fault rupture extending for 1300 km. The earthquake caused ground shaking over a wide region, but because of the extraordinary length of the fault rupture and the movement on it, the earthquake also triggered a massive and destructive tsunami, which devastated the coasts bordering the Indian Ocean, causing huge loss of life. The initial ground shaking was destructive throughout Aceh Province of Indonesia, particularly in the main city of Banda Aceh, and also in the Andaman and Nicobar Islands. But the tsunami carried the earthquake's energy over a much wider region, causing destruction throughout coastal northern Sumatra, and in all the countries bordering the Indian Ocean. Casualties caused by the tsunami were reported in 12 different countries, but most of the tsunami-related deaths occurred in Indonesia (165 000), Sri Lanka (36 000), India (16 000) and Thailand (8000). In Aceh Province of Indonesia, it destroyed virtually every village, town, road and bridge along a 170 km stretch of coast that was not more than 10 m above sea level. The death toll was over 16% of the entire population of the northernmost six districts of the province. Inundation depths reached up to 20 m in parts of Sumatra, 5–8 m in Thailand, and 2–5 m in South-eastern India and Eastern and Southern Sri Lanka (EEFIT 2006).

The tsunami was devastating to small buildings wherever the inundation depth was 2 m or more, and huge numbers of buildings of timber or traditional masonry were destroyed in Indonesia, Thailand and Sri Lanka (EEFIT 2006) (Figures 2.7 and 2.8). RC buildings of several storeys often survived but with serious damage, although there were cases of collapse through scour under the foundations. The huge loss of life was primarily due to the direct effects of the tsunami itself. Victims were either drowned directly or as a result of injuries caused by impact with debris from buildings or other objects: 'falling structures and waters full of swirling debris inflicted crush injuries, fractures and a variety of open and closed wounds' (WHO 2006). Tens of thousands were swept out to sea, and were ultimately recorded as missing, and were presumed drowned.

Figure 2.7 Damage caused by the 26 December 2004 tsunami at Unawatuna, Sri Lanka where the inundation depth was about 5 m. Damage to a masonry building. *Source:* EEFIT. Reproduced with permission.