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The impact of the earthquake activity in Western Europe from the historical and architectural heritage records

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Abstract

This chapter presents and discusses the impact of the earthquake activity in the plate interior region of Western Europe extending from the Lower Rhine Embayment to southern England. The present study is based on methodologies combining the historical and architectural heritage records to better quantify moderate and extensive damage from past earthquakes. These methodologies have been applied to seven destructive earthquakes with magnitudes ranging from 4.5 to 6.0, characteristic of the seismic activity of this area.

The extremely high seismic vulnerability of this region is illustrated by the destruction resulting from small shallow earthquakes such as the 1983 M = 4.6 Liège (Belgium) and 1884 M = 4¾ Colchester (England) earthquakes and the elevated financial losses produced by the 1992 M = 5.3 Roermond (the Netherlands) earthquake, despite the low observed intensities. This vulnerability is directly related to the very high density of population and to the substantial fraction of poorly constructed masonry dwellings in the building inventory in most of the cities of Western Europe. Indeed, the consequences of a rare M ~ 6.0 seismic event, such as the Verviers (Belgium) 1692 earthquake, could certainly be catastrophic in terms of victims and destruction.

Comparing the damage caused by past earthquakes in large structures such as churches or castles and classical dwellings provides information on their source and regional site effects. On the one hand, the earthquakes that caused moderate to heavy damage to large structures located far away from the epicentre had magnitudes greater than 5.0. On the other hand, the observation that churches were damaged in some localities of the Lower Rhine Embayment or the Brabant Massif while typical houses located in the same localities suffered less or had no damage appears to be related to the presence of a sedimentary cover with a

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low Q-factor that suppresses the high-frequency content of the seismic source, and (or) a thickness corresponding to a soil fundamental period that enhances ground motion in the frequency range of the large building natural resonance frequency.

8.1 Introduction

The damage caused by past earthquakes is an important source of information about the seismic vulnerability of a region and its study may be very helpful to validate seismic risk studies. Unfortunately, the available data on the impact of destructive earthquakes in plate interior regions, such as the tectonically stable Europe, are often imprecise, because strong earthquakes are rare and only a few of them have occurred since the developments of modern seismology.

The area of Western Europe extending from the Lower Rhine Embayment to the southern North Sea (Figure 8.1) is characterised by a moderate seismic activity, with the occurrence of 14 earthquakes with estimated magnitude greater than or equal to 5.0 since the fourteenth century (Camelbeeck *et al*., 2007). The most important of these earthquakes occurred on 18 September 1692, in the northern part of the Belgian Ardenne. Its magnitude

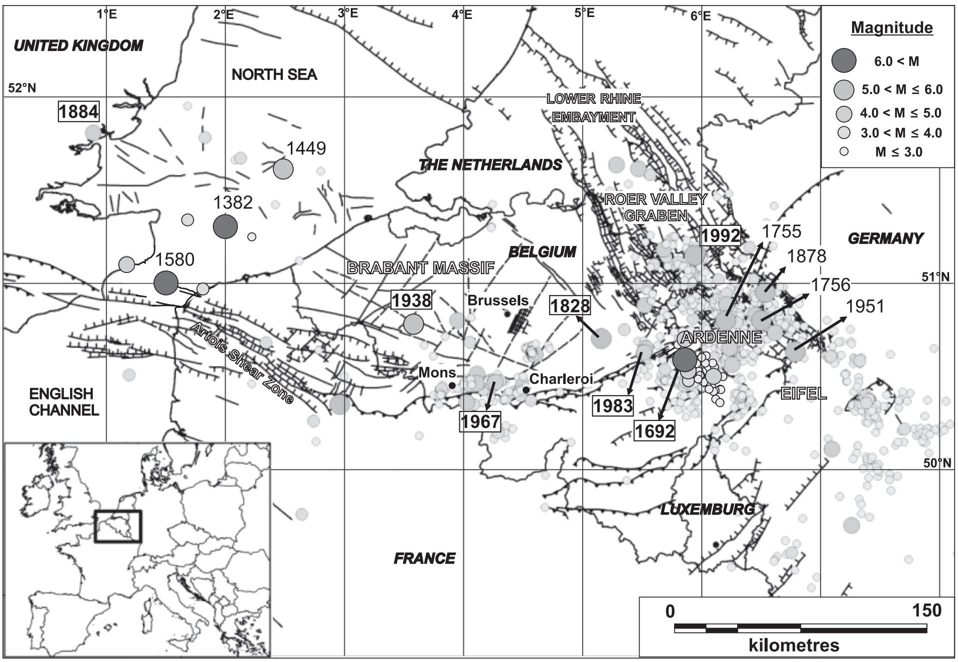

Figure 8.1 Seismic activity in the region extending from the Lower Rhine Embayment to southern North Sea from 1350 to 2012. Rectangles enclose dates of earthquakes studied in this chapter.

has been estimated as 6¼ (Alexandre *et al*., 2008). The heavy damage caused by the two recent M 4.6 and 5.3 earthquakes in Liège (Belgium) on 8 November 1983 and in Roermond (the Netherlands) on 13 April 1992 (De Becker, 1985; Plumier *et al*., 2005; Berz, 1994) enhances the need to quantify the possible consequences of the seismic activity in this part of Europe as the basis for earthquake mitigation strategies and policies of prevention.

An optimum dataset to evaluate the impact of an earthquake would be that for which specific damage is reported and described for each of the damaged buildings. In Western Europe, such detailed information has only been collected by the Belgian Federal Calamity Centre for the localities affected by the destructive earthquake that occurred in Liège (Belgium) on 8 November 1983. A sufficient dataset should include quantitative damage information that would allow accurate intensity values to be assigned. Even for recent earthquakes this kind of data is not necessarily available, resulting sometimes in bad intensity evaluation.

During the past ten years we have significantly improved our knowledge of the impact of some damaging past earthquakes in Western Europe by enlarging the historical data archive and developing the methodologies to identify earthquake traces in historical buildings. In this chapter, we present and discuss this methodological framework and the impact of seismic activity on the region from the Lower Rhine area to southern England based on damage information gathered for seven typical past destructive earthquakes. We also examine the influence of the sedimentary cover on the intensity of the damage caused by these earthquakes in the northern part of the study area.

8.2 Seismic activity between the Lower Rhine Embayment and the North Sea

The study area is the most seismically active region of Western and Central Europe to the north of the Alps (Figure 8.1). An important part of this activity is concentrated in the Roer Valley graben, part of the Lower Rhine Embayment that crosses the border region between Belgium, Germany, and the Netherlands (Hinzen and Oemisch, 2001; Camelbeeck *et al*., 2007). Seven earthquakes with M $\geq$ 5.0 have occurred there since 1350, the most significant had a magnitude M $\sim$ 5¾ and affected the region of Düren in Germany on 18 February 1756. More recent strong earthquakes occurred on 14 March 1951, near Euskirchen in Germany (M = 5.3) and on 13 April 1992 in Roermond, the Netherlands (M = 5.3). Ahorner (1975) provided a comprehensive seismotectonic study establishing the relationship between this seismic activity and normal faults in the Roer Valley graben offsetting Quaternary deposits up to 175 m. Paleoseismic investigations (Camelbeeck and Meghraoui, 1996, 1998; Vanneste *et al*., 1999, 2001; Meghraoui *et al*., 2000; Vanneste and Verbeeck, 2001) suggest that coseismic surface ruptures have occurred during earthquakes with magnitude in the range 6.0–7.0 during the Holocene and late Pleistocene. A synthesis of these results is given in Camelbeeck *et al*. (2007).

To the west of the graben, seismic activity is also well established in the north of the Belgian Ardenne and in the Eifel Mountains in Germany. The most significant event of the whole study region is the M = 6¼ earthquake that occurred in this zone on 18 September 1692, near the city of Verviers (Alexandre *et al*., 2008). At the northern limit of the Ardenne, two recent damaging earthquakes also occurred in the city of Liège on 21 December 1965 (M = 4.3) (Van Gils, 1966) and 8 November 1983 (M = 4.6).

Another zone of concentrated seismic activity is the region of the Hainaut province of Belgium, between the cities of Mons and Charleroi. Despite the fact that none of these earthquakes exceeded magnitude 4.5, some of them caused some damage locally due to their shallow depths (≤3–5 km). Reported damage during these earthquakes concerns mainly the collapse or partial collapse of chimneys, broken windows, cracked ceilings and walls. The tectonic origin of these earthquakes is debated, as it is possible that part of the reported activity in this area could be related to the extensive mining works that took place in this area from the end of the nineteenth century to the beginning of the 1970s (Descamps, 2009).

Another particularity of the study area is that part of the seismic activity appears to be spatially diffuse and sporadic, as is common in many plate interior regions worldwide. For instance, in the Strait of Dover and southern North Sea, seismic activity has been weak since the beginning of the seventeenth century; however, three historical earthquakes that occurred in this area on 21 May 1382, 23 April 1449 and 6 April 1580 produced significant damage in southern England, northern France, and Belgium (Melville *et al.*, 1996). In the same way, the Brabant Massif region has not shown any significant earthquake activity since the installation of the modern seismic network in Belgium in 1985, but this region was violently shaken on 23 February 1828 and on 11 June 1938 by two M ~5.0 earthquakes that caused widespread damage.

8.3 The background and methodologies of historical seismicity in Western Europe

The retrieval and analysis of information on earthquake effects, whatever the epoch of the earthquake, are part of the research field called “historical seismicity”. Most of the information on historical earthquakes in northwestern Europe, spanning a period from the earliest available sources (*c*. AD 700) to the present, can be found in the database that we have developed at the Royal Observatory of Belgium, which is partly accessible on the Internet (Camelbeeck *et al.*, 2009).

In this chapter, we will focus specifically on the information concerning reported damage with the purpose of evaluating the local and regional impacts of destructive earthquakes. This objective requires more detailed information on the damage characteristics and their spatial distribution than that of classical investigations evaluating earthquake location and magnitude from intensity datasets. According to the differences in the type of documentation that can be collected on damaging earthquakes, in this study we differentiate between the information that was collected before and since the development of regional and national seismic observatories, which corresponds roughly to the year 1900.

8.3.1 The period from 1900 to the present

In the study area of Western Europe, many permanent seismological observatories were established at the end of the nineteenth century or at the beginning of the twentieth century. For example, in France, the first seismological measurements were conducted in 1892 in

Strasbourg and in 1908 in the Paris Parc Saint-Maur Observatory. In Belgium, the seismic station of Uccle has been operational since 1899, while the seismic station located in the Netherlands Meteorological Institute in De Bilt was installed in 1907. These observatories published their seismic phase measurements and earthquake observations in the form of seismic bulletins that are still available. For the earthquakes that have occurred since this epoch, part of the available information describing their effects and the damage they caused comes from scientific reports published by these national or regional seismic observatories.

Nevertheless, there are few earthquakes that occurred in Western Europe for which data of sufficient quality exist to evaluate quantitatively the importance of the damage. The 1983 Liège earthquake is probably the best documented one, with detailed damage reports existing for each of the 16,000 buildings for which the owners asked for a contribution from the Belgian State for the repair costs of the damage. This dataset is stored as paper files at the Belgian Federal Calamity Centre and has been used in different investigations on the earthquake (Jongmans and Campillo, 1984; Jongmans, 1989; Jongmans and Plumier, 2000; Garcia Moreno and Camelbeeck, 2013).

The dataset established by Pappin *et al*. (1994) after a three-day damage survey in the 1992 Roermond earthquake epicentral area is less detailed, but it provides the percentage of the buildings of selected types that experienced slight and moderate damage from the earthquake. Residential masonry was the only building type sufficiently common to allow a statistical analysis.

Since 1932, every time an earthquake occurs the Royal Observatory of Belgium sends a standard questionnaire to the authorities of the Belgian localities affected by the seismic event. This document provides quantitative information on the damage to chimneys in each locality. This data is extremely useful to quantify the intensity of the damage as it can be assumed that the proportion of damaged chimneys is equivalent to the proportion of buildings presenting at least moderate damage (see Section 8.4). Therefore, these official inquiries provide relevant information allowing a comparison of the percentage of moderate and extensive damage for the best documented 1983 Liège and 1992 Roermond earthquakes with older ones. In Section 8.5, we will discuss such an evaluation carried out for the $M = 4.3$, 28 March 1967 earthquake that occurred in the Hainaut region and the $M = 5.0$, 11 June 1938 earthquake that strongly shook the western part of Belgium and northern France.

These data are complemented with information provided by scientific studies, such as for the British Colchester 1884 earthquake, for which the number of repaired buildings in the more affected localities is available in a scientific report performed at the time of the earthquake (Musson *et al*., 1990).

8.3.2 Pre-1900 period: historical seismicity and the architectural heritage

There are two main differences in the data available to study earthquakes before 1900 compared to those for the twentieth century. First, the earlier earthquakes were not recorded by seismic instruments and, second, there are far fewer scientific studies and less documentation describing their effects and damage. Hence, their investigation requires collecting accounts and eyewitness reports in different types of historical sources. Often, the most interesting sources are the individual narratives found in diaries, letters, and brief notes. Local chronicles and annotations in parish registers generally mention the seismic events, but often without detailed information. In fact, there is more chance of finding quantitative data on the damage in administrative sources, including reports from local authorities, account books indicating repair costs, or official civil or ecclesiastic reports asking for funds to repair damaged buildings or churches. Reports written some decades later can also include relevant information on the damage produced by an earthquake as indirect first-hand sources transmitted to us as second-hand sources. Newspapers and other periodical contemporaneous publications are another common source of information, after their origins during the seventeenth century in Western Europe (Alexandre *et al*., 2007).

In essence, all the historical reports are incomplete in the sense that they provide very little quantitative information on earthquake effects and, for a given earthquake, the geographical distribution of the localities for which they provide information often is not homogeneous. To improve our knowledge of the impact of historical earthquakes, it is thus necessary to collect more eyewitness accounts in record offices, in order to better characterize local damage and geographically extend our knowledge of earthquake effects.

Another way to better characterize the damage caused by past earthquakes is to look for repairs or weaknesses in present-day buildings that already existed at the epoch of the earthquake, in order to evaluate whether these disturbances can be explained by an earthquake. Such evidence is complementary to the historical reports and is an invaluable source of information on the destructiveness of past earthquakes, as will be shown in this chapter. Large buildings such as churches or castles appear to be the most appropriate structures for which to investigate such relationships, even if they are not the most adequate for evaluating intensity (Grünthal *et al*., 1998). Indeed, these buildings more easily survive the effects of aging than individual houses. Moreover, the construction and maintenance data for these buildings are generally noted in the archives of the local parish or local administration. Hence, there is more chance of retrieving information on their different phases of construction or reconstruction than for particular houses.

Establishing a link between an earthquake and possible damage to a specific building from observed pathologies or (and) repair traces needs a strict methodological approach. The first aspect to consider concerns the estimation of the age of the buildings and the dating of repairs and existing pathologies. Second, pathologies and repairs can result from numerous different causes other than the earthquake hypothesis. Therefore, it is necessary to confront the observations with the different possible hypotheses and to accept the earthquake origin only if sufficient scientific arguments can be given. A beautiful example in archeoseismology illustrating the importance of such detailed investigation, including numerical modelling, is given by the study by Hinzen *et al*. (2010) on the Lycian sarcophagus of Arttumpara in Turkey, which deciphered human and earthquake actions on the sarcophagus.

Part of this chapter is devoted to an analysis of the impact of damaging earthquakes on architectural heritage buildings in Belgium. In this regard, we conducted two different investigations to better evaluate the importance of the damage caused by two past earthquakes that demonstrate the real benefit of such an approach. We first investigated the repairs and pathologies of the churches in the epicentral area of the 23 February 1828 earthquake (Philipront, 2007), which are presented and discussed in Section 8.5.6 of this chapter. Second, we studied the houses in the centre of the village of Soiron, located in the epicentral area of the M = 6¼, 1692 Verviers earthquake, to estimate their age and identify pathologies and repairs that could be associated with this earthquake (Dewattines, 2010). This information is used in Section 8.5.7 to formulate hypotheses on the intensity of the earthquake in the village, which are discussed in the light of the information collected in historical sources.

8.4 Damage quantification

Most of the buildings damaged during the destructive twentieth- and nineteenth-century earthquakes that occurred in the study area can be classified as low-rise unreinforced brick-masonry buildings. That is because, even if the building types have evolved to either steel or reinforced concrete construction, low-rise brick masonry (or mixed concrete–brick) continues to be the type of construction typically chosen by the population. Thus, the building inventory continues to include masonry structures that are sometimes very old. Hence, the main information at our disposal concerns this kind of building. Nevertheless, knowing the range of vulnerabilities of such unreinforced masonry buildings and other types of buildings, it should always be possible to evaluate the potential damage for the other types of buildings by comparison with the damage observed to masonry buildings.

Because comparison of the impact of historical earthquakes and more recent ones can only be done using seismic intensity values, it seems advisable to define the seriousness of damage to the buildings by a damage scale associated with the intensity scale used. For this reason, we quantified the degree of damage according to the European Macroseismic Scale EMS-98 (Grünthal *et al.*, 1998). This scale distinguishes five different degrees of damage, where degree 1 (D1) corresponds to negligible to slight damage, degree 2 (D2) to moderate damage (cracks in numerous walls, partial falling of chimneys, etc.), degree 3 (D3) to heavy damage (significant cracks in most of the walls, chimneys rupture at the junction with the roof, etc.), degree 4 (D4) to very heavy damage (serious weakness of the walls, partial structural failure of roofs and floors), and degree 5 (D5) to complete or nearly complete building collapse.

Furthermore, by using the HAZUS fragility curves (FEMA, 1999) on the 1983 Liège earthquake dataset, Garcia Moreno and Camelbeeck (2013) were able to associate effective losses for this earthquake with the damage scale associated with HAZUS, providing a way to evaluate seismic risks (Figure 8.2). Therefore, it is also logical to use the damage scale defined by HAZUS for the present study. Fortunately, there is a good correlation between the damage scales associated with EMS-98 and the HAZUS fragility curves (FEMA, 1999)

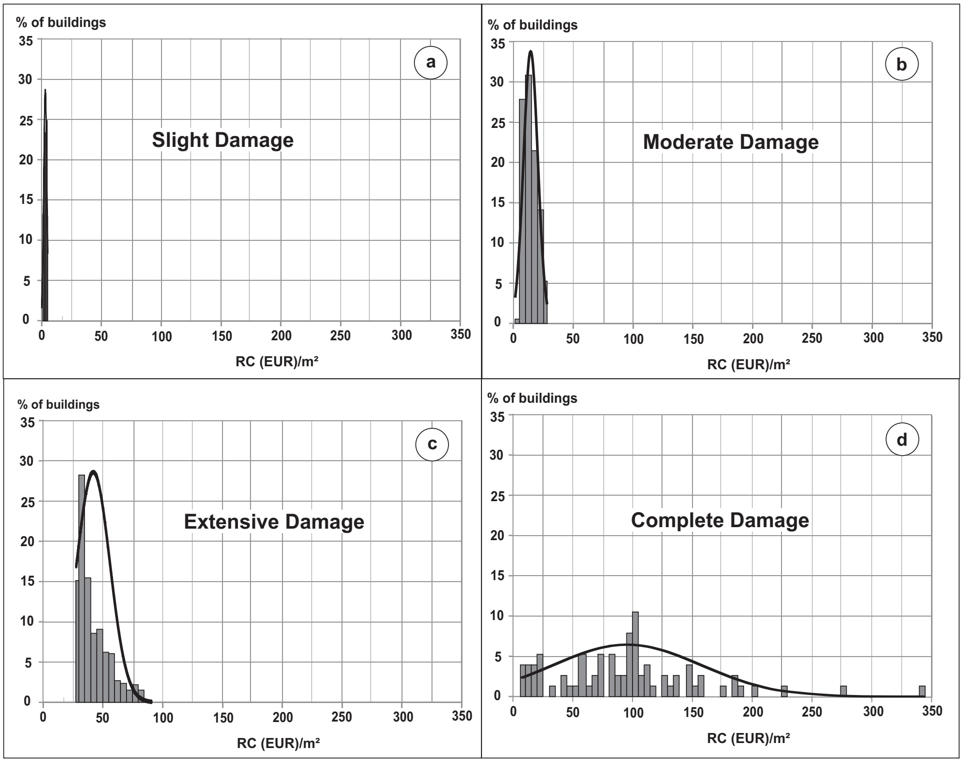

Figure 8.2 Statistics of the repair costs per unit surface for the different damage grades for the 1983 Liège earthquake (based on Garcia Moreno and Camelbeeck, 2013): (a) slight damage (SL), equivalent to damage grade 1 of the EMS-98 macroseismic scale (Grünthal *et al.*, 1998); (b) moderate damage (MD), equivalent to damage grade 2 of the EMS-98 macroseismic scale; (c) extensive damage (ED), equivalent to damage grade 3 of the EMS-98 macroseismic scale; (d) complete damage (CD), including damage grades 4 and 5 of the EMS-98 macroseismic scale. The cost information has been converted from Belgian Francs (BEF) to Euros (EUR). At the epoch of the earthquake, the cost of a two-floor unreinforced brick-masonry house with a ground surface area of 100 m^2 was around 1 million BEF or 25,000 EUR.

for unreinforced masonry (Hill and Rossetto, 2008). There is equivalence between EMS-98 degree 1 and slight damage in HAZUS, degree 2 and moderate damage, degree 3 and extensive damage, and degrees 4 and 5 with complete damage.

In the case of the 1983 Liège earthquake, Garcia Moreno and Camelbeeck (2013) showed that the repair costs begin to be important at the degree of damage D2 on the EMS-98 macroseismic scale, which also corresponds to moderate damage on the HAZUS damage scale (Figure 8.2). Therefore, this information should allow evaluation of the global repair costs of an earthquake. Hence, in Figure 8.3 we present maps reporting the percentage of damage greater than or equal to moderate in each affected locality for the five earthquakes for which we retrieved this detailed information, rather than the intensity.

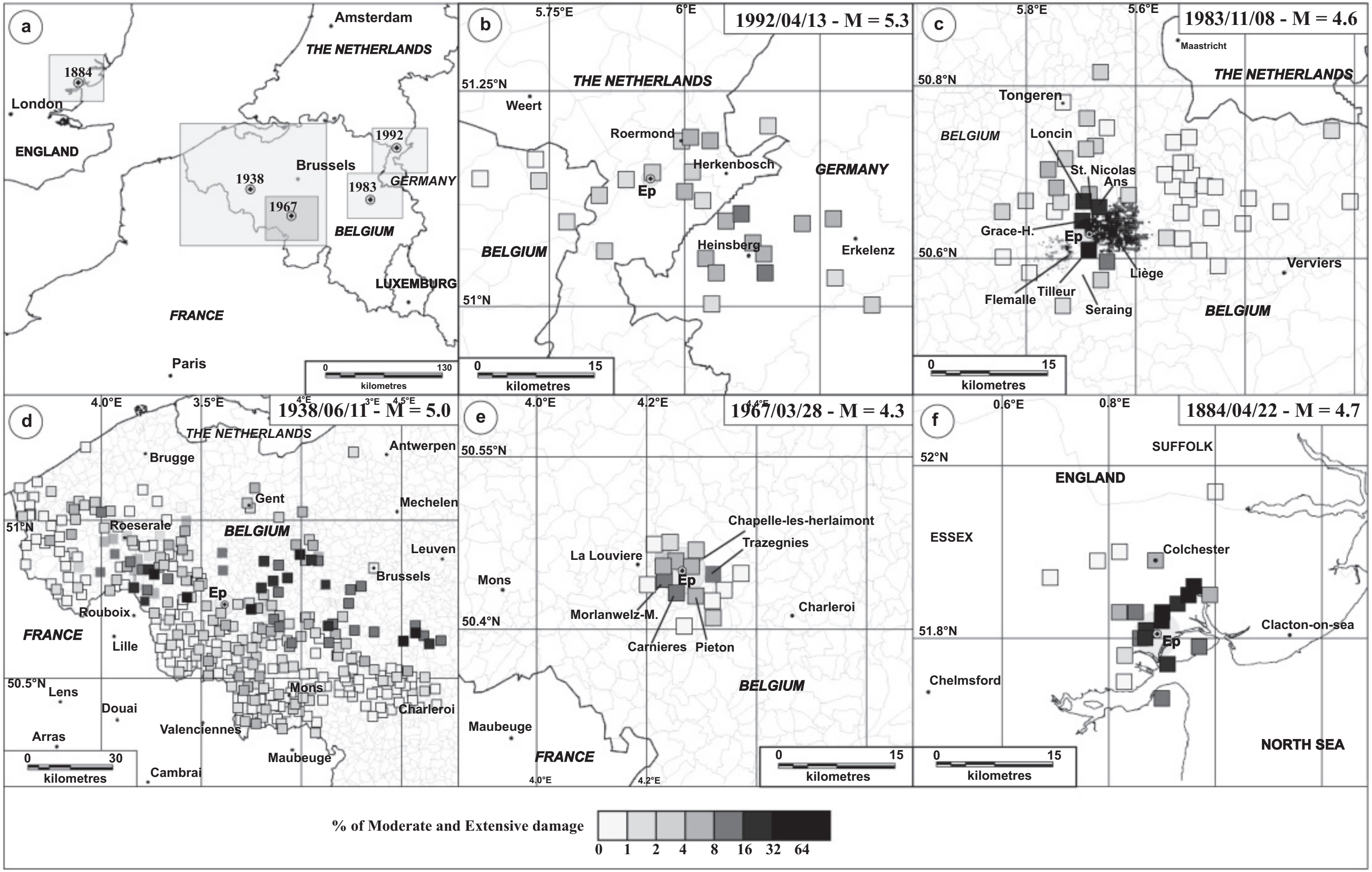

Figure 8.3 Statistics of damage greater than or equal to moderate for the 13 April 1992 Roermond (b), 8 November 1983 Liège (c), 11 June 1938 Nukerke (d), 28 March 1967 Carnières (e) and 22 April 1884 Colchester (f) earthquakes.

Considering that most of the low-rise unreinforced masonry buildings commonly found in these regions of Western Europe should be classified as vulnerability A and B (for the less vulnerable part of the stock), the quantitative information of moderate or extensive damage allows us to fix the intensity on the EMS-98 macroseismic scale: Intensity VI thus corresponds to grade 2 or moderate damage in a few buildings (up to 10%) of vulnerability class A and B. Intensity VII is associated with damage of grade 3 or extensive damage in many buildings (more than 10%) of vulnerability class A. Few of these buildings suffered grade 4 or complete damage. To reach intensity VIII, many of the vulnerability class A buildings would have to suffer degrees of damage 4, and a few of them should collapse.

For historical earthquakes, there is no or little quantitative information on moderate or more extensive damage. Therefore, in order to assign intensities, it is important to be aware of the often poor information and the necessity to use intensity ranges, indicating the uncertainty of the interpretation. Another significant problem is the lack of information on the vulnerability of the buildings for which descriptions of damage are given in the historical sources. Despite the great diversity of the materials used and the construction methods during historical times, it is often supposed that the vulnerability class of traditional houses ranges between classes A and B of the EMS-98 intensity scale, similar to that for the low-rise unreinforced masonry buildings typical of the twentieth century. This may not be totally correct, and is clearly an aspect that should be investigated more deeply when studying past earthquakes. In the next section, we will present our evaluation of the intensity based on the aforementioned hypothesis in the localities of the epicentral area of the $M = 5$, 23 February 1828 central Belgium and $M = 6\frac{1}{4}$, 18 September 1692 Verviers earthquakes.

For each of the studied earthquakes, we have compiled an inventory of the damage caused to large buildings of the architectural heritage, mainly churches. For these churches, we have considered the damage scale proposed by Meidow and Ahorner (1994) for the occasion of the 1992 Roermond earthquake. They define slight damage as “fine cracks in plaster, fall of small pieces of plaster and the loosening of pinnacles or comparable building parts”, moderate damage as “small cracks in walls and vaults, cracks between church tower and nave and the falling of pinnacles”, and heavy as “large and deep cracks in walls and vaults, and damage to load-bearing parts”. We added a fourth grade, D4, when parts of the church collapsed.

8.5 Typical damaging earthquakes in Western Europe

In this section, we present the results of an investigation on the impact of some destructive earthquakes that occurred in the study area. The list of seismic events studied is not exhaustive. It includes seven earthquakes presenting typical characteristics of the seismic activity of this part of Europe. This allows us to discuss the main characteristics of the damage caused by moderate and large earthquakes in the area.

8.5.1 The 13 April 1992 Roermond earthquake

The $M = 5.3$, 1992 Roermond (the Netherlands) earthquake is one of the largest earthquakes observed during historical times in the Lower Rhine Embayment (Figure 8.1). Its focal mechanism is pure normal faulting at a depth of 17 km on the Peel fault, which is the eastern border fault of the Roer Valley graben (Camelbeeck and van Eck, 1994; Ahorner, 1994).

This earthquake was felt over a large area of western and central Europe with a mean radius of perceptibility of about 440 km (Meidow and Ahorner, 1994). Bouwkamp (1994) noticed that the main damage was restricted to failure and cracking of brick masonry chimneys and parapets. There were very few cases in which the upper portion of chimneys had toppled over and damaged the tiles on the roof. A partial collapse of gable ends, inadequately tied to the wooden roof structures, was also noticed in a few cases, as well as diagonal shear cracking of exterior masonry walls. This damage was mainly observed in old masonry structures, some of them dating back to the eighteenth century. More modern steel and reinforced concrete constructions were far less affected by the earthquake.

Meidow and Ahorner (1994) also mentioned damage on 150 churches in Germany, predominantly in the epicentral area, but also at larger distances in Cologne, Bonn, and Koblenz (Figure 8.4a). Damage was also observed on different churches located in the Netherlands, with the most affected one being situated in Herkenbosch (Bouwkamp, 1994).

The official macroseismic inquiry (Haak *et al.*, 1994) reported a maximum intensity of VII (on the MSK scale), but there is no description of the way this intensity value was calculated. Another analysis of the seismic intensities caused by this earthquake was performed by Meidow and Ahorner (1994), who established a macroseismic map for the German territory. They also assessed the maximum intensity as VII (in the MSK scale) and justified this value based on the number of buildings that were significantly damaged in the localities to which this intensity has been attributed. They also mentioned that eight buildings were uninhabitable in Germany and had to be evacuated.

The only study that evaluated the amount of damage experienced by buildings in the localities affected by the Roermond earthquake is that of Pappin *et al.* (1994). The analysis of their observations is available at the Cambridge Earthquake Impact Database: www.ceqid.org/. These authors provided a statistical analysis of the damage caused to residential masonry buildings located in the Netherlands and western Germany. In the most affected localities, the percentage of moderate damage (EMS-98 degree 2) did not exceed 17% of the buildings and there are only two localities where a little (2 and 3%) extensive damage (EMS-98 degree 3) was observed (Figure 8.3b). From these numbers, they assigned a maximum intensity value of VI (on the MSK scale) to the most affected localities. We agree with this interpretation because in order to reach intensity VII (on the EMS-98 scale) many buildings (more than 10%) of vulnerability class A should have experienced extensive damage (EMS-98 grade 3), and this is clearly not the case. Note that Pappin *et al.* (1994) did not visit the locality of Herkenbosch where significant damage was notified.

The Roermond earthquake presents two particularities that are important to take into consideration for regional seismic risk studies. The first one, underlined by Meidow and Ahorner (1994), is that the observed maximal intensity is low for its magnitude by comparison with other earthquakes in the Lower Rhine Embayment. Its focal depth, which is deeper than usual in the Lower Rhine Embayment, is the first factor that explains the low epicentral intensity. A second factor is the strong seismic energy absorption by the 1500 m

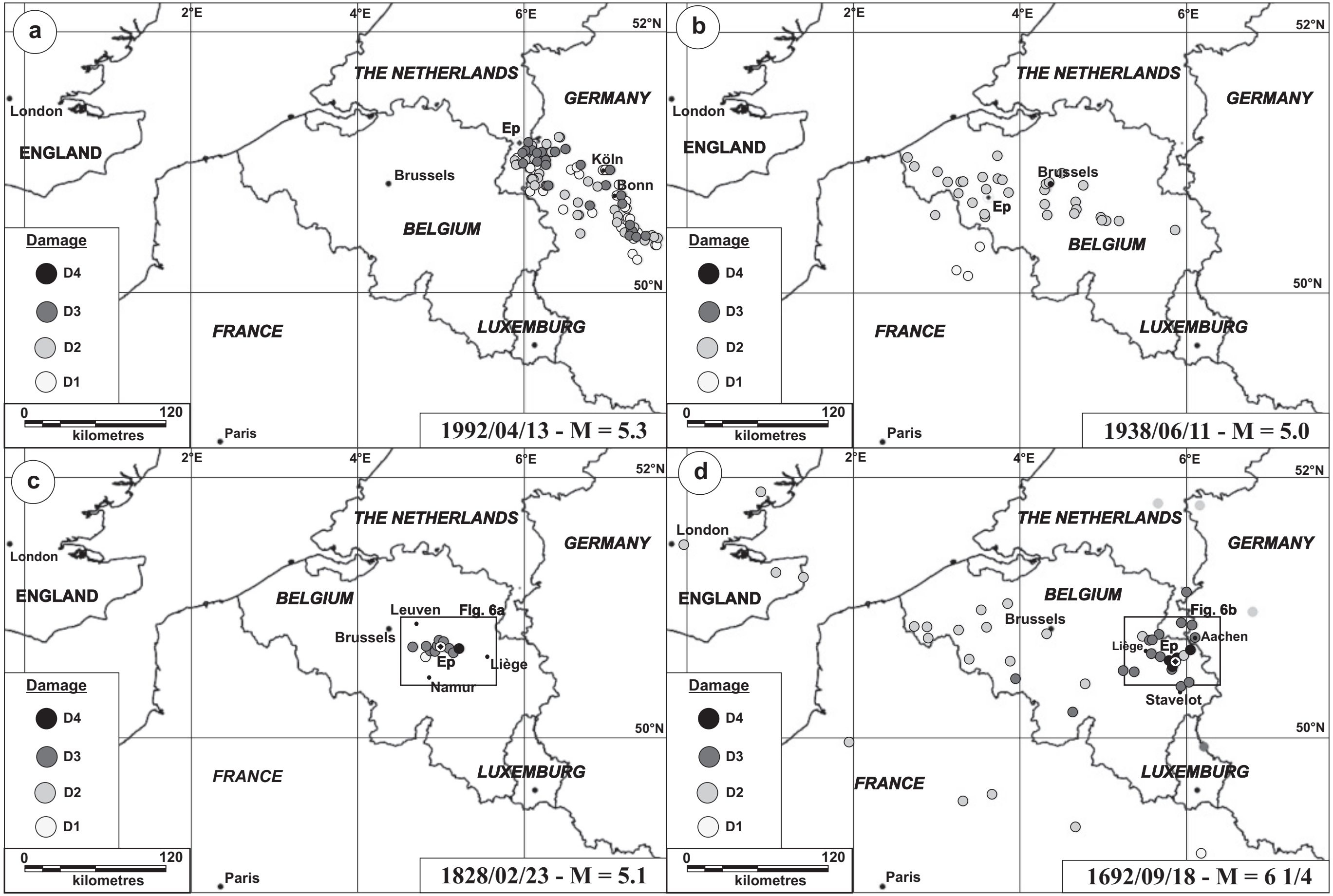

Figure 8.4 Observed damage to churches during M ≥ 5.0 earthquakes: the 13 April 1992 Roermond (a), the 11 June 1938 Nukerke (b), the 23 February 1828 Hannut (c) and the 18 September 1692 Verviers (d) earthquakes. The damage scale is that defined by Ahorner and Meidow (1994) for the Roermond 1992 earthquake. The rectangles in maps (c) and (d) indicate the epicentral area of the 1828 and 1692 earthquakes shown in Figure 8.5.

thick layer of soft Tertiary and Quaternary sediments in the Roer Valley graben in the region of Roermond.

The second particularity is that, despite the small value of the maximum observed intensity, the losses caused by this earthquake were evaluated at the time of the earthquake as around 125 million EUR (Berz, 1994). This may be due to the extent of the moderately damaged area, which is directly related to the earthquake magnitude and focal depth, in a region of dense population, industry, and important natural hazards insurance coverage.

A significant part of the estimated losses, corresponding to 24%, is actually due to the damage caused to churches. It is generally assumed (Grünthal *et al.*, 1998) that, even though they may be better built, monumental buildings such as churches may be more likely to sustain damage than ordinary buildings. This is probably true for slight damage, but in the present case, moderate and extensive damage have been observed in some churches, even in locations where houses suffered very slight or no damage.

This apparent difference in the behaviour of low-rise buildings and churches is essentially linked to the fact that seismic wave energy in the high-frequency range, which corresponds to the first mode natural frequency of houses, is largely attenuated before the waves reach the Earth surface by a significant thickness of sediments covering the bedrock. On the contrary, at lower frequency the energy content of the seismic signal is less modified by propagation through poorly consolidated sediments. As the Roermond earthquake source is large enough to generate seismic energy at frequencies around 1 Hz, in the frequency band of the first mode of vibration of large buildings such as churches, the seismic energy is sufficient to cause damage to churches, even at large distance.

Reports and eyewitness accounts from the newspapers about the Roermond earthquake can be found via the link: http://seismologie.be/cup2014.html.

8.5.2 The 8 November 1983 Liège earthquake

The earthquake that shook the region of Liège (Belgium) on 8 November 1983 at 0 h 49 m (UT) had unusual consequences considering its low magnitude, 4.6. Significant damage left more than 1,000 people homeless, causing serious logistical problems.

Within an area of 10 km^2 around the locality of Saint-Nicolas (Figure 8.3c), at the earthquake epicentre, more than 16,000 buildings were damaged by this earthquake (De Becker, 1985; Phillips, 1985; Plumier *et al.*, 2006). The most apparent damage was the fall of chimneys, bricks or ornamental features. The fall of these features caused damage to roofs and many cars in the street, suggesting that if the earthquake had occurred during the day the human consequences (two deaths and some dozen injuries) would have been more tragic. Many walls were also intensively cracked and it was necessary to shore up many of them. The worst structural damage was observed in older and poorly built structures. In the two most affected localities, Saint-Nicolas and Liège, 129 houses were declared uninhabitable and 37 were demolished. Well-constructed masonry buildings fared relatively well, with damage usually restricted to chimneys. The damage in two churches in the epicentral area was sufficient for the authorities to declare a temporary decree of uninhabitability. There was little damage to industrial installations, as expected, because most of them are located outside the most affected area.

Garcia Moreno and Camelbeeck (2013) collected and provided an overview of the available data on the damage caused by the 1983 Liège earthquake. The damage is especially well documented for each of the 16,000 houses for which the owners asked for a contribution from the Belgian State to help with the repair costs. These data are stored at the Belgian Federal Calamity Centre. Unfortunately, the informatics structure of this database has not been preserved to the present day, and the paper copies of these files are the only documents currently available. This dataset allowed Garcia Moreno and Camelbeeck (2013) to estimate the statistical distribution of damage in the localities of Saint-Nicolas, Liège, and Flémalle. The results from that study have been synthesized in Figure 8.3c, where the percentage of houses presenting moderate to extensive damage is shown in squares of 200 by 200 metres in these localities. For the other localities, the damage quantification is based on the official inquiry of the Royal Observatory of Belgium and is given by locality.

In the most affected squares in Saint-Nicolas, Liège, and Flémalle, the percentage of buildings with moderate or stronger than moderate (extensive and complete) damage is respectively 78%, 100%, and 75%, while the median values of the observed percentages of damage for the complete set of these squares are respectively 32%, 25%, and 4%.

In the localities close to Liège and Saint-Nicolas, the percentage of damaged chimneys is reported in the official inquiry done by the Royal Observatory of Belgium. It is 25% in Ans, 20% in Grâce-Hollogne, 21% in Loncin, 50% in Tilleur, and 14% in Ougrée. The number of damaged buildings in those different localities corresponds to half of the total damage reported to the Belgian Federal Calamity Centre.

This significant damage, which reached EMS-98 intensity of VII, has been attributed to the shallow depth of the earthquake, the amplification of ground shaking due to the local geology, and the consequences of former mining activity on the ground surface, which had already affected some of the buildings located in this area (Jongmans and Campillo, 1984; Monjoie, 1985; Jongmans, 1989; Jongmans and Plumier, 2000).

The reports and eyewitness accounts from the newspapers about the Liège earthquake can be found via the link: http://seismologie.be/cup2014.html. The statistics of damage averaged over the 200 m by 200 m squares are included as an electronic supplement to the paper by Garcia Moreno and Camelbeeck (2013). The whole dataset can be obtained by request to the first author of this chapter [TC].

8.5.3 The 28 March 1967 Carnières earthquake

This earthquake is typical of the damaging earthquakes that occurred in the Hainaut seismic zone during the twentieth century, which typically present magnitudes between 4.0 and 4.5 and are at a shallow focal depth.

This earthquake was strongly felt in the region between the cities of La Louvière and Charleroi (Figures 8.1 and 8.3e). The shaking frightened a large part of the population; some ran outdoors, while others took refuge in their cellars. In some localities, the power supply suddenly stopped. Reported damage included the collapse or partial collapse of chimneys, broken windows, cracked ceilings and walls (source: *La Nouvelle Gazette*, 29 March 1967).

From the official inquiry of the Royal Observatory of Belgium, the most affected localities were Carnières (20% of damage equal to or greater than moderate), Trazegnies (10%), Morlanwez-Mariemont, Piéton, and Chapelle-lez-Herlaimont (7%) (Figure 8.3e). Hence, this type of earthquake causes moderate and extensive damage at a local scale.

The reports and eyewitness accounts from the newspapers about this earthquake can be found via the link: http://seismologie.be/cup2014.html.

8.5.4 The 11 June 1938 Nukerke earthquake

On 11 June 1938 at 11 h 57 m (local time) an earthquake strongly shook western and central Belgium, and northern France. It was also felt in the Netherlands, southeastern England, the extreme west of Germany and the Grand Duchy of Luxemburg. The epicentre was located more or less 50 km to the west of Brussels (Figure 8.1). With a magnitude M = 5.0 and a focal depth around 20 km (Camelbeeck, 1993), this earthquake caused damage over a large area (Figure 8.3d). The investigation performed by Somville (1939) at the time of the earthquake describes the main effects produced by it. The main damage to buildings was numerous falling chimneys; roughly 17,500 chimneys were damaged in Belgium alone, which caused serious destruction of roofs and verandas. Many walls were cracked; some of them collapsed. Inside houses, ceilings were cracked, some fell down; windows were broken; numerous objects such as chimneypieces, large mirrors attached to walls, frames or plates were dislodged and broken when falling to the ground. Large pieces of furniture or beds were displaced.

In many localities, people inside buildings were frightened and ran outdoors, thinking that their houses were near to collapse. In the fields, farmers felt the soil oscillating under their feet and found it difficult to stand. Three people died and several dozen were injured.

Based on the inquiry done by the Royal Observatory of Belgium, the quantity of moderate to extensive damage in all the localities of western Belgium is shown in Figure 8.3d. The most affected localities were Rekkem (48% of the houses), Kerksen (44%), Kortrijk (40%), Bousval (37.5%), Outrijve (32%), and Court-Saint-Etienne (32%). The damage caused to houses is unequally distributed on the two sides of an axis elongated in a more or less northwest–southeast alignment with a length of 150 km centred on the earthquake epicentre. To the south of this axis, moderate damage was observed in Belgium and southwards to the French border. Unfortunately, there is no quantitative information from France to extend the observations into northern France. The most significant damage occurred more or less along the axis, sometimes at distances as large as 70 km (localities of Bousval and Court-Saint-Etienne). To the north of this line, damage appeared along an axis oriented northeast–southwest, which corresponds to river valleys that incise the Meso-Cenozoic sediments of the Brabant Massif. This damage distribution suggests that it is linked to the thickness of the soft sediment cover and corresponds to the region where the soft sediment cover ranges from a few metres to about 50 m (Nguyen *et al.*, 2004).

Heavy material fell down from high buildings, mainly from churches. An inventory of the churches damaged by the earthquake has been compiled by consulting the newspapers and testimonies sent to the Royal Observatory of Belgium at the time of the earthquake. Thirty-two churches damaged by the 1938 earthquake have been identified in Belgium, with damage states ranging from slight to moderate (Figure 8.4b). This list is of course not exhaustive. Indeed, when comparing the location of these churches with the areas presenting the majority of damaged houses (Figure 8.3d), they appear to be not exactly identical. The damaged church area is slightly shifted to the north by comparison with the damage region defined by the damaged classical low-rise buildings. The damaged church zone actually corresponds to the quasi east–west region where the natural periods of soil resonance are between 1 and 1.5 seconds, which are in agreement with the range of the fundamental mode of oscillation of this type of large structure (Nguyen *et al.*, 2004). To the west of the epicentre, there appears to be a better overlap between the damage distributions of churches and houses. This area corresponds to the valley of two large rivers, the Lys and the Schelde-Escaut, and therefore to places assumed to present soil conditions less resistant to seismic action.

The reports and eyewitness accounts from the newspapers about this earthquake can be found via the link: http://seismologie.be/cup2014.html.

8.5.5 The 22 April 1884 Colchester earthquake

Despite its relatively low estimated magnitude of around $M = 4\frac{3}{4}$, the Colchester earthquake is considered to be the most damaging British earthquake in the last 400 years (Figure 8.1). This event is very well documented due to the large number of local newspapers available and also the existence of local amateur scientific societies at the end of the nineteenth century. Musson *et al.* (1990) provided a complete study of the earthquake, including most of the reports written at the epoch of the earthquake and their associated sources. For the purpose of our study, we have considered the Musson *et al.* (1990) interpretation of the damage provided by the scientific work of Meldola and White (1885), the most prominent study at the time of the earthquake. This information is reported in Figure 8.3f.

Musson *et al.* (1990) concluded that most of the damage in the epicentral area of this earthquake ranged between EMS-98 damage grades 2 and 3. There is also evidence of grade 4 damage associated with gaps in walls or the collapse of parts of buildings, but they are rare and confined to buildings of the poorest districts. In fact, the importance and the large geographical extent of the damage generated by the 1884 Colchester earthquake appears relatively similar to those observed during the 1983 Liège earthquake in Belgium (Figure 3c). On the other hand, unlike the Liège earthquake, the Colchester seismic event caused moderate and extensive damage to churches in the epicentral area: the fall of parts of towers, damage to roofs, and cracks in masonry and plaster.

8.5.6 The 23 February 1828 Hannut earthquake

We have revisited the 23 February 1828 earthquake that occurred in the central part of Belgium (Figure 8.1), which was the first earthquake worldwide for which a scientist, Egen, drew up a macroseismic map applying an intensity scale (Gisler *et al.*, 2008). For that purpose, Egen used a scale he invented himself (Egen, 1828). We have synthesized and critically assessed the information provided by this and other contemporaneous scientific studies and newspapers of the Low Countries. To improve our knowledge of the damage and earthquake effects in its epicentral area, we also undertook a systematic survey of the official, private, and religious historical sources of this region. All these original witness accounts, as well as a description of their historical sources, are available at http://seismologie.be/cup2014.html.

8.5.6.1 Analysis of historical data

Based on some of the reports about the earthquake, it is possible to classify the effects of the 1828 earthquake as well as to approximate the intensity values on the EMS-98 macroseismic scale for the different affected localities (Grünthal *et al.*, 1998).

The descriptions of damage indicate that in the epicentral area houses experienced moderate to extensive damage. For many localities situated in the epicentral area, the descriptions concentrate on the amount of damage to chimneys or cracks in the walls, and do not mention the collapse or complete destruction of houses, as was the case, for example, for the 1692 Verviers earthquake, which happened in the north of the Belgian Ardenne (Alexandre *et al.*, 2008), discussed in the next section. This suggests that unreinforced masonry buildings presenting grades of damage 2 and 3 (moderate to extensive) may have been widespread in these cities. As already mentioned, Belgian traditional houses of this epoch were mainly unreinforced masonry buildings, which can be classified as vulnerability classes ranging from A to B. Hence, if buildings were all classified as vulnerability A, the corresponding intensity should have reached values of VII. On the other hand, if they had vulnerability B, the intensity could have been one order of magnitude higher (VIII). In either scenario, few buildings should have presented damage states equal to or greater than 4, which agrees with the damage observations. Some reports suggest that damage grade 4 could have been attributed to some of the building stock of Héron, Lens-Saint-Rémy, and Petit-Hallet. In these cases, it would thus be realistic to consider that the most affected buildings were of vulnerability class A; therefore we assessed an intensity of VII in these localities.

In view of the local reports, we have also attributed intensity VII to the following localities: Berloz, Crehen, Gelinden, Héron, Jauche, Lens-Saint-Rémy, Marilles, Petit-Hallet, Tienen, Waremme, and the nearby villages of Longchamps, Froidebise, and Walquin (Figure 8.5a).

We also associated a possible intensity range of VI–VII with the localities for which at least one report mentioned that many houses may have lost their chimneys or were cracked or damaged. This is the case for Andenne and Bilzen. Intensity values of VI–VII have also been assessed for the village of Grand-Hallet. For this locality, there is no report on the damage caused by the 1828 earthquake to the houses, but the repair costs of the church are close to those paid for the church of Berloz, suggesting significant damage.

For other localities situated in the epicentral area of this earthquake or at its periphery, damage is mentioned, but it appears as quantitatively less important. We assessed, nevertheless, intensity VI for those where a certain number of chimneys collapsed. This

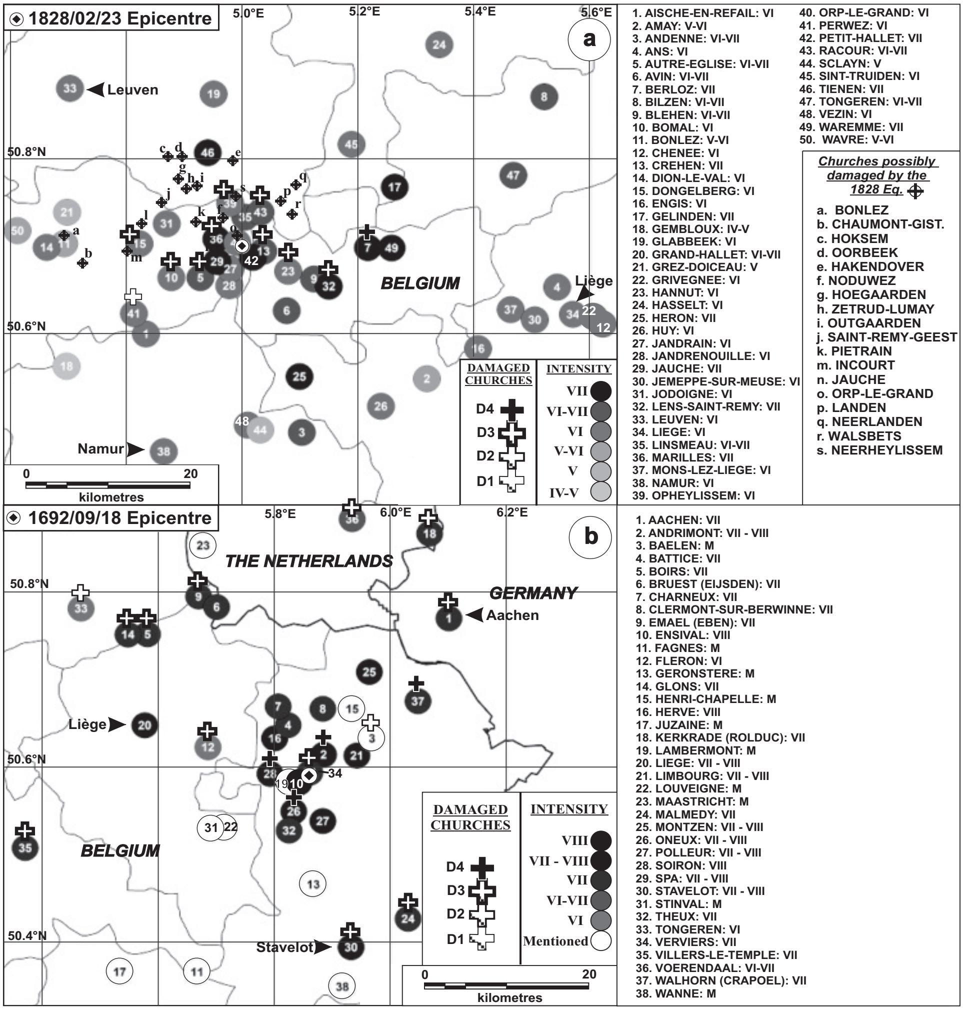

Figure 8.5 Macroseismic map of the epicentral area of the 23 February 1828 Hannut (a) and 18 September 1692 Verviers (b) earthquakes. The mapped areas correspond to the rectangles drawn on Figure 8.4c and d. Each locality for which a historical source mentioned the two earthquakes is identified by a number inside a circle. The estimated intensity (on the EMS-98 macroseismic scale) is easily identifiable by the tone of the circle. The churches for which damage is reported in historical accounts of the two earthquakes are indicated by a cross, showing the estimated damage grade on the damage scale defined by Ahorner and Meidow (1994). We also indicate the churches in which traces of repairs and pathologies could be associated to the 1828 seismic event.

was the case in the cities of Liège, Namur, Glabeek, Leuven, Hannut, Hasselt, Jemeppe-sur-Meuse, Opheylissem, Perwez, and Sint-Truiden.

In many reports from the 1828 earthquake epicentral area, it is also mentioned that frightened people ran away from the churches in the localities of Andenne, Hannut, Huy, Lens-Saint-Servais, Liège, Namur, Sclayn, Perwez, and Tongeren. In other localities, it is mentioned that all the people left their homes in a hurry: Andenne, Jodoigne, Namur, Sainte-Marguerite (suburb of Liège), Sint-Truiden, and Tongeren. These observations certainly correspond to intensity equal to or greater than VI on the EMS-98 macroseismic scale, confirming the range of intensities assessed from the damage discussed above.

8.5.6.2 Damaged churches during the 1828 earthquake

The earthquake that occurred 23 February 1828 caused severe damage to the architectural heritage, mainly the churches of Central Belgium. Several historical sources mentioned damage caused by the earthquake on such buildings: pieces of ceilings falling down, cracks on walls and vaults, collapse of vaults, the ruin of some parts of buildings, etc. This damage led to repairs that are sometimes mentioned in the historical sources too: cramp irons on facades, placing of ties on vaults. We have elaborated an interdisciplinary methodology to recognize the traces of damage produced by this earthquake on these buildings with the objective of improving our knowledge of other specific historical earthquakes, and also evaluating the vulnerability of the architectural heritage in the perspective of its preservation.

Seismic damage in churches attested by historical sources The first step in this analysis consisted of a survey of the 18 churches for which historical sources mentioned some damage (Figure 8.6). Visits to the churches that still exist allowed pathologies corresponding to those described in the reports on the earthquakes to be identified in some cases. Most of the damage has been repaired, but it can still be identified in the buildings and associated with repairs mentioned in historical documents. This is the case for the church of **Autre-Eglise** (Figure 8.6A): "The building took damage from the 1828 earthquake. The front was repaired in 1830; the cramp irons visible in the choir to the east up to a window also date from this epoch" (Tarlier and Wauters, *Géographie et histoire des communes belges*, 1872). At present, it can be observed that this church is built in stone except for a large part of the front, which is built in brick and was rebuilt after the earthquake.

In the village of **Marilles**, the tower of the church was also damaged by the 1828 earthquake, as attested by the many cramp irons presently holding the different walls of the tower (Figure 8.6B). Some of them at the top bear the date 1831, which is the date of the end of the repair work that followed the earthquake.

The church of **Petit-Hallet** (Figure 8.6C) was repaired in 1829, although it still presents recognizable damage, as substantial as cracks above and under the windows of the nave and the choir, many cramp irons in the face of the tower, and cracks in the middle of the arches of the vaults. This last observation can be directly linked to the descriptions in historical sources that mentioned that parts of the vault collapsed. Of course, not all the present pathologies are necessarily linked to the earthquake, and a specific investigation on the Petit-Hallet church was performed to show which of the existing pathologies and repair traces could be due to the 1828 earthquake (Philipront, 2007).

The historical sources mention major damage in the church of **Berloz** as well: cracks on walls, collapse of the vaults, and ruin of the tower. The two aisles had to be rebuilt in

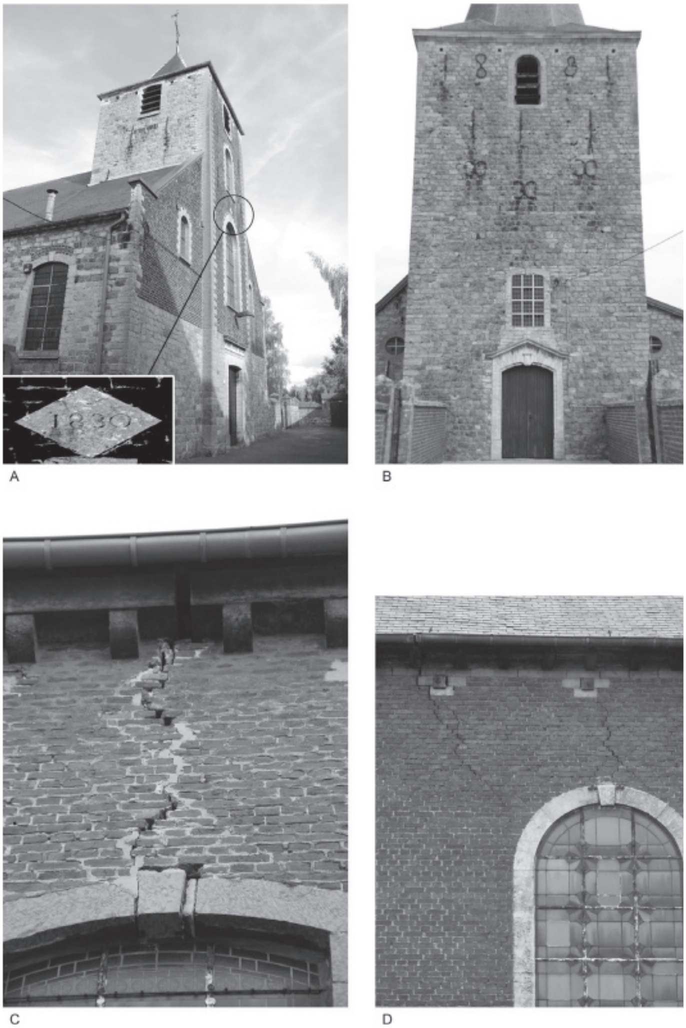

Figure 8.6 The impact of the M = 5 23 February 1828 earthquake on churches. (A) Photograph of Autre-Eglise church showing the gable end formed on a sub-foundation of stone before the earthquake with its upper part rebuilt in bricks after the earthquake, as noted in historical sources (see the inscription 1830 on the small white stone above the door, which indicates the date of the end of the repair work). The cramp irons visible on the tower are also repairs following the earthquake. (B) Photograph of Marilles church tower, damaged by the earthquake. Cramp irons indicate the date of the end of the repair work (1831). (C) Photograph of an opening in the nave wall of Petit-Hallet church, repaired in 1829, with cracks in the masonry above the opening. All the openings in the nave show the same kind of disturbance. One can also observe the introduction of a small stone to prevent the keystone from falling. (D) Photograph of an opening in the nave wall of Jauche church with double cracking of the upper-level masonry, as well as cross-shaped cracks. One can also observe small spiral cramp irons to prevent rocking of the keystone.

1829. The date is written on a stone of one of the windows of the choir. The church is presently in a good state, which makes the search for earthquake traces difficult. We could, however, tell that the side aisles were built more recently by their materials and better maintenance than the choir and the tower on which several cramp irons are visible.

In **Racour** the historical sources mention that the church was also damaged by the 1828 earthquake, especially its tower, which was cracked and of which the spire had to be pulled down. The examination of the present tower shows a significant number of cramp irons on one of its walls, which are also bulging.

In some other cases, the historical reports mention damage in churches without giving any detail, but a visit to these places revealed pathologies and repairs that correspond to damage typically observed with this earthquake. This is the case for the church of **Melin**.

In the case of the church of **Grand-Hallet**, there is no mention of specific damage, but the church council reported that the building repair costs were around 1500 florins. This cost is relatively similar to that necessary to repair the badly damaged church of Berloz, suggesting that the damage in the church of Grand-Hallet caused by the earthquake was also significant. Indeed, several pathologies and repairs are presently visible: cracks under and above windows, a displaced keystone, damaged reflex angles, cracks in the vaults, placing of ties in the vaults, and a strange Y-shaped crack at the level of the choir. Some of these must be consequences of the 1828 earthquake.

Several churches are so well restored that damage or repairs mentioned by the historical sources are not visible today. This is the case for the church of **Opheylissem**. Historical sources mentioned damage to such an extent that the church had to be closed for some time after the earthquake.

It is interesting to notice that, among the churches known to have been affected by the 1828 earthquake, there are a few that present important pathologies whereas historical sources do not mention serious damage caused by this earthquake. Some of these pathologies look like pathologies of seismic origin. The church of **Perwez** is a good example of this. The historical sources only mention the fall of objects and pieces from the ceiling. However, the walls under and above all the windows of this church are cracked inside and outside of the building. The ceilings of the side aisles and the vaults are cracked too. The tower was restored at one point and some cramp irons were emplaced. The keystones of windows are lowered and one of them describes a rocking motion, which is characteristic of earthquake damage.

Some of the churches were demolished at approximately the time of the earthquake. We therefore suspect that some of these churches could have been so badly damaged by the 1828 earthquake that they needed to be demolished afterwards. This seems to be the case for the village of **Dion-le-Val**, where a new church was built in 1837: "... an earthquake in 1828 significantly cracked the bell tower. The building was in danger of collapsing and it was necessary to build a new one." (*Bulletin du Cercle historique de Chaumont-Gistoux*, 44, 2003, p. 16).

In other localities, new churches were built, but without any relationship to the earthquake, even if damage and repairs related to this event were observed. This was the case in Dongelberg, Glabeek, and Lens-Saint-Remy.

Pathologies and repairs in churches not confirmed by historical sources The interpretation of all the damage observations discussed in the previous section provided a set of damage characteristics that earthquakes similar to the 1828 one might produce in churches. This damage dataset has been used to identify in the existing pathologies or visible repairs the consequences of the 1828 earthquake in other churches located in the earthquake epicentral area, and for which no report has been found describing the consequences of this seismic event. This damage has been classified in seven categories from CD1 to CD7. We list in Table 8.1 the churches where these different types of pathologies, damage or repairs have been observed.

The most frequently observed damage (CD1) is cracks above and under windows and especially at the level of the first window of the nave beyond the tower. One can observe such cracks in half of the inspected churches. Some of them even have all windows systematically cracked. These pathologies could arise from the earthquake but also from the problem of differential settling caused by the difference in height and weight of the tower in comparison with the nave, or from the problem of poor foundations or loose substrates. However, it is also possible that the settling of the ground may have been induced by the earthquake, which appears to be the case in the village of Jauche (Figure 8.6D).

Cracks on the tower or cracks at the intersection of two faces of the tower are also observed (CD2) in almost all churches. These types of damage are mentioned in historical reports for some of the church towers in the epicentral area of the 1828 earthquake. Their repair can be confirmed by the presence of cramp irons in the faces of some of these towers. They are used to hold a wall or two opposite faces together, preventing the splitting of walls and the detachment of the front from adjacent walls from bottom to top, which result from seismic action.

Face detachment (CD3) can also happen with the two perpendicular walls of the nave.

Cracks can also be observed in reflex angles (CD4) of the churches of Grand-Hallet, Perwez, Petit-Hallet, Hakendover, Incourt, and Jauche.

About 25% of the visited churches presented displacement of window keystones (CD5). In Jauche, one can see a similar principle of repair and consolidation with two small cramp irons, rounded spirals, at the two corners of the keystones (Figure 8.6d), which suggests repairs after the earthquake, as in Marilles and Racour.

Other pathologies and associated repair characteristics associated with earthquake shaking are cracked window sills (CD6) or cracks on the vaults (CD7).

From this investigation of churches in the central part of Belgium, we found evidence of pathologies and repair traces that could result from the 1828 earthquake because they are similar to those observed in the churches for which historical sources prove the damage. To confirm this hypothesis, we will first conduct a survey of churches outside the 1828

Table 8.1 *Types of damage in the churches of central Belgium related to the 23 February 1828 earthquake. The description of the different types of damage is given in the text.*

	Damage characteristics						
	CD1	CD2	CD3	CD4	CD5	CD6	CD7
Churches mentioned as damaged in historical sources							
Autre-Eglise		×	×				
Grand-Hallet	×			×	×		×
Marilles		×			×		
Melin	×	×				×	×
Perwez	×	×		×	×		×
Petit-Hallet	×	×		×	×	×	×
Racour		×			×		
Churches not mentioned in historical sources							
Bonlez	×						
Chaumont-Gistoux	×						
Hakendover	×	×	×	×			
Hoksem		×					
Hoegaarden							×
Incourt	×	×	×	×		×	
Jauche	×			×	×		
Laar						×	
Landen		×					
Lathuy	×						×
Neerheylissem		×					
Neerlanden	×	×			×		
Noduwez		×					
Oorbeeck	×	×					
Orp-le-Grand		×					
Outgarden					×		
Pietrain	×						
Saint-Remy-Geest		×					
Villers-le-peuplier	×	×					×
Walsbets		×	×				
Zetrud-Lumay		×					

earthquake epicentral area and analyze whether they present fewer pathologies and repairs than those in the area most affected by the seismic event. Second, we intend to use modelling to compare the observations on these buildings with the stress pattern expected from an earthquake with the same characteristics as the 1828 one.

8.5.7 The 18 September 1692 Verviers earthquake

The earthquake of 18 September 1692 is probably the largest known earthquake that has occurred in Western Europe north of the Alps (Figure 8.1). Recent investigations based on original reports of the effects produced by this earthquake suggest that its source was located in the region of Verviers in the northern part of the Belgian Ardenne and that its magnitude may have reached 6¼ (Alexandre and Kupper, 1997; Camelbeeck *et al*., 2000; Alexandre *et al*., 2005, 2008).

In the epicentral area, substantial to heavy damage and sometimes complete destruction are described for large buildings (castles and churches) and for houses. The ground shaking also appears to have been violently felt by the people (Alexandre *et al*., 2008). For the most affected villages (Figure 8.5B) (e.g., Herve, Ensival, Soiron, Walhorn), the reports mention that some houses were ruined, with the consequence that inhabitants were injured or killed. This suggests that some buildings presented complete damage (EMS-98 grade 4 to 5) in the earthquake epicentral area. Considering that the most affected houses had vulnerability class A, "few" buildings presenting damage of grade 4 would correspond to intensity VII, whereas "few" buildings with damage of grade 5 would suggest intensity VIII. The latter is in agreement with Alexandre *et al*. (2008), who propose that the intensity reached VIII in these localities. Outside the epicentral area, one characteristic of the 1692 earthquake is the significant spatial extension of the damage to large buildings of the architectural heritage in Belgium, France, Germany, and southeastern England (Figure 8.4d).

The original reports of the witnesses and the description of the historical sources are available at http://seismologie.be/cup2014.html.

As usual for historical earthquakes, the accounts of the damage caused by the 1692 earthquake are poor from a quantitative point of view, which renders intensity evaluation uncertain. Soiron, one of the more damaged localities, is a village presenting a structure that has stayed unchanged since the eighteenth century. We took this as an opportunity to study the existing building stock in the centre of the village that dated from the seventeenth and the beginning of the eighteenth century to find complementary arguments to the historical data that may help to evaluate the earthquake intensity in this village (Dewattines, 2010).

Two historical sources describe the effects of the earthquake in Soiron. The priest wrote in his notes: "A horrible earthquake that brought down houses, chimneys . . . " (Servais Ronval, *Notes*). A second historical source written by the lord of Soiron depicted the very heavy structural damage caused to the castle. The structure of the church also was heavily damaged and, with the exception of its tower, a new church was built from 1723 to 1727 due to the consequences of this earthquake.

Figure 8.7A shows a map of the centre of Soiron with the houses that retain a complete or partial structure dating from the seventeenth century. There are about 36 such buildings. Most of these houses were partly or totally reconstructed after the 1692 earthquake (11 buildings, 30.5%) or show repairs or pathologies that could be attributed to this earthquake (14 buildings, 39%). During the eighteenth century, some other houses were rebuilt (11 buildings, 30.5%) (Figure 8.7B). These buildings are included in the basic structure

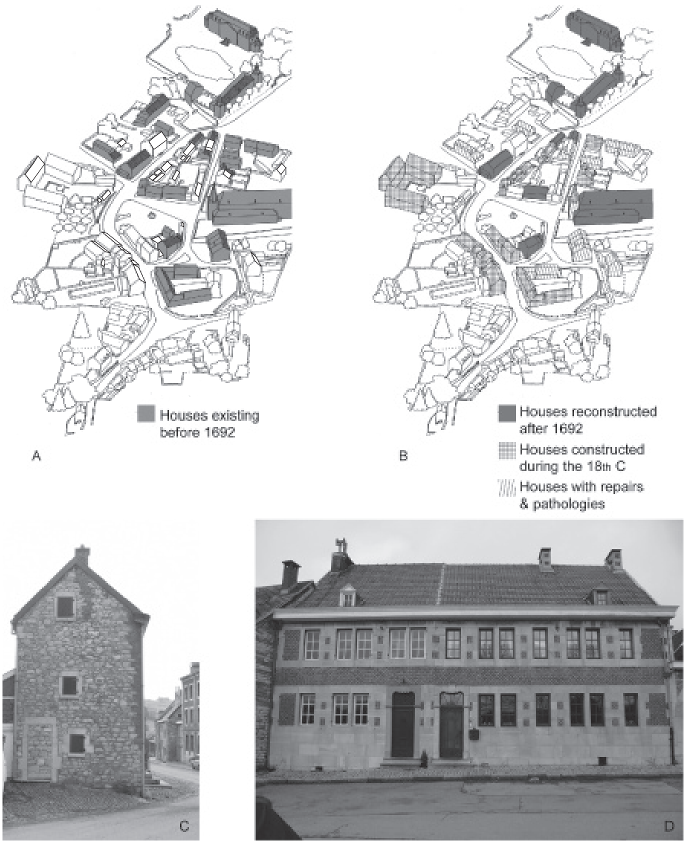

Figure 8.7 The impact of the M = 6¼ 18 September 1692 earthquake in the village of Soiron. (A) Isometric view of the historical centre of the village of Soiron, modified from Peters (1976), indicating the houses that existed during the seventeenth century before the 1692 earthquake occurred. (B) As for (A) but indicating the houses that our study evaluated as partially or totally rebuilt after the earthquake, the houses partially or totally built or transformed during the eighteenth century, and the houses showing disturbances or repair traces that could be attributed to the earthquake. (C) Photograph of the gable end of a house dating from the seventeenth century and showing disturbances that are characteristic of earthquake consequences: fall of a chimney taking away part of the upper wall and detachment of the facade from the gable end, with partial collapse of the facade, rebuilt with bricks after the earthquake. (D) Photograph of the main facade of two houses located on the church square, rebuilt after the earthquake in a style than we can attribute to the Late Mosan renaissance style (end of the seventeenth century).

of the village, suggesting that at least some of them may correspond to houses strongly damaged by the earthquake that were demolished and reconstructed or modified afterwards.

Regarding the repairs and pathologies still visible today, it seems that most of them concern fall of chimneys with parts of the pine walls (Figure 8.7C), stripping of the lateral walls and partial failure of roofs, damage that corresponds to extensive damage (grade 3 in the EMS-98 macroseismic scale).

For the houses presenting complete damage, equivalent to damage grade 4 or 5 on the EMS-98 macroseismic scale, it can be supposed that new houses were reconstructed. Some of them were reconstructed using the building style progressively adopted by richer families in this region since the second part of the seventeenth century (Figure 8.7D). The castle and the church were rebuilt in the years following the earthquake, but even if intensive works were required to stabilize the two edifices after the earthquake, they did not collapse (Nicolas Ignace de Woelmont, *Histoire de la maison de Woelmont*).

These observations and analysis suggest that most of the damage to the buildings in the centre of Soiron ranged from extensive to complete (grades 3 to 5 in the EMS-98 damage scale). Following our inventory, one-third of the damaged houses revealed extensive damage. These houses can be considered as the less vulnerable ones of the building stock of that epoch in Soiron, meaning very likely vulnerability class B at the best. Based on these hypotheses, the intensity can be evaluated as VIII on the EMS-98 macroseismic scale. This is in agreement with the intensity estimation from historical sources (Alexandre *et al.*, 2008) and not incompatible with the fact that the more vulnerable houses could have presented complete damage.

8.6 Discussion and conclusions

In this chapter, we have presented the methodological background associated with the investigation of the damage caused by past earthquakes in the region of Western Europe extending from the Lower Rhine Embayment to the southern North Sea. We have applied it to the study of seven earthquakes that represent typical seismic activity of this area and for which we have been able to retrieve relevant information on the characteristics, location, and extent of damage. Our study furnishes information on important seismological, geological, geographical, and architectural aspects influencing the consequences of earthquakes and helping to validate earthquake risk assessment.

8.6.1 Earthquake vulnerability of Western Europe

The precise inventory of the damage caused by the 1983 M = 4.6 Liège and 1992 M = 5.3 Roermond earthquakes has provided fundamental information on the present-day high seismic vulnerability of the major centres of population in this part of Europe. The vulnerability is especially high in regions where industrialization took place during the nineteenth and the early twentieth centuries. There are two main reasons for this high vulnerability. The first one is the very high population density, which explains the elevated estimated losses during the 1992 Roermond earthquake, despite the maximum macroseismic intensity barely reaching VI (EMS-98 scale). The second aspect to take into consideration is the extremely high vulnerability of the building stock composed of low-rise unreinforced brick-masonry constructions, which are sometimes very old. This has been dramatically demonstrated for the 1983 Liège earthquake. Of course, the more modern buildings constructed in steel or reinforced concrete were far less affected by the Liège and Roermond earthquakes and the application of the paraseismic Eurocode-8 building code should improve the resistance of new buildings in the future. Nevertheless, the risks will be present for a long time because poorly constructed masonry buildings will remain a significant part of the building stock in the old cities of Western Europe.

8.6.2 Damage and intensity

Using the Royal Observatory of Belgium macroseismic inquiry for earthquakes felt in Belgium since 1932, which includes a report on the percentage of damaged chimneys in each affected locality, we were also able to evaluate the quantity of damaged buildings presenting greater than or equal to moderate damage states caused in Belgium by the 11 June 1938 and 28 March 1967 earthquakes. We also added information provided by Musson *et al*. (1990) on the epicentral area of the British Colchester 1884 seismic event in our dataset. The complete dataset, presented in Figure 8.3, is more precise than the intensity for the destructiveness of the earthquakes and can be more directly related to the associated losses (Figure 8.2). This dataset is also, in essence, a basis on which to evaluate intensity in localities where damage was observed. It is very useful because, in the case of the most affected localities in the Netherlands and Germany during the 1992 Roermond earthquake, this allows us to evaluate the intensity as equal to VI on the EMS-98 macroseismic scale based on the damage statistics, which is less than the value of VII proposed by the official inquiry published after the earthquake (Haak *et al*., 1994).

8.6.3 The complementarity of studying damage in classical houses and churches

The fundamental mode of vibration of traditional masonry houses ranges from a few to 10 Hz, which means that these structures are sensitive to the high-frequency range of seismic energy. On the other hand, the major buildings of the architectural heritage such as churches and castles are of larger dimensions and often of very complex structure. Their fundamental mode is thus at lower frequency (~1 Hz). As an example, the fundamental mode of the Boussu church tower, located near the city of Mons, has been evaluated at a frequency of 1.41 Hz (Defaut and Deneyer, 1999). Therefore, analyzing the damage caused to these large structures and comparing it to that of traditional buildings can shed a different light on the factors influencing the damage produced by an earthquake (Figures 8.3 and 8.4).

We observe that the spatial extent and the magnitude of the damage caused to churches increase significantly with earthquake magnitude. Two of the studied earthquakes caused moderate to heavy damage at large distances from their epicentre, the 1992 Roermond and 1692 Verviers earthquakes (Figure 8.4). This is a clear indication of the lower frequency content of the seismic energy generated by these earthquakes, which is representative of magnitude 5.5–6.0 earthquakes. The 1938 Nukerke and 1828 Hannut earthquakes also caused damage to churches, but their extent is more limited to the region of intensity greater than or equal to VI, while the three smaller earthquakes with magnitudes around 4.5 caused damage to churches only in the limited regions of significant damage affecting masonry buildings.

Note that the damage caused to churches during the 1938 earthquake was enhanced by the thickness of the sedimentary cover, corresponding to a soil fundamental mode period between 1.0 and 1.5 seconds, as discussed by Nguyen *et al*. (2004). Our analysis differentiates the damage caused to masonry buildings from that observed in large buildings of the architectural heritage during the 1938 earthquake, permitting us to show that they differ slightly by location. The damage to traditional houses is more important in the area where the soil fundamental period is less than 0.3 second (or frequency higher than 3 Hz) (Figures 8.3 and 8.4). This difference can be explained by the progressive absorption of the high-frequency seismic energy when the thickness of the sedimentary cover increases, while the low-frequency cover is preserved and even amplified at the soil natural frequency. This phenomenon also explains the low intensity in the epicentral area of the 1992 Roermond earthquake by comparison to its magnitude (Meidow and Ahorner, 1994). Hence, by studying separately the two types of buildings, we provide information concerning two different frequency ranges in the response spectra, which is of high scientific and engineering interest. These results suggest that it is fundamental to take into account the regional soil properties in the studied part of Western Europe and that classical spectra that differentiate the soil effects by their properties in the first 30 metres under the surface are not sufficient to model earthquake strong ground motions in parts of the study area where the soil thickness reaches several dozen to hundreds of metres.

8.6.4 Risks from small and moderate earthquakes

Thanks to the outstanding study of the 1884 Colchester earthquake by Musson *et al*. (1990), we were able to compare the consequences of this seismic event, considered as the most damaging earthquake during the last 400 years in United Kingdom, with six of the numerous damaging past earthquakes in the region between the Lower Rhine Embayment and the southern North Sea. The amount of moderate to extensive damage in the localities most affected by this Colchester earthquake ranges between around 10% and 70% in an area with a radius of less than 10 km. This is very similar to the observed damage during the 1983 Liège earthquake in Belgium. These two earthquakes warn us of the consequences of such shallow small magnitude earthquakes that could occur everywhere in Western Europe. The danger is particularly of concern if the event occurs in the vicinity of a large historical city, such as Liège.

This is also the case for the three studied earthquakes with magnitude between 5.0 and 5.3. Of course, for these moderate earthquakes, the focal depth plays a role in the significance of the damage and associated geographical extent. Typical effects from a deep earthquake are well illustrated by the Belgian 1938 earthquake. With an estimated focal depth of around

20 km (Camelbeeck, 1993), the seismic action on the buildings was less strong than for a shallower earthquake with a similar magnitude because the seismic energy reaching the surface is more attenuated, but of course the affected area is of larger dimension. Hence, the moderate and extensive damage caused to houses and churches during the 1828 earthquake appear as more important than for the 1938 seismic event, but they are located in a more restricted region. This is particularly evident when looking at Figure 8.4, by the comparison of damage to churches.

8.6.5 Risks from large earthquakes

Three earthquakes of magnitude around 6.0 have occurred in the studied area since 1350. These earthquakes have a destructive potential that is important to evaluate. This is why we focused part of our work on evaluating the destruction caused by the $M = 6¼$, 1692 Verviers earthquake. The study of historical texts (Alexandre *et al.*, 2008) suggested that some buildings suffered damage of grade 4 and 5 in villages of the epicentral area. Based on a precise inventory of the houses and of their pathologies and repair traces in the centre of the village of Soiron, one of the most affected localities, we were able to formulate a hypothesis on the damage and destruction caused by this earthquake. This analysis is limited by a lack of knowledge on the vulnerability of the buildings. If the buildings are considered as a mixture of vulnerability classes A and B of the EMS-98 macroseismic scale, it is coherent to consider that the less vulnerable (of class B) were on average less damaged, probably corresponding to extensive damage states (one-third of the total number of houses). Together with the complete damage of the other part of the building stock, this is compatible with intensity equal to VIII.

Considering the high seismic vulnerability of part of the present-day building stock of the study area and its high population density, the consequences of an earthquake of this magnitude would certainly be catastrophic in terms of victims and destruction.

8.6.6 The importance of investigations of the architectural heritage

A few years ago, we found it hard to imagine that it was possible in Western Europe to retrieve traces of past earthquakes in heritage buildings. Our study on the village of Soiron in the epicentral area of the 18 September 1692 earthquake and the churches affected by the 23 February 1828 earthquake drastically changed our point of view on this problem. Our results suggest that most of the buildings of Belgium and its surrounding regions should present pathologies or repairs associated with earthquake activity if they were constructed before the end of the seventeenth century. Up to now, we have developed a naturalist methodology based on field observations and measurements. Future methodological advancements will require the evaluation of the seismic vulnerability of these buildings and numerical modelling of earthquake effects to compare them with the observations.

The results presented in this chapter are a strong motivation to investigate other destructive past earthquakes, and also to study in more detail the different aspects that influence earthquake risks in the area between the Lower Rhine Embayment and the southern North Sea that have been demonstrated in the study.

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