THE UMBRIA MARCHE EARTHQUAKES OF 26 SEPTEMBER 1997

A FIELD REPORT BY EEFIT

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INTRODUCTION

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On 25 and 26 September 1997, two earthquakes (magnitudes Ms = 5.5 and 5.9) occurred with their epicentres not far from the city of Assisi in the Italian Region of Umbria. Considerable damage was done to buildings in Assisi itself and neighbouring towns. A substantial number of buildings collapsed or were very seriously damaged, and eleven people were killed. The epicentral intensity was about 9MCS. The Basilica of San Francesco, a monument of great spiritual, architectural and art-historical importance because of the early Renaissance frescoes it contains, was particularly badly damaged, and some of its frescoes destroyed. Damage extended over a very wide area which contains many notable buildings and large numbers of masonry buildings typical of their era. The earthquake therefore represented an opportunity to improve our understanding of the performance of masonry buildings in earthquakes, to test some of the ideas developed in recent UK research on the subject, and to produce conclusions which could benefit those involved in the design of new masonry buildings, and the strengthening of existing ones, all matters of significance for the the UK. EEFIT decided very quickly after the earthquake to send a small team to conduct a field reconnaissance mission, with a special emphasis on the performance of masonry and historic structures.

The overall objective of the mission was to study the effect of the earthquakes on historic and unreinforced masonry buildings. Specific aims were:

- to apply a method of vulnerability assessment developed during recent research in the UK
- to study the performance of previously strengthened masonry buildings, by comparison with unstrengthened buildings
- to conduct local damage surveys around the sites of strong motion instruments triggered, to compare damage states and modes with measured ground motion effects.

Support was requested for this study from EPSRC, and approval of the grant was swiftly received. The field mission started with the arrival in Rome of Robin Spence on 7 October; the other members of the team arrived on 8 October, and assembled in Assisi. The activities of the field mission were then divided into two parts:

9-10 October:	Study of damage in epicentral area (with SSN and GNDT)
11-13 October:	Detailed study of damage to historic buildings in Assisi

Cooperation with the Italian authorities was essential for visiting the epicentral area. The mission was planned to coincide with a parallel visit by a group of Italian specialists from the Servizio Sismico Nazionale (SSN, the government department concerned with earthquake preparation and seismic risk assessment) and from the University-based GNDT (Earthquake Protection Research Group). At the time of the visit, there had been a continuing series of aftershocks of significant magnitude since 26 September, and many parts of the earthquake-affected area were inaccessible without permission and support from the local Civil Protection organisation and Fire Brigade. This was arranged by the SSN for the EEFIT team. As a consequence the combined team was able to make a much more detailed and extensive assessment of initial damage than would otherwise have been possible.

About ten of the worst damaged villages in the epicentral area were visited, and the team was also able to make an assessment of the state of damage in the one town in the epicentral area, Nocera Umbra. There were two strong ground motion recording instruments in the epicentral area; the team located both of these, and was able to make a survey of damage to the buildings closest to the instruments.

The second part of the study was concerned with the performance of buildings in Assisi itself. Although the Basilica of San Francesco was inaccessible at the time (it was considered unsafe in the event of continuing aftershocks); the team made visits to the other four major churches of Assisi (Santa Chiara, San Rufino, Santa Maria Maggiore, Chiesa Nuova) and recorded damage both externally and internally. In addition a number of historic residential buildings were investigated to assess their damage. A study of the variation of building types and the extent of previous strengthening was also carried out along one street (via Cristofani) where there was some concentration of damage.

On return to the UK analytical assessment was made, using the survey data collected, of the damage type and level in relation to known and inferred strong ground motion, both in Assisi and in the epicentral area. Robin Spence and Dina D'Ayala also had the opportunity to make return visits during February and March 1998, during which they took part in an ICOMOS workshop in Assisi concerning the Basilica of St Francis, and also revisited parts of the epicentral areas to obtain additional data.

This report aims to describe the damage and to draw some preliminary conclusions for the benefit of building designers, earthquake engineers and those concerned with the protection of historic buildings. The report is the work both of the EEFIT team and of Italian colleagues from SSN and GNDT who participated in the field reconaissance. It draws on a number of published papers and reports which have appeared since the earthquake, as indicated in the Reference lists following each Chapter.

1.0 THE EARTHQUAKE AND ITS SETTING

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1.1 Umbria and Marche

Umbria and Marche, the two Italian regions most seriously affected by the earthquakes of 26 September 1997, are central to Italy, both geographically and culturally (Figure 1.1). Each of the regions has its area of industrial development – in Umbria around Terni and the Vale of Spoleto in the south and in Marche along the coast – but the upland area along the border between the two regions where the epicentres were located is largely dominated by traditional agriculture and is apparently remote from urban life. Indeed, in recent decades there has been substantial out-migration of the rural population to the cities, to be replaced in part by affluent, often foreign, owners of second homes – a factor which may have reduced casualty levels in the earthquakes.

In the northern part of Umbria, tourism is a major element in the economy. The Basilica of San Francesco in Assisi has been a place of pilgrimage since the late thirteenth century, not only because of the continuing power of the story of St. Francis himself and of the religious community he founded, but also because of the extraordinary cycle of frescoes which cover the walls and vaults of the Basilica, universally acknowledged to represent a critical moment in the development of early Renaissance painting in Europe (White, 1993).

Although the attribution of many of the frescoes – including some long popularly attributed to Giotto – is a continuing subject of controversy among art historians (Palmer, 1997), their quality, story-telling power, and importance to art history is undisputed. In recent years they have been visited by upwards of five million visitors a year, making the Basilica in Assisi one of the most-visited locations in Italy, and one of Europe's most important historic sites.

The economy of Assisi and its surrounding area is very largely devoted to providing for these visitors, and it is remarkable how Assisi and its neighbouring hill towns such as Spello to the south, while catering to this level of mass tourism, have managed to preserve their medieval character both in size (they remain still largely contained within their medieval walls) and in built form. They retain their compact ancient hill-top form, with narrow steep streets, fronted by two, three or occasionally four storey buildings – almost exclusively in stone masonry – and opening onto squares which house the major public buildings, cathedrals, churches and town halls, many of which are architectural gems of the Romanesque and early Gothic periods.

Not only the towns but also the surrounding villages have to a great extent preserved their ancient form and character, and are still largely built of stone masonry.

The beauty and homogeneity of this landscape and its human settlements is praised by visitors to the region and remains one of the great attractions of the area; yet it is precisely the stone masonry form of construction which creates this harmonious and apparently timeless landscape that makes the region so vulnerable to earthquakes.

Thus the series of moderate earthquakes which began on 26 September caused physical loss and cultural damage apparently out of all proportion to their actual magnitude. Because of the vulnerable form of construction, hundreds of important architectural monuments and the works of art which they house - cathedrals, churches, town halls and palazzi - were damaged or destroyed in the event; and thousands of humbler buildings in towns and villages across a wide region were thrown down or damaged beyond repair. Media attention was understandably focused on the most famous damaged monument, the Basilica of San Francesco, but the cultural loss goes far beyond this.

The tragedy was aptly summed up by Andrew Gumbel writing in *The Independent* on Friday 17 October:

> "The most striking thing about these earthquakes is how out of place they seem. Umbria, with its green rolling hills, pretty white stone buildings, awesome artistic heritage and great food, is one of the most civilised places on earth. There is something awe-inspiring, even perverse, about such a natural calamity occurring here - underlining the grim fact that despite the eradication of war, poverty and plague in these parts, human progress has done precious little to protect itself against the unpredictable ravages of earthquakes."

The extent of the damage to historic buildings is discussed further in Chapter 3; but the earthquake inevitably raises serious questions about our ability to protect and preserve our artistic heritage in earthquake regions.

1.2 The seismotectonic context

The Central Appenines are part of a highly complex collision zone stretching from the Alps to North Africa between the convergent Eurasian Plate to the north and the African Plate to the south (Figure 1.1) (Degg and Doornkamp, 1991). There is an estimated overall convergence rate in this collision zone of about 1 to 3 cm/year, but convergence is not uniform; there are several separated blocks within this region, giving rise to a complex pattern of relative motions and surface faulting structures.

In the Central Appenines, the active faults are of the extensional type, overlying and overprinting older structures of the fold and thrust belt, and their development and evolution have been related to crustal thinning in the Tyrrhenian-Tuscan area (Cello et al., 1997). The Central Appenine Fault System is a zone of diffuse seismicity 50-60 km wide, trending NNW-SSE, as shown in Figure 1.2. Many of the faults shown in this figure have been analysed and shown to have been active in the Pleistocene-Holocene period. In this region the bedrock geology consists of folded and thrusted limestones, cherty limestones, marly clays and clays of the Upper Triassic-Lower Miocene period. In the mountain valleys are materials of the Upper Pleistocene-Holocene period.

Recent work by Cello et al. (1997) suggests that the network of discontinuous faults of the Central Appenine Fault System may be the surface expression of an underlying N-S trending deep-seated left lateral shear zone (Figure 1.3). The branching of the fault system through the upper crust transforms the underlying motion into a set of relatively short surface faults each capable of generating earthquakes of moderate magnitude, and of triggering movement on adjacent or connected faults.

A recent synthesis of published work and post-earthquake investigations by Galli et al., (1997) has identified in the epicentral area the principal faults shown in Figure 1.4, indicating that these are fragmented, and of relatively short length. Figure 1.4 also shows the epicentres of the two shocks on 26 September and the shock of 14 October, and indicates where fault-related ground movements were observed. The locations, magnitudes and slip-vectors observed at these locations suggest that the first two events were caused by fault movements on the previously mapped Colfiorito Fault and Cesi-San Martino Fault, while the third could have been caused by movement of previously unidentified faults near Rasenna and Mevale, north-east and north of Sellano respectively. A mechanism of triggering between adjacent faults is suggested as being responsible for the kind of earthquake sequence observed in 1997, as well as in previous earthquake sequences in the Central Appenine area (see Section 1.6).

The tectonic context and the observed ground deformations in the earthquake are dealt with in more detail by Cello et al., 1997, Galli et al., 1997, and Elnashai et al., 1997.

1.3 The earthquakes of 26 September 1997

The earthquake sequence which began on 26 September was unusual in global terms (though it conformed to the pattern of historically observed seismicity in the Central Appenines), in that the largest shock was preceded by a serious but somewhat smaller shock a few hours previously.

The first shock occurred at 02.33 local time, with magnitude $M_b = 5.5$, $M_w = 5.7$ (USGS) ML = 5.5 (ING), and was centred close to the village of Colfiorito (Figure 1.5). The second shock occurred at 11.40 local time, with almost the same epicentre (43.0° N, 12.85° E) with magnitude $M_b = 5.7$, $M_s = 5.9$, (USGS) $M_L = 5.8$ (ING).

The seismic sequence of which the 26 September shock was the culmination actually started in May 1997. On 4 September an earthquake of magnitude ML=4.4 caused minor damage in the villages of Cesi, Colfiorito, Annifo and Verchiano which were to be amonst the most seriously damaged villages in the main shocks of 26 September. Over the days and weeks after 26 September a number of other significant shocks occurred, three more of them with magnitudes greater than 5.0 and a further 17 with magnitudes greater than 4.0. The sequence of events prior to 20 October with magnitude greater than 4.0 as given by ING is shown in Table 1.1 (note that USGS= US Geological Survey; ING = Istituto Nazionale Di Geofisica, Rome). The epicentres of the major aftershocks tended to progress southwards, those on 3 October and 7 October also being close to Colfiorito, those on 12 October and 14 October being close to Sellano (Figure 1.5).

During March and April 1998 a further sequence of aftershocks occurred. The sequence began with a magnitude ML=4 shock on 21 March, and several more shocks of comparable magnitude occurred over the next two weeks including one of ML=5.5 on 26 March, and one of magnitude ML=5.0 on 3 April (Table 1.3). The epicentral location of these shocks was farther north than the 26 September epicentre, in the area of Gualdo Tadino; the depth of that on 25 March was 50 km. Only small additional damage, and no casualties were reported.

Date	Local time	Magnitude
26.9	02.33	5.5 M_L
26.9	11.40	5.8 M_L
26.9	11.46	4.7 M_L
26.9	15.31	4.1 M_D
27.9	10.08	4.0 M_D
27.9	21.56	4.0 M_D
28.9	13.24	4.0 M_D
2.10	13.00	4.0 M_D
3.10	10.55	4.8 M_D
4.10	08.50	4.0 M_D
4.10	17.07	4.1 M_D
4.10	18.13	4.3 M_D
4.10	20.47	4.0 M_b
7.10	01.24	5.3 M_L
7.10	07.09	4.1 M_D
12.10	13.08	4.5 M_D
14.10	17.23	5.4 M_L
16.10	00.53	4.0 M_D
16.10	06.53	4.1 M_D
16.10	14.00	5.3 M_D
19.10	18.00	4.1 M_D
20.10	03.28	4.1 M_D

Table 1.1 The earthquake sequence to 20 October 1997 (after ING, 1997)

One beneficial effect of this extended sequence of events was that inhabitants throughout the region evacuated their houses after the first shock at 02.33 and, following formal public warnings on television and radio from the Ministry of Civil Protection in the morning news bulletins on 26 September, which explained the risk of aftershocks, most inhabitants were still outdoors when the much more damaging shock occurred at 11.40. This action was in part responsible for the remarkably low death toll in the earthquake, considering the extent of damage.

However, the cumulative effect of the continual shocks undoubtedly increased the extent of structural damage to some degree - collapses of unstable masonry continued to occur up to and including the shock of 14 October; and this hampered the emergency operation of shoring and making safe as well as the task of providing temporary accommodation and support for the large numbers made homeless. In the 12 and 14 October shocks, several villages, notably Sellano, which had not been significantly damaged on 26 September sustained serious damage. And damage in the neighbourhood of Gualdo Tadino was reported after the March and April shocks.

1.4 Intensity distribution

Between 26 September and 3 October, a macroseismic survey of more than 250 villages and towns in the region was conducted by a joint team from ING, GNDT (Gruppo Nazionale di Difesa ai Terremoti), and SSN (Servizio Sismico Nazionale). The survey was conducted using the MCS scale (commonly used in Italy), details of which are shown in Appendix 1. The relationship between the MCS scale and the EMS scale used elsewhere in Europe is not simple, and is also discussed in Appendix 1. Three villages, Collecurti and Cesi (Basso) in Serravalle Province, and Colli di Verchiano in Foligno Province were assessed at intensity level MCS = 9.5, and a further six villages at MCS = 9 The location of these villages is plotted on the epicentral area map, Figure. 1.6. It will be seen that they fall within an ellipse centred on the 26 September epicentre with a major axis of 21 km and minor axis of 6 km with the major axis in the direction N 24°W, close to the trend of the Appenine mountains in this area.

In all the villages with intensity MCS = 9 or above at least some buildings collapsed, and many more were damaged beyond repair. Intensities exceeding MCS = 7 were experienced in more than 160 villages in the region over a much larger area. In all these villages some structural damage occurred in weak masonry buildings. Of the major towns in the region, Foligno was assessed as having sustained intensity MCS=7 , Fabriano and Assisi assessed as having experienced intensity MCS = 6-7, Spoleto, Terni and Gubbio MCS = 6, Norcia and Perguia MCS = 5-6.

The largest town within the epicentral region is Nocera Umbra (population about 6500), which was assessed at intensity MCS = 7-8. A more detailed description of damage in the worst damaged villages, and around Nocera Umbra and Assisi, follows in Chapters 2 and 3.

The expected areas of the EMS 6,7 and 8 isoseismals for a magnitude Ms = 5.9 earthquake of depth 10 km have been calculated using the attenuation formula of Ambraseys (1995) and conversions to MCS proposed by Margottini et al. (1993), (Table 1.2).

MCS Intensity	Area (km^2)
8	380
7	1250
6	3800

Table 1.2 Expected areas within EMS isoseismals

Ellipses of these areas centred on the Colfiorito epicentre, with an axis ratio of 3, and major axis direction N 24°W, are plotted on the map for intensities MCS = 7 and 8, Figure 1.6. This shows them to be reasonably consistent with the observed damage.

Ambraseys (1995) has proposed attenuation relationships for European earthquakes of the form

$$\log(a_i) = A + B\,(M) + C\,(r) + D\log(r)$$

where a is peak ground acceleration (PGA), M is magnitude Ms and where

$$r^2 = (d^2 + ho^2)\ ,$$

where d is the shortest distance from the station to the surface projection of the fault rupture, and A,B,C, D and ho are constants for historically experienced earthquakes. Taking values A = -1.242, B = .238, C = -0.00005, D = -.907 and ho = 4.04 as proposed by Ambraseys, (based on 434 recordings in 107 earthquakes in the range Ms=5.0 to 7.3), a mean attenuation relationship in terms of PGA has been deduced. This has been converted into an attenuation relationship in MCS intensity using the mean formula:

$$\log(a_i) = 0.525 + 0.22\, I_{MCS}$$

given for local MCS intensity by Margottini et al. (1993). For each intensity level, the average epicentral distance r has been calculated, using for r the mean radius of the ellipse based on the epicentre with proportions as given above. Figure 1.7 shows the mean attenuation relationship, and the average radial distance (based on the same elliptical geometry) for locations with intensities MCS = 8-9, 8, 7-8 and 7, showing again reasonable correlation.

1.5 Analysis of strong motion data

A list of the eight events with ML ≥ 5 of the Umbria-Marche sequence is reported in Table 1.3 together with the corresponding magnitudes (duration Md, local ML, surface Ms, moment Mw), epicentral coordinates and macroseismic intensities. With the notable exception of the event of 26 March, the focal depths range from 6 to 10 km.

No	day	local time	Md	ML	Ms	Mw	Long. E	Lat. N		h	I (MCS)
1	26-Sep	2.33		5.5 (1)	5.5 (2)	5.5 (1)	12.89	43.02	(1)	6.9	VIII
2	26-Sep	11.40		5.8 (1)	5.9 (2)	5.9 (1)	12.85	43.03	(1)	8.0	VIII-IX
3	3-Oct	10.55	4.8 (1)	5.1 (1)			12.84	43.05	(3)		VII
4	7-Oct	01.24	4.9 (1)	5.3 (1)			12.84	43.02	(3)		VII-VIII
5	12-Oct	13.08	4.5 (1)	5.1 (3)	5.2 (2)		12.97	42.87	(3)		VI-VII
6	14-Oct	17.23	4.9 (1)	5.4 (1)	5.5 (2)		12.94	42.91	(3)		VIII
7	26-Mar	17.26		5.5 (1)		5.3 (1)	12.85	43.20	(1)	50.0	VII
8	3-Apr	09.26	4.7 (1)	5.0 (1)		5.1 (1)	12.79	43.20	(1)	6.0	VII

Table 1.3 The eight events of the Umbria-Marche sequence up to 3 April 1998 with Ml>5.0

It is interesting to note that, starting from 12 October, the seismic activity, concentrated up to that moment around Colfiorito, moves southward to the area of Sellano and Preci. The macroseismic intensity formerly attributed to Sellano (6-7 MCS), was updated to 8-9 MCS after the shocks of 12 and 14 October.

Figure 1.5 shows the spatial distribution of the epicentres, numbered according to Table 1.3, and a preliminary hypothesis on the surface projection of the fault ruptured by the two main shocks of 26 September. This alignment, going from S.Martino to Aggi with a direction N27°W and a length of about 17 km, has been deduced (as illustrated in Figure 1.5) from geological and tectonic information, surface break evidence, focal mechanisms, aftershock distribution, and damage distribution (Decanini and Sabetta, 1997; Galli et al., 1997). Both instrumental and macroseismic data show that the first shock (02.33 local time) was felt stronger southward of Colfiorito and the second shock (11.40 local time) northward. On this basis it is suggested that the first shock could have been propagating from Colfiorito toward SSE along a rupture of about 7 km (continuous line in Figure 1.5) and the second in the opposite direction along a rupture of about 10 km (dashed line in Figure 1.5).

The main shocks of 26 September triggered respectively 15 and 20 strong motion instruments over an epicentral distance range from 3 to 100 km. The majority of instruments are of analogue type (SMA-1) and managed by the National Electric Company (ENEL). Two digital instruments (Cerreto di Spoleto and Norcia) have been installed by ENEA (National Environmental Agency), and one, in the basement of the Sacro Convento of Assisi, by Servizio Sismico Nazionale (SSN). Tables 1.4 and 1.5 show the values of and Peak Ground Velocity (PGV) and Peak Ground Acceleration (PGA) recorded by the above mentioned stations respectively for the first and second shock. Figure 1.8 gives the spatial distribution of the ENEL stations triggered by the second shock.

Owner	Station name	fault dist. (km)	PGA NS (cm/ s^2)	PGA VT (cm/ s^2)	PGA EW (cm/ s^2)	PGV NS (cm/s)	PGV VT (cm/s)	PGV EW (cm/s)
ENEL	Colfiorito	2.6	191.5	156.1	271.3	18.03	7.47	13.14
ENEL	Nocera Umbra	4.7	550.1	467.7	491.3	30.45	30.76	33.53
SSN	Assisi-convento	18.0	184.7	75.4	167.3	9.63	3.45	8.71
ENEL	Matelica	20.8	115.0	49.4	106.4	7.52	3.41	6.57
ENEA	Cerreto di Spoleto	22.0	79.6	46.4	100.0	3.31	1.59	4.48
ENEL	Castelnuovo di Assisi	23.1	168.6	50.0	103.1	14.27	4.63	11.92
ENEL	Monte Fiegni	23.7	24.2	19.6	31.7	1.49	1.01	1.07
ENEL	Bevagna	25.5	77.5	35.4	71.4	8.05	3.38	9.21
ENEA	Norcia	29.6	32.4	24.3	25.2	3.02	1.64	2.63
ENEL	Gubbio (Piana)	30.3	91.1	64.6	92.5	13.03	13.60	17.72
ENEL	Gubbio	33.4	62.2	39.6	82.4	3.23	2.04	2.82
ENEL	Cascia	34.2	21.6	15.7	20.5	1.15	0.80	1.08
ENEL	Forca Canapine	38.0	31.8	16.8	31.5	0.75	0.58	1.20
ENEL	Pietralunga	47.3	43.8	18.9	68.0	2.26	1.58	2.88
ENEL	Cagli	50.1	12.6	19.8	19.8	0.78	1.02	1.35
ENEL	Leonessa	50.5	32.7	12.7	21.7	1.26	0.65	1.00
ENEL	Rieti	65.0	17.0	8.4	18.4	1.78	0.50	1.83
ENEL	Senigallia	71.1	47.1	11.0	31.5	4.45	0.90	3.55
ENEL	Peglio	73.0	58.2	25.2	67.7	2.46	1.17	2.65
ENEL	Pennabilli	91.1	14.2	6.0	15.6	1.00	0.69	1.31

Table 1.4 Strong Motion Stations triggered by the shock of 26 September at 11.40

Owner	Station name	fault dist. (km)	PGA NS (cm/ s^2)	PGA VT (cm/ s^2)	PGA EW (cm/ s^2)	PGV NS (cm/s)	PGV VT (cm/s)	PGV EW (cm/s)
ENEL	Colfiorito	2.6	330.1	358.6	252.4	20.46	12.21	22.64
ENEL	Nocera Umbra	15.0	501.4	144.5	267.8	20.65	5.72	10.21
ENEA	Cerreto di Spoleto	17.8	191.0	97.2	170.0	4.80	4.73	4.43
SSN	Assisi-convento	20.8	111.3	39.6	150.8	4.65	1.53	6.04
ENEL	Monte Fiegni	22.7	22.7	17.0	24.0	0.80	0.78	0.92
ENEA	Norcia	24.0	34.4	30.5	40.4	3.00	2.64	3.57
ENEL	Castelnuovo di Assisi	24.8	98.2	28.6	70.0	5.87	2.16	3.64
ENEL	Bevagna	25.3	37.1	41.8	50.9	4.06	1.84	6.19
ENEL	Matelica	26.8	44.7	22.9	47.2	1.59	0.99	2.00
ENEL	Cascia	29.3	28.1	15.6	27.1	1.16	0.90	1.04
ENEL	Spoleto Monteluco	31.7	35.3	15.4	47.2	1.72	0.65	1.79
ENEL	Forca Canapine	33.0	63.2	30.7	63.7	1.79	0.88	2.25
ENEL	Gubbio (Piana)	40.6	33.0	16.7	32.6	3.47	2.72	3.68
ENEL	Leonessa	46.0	25.8	14.0	23.3	1.26	0.72	1.13
ENEL	Rieti	61.4	25.1	8.2	22.5	2.09	0.60	2.50

Table 1.5 Strong motion stations triggered by the shock of 26 September at 02.33

Figures 1.9 and 1.10 show a comparison of the PGA and PGV, recorded respectively during the first and second shock, with the attenuation relationship valid for Italy (Sabetta and Pugliese, 1996). The distance of the stations from the closest point of the surface projection of the fault trace has been estimated referring to the segments indicated as F1 and F2 in Figure 1.5. The regression on the data, marked as Umbria 1 in Figures 1.9 and 1.10, was performed estimating the values of a, b and h in the following relation:

$$\log y = a + b \log (R^2 + h^2)^{1/2} \qquad (1.1)$$

where y is the parameter to be estimated (PGA or PGV) and R is the fault distance as defined above.

The use of epicentral distance in place of fault distance for R gives similar results with a worse correlation index. The number of recordings was not sufficient to get a statistically significant estimation of the site effect.

As shown in the figures the data are very scattered with high values in particular for the stations closest to the fault. Nevertheless the curve obtained through equation (1.1) is slightly higher than the average national attenuation for the first shock and lies between the curves referring to stiff and alluvial sites for the second shock.

Figure 1.11 shows the correlation obtained for PGA versus macroseismic intensity compared with similar relationships available in the literature. The poor fit of the Umbria data with respect to the other relationships is evident, indicating either an overestimation of the PGA, or an underestimation of the intensity.

The intensity values refer to global surveys carried out in the corresponding villages, but preliminary results of specific damage surveys around the recording instruments do not show significantly different values. The case of Nocera Umbra deserves special mention, with a PGA of 0.56 g, a PGV of 33.5 cm/s and a MCS intensity of only 7.5. This station, as confirmed by the very high PGA recorded during previous earthquakes, is in all probability affected by a local amplification effect. The time histories of acceleration, velocity and displacement of the NS component recorded during the shock at 11.40 are illustrated in Figure 1.12 and show a level of acceleration above 0.3g sustained at least for 4 seconds. This does not fit well with an intensity of MCS=7.5 confirmed by a damage survey around the instrument (see Section 2.6 in this report). Figure 1.12 shows time histories of the strong motion instruments triggered by the main shock at Nocera Umbria and Colfiorito.

1.6 History of earthquake occurrence in the region

Umbria and Marche have a long history of significantly damaging but not catastrophic earthquakes. The NT4-GNDT earthquake catalogue (GNDT 1998) lists 22 events with epicentral intensities exceeding MCS=8 in the region bordered by 42° 40' to 43°20' North and 12° 20' to 13° 20' East, i.e. within about 40 km of the 1997 epicentres. The dates, magnitudes and epicentres of these are shown in Table 1.6. Most of these are to the south of the September 1997 epicentres in an east-west band stretching in southern Umbria and Marche from Aquasparta through Spoleto and Cascia to Norcia and Amatrice. The Valnerina area, Cascia and Norcia have been the most frequent epicentral areas, with the most recent event only 20 years ago in 1979.

Year	Mo	Day	Location	Io(MCS)	Ms	Long	Lat
1277			SPOLETO	8.0	5.5	12.73	42.73
1279	4	30	CAMERINO	10.0	6.7	12.90	43.10
1298	12	1	REATINO	9.5	6.4	12.88	42.5
1328	12	1	NORCIA	10.0	6.7	13.0	42.87
1389	10	18	BOCCA SERRIOLA	9.0	6.2	12.35	43.53
1599	11	5	CASCIA	8.5	5.9	13.02	42.71
1639	10	7	AMATRICE	10.0	6.7	13.25	42.63
1703	2	2	L'AQUILA	9.0	6.2	13.25	42.14
1703	1	14	NORCIA	10.0	6.7	13.17	42.67
1730	5	12	NORCIA	8.5	5.9	13.08	42.78
1741	4	24	FABRIANESE	9.0	6.2	12.98	43.38
1747	4	17	FIUMINATA	9.0	6.2	12.82	43.20
1751	7	27	GUALDO TADINO	10.0	6.7	12.75	43.25
1781	6	3	CAGLIESE	9.5	6.4	12.5	43.58
1785	10	9	PIEDILUCO	8.0	5.5	12.75	42.53
1799	7	28	CAMERINO	9.0	6.2	13.17	43.17
1832	1	13	FOLIGNO	8.5	5.9	12.65	42.95
1838	2	14	VALNERINA	8.0	5.5	12.83	42.87
1859	8	22	NORCIA	8.5	5.9	13.1	42.8
1878	9	15	MONTEFALCO	8.0	5.5	12.68	42.85
1916	8	16	RIMINESE	8.5	6.1	12.74	43.08
1979	9	19	NORCIA	8.0	5.9	12.95	42.72

Table 1.6 Historical earthquakes in the region bordered by 42° 40' to 43° 20' N and 12° 20' to 13° 20' E with epicentral intensities equal to or greater than MCS=8.

A smaller group of earthquakes has occurred in the Assisi-Spello-Foligno region with intensities as shown in Table 1.7 (Postpischl, 1985).

Year	Location	Io (MCS)
1702	SPELLO	7
1790	MONTEFALCO	7
1832	SPELLO	8-9
1854	ASSISI	7
1878	MONTEFALCO	8
1915	ASSISI	7

Table 1.7 Historical earthquakes in the Assisi-Spello-Foligno region

In the immediate epicentral area of the September earthquakes, there have been relatively few earthquakes in the recent past. Galli et al. suggest that the most recent destructive earthquake in the area was that of 1279, epicentre Camerino, which had an epicentral intensity MCS=10. Two smaller events occurred in 1791 (epicentral intensity MCS=7-8), epicentre slightly south of the September 1997 ones, and 1838 (epicentral intensity MCS=8), epicentre near Sellano. The seismic history of the whole Umbria area is described in more detail by Galli et al. 1997, and Camassi et al. 1998.

Historical accounts testify to the damage to the major towns of the region caused by earthquakes over the centuries. The 1751 earthquake brought down all of Gualdo Tadino's principal civic buildings from the Middle Ages. The 1832 earthquake caused the collapse of most of the nave of Santa Maria dei Angeli near Assisi, and badly damaged the Palazzo Trinci in Foligno. Cascia has been destroyed or badly damaged five times in 1300, 1599, 1703, 1812 and 1979, while Norcia was badly damaged six times in 1328, 1567, 1703, 1730, 1859 and 1979 (Campbell-Ross, 1996).

A common feature of earthquake occurrence in the whole region is the continuation of a series of shocks of significant magnitude over a period of many months. The 1703 earthquake was destructive over a wide area, and included three main shocks: the first of intensity MCS=10 on 14 January, located near Norcia; the second of intensity MCS=8, located near Montereale, 30 km to the south, and the third, intensity MCS=9, a further 15 km to the south near L'Aquila on 7 February (Galli et al. 1997).

Likewise during the September 1979 sequence in the Valnerina zone a series of seven shocks exceeding M_L = 3.5 were recorded over three days (19 to 21 September), the largest reaching M_L = 5.5, with further shocks of $M_L = 3.7$ on 6 October, $M_L = 3.5$ on 8 November, $M_L = 3.9$ on 13 December, $M_L = 4.0$ on 14 December and $M_L = 4.0$ on 29 December, three months after the main shock. Significantly, this sequence, like the present one, was preceded by an earlier smaller shock $M_L = 3.7$ on 3 September, two weeks before the largest shock of the episode.

Similarly, in 1915, an intensity MCS=7 shock centred on Assisi on 26 March was followed by an intensity MCS=5 shock on 27 March, two further shocks of MCS=5 and 6 three months later on 2 and 3 June, and a further shock of MCS=4-5 on 5 April 1916, over a year later. This sequence also was preceded by smaller events in the neighbourhood, MCS = 5 at Foligno on 16 March and MCS = 6 at Colfiorito on 15 March 1915 (Postpischl, 1985).

In summary, damaging events have occurred very regularly in the region, and this has had its effects on building form and standards, as will be discussed later. There is also a pattern of repeated significant shocks occurring over a period of weeks or months, as happened in this case, and it is by no means unusual for the largest and most damaging shock to be preceded by a smaller one nearby a few days or weeks earlier.

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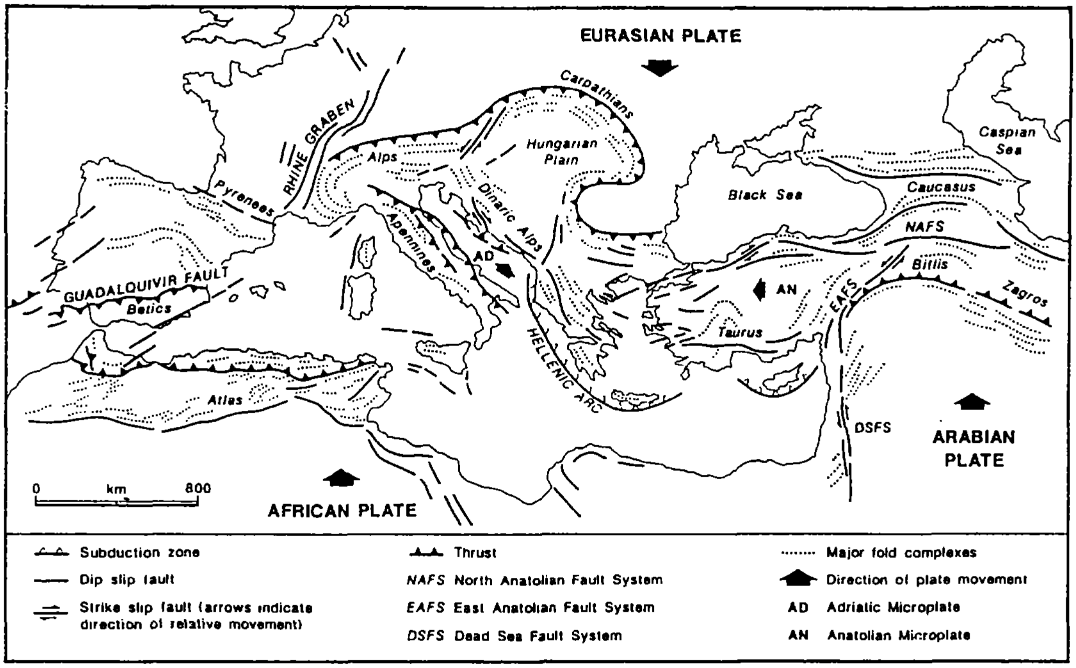


Figure 1.1: Schematic tectonic map of Southern Europe and the Mediterranean Basin (after Degg and Doornkamp, 1991)

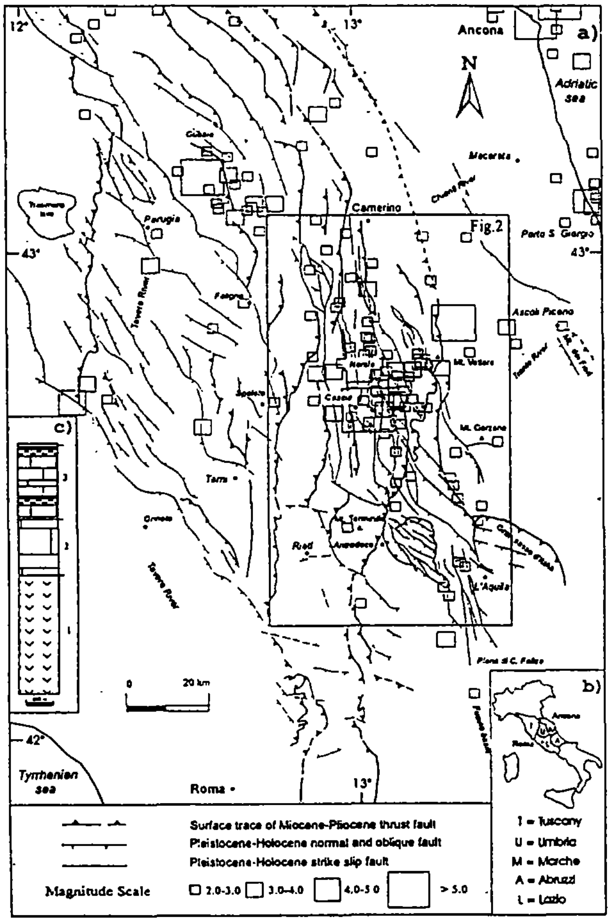


Figure 1.2: Structural map of the Central Appenine Fault Zone (after Cello et al., 1997)

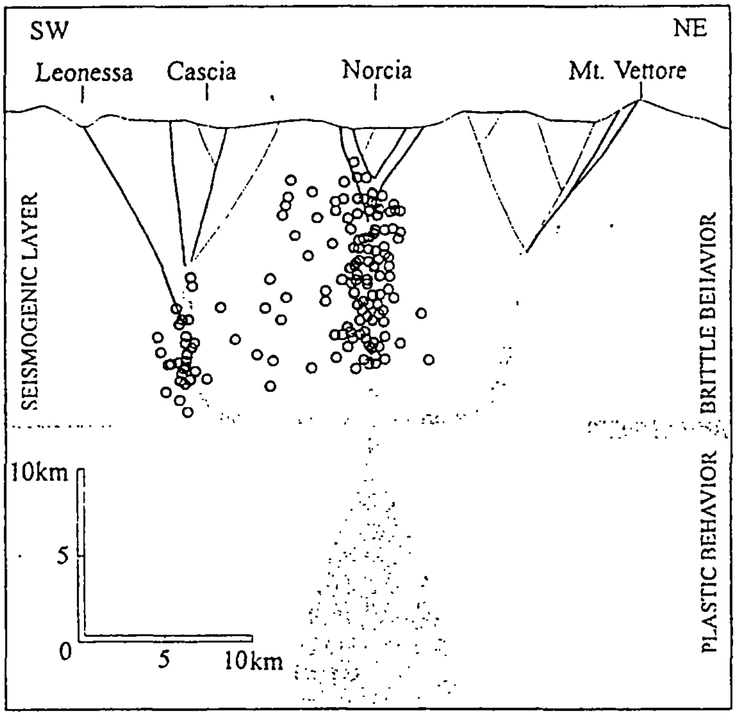


Figure 1.3: Inferred crustal structure of the Central Appenine Fault Zone (after Cello et al., 1997)

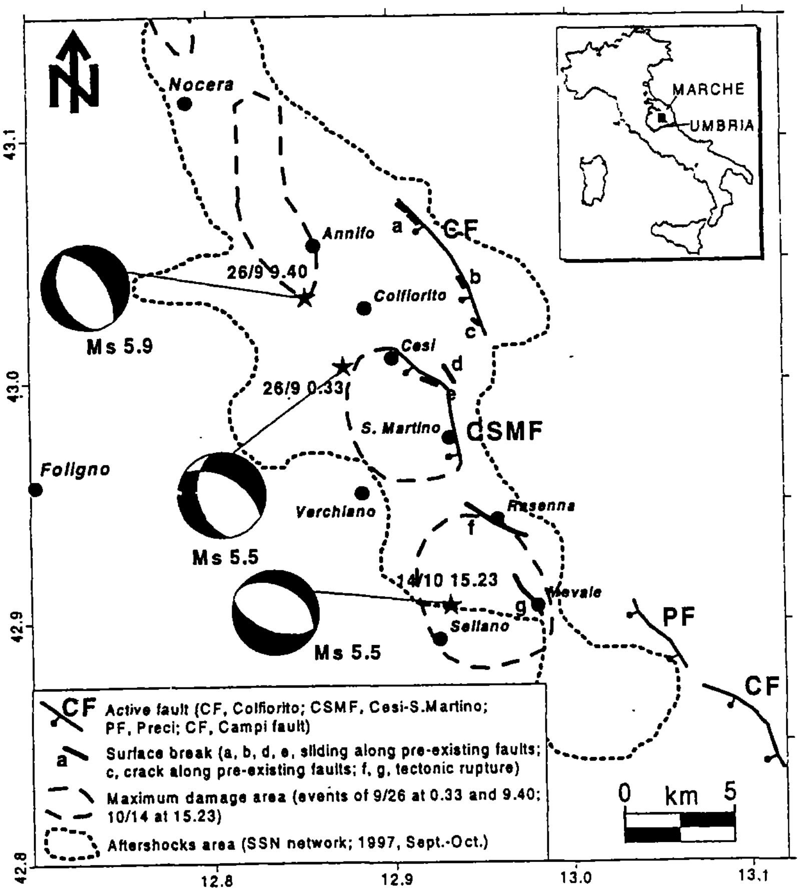


Figure 1.4: Active faults, epicentres and observed ground deformations (after Galli et al., 1997)

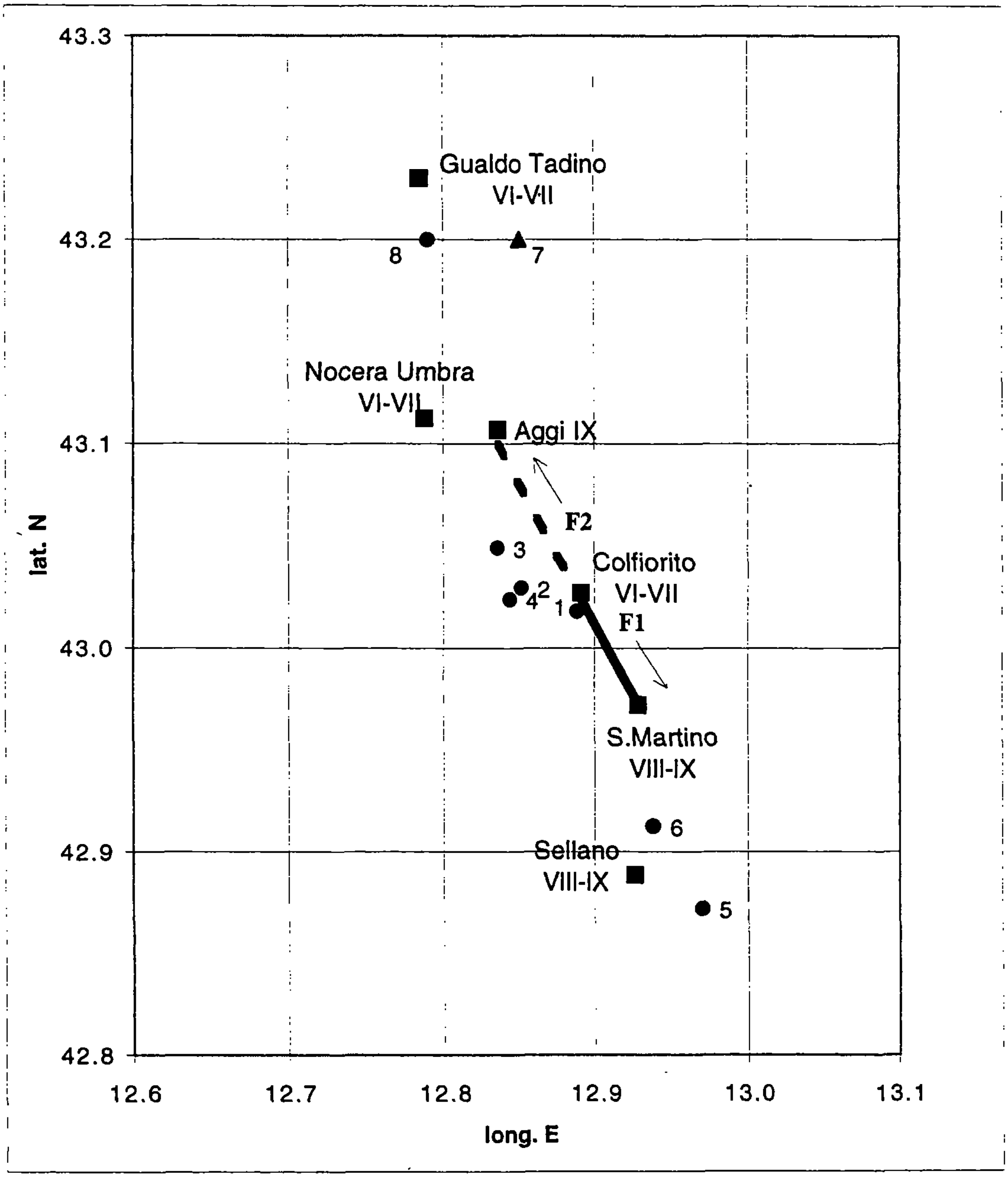


Figure 1.5: Epicentres of earthquakes with Ml>5.0 from 26 September to 3 April 1998 and suggested fault breaks

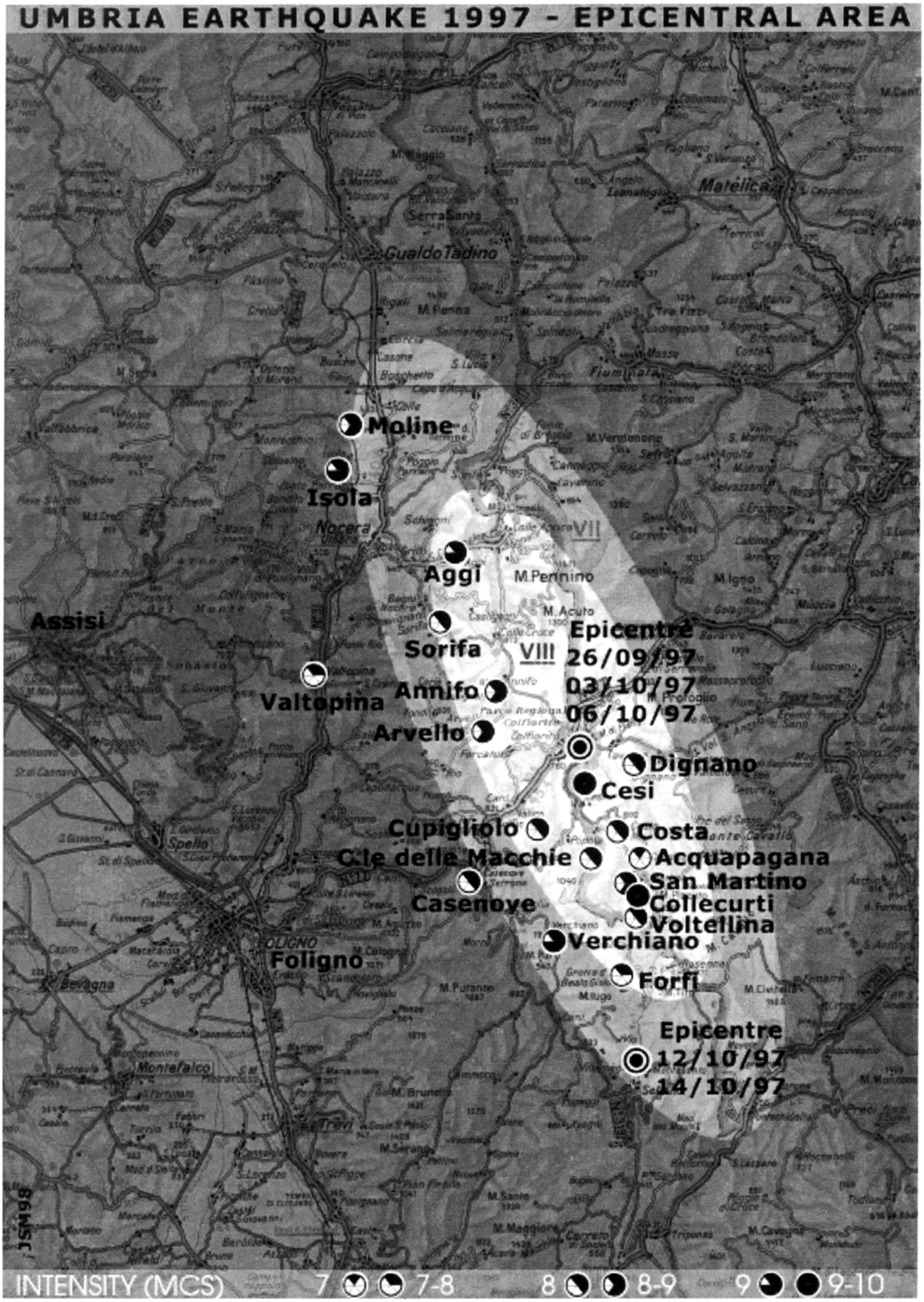


Figure 1.6: Intensity distribution in the Epicentral Area after 26 September (after ING)

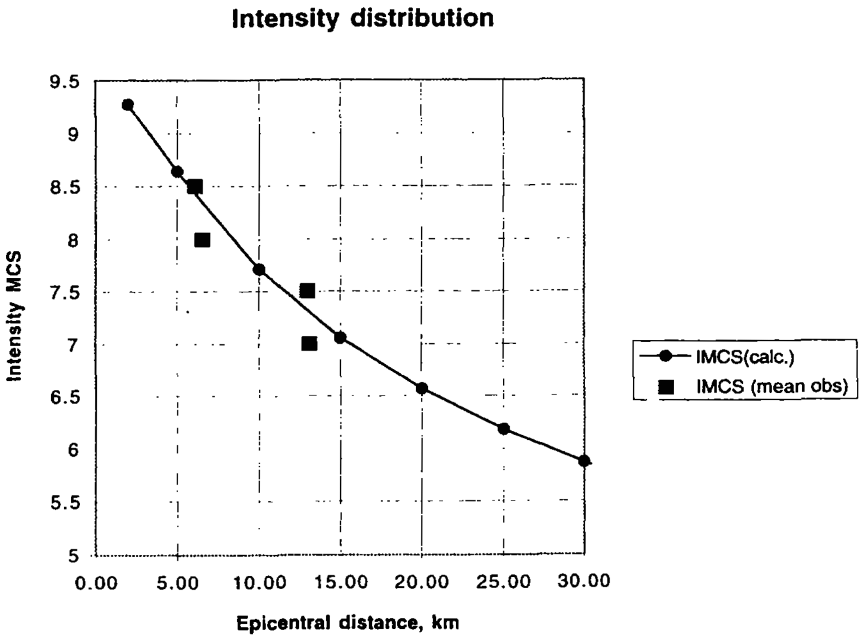


Figure 1.7: Expected and actual intensity attenuation in the epicentral region

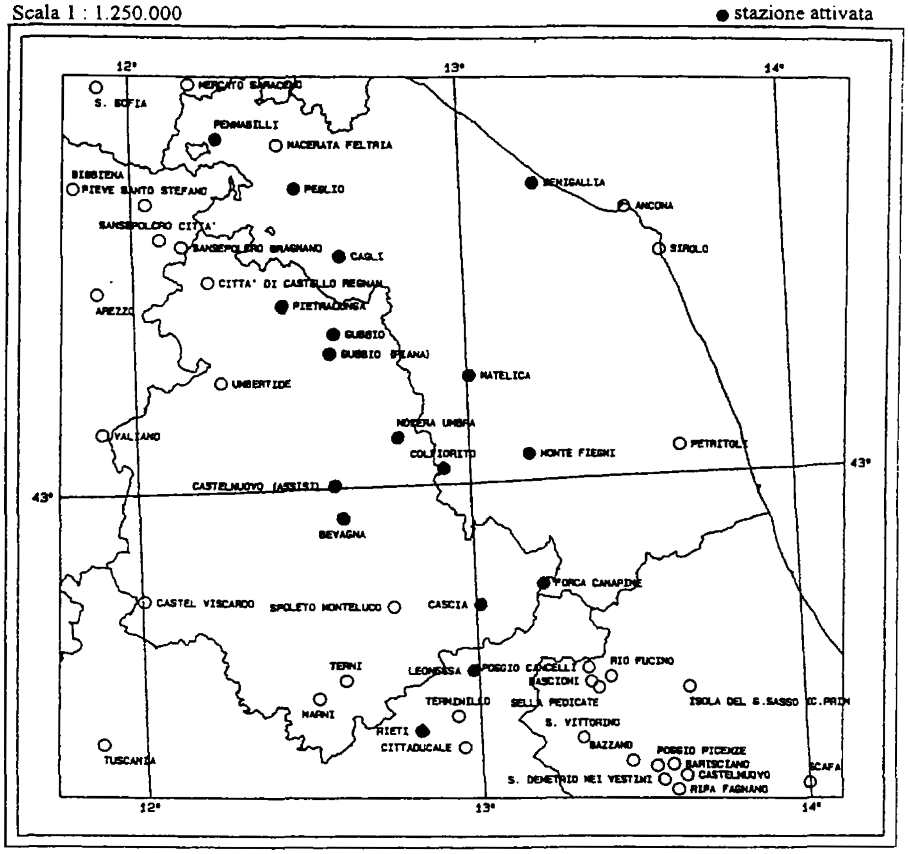


Figure 1.8: Locations of accelerometer stations of the ENEL network activated by the 11.40 shock of 26 September

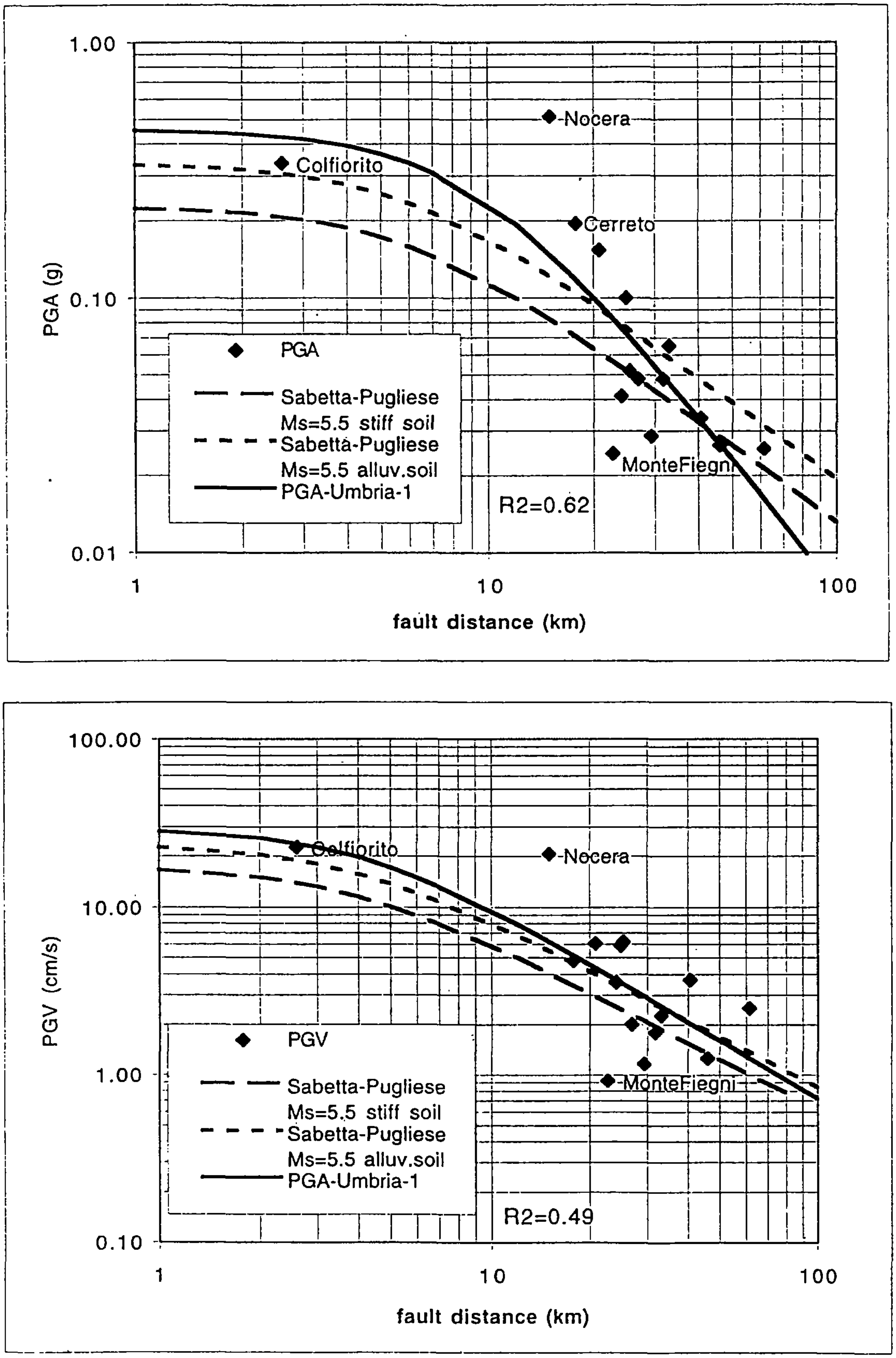


Figure 1.9: Attenuation of principal ground motion parameters in the 02.33 shock of 26 September

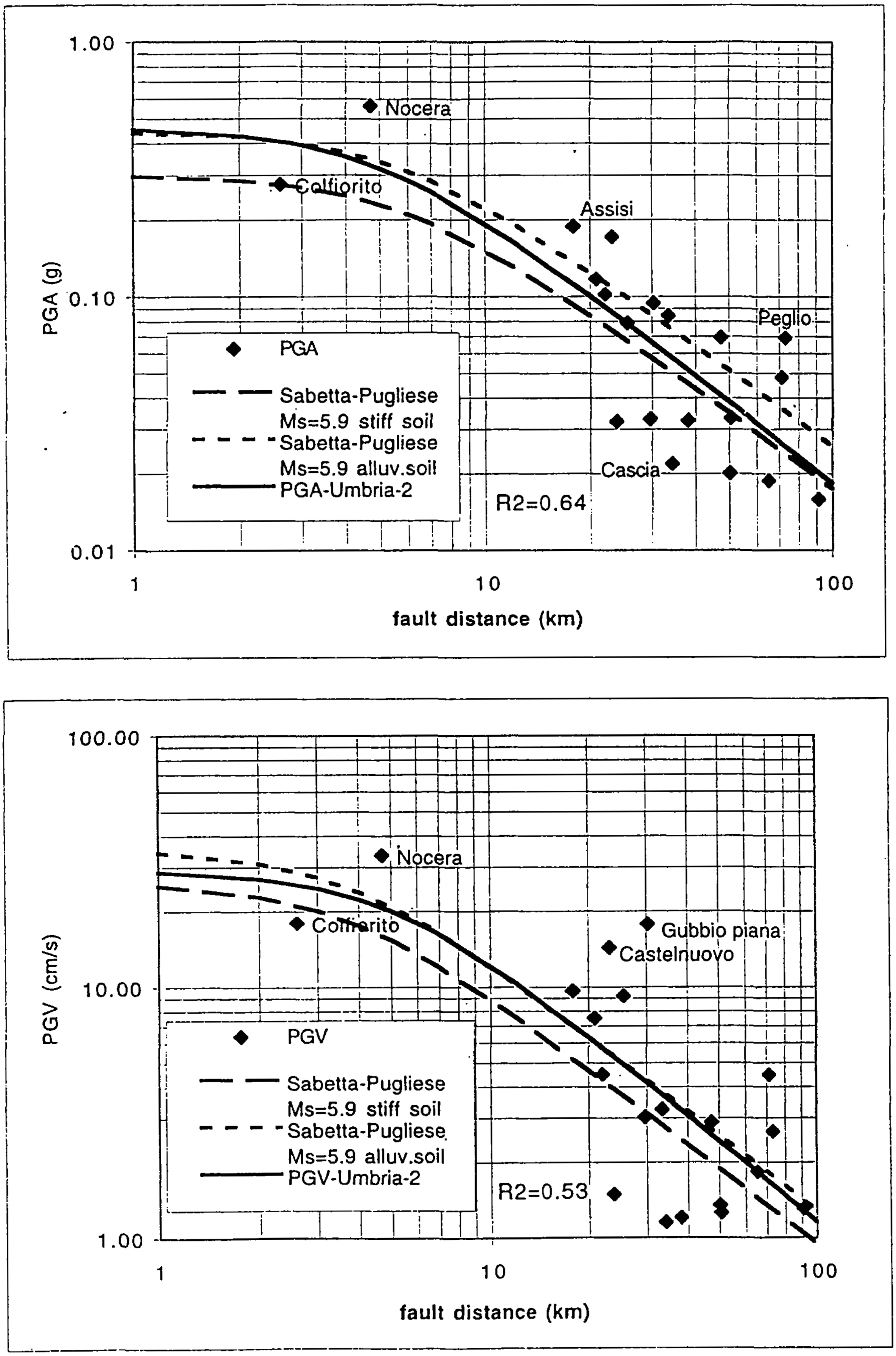


Figure 1.10: Attenuation of principal ground motion parameters in the 11.40 shock of 26 September

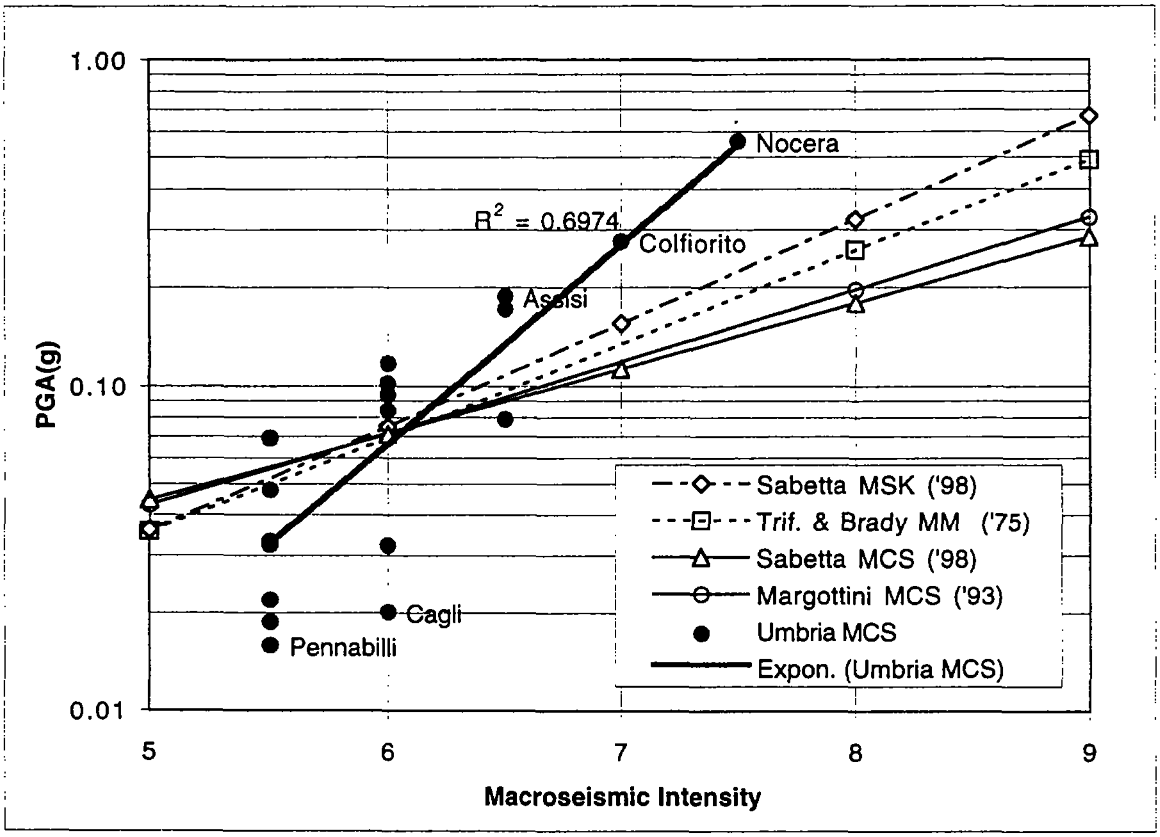
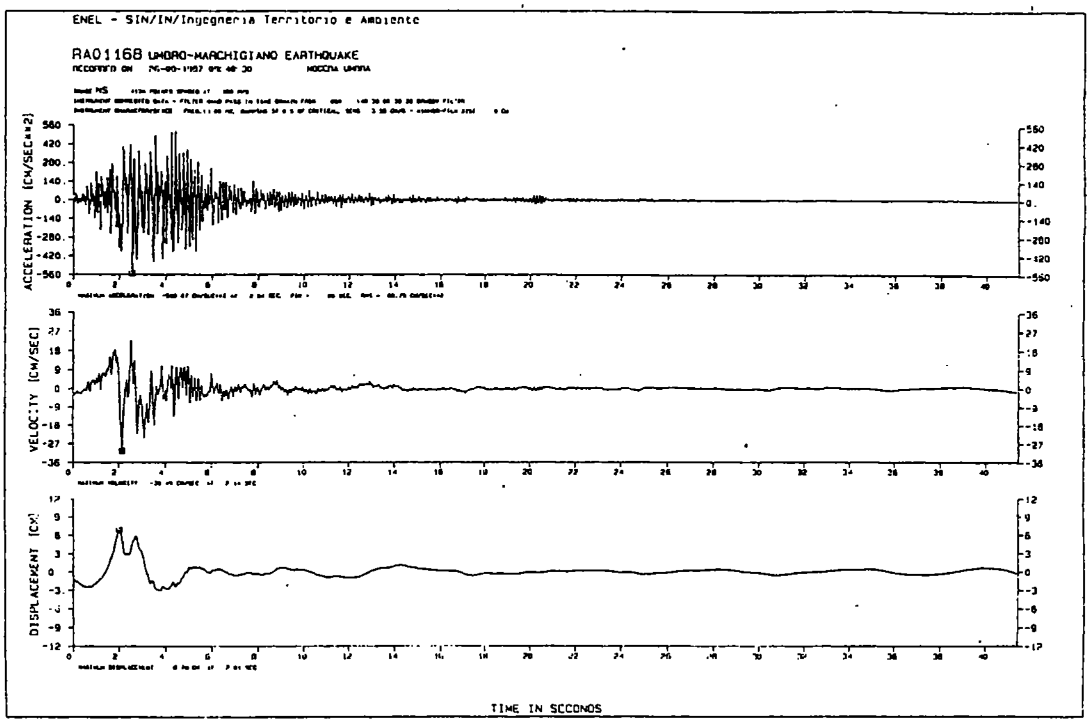


Figure 1.11: Correlation of peak ground acceleration with macroseismic intensity: 11.40 shock of 26 September



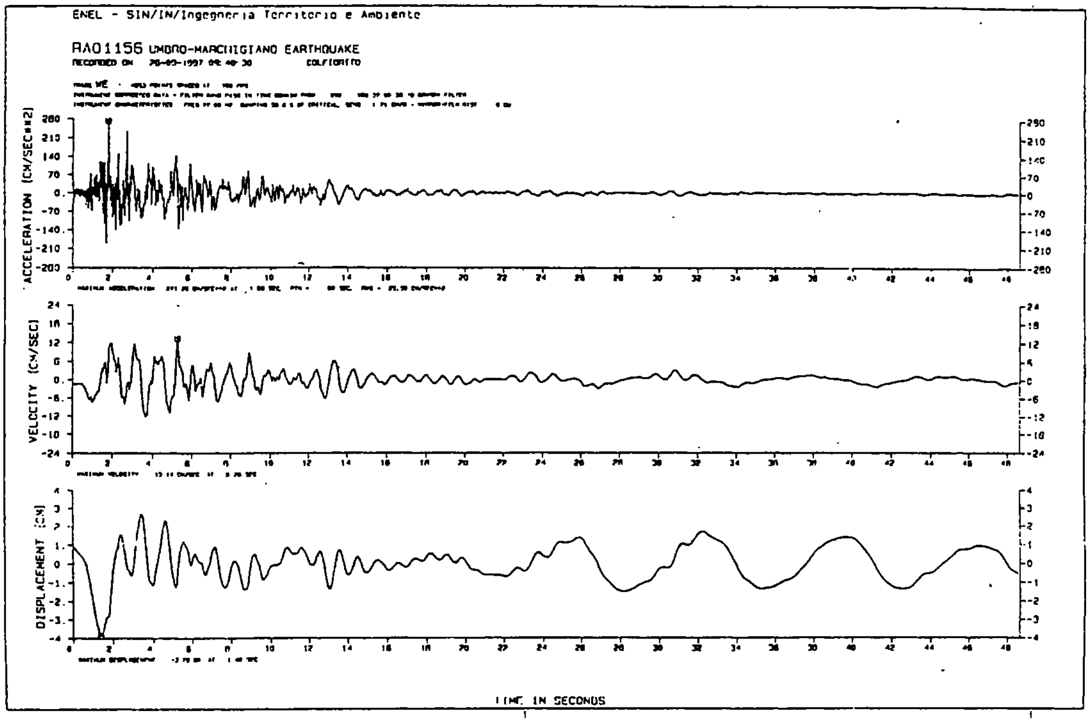


Figure 1.12: Strong motion records at Nocera Umbra NS (R=4.7 km) and Colfiorito EW (R=2.6 km) from the earthquake of 11.40 on 26 September

2.0 BUILDING DAMAGE

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2.1 Urban and rural secular building types prevalent in Umbria

Umbria and Marche, together with Tuscany, form a transitional belt across the Italian peninsula, connecting the agrarian south and the industrial north, sharing a common pattern in urban and rural settlements, cultural inheritance and construction technology.

The most characteristic feature of the Umbrian landscape are hill towns and fortified *borghi*, village-castles, perched on rocky precipices, representing once self-sufficient communities, with the larger ones forming the economic and administrative centres of the countryside around them (Plate 2.1). Defence against hostile incursion was the determinant factor of this prevalent urban pattern, encouraging the primarily agrarian population to cluster around defensible strategic points and to adopt fortification construction technology, such as massive masonry.

Architectural Archetypes

The layout of the urban settlements is a testimony to the tumultuous history of the region, dominated by war and battle since the settlement of its earliest inhabitants, the Samnite and Umbrian tribes and throughout the Etruscan and Roman periods (Duncan, 1993). Dependent on both the impregnable security of the hills and the fertile, but unsafe valleys amongst rivers, lakes and fenlands (drained by the Romans), settlers decided to dwell on the hills and only venture out of the walled enclaves to cultivate the land in the immediate neighbourhood. After the fall of the Roman Empire, the region was subjected to the invasions of Goths, Huns and Lombards, its inhabitants succumbing to plague, famine and poverty. After a brief period of relative peace under the Frankish Empire in the eighth century, rivalries between powerful families plunged Umbria back into chaos and warfare even between neighbouring towns.

Under these circumstances, farming was a perilous occupation, and all over Umbria ancient towerhouses with a single entrance at ground level and two rooms within, one above the other linked by a wooden staircase, formed easily defensible refuge space for farmers during the harvest season. Many of these were later converted and extended into farmhouses.

Within the fortified towns, Roman urban building types have been largely sustained in the form of multi-storey apartment blocks, with cantinas, workshops, storerooms, shops and bars on the ground floor open to the street, and living spaces above. Narrow, cobbled streets and wide overhanging eaves prevail for environmental purposes in a Mediterranean climate characterised by hot and dry summers. Construction materials are brick or plastered masonry, minimising fire risk (Duncan, 1993, Castellano, 1986).

During the Middle Ages, rural areas of Umbria were organised under the *mezzadria* system of estate management, whereby farmland owned by individuals or Church institutions and managed by agents was divided into very small plots farmed by sharecroppers, thus nurturing widespread rural poverty and misery (Desplanques, 1970).

The architectural manifestation of the *mezzadria* were the *casa colonica* (tenant farmer's house) and the *casa mezzadrile* (land agent's house). With urban building types often transposed to rural settlements, the *casa colonica* is related to the urban apartment block of Roman origin, whereby the *cantine* served as wineries, store rooms or even animal sheds. Each *cantina* benefits from its own external entrance which is frequently arched. Barrel or groin vaults in clay bricks are encountered in some buildings, sometimes plastered, depending on function. Internal walls often have openings supported by timber lintels or round arches with stone voussoirs. Nevertheless, room widths are limited to approximately 3-6m by trabeated construction (Richings, 1997, Bosi, 1990).

The living quarters above on one or several floors are accessible by narrow external masonry staircases, often constructed over an arch acting as a wood store. In more prosperous homes these staircases are roofed and culminate in covered loggias. The entrance to the living area leads to a kitchen/living room with an open fireplace against an internal wall. A corridor allows access to bedrooms, and additional sleeping accommodation is sometimes provided below the roof rafters.

While rooms at the top of the building are often open to the roof rafters, ceiling heights can be as low as 2m. Window openings are small and usually have a regular arrangement, are set high in the wall on the ground floor and are fitted with security grills. Frames are made of timber and accompanied by internal or external wooden shutters. Roofs are generally ridged with a pitch of about 14° and tiled with loose pantiles laid in upright and inverted overlapping courses. Barns are usually located in close vicinity, mostly separated due to risk of fire and infestation.

The *casa mezzadrile* is usually based on a rectangular plan consisting of *cantine* characterised by arcades on the ground floor and living quarters on the first floor, as well as a large, dominant masonry tower projecting from the hipped roof. Sometimes an attic storey exists, with oval windows just below the roof line. Larger examples are arranged around an internal courtyard with access to *cantinas* or peasant accommodation, usually located centrally on the main façade and entered through an arcade. Often, architectural elements derived from urban buildings, like loggias, verandas, grand salons or *trompe l'oeil* are introduced.

By the middle of the seventeenth century onwards, Umbria had fallen to the Papacy and benefited from a relatively tranquil period which enabled many settlers to move from the hills down to the fertile grounds of the Tiber Valley (Duncan, 1993). This area now constitutes the most highly populated area of Umbria.

Umbria has always been an agricultural region, which is one of the reasons why building typologies have not changed much, with many of the *case coloniche* remaining in their original use over several generations of the same family. Now, however, subsistence farming has lost the importance which it once had and more and more Umbrians live in towns, leading to the internal transformation of traditional types to accommodate tourists, absentee owners who live in Rome, or the members of the family who were the original owners.

Nevertheless, the need for modern administrative, social and cultural centres has necessitated the introduction of modern construction methods in Umbria, too. Office buildings, schools and apartment blocks are predominantly built on the basis of standard European typologies with the aid of modern construction technologies, mostly based on reinforced concrete.

Building materials

For most vernacular buildings, the main building materials are local stone, lime mortar, mud, lime or cement render and terracotta for roofing and flooring. Walls consist mainly of random rubble with a variety of different forms (Plates 2.2 to 2.4). Lime mortar and mud are the principal binders. Weatherproofing is improved through external coats of render, often colour-washed in heat-reflecting tones of terracotta. Lintels, window architraves, thresholds and door jambs are made of *pietra serena* or *terracotta mattoni* (clay bricks 30x12x3cm) or both (Richings, 1997).

However, there are local preferences and variations from region to region. Towards the northern end of the Tiber Valley, wall construction of countryside houses consists of regularly shaped blocks of sandstone which are laid together using a dry construction technique. In the Umbertide area, walls are constructed of regular rows of limestone blocks and gaps are filled in with splinters of stone and brick of different colours. The door and window surrounds of precisely cut stone blocks contrast with the rough texture of the walls and also add structural rigidity. Grey granite is the preferred building stone in the

Gubbio area, which renders a very different urban atmosphere to that of places like Assisi or Todi, characterised by golden coloured stone (Duncan, 1993).

Nevertheless, in many cases a whole array of masonry construction techniques and materials will be encountered within a short distance or even on one single building due to various extensions and repair works undertaken over time. Underneath the rendered surface, bricks and terracotta tiles of Roman origin can be found next to medieval masonry and window arches, rounded or pointed, sometimes blocked up and occasionally reused. Moreover, iron wall ties, anchors, braces and rods have been used since the Middle Ages as an efficient mitigation effort against the recurring earthquakes in the area and continue to be applied to many masonry buildings throughout the region (Plate 2.5).

Plate 2.6 summarises the range of stone masonry techniques to be found along a 500 m length of the slightly damaged Via Cristofani in Assisi, based on a photographic survey on October 11th 1997. The extent and range of traditional reinforcing techniques, and the level of damage sustained, is clearly visible.

While vernacular construction technology still persists and represents the overwhelming majority of the current building stock, modern buildings, and in particular high-rise residential buildings of four to nine storeys, are constructed of reinforced concrete, typically as frame structures with hollow clay tile infill, often plastered. Prefabricated elements, like reinforced concrete columns, floor slabs and façade elements are sometimes used for apartment blocks, but mostly for offices and farm buildings of larger spans (Plate 2.7). Vernacular buildings can sometimes be observed to have been fitted with reinforced concrete roofs, replacing traditional timber, as well as with various, mostly retrofitted, bracing elements of reinforced concrete. In some instances, an ad hoc, non-engineered mixture of traditional and modern construction techniques can be observed, for instance in the case of horizontal or vertical extensions of existing masonry structures with reinforced concrete additions (Plate 2.8).

2.2 The development of codes and aseismic regulations

Italy's first national set of earthquake resistant design regulations followed the 1908 Messina earthquake in which about 80,000 people died; the provisions then prescribed horizontal forces equal to 1/6 of the weight at each floor level of a building higher than 12 m. This was accompanied by a first classification of seismic areas - those damaged by the event and adjacent areas with historical seismicity. These provisions were updated and refined in 1916 following the Avezzano earthquake, and again in 1924 (Benzoni and Gentile, 1994). A two-level zoning was introduced in 1927; for the second seismic zone, a horizontal force of 1/10 of the floor weight was required.

The framework of today's code was introduced in the 1975 code and further updated in 1986 and 1996. This code requires both static and dynamic analysis for most buildings. It defines a seismic intensity factor which depends on the zoning, a response factor based on a generalised response spectrum, and a building importance factor. There are special provisions for calculating the loading to be used in framed structures, masonry buildings, buildings with structural walls and timber buildings. The 1996 code contains a complete set of provisions for the repair and strengthening of existing buildings, including masonry buildings (see Section 3.1).

The present day zoning defines three degrees of seismicity S = 12, 9 and 6 for the first (highest), second and third degree zone, corresponding approximately to expected PGA values of 0.35g, 0.25g and 0.15g respectively. These three degrees of seismicity correspond to three values of the seismic intensity factor C, which define the equivalent lateral force coefficient to be designed for – 10% of weight in the first zone, 7% in the second zone and 4% in the third zone. The regulations also set different maximum heights for new buildings in each of the three zones. A series of decrees between 1980 and 1984 fixed the boundaries of these seismic zones, covering the whole Italian territory for the first time. About 45% of the territory and 40% of the population is today covered by one of the three seismic zones, and most of Umbria now belongs to the second category.

Prior to 1980, however, the area most affected by the 1997 earthquake was outside the zoning classification. According to SSN (1997), in many *comuni*, for instance Nocera Umbra and Serravalle di Chienti, more than 90% of the population live in buildings which preceded the classification. Thus many of the buildings in the area today, even modern structures, may not have been designed with an acceptable level of resistance, although some local rules have applied in certain areas affected by the 1979 Valnerina and the 1984 Gubbio earthquakes.

2.3 Damage to non-engineered structures in epicentral region

The epicentral region is extensive and hilly, and at the time of the EEFIT study access was prohibited in some areas still considered too dangerous to enter. In a short reconnaissance visit it was not possible to cover the entire territory, but the team visited four of the most severely damaged villages - Collecurti, intensity MCS=9; Annifo and Isola, intensities MCS=8-9; and Colfiorito, intensity MCS=7. The team also visited Nocera Umbra, the one town in the epicentral area, intensity MCS=7-8 and a semi-urban area Nocera Scalo, intensity MCS=7-8. These locations are shown on the map of the damaged area (Figure 1.5). Damage reconnaissance was also carried out in the immediate vicinity of two of the ENEL strong-motion instruments triggered by the earthquake, at Colfiorito and Nocera Umbra, which is discussed in Section 2.6.

In the villages visited, most buildings were of two storeys and the predominant form of construction was masonry. Walls of the older buildings were of rubble stone, generally upwards of 0.5m thick, poorly bonded with lime mortar, and often externally plastered. Floors and roof structures were commonly of timber, sometimes large round sections poorly bedded into the walls. Roofs were of tile on timber, with about 20° pitch; commonly rafters were supported on timber purlins resting on masonry crosswalls. Several collapsed houses showed evidence of attempts to strengthen them with inserted reinforced concrete ring-beams or lintel beams (Plate 2.9). In other places ties were in evidence (Plate 2.10) Alterations in newer masonry were also observable in some damaged houses (Plate 2.11) From the damage patterns observed in the villages with lower intensity, it appears that damage to such buildings has occurred initially by the separation of orthogonal external walls at roof level, leading to independent movement of the major walls, and out-of-plane failure (Plate 2.12). This damage pattern is very frequently observed in untied rubble masonry buildings (Coburn and Spence 1992). Most of the partly or totally collapsed buildings observed were of this type (Plates 2.13, 2.14, 2.15). Typically, the worst damaged buildings appeared to be in a poor state of repair, possibly resulting from low utilisation in recent years.

More recent buildings in the epicentral villages were also of masonry construction, but had reinforced concrete floors and roof structures. Walls were either of burnt clay bricks, concrete block or extruded hollow clay bricks. Although no collapses were observed among this type, a number had sustained very serious damage to walls, with the form either of X-cracking typical of weak unreinforced masonry walls in shear (Plate 2.16) or corner failures (Plate 2.17). These buildings, though probably unrepairable, were clearly saved from collapse through the diaphragm action of the floor and ceiling slabs. Plate 2.18 shows a house in Collecurti where the lower storey stone masonry walls have failed, causing the upper storey to collapse on top of it, apparently intact.

At Nocera Scalo, on the main north-south route 53 (via Flamina), a more recent mix of building types was observed. Masonry buildings were mostly of burnt clay brick construction with reinforced concrete floor and roof slabs. Several buildings were of infilled reinforced concrete frame. Major shear failures of the masonry walls were observable in a number of buildings (Plates 2.19, 2.20).

An analysis of the distribution of damage was possible at Nocera Scalo, enabling an assessment of the local intensity to be made using the EMS scale. The EMS scale, described in Appendix 1, defines six vulnerability classes, A to F, and six damage levels or grades D0 to D5. Of the 14 vulnerability class B masonry buildings at this location, the damage levels assessed were as shown in Table 2.1.

Level of damage	Description	Number of buildings	Percentage of sample
D0,D1	No externally observable damage	6	43%
D2	Moderate damage	3	21%
D2/3	Damage level between D2 and D3	3	21%
D3	Heavy damage	2	14%

Table 2.1: Distribution of building damage at Nocera Scalo

This is consistent with damage at EMS Intensity 7, at which intensity "many buildings of vulnerability class B have damage grade 2".

There was one three-storey reinforced concrete frame building at Nocera Scalo, with a hollow clay block masonry infill. Throughout the ground floor, there was evidence of deformation of the frame causing damage to the infill which had fallen away in one section (Plate 2.21). Inside, the partition walls were severely cracked. The neighbouring building was of brick masonry, and was at the time of the earthquake undergoing strengthening by jacketing (reinforced plaster layer on both sides of wall) (Plate 2.22). This building showed no external evidence of damage.

2.4 Modes of failure

General considerations

Different shapes generate tensions in different areas under lateral loading; this was reflected in the damage suffered by masonry buildings of different shapes. The general trends linking building shape to damage are listed below.

Generally the forms that were most susceptible to damage had little provision of buttresses or ties, were significantly asymmetrical, or included sudden changes in stiffness. However, it was notable that although the bell tower in Foligno was heavily damaged and subsequently collapsed, the many bell towers in nearby Assisi were apparently undamaged. This difference may be partly due to the different ground conditions in the two towns: Assisi is a hillside town, while Foligno is in a valley, presumably built on alluvial deposits. Therefore the period of the earthquakes is likely to have been longer in Foligno, and closer to the natural period of the bell tower. This highlights the fact that the shape of a building affects its natural period and hence its susceptibility to earthquakes in a particular location.

Damage to corners

Corners were particularly susceptible to damage during the earthquakes (Plate 2.23). A relatively small degree of buttressing of the corners or ties back to the rest of the structure was very effective in limiting damage to the corners.

Out-of-plane wall failure

Generally the cellular arrangement of the smaller domestic scale buildings ensured that return walls provided sufficient restraint to prevent the out-of-plane failure of walls. Masonry buildings of a larger scale were generally provided with sufficient buttressing to avoid out of plane failure of walls. However, cases of out-of-plane failure of a limited number of long slender load-bearing walls were found. In these cases commonly the effect of the out-of-plane earthquake loads had combined with an outward thrust from rafters at the head of the wall to cause collapse.

Many examples of cracking around infill panels were seen, both around infills to disused door and window openings in masonry buildings and around blockwork infill panels to framed buildings. Masonry partitions poorly bonded to the surrounding structure were also prone to cracking and in some cases collapse.

Masonry wall separation

The separation of the two layers of a double skin stone masonry wall was a commonly observed form of damage; the gable walls of rectangular buildings were most susceptible to this type of damage. The walls affected were all well restrained at the sides but poorly restrained at the top; generally the walls had a large height to width ratio. The damage was most pronounced in the upper parts of the walls (Plate 2.24).

Shear cracking

X-cracking of masonry walls was widespread throughout the area. Domestic scale buildings were particularly susceptible to this type of damage. X-cracking occurred around levels that were significantly less stiff than the surrounding structure; typically piers between windows were affected. The lower storeys were more seriously damaged than the upper storeys (Plate 2.25). Where a larger pier had been retained adjacent to the corner of the building this tended to act as buttressing to accommodate the horizontal loads and hence limit X-cracking. Shear cracking of some poor quality buttresses was also seen but since the buttresses had an initial horizontal pre-stress the cracks were aligned in one direction only (Plate 2.26). Sliding shear was not seen.

Hinges and mechanisms

There were very few clear examples of hinging mechanisms forming. The structures that were affected tended to be delicate and poorly buttressed against the particular mechanism that formed. The clearest example was a masonry column below a reinforced concrete cantilever balcony in Isola (Plate 2.27).

The widely shown video recording of the collapse of the vault in the main basilica in Assisi (Plate 4.1) shows that the vault initially formed a mechanism that led to its collapse. Cracks in the barrel vault above the nave of San Rufino in Assisi suggest that it may have generated a series of hinges during the earthquake; however, in this case the mechanism did not lead to the collapse of the vault. See Chapter 3 for further discussion of these structures.

Sudden changes in stiffness

Many buildings had some cracking at sudden changes in stiffness on elevation or on plan, however the damage was generally slight compared to the other types of damage that were seen.

Asymmetry

There were few examples of buildings with asymmetrical forms. The clearest example was found in a modern villa near Nocera Umbra. The rooms had been arranged to take advantage of the views down the valley with the larger living spaces concentrated on the valley side of the house. This had the effect of making the centre of stiffness of the building eccentric from the centre of mass giving rise to a torsional response. The villa was heavily damaged on the side farthest from the centre of stiffness.

A note on quality of construction

It seems that where the shape of the structure maintained the structure in compression despite the earthquake loads, the quality of construction was of less importance for the survival of the building. However where the shape of the structure was such that it would have generated tensions under earthquake loads, good quality masonry accommodated the loads better, presumably because it was able to maintain its structural integrity despite some cracking.

2.5 Effects of soil and topography on extent of damage

Significant differences in the general levels of damage were observed in a number of locations in the epicentral area; for example between Cesi and Cesi Villa, between Collecurti and nearby Forcella, in different parts of the village of Annifo, and between Nocera Umbra and Nocera Scalo. These differences were in most cases greater than could be explained by possible differences in types or quality of construction. In Assisi also, most buildings in the adjacent town did not appear to have experienced the same level of ground motion as the Basilica of San Francesco.

The nature of the underlying soil and its possible effect in amplifying strong ground motion was not examined by the EEFIT team, but subsequent investigations conducted by Capotorti et al. (1998) have shown that:

- there are significant differences in each of the cases mentioned above in the superficial geology, and typically, the worst damaged of two adjacent settlements was located on loose debris or soft alluvial deposits of some thickness;

- site response spectra for several of the sites, determined by a modified Nakamura method (Mucciarelli et al., 1996), showed significant amplification in the frequency range 1.5 to 3 Hz, the frequency range most critical for stiff masonry buildings. An example, for Cesi and Cesi Villa, is shown in Figure 2.1.

Tographical effects may also be at least partly responsible for the excessive damage at Collecurti and at the site of the Basilica of San Francesco at Assisi, both of which are located on ridges with their axes roughly aligned with the fault.

Soil failures were frequent in the epicentral area, causing small landslides, ground settlement under building foundations, and the rupture of some roads. The settlement of a railway embankment near

Isola was observed by the EEFIT team (Plate 2.28). Fortunately, however, the disruption to railways and roads caused by these ground movements was relatively slight. There were no failures of earth dams.

2.6 Damage surveys around strong motion instruments

There were two strong motion instruments (SMIs) in the ENEL network in the epicentral region at Colfiorito and Nocera Umbra (Figure 1.8). The PGA values at these two instruments, derived from the data in Tables 1.4 and 1.5, were as shown in Table 2.2:

		02.33 Shock	11.40 Shock	Intensity (EMS)
Colfiorito	H1	330	191	7
	H2	252	271	
	V	358	156	
Nocera Umbra	H1	501	550	7-8
	H2	267	491	
	V	144	467	

Table 2.2: Reported PGA levels (cm/sec^2) and observed intensity around strong motion instruments

With the help of ENEA, these two instruments were located, and the damage in their immediate vicinity was recorded. The Colfiorito SMI (Plate 2.29) was located close to a farm, where buildings included a large 3-storey farmhouse of rubble masonry, of typical Umbrian style, a small masonry chapel, an old barn, and two modern concrete frame sheds. All the masonry buildings showed significant structural damage (Plates 2.30, 2.31, 2.32), with vertical cracks in walls. The barn, its roof under repair, had very large cracks adjacent to the gable wall (Plate 2.31). Even one of the modern barns experienced some damage, its panel construction showing signs of severe relative displacement (about 3-4 cm) at the corner (Plate 2.33). An intensity level of EMS=7 is appropriate in this location.

The Nocera Umbra instrument was situated in a small brick building (Plate 2.34) located in a relatively recently developed residential area, with numerous buildings of various ages and forms of construction in the vicinity. A preliminary survey of those closest to the strong motion instrument (eleven buildings) indicated that forms of construction and damage levels were as shown on Table 2.3. The damage distribution has again been analysed using the vulnerability classes and damage levels of the EMS (Appendix 1). If these buildings were not designed for earthquake-resistance, the level of damage is consistent with intensity EMS=7, but if some design for earthquake resistance was incorporated, an intensity level of EMS=8 is more appropriate. Some examples of the damage at this location are shown in Plates 2.35 to 2.40.

Building no	Type	Damage description	Damage level (EMS)
1	Masonry B 3fl apt	X cracks on GF	D2
2	Masonry A 2fl res	Severe cracks at FF	D3
3	Masonry B 3 fl apt	Severe cracks at GF	D2/D3
4	Masonry B 2fl res	Severe cracks at GF	D2/D3
5	Masonry B 3 fl apt	X cracks on GF	D2
6	Masonry B 2 fl res	Severe cracks at GF	D2/D3
7	Masonry A 1 fl shed	Masonry cracks	D2
8	Masonry B 2 fl res	Eaves cracks	D3
9	Masonry B 1 fl res	Roof damage	D2
10	Masonry B 1 fl res	Roof damage	D2
11	Masonry B 2 fl res	Roof damage	D2

Table 2.3: Damage around Nocera Umbra strong motion instrument

The damage levels at each of the strong motion sites has also been assessed using the PSI scale of damage (Spence et al., 1992). These are plotted in Figure 2.2 alongside other datapoint derived from 14 earthquakes worldwide (Coburn and Spence, 1992). It will be seen that, as indicated also in Section 1.5, the reported accelerations are substantially higher than would be expected given the level of damage observed in their immediate vicinity. The reasons for this are discussed in Section 1.5, and deserve more detailed investigation once the full spectral response for this instrument becomes available.

2.7 References

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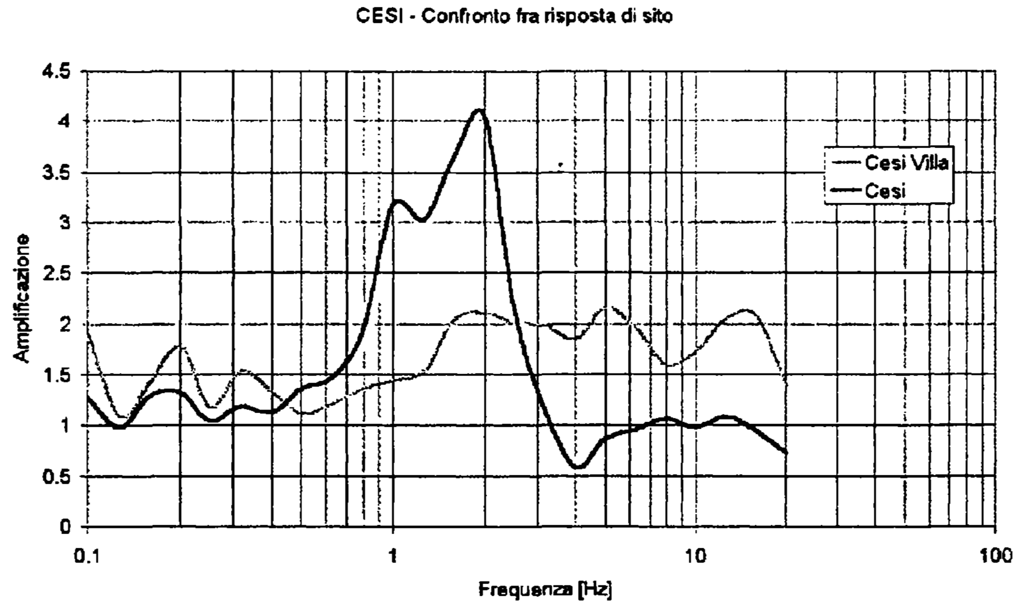

Figure 2.1: Site response spectra for Cesi Basso and Cesi Villa (after Capotorti et al., 1997)

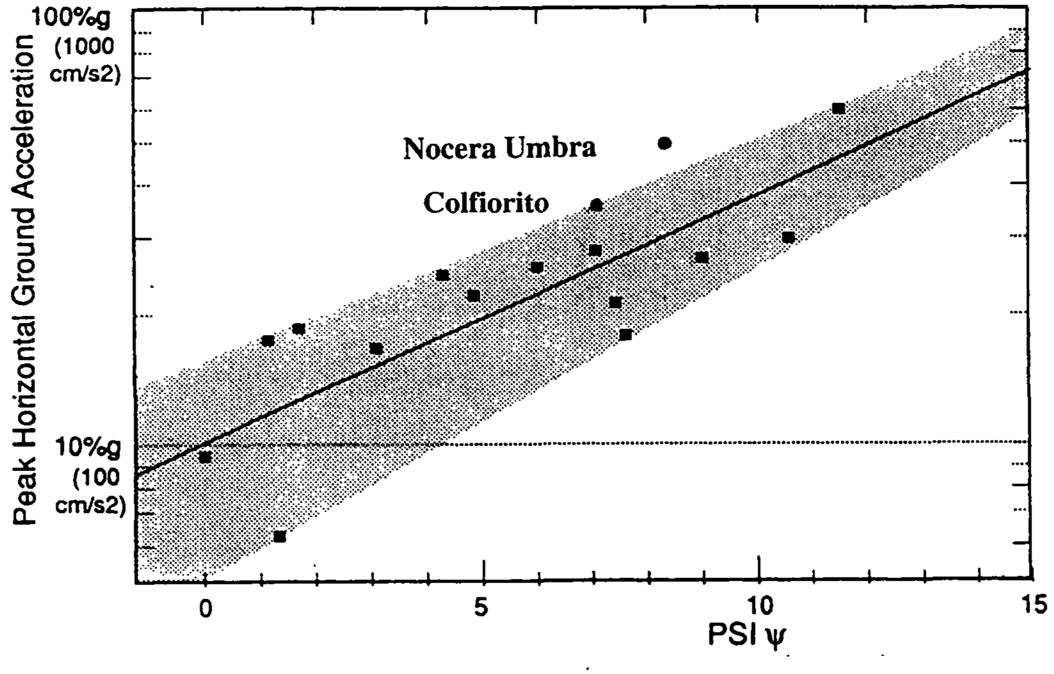

Figure 2.2: Damage assessed on the PSI scale compared with typical damage in relation to peak ground acceleration (after Coburn and Spence, 1992)

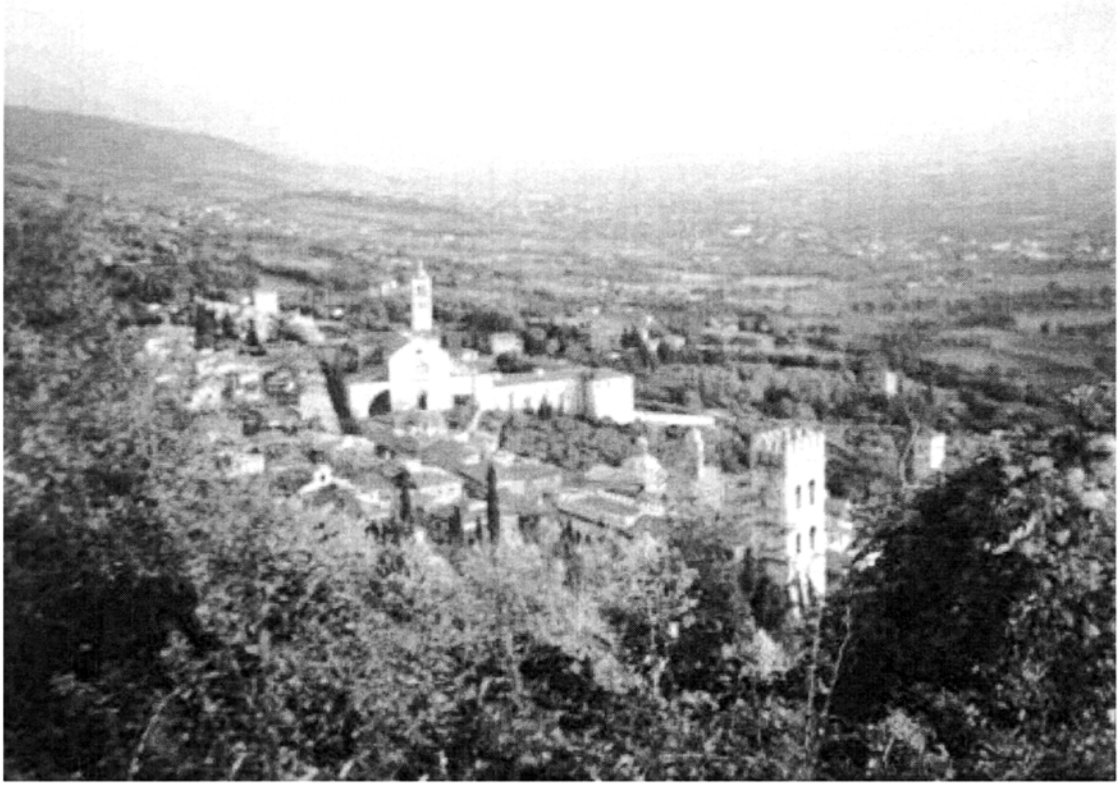

Plate 2.1: Assisi: a typical Umbrian hill town

Plate 2.2: Stone masonry wall construction: example from Annifo village

Plate 2.3: Stone masonry wall construction: example from Nocera Umbra

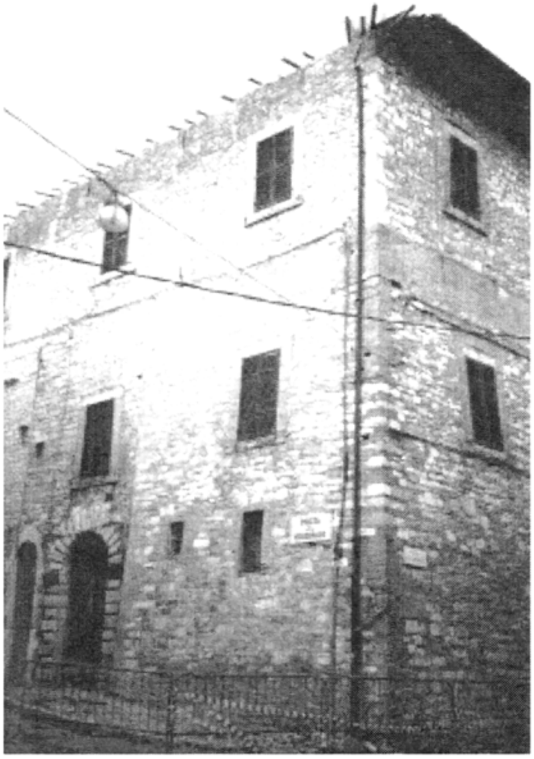

Plate 2.4: Stone masonry wall construction: example from Assisi

Plate 2.5: Traditional form of wall tie: Assisi

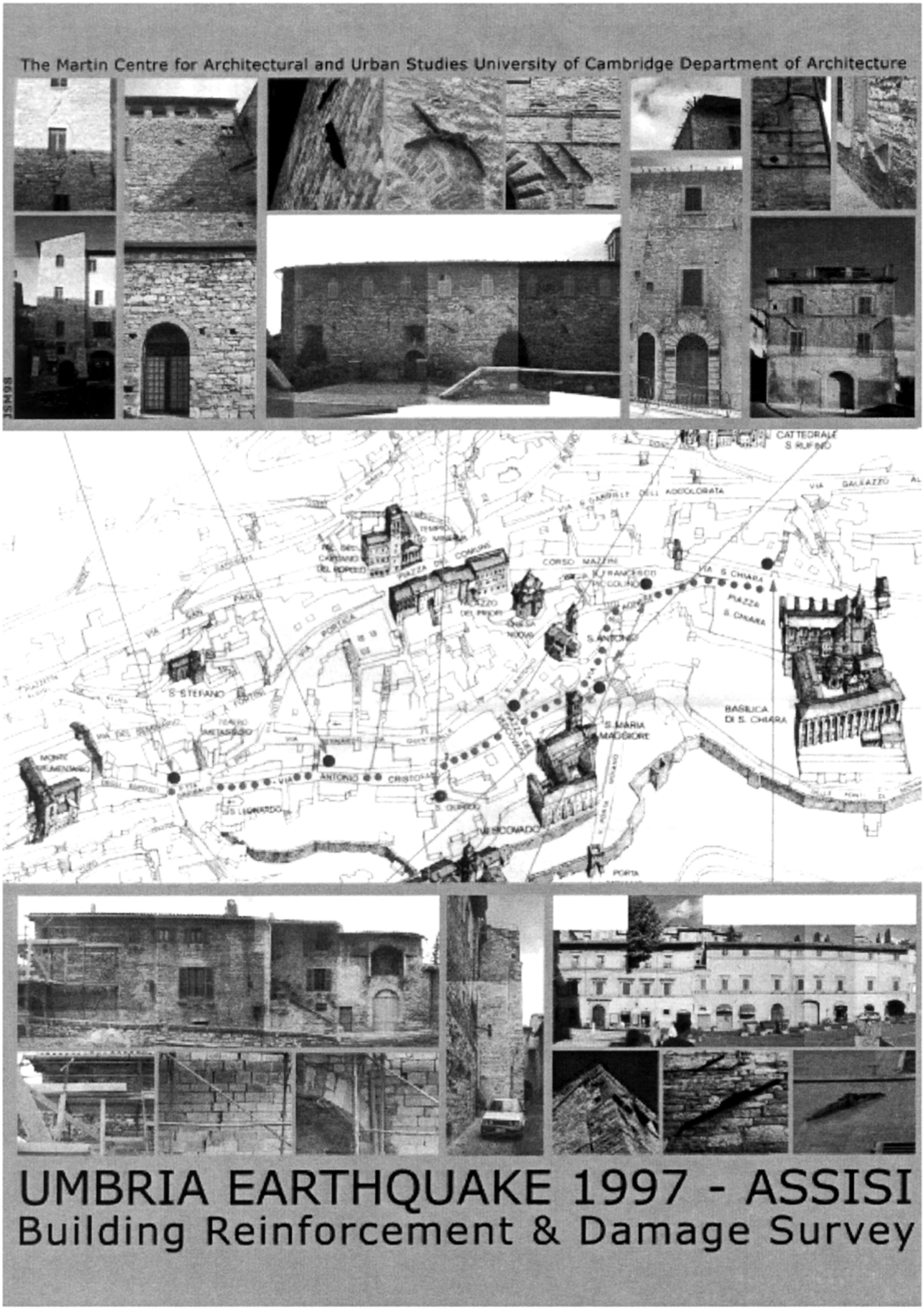

Plate 2.6: Analysis of building reinforcement and damage survey in Via Cristofani, Assisi

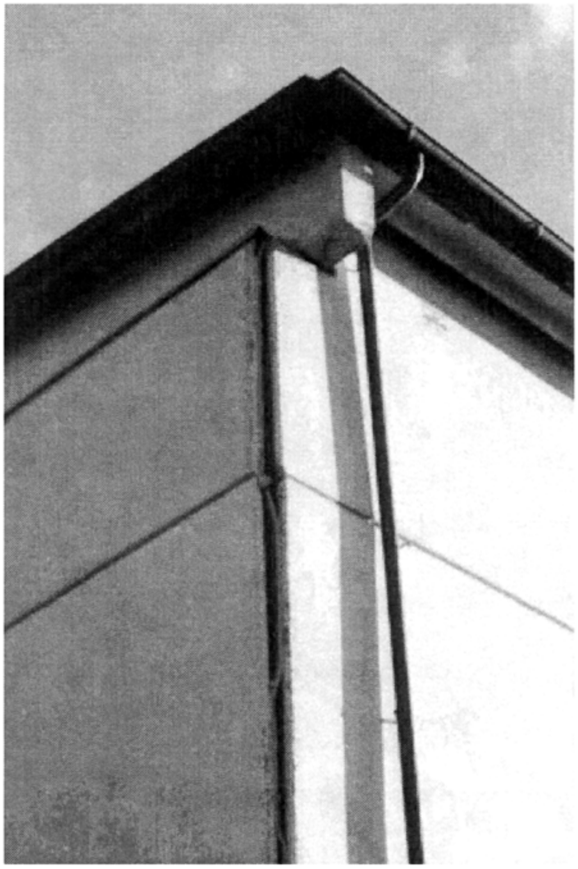

Plate 2.7: Farm building in precast concrete sections: Colfiorito

Plate 2.8: Extensions to traditional house using modern materials: Collecurti

Plate 2.9: Collapsed house with inserted reinforced concrete beam: Collecurti

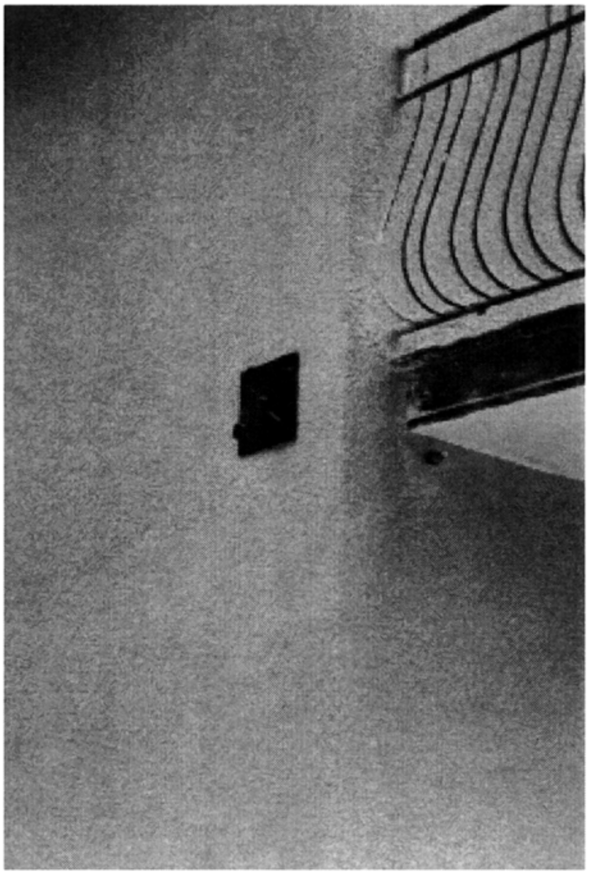

Plate 2.10: Wall tie in rural construction: Isola

Plate 2.11: Collapsed buildings with modifications in newer masonry

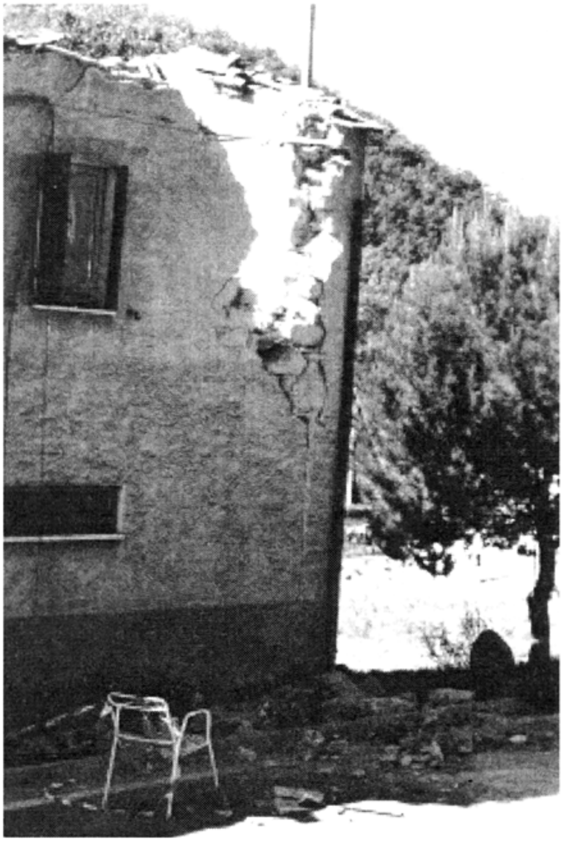

Plate 2.12: Out-of-plane wall failure: Casenove

Plate 2.13: Partly collapsed unreinforced masonry building: Casenove

Plate 2.14: Partly collapsed unreinforced masonry building: Annifo

Plate 2.15: Totally collapsed unreinforced masonry building: Annifo

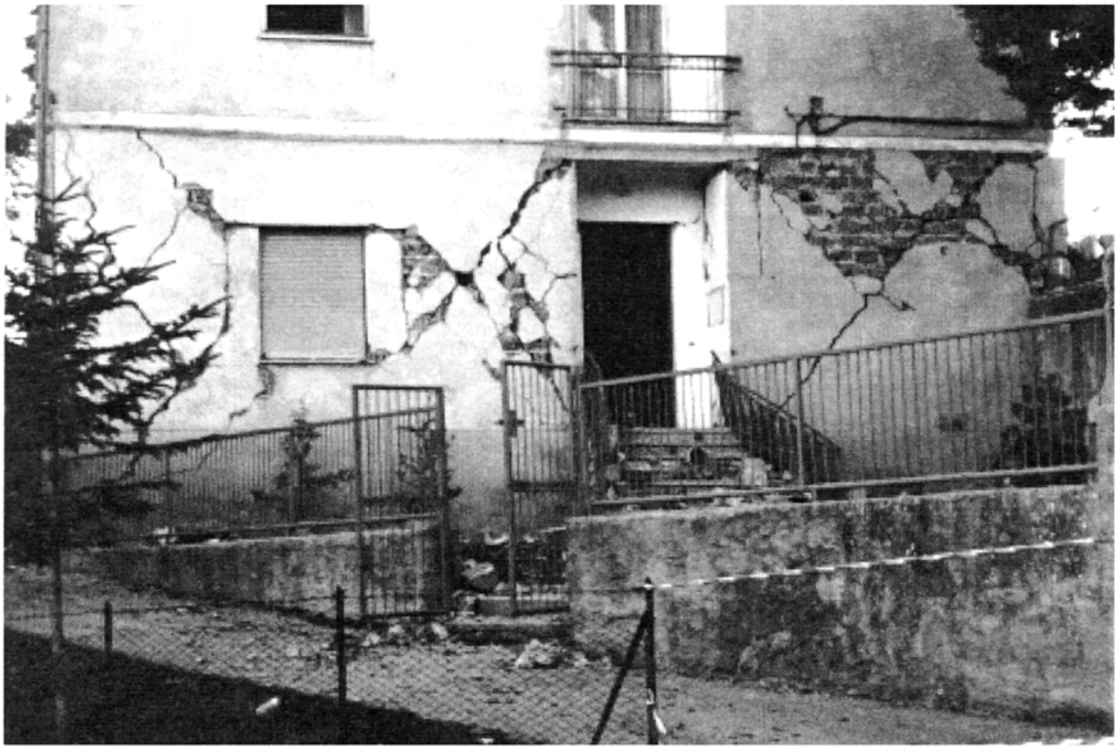

Plate 2.16: Masonry building with reinforced concrete first floor slab: Annifo

Plate 2.17: Clay block masonry with corner failure: Collecurti

Plate 2.18: Failure of lower storey walls: Collecurti

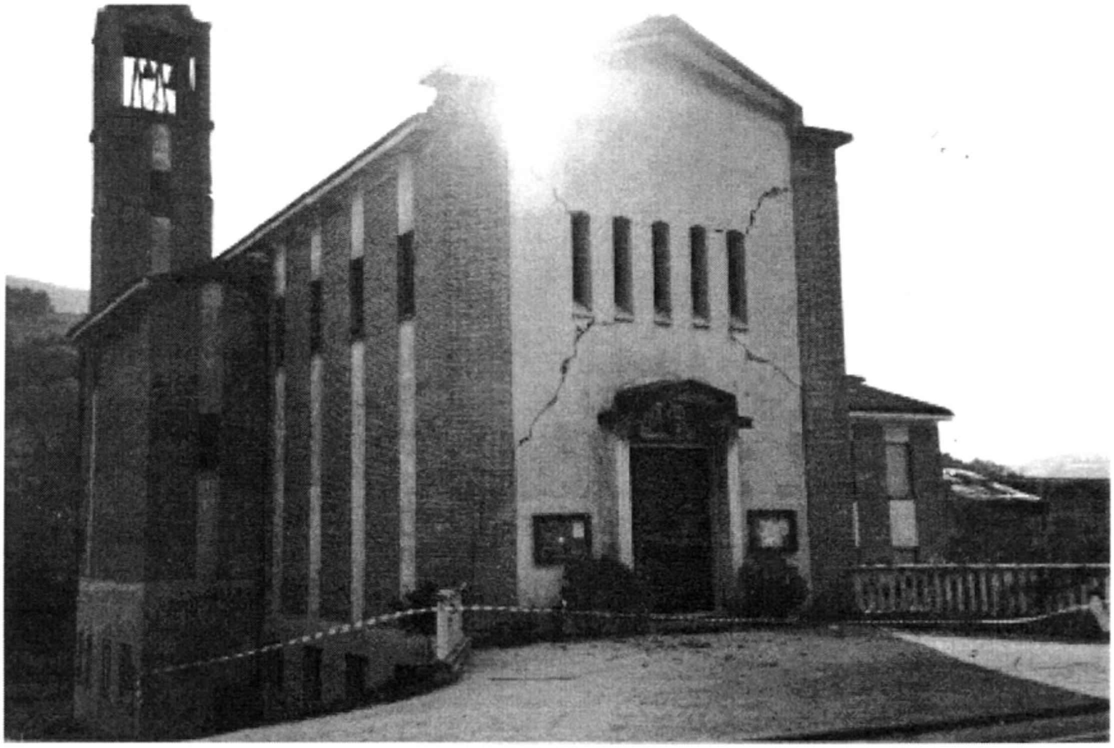

Plate 2.19: Church with masonry-infilled reinforced concrete frame: Nocera Scalo

Plate 2.20: Shear failure in lower and upper storey walls: Nocera Scalo

Plate 2.21: Failure of masonry infill in reinforced concrete frame building: Nocera Scalo

Plate 2.22: Undamaged masonry building undergoing strengthening: Nocera Scalo

Plate 2.23: Rubble masonry building with corner damage: Annifo

Plate 2.24: Masonry wall peeling: Cesi

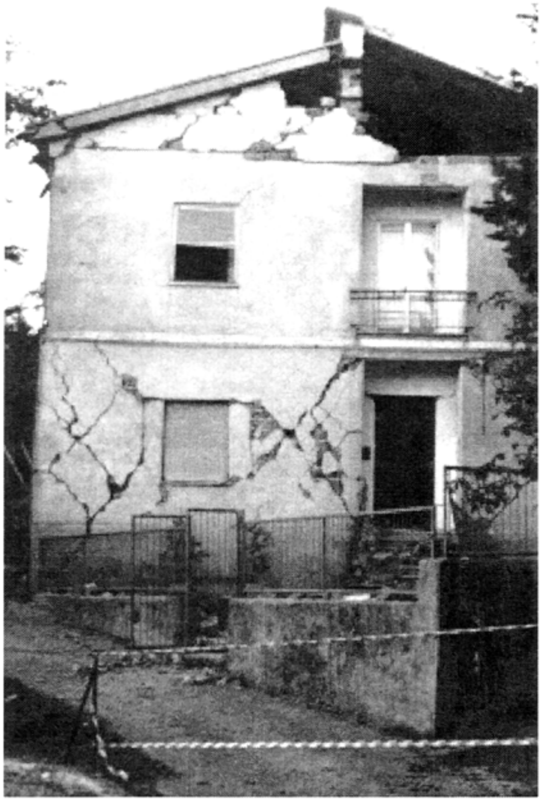

Plate 2.25: X-cracking in lower storey: Annifo

Plate 2.26: Shear cracking in buttress of church: Cesi

Plate 2.27: Column sidesway failure mechanism: Isola

Plate 2.28: Embankment displacement: Isola

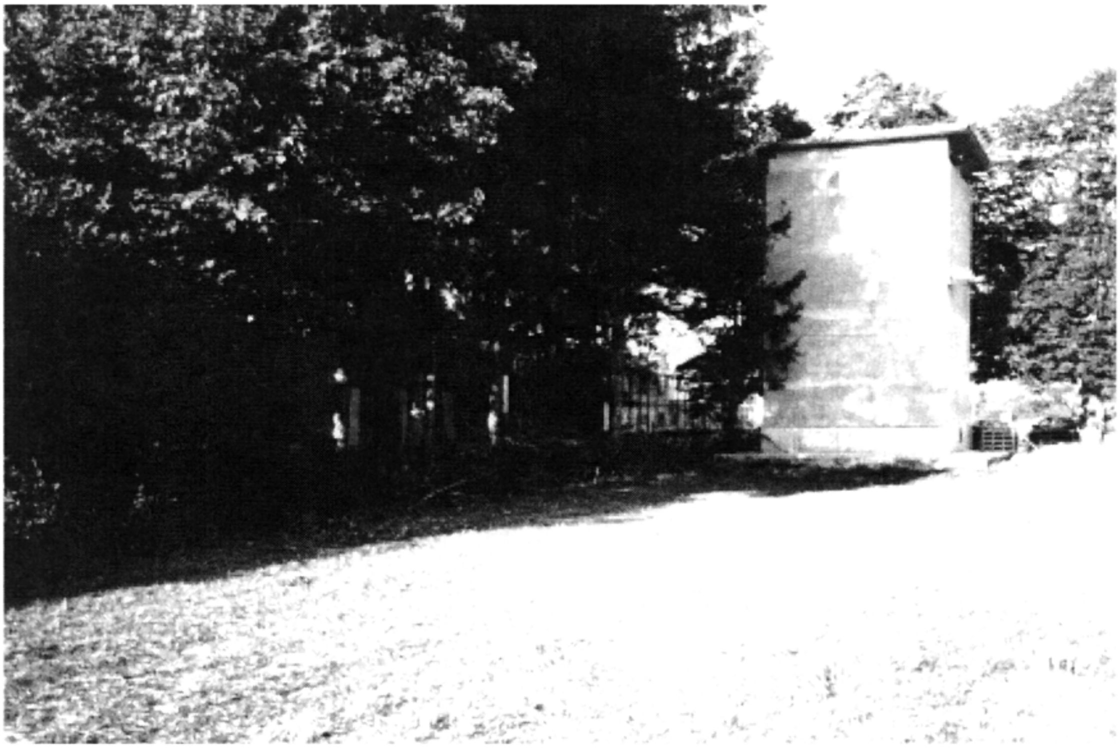

Plate 2.29: Colfiorito strong motion instrument location

Plate 2.30: Damage to masonry buildings: Colfiorito SMI site

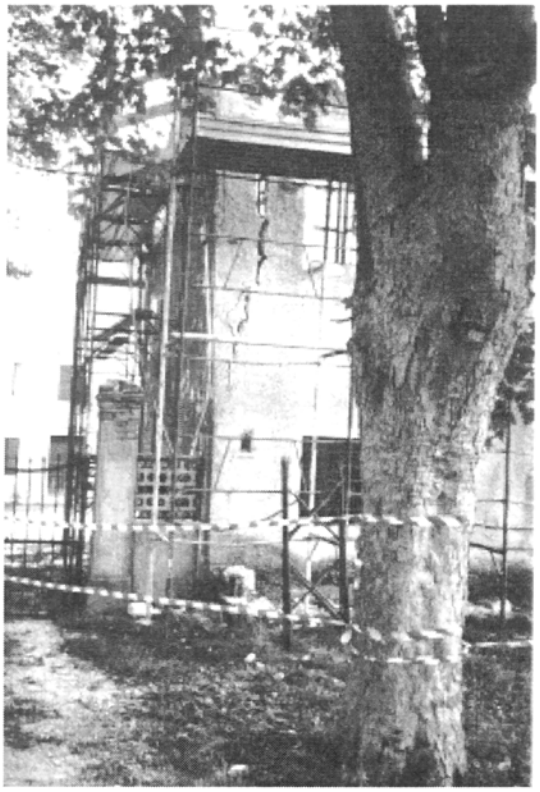

Plate 2.31: Damage to masonry buildings: Colfiorito SMI site

Plate 2.32: Damage to farmhouse: Colfiorito SMI site

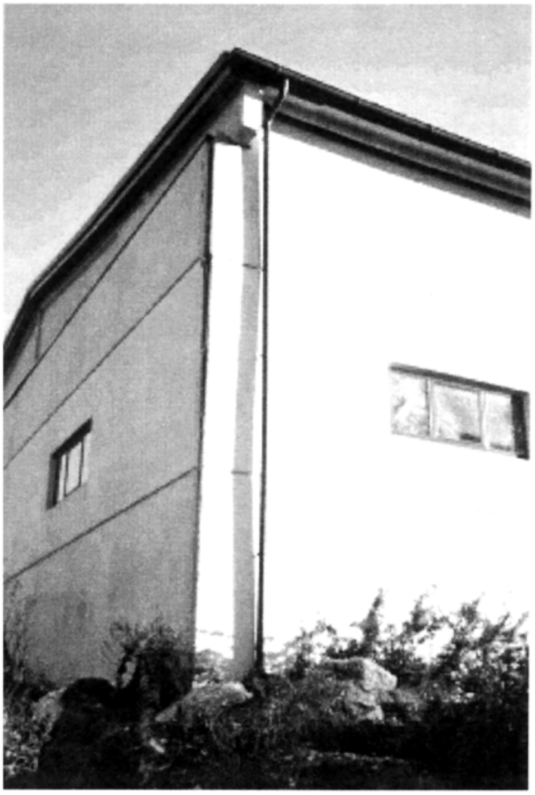

Plate 2.33: Damage to precast concrete barn structure: Colfiorito SMI site

Plate 2.34: Nocera Umbra strong motion instrument site

Plate 2.35: Building damage: Nocera SMI site

Plate 2.36: Building damage: Nocera SMI site

Plate 2.37: Building damage: Nocera SMI site

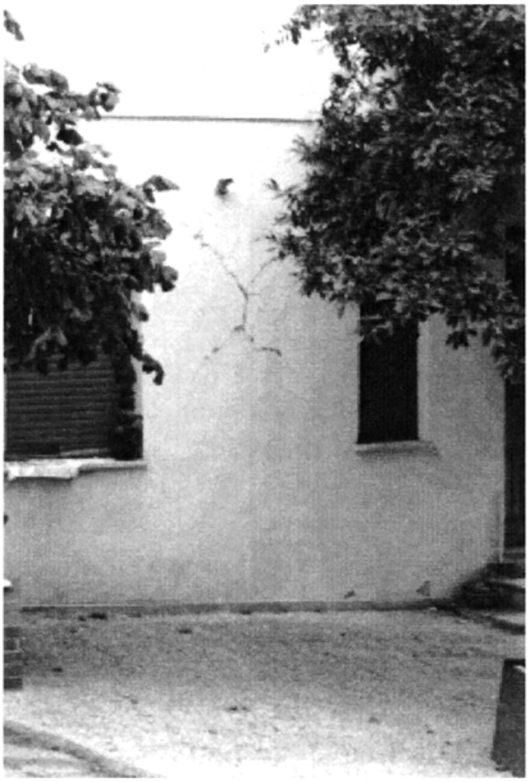

Plate 2.38: Building damage: Nocera SMI site

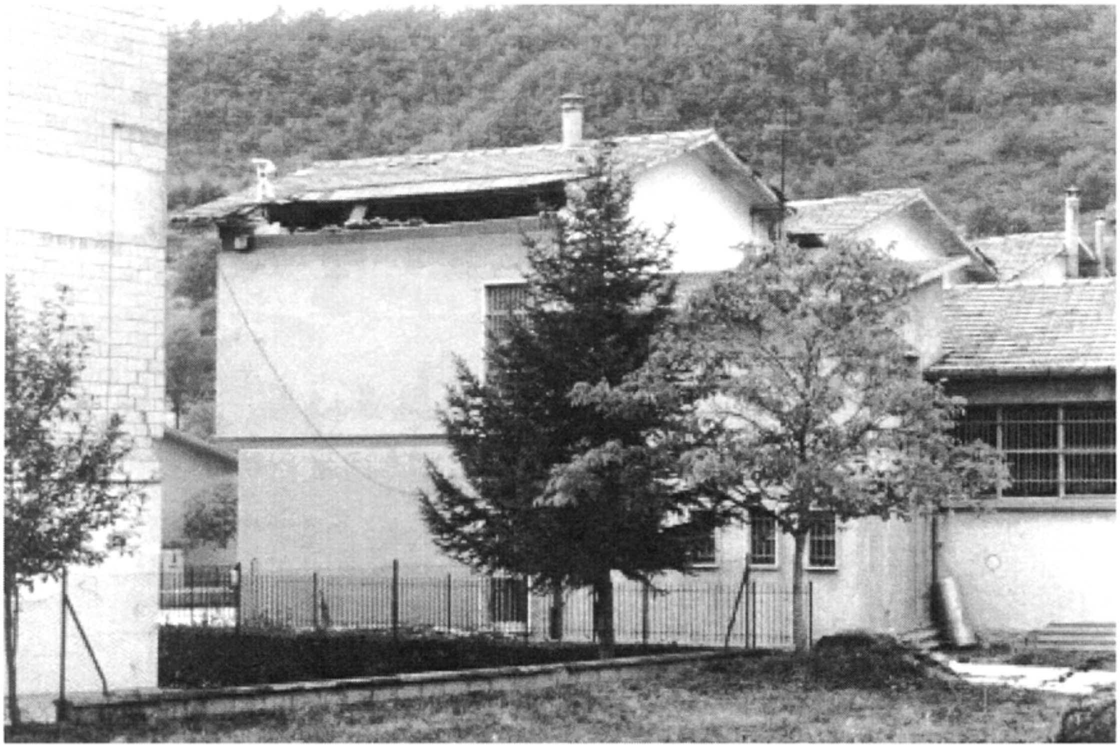

Plate 2.39: Building damage: Nocera SMI site

Plate 2.40: Building damage: Nocera SMI site

3.0 THE PERFORMANCE OF HISTORIC BUILDINGS AND MONUMENTS

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3.1 Specific seismic provision for historic buildings

In July 1981, following the November 1980 Irpinia earthquake, technical guidelines were issued defining the repair and strengthening techniques for masonry structures. These guidelines detailed the type of strengthening to be carried out on different structural elements and ways of implementing them, and also provided details of calculation methods to assess the building. The underlying philosophy was to produce greater stiffness and three-dimensional behaviour by the introduction of reinforced concrete slabs and connections between orthogonal walls. This was often achieved by grouted stitching. The shortcomings of this approach have been recognised and widely discussed elsewhere and the philosophy and technology of repair have since improved greatly.

However, at this time these measures were extensively applied to the strengthening of churches and monumental buildings. This led to the extensive connection of orthogonal walls by stitching with reinforcement bars in cement grouted diagonal drilled cores, and the introduction of massive concrete flooring structures either in replacement of timber or over vaulted masonry. After the immediate post-earthquake emergency, it was widely recognised that such techniques were not only obtrusive and damaging to existing artefacts and frescoes, but also were not necessarily effective from a structural point of view. Consequently, a more accurate analysis of this type of building and its specific vulnerability and a more sensitive strengthening policy developed.

A first improvement was the specific attention given to masonry buildings in a new seismic code issued in 1986 (Ministerio dei Lavori Pubblici, 1986). However the assumption that ultimate limit state should be considered for this class of building, and the safety factor associated with it, implied that masonry structures were penalised with respect to other structures, pending the lack of proper technical knowledge.

Parallel work carried out on the specific issue of repair of buildings of historic and monumental value resulted in a document approved in July 1989 by the National Committee for the Prevention of Architectural Heritage from Seismic Risk, and it subsequently became 'Guidelines' assumed by the Ministry of Environment and Cultural Heritage.

In subsequent years the strategy chosen was to obtain the inclusion of specific rules for monumental buildings in Eurocode 8. This was pursued by Gavarini and Giuffre and annexed to EC8 PT6 Part 1.4 'Repair and Strengthening', Annex D 'Vulnerability Methods' and Annex G 'Particular Consideration for Historical Buildings and Monuments'. These two annexes were approved as pre-standards in January 1996, and work to convert them into standards should commence in January 1999.

Further to this, at a national level, the release of the updated earthquake code on 16 January 1996 (Ministero dei Lavori Pubblici, 1996), included specific provisions for the improvement and upgrading of existing buildings. The concept of improvement is directly relevant to existing buildings of architectural and historic value. A seismic improvement is the execution of strengthening works to isolated elements of the structure with the aim of increasing the security level against earthquake without substantially altering the global structural behaviour. Furthermore, it is compulsory to carry out structural improvement in this way whenever a permit for structural alteration or renovation is requested. The important aspect of this clause is the fact that while limited strengthening is encouraged.

when directed at improving the behaviour of the single most vulnerable elements, the structural design does not need to comply with the requirements for new buildings, henceforth limiting the introduction of new structural elements or materials and extensive alteration of the original fabric.

This approach was implemented with a directive subscribed by the Ministries of Public Works and Cultural Heritage on 23/11/97, which provides guidelines for the preparation of restoration projects for buildings of historical architectural value in seismic areas.

3.2 The vulnerability of churches and a specific survey form

The problem of a suitable survey form for post-earthquake reconnaissance and damage assessment has been debated in Italy and at international level for a number of years (Gavarini, 1987; Bernardini et al. 1990; Coburn and Spence, 1992). The issues still open are:

- the correlation of a vulnerability measure with structural and non-structural damage, economic and heritage loss and safety, insofar as these matters can be assessed by quick surveys in the immediate aftermath of an earthquake
- a measure of the reliability and impartiality of information collected in this way
- a measure of the efficiency of strengthening devices and indications for further interventions (D'Ayala et al., 1997)

After this event, a GNDT group from the University of Genoa, led by Dr. Lagomarsino (1998), has surveyed about 600 churches in Umbria and Marche. The form, developed specifically for the purpose, evolves from work conducted by GNDT for the Friuli earthquake in 1974 and the more recent earthquake in 1987 in the western region of Emilia Romagna (Doglioni et al., 1994).

The form aims to enable a large numbers of buildings to be surveyed relatively quickly while being detailed enough to:

- provide location and measures of damage
- assess the intrinsic vulnerability of the fabric
- determine the increased vulnerability of the fabric associated with the seismic damage.

The methodology used is to identify a number of macro-elements that can be considered as independent structural elements. For each macro-element, in relation to the connections to the others, a number of possible collapse mechanisms are considered, which can be triggered by seismic action, and to each of them a vulnerability index and a damage index are associated, respectively.

The damage index is a global measure between 0 and 1 of the mean damage to the church, and the vulnerability index is a global measure between 0 and 1 of recognised weaknesses in the church fabric which make it prone to seismic damage. Finally, a combination of these two indices is computed to provide a measure of the increased vulnerability of the church due to the surveyed damage. This number is in the range 0 to 2.5 and gives a measure of the tendency of the church to be further damaged by subsequent shocks and the necessity of providing emergency repair.

This form (see Appendix 3) was used by the EEFIT team during the visits to the churches of Assisi, and the outcome is discussed in Section 3.3.

In Table 3.1 the assessment results for the churches surveyed in Umbria by the GNDT group are presented by comune and the mean damage index is compared with the macroseismic intensity associated with the site, after the first two shocks. The mean damage to houses is included for comparison; this has been obtained from the Servizio Sismico Nazionale damage model forecast based on the latest Census data on distribution of building types.

It is worth noting that the damage index does not necessarily correlate to the macroseismic intensity. This is due to the specific vulnerability of some churches and to the attenuation model used. Comparing the data on churches with the mean damage value expected for housing, a difference can also be noted. Apart from a few cases the damage to churches is usually higher than the corresponding damage to houses, notwithstanding the usually better fabric and maintenance of churches. This demonstrates the greater vulnerability of churches to medium intensity earthquakes.

Two principal causes of this can be identified:

- intrinsic greater structural vulnerability due to open plan, greater height to width ratio and thrusting horizontal structures;
- less tolerance to cracking of the surface decorative features and presence of false ceilings and other non-structural elements less ductile than the structure itself.

One specific objective of the EEFIT mission was to study the correlation between damage to houses and churches by field observation. For this reason a number of houses in the vicinity of the churches considered have also been surveyed by using a Level 1 form designed by SSN and GNDT. This form is used by fire brigades to assess the usability of ordinary buildings in the immediate aftermath of an earthquake. Results of this survey are discussed in Section 3.3.

Below, after a brief introduction of the historic seismicity of Assisi and Nocera Umbra, a detailed account is presented of the damage to churches and convents visited in the two towns.

Comune	No. of churches	Usability	Damage index	Mean damage to houses (SSN forecast)	Macroseismic intensity MCS
PRECI	12	8%	0.45	0.37	7.4
VALTOPINA	20	20%	0.39	0.325	7.7
CANNARA	2	0%	0.38	0.228	6.8
FOLIGNO	38	16%	0.38	0.25	7.4
NOCERA	5	20%	0.33	0.32	7.5
BEVAGNA	19	37%	0.31	0.27	6.9
SPOLETO	31	39%	0.30	0.19	6.5
ASSISI	27	56%	0.28	0.22	6.9
CERRETO DI SPOLETO	15	47%	0.28	0.33	7.2
PERUGIA	40	30%	0.24	0.11	6
GUBBIO	42	71%	0.23	0.16	5.9
NORCIA	18	50%	0.23	0.24	6.7
GIANO DELL' UMBRIA	7	86%	0.22	0.20	6.5
CAMPELLO SUL CLITUN.	8	75%	0.21	0.28	7.0
GUALDO TADINO	37	54%	0.21	0.19	6.8
DERUTA	2	50%	0.19	0.17	6.2
POGGIODOMO	4	75%	0.18	0.29	6.5
SELLANO	8	62%	0.16	0.385	7.8
SPELLO	29	50%	0.16	0.27	7.3
SCHEGGINO	14	79%	0.15	0.28	6.5
Total surveyed churches	378				

Table 3.1: Comparison between damage index of churches surveyed in Umbria and mean damage to houses. (Note: a *comune* is the lowest tier of local administration in Italy; all *comuni* listed here are part of the province of Perugia, which is also the capital of the Umbria region.)

3.3 Damage to churches in Assisi

Assisi is a small medieval hill town (500 m. altitude) built on an earlier Roman settlement in which the south-east north-west alignment of the original castrum has been maintained. This alignment coincides with the spine of the hill. Because of this, the urban fabric is made of long terraces of houses with façade walls founded at different levels. It is worth noting that the alignment of the hill is northwest-southeast, parallel to the main Apennines mountain range and to the fault system from which the earthquake originated. Assisi has a population of about 6000 living within the ancient city walls whose perimetral length is approximately 5 km. Of the eight wall gates, five had been closed down after the earthquake. The only casualties in the town were the four deaths caused by the collapse of the San Francesco Basilica.

Although Assisi has never been the site of a seismic epicentre, and its territory has only since 1981 been classified as prone to medium seismicity (Coefficient s=9), the seismic history of Assisi as reported in Figure 3.1 and Table.3.2 (Monachesi and Stucchi, 1998) shows at least four occurrences in which intensity MCS=7 has been exceeded.

The best documented of these occurrences is the earthquake of 1832, which caused the collapse of the main nave barrel vault of Santa Maria degli Angeli, and the loss of most of the frescoes in Santa Chiara and in Santa Maria Maggiore. On that occasion the Basilica of San Francesco was not significantly damaged.

Date	Macroseismic intensity	For the earthquake of			
Year Mo Day	Is (MCS)	Epicentral area	Ref.	Ix	Ms
1349 09	7.5	Venafro	ENL85	10.5	6.7
1747 04 17	7	Fiuminata	MON87	9	6.2
1751 07 27	7	Gualdo Tadino	MON87	10	6.7
1832 01 13	7.5	Foligno	MON87	8.5	5.9
1854 02 12	6.5	Bastia	GDTMC	7.5	5.2
1878 09 15	4.5	Montefalco	MON87	8	5.5
1881 03 11	4	Spoleto	GDTSP	5.5	4.2
1898 06 27	4	Rieti	SPA85	8	5.2
1903 11 02	4	Valnerina	GDTSP	6.5	4.7
1915 01 13	5.5	Avezzano	MOA96	11	7.0
1915 03 26	7	Assisi	MON87	7	4.7
1917 04 26	3.5	Monterchi-Citerna	CAA96	9.5	5.6
1918 04 14	4	Giano Dell`Umbria	GDTSP	6.5	4.7
1920 09 07	3.5	Garfagnana	FEA85	10	6.5
1936 04 05	5	Foligno	GDTSP	6	3.7
1936 12 09	5	Caldarola	MON87	7.5	4.2
1950 09 05	4	Gran Sasso	MOC92	8	5.6
1951 09 01	5	Sarnano	GDTSP	7	5.0
1979 09 19	55	Norcia	SPA81	8.5	5.9

Table 3. 2: Seismic observations for Assisi

The churches to which reference is made in this report are the Upper Basilica of San Francesco, Santa Chiara, San Rufino, Santa Maria Maggiore and the Chiesa Nuova. With exception of the Chiesa Nuova, they were all considered at risk and had been closed down. Emergency works included:

- scaffolding around the tympanum of the southern transept of San Francesco
- scaffolding extending the entire height of the façade and a walkway in the space between the fallen vault and the roof of the main nave in San Francesco
- shoring of the Santa Chiara façade, the Palazzo dei Priori, and the Civic Tower.

Also closed down were the Church of San Damiano, and the Basilica of Santa Maria degli Angeli, in the lower valley, outside the city walls.

San Francesco

The most damaged building in Assisi was certainly the Upper Basilica of San Francesco, both in terms of value of loss and extent of damage. During the period of the EEFIT visit it was not possible to enter the basilica; a second visit, sponsored by ICOMOS, took place at the end of February 1998, and we had the opportunity to walk in the roofspace, just above the collapsed vaults, and to discuss the emergency measures with the designers and a panel of international experts.

The images of the collapse and the distribution of the damage have been widely published and it is perhaps one of the few occasions on which the development of a collapse mechanism in a church caused by an earthquake has been caught on camera and recorded. The most important damage in the upper basilica comprises:

- the first bay cross vault from the façade (Plate 3.1))
- the cross vault at the crossing between main nave and transept (Plate 3.2)
- the tympanum of the transept facing south (Plate 3.3)

Further damage is reported within the convent, which could not be surveyed by our team. The external dimensions of the upper basilica are 73x22.8 m with a total height of 38.50 m (Argan, 1975).

An idea of the seismic action which caused such damage can be obtained from the recording of the two main shocks produced by accelerometers installed by the Servizio Sismico Nazionale (SSN) at the south-west base of the buttress wall which encloses the convent (Plate 3.4). The data have not been filtered, but the comparison of the two records is most interesting, especially as it occurred at such short distance from the observed damage. From the recordings it would appear that the maximum acceleration for both shocks is rather similar (around 0.16 g) for the E-W component, while clearly greater in the second case for the N-S component (almost 0.2g for the second shock against 0.12 g for the first) (Figure 3.2). It is worth noting that these values are all greater than the lateral force coefficient associated with the seismic second category classification (a/g= 0.07) of the Italian code.

More importantly to the understanding of the damage, the second shock had a much greater number of oscillations close to peak acceleration and for a longer interval, corresponding to a greater quantity of energy input in the structural system as can be seen by comparing the areas under the pseudo-acceleration spectrum curves (Figure 3.3). From these last curves it is also possible to notice that the value of natural period corresponding to the greater value of pseudo-acceleration shifted from around 0.20 sec for the first shock to 0.35-0.40 sec for the second shock, in direction N-S. The higher periods corresponded to a structure already weakened by light damage, due to the first shock, and therefore the shock would be more damaging.

The upper basilica is oriented roughly with the main nave on the E-W direction and the transept N-S. Therefore, the transept façade received the N-S component as out of plane action, triggering the weakest collapse mechanism. Closer inspection of the transept revealed that the damage caused in the part of the façade above the roof ridge was mainly due to the poor compaction of the rubble constituting the fill of the wall masonry. What actually collapsed was the external leaf which had little connection with the internal one. During the second visit the team was also able to inspect the internal side of this wall at the level between the extrados of the vaults and the roof, and there was no sign of major damage. A number of sub-vertical cracks were visible running from the ground to the level of the windows, some of which appeared as re-opening older failures. The width of these cracks was in the range of a few centimetres, with some loss of material.

The façade of the main nave took the seismic action mainly in its own plane, and its greater stiffness compared to the rest of the structure in that direction would have caused a high transfer of shear on the vault system, especially on the first bay. A mechanism developed in the bay arch with an hinge forming roughly half way between the apex and the springing, as can clearly be seen in the second photogramme of the filmed collapse. This could have been triggered by horizontal in plane action (Plate 3.5). The collapse of the vaults occurred at the two ends of the nave where the connection with the rest of the structure is stiffer. On our second visit we were able to inspect the extrados of what was left of the vaults. The web of the vault made of bricks seems to be simply supported over the ribs also made of bricks. There was a diffuse crack pattern to the whole extrados of the vaults which had been sealed temporarily using epoxy resin and kevlar strips. The vaults had also lost shape and much of their curvature. The other urgent repair measure set in place was to suspend the vaults with carbon fibre cables to the brick-arch structure above, which is an addition of the fifteenth century. The cables were attached to the vaults with kevlar anchorage devices and coupled with a system of springs to maintain constant tension in the occurrence of further shocks or temperature variation (Croci. 1998).

The vertical component of the seismic acceleration was also non negligible (peak value of about 0.06g) and probably sufficient to reduce the thrust in the transversal arch associated with the gravity loads. After the earthquake, a large quantity of fill above the haunches of the vaults was discovered. This fill. in part waste material left there after the works, which in the 1960s set in place a concrete ring beam and roof, and partly of older origin, has since been removed. But its presence could have significantly contributed to the collapse.

It is difficult to provide a single combined measure of the damage level since it is very uneven. The medieval vault system experienced damage level D4 and greater while the rest of the structure was damaged to level D2.

Santa Chiara Basilica

Santa Chiara is built on partially filled land in an area which at the time of St. Francis was still outside the city walls and where the small church of St. George had previously stood (Plate 3.6). After the death and canonisation of St. Clare, the nuns in 1257 obtained ownership and started building the basilica that was completed in 1265. The main nave is divided into four bays covered with a high cross vault, a protruding transept and a polygonal apse. The shape is the same as that of the Upper Basilica of San Francesco, with slender proportions and greater simplicity. The overall external dimensions are 56.30 x 17m for the main nave (Plate 3.7) with a height of approximately 30 m (Bigaroni et al.. 1994). The façade, of the barn type, extending considerably above the ridge of the roof, is articulated by two horizontal cornices and a tympanum and presents two large central openings. the main door and the rose window. The columns defining the length of the bays and flanking the nave walls have polygonal shapes.

In 1351 three large flying buttresses were introduced on each side of the nave to contain the thrust of the cross vaults. Those on the southern end were later walled in forming a lateral nave. Other repair and restoration work took place in later years, the better documented of which was concluded in 1741. probably following the damage of the 1703 earthquake. The church also suffered extensive damage during the earthquake of 1832.

The fabric of the masonry is made of square blocks of pietra serena. the local limestone which was the main building material for ecclesiastic and monumental architecture during Medieval and Renaissance periods in central Italy. The fabric appears to be rather loose on the north wall. with gaping cracks running through the entire height. Two main cracks are visible on the longitudinal walls adjacent to the façade (Plates 3.8 and 3.9). While they both seem old cracks related probably to the event of 1832, two corresponding cracks have opened inside the main nave and this is quite alarming. At the time of the visit, there was fear of aftershocks and the electric lighting had been disconnected. Consequently the EEFIT survey was conducted in a hurry and with little daylight filtering through the small windows. Therefore the team did not have enough time to study the exact location of these cracks and whether they extended through the thickness of the wall.

More cracks were present in the vaults, in the first bay from the façade. and in the bay adjacent to the decagonal apse. The extent of this damage was difficult to quantify given the lack of light and the distance, but it can be attributed to the hammering of the façade against the vaulting structure in a manner similar to the Basilica of San Francesco. Numerous cracks of different depth were also present in the vaults and at the junction of transversal walls in the lateral chapels. Shortly after our visit the façade was shored. Later images of other teams' surveys show loss of material in the tympanum of the façade on the inner leaf above the level of the roof. The original roof has been replaced with a concrete structure in the 1960's. The level of damage to the Santa Chiara Basilica was assessed as D2/D3.

The convent is built on a relatively steep slope to the south of the church. The most ancient wing is the one facing west. The rest of the complex. partially built on the city walls. was extended several times between the 14th and the 16th century (Plate 3.10).

A walk around the external perimeter of the convent, while revealing numerous pre-existing disconnections and alterations of fabric, with opening and closing of windows at different locations. together with a rather consistent system of iron ties, failed to disclose any major damage. The exception was part of the roof at the southeastern corner. where some collapse had occurred, and it was covered in plastic sheeting at the time of the visit (Plate 3.11).

The inspection of the interior was very different. In the eastern wing, which had undergone a series of strengthening works, some as recently as 1992, most cross walls and non-load-bearing walls presented double diagonal shear cracks. One particularly worrying one was a wall supporting a staircase which presented diagonal shear cracks and had also buckled laterally (Plate 3.12). In many parts the long extruded clay tiles spanning over steel joists to form the false ceiling had fallen down, revealing a 1960's reinforced concrete floor above. (Plate 3.13). While this is not to be considered as serious structural damage, it represents a major hazard for the safety of people.

The southern wing contains the kitchen and the refectory, two relatively wide rooms, and other smaller service rooms. Witnesses claimed to have seen the external wall waving outwards during the second shock. One of the arches bearing this part of the structure in the inner side of the cloister had collapsed and had been propped (Plate 3.14). While there was no apparent damage on the external side of the southern wall, many of the rooms facing south had severe damage with detachment of lateral walls and partial collapse of ceilings (not always structural) and wide cracks stemming from lintels over windows (Plate 3.15). While the false ceiling had consistently failed in most parts of the building, the traditional brick jack-arches on I-beams (probably dating from the beginning of this century) seemed to have performed rather well (Plate 3.16). The EEFIT team was not able to visit the western wing of the convent but we were told that damage was present there as well. The whole complex had been evacuated at the time of the survey, and the nuns were awaiting 'partial usability' permission. The damage was assessed as level D3.

San Rufino Cathedral

San Rufino Cathedral is one of the masterpieces of Umbrian Romanesque architecture, built between 1140 and 1253 when the façade was finally completed. In plan the cathedral measures externally 80.60 x 35.20 m, the height to the apex of the original vaults is 26.30 m, while the total height of the façade is 36.80 m (Argan, 1975) (Plate 3.17). The bell tower appears in an awkward position near the front of the church because it was built prior to it and was related to an older cathedral occupying the area of the present square in front. Like San Francesco and Santa Chiara, it is also built with the local limestone and covered with pointed arches of brick masonry, which today support a concrete roof. The interior of the church was radically changed by Galeazzo Alessi, also the architect of Santa Maria degli Angeli, between 1571 and 1586, due to instability of the original fabric. The centre nave was covered by a barrel vault, the crossing topped by a dome, while the size of the pillars separating the main nave from the aisles was considerably reduced (Plate 3.18). The lateral aisles are covered with cross vaults. All vaults in the main nave and over the aisles have transversal iron ties.

The main damage observed during the survey was:

- a longitudinal crack at the apex of the barrel vault at the intrados running the entire length of it, accompanied by the detachment of plaster from the vault arch ribs, springing from the internal pillars (Plate 3.19)
- vertical cracks on the perimetral wall of the two first bays of the aisles indicating the development of the mechanism associated with the detachment of the façade from the rest of the structure

All damage seemed rather light (Level D2) and a visit to the space above the barrel vault failed to disclose the presence of cracks in its extrados or failure in the Romanesque arches. Ten days after the main shocks the church was still closed to the public.

Santa Maria Maggiore

This is the original cathedral of Assisi (Plate 3.20). While legend dates it back to the 4th century, archaeological excavation conducted in 1954 established that the church was built over a Roman dwelling, next to the city walls and to the site of a Janus temple. An 8th century sarcophagus was also discovered and it is likely that the original building was extended in the 9th century. In 1035 the title of cathedral was transferred to San Rufino, while the bishop kept his seat here. In 1162 the façade was rebuilt and in 1216 the apse area was reconstructed. The structure consists of a tall and narrow main nave with roof trusses separated by arched walls from two much shorter aisles. The church is built in dressed blocks of pietra serena, with thin mortar joints, for the external leaf of the walls, while the internal leaf, as visible from the unplastered apse, is of the same masonry made with more irregular blocks. The roof is supported by king-post trusses and there is no vault on the main nave. The decorations were destroyed by the earthquake of 1832. Plan dimensions are approximately 24x12 m and the façade height is estimated at 14 m.

Of all churches visited this is probably the one which sustained the greatest damage:

- The façade was severely affected, with vertical cracks running through the centre of the upper portion and loss of material along the perimeter of a walled-in opening (Plate 3.21).
- Vertical cracks, running at the connection of the façade wall with the aisle walls, show the development of the overturning mechanism of the façade.
- All the longitudinal beams resting on the façade had slid out of their support for at least 150 mm, confirming the deduction associated with the previous observation (Plate 3.21).
- There was no sign of thrust of the trusses being transmitted to the longitudinal walls (Plate 3.22) which appeared intact with the exception of vertical cracks developing above the crown of the archway connecting the first bay of the northern aisle with the main nave (Plate 3.23).
- Cracks of lesser width were also visible in the area of connection of the apse with the longitudinal walls (Plate 3.24).

Damage was assessed at level D2/D3. No damage was observed to the bell tower which has been strengthened with iron ties. The adjacent Palazzo del Vescovado suffered extensive damage with partial collapse of the roof and was estimated to have suffered damage level D3.

Chiesa Nuova and Convent of Frati Minori

The Chiesa Nuova was built from 1615 above the house of Giovan Battista Bini, supposedly where St. Francis was born, based on the model of Sant' Eligio degli Orefici in Rome. This is the only example of a Renaissance central plan church in Assisi, with a central octagon and four equal length arms, the centre topped by an hemispheric eight-ribbed dome and lantern. The building, in use by 1621, is made of brickwork, probably using cavity walls with rubble infill of up to 900 mm thickness (Plate 3.25). The damage suffered by the church was minimal with some loss of plaster from the vaults above the naves, but no damage was visible to the dome or to the lantern.

The condition of the adjacent Convent of the Frati Minori was very different. This develops eastwards longitudinally from the church over two main levels (Plate 3.26). At the upper level (the same as the church) the damage observed was:

- in the refectory the main timber beams, spanning transversally the width of the building, had lost about 50 mm of the support and contact to the longitudinal bearing walls (Plate 3.27),

- extensive diagonal cracks, some with major relative movement of up to 30 mm, intersected many of the cross walls of the monks' rooms, especially those farther away from the church where the height of the building is greater as the road runs downhill. The cracks and loss of plaster revealed a rubble masonry structure, in some places integrated with brickwork (Plate 3.28).

At the lower level is found the ancient library, specialising in Franciscan studies, which contains a rich collection of illuminated manuscripts and the correspondence between St. Francis and the Pope at the time of the institution of the Franciscan order. In this part of the building, originally part of a small church:

- The cross vault presented a relatively small crack running at the apex in the intrados and had detached from the supporting perimetral wall (Plate 3.29).
- There was no sign of other cracks at the intrados which would denote the development of a mechanism, and hence a dangerous situation. However the vault had been shored and this area evacuated.
- The adjacent new library, a floating double height steel structure, defining a spacious conference room, inserted within the original masonry fabric, was undamaged as were the containing perimetral masonry walls, showing recent repointing and probably grouting.

The damage to the convent was of level D2 to D3.

Evaluation of vulnerability and damage with the GNDT form for churches

For each of the churches described, a GNDT form was compiled, identifying the intrinsic vulnerability of the church, the damage level and its present vulnerability following damage. The relevant data are presented in Table 3.3. Besides the surveyed types of mechanisms, the parameters are:

- **Dix**, the level of damage associated with a specific collapse mechanism; there are three levels of damage: low-1, medium-2, high-3.
- **Vix,** the vulnerability index, identified by constructive deficiencies or faults; there are two levels: medium-1, high-2.
- **Number of mechanisms** activated by the seismic event and recognisable by presence of damage
- **D**, total damage index obtained as sum of **Dix** divided by three times the number of mechanisms
- **Vi**, intrinsic vulnerability index obtained as sum of **Vix** divided by twice the number of mechanisms
- **Va,** present vulnerability index, obtained as sum of **Dix** and **Vix** divided by twice the number of mechanisms

Church	Mechanism	Dix	Vix	Number of mechanisms	D	Vi	Va
San Francesco	Hammering of façade (transept)	3	1				
	Main arch	3	2				
	Main nave vaults	3	2				
	Shear cracks in walls	1	1				
	Disconnection of walls	1	1	5	.73	.7	1.8
Santa Chiara	Overturning of façade	1	2				
	Hammering of façade	0	1				
	Transversal behaviour	2	2				
	Main arch	1	1	4	.33	.75	1.25
San Rufino	Overturning of façade	1	2				
	Transversal behaviour	1	1				
	Main nave vaults	1	1				
	Overturning of apse	1	2				
	Apse vaults	1	1	5	.33	.7	1.2
S. Maria Magg.	Overturning of façade	2	2				
	Hammering of façade	2	2				
	Cracks in façade	1	1				
	Hammering of roof beams	2	1				
	Overturning of apse	1	2				
	Shear cracks in walls	2	2				
	Disconnection arch- vault groin	1	1	7	.52	.78	1.57

Table 3.3: Evaluation of damage and vulnerability indices of churches in Assisi

The global measures of damage and the relative measures for the four churches reflect well the field observations. It should be noted that the most common mechanism is the overturning of the façade, characteristic of this type of church, irrespective of the connection between façade and horizontal structure. The very similar typology also implies similar values of intrinsic vulnerability as can be noted in Table 3.3. Finally the value of present vulnerability seems able to provide a unified and meaningful measure of the post-earthquake condition and hence the necessity for intervention. It is worth noting that none of these parameters relate to the actual dimensions of the church, nor the masonry fabric quality nor the foundation system and soil.

Damage to other buildings

A number of common residential houses and other public buildings of regular shape were also surveyed externally and for five of these a Level 1 form, developed by GNDT-SSN, was compiled. These buildings were chosen because they were adjacent or near the churches.

Buildings close to the Chiesa Nuova

The monumental Palazzo dei Priori, built between 1275 and 1295, housing the council offices and the Pinacoteca, had been evacuated and closed, so that the EEFIT team could not visit it. From talks with the Council's Technical Officer, it emerged that there was serious damage to the vaults of the first and second level, and these had been shored. Damage level D3 was estimated.

A block of three buildings of different height and age, with many visible alterations, just north-east of the church, had been seriously hit by the earthquake and was leaning outward so that it had been shored against the longitudinal wall of the convent and the whole area was closed off. The most recent part of this building, built at the beginning of the century, with poorer workmanship and greater height and span dimensions than the medieval fabric, housed the local National Health agency and had been closed down. At the time of the visit scaffolding was still to be erected. From the only visible façade the pattern of cross diagonal cracks on spandrel walls under and above windows was evident, but it was not possible to quantify the level of damage to inner structures and in particular the floors. Damage level was assessed as D3. This block was connected to the adjacent one on the west by a medieval arch which had not moved at all, except for very fine hairline cracks in the plastered portion.

Buildings close to Santa Chiara

The buildings that close the Piazza Santa Chiara on the northern side constitute a long array of three storeys, with similar height, age of construction, distribution of openings and state of maintenance. The floor structure between ground and first floor is of barrel vaults, while the second floor and roof are of timber. A sparse system of ties orthogonal to the façade is visible at the second floor. No damage to the façade was noticeable, while a system of fine cracks was present in the intrados of the vaults. The buildings were in use. Opposite Santa Chiara on the western side of the square the building is positioned at the end of a thin block developing east-west with the south elevation founded at a lower level than the northern one. The lintel over the main entrance on the east façade had collapsed and there were signs of shear cracks above the windows of the second floor. The building at the other end, of similar dimensions but inferior architectonic features and poor state of maintenance, nevertheless showed a lower level of damage. Both buildings had been evacuated.

Finally, a building on the Via Santa Agnese, east of Santa Chiara, with south and north elevation founded at different levels, had undergone substantial alteration and some structural intervention. This building showed deep shear cracks in the north wall and the collapse of an archway on the east wall but no apparent damage on the south wall. The building opposite to it on the north side had no apparent damage and was in use.

General considerations

From the analysis of damage to the churches it seems that the greatest element of vulnerability is the so-called 'sail façade', i.e. the upper part of the façade tympanum extending above the roof structure. This shape of façade is common to all churches and also applies to the transept of the Basilica of San Francesco. The façade of San Francesco, however, is slightly different in that its depth is related to the presence of two towers on each side (in Gothic style) which create a sort of narthex, covered by a short barrel vault, between the façade proper and the modular development of the nave. This implies that while the other façades can be modelled from an horizontal load point of view as vertical cantilevers with rectangular cross section, the San Francesco façade is closer to a C cross section.

Some attention should also be paid to the connection of the façade with the horizontal roof structures which can be assumed to represent a horizontal monolateral constraint. In this respect each façade is different. The least connected is that of Santa Maria Maggiore with point restraints where the longitudinal beams meet the façade wall; better restrained is San Rufino with the columns of the first bay built against the façade and connection in the upper part with the two systems of vaults.

The Basilica of San Francesco, the most severely damaged at the level of the original vaults, had a bilateral connection (able to withstand tensile action) at a level just above the apex of the vaults, represented by a system of reinforced concrete beams running along the perimetral walls between the bays of the system of arches implemented in the 15th century. This system introduced in the 1960's, had not been conceived as a ring beam, as it did not run along the façades of the main nave and the transepts, but mainly as support and connection for the contemporary reinforced concrete structure constituting the roof. However, given the greater stiffness of the beams with respect to the vault system, this level can be regarded as a fixed point in the horizontal oscillation of the façade; it is then evident how the vaults might have suffered not only consistent tensile action, but more importantly high compressive horizontal load that might have caused them to buckle and collapse. This is of course only one of the plausible mechanisms which should be further studied, properly quantifying important parameters such as the thickness of the vaults and the details of the connections.

No damage was detected to any of the bell towers in Assisi, to be compared with the damage to the civic towers and the bell towers in Nocera Umbra and Foligno.

3.4 Nocera Umbra

Nocera Umbra has prehistoric origins and became an important centre during the Roman republican period as one of the main stations along the Via Flaminia, the consular road which ran from Rome to the Adriatic sea. In Medieval times it was conquered and redeveloped by the Longobards as a town fortress. This was destroyed by Federico II and the present plan of the historic centre is very close to the one rebuilt in the second half of the 13th century (Plate 3.30).

Like Assisi, Nocera Umbra is a hill town with main orientation northwest-southeast, about 20 km from Assisi and about 10 km from the epicentre of the two major shocks. While strong motion records are not available within the historic centre, a station is situated on the opposite hill and the records are presented in Chapter 2.

The seismic history of the town is summarised in Table 3.4 below, and Figure 3.4. It is characterised by fewer events than Assisi, but some of greater intensity (Monachesi and Stucchi, 1998).

Date	Macroseismic intensity	For the earthquake of			
Year Mo Day	Is (MCS)	Epicentral area	Ref.	Ix	Ms
1279 04 30	9	Camerino	MON87	10	6.7
1741 04 24	7	Fabrianese	MON87	9	6.2
1747 04 17	9	Fiuminata	MON87	9	6.2
1751 07 27	8	Gualdo Tadino	MON87	10	6.7
1915 01 13	5	Avezzano	MOA96	11	7.0
1915 03 26	5	Assisi	MON87	7	4.7
1930 10 30	4	Senigallia	MOM92	8.5	6.0
1950 09 05	5	Gran Sasso	MOC92	8	5.6
1961 03 23	3.5	Gubbio	GDTSP	7	3.3
1979 09 19	6	Norcia	SPA81	8.5	5.9

Ix= epicentral intensity (MCS), Is = intensity at Nocera Umbra (MCS), Ms=estimated magnitude

Table 3.4: Historic seismic observations for Nocera Umbra

The report of the local newspaper of 27 September states that the first shock caused relatively little damage, while the second damaged, to different extent, up to 80% of the houses in the historic city centre. Only light injuries were reported. The difference in damage would be in agreement with the assumption that the epicentre had translated north toward Nocera for the second shock (see Chapter 1). The earthquake also resulted in temporary disruption of electricity and water supply. The newspaper reported a figure of 5000 homeless out of a total population of 6500 (Corriere Dell'Umbria, 1997).

Nocera is a particularly interesting centre because of the high level of preservation of the historic urban and building fabric. Following the damage produced by the Valnerina earthquake in 1979 and the more moderate one in 1984, many houses had been strengthened to different degrees with the introduction of reinforced concrete floors and roof structures, and/or tie-rods systems. However, most of this work was not aimed at upgrading to the code specifications, but more in line with the concept of general improvement of the fabric.

The historic centre had been completely evacuated and only temporary access accompanied by the Fire Brigade was granted to the population which wanted to collect their belongings. This was the situation ten days after the main shock when the EEFIT team visited. At the same time shoring and other emergency interventions were carried out by specially recruited teams. Due to this situation we only had access to the Pinacoteca in the historic centre, while all other buildings could only be assessed from outside. Given the high profile of this centre, however, it has become the object of a research project, co-ordinated by D. D'Ayala in collaboration with SSN, aimed at establishing the quantitative relationship between vulnerability function and observed damage. Further survey, collection and analysis of data is in progress.

The general level of maintenance is varied. The masonry of the majority of buildings is of roughly dressed limestone mixed with brickwork, with stone lintels over openings and gigantic dressed stone corners of sandstone. In some cases regular horizontal courses of bricks are introduced at the floor levels. While the use of ties, whether old or recent is rather frequent, their distribution is not always regular within one building. In most cases they seem to have been able to avoid or contain the overturning mechanism of the façade. However, where the presence was limited and the location random, widespread shear cracks had developed. In a number of cases it has been noted that the new reinforced concrete roof or floor structure had completely separated from the vertical walls giving rise to horizontal cracks of diverse depth and extent. The following description of a number of buildings of specific historic value gives some evidence of this phenomenon.

Among the buildings of historic importance that suffered most, the Civic Tower collapsed (D5), the Cathedral had serious damage both to the church and the bell tower (D4) (Plate 3.31). The Comune, a new concrete structure built in the 1960's to which an ancient façade had been connected, had suffered the detachment of the façade and shear cracks at the lower infill panels. Consequently it had been evacuated (D4) (Plate 3.32). The Church of San Francesco, at present the Pinacoteca, one single room of rather impressive dimensions, had also suffered serious damage, the main pillars having been severed horizontally at an height of approximately 1.00 m from the floor (D3) (Plate 3.33). At the time of the inspection work was in progress to shore and secure the external wall with a system of bracing cables (Plate 3.34).

Up the hill toward the main square most houses had lost their windowpanes, but there was little evidence of damage to the external walls. A major collapse of the roof and internal floor system took place at the City Council Archive, 200 m downhill from the Civic Tower. The wall facing the street was still standing but showed severe bulging. This building was probably one of the worst affected, with damage level D4. Work was in progress to prepare a substantial shoring (Plate 3.35).

On the other side of the road a recently refurbished building with new brick cladding did not appear damaged (Plate 3.36). Another building of bigger proportions with metal ties inserted at floor level had withstood the shock but with diagonal shear cracks on the anchored wall. Damage was assessed at level D3.

The western slope of the hill was included since 1984 in a project of soil consolidation a situation of general subsidence had been recognised. The major sign of the interaction between this and the earthquake effect is a longitudinal crack running on the level across Piazza San Filippo. The same crack is recognisable on the intrados of the vaults which cover the arcade passage along the city walls, and above which are built two and three-storey houses.

Among buildings severely damaged on this site is the Chiesa di San Filippo, built last century in mixed masonry with dressed stone columns. Part of the rose window of the façade collapsed and the right and left transept walls both presented quite pronounced shear cracks (Plate 3.37). The right column of the façade also showed cracks due to high flexural action. The damage level was assessed at D3/D4. It was not possible to see the inside damage. The bell tower of the church showed severe leaning, for which remedy had been previously sought without success.

A building opposite the church at the southern end of the arcade alley, which appeared recently replastered, showed a vertical crack running the whole height of the two upper storeys in the wall facing south. A number of vertical cracks also ran along the eastern elevation. The damage was assessed at D3/D4 (Plate 3.38).

3.5 Conclusions

In the geographical area affected by this earthquake there are numerous historic centres, and historic masonry buildings represent the majority of the stock in many of the towns which were damaged, to a decreasing extent from Nocera Umbra, to Foligno, Camerino, Fabriano and Assisi. The general observation of the damage distribution on these sites showed that masonry structures of good fabric are able to withstand the earthquake by a combination of strength and equivalent ductility. This behaviour was particularly apparent in centres further afield from the epicentral area, such as Assisi, where the damage mainly occurred at the structural connections, rather than in the load-bearing walls.

In centres with a masonry fabric of poorer quality, either due to poor mortar or poor dressing and coursing of the masonry units, most of the energy was dissipated through diffuse dislocation of the external masonry leaves. This phenomenon is associated with pulverisation of the material, the impossibility of supporting vertical loads and hence the final collapse. In such cases the presence of reinforced concrete floor or roof structures, with a mass comparable to the walls, even when connected to the masonry structure, can be a hindrance rather than an improvement. In fact, failing to develop a robust three-dimensional system, they attract more inertial force and may act as a pounding agent at the top of the walls.

A greater level of damage, as expected, was observed for buildings at the end or corners of blocks and terraces. For these buildings special provisions should be sought to reduce their vulnerability.

An important generalised feature is the observed substantial contribution in strength provided by the presence of tie rods, whether of recent or historic implementation. The tie rods ensure the connection and transfer of action between orthogonal walls, even in poor masonry. By reducing the displacement at the upper levels of the walls, the ties prevent main beams from slipping off the walls and hence floor collapse, as well as limiting the onset of cracks at corners and hindering the overturning of walls.

Thus the field observation has confirmed results obtained from an EU research project (TOSQA EV5V-CT93-0305), (D'Ayala, Spence, Oliveira and Pomonis, 1997): in this case, survey, statistical elaboration and theoretical mechanics had outlined a favourable cost/benefit ratio for the use of tie-rods.

Figure 3.5 shows the vulnerability curve for an out-of-plane collapse mechanism, as developed in the TOSQA project, for sixty buildings surveyed in Assisi, and compared with the sample from the Alfama district of Lisbon studied in the TOSQA project. It is worth noting that most of the buildings in Assisi show a value of overturning acceleration less than 0.1g. However, it was not possible to confirm whether some of those actually had roof strengthening. The maximum acceleration recorded in Assisi at the location of the Basilica of San Francesco was 0.19g, and although only a minority of the buildings surveyed showed evident signs of damage on the external façade, the ones that could be inspected internally showed serious crack patterns and damage in general of level D3.

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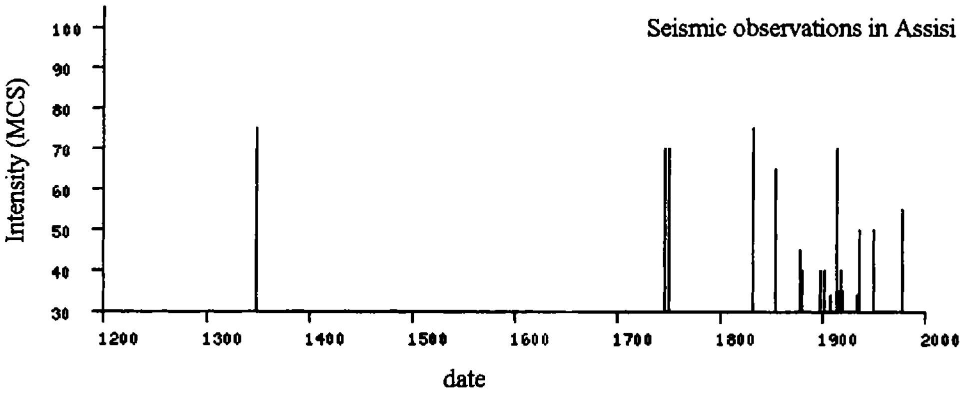


Figure 3.1: Seismic history of Assisi from 1200 to 1980 A.D.

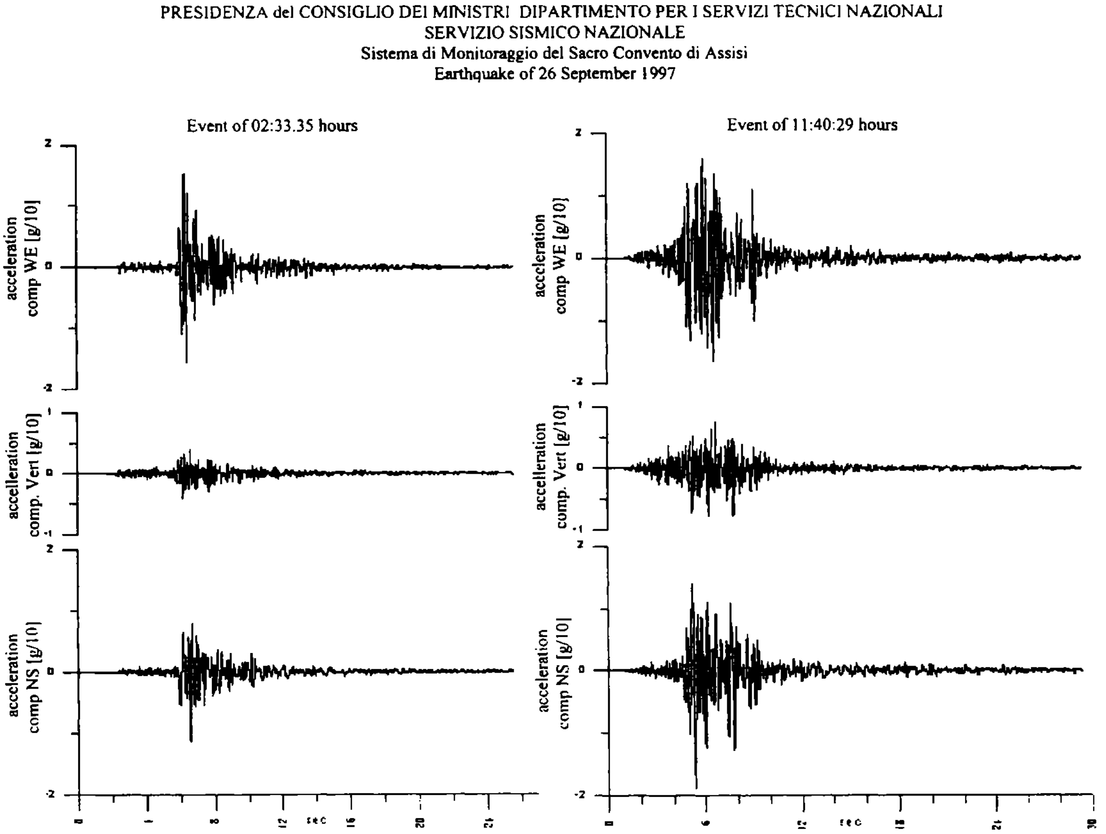

PRESIDENZA del CONSIGLIO DEI MINISTRI DIPARTIMENTO PER I SERVIZI TECNICI NAZIONALI
SERVIZIO SISMICO NAZIONALE
Sistema di Monitoraggio del Sacro Convento di Assisi
Earthquake of 26 September 1997

Figure 3.2: Accelerograms for the two shocks of 26 September 1997

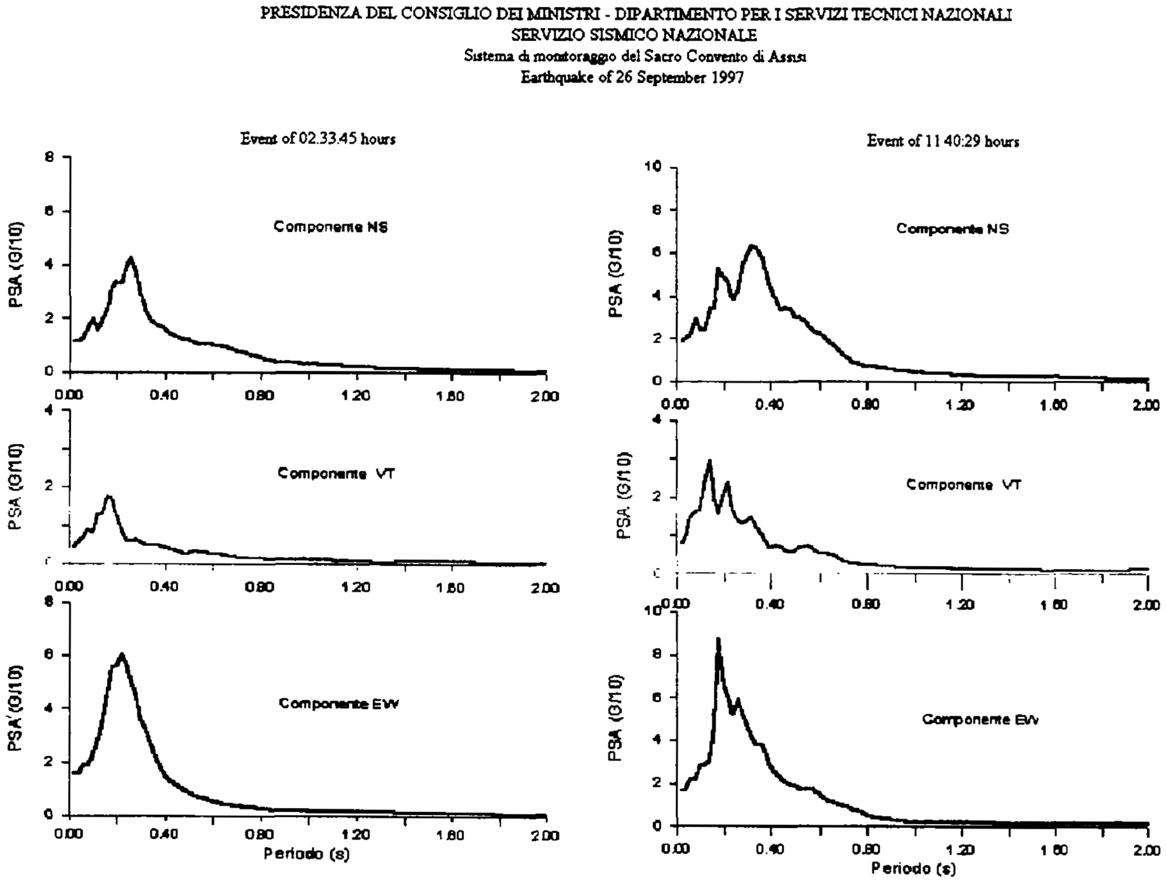


Figure 3.3: PSA spectrum for the two shocks of 26 September 1997

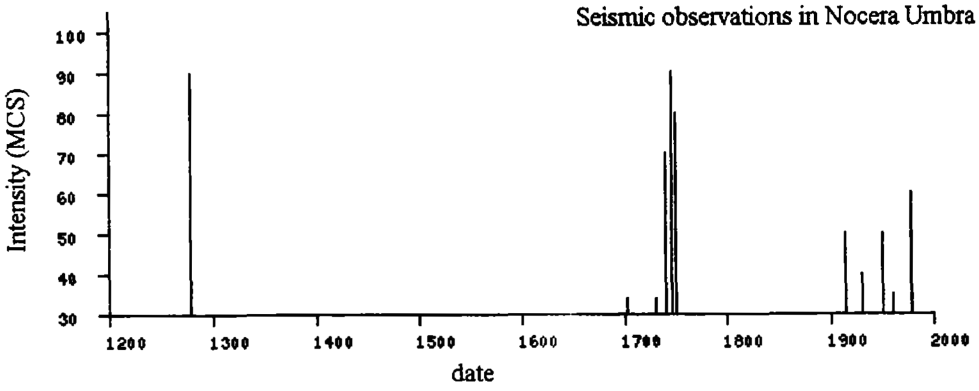


Figure 3.4: Seismic history of Nocera Umbra from 1200 to 1980 A.D.

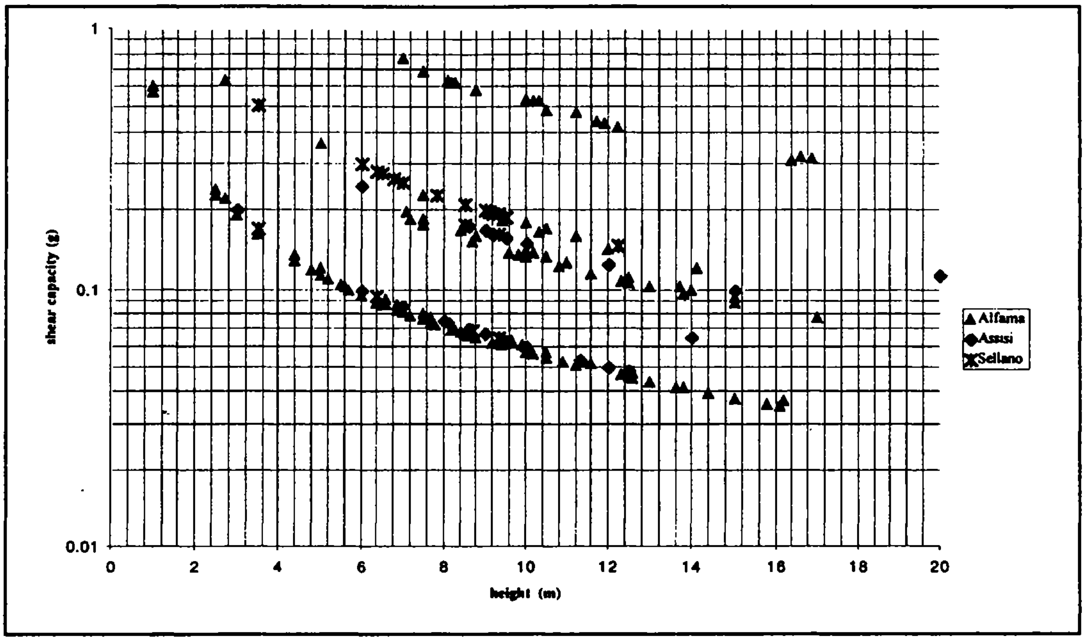


Figure 3.5: Resistance to out-of-plane mechanism of buildings surveyed in Assisi, Sellano and Lisbon

Plate 3.1: Damage to the vault of the first bay of San Francesco Upper Basilica

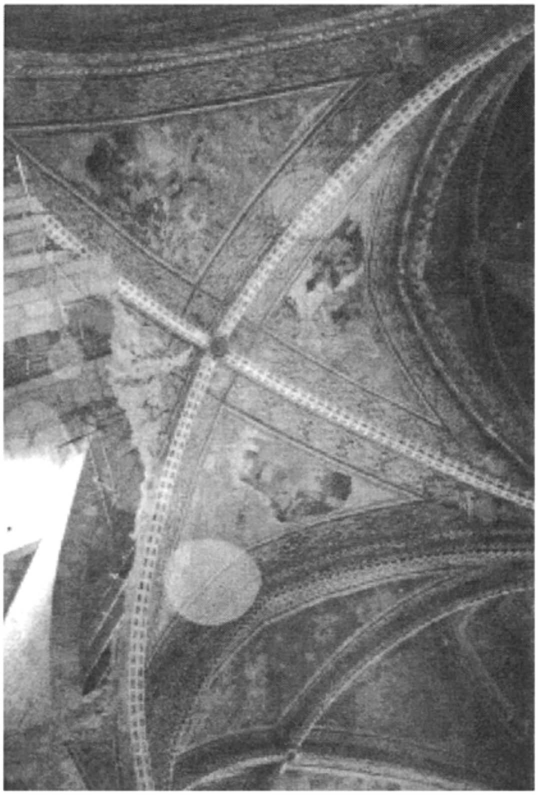


Plate 3.2: Damage to the vault above the crossing of San Francesco Upper Basilica

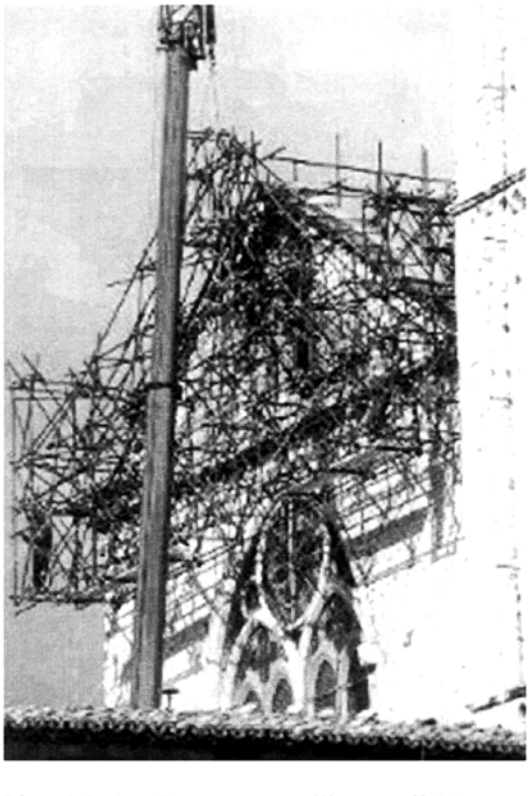


Plate 3.3: San Francesco Basilica: scaffolding around the transept tympanum

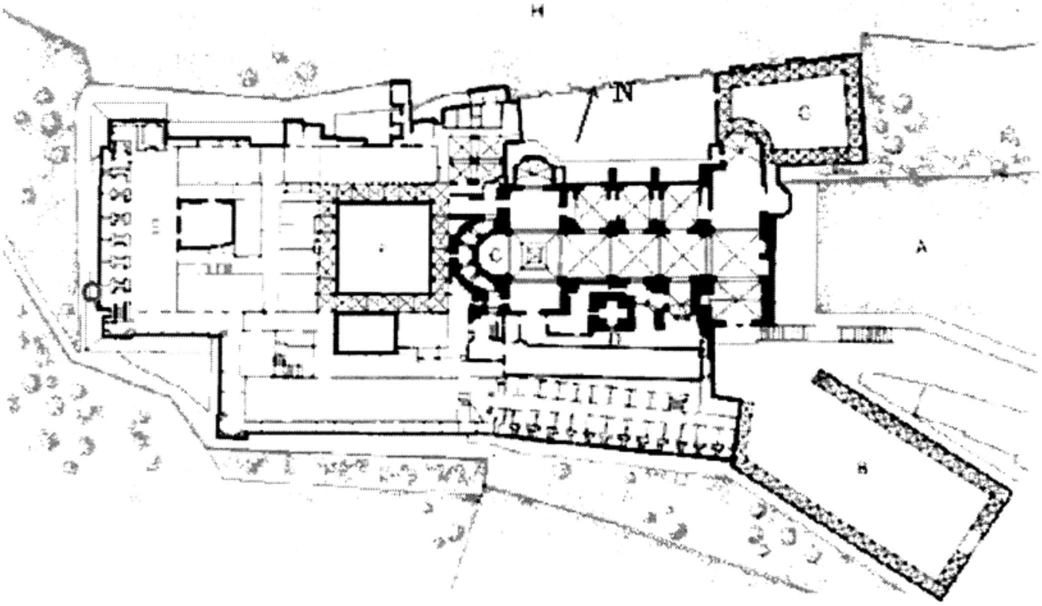


Plate 3.4: Plan view of Convent and Lower Basilica of San Francesco and location of accelerometers

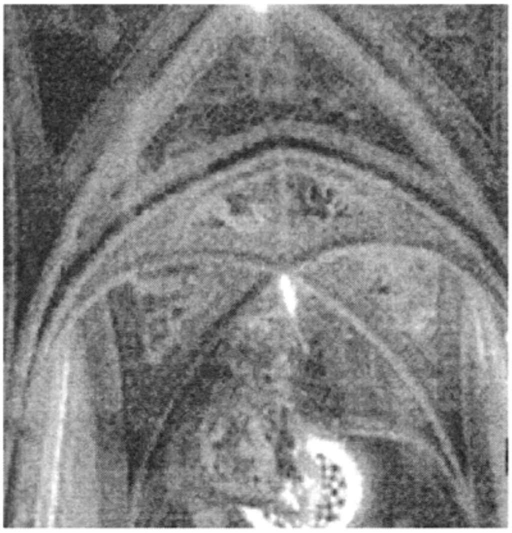


Plate 3.5: San Francesco Upper Basilica: collapse mechanism in the arch of the first bay

Plate 3.6: Santa Chiara Basilica: general view

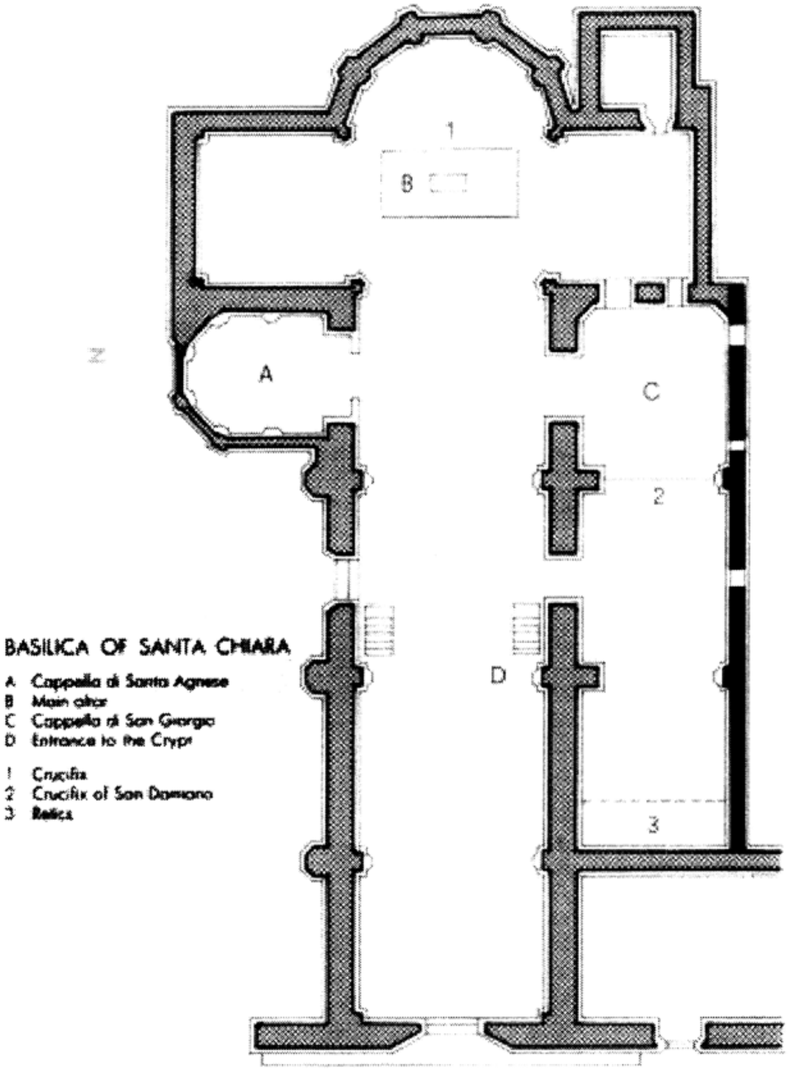


Plate 3.7: Plan of Santa Chiara Basilica

Plate 3.8: Santa Chiara Basilica: subvertical cracks on the southern longitudinal wall

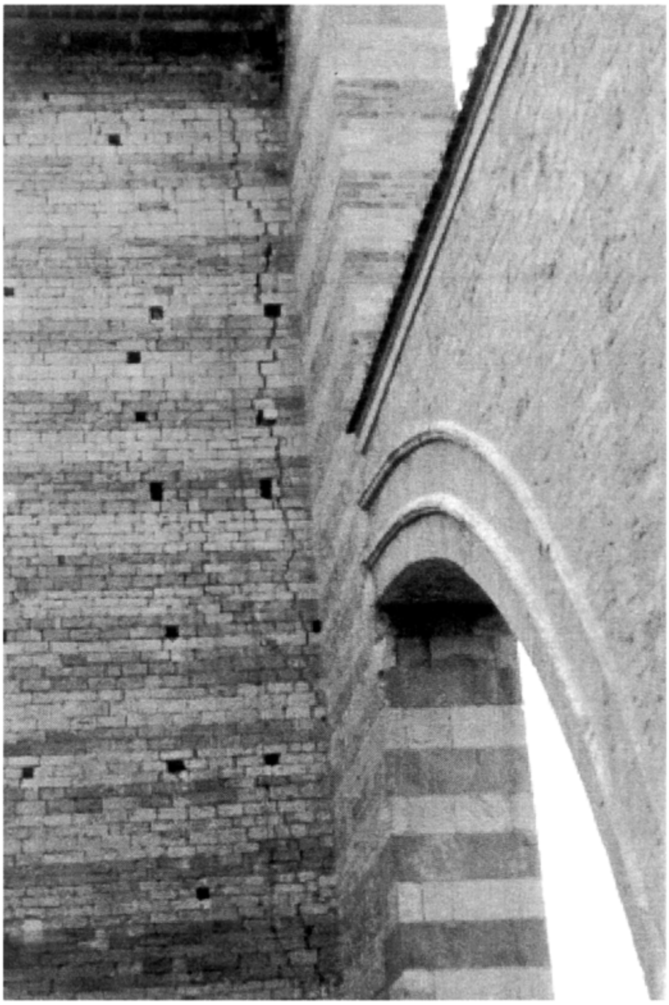


Plate 3.9: Santa Chiara Basilica: vertical cracks on the northern longitudinal wall

Plate 3.10: Aerial view of Santa Chiara complex

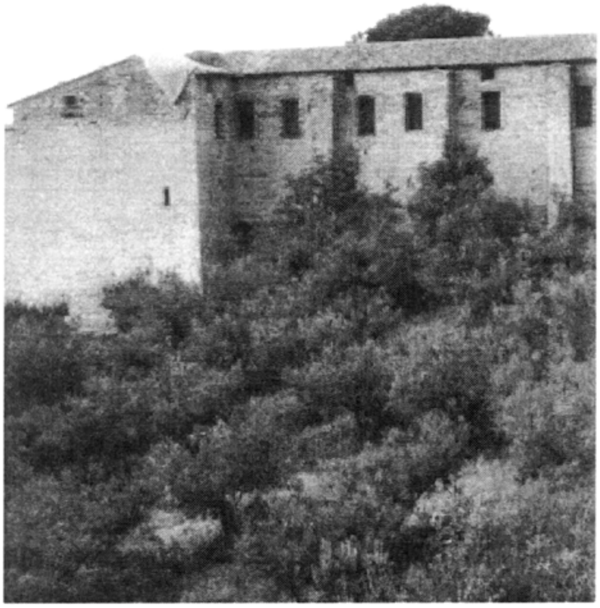


Plate 3.11: Santa Chiara Convent: external wall of the eastern wing

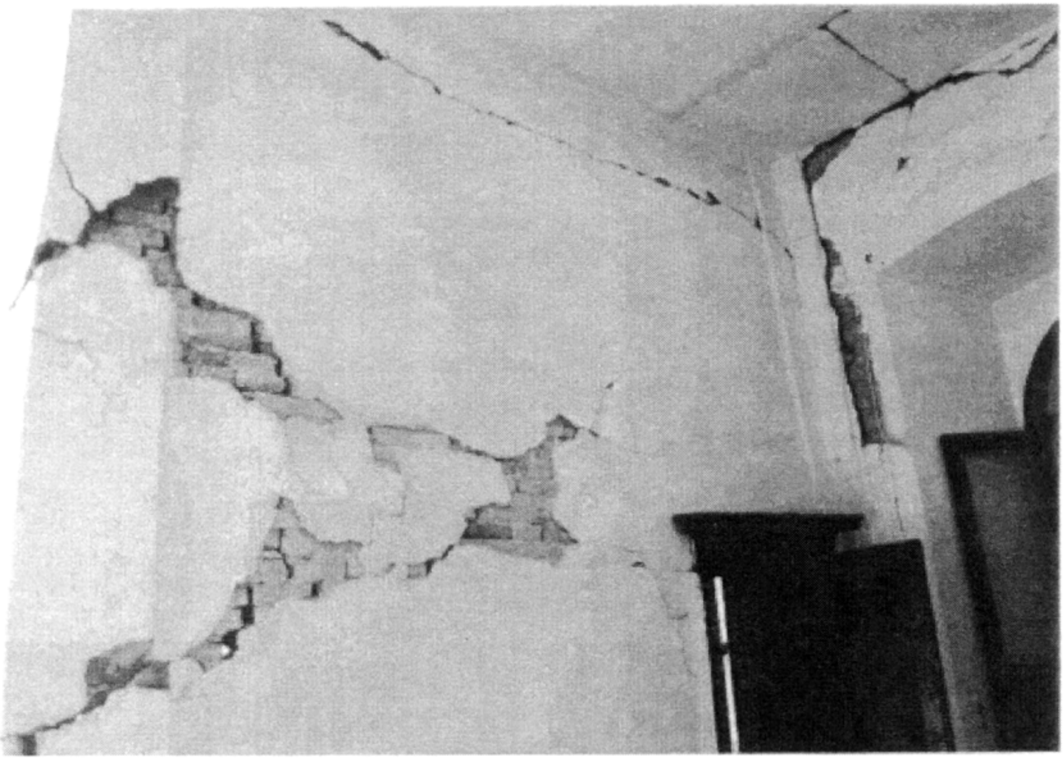


Plate 3.12: Santa Chiara Convent: an internal bearing wall with shear cracks and buckling collapse at the wall junction

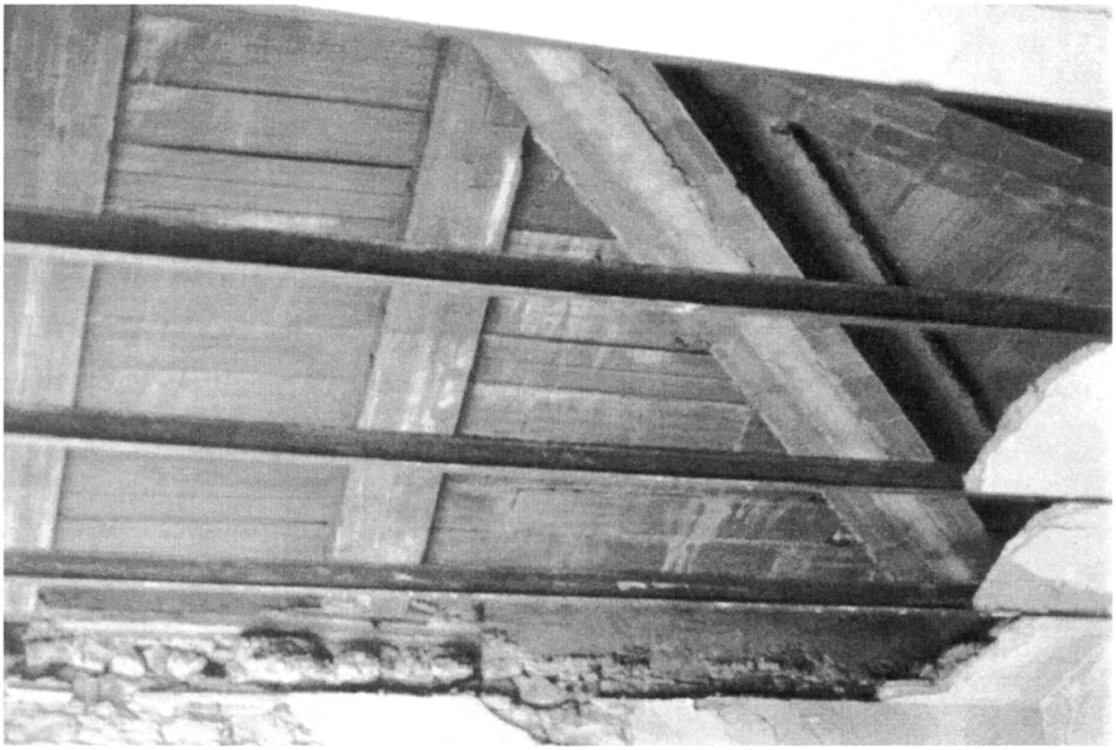


Plate 3.13: Santa Chiara Convent: collapse of the false ceiling and the roof structure at the southwestern corner

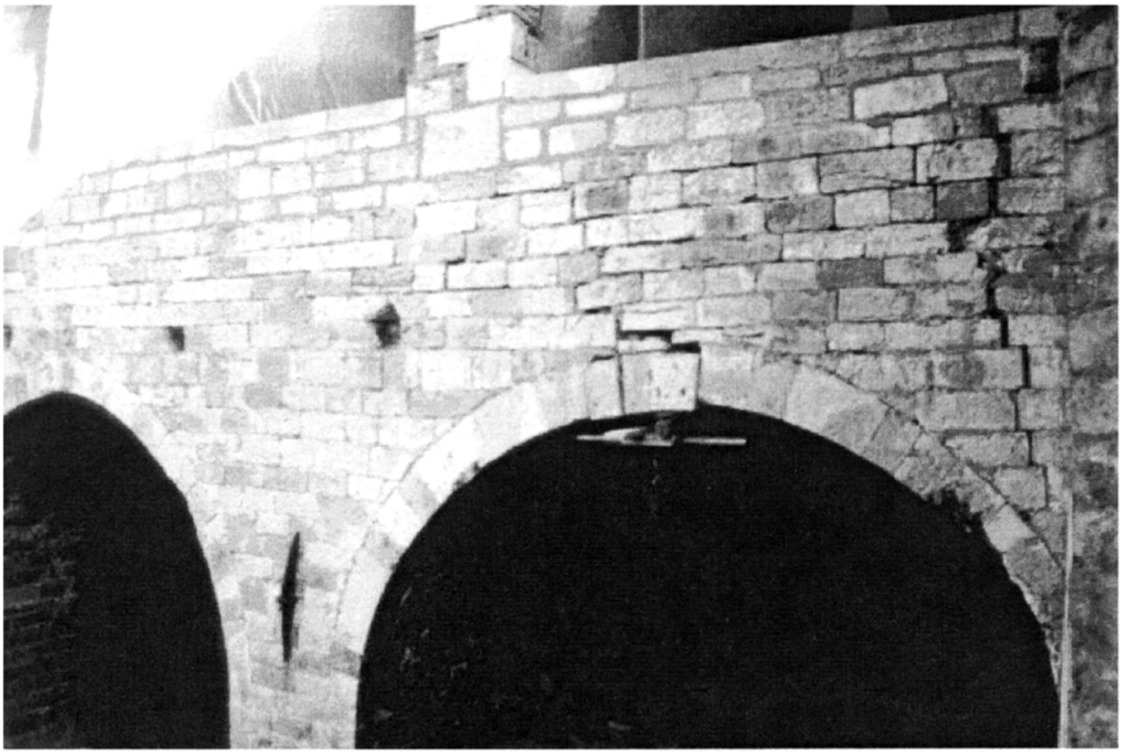


Plate 3.14: Santa Chiara Convent: arch collapse on the cloister south front

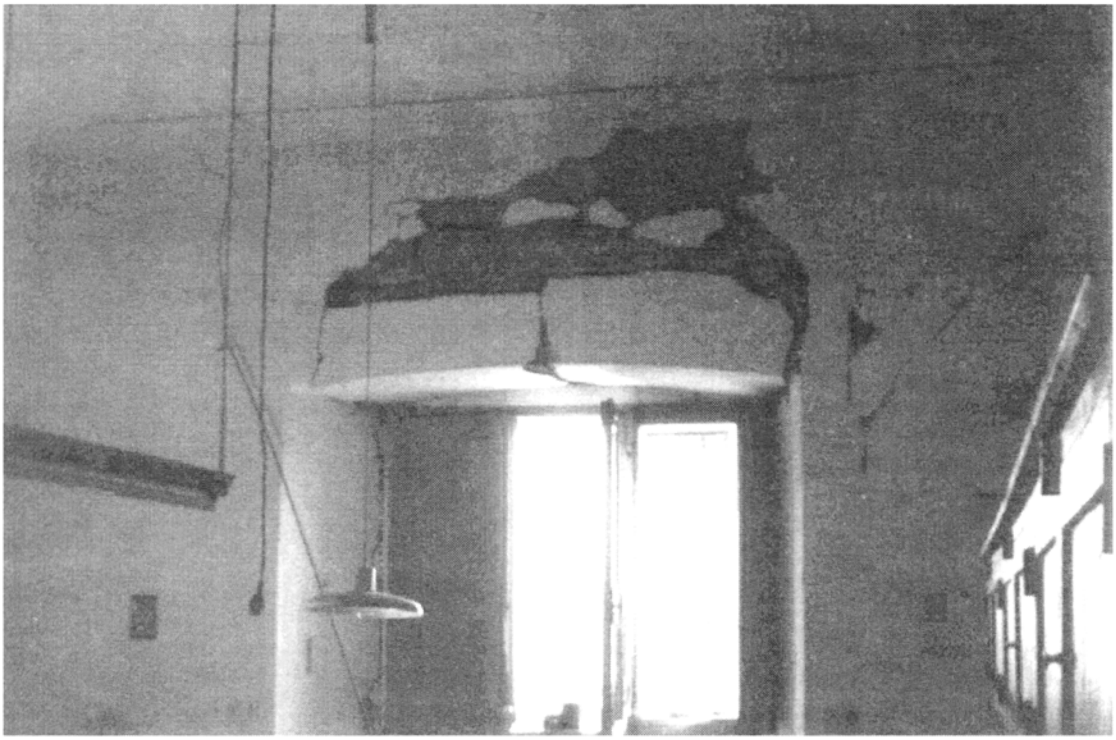


Plate 3.15: Santa Chiara Convent: the internal elevation of the south wall

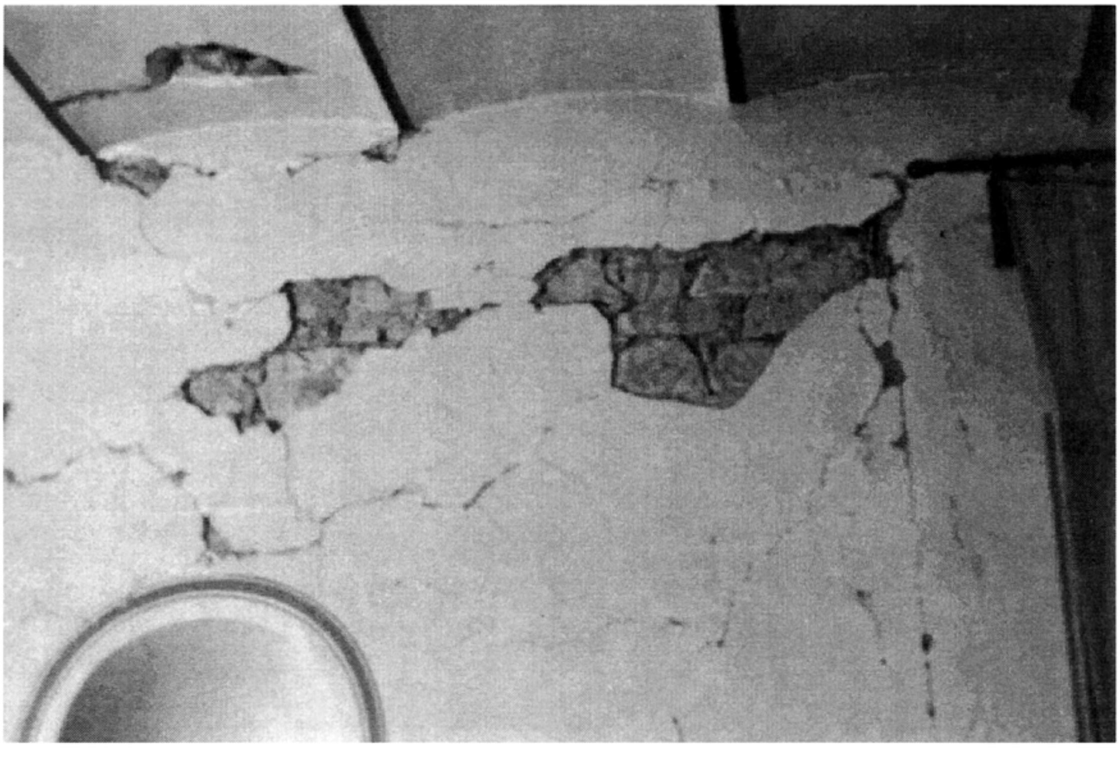
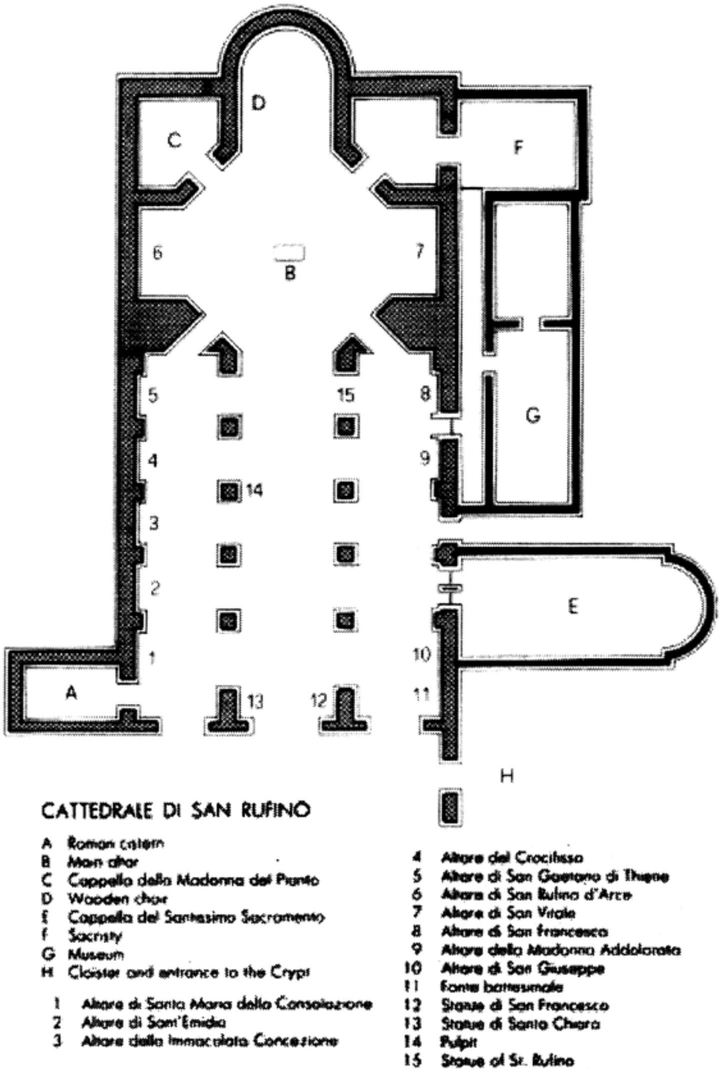


Plate 3.16: Santa Chiara Convent: traditional floor structure in the refectory

Plate 3.17: San Rufino Cathedral: Romanesque façade



CATTEDRALE DI SAN RUFINO

A Roman cistern
B Main altar
C Cappella della Madonna del Pianto
D Wooden choir
E Cappella del Santissimo Sacramento
F Sacristy
G Museum
H Cloister and entrance to the Crypt

1 Altare di Santa Maria della Consolazione
2 Altare di Sant'Emidio
3 Altare della Immacolata Concezione
4 Altare del Crocifisso
5 Altare di San Gaetano di Thiene
6 Altare di San Rufino d'Arce
7 Altare di San Vitale
8 Altare di San Francesco
9 Altare della Madonna Addolorata
10 Altare di San Giuseppe
11 Fonte battesimale
12 Statue di San Francesco
13 Statue di Santa Chiara
14 Pulpit
15 Statue of St. Rufino

Plate 3.18: Plan view of San Rufino Cathedral

Plate 3.19: San Rufino Cathedral: longitudinal cracks along the intrados of the main nave barrel vault

Plate 3.20: External elevation of Santa Maria Maggiore

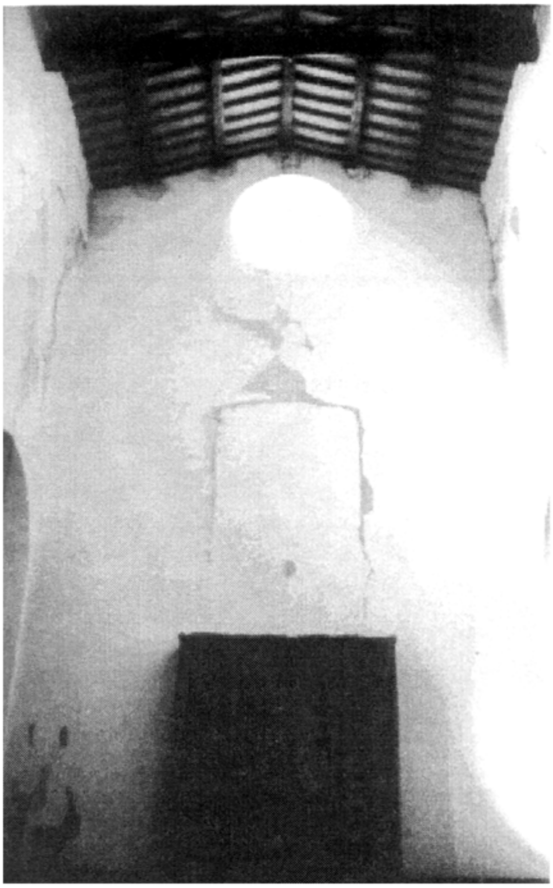


Plate 3.21: Santa Maria Maggiore: internal elevation of the façade; damage caused by oscillation of the façade out-of-plane

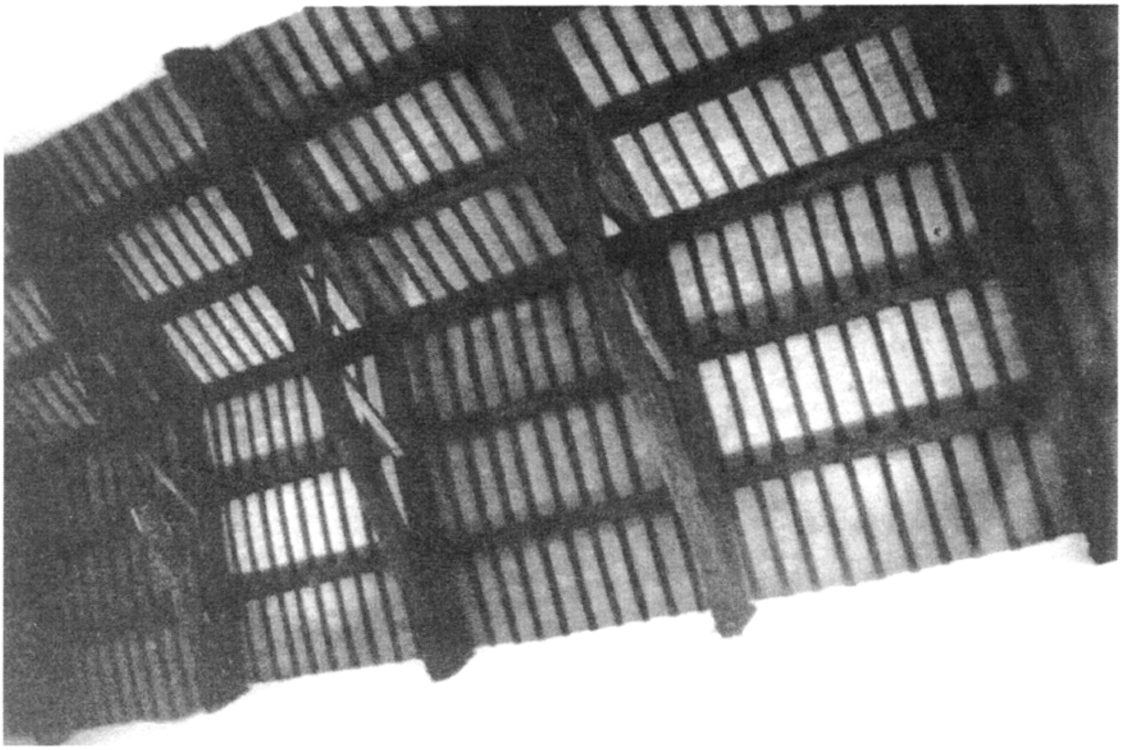


Plate 3.22: Santa Maria Maggiore: the truss roof structure

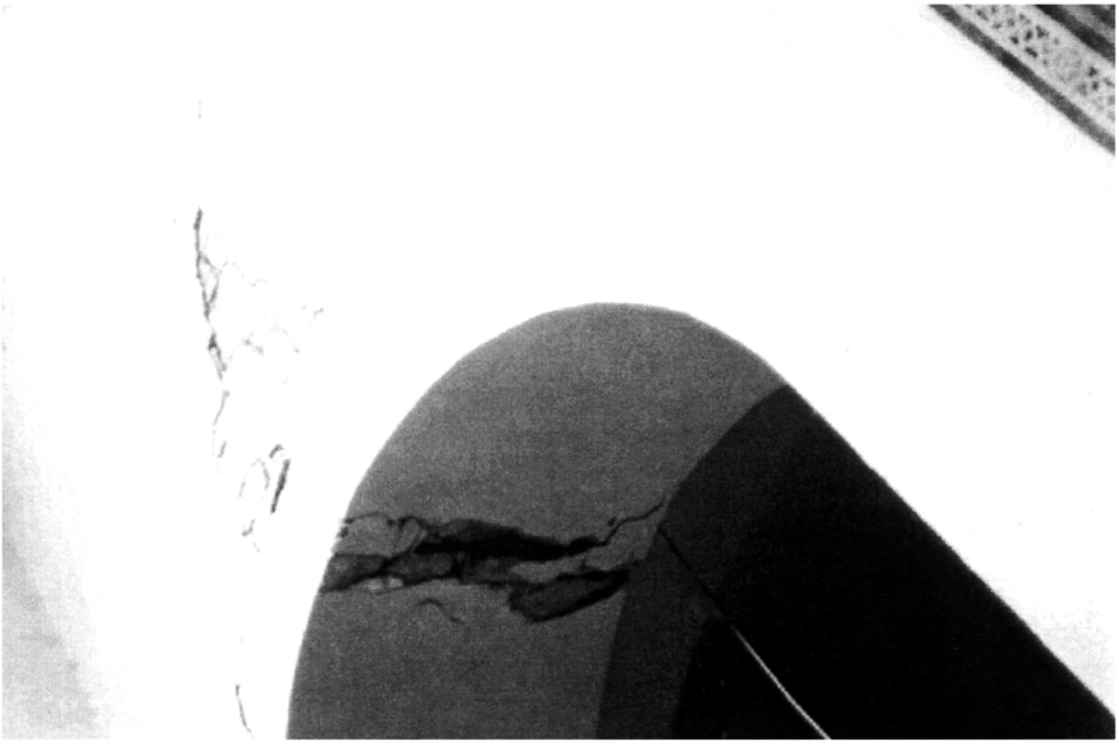


Plate 3.23: Santa Maria Maggiore: shear cracks over the archway between main nave and aisle

Plate 3.24: Santa Maria Maggiore: vertical crack at connection between apse and lateral walls

Plate 3.25: External elevation of the Chiesa Nuova

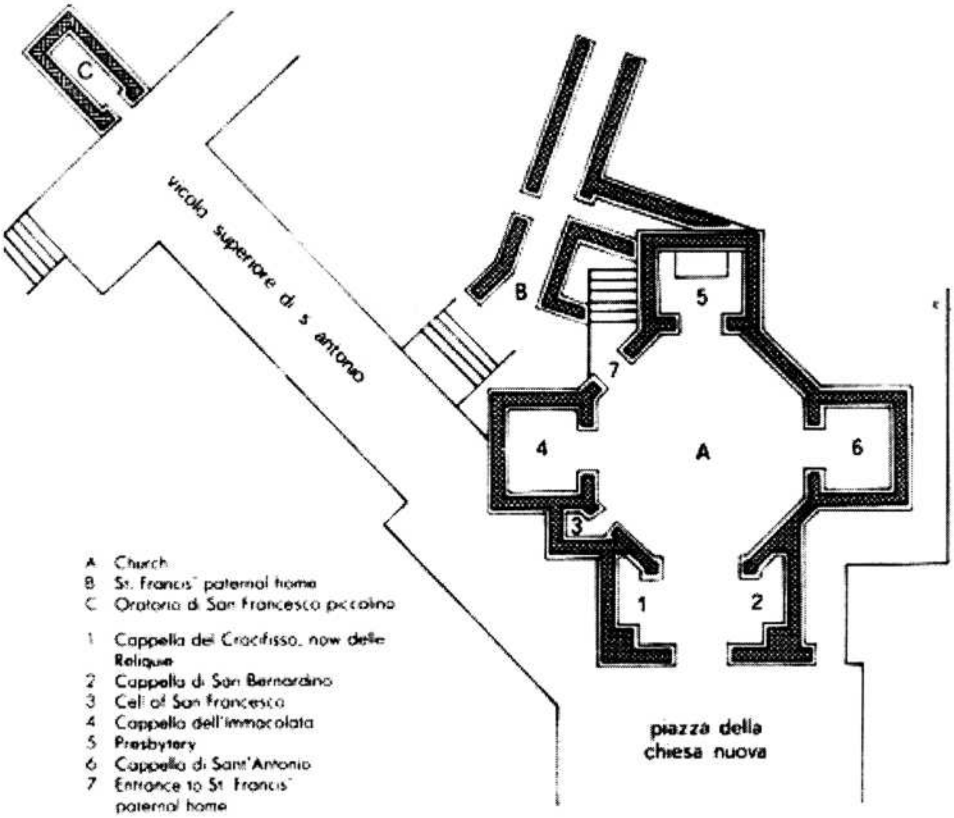


Plate 3.26: Plan view of the Chiesa Nuova

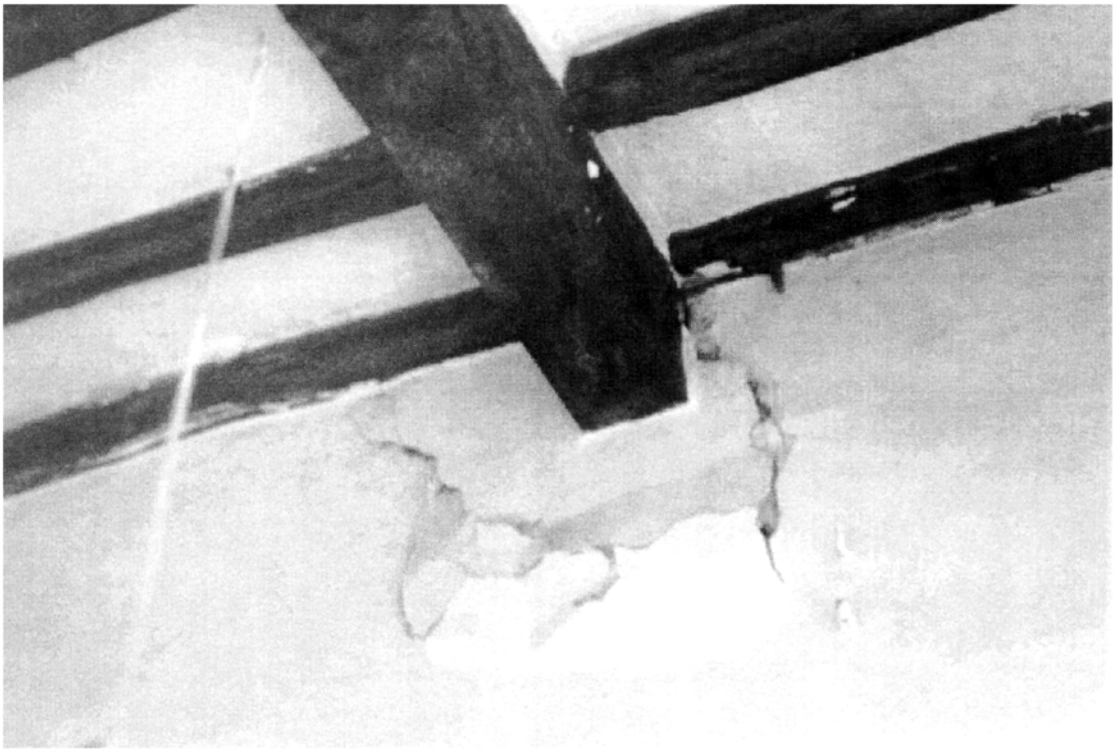


Plate 3.27: Frati Minori Convent: the main beam in the refectory has lost 50 mm or more of its seating, detaching adjacent plaster and masonry.

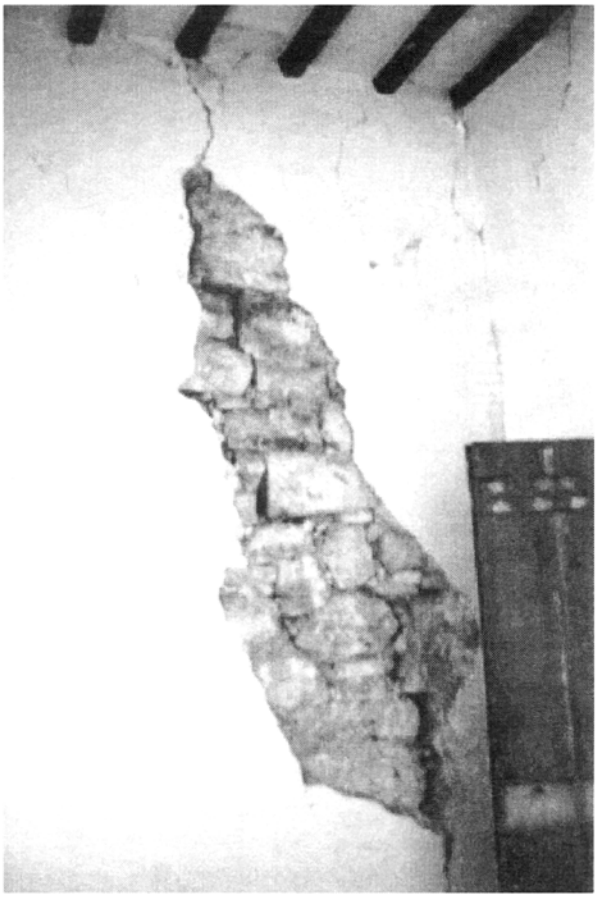


Plate 3.28: Frati Minori Convent: shear cracks in cross walls reveal rubble masonry with stone wedges and bricks.

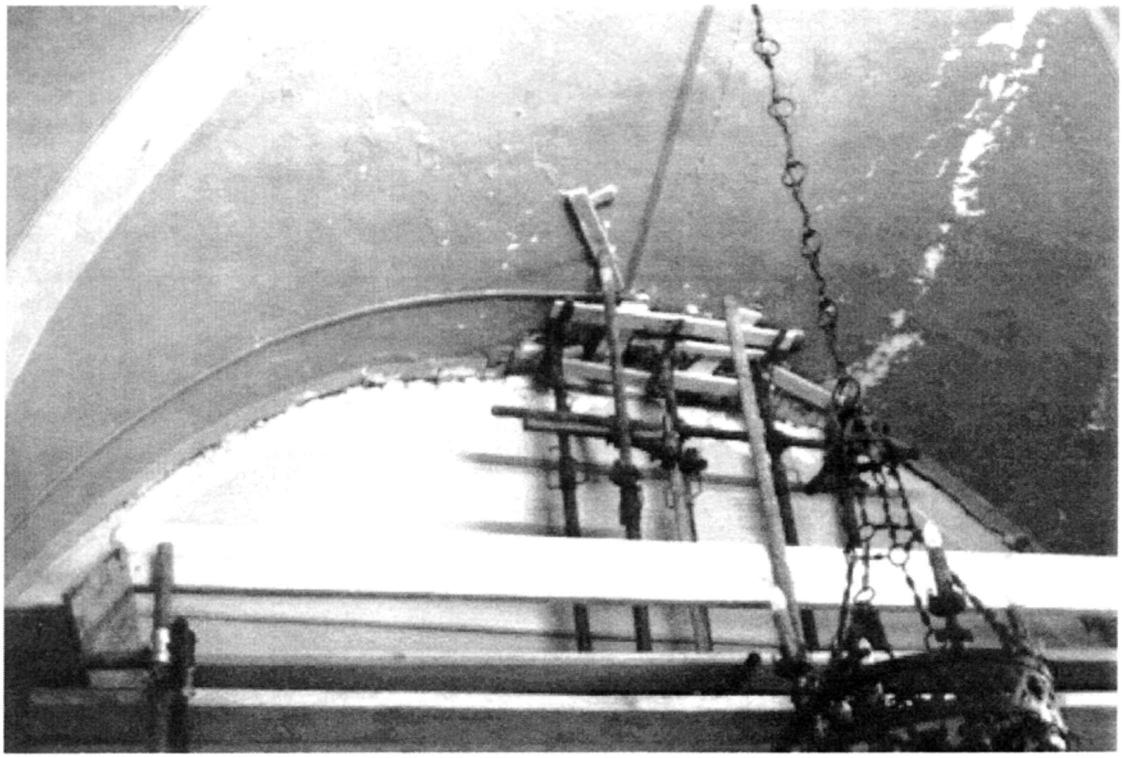


Plate 3.29: Frati Minori Convent: damage to the vault of the library and shoring

Plate 3.30: Panoramic view of Nocera Umbra historic town centre

Plate 3.31: Nocera Umbra:shoring work after the collapse of the Civic Tower (right) and urgent repair measures to the Cathedral

Plate 3.32: Comune, Nocera Umbra: detachment of perpendicular walls and shear cracks in infill panels within new reinforced concrete structure

Plate 3.33: Pinacoteca, Nocera Umbra: horizontal cracks at the base of columns

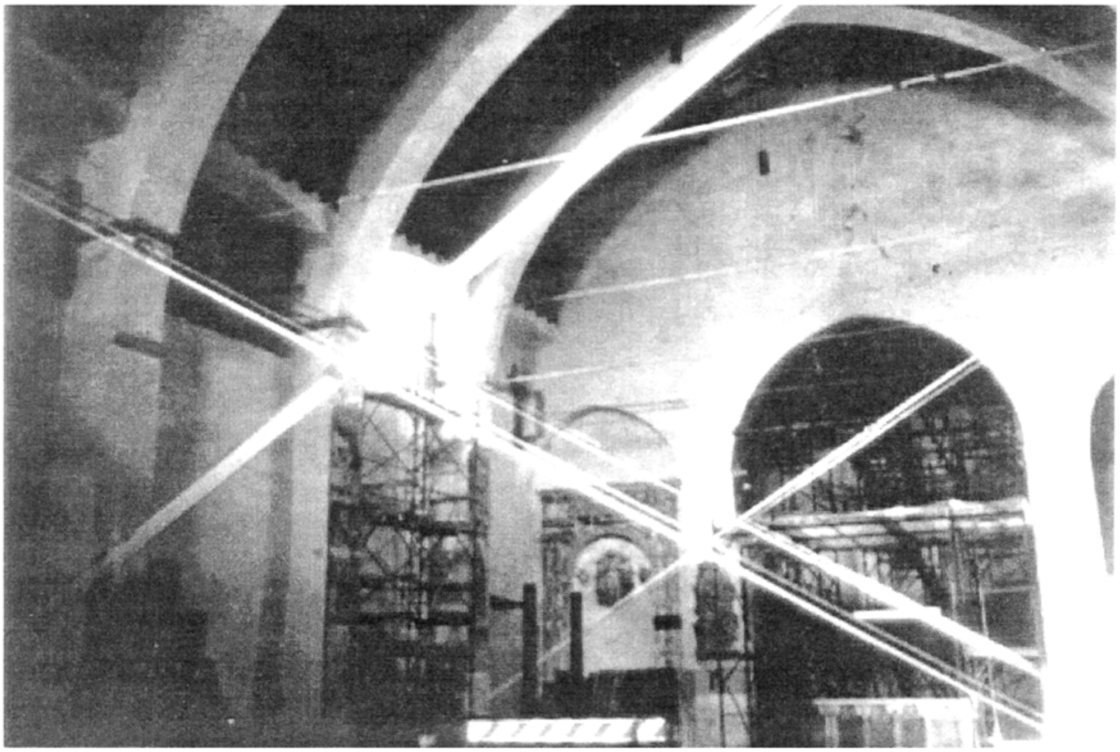


Plate 3.34: Pinacoteca, Nocera Umbra: diagonal bracing to contain thrust and prevent further damage in structural vaults

Plate 3.35: Nocera Umbra: out-of-plane overturning of the Civic Archive façade

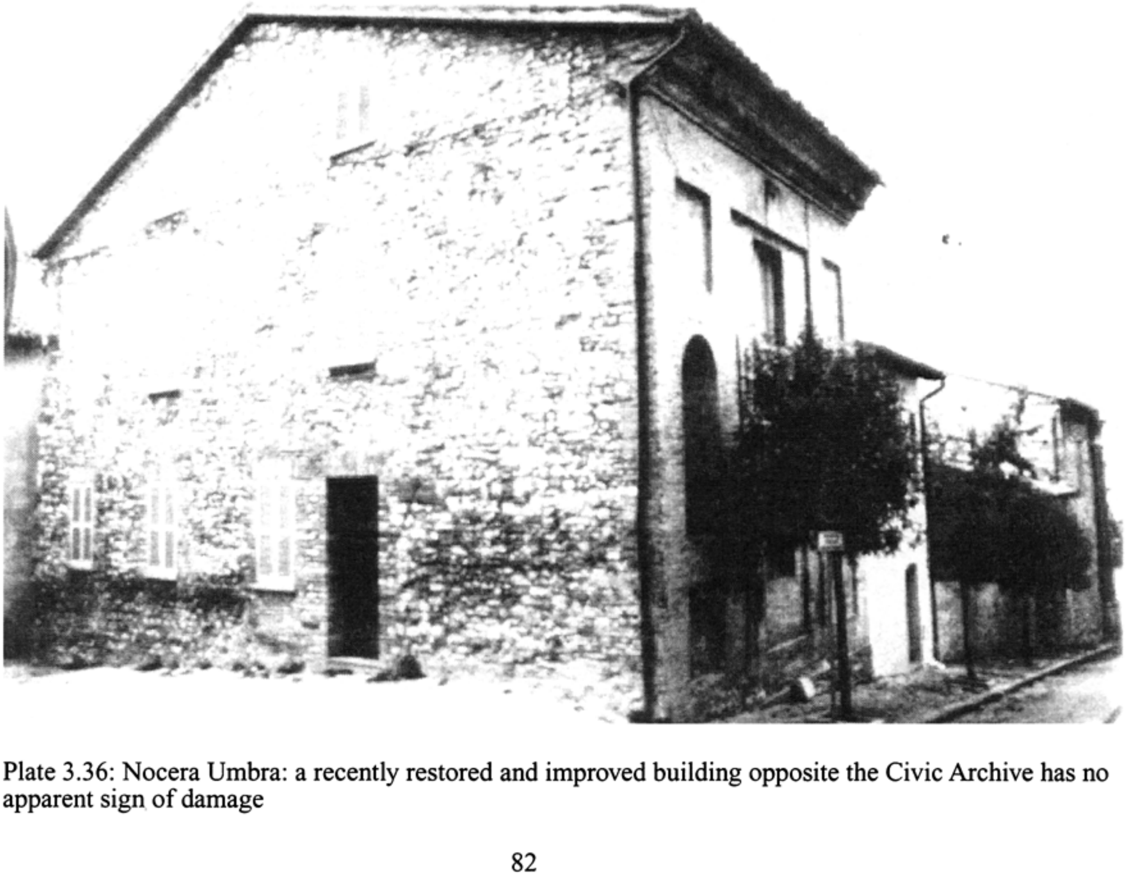


Plate 3.36: Nocera Umbra: a recently restored and improved building opposite the Civic Archive has no apparent sign of damage

Plate 3.37: San Filippo Church, Nocera Umbra: damage to the upper part of the façade (overturning mechanism)

Plate 3.38: Nocera Umbra: central sub vertical cracks in building opposite San Filippo church, associated with ground movement

4.0 THE EARTHQUAKE DISASTER AND ITS IMPLICATIONS

R Spence
University of Cambridge

4.1 Human casualties

The total death toll in the earthquakes of 26 September.was 11, with 126 people injured. Of the 11 people killed, four were in the Basilica of San Francesco in Assisi, at the time of the second, 11.40, shock, inspecting the damage caused by the 02.33 shock. Two of these were monks, two were art conservation specialists. They were among some 30 people who were in the Basilica at the time. A video camera recorded the moment of the collapse of the vault, (Plate 4.1). Tourists had been excluded after the first shock, otherwise the death toll in this building could have been much higher.

A further four of those killed were two elderly couples buried by the collapse of their houses, one couple in Cesi and one in Collecurti. It is not clear whether this was in the 02.33 shock or the 11.40 shock. The remaining three deaths are said to have been caused by heart attacks induced by the earthquake.

Details of the types and locations of the 126 injuries are not available, and analysis will be made difficult because of the extensive damage caused to the hospital in Foligno, which had to be evacuated. One press report describes how a group of doctors in the maternity ward refused to abandon their posts as the walls of the hospital crumbled, and minutes later delivered a baby girl.

The CAR human casualty model (Spence et al., 1998) has been used to estimate the likely proportion of dead and injured among the population, had they not been evacuated, given the intensities and building types involved (Table 4.1).

	Mean	Range
Estimated number of collapsed buildings	40	20 to 80
Estimated number of partially collapsed buildings	160	80 to 300
Estimated number of deaths caused by building collapse	15	5 to 50
Estimated number of injuries (serious and moderate)	30	10 to 100
Reported number of deaths caused by building collapse	8	
Reported number of injured (all levels)	126	

Table 4.1: Estimated and reported human casualties

It is clear that the number of deaths is fewer than could be expected given the number of collapsed and ruined buildings. Two partial explanations for this are as follows.

1) The first shock, magnitude ML=5.5, caused relatively few houses to collapse, but sufficiently alarmed occupants that all but the least mobile left their houses, and were still in the open when the second, more devastating shock, ML=5.8, occurred 9 hours later affecting very much the same area.

2) The weekday resident population of the villages is quite small, as a result of out-migration of the population in the post-war years (Catling, 1994). Many are now second homes, used primarily at weekends and during the summer months. Early on a Friday morning in October, the average occupancy level of the village houses would be rather low, perhaps lower than the resident population given by official statistics.

4.2 The emergency operation

The earthquake resulted in the largest Civil Defence operation for an earthquake in Italy since the 1980 Irpinia earthquake in which about 4,500 people were killed. In the immediate emergency phase, prolonged because of the series of aftershocks, an estimated 90,000 houses were abandoned, and around 130,000 people were sleeping out (Sunday Times 29.9.97, Panorama 9.10.97).

Within ten days, the Civil Defence and other volunteer agencies had provided temporary accommodation for about 14,000 people, in 1,500 tents and about 300 caravans, located in 20 or more 'tentopoli' throughout the area (Plates 4.2 to 4.4). Each was fully serviced with washing and cooking facilities. The Italian News Magazine 'Panorama' reported that by 9 October, 36,000 hot meals had been provided. The EEFIT team and news reporters were impressed with the level of organisation in these camps and by the high standard of catering (Plate 4.5). By the time of the EEFIT visit substantial numbers of those who were sleeping rough after the earthquake had returned to their houses, but the villages in the epicentral zone were all evacuated, and so was the historic centre of Nocera Umbra.

Civil Defence units and Fire Brigades from all over Italy were involved in the emergency activity, a total of 4,500 workers, supported by around 2,000 volunteers. In addition to the temporary accommodation, action taken in the immediate aftermath of the earthquake included shoring dangerous buildings (Plate 4.6), removing damaged and dangerous masonry and loose roofing material (Plate 4.7), providing tarpaulins to cover damaged roofs, identifying and controlling access to areas considered unsafe (Plate 4.8), and surveying and classifying buildings. In several areas, a special unit of the Protezione Civile was engaged in careful removal of rubble from damaged churches, and identifying and organising the remains of damaged frescoes (Plate 4.9).

Much of this work was in progress during the EEFIT visit. In Nocera Umbra, for instance, the Alpine Mountain Rescue attempted to secure a large piece of damaged masonry wall of the cathedral of Santa Maria Assunta with webbing straps to prevent further collapse (Plate 4.10).

4.3 The press and international reporting

The earthquake was unusual for the extent of international press interest in the event, and in the maintenance of a high level of interest over several months. The main reason for this interest was of course the enormous importance to both art history and tourism of the town of Assisi and the Basilica of San Francesco.

The first international reports from the area on 27 to 29 September were concerned almost exclusively with the collapse of the Basilica vaults, with the ensuing deaths, with speculations as to the cause of the collapse, and with the rescue of moveable art treasures from the Monastery. Very little attention was paid at this stage to the much more serious destruction of the towns and villages in the epicentral area. (Times, 27.9, 29.9, Telegraph, 27.9, 28.9, 29.9, 30.9). The impression was thereby created that Assisi was at the centre of the earthquake, and this impression was further reinforced when the Piazza in front of the Basilica became the focus for much of the television reporting and interviewing from the earthquake area. This false press emphasis on Assisi has been blamed by some local traders for the serious decline in tourism which the town was experiencing in the early part of 1998.

The plight of the homeless in the epicentral area, mentioned only briefly in the first days after the earthquake, became the subject of several reports in subsequent weeks, with an emphasis on the continuing aftershocks and the fear and disruption to the emergency operation which they caused (Times 29.9, Observer 5.10, Independent, 17.10).

The vain attempts to piece together the damaged frescoes and other aspects of the stabilisation and restoration of the damaged monuments was the subject of several reports in February and March 1998 (Times 28.2.98, Telegraph 21.3.98).

In March and April the renewed outbreak of seismic activity was briefly reported in the international press and in television reports, and this was coupled with the first international reporting on the consequences to the Umbrian economy of the loss in tourist revenue caused by the earthquake (Independent on Sunday 12.4.98).

4.4 Organisation of scientific study

General

Because of the frequency of natural disasters in its territory, the Italian government has well-rehearsed procedures for initiating appropriate scientific and technical evaluations in the emergency phase. Thus, in the hours immediately following the earthquake on 26 September, a commission was established at the Ministry of Civil Protection, including the Servizio Sismico Nazionale and the GNDT to initiate the necessary scientific and technical work.

The tasks initiated by this commission included

- a large-scale macroseismic survey
- the establishment of temporary accelerometric and strong-motion instrument networks
- obtaining and analysing the data from the fixed instrument networks
- survey of damage and useability of buildings
- investigation of ground failures
- survey of sites for the establishment of temporary settlements

The macroseismic survey

The first survey was conducted over the period from 27 September to 22 October, but has been subsequently updated on several occasions.

This first survey was conducted by:

- first-hand investigations, through visits by the survey team, to all locations with effects greater than MCS = 7 and many with lesser effects
- analysis of information published in local newspapers – used to assess which locations to visit
- telephone interviews with local officials – used for areas distant from the epicentre

The MCS scale was used, because it can be applied more quickly than the EMS/MSK scale; a test study of EMS is nevertheless in progress. Three particular difficulties experienced in the survey were:

- difficulties in distinguishing the effects of the separate shocks: this entailed several visits to some of the most damaged locations
- widespread higher vulnerability of the buildings in the mountain area, which were initially poorly constructed and often had poorly conceived modifications in modern materials, which will have adversely affected intensity assignment (see Appendix 1)
- considerable lack of homogeneity in the damage distribution on account of local ground conditions and soil effects (see Section 2.5)

In all, 163 locations were identified as having experienced intensities greater than MCS = 6.5; the map of intensities showing those closest to the epicentre is shown in Figure 1.6. The macroseismic survey has been described in detail by Camassi et al. (1997), and is published on the Internet (OSGM 1997).

Accelerometric and strong motion records

The permanent teleseismic network of accelerometers is the responsibility of the Istituto Nazionale di Geofisica. In the hours immediately following the earthquake, OGSM (Osservatorio Geofisica Sperimentale di Macerata) in collaboration with SSN started to install a mobile accelerometer array in the epicentral area, and the data from this array was used for a first focal plane mechanism solution by ING (Figure 1.4).

Responsibility for the permanent network of strong motion instruments has recently been assumed by SSN from ENEL. The data from these instruments, of which 15 were triggered by the first earthquake of 26 September, and 20 by the second, was retrieved and assembled by SSN, and the initial findings are summarised in Section 1.5.

SSN also installed a mobile array of strong motion recorders in the epicentral area soon after the earthquake, (Plate 4.11). Data from these instruments which was captured in the long aftershock sequence will be valuable in establishing the significance of site effects, details of which will be published in due course.

Survey of damage and useability of buildings

Because of the scale of damage, the survey of damage and useability was entrusted to three local commissions, one for the region of Umbria (based in Foligno) and two for the region of Marche (based in Serravalle and Fabriano). These Centri Operatori Misti (COM's) were also charged with coordinating the health assistance, provision of tents and the technical activity of planning temporary settlements. This note concerns the technical aspects only.

For each COM, the survey was divided into three categories: public buildings, residential buildings, and monuments; several different survey forms were used, reflecting the relative interests of the separate regional authorities conducting the survey (with a different degree of concern for the importance of detailed recording of damage level as well as the essential task of defining the state of useability). Each building surveyed was categorised on a three point scale of 'agibilita' (useability).

About 200 public officials and large numbers of specialists from local and national universities were involved in the survey. Within 28 days, the total number of buildings which had been surveyed included in excess of:

- 48,000 private and residential buildings
- 600 churches
- 500 schools
- 100 hospitals, and
- 600 other public buildings

The data contained in the forms completed for all these buildings have been assembled by SSN for future analysis. For the churches, a special form and vulnerability methodology was used..The surveys are described in detail by Largomarsino et al (1997), and GNDT and SSN (1997).

Use of the Internet

A particular feature of the Umbrian earthquake emergency was the extensive use of the Internet for the publication of data of general importance. Within a few days of the earthquake, SSN had published on their website (SSN, 1997) a document comprising over 50 pages of preliminary data and damage estimates. This was regularly updated as more information was acquired, and as further aftershock altered damage distribution patterns. Likewise the Istituto di Geofisica published on their website (IGN, 1997) data on the time and location of all the shocks and their preliminary magnitude determinations, with examples of some of the key accelerometric recordings obtained in the major shocks, and the GNDT website (GNDT, 1997) made much further data available.

Several research groups also provided Internet versions of their research data and findings immediately these became available, rather than waiting for publication. All of this was of great benefit to the scientific community and not least to international teams visiting the region and preparing mission reports.

Surveys of ground failures

Geologists of the Servizio Sismico, in collaboration with local officials, carried out extensive investigations in the epicentral area wherever ground failures were reported. Within the first month 52 such locations were investigated. Of these:

- 30 concerned failures of the road network, either landslips on to the road surface, or failures of the road surface
- 20 concerned foundation settlement affecting either infrastructure or inhabited settlements
- 2 were cases of old landslides which had been reactivated by the earthquake

Details of this work are reported in GNDT and SSN (1997).

4.5 Costs and economic effects

Overall, some 100,000 structures were damaged in the earthquake, most of them homes, but also including significant numbers of churches, historic monuments, and public buildings, as well as some shops and smaller commercial buildings. There was also damage to many agricultural buildings, to a few industrial buildings, and to a limited extent to roads, railways and power cables (Partner Research, 1997, Prestininzi et al., 1998). Dams and other civil engineering structures in the region appear to have been unharmed.

The total economic cost includes not just the physical reinstatement of the lost buildings and repair of the damaged buildings and infrastructure, but the economic loss associated with loss of agricultural and industrial output and loss of tourist revenue. None of this can be properly calculated at present, and in particular, the loss of tourist revenue seems to be very severe in Assisi and Spoleto, two historic towns whose economy depends heavily on short visits by groups of overseas tourists. According to early estimates, the total economic loss is likely to be in excess of $4.5 billion, but for the reasons given above this is likely to be an underestimate.

The role played by insurance in meeting this loss is very small, and it has been estimated that only about 2% of the loss is commercially insured (Partner Re, 1997). Few residential and commercial buildings in Italy carry earthquake insurance; it is estimated that in the country as a whole only 15-20% of fire insurance policies have additional earthquake cover. However, the buildings carrying this cover are in most cases modern buildings designed according to recent earthquake-resistant design regulations, whereas those damaged by the earthquake are mostly the older, more vulnerable structures, for which cover is either unavailable or too costly. It is likely, however, that as a result of recent discussions among Italian insurers, new modes of offering earthquake cover may be introduced in the near future, reducing the cost of earthquake cover, and thus enabling the insurance industry to extend its involvement (Insurance Day, 15.10.97).

Most householders and businesses will depend on the Government to compensate them for their loss. A Government decree was published in March 1998 detailing the process for presenting plans for repair or reconstruction of buildings damaged by the earthquake, and detailing the levels of grant which can be expected, ranging from 40% to 90% of costs, depending on the type of property damaged, and the total costs involved (Candolfini, 1998). Inevitably, most of the losses beyond the physical cost of repair will be borne by the affected householders or businesses themselves.

The damage to the churches and other public buildings will also have to be met from public funds. The cost of this damage is huge, and because of the need for sensitive and complex work in repair or restoration, it is likely to take a very long time. A preliminary listing of damaged monuments in the Region of Umbria (Regione dell'Umbria, 1997). identifies over 1000 damaged monuments, and a similar number have been damaged in the Region of Marche.

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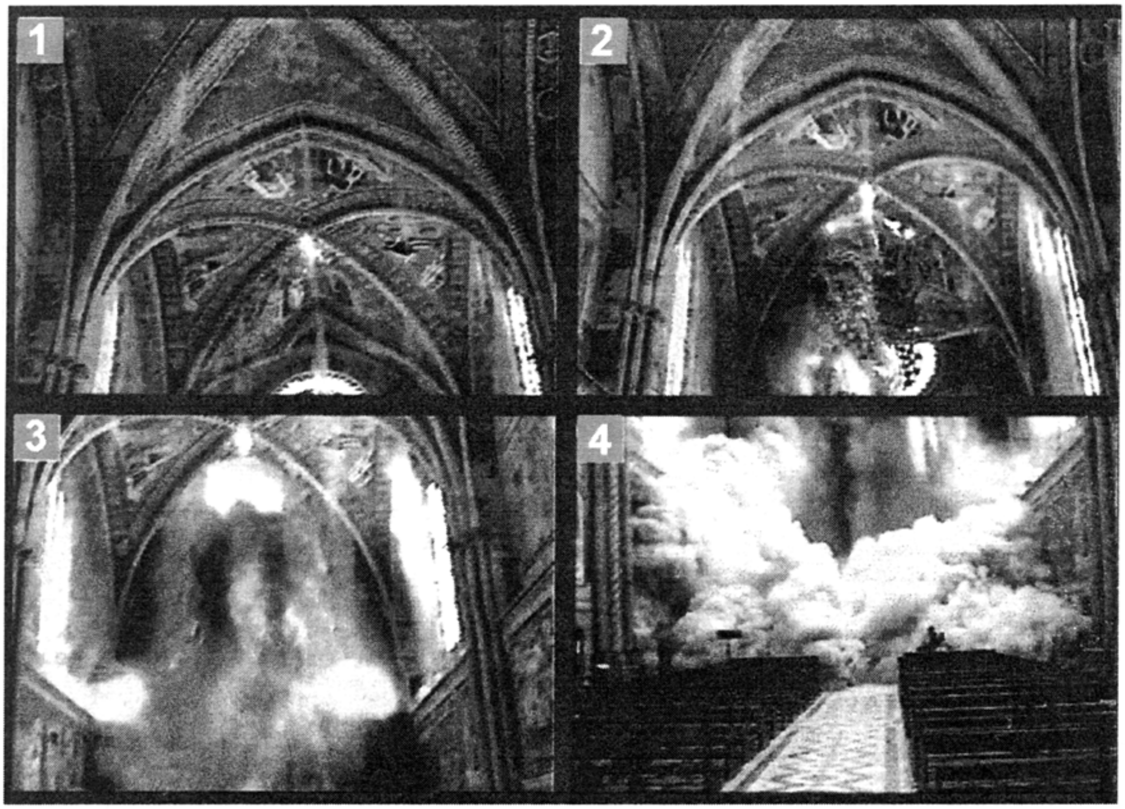

Plate 4.1: Collapse sequence of the vault of the Basilica of San Francesco

Plate 4.2: Temporary accommodation 10 and 11 October: Annifo

Plate 4.3: Temporary accommodation 10 and 11 October: Nocera Umbra

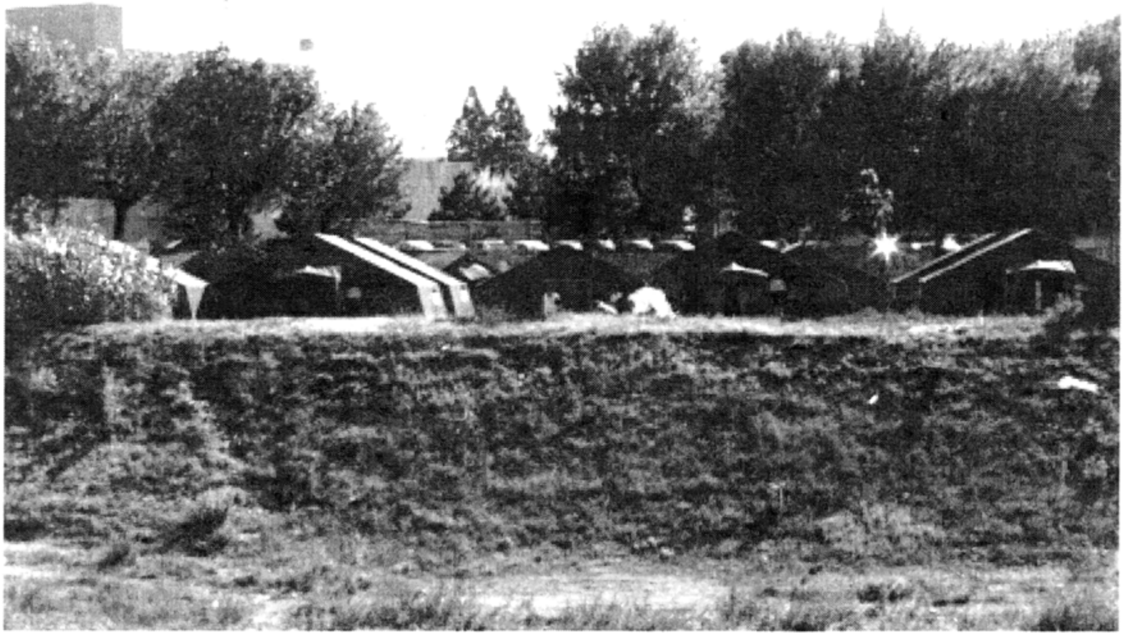

Plate 4.4: Temporary accommodation 10 and 11 October: Foligno

Plate 4.5: Temporary accommodation: catering at Nocera Umbra

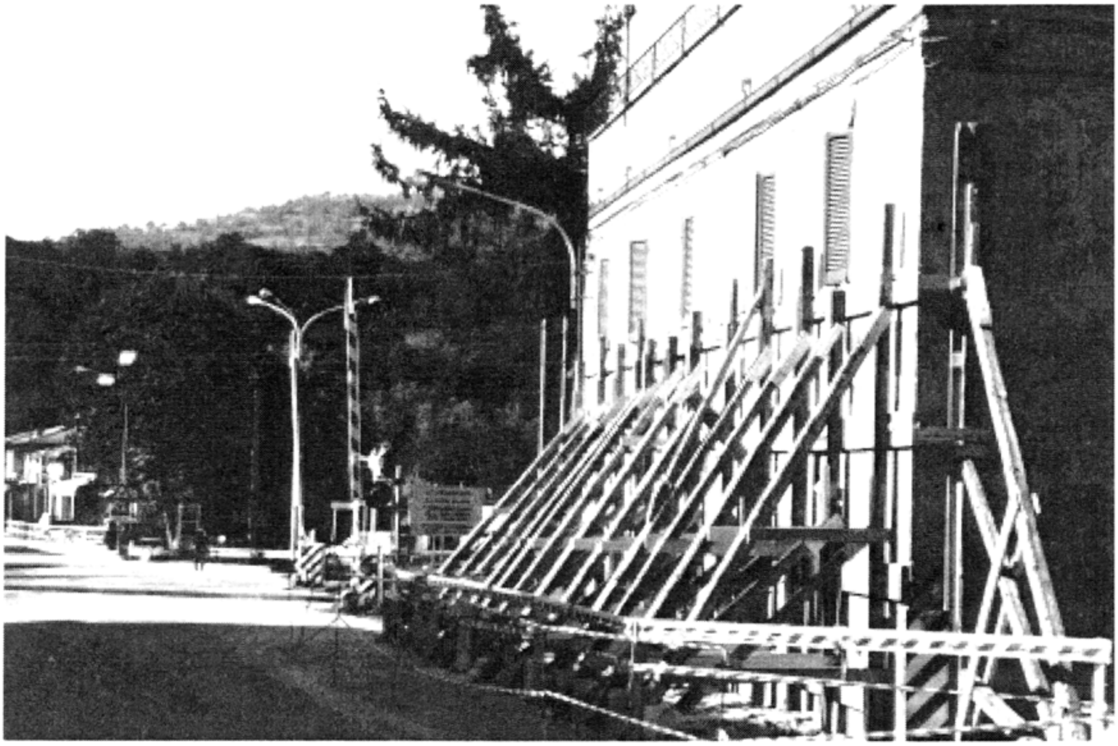

Plate 4.6: Emergency activities 10 and 11 October: shoring buildings on major routes: Nocera Scalo

Plate 4.7: Emergency activities 10-11 October: removing loose roof materials: Nocera Umbra

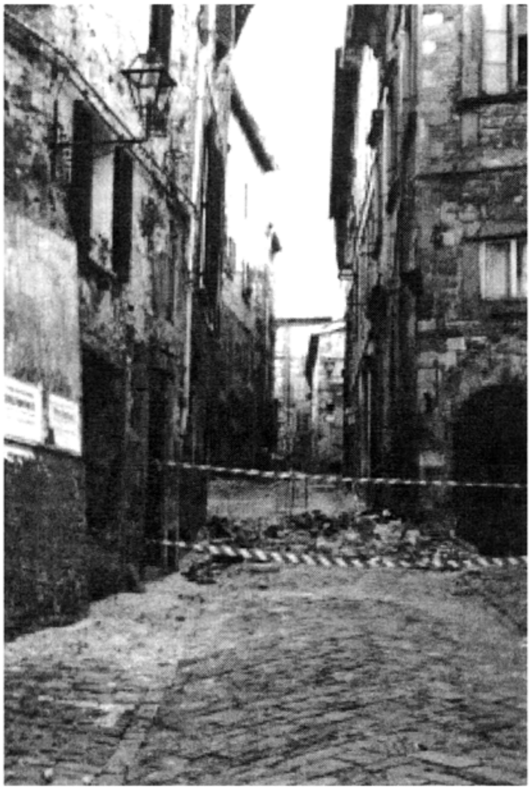

Plate 4.8: Emergency activities 10-11 October: securing dangerous areas: Nocera Umbra

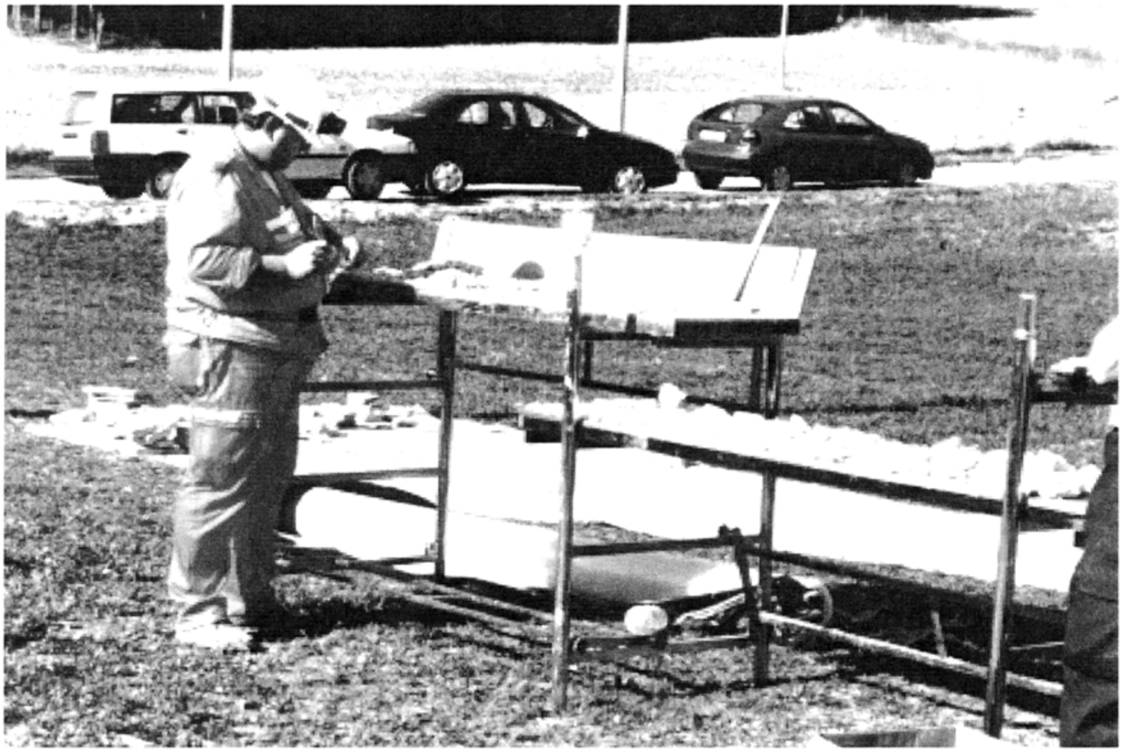

Plate 4.9: Emergency activities 10 and 11 October: retrieving damaged frescoes: Cesi church

Plate 4.10: Emergency activities 10 and 11 October: strapping dangerous masonry: Nocera Umbra

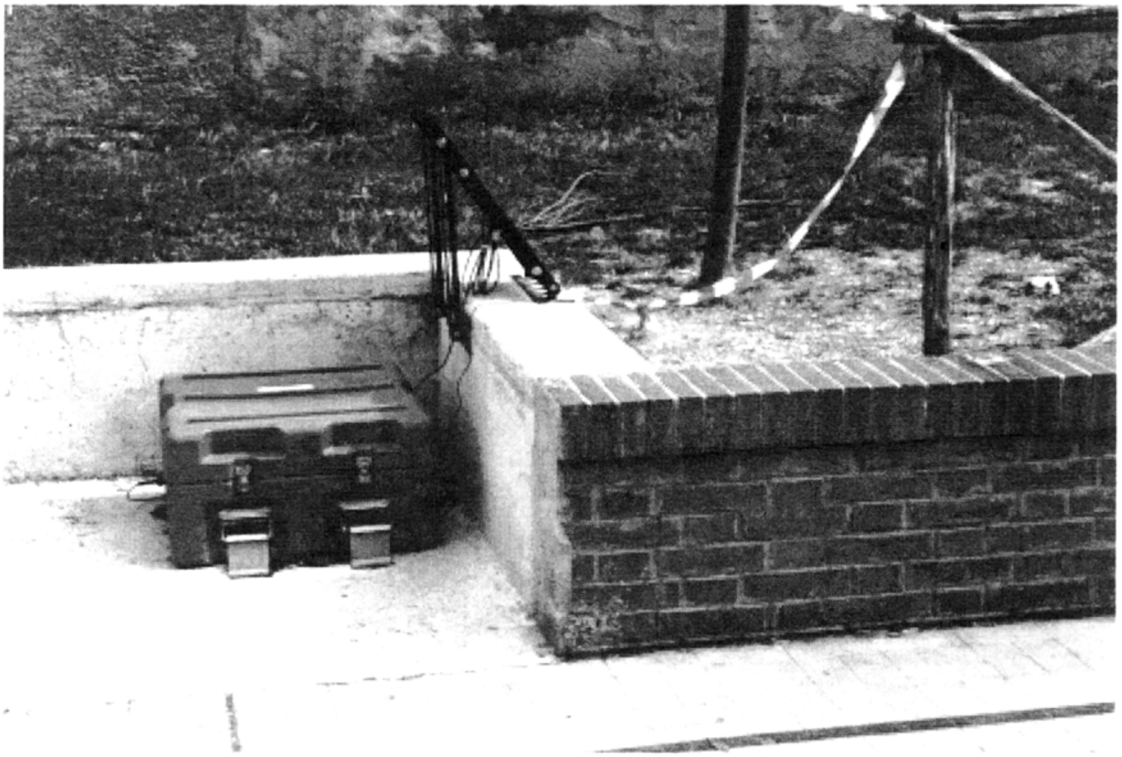

Plate 4.11: Temporary strong motion instrument: Nocera Umbra

APPENDIX 1 SCALES OF EARTHQUAKE INTENSITY

R Spence
University of Cambridge

Intensity is a measure of the severity of ground shaking in an area, determined from felt effects by people, damage to buildings, and the effects on the ground. Several scales of intensity are in use internationally, the most common being the Modified Mercalli scale (MM, most commonly used in the United States and New Zealand) and the MSK scale, which has been most commonly used in Europe in recent years, but since 1996 has been replaced officially by the EMS (European Macroseismic Scale), (Grünthal, 1993).

The Mercalli Cancani Seiberg (MCS) scale, first proposed in 1916 was the forerunner of both of these scales, and has been used continuously in Italy for initial macroseismic intensity evaluation in preference to either of the more advanced scales, although it is no longer used elsewhere.

Each of the three scales has 12 points, and a summary of the definitions of intensity levels 6 to 10 on each of the three scales is shown in Table A1.1 below.

The principal reasons for the continuing use of the MCS scale in Italy are that:

- it is independent of classification of building classes, and hence can be used quickly by seismologists without having to assess the distribution of building types in each locality.
- MCS intensity assignments and maps have been employed continuously over a long period of time, and any change in scale would create a break in that continuity, and difficulty in comparing earthquake effects in different time periods.

The problem associated with this is that the intensity level defined at any point depends partly on the quality of the buildings at that point. Camassi et al. (1997) have acknowledged that the intensity assignments in some of the mountain villages in this event was affected by their poorer quality of construction.

Strictly no subdivision of the scale is permissible, and it is for this reason that Roman numerals have been adopted for the scale points in all three scales. However, the use of half intensity points is very common, the use of intensity 6.5 MCS, for instance implying that the intensity lies roughly halfway between the definitions of level VI and level VII. In this document, following Italian publications, intensities have been defined in Arabic numerals throughout.

Different standard formulae are used for converting MCS intensity into EMS/MSK intensity. A common assumption is that MSK intensity is one unit lower than MCS intensity, in the range 5 to 9. However Margottini (1993) gives local intensities for more than 50 accelerometric stations in terms of both EMS/MSK and MCS intensity scales, from which it can be deduced that, on average:

$I_{EMS} = I_{MCS}$ for $I_{MCS} < 6$, and
$I_{EMS} = I_{MCS} - 0.4$ for $I_{MCS} =$ 6 to 8

Unfortunately, no simple correlation can be given, because, as can be seen from the above definitions, the relative postioning on the intensity scales will vary according to the number of recent, or better quality masonry buildings in the set of buildings surveyed in any location. Differences between intensity measured on the MCS and EMS/MSK scale are thus likely to change with time as the quality and resistance of the building stock changes. This time-dependence has been discussed by Spence (1998).

Intensity Level	MCS Scale Definition	MMI Definition	EMS Definition
VI	**Heavy** Felt by everyone with fear; many people escape outside; pictures, books fall down Furniture moves Bells ring Some buildings with strong structure suffer light damage Weak buildings suffer heavier damage Some tiles and chimney pots fall	Felt by all Many frightened and run outdoors Books, pictures fall Furniture moves Small bells ring Weak plaster and Masonry D cracked	**Slightly damaging** Felt by most indoors and many outdoors; many frightened and run outdoors Small objects may fall and furniture shift Damage of grade 1 sustained by many buildings; a few suffer damage grade 2
VII	**Very heavy** Serious damage to furniture and objects Moderate damage for strong buildings - light cracks in walls, plaster falls, tiles slide and chimney pots fall Some badly built buildings are destroyed In frame buildings, heavier damage to plaster	Difficult to stand Hanging objects quiver; furniture broken Damage to masonry D, including cracks: Weak chimneys broken at roof line. Fall of plaster, loose bricks tiles cornices, unbraced parapets	**Damaging** Most people frightened and try to run outdoors Furniture shifted or overturned; objects fall from shelves in large numbers Many buildings of class B and a few of class C suffer damage grade 2 Many buildings of class A and a few of class B suffer damage grade 3 A few of grade A suffer damage grade 4
VIII	**Ruinous** Heavier furniture moves far Statues, monuments overturn About a quarter of houses suffer heavy damage; some collapse or become uninhabitable Framed buildings suffer larger damage	Steering of cars affected; Damage to masonry C; partial collapse Some damage to masonry B. None to Masonry A Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks	**Heavily damaging** Furniture may be overturned Tombstones occasionally displaced twisted or overturned Many buildings of class C suffer damage grade 2 Many buildings of class B and a few of class C suffer damage grade 3 Many buildings of class A and a few of class B suffer damage grade 4 A few buildings of class A suffer damage grade 5
IX	**Destructive** About half of masonry buildings seriously damaged; many buildings collapse; most become uninhabitable; framed buildings are deformed and move off masonry foundations	General panic Masonry D destroyed; masonry C heavily damaged sometimes with complete collapse; masonry B seriously damaged. General damage to foundations. Frame structures if not bolted shifted off foundations	**Destructive** General panic Many monuments and columns fall or are twisted Many buildings of class C suffer damage grade 3. Many buildings of class B and a few of class C suffer damage grade 4 Many buildings of class A and a few of class B suffer damage grade 5
X	**Completely destructive** Heavy destruction for about 75% of buildings; most collapse Even well built wooden buildings suffer heavy damage or are destroyed	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed	**Very destructive** Many buildings of class C suffer damage grade 4. Many buildings of class B and a few of class C suffer damage grade 5 as do most buildings of class A

Table A1.1: The three principal scales of seismic intensity and brief definitions in the range VI to X

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APPENDIX 2 IMPLICATIONS FOR THE DESIGN OF NEW UNREINFORCED MASONRY BUILDINGS IN EARTHQUAKE AREAS

B Martin
Alan Baxter and Associates

A2.1 General considerations

Section 2.4 indicated that the shape of the building can be chosen to avoid tension developing under earthquake loads. It was also noted that the shape of the building has an effect on the natural periods of the building and hence the loads that it is subject to during an earthquake.

This suggests that the structural form for unreinforced masonry structures in earthquake areas should ideally be chosen so that the building can accommodate lateral loads without generating tensions in the structure. It also suggests that where possible the shape should be chosen so that the natural period of the structure is such that earthquake loads are minimised. Section 2.4 also indicated that a masonry structure of good quality construction will be less seriously damaged than one of poor quality construction if earthquake loads exceed the design conditions.

A2.2 Choice of shape to accommodate earthquake loads

For the design of two dimensional masonry elements (such as arches) it can be assumed that if a compressive load-path can be found that remains within the structure for a particular loading condition then the structure will be able to support that loading condition.

For the design of several new masonry buildings, Alan Baxter & Associates has extended this principle to cover masonry surfaces. It has been assumed that if a combination of compressive axial and hoop loads can be found that remain within a structure for a particular loading condition, then the structure will be able to support that load combination (Figure A2.1).

This approach allows the designer to estimate under what load cracking will occur, and more importantly to identify the areas where additional buttressing or ties would be most useful. The recent earthquakes made possible a qualitative assessment of the approach, by comparing the areas where the approach would cause us to expect cracking with the areas where cracking actually occurred (as set out in Section 2.6 above). A summary of the comparison for simple rectangular buildings is set out in Figures A2.2 and A2.4.

In generating these sketches it is assumed that walls B and D, the long walls are too slender to arch horizontally, and that walls A and C, the shorter walls are able to arch horizontally The proportions of the building make walls A and C stockier than walls B and D (Figure A2.2).

The cracking at the high level adjacent to the corners of rectangular buildings suggested by the sketches for Load Case 1, Figure A2.3, is compatible with the damage caused to unreinforced masonry buildings by the earthquakes. The horizontal loads applied to walls B and D by the roof rafters suggested that the hoop tensions will be greater in wall D than in wall B. Therefore failure will be more likely for wall D than for wall B; this suggests that any out of plane wall failure is likely to occur outwards from the building. This is consistent with the damage seen.

Similarly the propping provided by the roof to wall A in Load Case 2, Figure A2.4, suggests that it is likely that wall C will shed its outer face before wall A sheds its inner face. This is consistent with the damage caused by the recent earthquakes; the upper part of the outer face of several gable walls had come away from the remaining masonry. The cracking that was found in the return walls adjacent to several church facades is consistent with the risk of cracking identified on the sketch dealing with wall C (Load Case 2).

The comparison has shown that the approach can be used to correctly predict the areas where cracking is most likely to occur. However for more complicated structures it may be difficult to identify a suitable load-path arrangement to predict crack locations without carrying out an accurate numerical analysis.

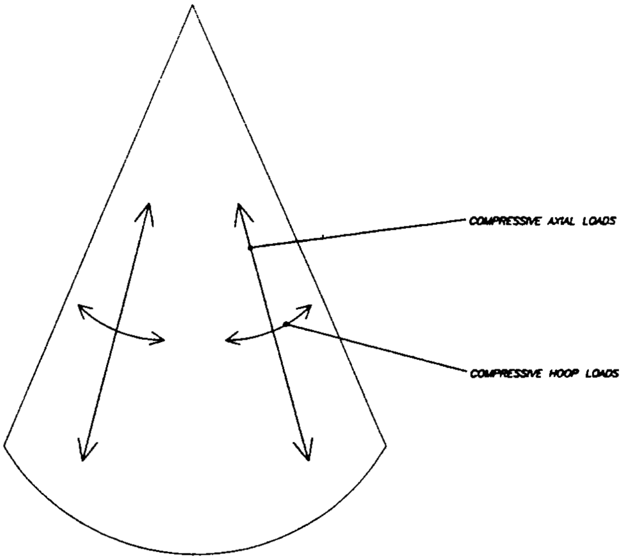


Figure A2.1 General loading in a curved masonry surface

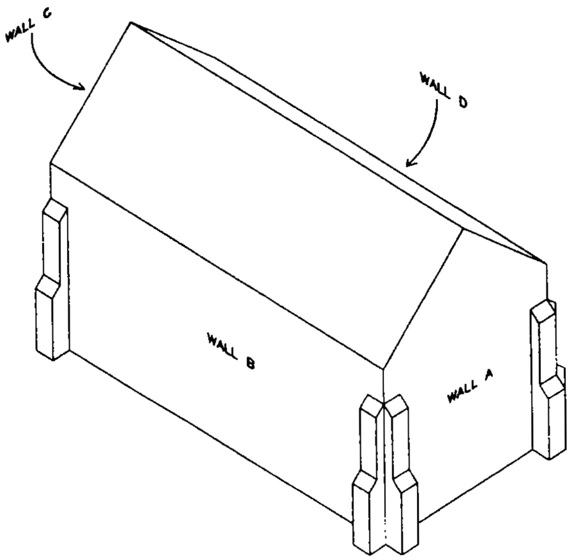


Figure A2.2 The simple rectangular building considered

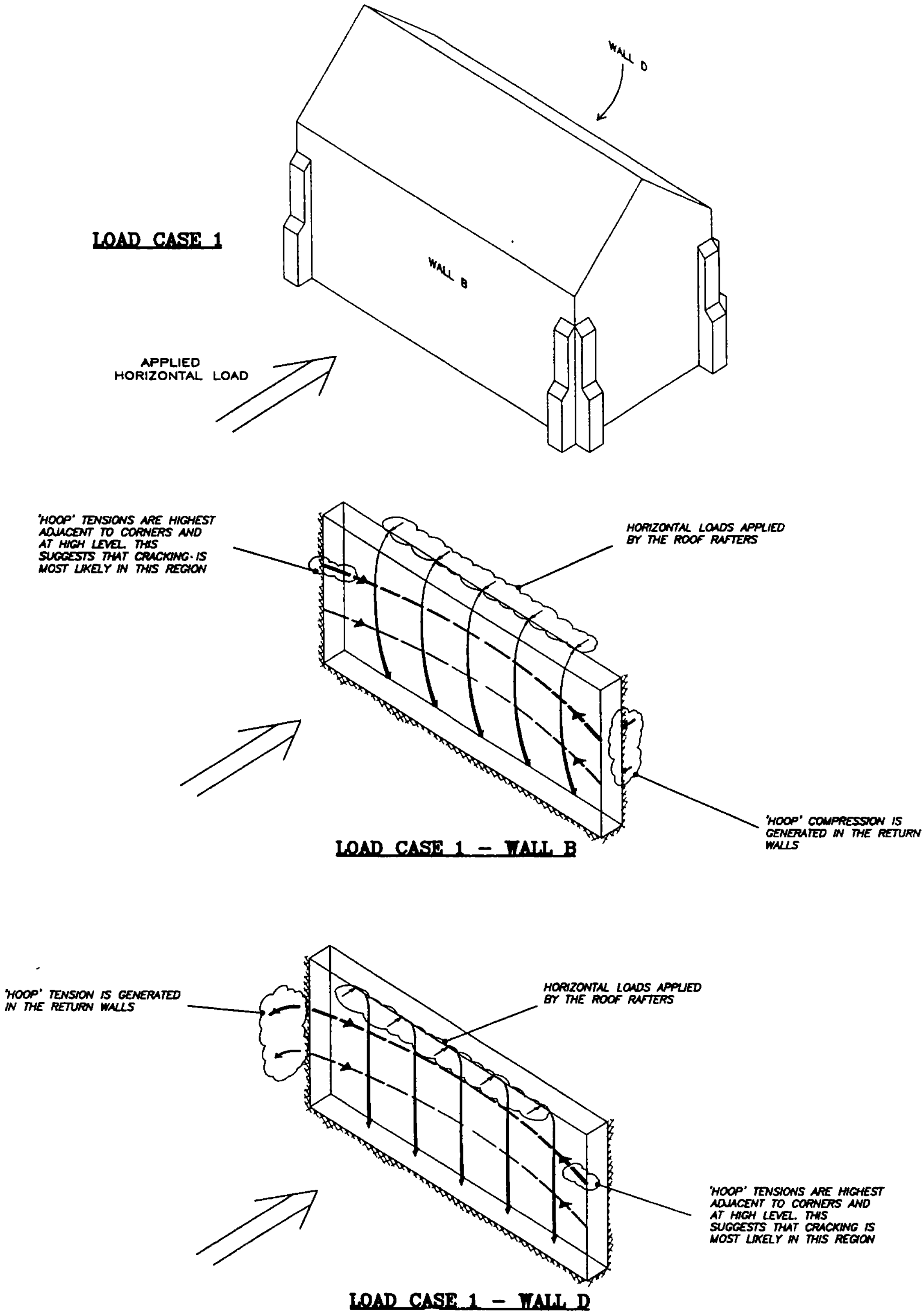
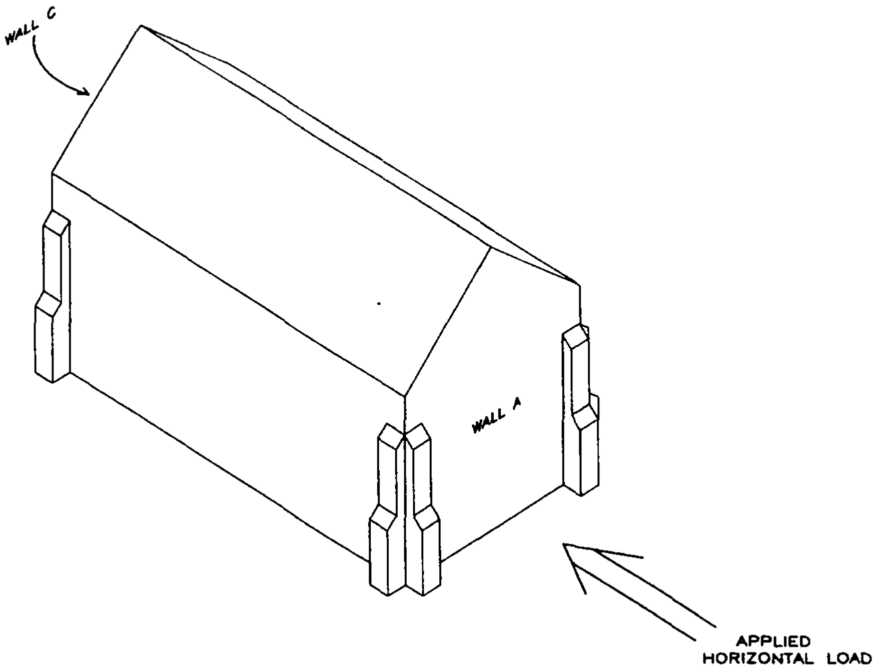
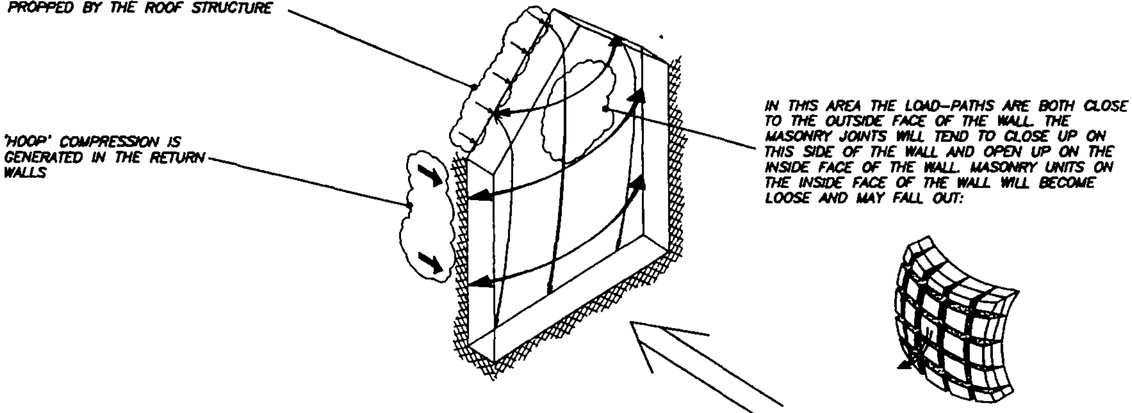


Figure A2.3 Load Case 1: Horizontal loading perpendicular to wall B

LOAD CASE 2

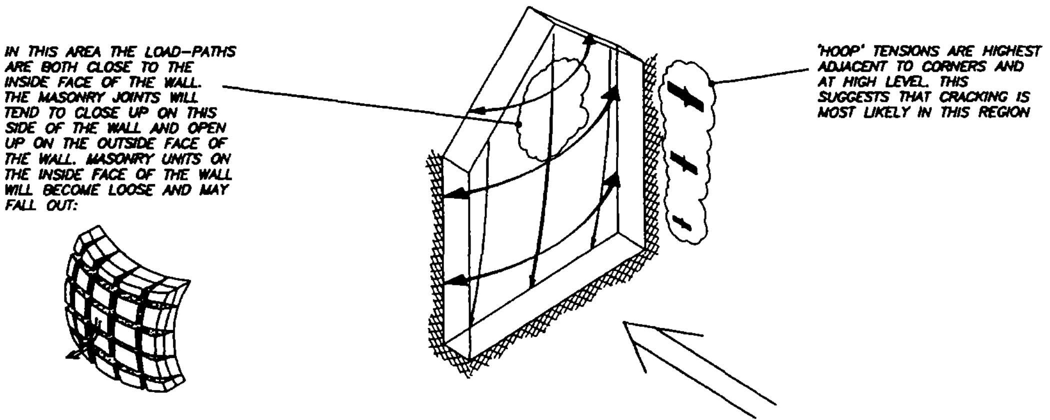




'HOOP' COMPRESSION IS GENERATED IN THE RETURN WALLS

IN THIS AREA THE LOAD-PATHS ARE BOTH CLOSE TO THE OUTSIDE FACE OF THE WALL. THE MASONRY JOINTS WILL TEND TO CLOSE UP ON THIS SIDE OF THE WALL AND OPEN UP ON THE INSIDE FACE OF THE WALL. MASONRY UNITS ON THE INSIDE FACE OF THE WALL WILL BECOME LOOSE AND MAY FALL OUT:

LOAD CASE 2 - WALL A



IN THIS AREA THE LOAD-PATHS ARE BOTH CLOSE TO THE INSIDE FACE OF THE WALL. THE MASONRY JOINTS WILL TEND TO CLOSE UP ON THIS SIDE OF THE WALL AND OPEN UP ON THE OUTSIDE FACE OF THE WALL. MASONRY UNITS ON THE INSIDE FACE OF THE WALL WILL BECOME LOOSE AND MAY FALL OUT:

'HOOP' TENSIONS ARE HIGHEST ADJACENT TO CORNERS AND AT HIGH LEVEL. THIS SUGGESTS THAT CRACKING IS MOST LIKELY IN THIS REGION

LOAD CASE 2 - WALL C

Figure A2.4 Load Case 2: Horizontal loading perpendicular to wall A