THE AUGUSTA, SICILY EARTHQUAKE OF 13 DECEMBER 1990

A FIELD REPORT BY EEFIT

R E Hughes
International Heritage Conservation
& Management, London

R Nichols
Allott & Lomax, Manchester

T S Paul
Ove Arup & Partners, London

J Riding
British Nuclear Fuels plc, Warrington

EEFIT
Earthquake Engineering
Field Investigation Team
Institution of Structural Engineers
11 Upper Belgrave Street
London SW1X 8BH
United Kingdom

SUMMARY

On 13 December 1990, a moderate earthquake, magnitude $5.1M_B$, struck the southeast of Sicily causing damage to historical and vernacular buildings. The statistics indicate that 19 people died, 200 people were injured and approximately 2,500 were left homeless. Three weeks after the earthquake a four man team from EEFIT travelled to Sicily and spent 3 days on the eastern side of the island carrying out visual inspections of engineered and non-engineered structures in the epicentral region.

The majority of the observed damage was to unreinforced masonry buildings, both historical and modern. In particular, at Carlentini situated on the steep slopes of a hill spur the damage appeared to be more concentrated despite being approximately 50km from the epicentre. Generally, unreinforced masonry buildings that had been strengthened by steel tie bars and anchor plates resisted the ground motions satisfactorily, with little damage.

Engineered buildings generally resisted the earthquake without any damage. However in Augusta major damage to a residential flat complex was observed. The five storey flat structures contained a "soft storey" at ground level to allow car parking and were built on reclaimed land over approximately 30 metres of soft clay. This indicates that vulnerable engineered structures will be damaged by moderate levels of ground motion such as those caused by the 1990 Sicilian earthquake.

The Augusta region contains one of the largest concentrations of petrochemical installations in the world. No damage was observed to structural steelwork, storage tanks or main pipework tracks. Some installations were temporarily shutdown for precautionary safety inspections following the earthquake.

RIASSUNTO

Il 13 dicembre 1990, un terremoto di modesta entità (magnitudo 5.1Mb) scosse la regione sud-est della Sicilia, causando danno ad edifici storici. Le statistiche indicano che le vittime furono 19, 200 i feriti e approssimativamente 2550 i senzatetto. Tre settimane dopo, un gruppo composto da quattro membri dell'EEFIT si recó in Sicilia, dove durante tre giorni ispezionó le strutture nella regione epicentrale.

La maggior parte del danno osservato, fu arrecato a strutture non armate in muratura, sia di tipo storico che moderno. In particolare a Calentini, situata sulle più pendenti chine dello sperone di una collina, il danno appare più concentrato, malgrado il sito si trovi ad approssivativamente 50km dall'epicentro. Generalmente, le strutture in muratura rinforzate da barre di legatura e piastre di ancoraggio resistettero alle scosse in modo soddisfacente, riportando solo danni di modesta entita.

Le moderne strutture in cemento armato sopportarono il sisma senza alcun danno. Tuttavia ad Augusta furono osservati gravi danni ad un complesso residenziale. L'edificio di cinque piani aveva una scarsa rigidezza al piano terreno per permettere il parcheggio delle autovetture; inoltre la costruzione sedeva su un terrapieno costituito da circa 30m di argilla soffice. Questo fatto indica che anche le strutture in cemento armato vulnerabili possono essere danneggiate da scosse di modesta entità, come quelle causate dal terremoto del 1990.

Nella regione di Augusta, malgrado essa possegga una delle piu' alte concentrazioni di installazioni petrolchimiche del mondo, nessun danno apparente fu arrecato a costruzioni in acciaio, serbatoi o condotti. Alcune installazioni furono temporaneamente chiuse e ispezionate per misure precauzionali in seguito al sisma.

CONTENTS

1 INTRODUCTION

1.1 Background to Field Mission

Three weeks after the Sicilian earthquake of 13 December 1990 a four man team from the UK based Earthquake Engineering Field Investigation Team (EEFIT) travelled to Sicily and spent 3 days on the eastern side of the island. The team, comprising the four authors of this report, visited a number of representative sites in the epicentral area carrying out visual inspections of engineered and non-engineered structures, and having discussions with local representatives including engineers and architects. The locations of the sites visited are shown in Figure 1.

1.2 Report Authors

- **Richard Hughes** is a director of International Heritage Conservation and Management (IHCM). He specialises in the conservation of historic buildings and acts as a Consultant to UNESCO, the Aga Khan Foundation and Ove Arup and Partners. Mr. Hughes has carried out field investigations of earthquakes in Yemen, Turkey and Pakistan specialising in masonry and adobe buildings. He acted as leader of the EEFIT team.

- **Tim Paul** is a geotechnical engineer with Ove Arup and Partners, London. He has carried out seismic hazard assessments and site response studies for a wide range of structures worldwide. In addition Mr. Paul has particular interest in assessment of liquefaction potential and seismic design of foundations.

- **Bob Nichols** is a principal engineer in Allott and Lomax's Special Projects Group. He has been responsible for the seismic design of dams and other structures in Turkey, Pakistan, Algeria, Peru and Armenia. He is currently involved with the seismic appraisal of UK Nuclear Facilities.

- **John Riding** is a senior structural engineer with British Nuclear Fuels plc, where he leads teams of engineers in the design of nuclear related structures, including seismic design. In addition to new structures he is involved with seismically upgrading existing structures and seismic damage assessment.

1.3 EEFIT

EEFIT was formed in 1982. Its principal activity is conducting field investigations of damaging earthquakes in order to report on the behaviour and performance of building, civil and industrial structures under earthquake ground motions. Its members, based in Britain, comprise mainly engineers and architects from both academic and industrial organisations. EEFIT has investigated 11 earthquakes in the period 1983-1992 and reports have been published or are in preparation for these events.

2 THE EARTHQUAKE AFFECTED AREA

2.1 Topography

The earthquake affected area includes a broad coastal plain comprising two or more low horizontal terraces (+20 and+80mOD) backing a slight shore line cliff (+5mOD). These distinctive terraces and the absence of an extensive flood plain are indicative of "recent" coastal uplift. This landscape is approximately 3km wide and is edged to the west by a significant mountainous scarp, approaching 500m high, and with denuded foothills (+150 to 200mOD) of a former terrace, Plate 1. This "old" cliff line, running parallel to the coast, is regularly dissected by steep sided gorges, giving further evidence of active tectonic readjustment.

2.2 Geology

The underlying geology consists of horizontally bedded limestones and sandy limestones. Where exposed along the scarp and in gorges they form a dramatic contouring effect. Inland of the scarp line is an extensive high plateau with broad exposures of a limestone peneplain, which is cut into by an intricate network of minor steep sided valleys. To the north of the affected area extrusive volcanic materials are superimposed on the plateau limestone.

2.3 Economy and Population

Augusta and Siracusa are historic port towns on locally exposed limestone outcrops and this has led to the development of major petrochemical works along the coast. Avola is a market town located central to the broad flat terraces, that are extensively used for citrus fruit cultivation. Noto, Carlentini and Melilli are all located inland along the scarp, on hill spurs formed between the deeply incised eastward descending valleys. In this terrain there are extensive vineyards and olive orchards. Siracusa is by far the biggest of the affected cities with a population approaching 120,000. Augusta is relatively small with a population of 40,000. Noto is the largest of the inland urban centres with a population of approximately 25,000.

3 SEISMOLOGICAL ASPECTS

3.1 Regional Tectonic Setting

Sicily is located in a complex tectonic environment at the boundary between the Eurasian and African plates (see Figure 2).

The western extent of the Calabrian Arc passes through Sicily and these thrust mechanisms indicate predominantly north-south compression. In the Straits of Messina, a region of active extension, dip-slip fault mechanisms are more significant.

3.2 Historical Seismicity

Eastern Sicily has a long history of experiencing destructive earthquakes. Figure 3 shows the epicentres of major earthquakes occurring in the period 1900-1980. This indicates that the seismic activity is concentrated in the Straits of Messina and around the Mount Etna volcano.

The eastern side of Sicily has experienced several such devastating earthquakes, with the catastrophic Messina earthquake of 1909 being the worst this century. Minor earthquakes regularly occur around Mt Etna, and interrelate will volcanic activity (Hughes, 1985).

One of the prime reasons for visiting this earthquake was because of Noto, a famous Late Baroque city, that was built as an entity in the early 18th century following a major earthquake. On the 9 January 1693 then again on 11 January the town of Noto and 40 others were struck by a major earthquake, "the like of which had not been felt before in southern Sicily". The local intensity at Noto was IX-X MSK. The epicentral magnitude was estimated from macroseismic data to have local Richter magnitude in excess of 7.5.

Noto was totally destroyed by the earthquake and approximately 3,000 people were killed there. It is reported that in the whole area more than 53,000 people were killed, but this is felt to be highly exaggerated. For example, it is recorded that more than 90% of the population of Catania was killed. Certainly the death toll was high, this perhaps being due to the timing of the main shocks, 2.45 and 4.30am respectively when people were asleep. Apart from building damage various rock falls and landslides occurred, the most dramatic of which was just to the south of Noto. The site of Noto was subsequently abandoned and a new city, visited by the EEFIT team, was built some 10km east, nearer the sea.

3.3 Earthquake of 13 December 1990

The earthquake on 13 December 1990 occurred at 01.24 hours local time. The epicentre was located approximately 10km northwest of Siracusa (see Figure 1). Preliminary calculations by various seismological organisations indicated the following range of magnitudes:

5.3 M_{sz}	(Source: CSEM, France)
5.5 M_B	(Source: British Geological Survey)
5.1 M_D	(Source: ING, Italy)
5.4 M_B	(Source: US Geological Survey)

The focal depth of the earthquake was estimated to be 10km.

In the two week period following the main shock there were four significant aftershocks (ING, 1991) whose details are summarised in Table 1.

Table 1 : Summary of main aftershocks (ING:1991)

Date	Time(Local)	Magnitude (M_D)
13/12/90	01.33	3.5
16/12/90	14.50	3.9
24/12/90	14.44	3.0
24/12/90	23.26	3.0

3.4 Strong Ground Motion Records

Figure 4 shows the locations of the ENEL accelerometer stations in Sicily and indicates those that were triggered by the earthquake. The maximum peak ground acceleration of 0.22g was recorded at Catania where the instrument is installed on the surface of thick alluvial deposits. In general, the peak horizontal ground accelerations were within the range 0.06-0.08g in the epicentral region (ENEL, 1991). The instrumental records indicate a relatively long duration of ground motion, 30-40 seconds. This was generally confirmed during discussions with people living in the epicentral area.

4 NON-ENGINEERED BUILDINGS

4.1 Sicilian Building Stock

4.1.1 General

The traditional structures of eastern Sicily are of three basic types:

i) One and two storey houses of lower income families in towns and villages and of farms. These structures are mostly built in load bearing limestone rubble and lime mortar.

ii) Two to four storey domestic commercial and administrative buildings. They are predominantly of load bearing random rubble masonry walls incorporating in their façades ashlar stone work ornamentation such as complex entablatures, pilasters and pediments, Plate 2.

iii) Three to five storey ashlar (cut stone) faced palaces, churches and public buildings. In most cases the ashlar stone is a veneer to lesser quality rubble stonework behind. Rear and party walls, those of lesser value for giving an image, are normally built in rubble stonework, Plates 3 and 4.

Noto and many other Late Baroque towns of eastern Sicily (including Avola and Carlentini) are unlike their medieval predecessors in having a formal street layout in a grid pattern. This required sites where there was a relatively flat topography. The smaller villages and towns (such as Melilli), because they are located on the crest of hill tops, have been forced to continue the medieval traditions of winding lanes. In the formal towns the public and religious structures occupy a central location with a surrounding area of commercial and middle class structures. The working classes then occupy fringe zones. In the more traditional hill top settlements there is clearly a considerable mixing of building types and functions and this has led to a more uniform density of occupation. This is in contrast with places like Noto where there is a very low central density with nearly a total absence of people at night. It is also very noticeable in all settlements that the growing population is now expanding onto lower quality and marginal land surrounding prime sites.

A special visit was made to Noto because one member of the EEFIT team had previously carried out building vulnerability studies there with colleagues from the Martin Centre, University of Cambridge (Coburn et al 1984).

4.1.2 Noto Building Stock

Noto, like most of the other Late Baroque towns has maintained its historic core intact and is therefore of major architectural importance.

In very general terms 64% of the historic buildings of Noto use a mixture of rubble and ashlar stonework. More than 75% of these are two storeys high and 18% are three or more storeys. The remaining 36% of the historic buildings are totally of random rubble masonry construction and some 60% of these are single storey.

Usually the degree, quality and extent of ornamentation increases with the wealth of the original occupant. The ornamentation consists of horizontal elements at ground and roof levels - pediments and entablatures respectively and a vertical pilaster element connecting these. On the ordinary domestic housing stock some cheaper imitation ornamentation is to be seen.

Common to most structures is the reliance on simple pitched roofs with a tile covering. Only in some of the grander churches and public buildings are triangular trusses and structural vaults seen. The ground floors generally have a high stone vaulted ceiling. Other floors are simple beams and planks. Generally, floors span between party walls so the façades only bear the load of the roofs.

The basically very simple box form random rubble building technique is based on a long tradition with many surviving medieval examples through the Catholic Western Mediterranean, particularly in Italy but also Spain and Portugal. Clearly all these types of structures are part of a common tradition once common throughout the Roman Empire.

Structures using ashlar stonework are also based on earlier traditions. Hence the Late Baroque structures of Noto draw upon Renaissance concepts that were ultimately inspired by classical Roman forms and Tuscan landscapes. In such a conservative landscape the early 18th century styles continued in weak Neo-Classical forms into the 19th-20th centuries, when concrete and steel permitted new architectural adventures.

The mixed ashlar-rubble constructions, perhaps the characteristic building type in the seismic areas of Eastern Sicily, were clearly designed to cheaply imitate and complement the grander structures. The stone rubble wall panels were rendered, whitewashed or painted and even made to imitate ashlar stone. The structure then heavily relies on a few refined elements such as ashlar pilasters, ornamented cornices, carved balconies and elaborate door/window surrounds. Such upstanding features were those generally more exposed and where better structural durability was required.

4.1.3 The Vulnerability of Noto

Historic Noto, very representative of the surrounding towns, consists of a mixture of the three types of structures described above. They all date to the early years of the 18th century, for a new town of a new age and on a new site. Since then, they have together experienced many effects of smaller earthquakes but individually have gone through many phases of deterioration, repair and internal modification. It is not surprising therefore to find that 37% of a significant sample (536 buildings) of old stone masonry structures are seriously deteriorated (Coburn et al, 1984):

Table 2 : Damage Survey in Noto - 1984

Characteristics of damage for all deteriorated buildings	%	No of affected buildings in the sample	Total affected buildings extrapolated for Noto
Wall fabric disintegrating	32	63	795
Cracking around windows and door openings	40	79	997
Vertical cracking at corners (wall-wall separation)	26	51	644
Mid-wall cracking	19	38	480
Lintel cracking	6	12	151
Diagonal cracking at corners	3	6	76

This survey may have seriously underestimated the poor status of the structures since it was based only on two types of external problems - cracking and fabric decay.

The same survey interestingly showed that only 11% of their sample had obviously repaired cracks, this suggesting a poor maintenance record. Of those buildings with obvious deterioration 14% had been tied with steel rods. This may suggest a significant proportion of severely distorted structures had required attention. The survey also suggested that a total of some 25 structures in historic Noto were abandoned through being partially collapsed. There may be other dangerous structures, but it is difficult to tell if the boarding up was an abandonment or just vacation during winter months.

4.2 Damage to Unreinforced Masonry Buildings

4.2.1 General

The EEFIT field mission enabled general viewing of buildings in Siracusa, Avola and Augusta and of rural buildings throughout the region. More detailed observations were made in Noto, Melilli and Carlentini. Throughout the earthquake affected area the traditional building stock was found to be remarkably homogeneous, conforming to the previously described three types (see 4.1.1). The building conditions in all three towns were felt to be consistent to that determined for Noto in the Cambridge survey (Coburn et al, 1984).

Review of damage throughout the area conclusively showed greatest effects were experienced in Carlentini, that is, at some distance from the epicentre NE of Augusta.

Virtually no damage was observed in Siracusa and Augusta, nearest towns to the epicentre and in settlements further afield than Avola, Noto, Melilli and Carlentini. Since the traditional building stock is so similar throughout the region the variations in damage appear to result from local ground conditions or topographic effects.

In Noto and Melilli there was no noticeable concentration of damage and no apparent pattern to the distribution of damage. In Carlentini damage to old, and new, buildings was highly concentrated in just the NW corner of the town and adjacent to a cliff edge. It was very noticeable that within all three of the hill spur towns the character of damage was very similar.

The more severe damage was defined by safety hoardings, shoring and security fences, Plate 5. Hoardings, stopping entrance to buildings, were perhaps indicating dangerous internal conditions, but were rarely seen. Most of the damaged structures had their façades shored indicating the out of plane leaning of the whole wall. In these buildings it is possible that there was sufficient internal structure remaining to permit strengthening and repair. Security fences, limiting passage of pedestrians along the pavement, defined those structures where ashlar stones from the entablatures or where loose roof tiles had fallen off. At these places there was a high probability that other materials could fall off. The bracing of windows and doors was only occasionally seen and was associated with the sagging of the keystones of horizontal multi-piece lintels. Minor movements were noted to arched openings but not affecting their overall in-plane stability.

Generally, throughout the earthquake affected area, wall roof and floor collapses were extremely few in number. In Siracusa, Augusta and Avola no cases of collapse were found and in Noto only three cases were seen. In Melilli again only a few cases of collapse were seen while in Carlentini where the damage was severe, collapse of the traditional structures was concentrated on those buildings where there had been recent additions to the superstructures and where the buildings were very much inter-mixed with new sorts of houses. Because of the overall limited number of buildings collapses there was insufficient data to define the sequence of the failure mechanisms.

It was surprising not to see many forms of slight damage that in other earthquakes are the first forms of distress to occur, such as the dislodgement of stones and rubbish on the edge of roofs; the falling of flower pots off window sills; and the failure of chimneys and water tanks on roofs.

4.2.2 Damage in Noto

The poor condition of the many fine structures along the main axial road of Noto had been recognised in the Cambridge University surveys (Codurn et al, 1984 and Hughes, 1984) and their high earthquake vulnerability reported. The quality of the building clearly relates to the topography and ground conditions (Hughes, 1985). Many of these structures were subsequently shored and some are presently being strengthened and renovated. No damage resulting from this earthquake was reported in these structures. The main façade of the Cathedral had in 1984 been seen as vulnerable since many joints were opened and the elaborate entablature had rotated outwards on its supporting complex arrangement of columns (Hughes 1985). The two bell towers which were seen as particularly weak, perhaps the result of previous earthquakes as well as well as due to the growth of vegetation in joints, had not been strengthened. No damage to the main façade and to its statuary was observed. There was however extension of cracks in the two bell towers, reinforcing the need for their strengthening.

Elsewhere in Noto most damage was found in the upper city in the two storey buildings, Plates 6 and 7. Here damage was recognised by shoring and by pavement barriers and represents the out of plane tilting of walls and entablature failures respectively. Surprisingly, damage of inferior party and side walls was not found, this perhaps reflecting their use for taking floor loads - from the ground floor stone arches and wooden beam system above. In the upper city no churches appear to have their façades shored up.

It would appear that damage was so limited that there was no systematic documentation of damage character and monitoring of deformation. The shoring on domestic structures was probably privately carried out. Only one tell-tale (an Avongard standard pair of plastic plates) was seen and this on a structure where there was a complex system of cracks requiring the façade to be shored.

In Noto, there was no recognisable correlation of damage to the geotechnical zones derived from topographical, geological and hydrological mapping (Hughes, 1985). For example, no damage was noted along the Travatine Cliff that divides the historic core of Noto into two. No problems seemed to have occurred where roads had cut down into the rock leaving building foundations as upstanding stone plinths. In the NE corner of the old city the main road that circumnavigates along the top of the hillside is founded on fill, formerly by tipping away from the platform edge. Buildings founded beyond the road, on the fill and steep hillside, had significantly moved. However, it was clear that the road had on many occasions subsided and had been built back up to grade, suggesting an ongoing serious slope stability problem.

4.2.3 Damage in Melilli

Melilli unlike Noto is built on the crest of an acute hill spur. It is an example of a more typical and traditional medieval town of the region with no urban planning producing a grid system of streets and no central administrative area. Generally, the town is based on roads that run around contours of the spur connected through with a complex system of winding steep and narrow lanes. Most of the buildings are two storeys high with less façade ornamentation, such as pilasters, balconies, window/door canopies, than seen in Noto. A significant number of structures had no corner pilasters. Compared with Noto there appears to be a greater mix of building styles and ages, perhaps reflecting a greater social mix. Clearly Melilli is a working town and not a regional administrative centre, and hence has very few grand public buildings to compare with Noto. It is possible that when the owner decided to reconstruct his house it was no more than a gentrification by replacement of the façade in a new fashion.

It may be for this reason that the overall impression of damage was one of effects to façades. Very little damage was seen to party walls, normally the weaker structural element. Those façades that were shored seemed to have a problem stemming from the first floor where a line of weakness perhaps exists formed by tops of window openings and floor beam sockets.

As in Noto there was a noticeable level of damage to corner structures where the pair of adjoining walls both moved out of plane. Only one structure seen had the classic corner wedge failure, Plate 8. A structure adjacent to this had a complete load bearing façade failure. Here the beam ends were found to be severely decayed.

One old structure had been extended with an additional storey and this included insertion of a new chimney duct inside the wall thickness. This structure was severely cracked and was temporarily tied together with a system of steel cable straps (Plate 9). Most of those structures with out of plane tilting of façades had no obvious signs of window/door lintel block displacement. However, as in Noto many structures showed the displacement of ashlar blocks in the entablature.

4.2.4 Damage in Carlentini

Carlentini like Noto is laid out on a formal grid pattern of streets on a plateau feature of a hill spur crest. Like Noto the spur is surrounded by very steep slopes and cliffs, Plate 10. Throughout most of the town no damage was observed to old and new buildings and no shoring and pavement barriers were present. In the main town square one formal building had entablature damage and all windows were strutted to support the lintels.

The significant damage in Carlentini occured in the NW corner of the town near to a cliff edge where there had been significant collapse of modern three storey houses. Approximately 30 street "blocks" had been cordoned off and all the buildings evacuated, Plate 11. Here the damage could have resulted from local site amplification effects, perhaps exacerbated by reuse of old foundations or building over old basements cut into the underlying limestones. Damage to the traditional houses was much less severe than to the new, but with similar failure mechanisms to those seen in Noto and Melilli. Most damage was to two storey houses with out of plane tilting of façades and falling off of insecure entablatures. No exacerbated effects were apparent where the old type of houses were mixed in with the new and had even been modernised, for example, with the covering of the façades with glazed tiles. It was the collapse of structures here (Plates 12 and 13) that caused the reported 19 deaths.

5 ENGINEERED STRUCTURES

5.1 Damage to Engineered Structures

The EEFIT team carried out visual inspections of commercial office blocks, retail centres and medium rise residential buildings in the epicentral areas at Siracusa, Melilli, Augusta and Carlentini.

In general, little or no evidence of damage was observed. However an exception to this was a residential flats complex in Augusta which experienced extensive damage to masonry infill panels. This is described in detail in Section 5.2. In Noto slight movement of reinforced concrete frames was evident by mosaic cracking away from their motor bedding. There was no evidence of infill panel damage at the majority of the modern blocks of flats in these areas.

5.2 The Augusta Flats Complex

The modern blocks of flats in Augusta, inspected by the EEFIT team, are typical of this type of building as observed in this area of Sicily. The flats are no more than ten years old and due to earthquake damage had been evacuated at the time of inspection. These flats were of particular interest as they are located no more than 10km from the earthquake epicentre and therefore would have experienced the earthquake to a greater extent than other structures inspected.

The flats are five or six storeys in height, the ground storey being mostly open to allow personnel access and car parking, thus providing a 'soft storey' at ground level, Plate 14. A reinforced concrete (RC) frame of columns and beams linked with reinforced concrete slabs form the basic building structure. The RC frame is infilled by exterior and interior masonry panels, in the form of either clay bricks or more commonly hollow tile blocks.

Constructed on a coastal plain, on reclaimed land, the flats are reportedly founded on bored piles which penetrate 3m of imported fill material, 30m of soft alluvium with the pile toe penetrating approximately 20m into stiff clay.

It was immediately apparent that some blocks of flats had suffered significant damage, and were uninhabitable. The masonry infill panels, both internal and external, had suffered particularly badly. Complete panels had collapsed out of plane, away from their supporting frames, leaving no evidence of ties between the two building elements, Plate 15. In-plane failure of masonry panels was evident by the presence of large diagonal cracks which passed through both the bricks/blocks and the bedding joints. In-plane cracks were most significant in ground storey masonry panels measuring up to 60mm in width, Plate 16.

The reinforced concrete frame appeared to be intact. Masonry panels which had collapsed revealed the concrete frame in many areas and after close inspection only one crack was detected. This crack was at the junction of a column and beam, with a width of approximately 1mm.

Further evidence of movement was provided by the consequential damage caused by adjacent structures pounding against each other at movement joints. At these locations concrete had crushed and spalled revealing reinforcement. It was noticeable that there were only a few areas of spalling not associated with pounding, which suggested that the RC frame had performed reasonably well.

In the paved area external to the flats there was evidence of ground movement. Paving tiles had cracked and the walkways were uneven, with level variations in the order of 25mm. Inspection of columns as they pass through the pavement did not reveal any indication of movement either vertically or horizontally, thus providing no clear evidence of settlement.

From the instrument recordings it is estimated that the peak free field horizontal ground accelerations at Augusta were in the order of 0.1g to 0.2g. Considering the nature of the substrata it could be classified as a 'soft site' with a frequency in the order of 1 to 2Hz. The blocks of flats, with a soft ground floor storey, would have a natural frequency in the order of 2Hz to 3Hz therefore creating a potential for resonance between the soil and the structure.

The potential for accelerations being enhanced by the effects of soil-structure interaction, together with the long duration of the earthquake (45 seconds) and the non-existence of masonry ties offer reasons why these buildings performed poorly in what was a relatively minor earthquake.

5.3 Effects on Industrial Facilities

The area north and south of Augusta contains one of the largest concentrations of petrochemical installations in the world. Augusta is located on the coast approximately 10km from the epicentre of the earthquake. Based on the recorded ground accelerations shown in Figure 1, Augusta would have experienced ground motions of the order of 0.1g. Although members of the EEFIT team were unable to arrange access to these industrial facilities during the short visit, observations were carried out from the perimeter of some of the sites. These basic inspections and local comment indicated that no damage had occurred to structural steelwork, storage tanks or main pipework tracks, Plates 17 and 18.

A number of major plants shut down their chemical process operations to carry out safety checks, following the earthquake.

6 CONCLUSIONS

6.1 General

The main conclusions reached by the EEFIT team were:

i) Selective damage was caused to modern buildings located on soft ground sites near the epicentre and traditional masonry structures near steep slopes further afield, reflecting amplification of ground motion by site response and topographic effects.

ii) The strengthening of masonry buildings using steel tie rods and wall plates improved their earthquake resistance.

iii) Engineered industrial facilities constructed primarily from steel were observed to be undamaged.

6.2 Relevance to UK

The evidence and form of damage inspected is useful and relevant to British seismic engineering design and the following three points are pertinent:

i) Masonry construction performs poorly in moderate earthquakes if not effectively designed, detailed and constructed. Attention to tie details, mortar strengths and unit (brick/block) quality is important. If these features are deficient, the robustness and integrity of the masonry structure are reduced.

ii) Reinforced concrete performs well if detailed effectively. The isolated structural damage observed, such as reinforcement anchorage failure and vertical column reinforcement inadequately bound by links bursting through the concrete cover, emphasises the importance of attention to detail.

iii) Structural steelwork generally performs well when subjected to earthquakes. Although damage to structural steelwork was not detected in Sicily it is noted that the major structural steelwork construction is in the industrial zone where access was restricted.

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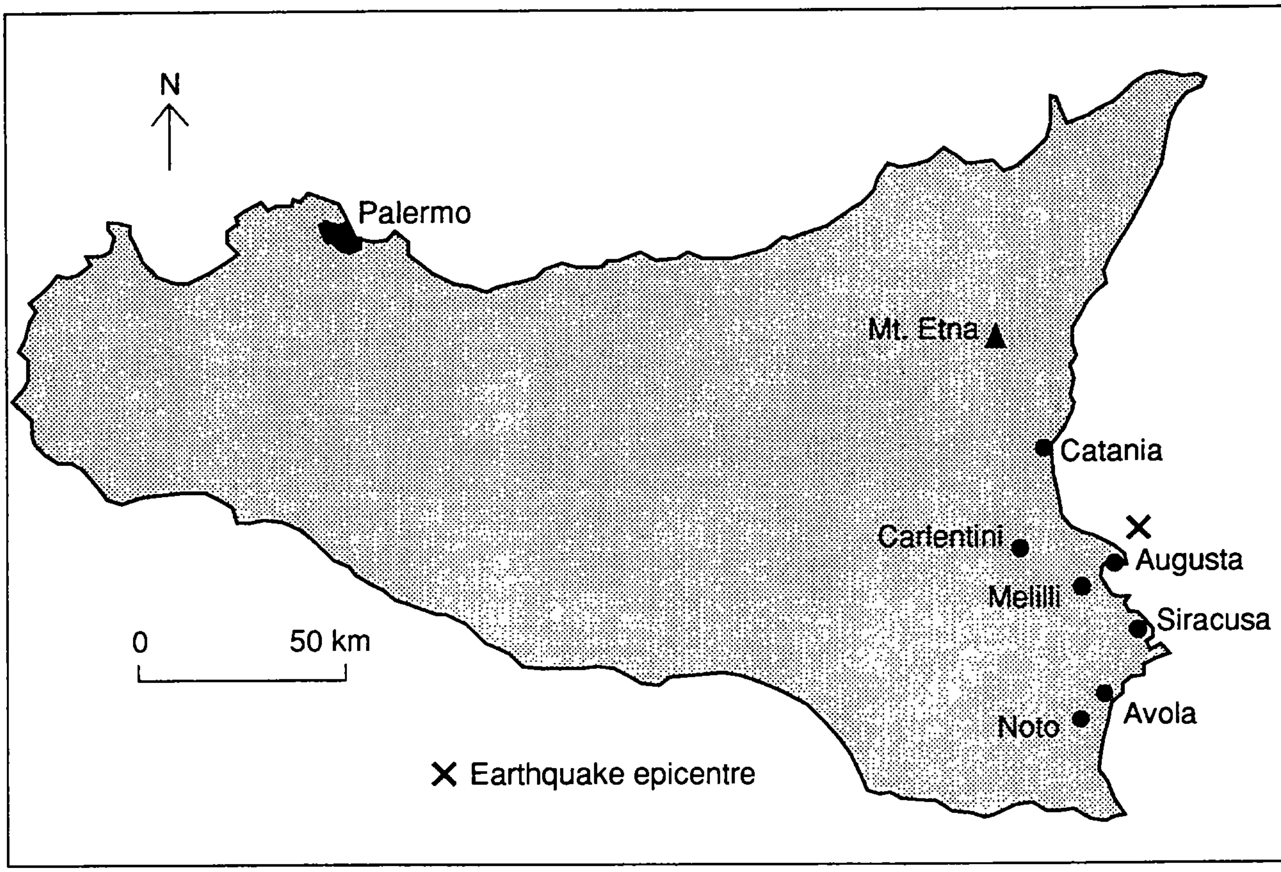
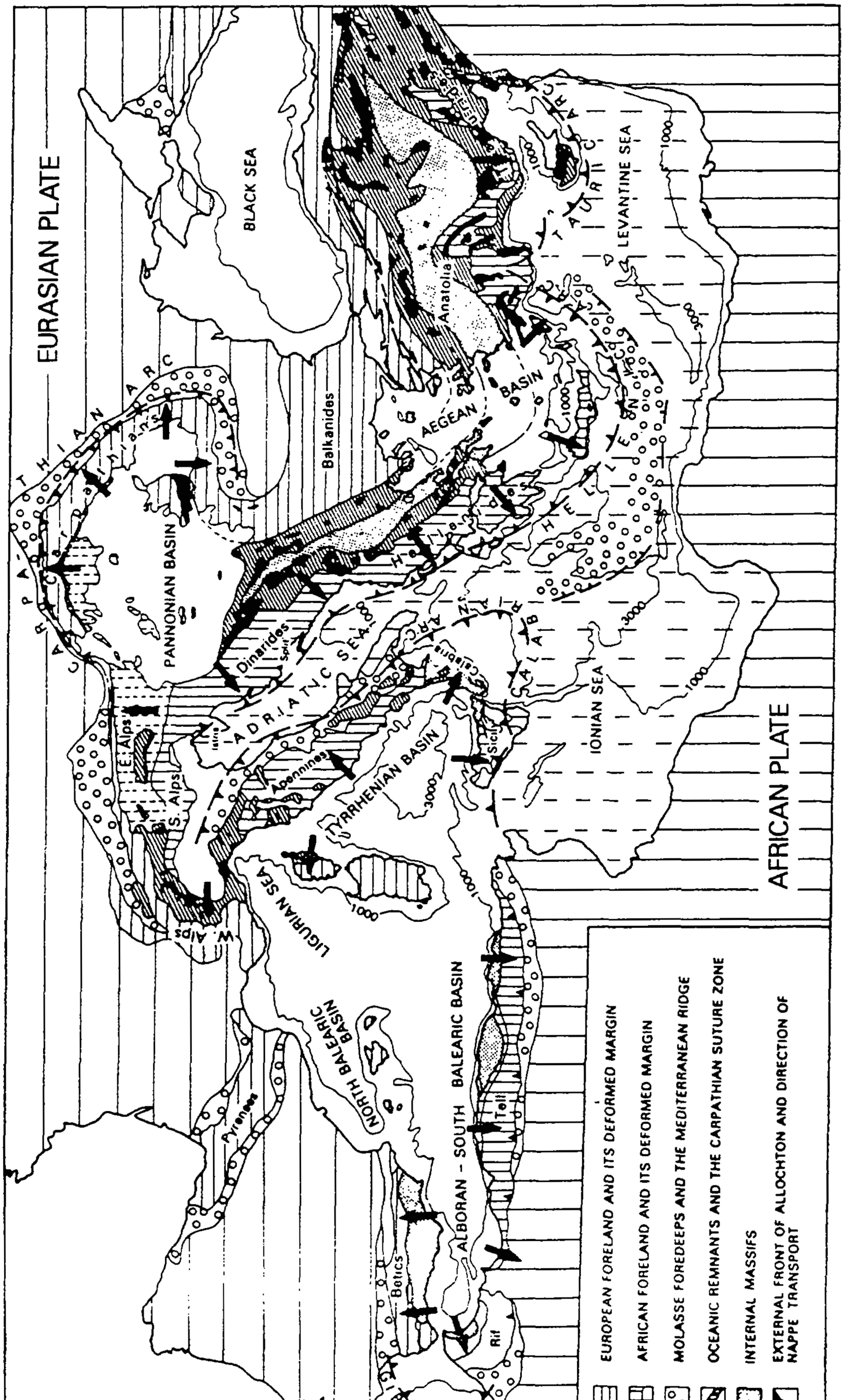
- Mr Z A Lubkowski (Ove Arup and Partners, London) assisted with the final report production.

FIGURES AND PLATES



Location map

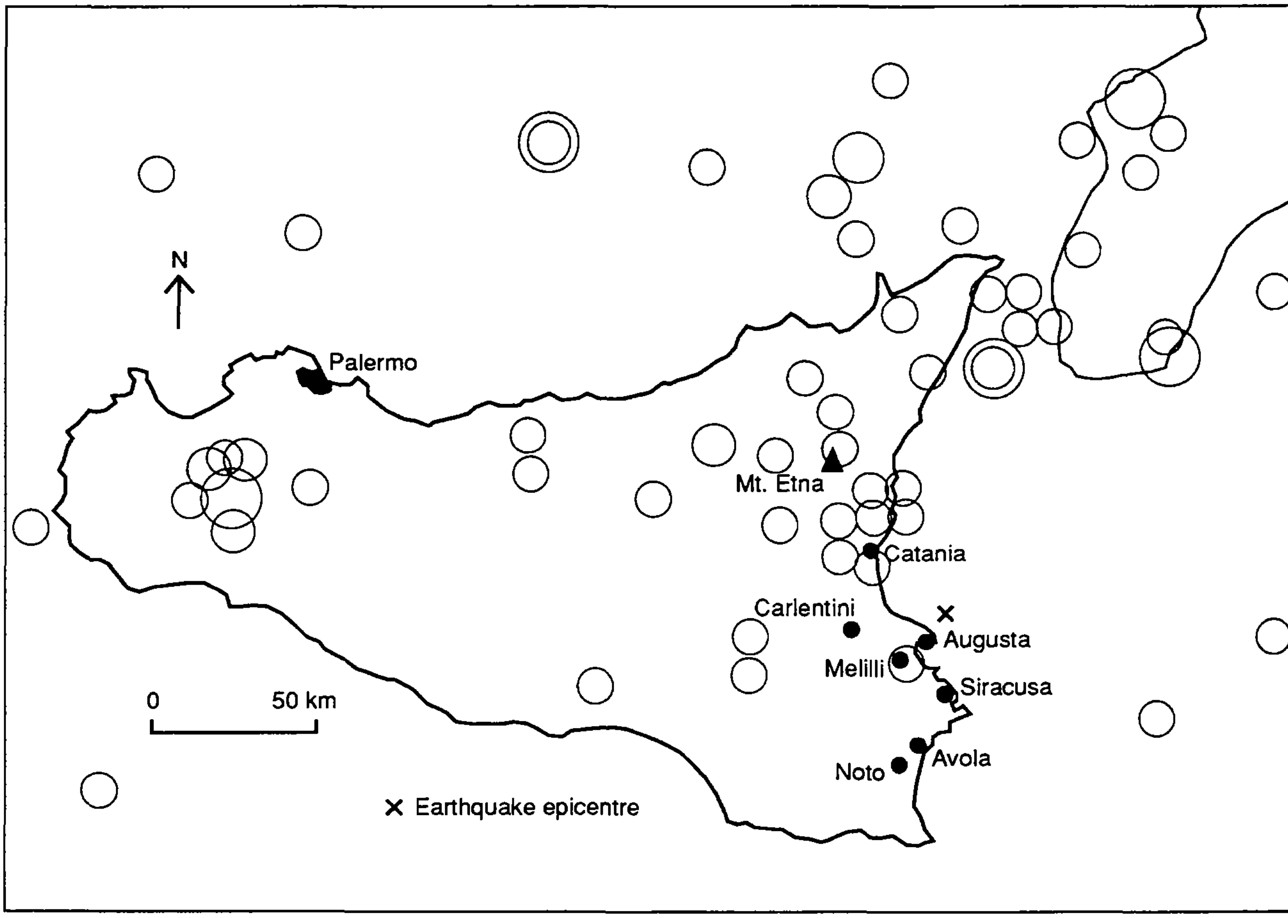
Figure 1



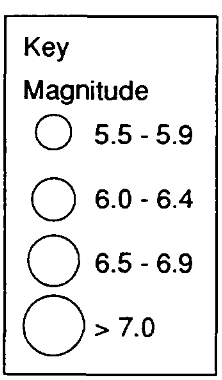
(Ref: Horvath, 1988)

Tectonic scheme of the Alpine-Mediterranean region

Figure 2

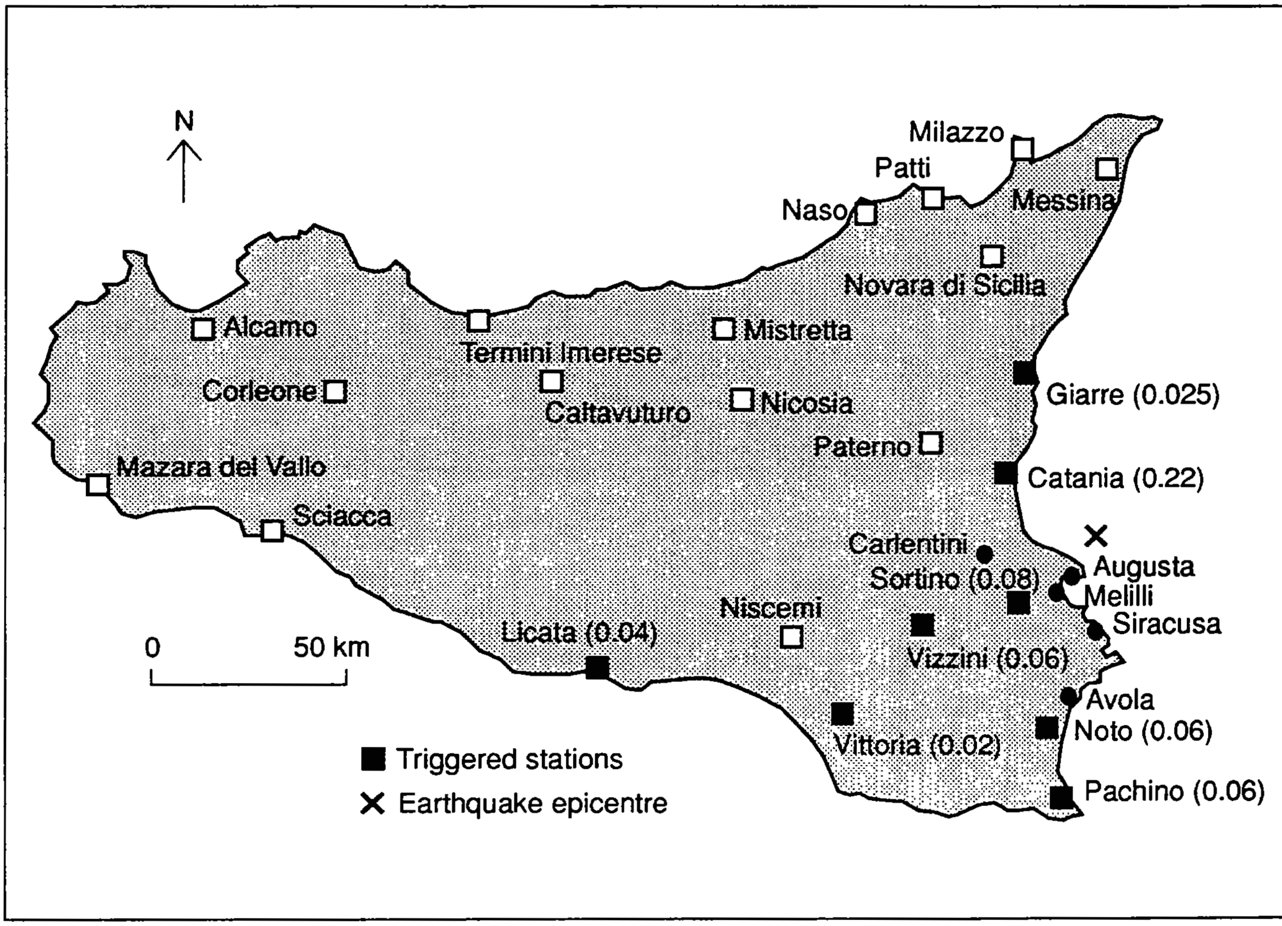


(Ref: Based on, Coburn et al, 1984)



Earthquake activity 1900 - 1980

Figure 3



(source: ENEL, 1991)

Recorded ground accelerations ('g')

Figure 4

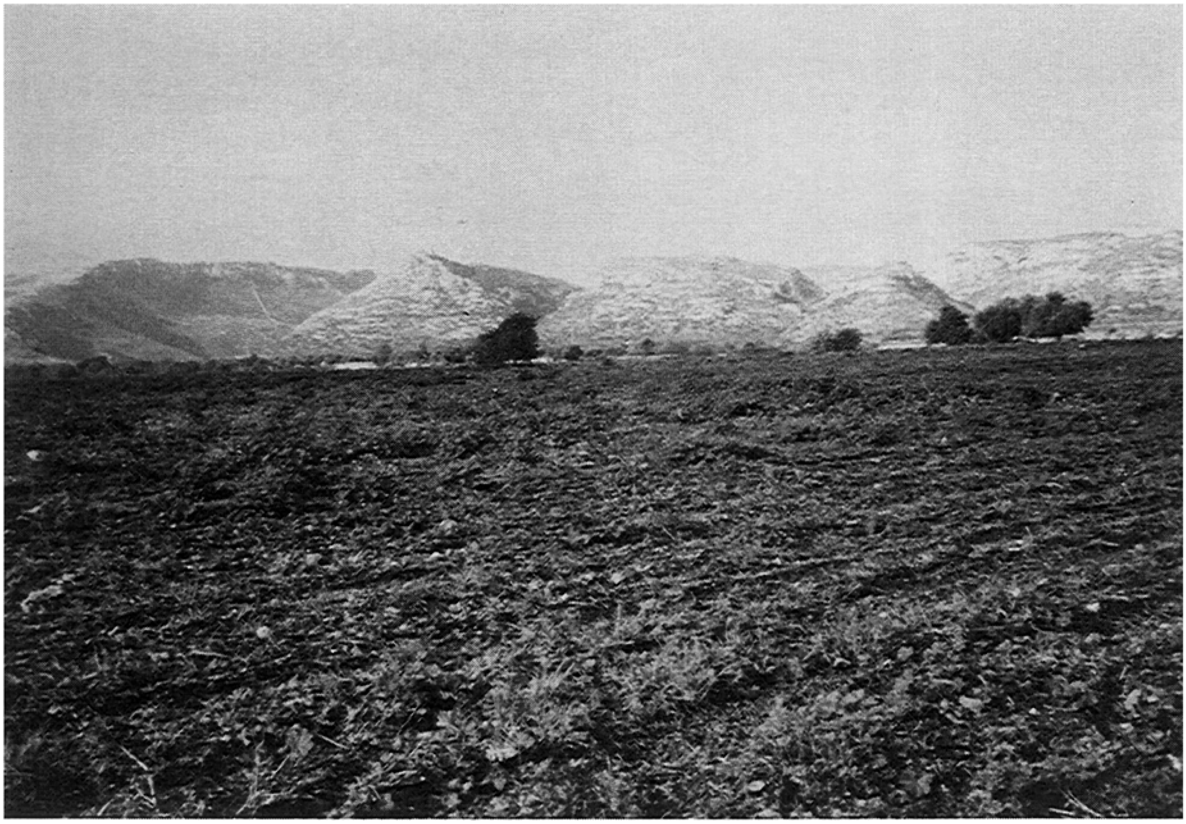


PLATE 1 *Topography of epicentral area (view from coastal plain inland)*

PLATE 2 *Typical residential building in Noto*

PLATE 3 *Town Hall in Noto*

PLATE 4 *Noto Cathederal*

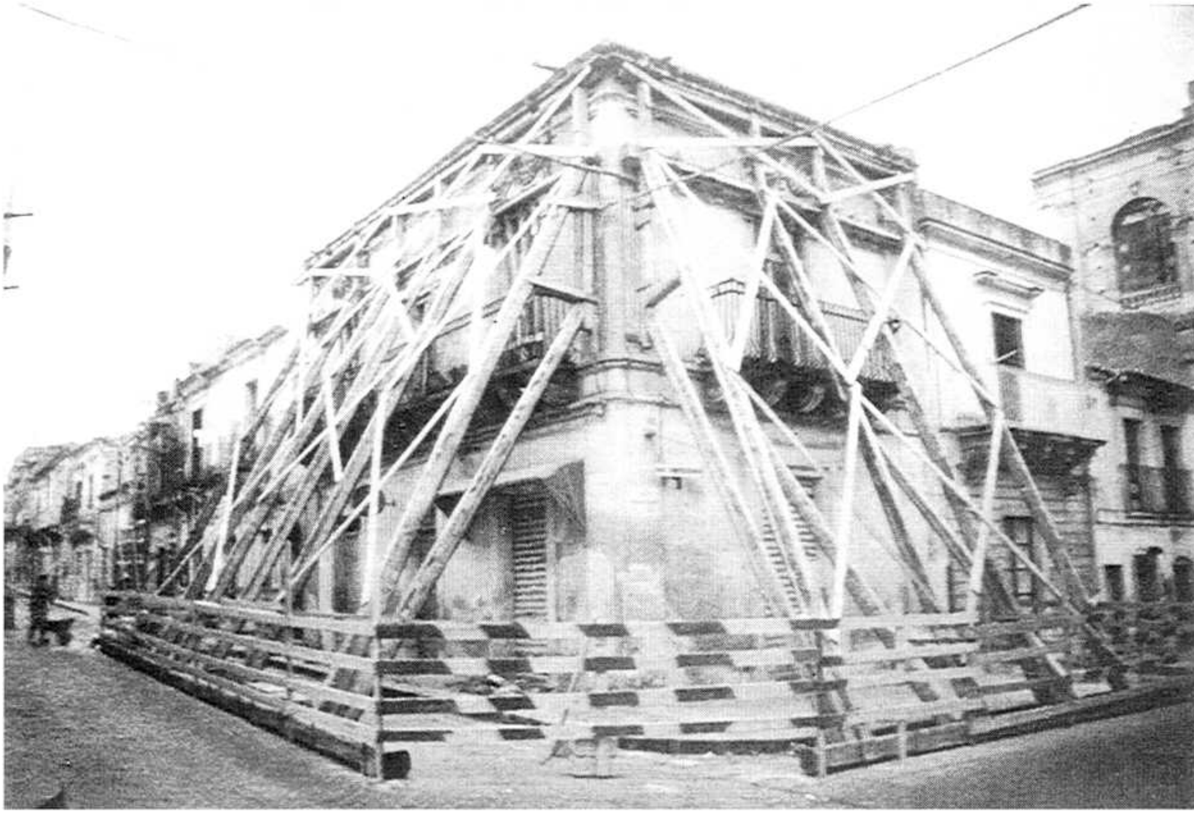


PLATE 5 *Temporary shoring and safety barriers around a damaged building*

PLATE 6 *Out of plane wall failure - Noto*

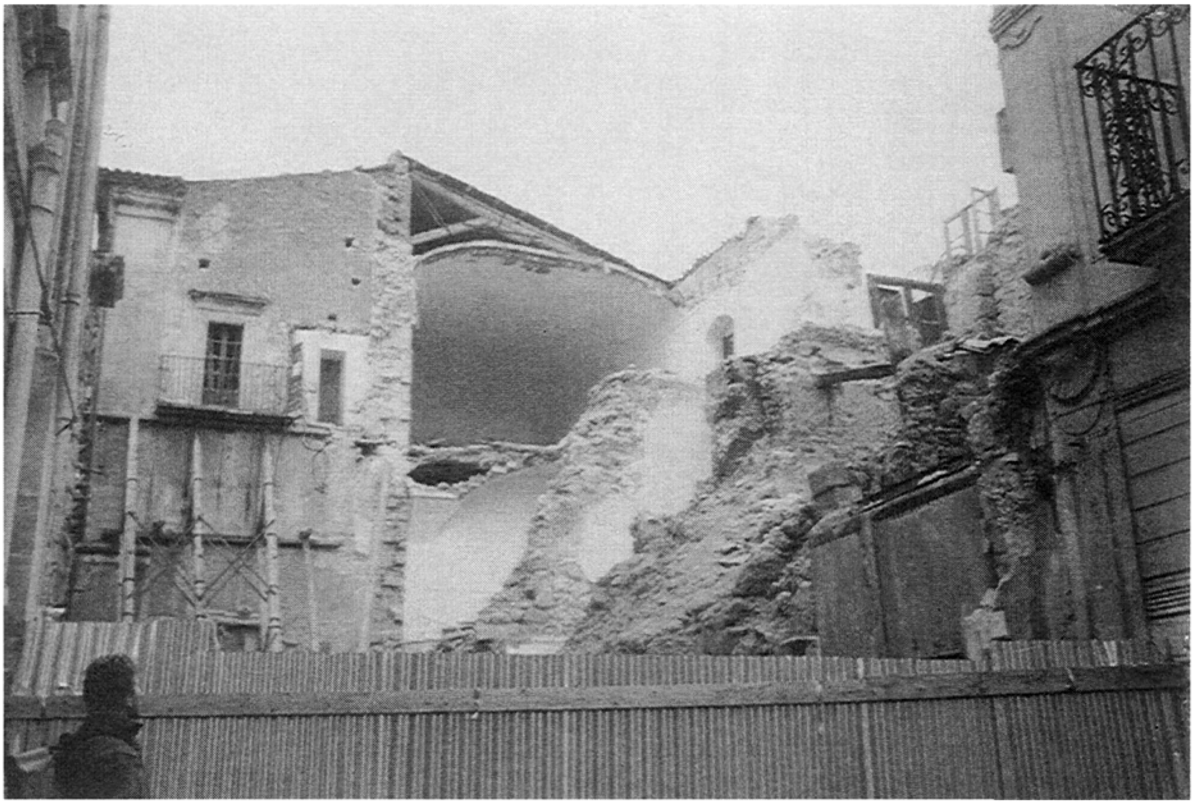


PLATE 7 *Out of plane wall failure - Noto*

PLATE 8 *Typical corner failure - Melilli*

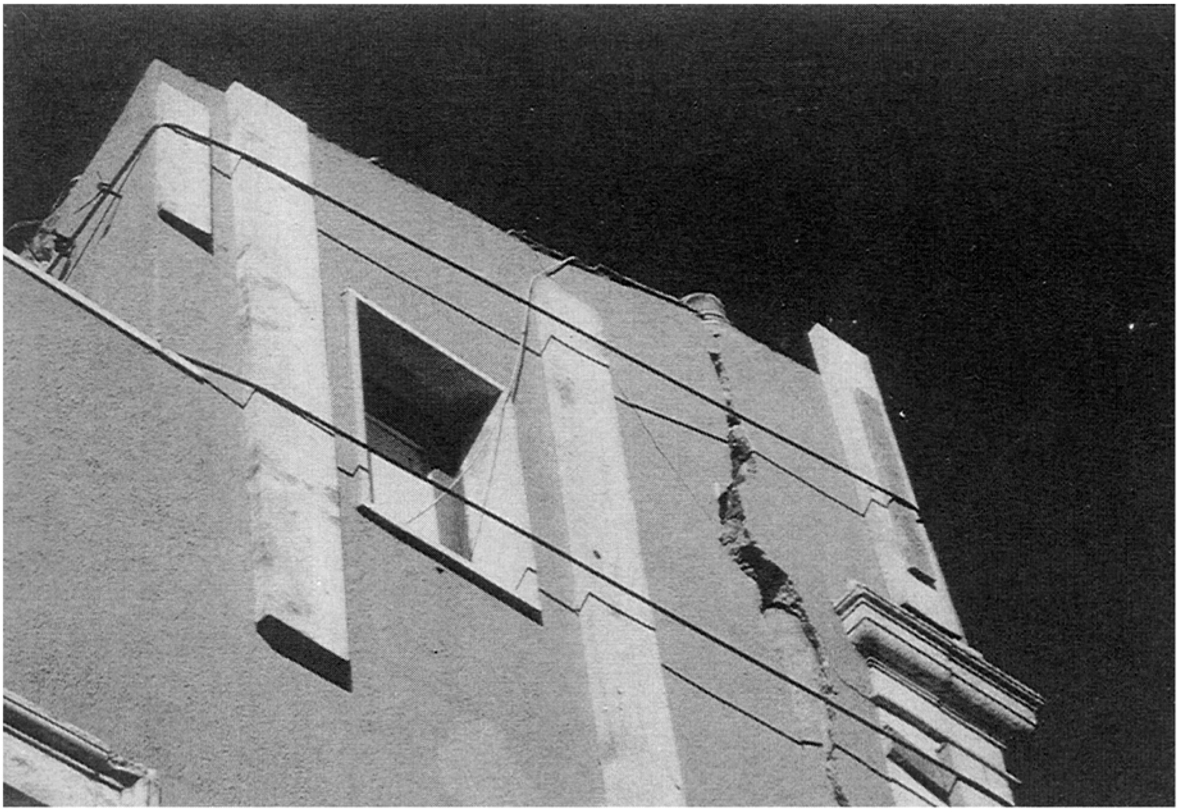


PLATE 9 *Wire-strapping of residential building in Mellini*

PLATE 10 *General view of Carlentini*

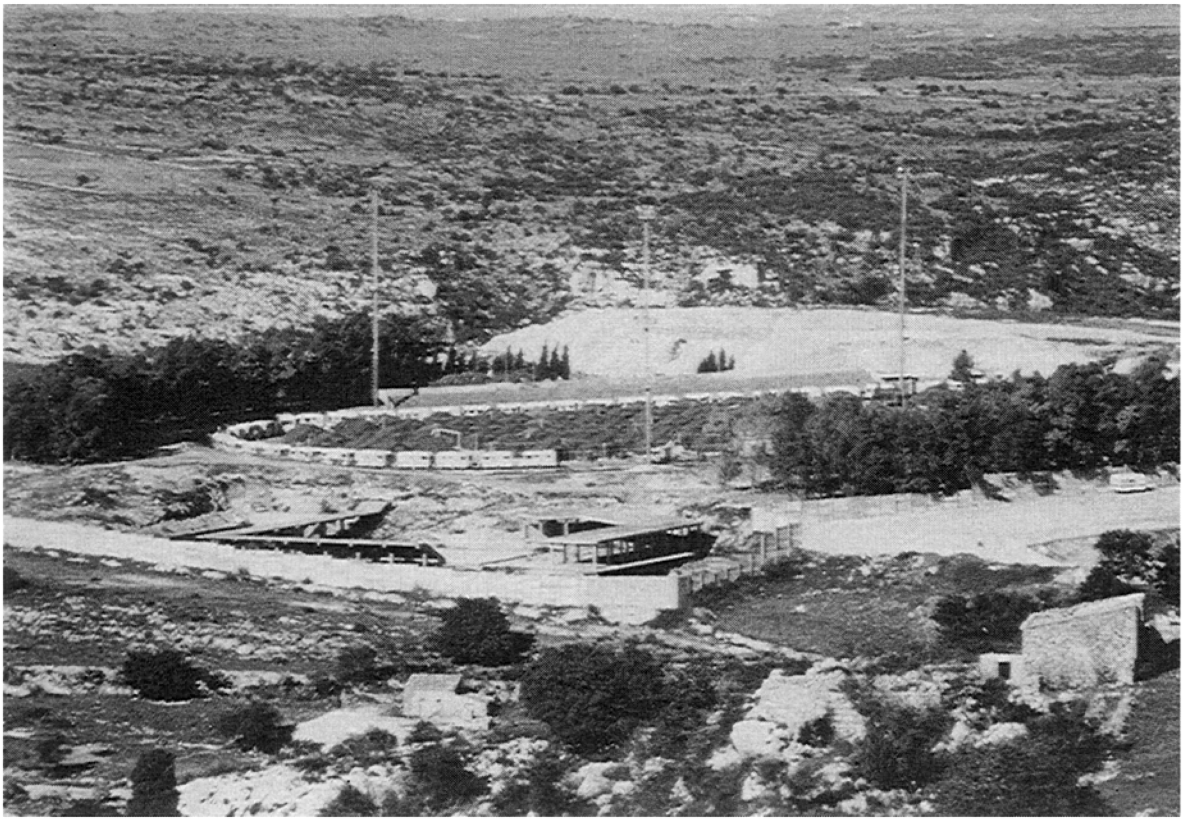


PLATE 11 *Refugee camp mear Carlentini*

PLATE 12 *Building damage - Carlentini*

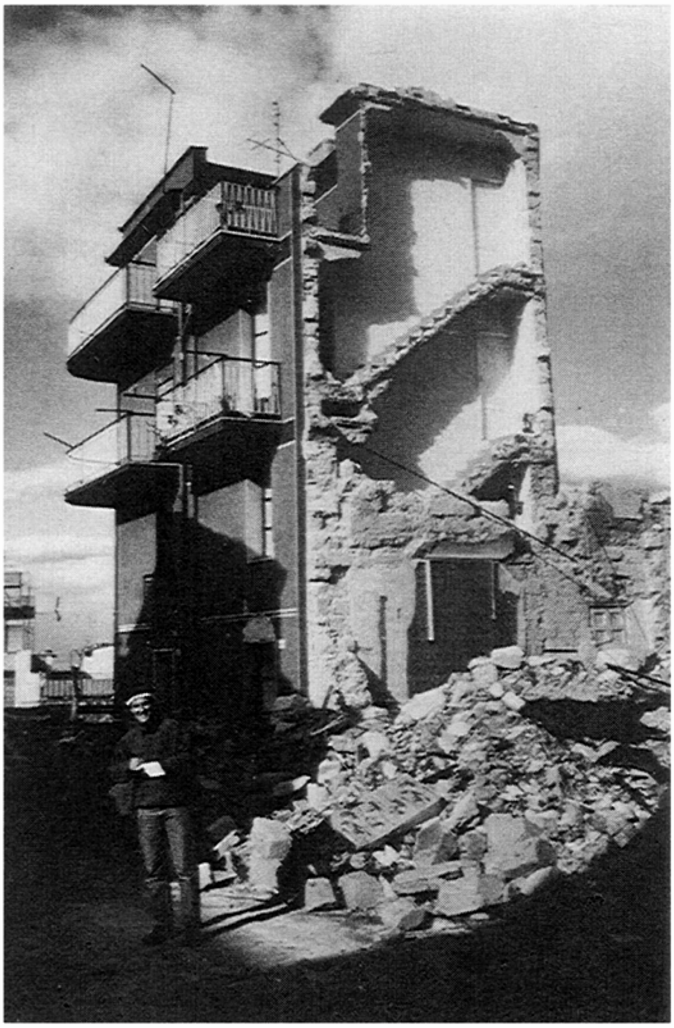


PLATE 13 *Collapse of three storey residential building in Carlentini*

PLATE 14 *Modern flat complex - Augusta*

PLATE 15 *Failure (out of plane) of reinforced masonary infill panels*

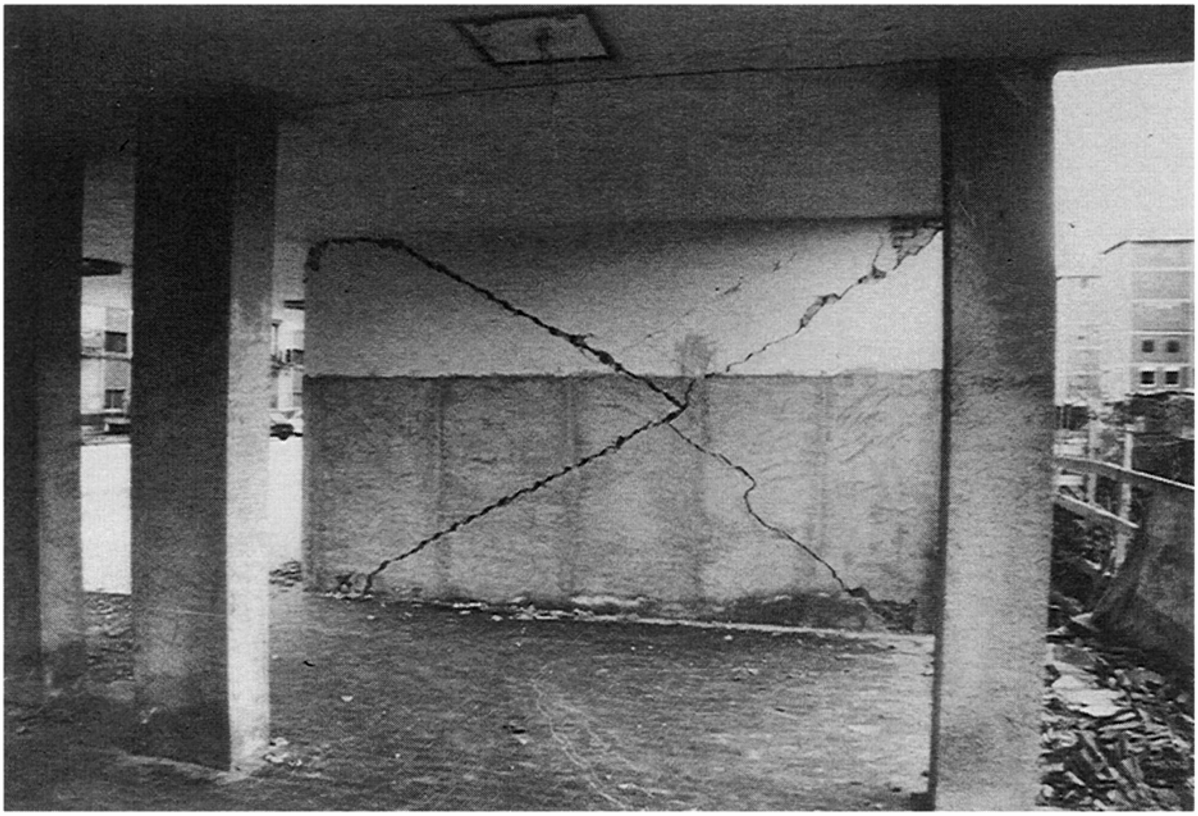


PLATE 16 *Shear failure of stairwell at ground level - Augusta*

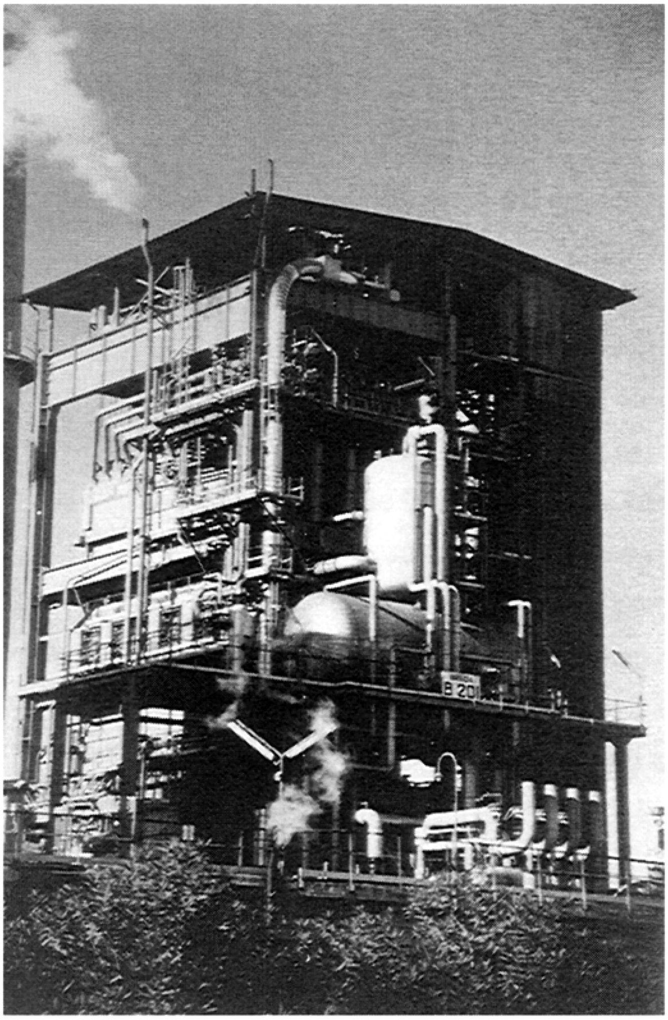


PLATE 17 *Undamaged industrial facilities - Augusta*

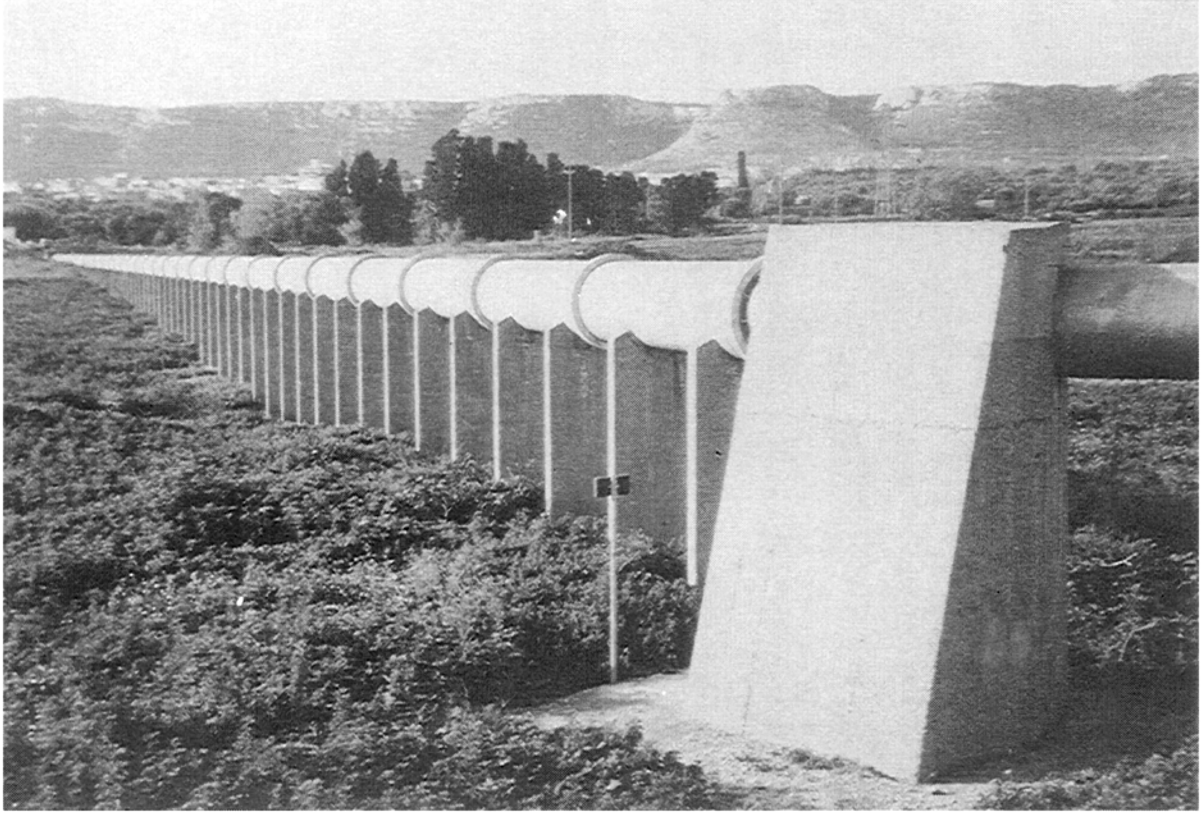


PLATE 18 *Undamaged elevated water main*

APPENDIX A : List of slides taken by EEFIT team

Copies of the slides listed below are available , at cost, by application to EEFIT.

1. Title Slide.
2. Map of Epicentral Area.
3. Preliminary isoseismal map.
4. Earthquake seismological details.
5. Temporary shoring and safety barriers around a damaged building.
6. Out of plane wall failure - Noto.
7. Typical wall corner failure - Mellili.
8. Wire strapping to stabilise residential building - Mellili.
9. General view of Carlentini.
10. Building Damage - Carlentini.
11. Collapsed three storey residential building - Carlentini.
12. General view of modern flat complex - Augusta.
13. Out of plane failure of unreinforced masonry infill panels at flats complex - Carlentini.
14. Shear failure of stairwell at ground level - Augusta.
15. Undamaged industrial facilities - Augusta.
16. Undamaged elevated water pipeline - Augusta.