

## VULNERABILITY AND SEISMIC RISK ASSESSMENT OF BUILDINGS FOLLOWING THE 1989 NEWCASTLE, AUSTRALIA EARTHQUAKE

A.M. Chandler<sup>1</sup>, J.W. Pappin<sup>2</sup>, and A.W. Coburn<sup>3</sup>

### ABSTRACT

Ten days after the Newcastle, Australia earthquake of 28 December, 1989, the UK-based Earthquake Engineering Field Investigation Team (EEFIT) mounted a five day mission to the affected area. This paper presents the findings of the EEFIT investigation and subsequent follow up studies in relation to the extent of building damage and its distribution within the City of Newcastle and the surrounding urban area. Results are based on both detailed street surveys and general damage surveys, the former carried out in two areas, namely the heavily damaged suburban district of Hamilton (3km west of the City centre) and the Newcastle central business district. The findings of these surveys have provided valuable information on the vulnerability of building stock of types common to other parts of Australia, the UK and elsewhere, and hence form an important database for the accurate assessment of seismic risk to buildings in regions of low seismicity. This information will assist the development of realistic, economical seismic code provisions for building design and construction in low-risk areas. An important feature arising from the surveys and subsequent analytical studies of site response in the heavily damaged districts within the Hunter River alluvial basin is that, contrary to reports published by the Institution of Engineers, Australia amongst others, the areas of deep alluvial soil and fill do not correlate strongly with the more heavily damaged districts determined from post-earthquake assessments. Hence, suggestions that this form of site soil amplification effect played a major part in the distribution and extent of heavy damage in this earthquake are somewhat misleading for the future development of planning and design regulations. Furthermore, the results of site response analyses show that it is more likely to be the shallower soils near the border of the alluvial basin which tend to amplify bedrock ground motions generated by this type of earthquake.

### INTRODUCTION

The EEFIT team investigating the Newcastle, Australia earthquake spent four days in the affected area carrying out damage surveys and one day in Canberra at the Australian Seismological Centre. Considerable assistance was received from Ove Arup & Partners, Sydney who organised travel and other arrangements, and meetings with local authorities and organisations. In addition the New South Wales Public Works Department and the Newcastle City Council provided a great deal of useful information and allowed access to damaged buildings.

The principal aims of the EEFIT team were to make an overall assessment of the distribution and scope of the damage, and to study particular failures with an emphasis on engineered structures. Also of interest were the effect of the earthquake on the

local infrastructure, its sociological impact and the methods by which the return to normal life was managed.

The EEFIT team carried out most of the damage surveys by exterior visual inspection, and by later analysis of the detailed photographic record obtained in some of the more heavily damaged districts. The team used a 1:4000 scale aerial photographic montage of the City, dating from August 1986. A section of the montage is reproduced in Figure 1, where individual buildings are readily identifiable. During the surveys the damage level was recorded directly onto the photographic montage. In two of the more heavily damaged areas a more detailed survey was carried out, with photographs being taken of every building. This enabled reliable percentages of damage at defined levels to be assessed subsequently, as described in a later

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1 Department of Civil and Environmental Engineering, University College London, UK

2 Ove Arup and Partners, London, UK

3 Cambridge Architectural Research Ltd, UK

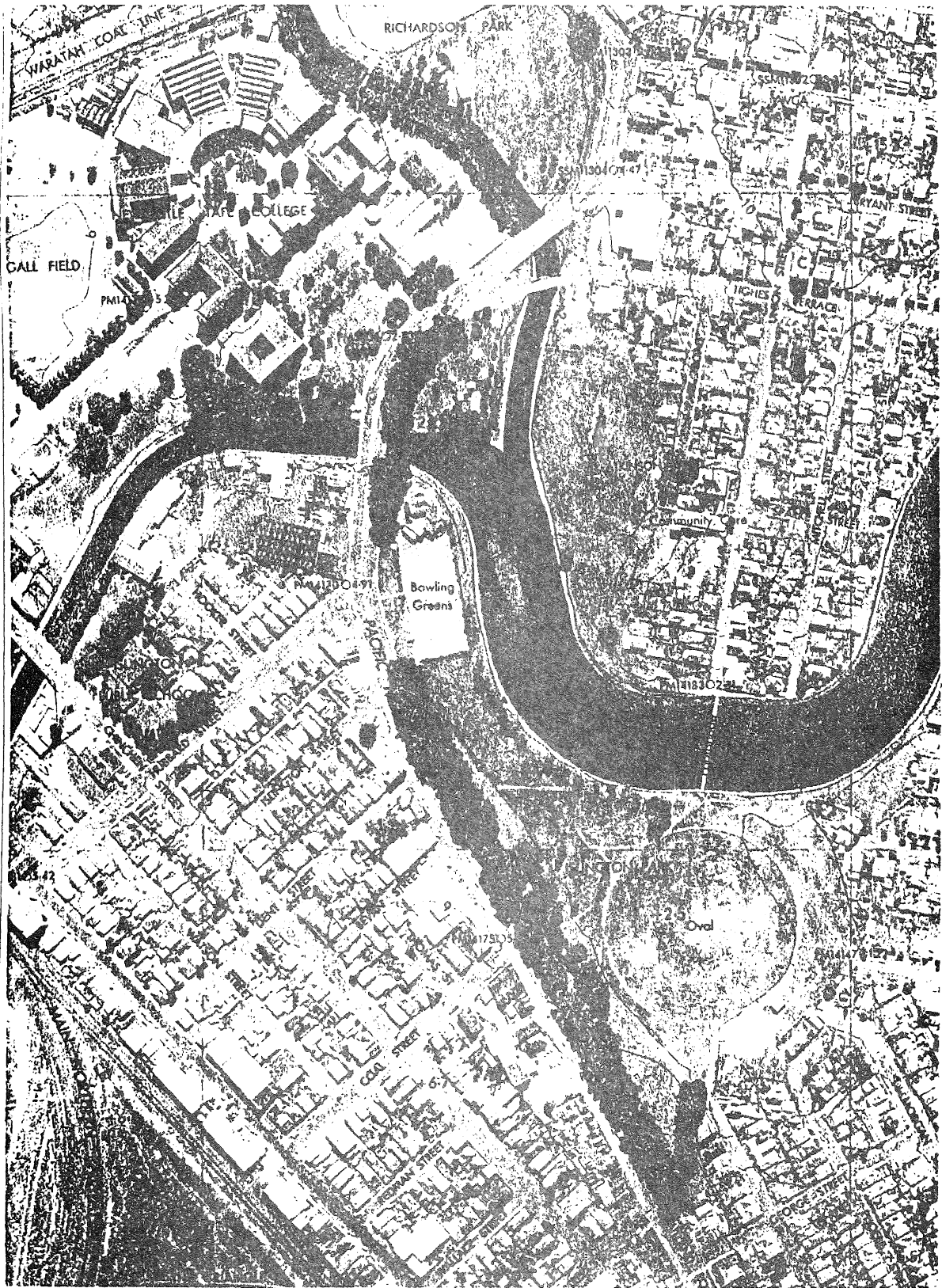


FIGURE 1 PART OF AERIAL PHOTOGRAPHIC MONTAGE OF NEWCASTLE, NSW (SCALE 1:4000)  
 (Source: Central Mapping Authority of N.S.W. "Orthophotomap" Sheet "Adamstown U6350-3", 1988)

section. These follow-up studies were carried out in the UK to compile a damage database by analysing the construction types and damage patterns from the photographic evidence.

A number of previous studies have analysed the seismological features [1-3] and engineering aspects [4-7] of this and previous Australian earthquakes, and hence only brief treatment of the former are given in the present article. Reference [8] published in this journal summarises the damage to building structures and services, categorising the former into commercial and retail buildings, residential buildings and emergency facilities and places of assembly. Reference [8] also presents useful information on insurance aspects, the response of local authorities and emergency services, and possible or recommended changes to building regulations in Australia and other countries or regions of comparable seismicity. These aspects have also been extensively covered by the authors in their detailed report on the earthquake [4]. Hence this article concentrates on the results of the detailed damage surveys outlined above, including a statistical analysis of the resulting database. The information gives valuable guidance for the formulation of earthquake preparedness and planning procedures, as well as revised design and construction regulations for Newcastle and other areas within Australia and the UK, in particular, which have comparable building stock and similar levels of seismic risk.

Also presented are the results of analyses of site response effects which contradict the conclusion of the Institution of Engineers, Australia report [5] that soil amplification effects in the deep alluvial and fill deposits were primarily responsible for the observed damage distribution. The effects of mining and its correlation with patterns of damage is also discussed, with possible explanations for the apparent relationship between damage and the borders of mining activity.

#### KEY SEISMOLOGICAL ASPECTS

From instrumental data the Australian Seismological Centre (McCue et al., Ref [1]) has estimated that the location of the earthquake epicentre was at 151.61°E and 32.95°S. Due to the sparse instrumental coverage the accuracy of this data is limited to ±15km, and hence the earthquake could have occurred almost anywhere under Newcastle. However, from the data given above it is more likely to have been in the western part of the city, perhaps near the town of Boolaroo situated about 14km west of the City centre. The earthquake depth has been assessed from surface reflections observed on seismograms recorded in Scotland [1], which show a focal depth of about 10km. The magnitude of the earthquake has not been precisely computed, but it has been estimated using various methods. A Richter magnitude ( $M_L$ ) of 5.6 has been assigned by McCue et al. [1].

#### Strong Motion Parameters

No instruments were installed near Newcastle at the time of the earthquake, but observers in Newcastle described the event as being like an explosion and agreed that its duration was very short, lasting no more than about 3 seconds. Others reported difficulty in standing and some observed waves travelling down the road or pavement [1].

Assuming that the focal depth was about 10km, then the hypocentral distance of the earthquake from the City of Newcastle would be about 18km for the probable epicentre, reducing to around 12km if the epicentre was in fact close to the City. On this basis, the attenuation laws published by Gaull et al. [3] for Southeastern Australia give the ground motion parameters listed in Table 1.

Predictions of ground motion parameters have also been carried out using the attenuation laws derived by Toro and McGuire [9] and Atkinson and Boore [10] for the Eastern United States. The response spectra appropriate to a rock outcrop calculated using their relationships are shown in Figure 2. The peak acceleration values, represented by the spectral values at a structural period of 0.025 seconds, are seen to agree well with those calculated using Gaull et al. [3] listed in Table 1. The peak velocity values from the Gaull relationship are however about three times higher than those indicated by the response spectra in Figure 2.

The observed damage [4] indicated that there was a distinct directionality of ground motion. Buildings in Hamilton (and Beaumont Street in particular) showed that the motion was stronger in the east-west direction with the main thrust being eastward. An easterly direction was also indicated by the damage in the central business district. Buildings in Silsoe Street, on the borders of Georgetown and Mayfield, showed a principal direction of ground motion of northeast-southwest, as confirmed by Brunson [8].

#### TYPES OF DAMAGE: GENERAL OVERVIEW

This section summarises the types of damage observed in Newcastle and its environs both to non-engineered buildings, and to other facilities. A high proportion of the damaged buildings were constructed of unreinforced brick masonry with little resistance to lateral loading. Particularly vulnerable were gable ends, parapets, facades and chimneys. Brunson [8] gives more detailed descriptions and photographic examples of these types of damage in both residential and commercial buildings.

The central business district and other older commercial areas experienced a very high density of damage to unreinforced brick masonry buildings, particularly older shops and warehouses which often had weakened street facades resulting from the requirement for ground floor access. It was also evident that single storey buildings performed much better than multi-storey buildings, with chimneys and roof parapets

TABLE 1: PREDICTED GROUND MOTION PARAMETERS

Ground Motion Parameters	Hypocentral Distance (km)	
	12	18
Peak Intensity (MM)	8.1	7.4
Peak Velocity (m/sec)	0.22	0.14
Peak Acceleration (g)	0.21	0.13

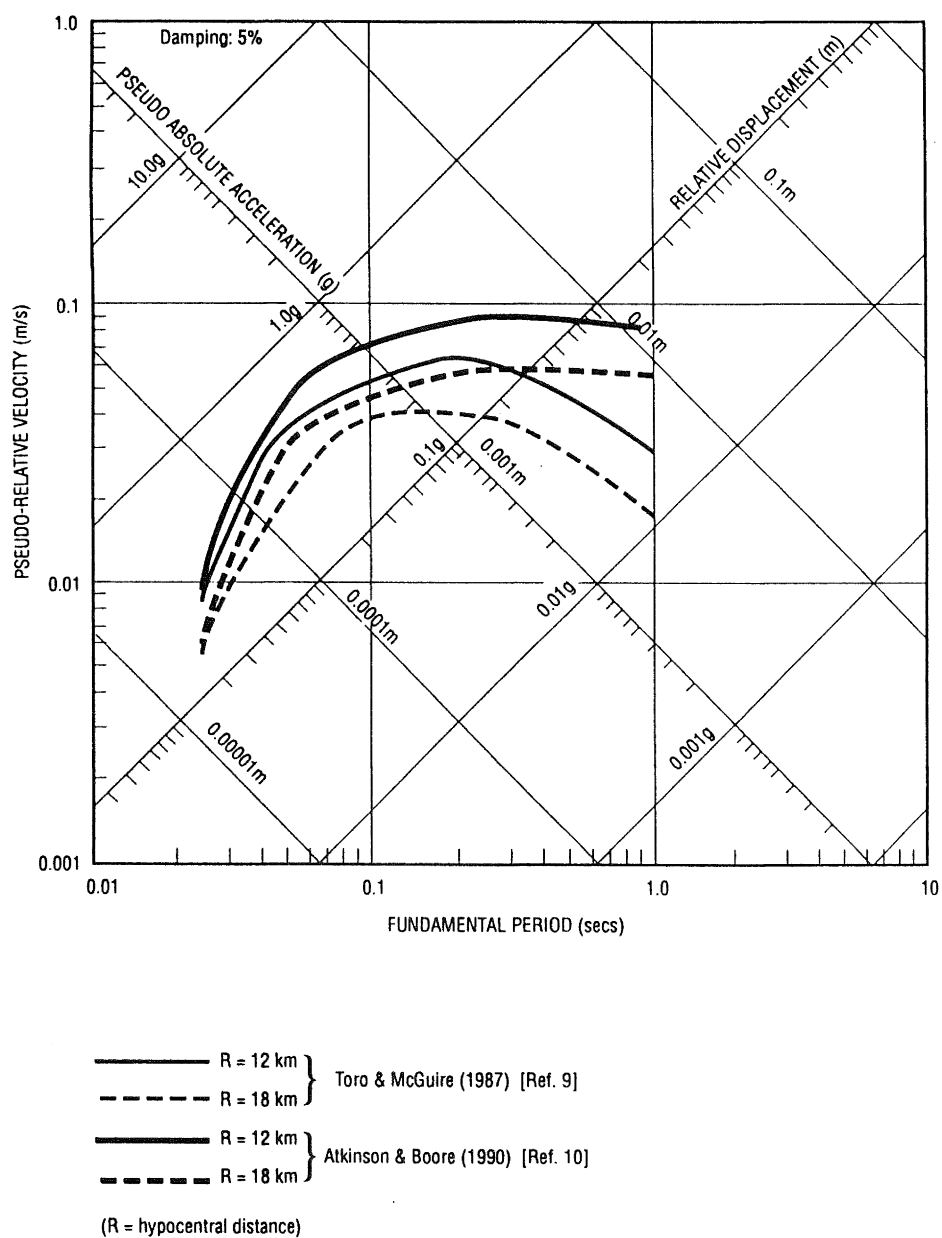


FIGURE 2 RESPONSE SPECTRA FOR ROCK SURFACE MOTION DERIVED FROM REFS. [9] AND [10]

being particularly vulnerable in the latter case. The detailed damage surveys reported in the following section give numerical data on these and other variations. Similar damage was caused to older two-storey houses, and those with double leaf cavity construction suffered heavily from the lack of adequate ties, with the outer leaf collapsing as a result of the lack of restraint (see Figures 9 and 10 in Reference [8]). Examples of this were also found in schools and colleges, some of relatively modern construction. Unreinforced masonry used as infill walls in reinforced concrete frame buildings also suffered extensive minor damage due to shear cracking, and there was also some evidence of damage to cladding.

Few modern engineered reinforced concrete or steel frame buildings suffered more than relatively minor non-structural damage, such as cracking of in-fill panels or facades. The collapse of the Working Mens' Club (or Workers' Club) in King Street, which caused 9 of the 12 fatalities due to the earthquake, was an exceptional case. Failure of this structure was caused probably as a result of the poor detailing to reinforced concrete floor slabs at their column and wall connections, combined with the failure of an exterior wall which triggered the sudden roof collapse. Another notable example of poor resistance to dynamic earthquake loading was the Junction Motel, a three-storey reinforced concrete frame building with pronounced vertical and horizontal stiffness irregularities. This building was demolished following failure of the ground floor outer columns along one side of the structure.

There was some moderate damage to most church spires and towers, and to other monumental buildings, mostly resulting in the cracking and loosening of masonry, which made the structures and surrounding areas unsafe. In the outlying residential areas the predominant form of housing construction is timber weatherboard of relatively flexible, lightweight construction, although many modern buildings have a brick masonry veneer attached to the timber framework. These types of buildings, which are mostly single-storey, were largely undamaged by the earthquake due to their greater flexibility and ability to absorb the energy transmitted to them by the ground motions. There was no reported damage to industrial facilities or equipment, although some minor spalling of concrete storage silos was noted, and similarly services and transportation suffered only minor disruption as a result of the earthquake.

References [4]-[8] give extensive details of damage to engineered and non-engineered buildings, industrial facilities and services in the affected region.

#### DISTRIBUTION AND EXTENT OF BUILDING DAMAGE

##### Detailed Photographic Surveys: Methodology

Two detailed street surveys were carried out, the first in Beaumont Street and Lawson Street, Hamilton and the second in Hunter

Street, which is the main thoroughfare in the Newcastle central business district. A total of 625 buildings were logged photographically, in sufficient detail for later analysis. Each survey involved photographing externally every building (either individually or in small groups), on both sides of the street. The survey in Hamilton covered approximately a 1.5km length of Beaumont Street, working south from its start at Maitland Road to the junction with Dumaresq Street at the corner of the Newcastle Racecourse (Figure 3), and then continued in the reverse direction along a 1km length of Lawson Street from its junction with Dumaresq Street to its termination at Donald Street. The building stock in the surveyed part of Beaumont Street consists primarily of older commercial unreinforced brick masonry buildings, mostly one or two storeys in height. There are some brick masonry and timber residential buildings in the southern part in the approaches to the Racecourse. Lawson Street is primarily residential (dominated by low-rise timber framed dwellings) with some commercial/office developments and the steel framed Telephone Exchange building clad with unreinforced brick masonry. Three kilometres of Hunter Street was surveyed, from its eastern end at the junction with Telford Street, to the junction with Tudor Street at the boundary of Newcastle West and Hamilton (Figure 3). This is primarily a commercial and business district dominated by multi-storey shops and offices, mostly of reinforced concrete frame or unreinforced masonry construction.

The following parameters were recorded for each building:-

(i) Location by Australian Grid Reference

(ii) Primary Classification of Construction Type

Categorisation of Primary Construction Type could usually be carried out with relatively high confidence from the general appearance of the building. For example, load bearing brick masonry buildings are usually fair-faced, and timber framed buildings often weather-boarded. Where building type was ambiguous or uncertain, due for example to heavily rendered exteriors or where external masonry may have been used as a cladding rather than for structural purposes, other indicators such as size and regularity of fenestration, beams and timber framing elements were used to determine the construction type.

(iii) Secondary Classification of Construction Type

Categorisation of secondary construction type was important mainly for brick masonry buildings. Part of the investigation of the earthquake damage was to establish the seismic vulnerability of cavity construction masonry, which is also a common building method in

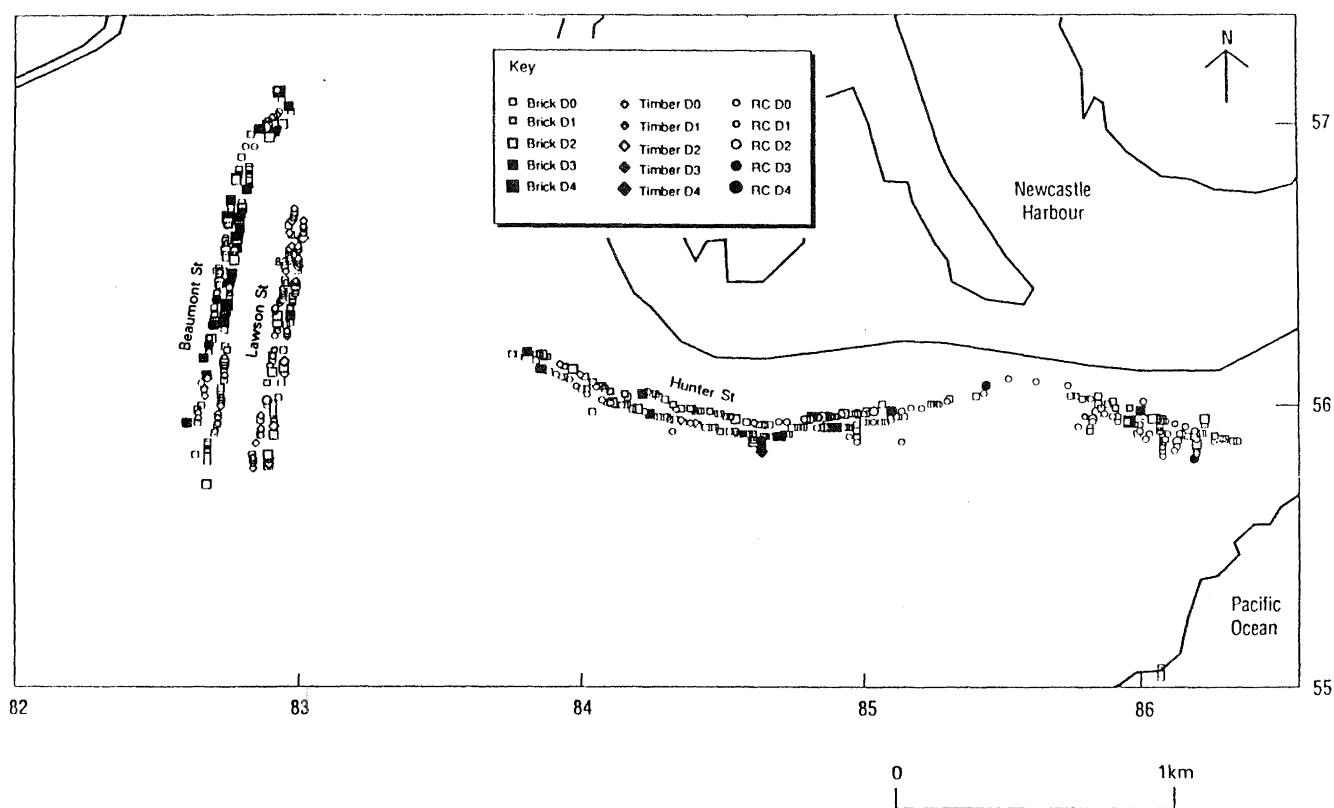


FIGURE 3 LOCATION OF DETAILED PHOTOGRAPHIC SURVEY AND SUMMARY OF RESULTS

the UK, but rarely found in active earthquake zones. The Newcastle earthquake provided an opportunity to assess the comparative performance of solid masonry construction with two leaves of masonry through-bonded, against that of cavity construction. Cavity construction was identifiable from the stretcher bond of the exterior wall, air vents in the lower courses and moisture weep holes or flashing around openings. Cavity masonry is also identifiable with a certain period of construction, not being a common technique until the 1930's. Solid masonry was identified from Flemish bonding, thickness of masonry walls, use of decorative or moulded brickwork, pilasters and other such indicators. The categorisation of secondary construction type is less reliable because the detail needed to determine this parameter with any confidence cannot always be obtained from photographs. Construction type can be determined more accurately at high levels of damage, because walls are split apart revealing their exact form of construction, generally related to the construction period and architectural detail of the building.

(iv) Number of Storeys

The number of storeys could also be determined with confidence from the photographs in all but a few cases.

(v) Age Classification

The age was determined from the stylistic treatment of the architectural form and facade. In a number of cases the actual date of construction is given on the exterior of the building and this was used to confirm dating of building styles. The classifications of age used were fairly broad, relating to quite clear periods of construction in Newcastle, i.e. pre-1920, 1920-1940, 1940-1960, and post-1960. These periods relate to the phases of development of the City, with many buildings in the main streets being older than the buildings in adjacent districts and intermixed with a recent phase of commercial development in the City centre.

(vi) Usage Category

A few broad categories of usage were employed, depending on the exterior appearance of the building. Generally the distinction being sought was between residential and commercial building stock. Where a

particular use was obvious, for example a bank or school, this was noted. The usage category has a significant link with architectural style. Shops and delicatessens have large front facade parapets, often in masonry, to signify their purpose. Larger stores tend to have free openings or long spans on the ground floor with office premises on the floor above. Residential buildings tend to be detached or occasionally terraced, in their own grounds.

(vii) **Damage Level**

The MSK categorisation of damage was employed, as in previous damage surveys carried out by EEFIT and the Martin Centre, Department of Architecture, University of Cambridge [11]. The damage levels have been summarised in Table 2, based on an evaluation of the exterior of a structure, and were generally easily identifiable for the buildings in this survey. The lower levels of damage, such as D1, were not so readily identifiable as these caused narrow cracks not easily seen from the photographs.

(viii) **Damage Type**

The damage observed on the photographs was recorded in the database. Generally this meant noting the type and extent of cracking, and in the more severely damaged buildings recording which parts of the structure collapsed.

**Building Database**

The database which has been compiled from the detailed photographic surveys carried out in Newcastle consists of 625 buildings (Figure 4), classified by the primary construction type into brick masonry (372 buildings or 60% of the total), reinforced concrete frame (137 buildings, 22%), or timber frame (104, 16%); the remaining 12 buildings (2%) were either steel frame or composite construction. Of the 372 brick masonry buildings in the survey, the great majority (99%) were of either solid double (31%) or cavity construction (68%). The remaining 1% were of solid single leaf construction.

Each building was designated either commercial or residential, according to its primary usage (Figure 4). Of the 625 buildings surveyed, 428 or 68.5% were commercial and 147 or 23.5% were residential. The remaining 50 buildings (8%) consisted of car parks, a police station, sports buildings, churches, meeting halls and so forth.

Further classification of the surveyed buildings was carried out by age of construction and by height in number of storeys. Classification by age is shown in Figure 5. A total of 48 buildings were dated pre-1920 (8%), mostly of brick masonry construction. The greatest proportion of buildings (260 or 42%) were built between 1920-1940, whilst 176 buildings (28%) were from the period 1940-1960. Recently constructed buildings (post-1960) numbered 126 (20%). Of the remaining 15 buildings (2%), 12 were of non-classified construction

TABLE 2: DEFINITION OF DAMAGE LEVELS

Damage Degree	Definition for load bearing masonry	Definition for reinforced concrete frame buildings
D0 Undamaged	No visible damage	No visible damage
D1 Slight Damage	Hairline cracks	Infill panels damaged
D2 Moderate Damage	Cracks 5-20mm	Cracks <10mm in structure
D3 Heavy Damage	Cracks >20mm or wall material dislodged	Heavy damage to structural members, loss of concrete
D4 Partial Destruction	Complete collapse of individual wall or individual roof support	Complete collapse of individual structural member or major deflection to frame
D5 Collapse	More than one wall collapsed or more than half of roof	Failure of structural members to allow fall of roof or slab

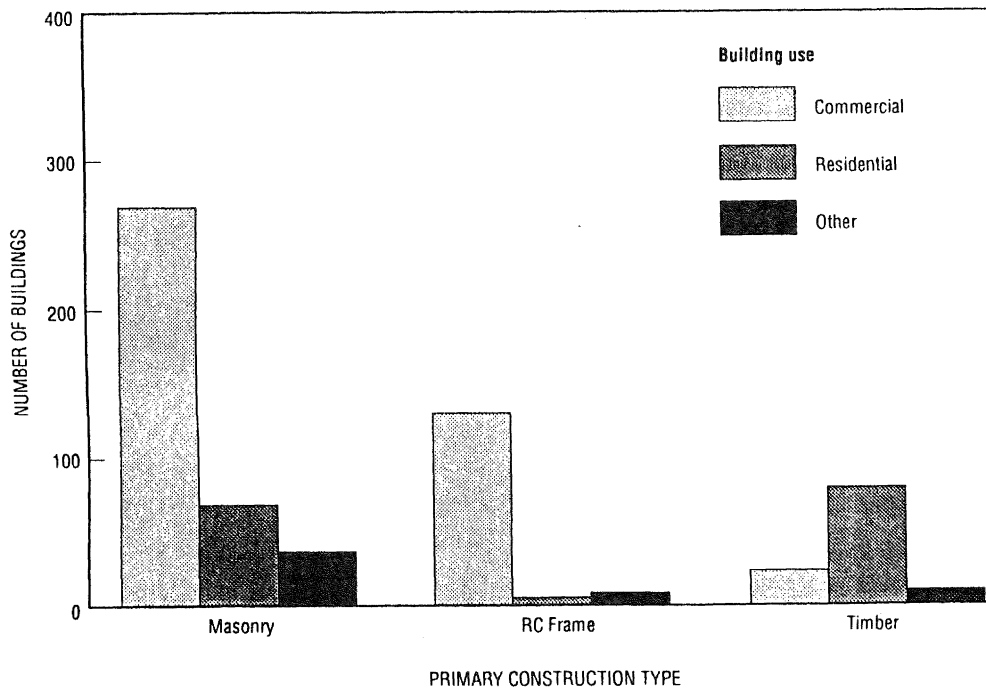


FIGURE 4 NUMBER OF BUILDINGS BY PRIMARY CONSTRUCTION TYPE AND USE

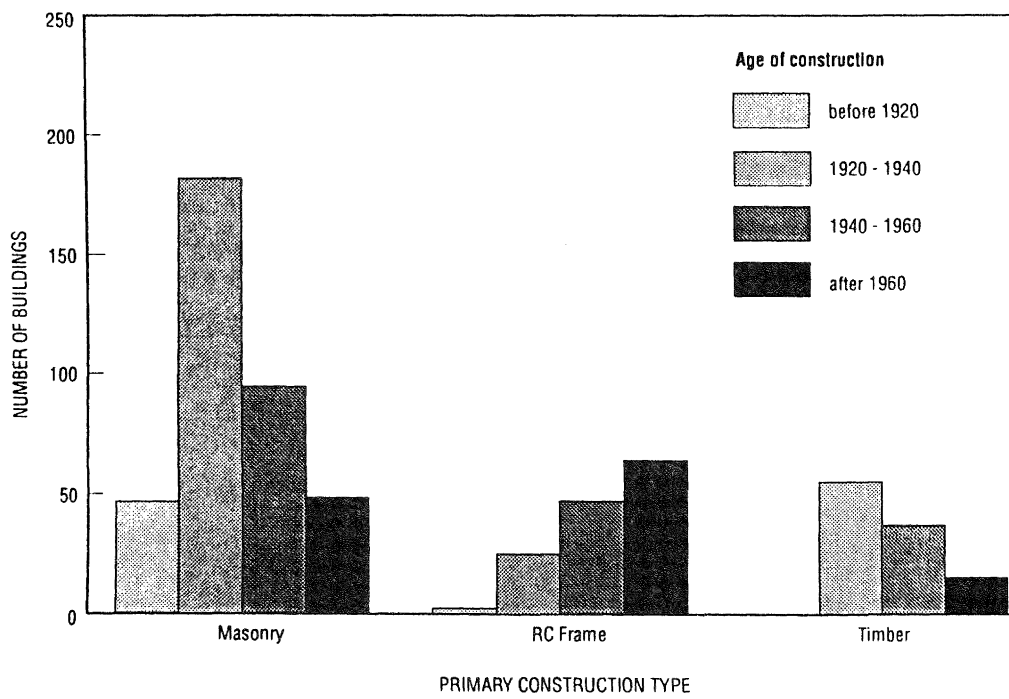


FIGURE 5 NUMBER OF BUILDINGS BY AGE OF CONSTRUCTION

types and 3 were brick masonry buildings of unknown age. Over half of the timber framed buildings dated from the period 1920-1940, whilst 80% of the reinforced concrete frame buildings dated from post-1940.

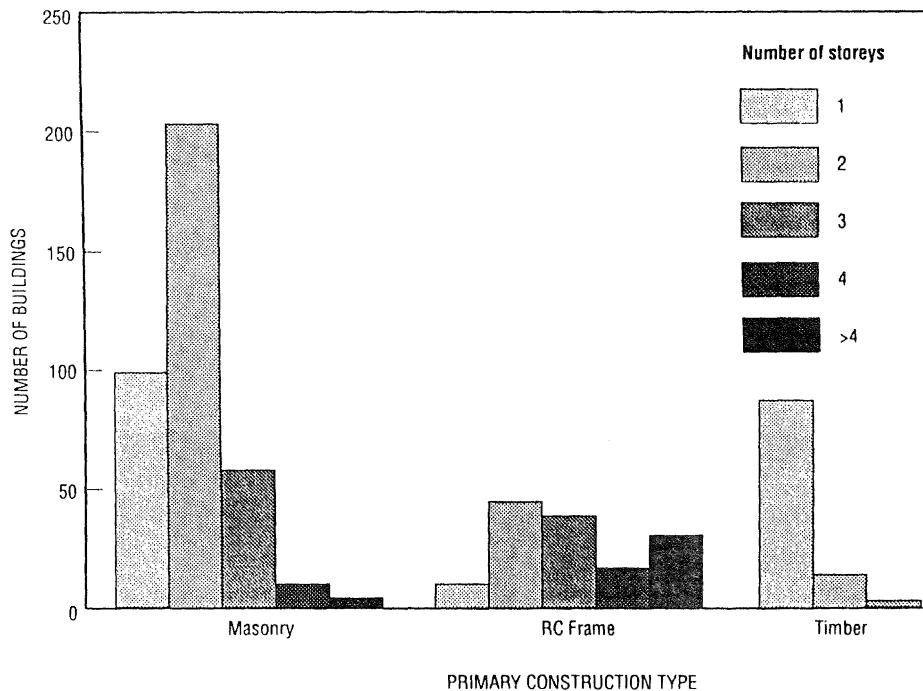
Classification by height in number of storeys is shown in Figure 6. The majority of the buildings surveyed were low-rise with less than 5 storeys, with only 34 buildings (6%) being in the mid-height range, namely 5-10 storeys (classified in Figure 6 as greater than 4 storeys). No buildings of more than 10 storeys were surveyed. These figures are representative of the City as a whole, where low-rise construction dominates. The proportion of buildings with 1, 2, 3 and 4 storeys in the survey was 31%, 44%, 15% and 4%, respectively. A high percentage of the brick masonry buildings (55%) were of 2 storeys height, with only 19% being 3 storeys or higher. The reinforced concrete frame buildings were almost entirely multi-storey (93%), as expected, with 30 buildings (22%) being over 4 storeys in height. In contrast, 85% of the timber framed buildings were single storey.

**Seismic Vulnerability Estimation**

The building database has been used to estimate the vulnerability to earthquake damage of the three main types of construction prevalent in Newcastle, namely unreinforced brick masonry, reinforced concrete frame and timber frame. The majority of the categories into which the buildings have been classified contain at least 20 buildings, and hence the results of the survey are statistically viable and are considered to give an accurate assessment of the vulnerability and seismic risk associated with the building categories

analysed. From examination of statistical samples of building damage, the performance of a sample of less than 20 buildings of any classification is considered too influenced by the performance of individual structures to be representative of the classification [11]. In this context, categories such as solid single leaf brick masonry buildings (4 in total), residential reinforced concrete frame buildings (1) and pre-1920 reinforced concrete frame buildings (2) have not been included in the damage survey results.

The results of the damage survey have been presented for each category in terms of the percentage of buildings with damage level greater than or equal to D1, D2, D3 and D4. Figure 7 shows the damage level distributions associated with the three main building types, divided where appropriate into commercial or residential usage. Greatest damage was observed, as expected, in the brick masonry buildings where more than one third (37%) suffered at least light damage (D1), and 21% experienced moderate to heavy damage ( $\geq D2$ ). The solid double leaf and cavity construction showed similar damage proportions for  $\geq D1$ , but considerably fewer cases of D2 or D3 were observed for the solid double brick masonry buildings. For the reinforced concrete frame buildings, the percentages suffering  $\geq D1$  (20%) and  $\geq D2$  (12%) are about half those for brick masonry buildings, whilst for timber framed buildings the majority of the damage occurred at level D2 (14 of 104 buildings, or 13%). Very few buildings in Newcastle suffered damage of Level D4 (Partial destruction, involving the collapse of a complete wall). Overall, only 5 brick masonry buildings and one timber framed building were assigned this damage level, representing 1% of the surveyed buildings. Apart from the Working Mens' Club and The



**FIGURE 6 NUMBER OF BUILDINGS BY HEIGHT IN STOREYS**

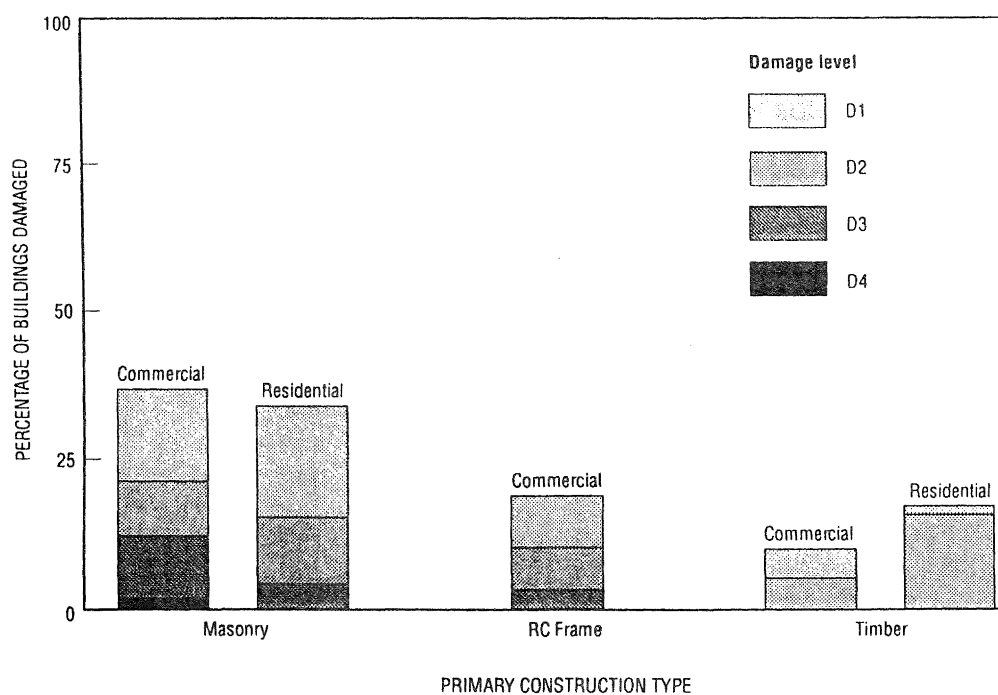


FIGURE 7 VARIATION OF DAMAGE LEVELS WITH PRIMARY CONSTRUCTION TYPE AND USE

Junction Motel, no buildings experienced damage classifiable as D5, involving the collapse of roofs or floors.

The effectiveness of sub-dividing the data to analyse the effects of other characteristics of the building stock is limited by the size of the data sample. Figure 7 shows the distribution of damage levels by commercial or residential usage, within each primary building type. For brick masonry construction, there were considerably higher proportions of commercial buildings with heavy damage or partial destruction than for residential buildings of similar construction type. The proportions suffering light or moderate damage, however, were very similar. As expected, the reinforced concrete frame buildings were almost entirely commercial and hence the damage distribution was representative of this construction type as a whole. Timber frame buildings, however, were primarily residential and these suffered considerably more light to moderate damage than commercial timber buildings.

Figure 8 shows the vulnerability of brick masonry and reinforced concrete frame buildings according to their age of construction. There is a clear trend towards greater light or moderate damage in the older brick masonry buildings, with over half of the pre-1920 buildings suffering some damage. Conversely, 79% of the post-1960 buildings escaped without externally visible damage. For reinforced concrete frame buildings, the proportion of buildings with some damage is about 20% for all ages, but surprisingly no buildings constructed in the period 1920-1940 suffered more than slight damage, whereas for more recent

buildings there was significant moderate to heavy damage, the effect being noticeably worse in the buildings of recent (post-1960) construction, possibly due to reduced conservatism in design codes.

Finally, Figure 9 shows the effect of building height on the extent and distribution of damage. For brick masonry buildings, those with more than one storey showed about twice as much damage overall than the single storey buildings, with consistency for damage  $\geq D1$  for those with 2, 3 and  $>3$  storeys. For buildings with moderate or heavy damage ( $\geq D2$ ), those with  $>3$  storeys were about 4 times more vulnerable than single-storey buildings and about twice as vulnerable as buildings with 2 or 3 storeys. None of the single storey reinforced concrete frame buildings suffered any noticeable damage, but about 20% of the multi-storey buildings showed at least slight damage. This value is about half that for brick masonry buildings. Single storey timber framed buildings were found to be only half as vulnerable to damage  $\geq D2$  as compared with two-storey timber framed buildings. One two-storey building was damaged to level D4, but no single-storey buildings were observed in this category.

#### Discussion of Results

The detailed photographic survey of building damage in two of the worst affected areas of Newcastle has revealed significant and consistent trends in the variation of vulnerability and risk of earthquake damage for three important types of construction. The results are particularly important in assessing the levels of damage to commercial building stock, which formed over 68% of the

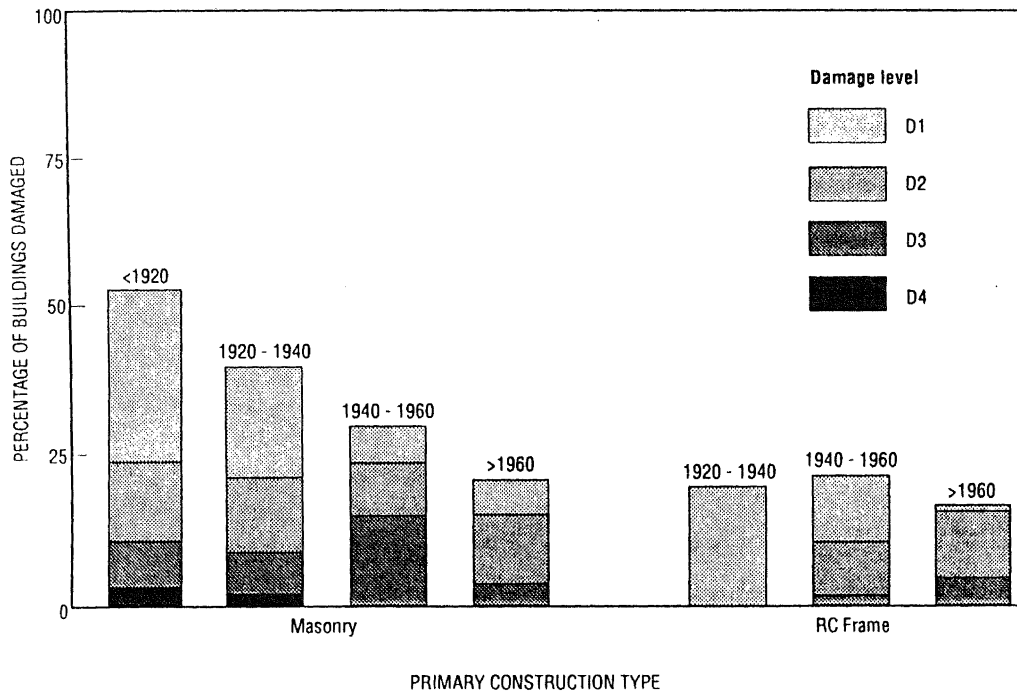


FIGURE 8 VARIATION OF DAMAGE LEVELS WITH AGE OF CONSTRUCTION

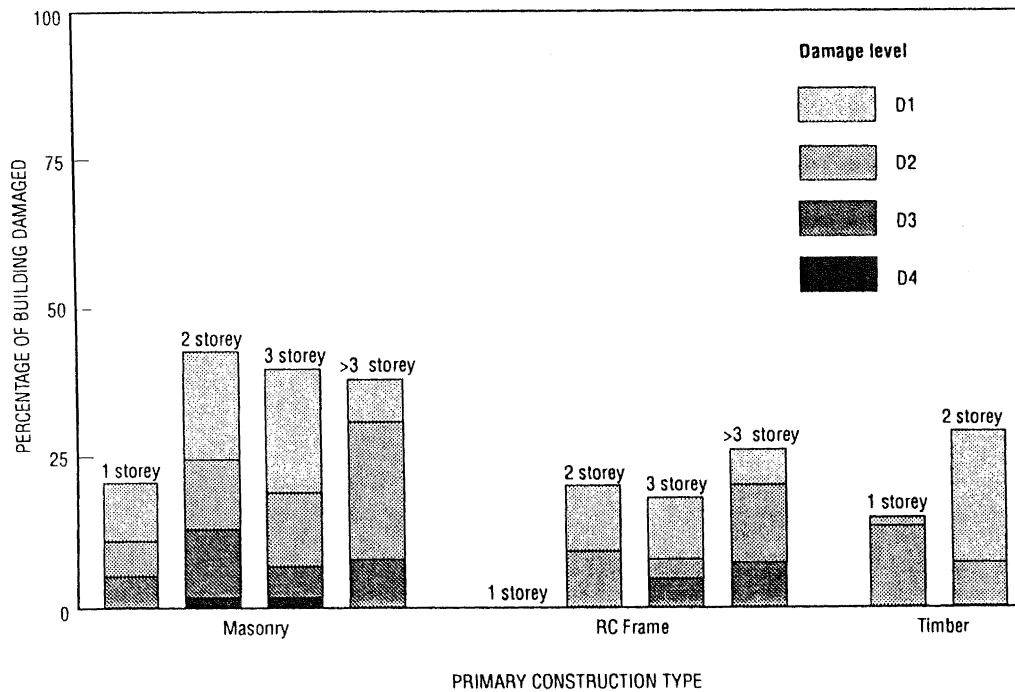


FIGURE 9 VARIATION OF DAMAGE LEVELS WITH HEIGHT IN STOREYS

buildings incorporated in this detailed survey. The results have been further analysed for the effects of building usage, age and height. A summary of the results has been presented in Figure 3, which shows the locations of the 625 buildings on which the survey was conducted, together with the level of damage D0-D4 for the three main types of construction.

The distributions of damage observed in Newcastle appear to conform with distributions of damage to similar building types observed in other earthquakes elsewhere [11], as shown in Figure 10. With about 10% of brick masonry buildings damaged to D3 or worse, as in this earthquake, it is unusual to find any collapse (no damage D5) and typical distributions consist of D4 of

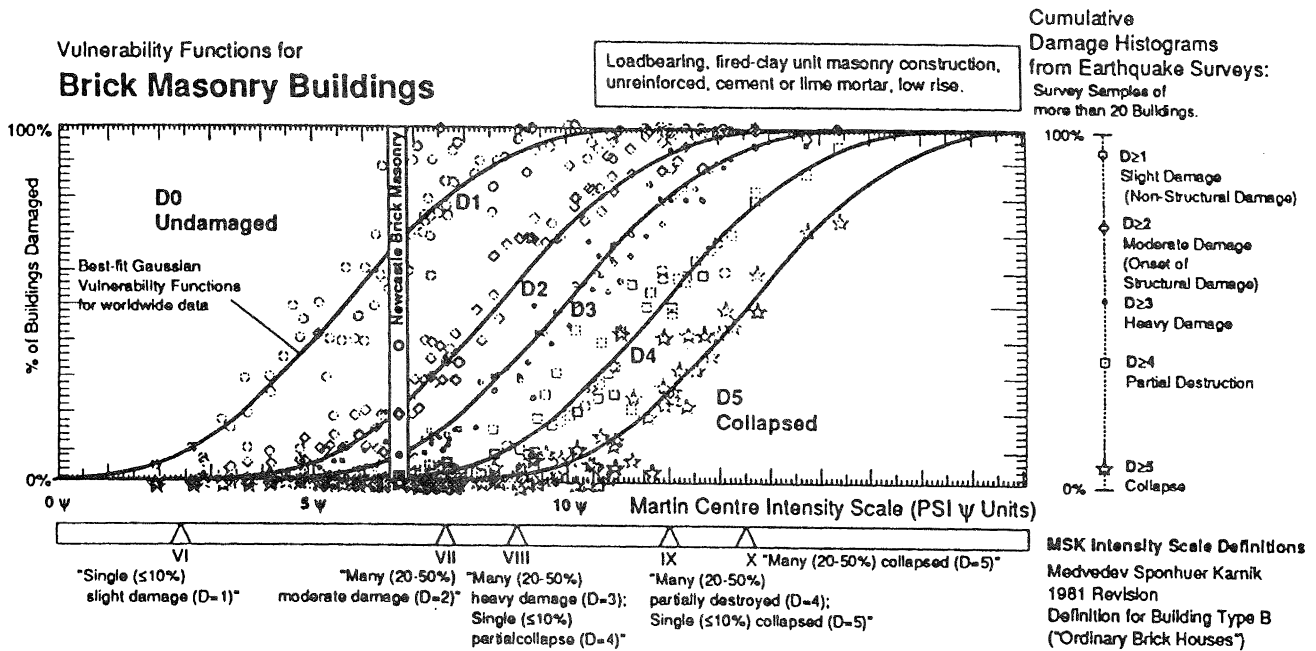


FIGURE 10 DISTRIBUTION OF DAMAGE TO NEWCASTLE BRICK MASONRY BUILDINGS COMPARED WITH SIMILAR BUILDING STOCK IN OTHER EARTHQUAKES WORLDWIDE (FROM MARTIN CENTRE VULNERABILITY DATABASE, REF. [11])

a few percent and damage to at least D2 of between 20 to 30%. One major difference between the distributions of brick masonry damage recorded in Newcastle compared with distributions surveyed elsewhere is that in the latter case the average percentage of at least D1 corresponding to 10% damage of D3 or worse is 70%. In the Newcastle photographic survey, the proportion of at least D1 is less than 40%. One explanation of this is that the threshold of damage for D1, the hairline cracks normally noted on building survey forms, may be less discernable from photographs and hence the photographic interpretation of damage may have missed a number of minor cracks.

The relative levels of damage in Newcastle between reinforced concrete buildings and brick masonry structures also appears consistent with relative damage levels from other earthquakes. However, it should be noted that the relative vulnerability of unreinforced brick masonry structures and reinforced concrete frame structures without seismic design has considerable scatter, using data collected worldwide. The difference in vulnerability may be slightly less than worldwide averages; in Newcastle 12% of reinforced concrete frame structures suffered damage level D2 or worse compared with 21% of brick masonry buildings. In locations elsewhere in the world where 21% of brick masonry buildings have suffered damage D2 or worse, the average of damage at the same level to reinforced concrete frame structures without seismic design is about 8%, but the scatter is large [12]. If this observation is valid then either brick masonry structures are stronger in Newcastle than elsewhere or the reinforced concrete structures are slightly more prone to low damage levels.

The general distributions of damage, particularly to brick masonry buildings, suggest that the damage level is at the low end of MSK Intensity VII ("Many [20 to 50%] brick buildings suffering moderate damage D2"), see Figure 10. Fitting the Newcastle distributions to the average Gaussian vulnerability functions derived from the Martin Centre database suggest a best fit at around an intensity level of 6.7  $\psi$  units (Martin Centre Intensity Scale, see Reference 13 for further details). Damage distributions of this order surveyed around strong motion instruments, such as at Bisaccia in the Italian earthquake of 1980 (16% D2 or worse for brick masonry structures) correlate with a peak ground acceleration around 100cm/s<sup>2</sup> (0.1g) [13]. It should be noted that this comparison with Bisaccia is for the effects of an earthquake at distance from a larger magnitude event rather than, as in Newcastle, close to the epicentre of a smaller magnitude event, so other characteristics like duration, frequency content and vertical components may be significantly different.

#### General Damage Survey

As described earlier, a general survey was carried out with buildings having visible damage being marked onto the 1:4000 scale aerial photographic montage (Figure 1). In the Hamilton area and central business district all streets were surveyed. In the adjacent areas generally alternate streets were surveyed due to time limitations. Two levels of damage were recorded as follows:-

Moderate Damage	Yellow	Clear visible damage that is repairable and is unlikely to cause severe injury. Collapsed chimneys were included in this category.
Heavy Damage	Red	Partial collapse of the structure sufficient to cause severe injury (if people had been within or adjacent to the structure)

Generally the Yellow category is similar to damage level D2 described previously, and the Red category is similar to damage level D3 or greater. The primary intention of this survey was to establish the density and extent of the earthquake damage. It must be noted, however, that the ground survey is not as thorough as the detailed photographic survey and the risk of not identifying damage is much greater. The observed damage must therefore be considered as a lower bound, and it is likely that considerably more damage occurred than was actually recorded.

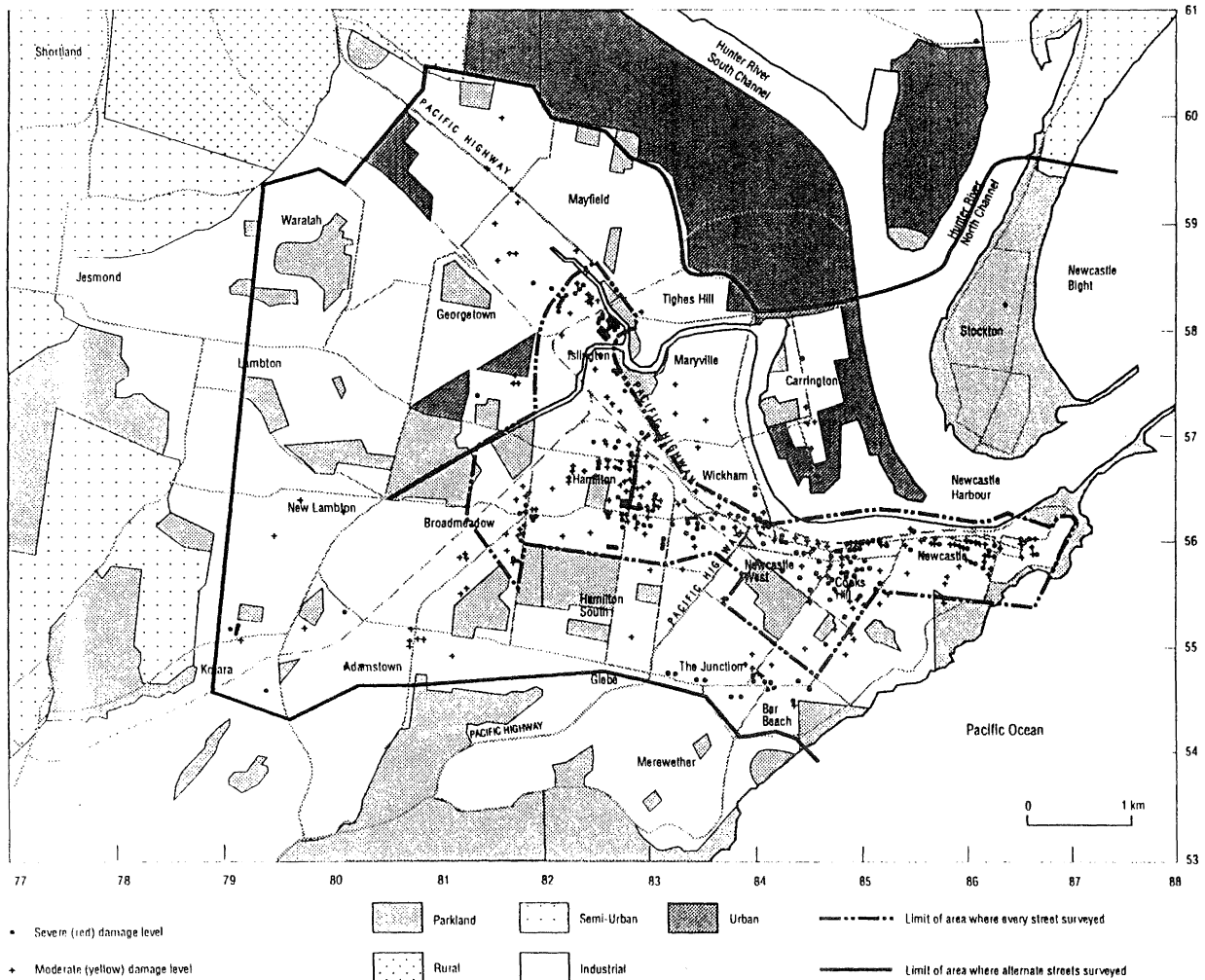
Figure 11 shows the locations of buildings with moderate or heavy damage observed in the EEFIT general survey. Whilst it can be seen that the areas of heaviest damage are in the vicinity of the detailed photographic survey, there is also considerable damage in the areas of The Junction, Tighes Hill and Broadmeadow. This correlates well with the data collected by the Newcastle City Council in their damage survey, as described below.

**Other Damage Survey Data**

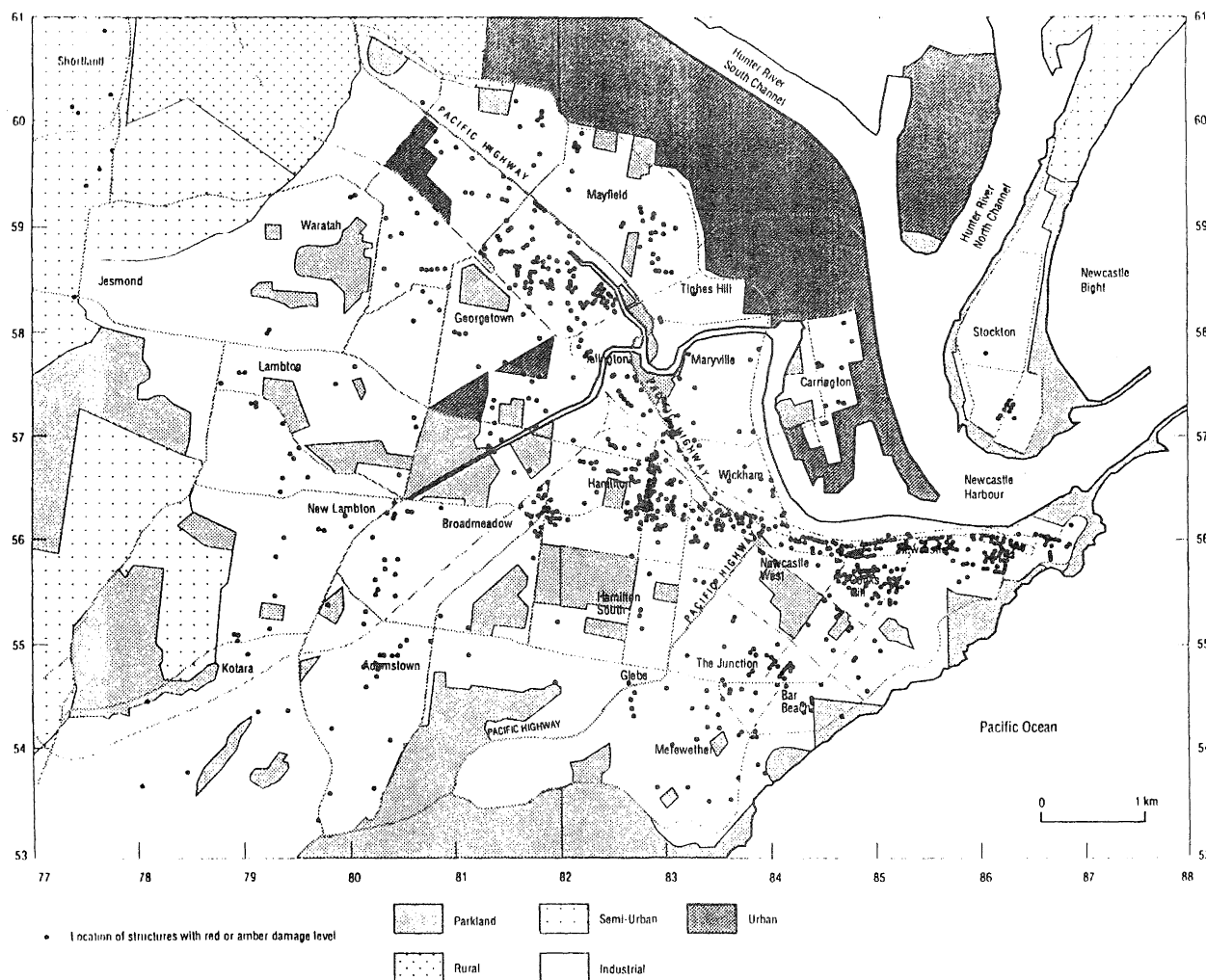
The Newcastle City Council inspected most buildings in the days after the earthquake [14]. Their inspectors employed a four-colour coding scheme as follows:-

- Red - severe damage, immediate public danger
- Amber - severe damage, possible danger
- Blue - damaged, but habitable
- Green - minor damage

From the descriptions given above, their Red classification is similar to that adopted by EEFIT and their Blue and Amber correspond



**FIGURE 11 LOCATIONS OF STRUCTURES WITH MODERATE OR HEAVY DAMAGE FROM EEFIT GENERAL SURVEY**



**FIGURE 12 LOCATIONS OF STRUCTURES WITH MODERATE OR HEAVY DAMAGE FROM NEWCASTLE CITY COUNCIL DATA**

approximately to the Yellow classification used by EEFIT. It must be noted that there will be considerable variability in the assessments between different inspectors and, as for the EEFIT survey, not all damage is recorded. In addition, damage to schools, colleges, churches, and so forth does not appear to have been reported. The Newcastle City Council map showing the locations of all residential buildings damaged in the Red and Amber categories is reproduced in Figure 12. The pattern of damage is similar to the EEFIT survey, except for Merewether which was not surveyed by EEFIT, and in Mayfield where the density of damage recorded by EEFIT was much less than that indicated in Figure 12.

Percentage damage levels for the residential areas using the EEFIT data and the Newcastle City Council data are shown in Figure 13. The levels of damage are much lower than that observed in the EEFIT detailed photographic survey (Figures 3 and 7), and are believed to reflect a combination of:-

- i) poorer data in that more damage is missed;
- ii) residential districts (particularly in the outlying areas of Newcastle) had a much smaller proportion of vulnerable

brick masonry buildings compared with the commercial areas (Figure 4), and greater than 50% of residential buildings covered in the general survey are of timber frame construction which showed significantly better earthquake resistance (Figure 7);

- iii) less damage occurred away from the principal streets.

In areas away from principal streets the buildings are predominantly single storey with timber frame construction dominating. However, in Silsoe Street on the borders of Georgetown and Mayfield, there was a concentration of 1930's residential single-storey masonry construction which suffered significant damage.

In areas where comparisons between the EEFIT and Newcastle City Council data are shown (for example in the more heavily damaged areas of Hamilton and Newcastle city centre) there is good agreement based on the Red and Yellow/Amber categories, with the Newcastle City Council data showing higher overall damage levels as a result of the data assigned to the Blue and Green categories representing relatively minor damage.

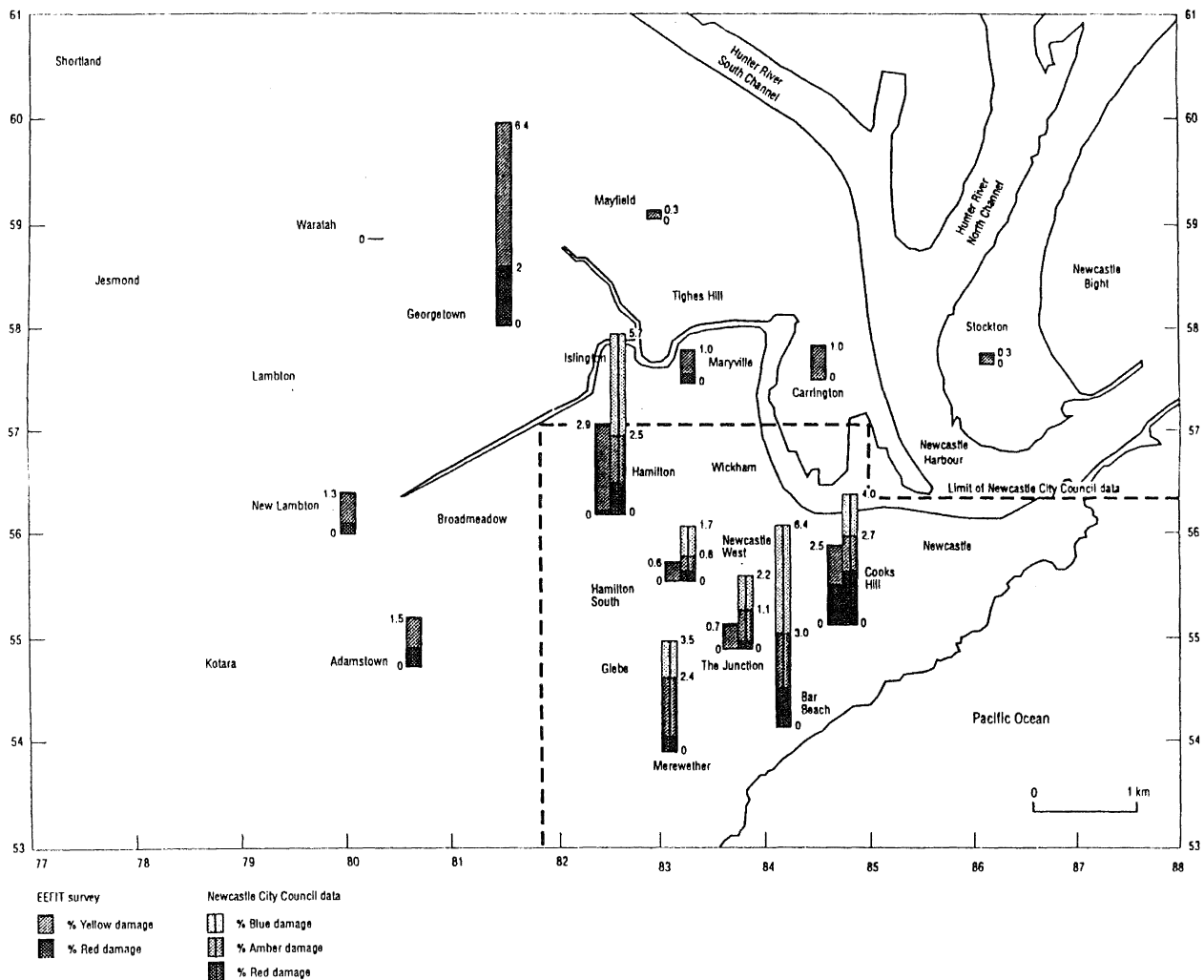


FIGURE 13 PERCENTAGES OF DAMAGE TO RESIDENTIAL BUILDINGS

**FACTORS INFLUENCING SPATIAL DISTRIBUTION OF DAMAGE**

Figures 11 and 12 show that the heaviest concentration of damage was in Hamilton and the Newcastle central business district. The detailed damage survey has demonstrated that the weak masonry structures that suffered the worse degrees of damage, and to some extent the reinforced concrete structures that also exhibited the more severe categories of damage, are predominantly commercial building types. The residential buildings that populate much of the region affected by the earthquake are primarily the less vulnerable timber framed construction and have consequently suffered much lower damage levels. The concentrations of damage along Hunter Street in Newcastle and Beaumont Street and Lawson Street in Hamilton chiefly indicate the older commercial streets of the original settlements where the concentrations of the most vulnerable building stock are found.

How the locations of worst damage relate to the position of the epicentre is not clear. The teleseismic instrumental location for

the epicentre is some 10 to 14km from the worst-damaged areas. This location is to some degree uncertain and could have been closer to the most damaged areas. However, the central business district of Newcastle has the greatest concentration of masonry (particularly older masonry) buildings for at least 30km around, and it is likely that any earthquake occurring in this region would have caused higher damage levels in the older central business district of Newcastle than in the residential areas around it. In the detailed building survey, the damage distributions in Beaumont Street and Lawson Street in Hamilton are almost identical to the damage distributions of similar building types in Hunter Street in the central business district. The intensity appears relatively uniform across the four kilometres covered by the detailed survey and it is not possible to determine from the damage plots (Figures 3 and 11) any particular concentrations of damage that might mark the focus of a localised earthquake epicentre.

There may however be additional influences on the spatial distribution of damage, and

these are considered further in the following sections.

**Soil Response Effect**

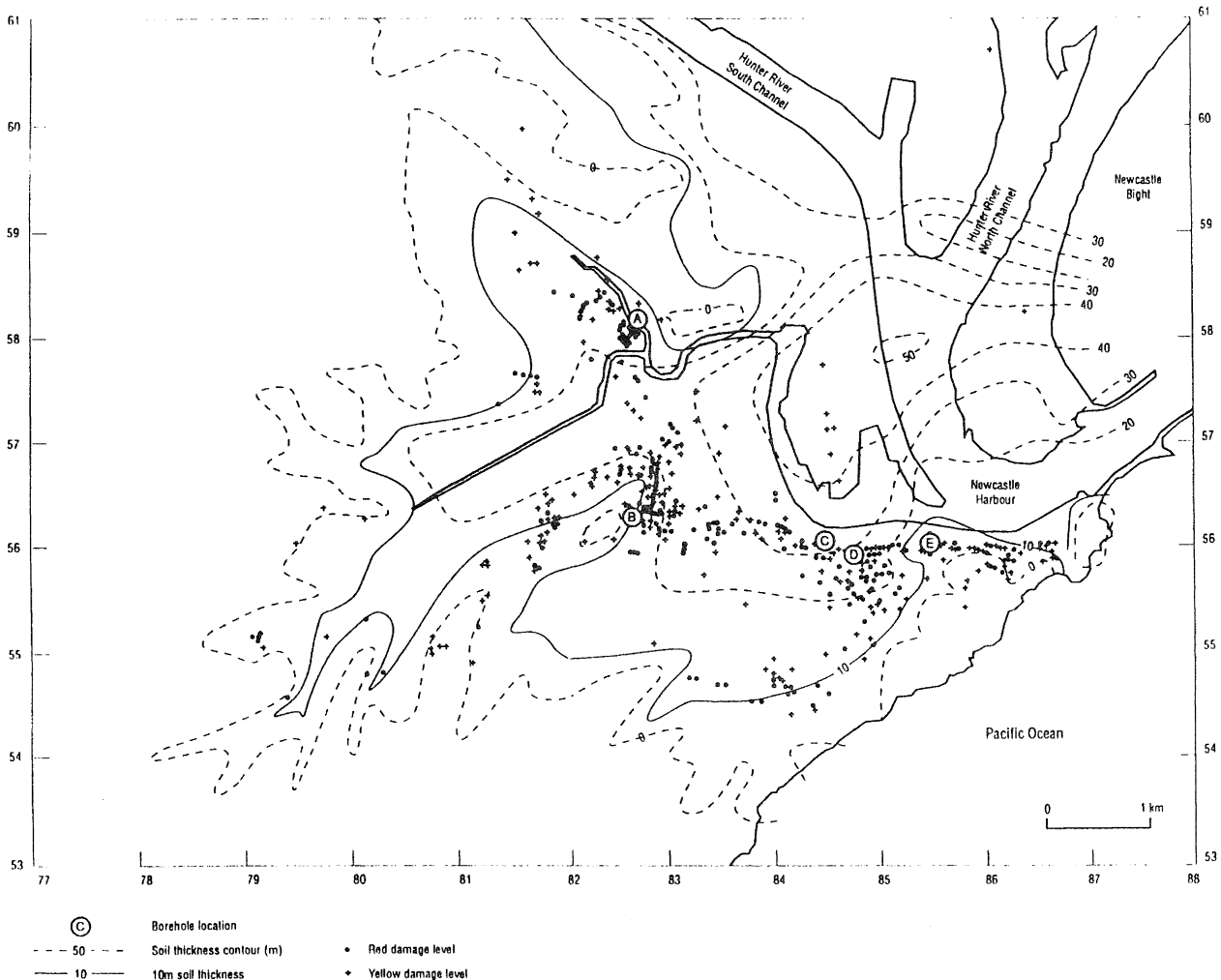
The Institution of Engineers, Australia report [5] concludes that deep soil amplification effects were largely responsible for the observed damage distribution.

Coffey and Partners International Pty Ltd provided the EEFIT team with logs of 38 boreholes in the Newcastle area. The boreholes are between 5 and 36m deep with about two thirds penetrating the underlying coal measures. The soils encountered in the boreholes vary considerably from loose silty sands to dense sands and from very soft clays to hard clays. Soils that are residual rather than alluvial, that is derived from weathered coal measures, are generally stiff clay to sandy clay. While generally there is up to 8m of residual soils where the coal measures outcrop, in the alluvial areas the soils sometimes lie directly over hard rock.

Because of the great variability of soil types and consistency it has only been

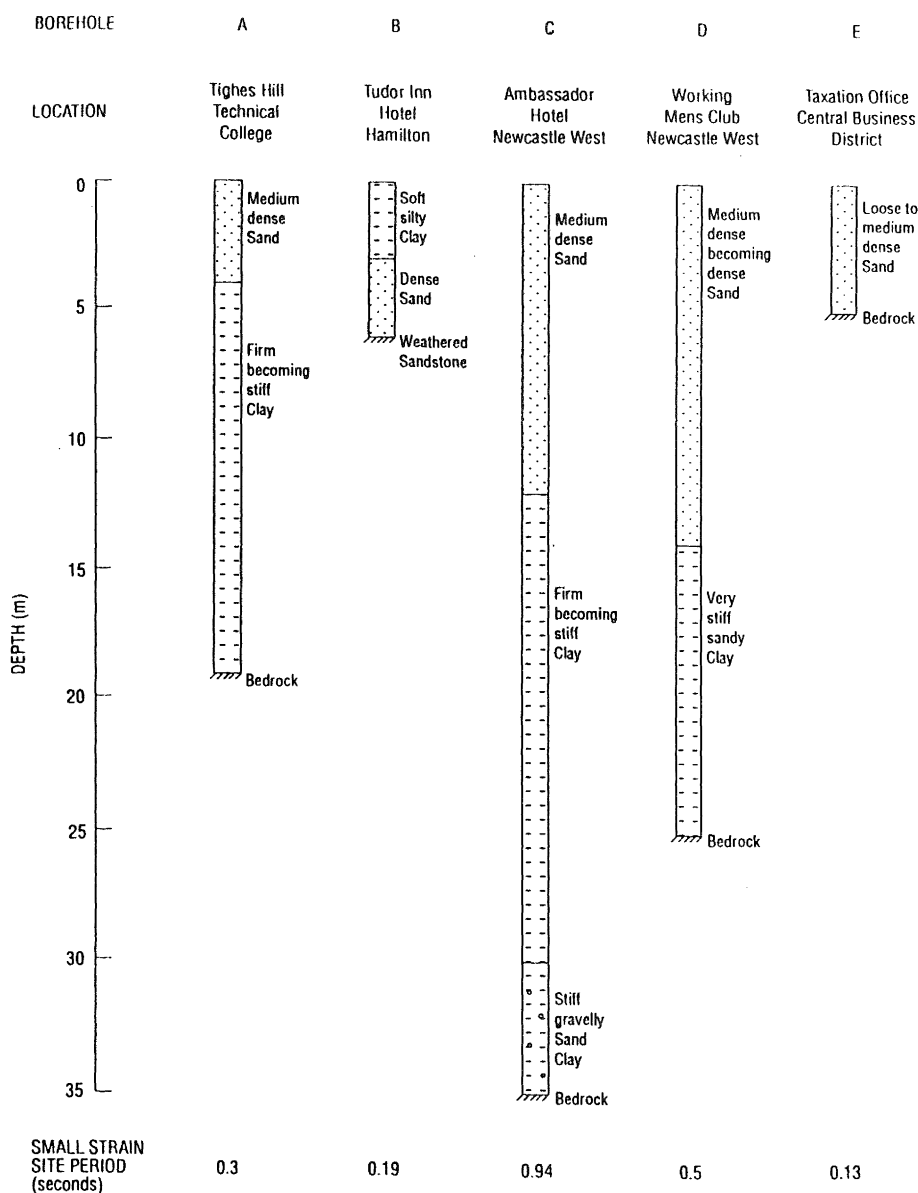
possible to plot the thickness of soil overlying the coal measures. The Coffey and Partners plot (reproduced from the Institution of Engineers, Australia report [5]) is shown in Figure 14 and clearly shows a much greater soil thickness (up to about 40m) under the port area. The industrial areas to the north of the Hunter River are partially sited on land reclaimed with hydraulic fill during dredging of the river bed carried out to enable larger ships to use the port facilities.

Figure 14 shows the damage distribution from the general survey superimposed on the soil thickness diagram. Generally, there is seemingly no correlation between damage distribution and soil thickness. The damage recorded in the detailed photographic survey in Hunter Street in the City centre (Figure 3) seems to confirm this. A fairly uniform distribution of damage was observed, even though the soil thickness varies from near zero at the eastern end to about 30m at the western end. The extent of damage in Hunter Street is comparable to that in Beaumont Street, Hamilton where the soil thickness is between 10 and 20m. In these areas, with a high concentration of the more vulnerable multi-storey older brick masonry buildings,



**FIGURE 14 DISTRIBUTION OF DAMAGE IN RELATION TO SOIL THICKNESS**





See Figure 14 for borehole locations

**FIGURE 16 BOREHOLE DATA FOR STUDY OF SITE SOIL RESPONSE EFFECTS  
(COURTESY OF COFFEY AND PARTNERS INTERNATIONAL PTY LTD)**

soil properties were derived from SPT results and soil descriptions as given in Heidebrecht et al [15] and Henderson et al [16].

The resulting calculated ground surface acceleration response spectra for 5% structural damping are shown in Figure 17 over the range of fundamental building period (0.1-1.0 seconds) relevant to buildings in Newcastle.

It is clear that the shallow soil deposits (Boreholes B and E) amplify the short period motion (in the range 0.1-1.3 seconds) by factors of 2½-3. Low-rise structures of up to 3 or 4 storeys would therefore be expected to have shown a greater level of

damage in the areas underlain by these soils. As the soil thickness increases (Boreholes A and D) the amplification is seen to reduce in magnitude but extend over a wider period range. For the deepest deposit (Borehole C) a slight attenuation compared with bedrock motion is indicated. These results agree reasonably well with the trends observed in Figures 14 and 15, but there is too large a variability in the data to draw any firm conclusions.

The calculations show that unlike other earthquakes such as Mexico City in 1985 [17] and San Francisco in 1989 [18], deep soft soil deposits do not necessarily amplify the bedrock ground motion to any significant extent. This is confirmed by the results of

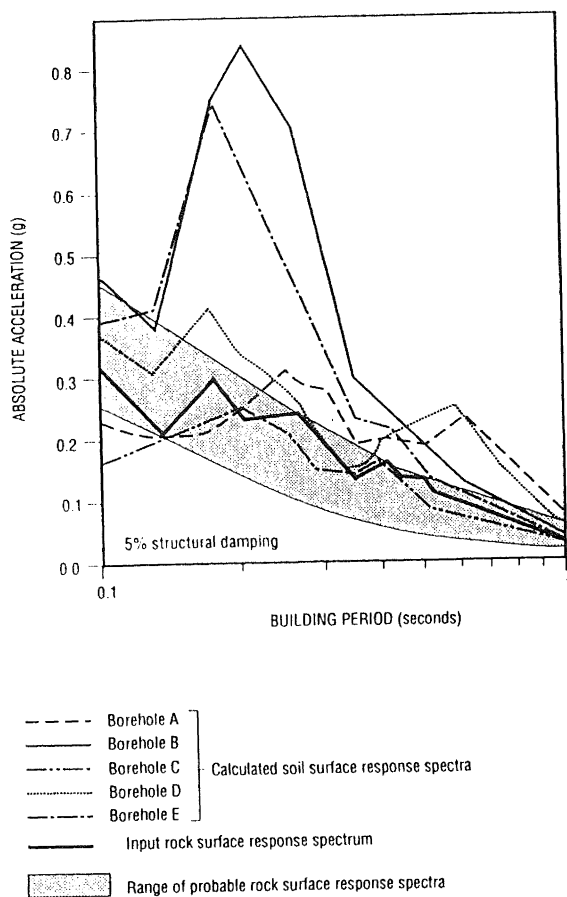


FIGURE 17 RESPONSE SPECTRA OBTAINED FROM STUDY OF SITE RESPONSE EFFECTS

detailed site response analysis by Heidebrecht et al [15] who conclude that spectral amplification is most significant when the seismic excitation has substantial energy in the region of the site period (which for deep soft sites could be in the order of 1-2.5 seconds). The very high site amplification effects recorded in Mexico City (with factors of about 6) and San Francisco resulted from far field earthquakes (epicentral distances of about 400km and 100km, respectively) where the attenuated bedrock motion had a frequency content shifted towards the longer periods. For the lower magnitude, near field earthquake in Newcastle the energy would almost certainly have been concentrated at the shorter periods (Figure 2) and would therefore tend to excite site resonance effects in the shallower, stiffer soil deposits as indicated in Figure 16.

Hence it is concluded that the suggested correlation of greatest damage with the areas of deep alluvial soil deposits in Newcastle ([5],[8]) is not substantiated by the observed damage distribution or by the analytical results presented here. The actual situation is clearly more complex with the possibility of some quite localised ground motion amplification effects in the shallower and/or stiffer soil deposits. The widespread variation of soil types and thickness in the Newcastle area (Figure 14)

together with the analytical results presented herein show that the attempt to relate damage distribution simply to soil depth or type is unlikely to lead to useful or accurate results. The overall result of this study is that whilst the analytical studies are useful for indicating localised variations of ground motion, amplitude and frequency content, the complexity of the problem makes it very difficult to develop generalised conclusions regarding the significance of site effects in the response distribution. However, it is clear that the deeper, softer sites are unlikely to have demonstrated any significant amplification effects in this earthquake.

#### Effects of Mining

Newcastle lies on the remains of the Hunter and Mooki thrust system which originally extended about 1000km northwards from the present-day City. The movements across the thrust system led to marine sediments in the Sydney area and mainly terrestrial sediments in Newcastle. The sediments are referred to as the Newcastle Coal measures, and consist of layers of Coal (12%), Tuff and Claystone (19%), Shale (17%), Sandstone (23%) and Conglomerate (29%)[19]. The Newcastle geological map [20] shows recent alluvium overlying these coal measures. Generally the map shows that areas less than 10m above sea level are alluvial and areas above 10 to 30m are underlain directly by the coal measures.

Directly beneath Newcastle the main economic seam to be worked is the borehole seam which is about 2m thick. Figure 18 shows the extent of coal extraction from the seam and contours to the base of the seam [19]. The method of coal extraction under Newcastle is pillar and stool with long wall methods being employed south and west of the town. It is known that there are older workings in higher seams but the location and extent of these is largely uncertain.

It is noticeable that in several earthquakes damage has been associated with mining activity. In the Liege earthquake, this was associated with ground settlement induced by mining [21]. In Newcastle there has been no evidence of damage to mines currently in use. If, however, the pattern of damage is plotted together with the area of coal extraction as in Figure 18 there appears to be a clear correlation between damage and the edge of mining activity. This may be due to motion being concentrated at the perimeter of the coal extraction. An alternative explanation is sociological in that the mine perimeters tend to be aligned along major roads. This is also where the most vulnerable buildings are situated and consequently there may be strong historical reasons why the damage is concentrated as it is.

#### DISCUSSION AND IMPLICATIONS

The reasons why the most severe earthquake damage occurred apparently 10 to 14km from the epicentre is not clear, although it must be recognised that there is still significant uncertainty in the epicentral

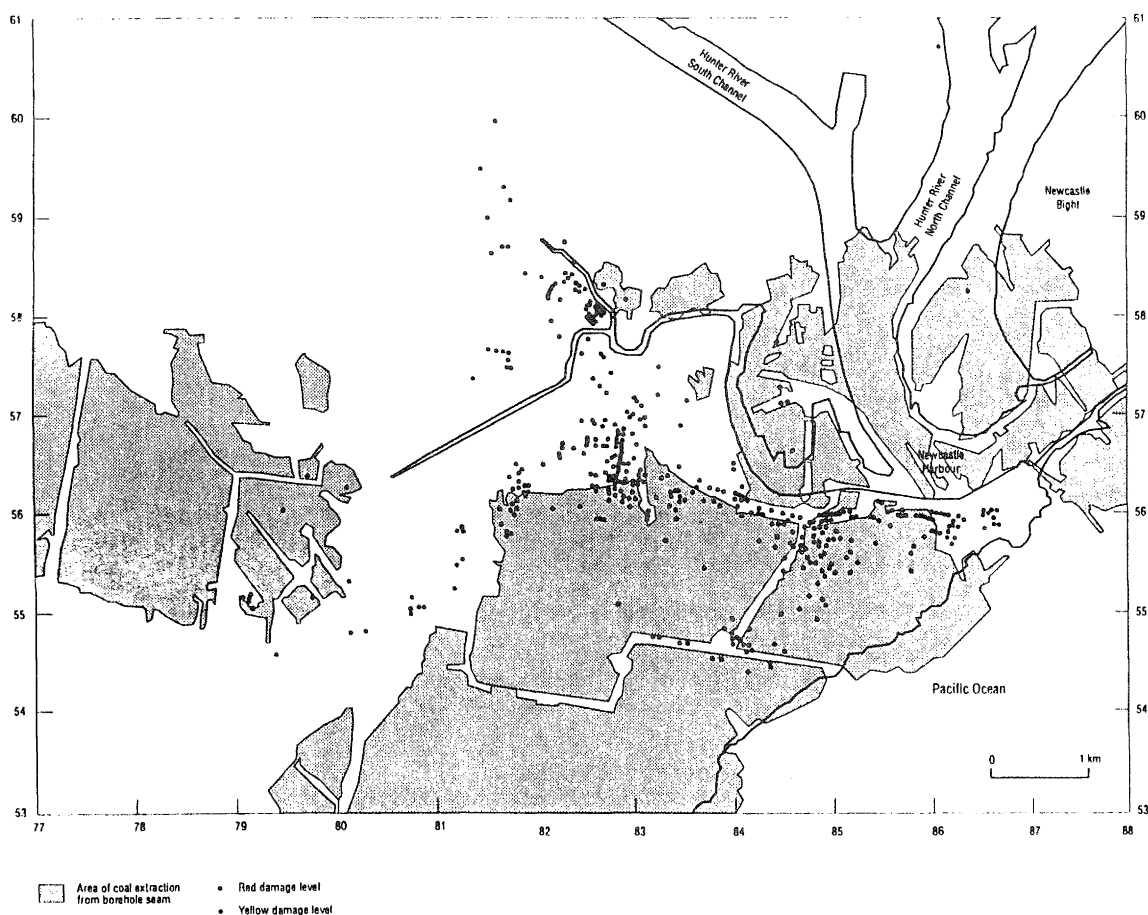


FIGURE 18 DISTRIBUTION OF DAMAGE IN RELATION TO AREAS OF COAL EXTRACTION

location. Possible explanations are that some geological feature directed the strong ground motion towards the heavily damaged areas such as Hamilton and the Newcastle central business district, or that the most vulnerable buildings are located principally in these areas. As in many earthquakes, the most likely explanation involves a combination of these effects, since rarely is it obvious why certain damage distributions are observed. The exception to this is when soil amplification effects are dominant, as in Mexico City in 1985 [17] and San Francisco in 1989 [18]. In both cases there was a clear, unambiguous correlation between building damage and soil type, but as indicated in this study, this was not the case in the Newcastle earthquake.

The most significant lesson learned from the extensive damage caused by the Newcastle earthquake is the importance of proper detailing required in order to ensure adequate earthquake protection. This is applicable to buildings of all types of construction, but particularly to unreinforced brick masonry buildings, about 37% of which were damaged in the earthquake (Figure 7), with 21% suffering moderate damage such as partial collapse of parapets, awnings and/or chimneys, and severe cracking of walls or cladding. Much of this damage

could have been prevented or reduced by the more widespread use of wall ties for cavity construction and stronger methods of support for awnings. Improved detailing of such features and other unsupported brickwork would have greatly reduced the risk of falling masonry, which led to three deaths in this earthquake. If the earthquake had occurred in a normal working week and not in a holiday period, the loss of life could have been many times worse. Lack of proper maintenance and the consequent deterioration of older brick masonry buildings also played a significant role in the increased risk of earthquake damage [6].

The revision of the SAA Earthquake Code [22] which was in progress even prior to the Newcastle earthquake will ensure that greater attention is given to detailing to enhance structural continuity in new structures, particularly in joint design. It is also important that the code should give greater attention to the provision of lateral support, particularly for unreinforced masonry construction. This may involve tightening up the requirements for wall ties, and the ductility requirements for both reinforced concrete and steel structures.

For existing buildings and domestic construction (which at present is not

covered by the design code except for multi-storey isolated dwellings [8]), the problem is more complicated. Retrofitting of existing buildings is expensive and in many cases the age and construction (particularly for masonry buildings) makes such procedures uneconomical. At the conference on the earthquake held at Newcastle University on February 15-16, 1990, and sponsored by the Institution of Engineers Australia and the Royal Australian Institute of Architects, proposals were made for tying parapets to roof trusses or the use of a reinforced concrete capping beam, in order to prevent their collapse under earthquake loading (Figure 19). It is likely that these or similar proposals will be included in the detailing requirements of the revised earthquake design code. The outcome of these on-going discussions should be a significantly revised and improved SAA Earthquake Code, with an emphasis on improved detailing for features known to be vulnerable to lateral forces. Provided the provisions are formulated on a rational and realistic basis, the additional cost of such design features should be minor compared with the benefits arising from increased safety and earthquake resistance, for the prevention of damage and (in moderate or severe earthquakes) possible loss of life.

A report published in March 1990 by the Newcastle Town Clerk's Co-ordination Committee on Matters Relating to the Health and Building Services Divisions [23] outlines the Council policy on interim requirements for the design of earthquake resistant buildings. It recognises that whilst regional and national standards and legislation are to be reviewed in the light of the Newcastle earthquake, it will take one to two years for such amendments to be effected. The report, therefore, reflects the urgent need to set interim requirements to provide guidelines for construction of new buildings in the Newcastle area, and to address the upgrading and maintenance of existing buildings. This urgency was highlighted by the amount of repair and reconstruction work being undertaken in the aftermath of the earthquake, without formal guidelines in regard to earthquake-resistant construction. For new buildings, the report proposed that the interim requirements should be based on AS 2121 - SAA Earthquake Code [22] for buildings in Zone A with the exception of post disaster buildings whereby it is proposed that construction will be in accordance with Zone 1 requirements. The implications of these proposals are negligible in regard to ductile buildings (having ability to withstand inelastic deformations) in Zone A. However, non-ductile buildings (Zone A) and post-disaster buildings (Zone 1) will be of a higher standard than currently required.

The Newcastle earthquake has important implications for many areas of low seismicity such as the UK. In global terms, it was of moderate magnitude (5.6), and given the present understanding of earthquake source mechanisms it is possible that earthquakes of this size could occur, albeit with low probability, in virtually any location. Generally, however, such shocks cause little damage to engineered

structures because of their remoteness from populated areas. The exception with Newcastle is that the earthquake occurred near a city, which having no special provision against earthquakes was vulnerable to the effects of seismic ground motion.

The earthquake represents a graphic demonstration of what would happen in any other similar large town or city which has been constructed with no special measures incorporated for earthquake loadings. The lesson for these sites is clear; namely, widespread failure will occur in structures or details which are known to be vulnerable to seismic loading effects. Engineers need therefore to evaluate the risk associated with existing building stock and those under construction using present-day codes (with no earthquake provisions) as compared with the additional cost of incorporating minimum earthquake design and detailing requirements. For example, decisions need to be made on whether all new parapets be reinforced, and existing parapets be demolished or strengthened (Figure 19), whether structures designed with high eccentricity of stiffness or mass (such as The Junction Motel which was demolished soon after the earthquake as a result of column failure) or structures containing 'soft' storeys should be designed with more stringent controls to ensure they have

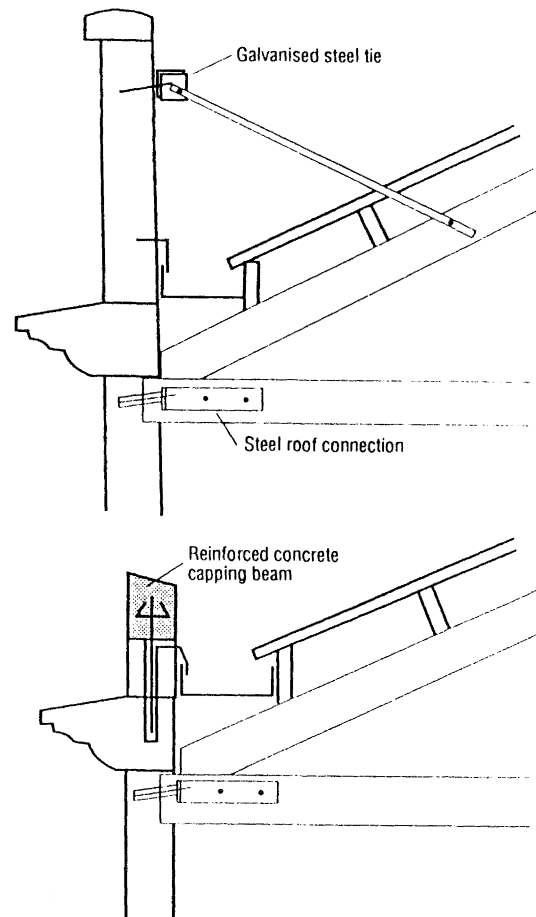


FIGURE 19 RECOMMENDED ARRANGEMENTS FOR TYING OR ATTACHING PARAPETS

adequate capacity to withstand moderate earthquake loadings. From an engineering viewpoint, the answers to these issues are clear. The only remaining question is whether the cost to society can be afforded, given the level of risk of earthquake damage compared to other types of natural or man-made hazard.

#### CONCLUSIONS

The field investigation and detailed follow up studies reported in this paper have led to the following summarised conclusions:

1. The type of building stock most vulnerable to moderate or severe earthquake damage in areas of relatively low seismic risk (where building regulations do not make any specific allowance for lateral earthquake loading) is unreinforced brick masonry. This construction type, particularly in commercial usage, is about twice as vulnerable to damage compared with reinforced concrete frame buildings, and nearly three times as vulnerable as buildings of timber frame construction.
2. The detailed and general surveys of building damage in Newcastle carried out by EEFIT have given data which correlates very closely with that obtained from similar surveys following other earthquakes of similar magnitude in Europe and elsewhere. This consistency of damage data for various common forms of construction leads to the conclusion that accurate estimates of seismic vulnerability of existing building stock are possible in areas of low risk such as the UK and Australia.
3. A rigorous analytical approach to the study of site soil amplification effects due to this earthquake has indicated, contrary to previous reports, that such effects were evident primarily for the shallow, stiff soils near the border of the alluvial basin, and that there was a reasonable correlation between such areas and the locations of the most severe building damage. For a near-field earthquake of this type, deep soft soils tend to attenuate the bedrock ground motion, except in the long period range which is relevant only to buildings taller than those currently existing in the Newcastle area.
4. The comparison of damage distribution with the perimeters of coal mining activity showed a degree of correlation which should be recognised as a significant feature of the earthquake damage pattern. This may be connected with historical and sociological urban development since the mine perimeters tend to be aligned along major roads, which is also where the most vulnerable buildings are situated, such as older, commercial brick masonry building stock.

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