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Field Investigation of the Kobe Earthquake

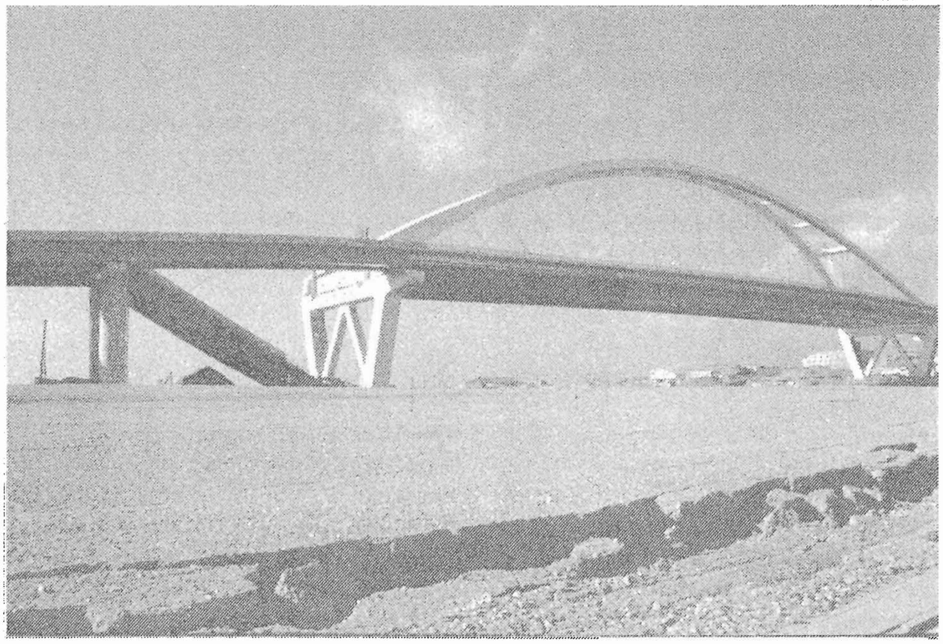
Two weeks after the Kobe earthquake struck, members of EEFIT, the UK's Earthquake Engineering Field Investigation Team, arrived to assess the damage. ***Adam Crewe*** *reports*

Kobe is a large city, with a population of over 2 million, near Kyoto in Japan. The city is a major industrial centre and the container port on Rokko Island is the 5th largest in the world. This port handles over 12% of all Japanese exports and the area around Kobe generates a substantial proportion of Japan's wealth.

Before the city was hit by this earthquake the area was perceived to be at low seismic risk. However, on 17th January at 6.46am the citizens of Kobe were woken by an earthquake that measured 7.2 on the Richter Scale. This was largest earthquake to hit that area in over 50 years. The epicentre of the earthquake was only 15 km from the centre of the city, with the fault occurring just 13 km beneath the surface of Awagi Island. The earthquake killed over 5,000 people and injured more than 26,000.

Two weeks after the earthquake the EEFIT team, comprising nine UK academics and practising engineers with varying backgrounds, went out to Kobe to study the damage. I was particularly interested in the performance of structures built after 1980, to current Japanese design codes, as these structures would give a good indication of the effectiveness of modern seismic design practices.

My overall impression of this earthquake was that whilst some residential areas of Kobe were completely destroyed by the earthquake or by fire, most buildings in the city centre performed reasonably well. There were still many spectacular failures, but for every building that would have to be demolished, several needed little or no structural repair. Within two weeks of the disaster, many buildings were being re-occupied and electricity had been restored to most areas of Kobe. However, the water supply was still very limited and most of the population were using stand-pipes. The main gas lines were still being repaired and it appeared that restoration of full services to all parts of the city would take many months.



Collapsed approach span on a highway bridge

Just after the earthquake I had seen many spectacular pictures in the news, but much of major damage appears to have been overlooked by news reporters. We all saw the pictures of the section of the Hanshin freeway that had toppled over, but this was only 500 m out of about 20 km of elevated freeways and railways. While we were in Kobe, we looked at over 10 km of these elevated structures and about 70% of all the columns we saw were badly damaged.

One of the main surprises about the elevated freeways was the number of different construction forms that had been used. There seemed to be no consistent design methodology for the freeway system and we saw single columns made from both steel and concrete supporting sections of the freeway. The columns also varied in cross-section, with round and square columns predominating, although there were also some instances where tapered columns had been used. We saw failures in all these forms of construction and only where portal

Overthown derricks on Port Island

frames had been used to support the freeways was the damage significantly reduced. Indeed, the toppled section of freeway that we saw pictures of appeared to be the only section of the whole system that had been designed as a series of inverted pendulums with no bearings between the columns and the deck.

In general, the reinforcement details in the freeway structures were less than ideal. We saw fractured butt-welds in the main reinforcement and all the failed concrete columns had inadequate shear reinforcement. On a more positive note, we saw no instances of failures caused by poor quality concrete and only one case of a badly constructed freeway column where a shear crack had formed along the construction joint. The freeway failures were not limited to the concrete columns and we saw several square steel columns with buckled steel plates. Many tubular steel columns had also buckled at mid-height where two sections of tube had been spliced together with a butt-weld. Many of the bearings between the columns and deck had also failed with some decks moving laterally up to 3 m on their cross-head supports. In other cases the decks had moved longitudinally up to 400 mm, fallen off their bearings and the spans had collapsed.

The port facilities were also badly damaged by the earthquake. On the artificial islands around Kobe almost every wharf had experienced major liquefaction of the soil under its foundations accompanied by lateral spreading of the dock walls. Some of the dock walls had moved laterally several meters buckling the legs of the cranes supported on them. A uniform settlement of about 0.5 m had also occurred over the whole of Port Island as the granular fill had compacted during the earthquake. The islands were completely man-made using rock from local quarries which had been dumped in-situ. It was this fill that had liquefied and compacted during the earthquake. One effect of this settlement is that those buildings with piled foundations now appear to poke up out of the ground by half a metre. Other structures on raft foundations appear to have settled with the soil and have suffered no obvious distress. I saw no cases where a foundation failure had directly caused structural damage although I saw several instances where warehouses had collapsed when dock walls had moved.

Geotechnical failures were not limited to the artificial islands. In the Nigawa district a mountainside had crumbled causing a landslip 300 m wide and 800 m long. The area had been densly populated, more than 100 homes were destroyed and over 80 people were killed. Elsewhere traditional timber frame houses had also performed badly. They had heavy clay tiled roofs and generally showed a soft storey collapse. In some areas of Kobe fire also caused a great deal of damage. A strong wind at the time of the earthquake turned small fires into fire storms which destroyed large areas of housing. Over 75,000 buildings were destroyed by this earthquake and more than 310,000 people have been made homeless.

The performance of larger engineered buildings varied a great deal. The buildings designed after 1981 to the most recent codes generally performed well although there were still a few that would require some structural repair. In central Kobe it was the older buildings that suffered most. Generally the reasons for the failure were obvious. Stiffness discontinuities, poor distributions of columns, a lack of shear walls and mass or spatial eccentricities in plan all caused collapses. However, we still saw several unusual failures. A larger number of buildings than normal showed mid-height collapses and although in most cases the cause could be attributed to one of the problems noted above, there were still some failures that currently defy explanation.

The typical Japanese office or retail building also performed badly. Its bottom three storeys are devoted to commercial activities with open plan floors, while the top three or more are residential. In several cases collapse had occurred at the third storey where there was a change in stiffness. Many buildings suffered because they were not adequately reinforced and we saw a few interesting reinforcement details in the older structures. Several collapsed buildings had deformed high yield bars in the beams but only mild steel bars in the columns. We also saw alternating deformed and milld steel bars in some columns. A weak column, strong beam design approach was also evident in some buildings.

As with the freeway structures, the designers of the older buildings that collapsed cannot be criticised as they were working to the best design codes available at that time. However, I believe we should start looking more seriously at ways of dealing with these older structures. It is not enough for us to use progressively more sophisticated design techniques without looking at ways to bring older structures up to the same standards. As engineers we have a responsibility to research and investigate any cost-effective technique for retrofitting and strengthening these structures. The failures, albeit minor, in modern structures also show us that as engineers, we have some way to go before we can be really confident in our ability to overcome nature.

Estimates of up to £200 billion have been placed on the damage and loss to economic activities caused by this earthquake. This will have an enormous impact, not only on Kobe and the surrounding area, but also on the whole of Japan. However, even with so much damage still around them the Japanese were starting to recover and were rebuilding their lives and city. During the week I was there I got the impression that the whole population was working together to restore the city to normality. I learnt a great deal by visiting the aftermath of a recent earthquake, and seeing the effects of this earthquake has, in my case, confirmed the value of all earthquake engineering research that ultimately aims to avoid the damage I saw in Kobe.

***Adam Crewe** is a lecturer in the Earthquake Engineering Research Centre, Bristol University, UK.*

A Summary of 1994 Earthquakes

*Each issue of the SECED Newsletter carries a list of notable earthquakes supplied by the British Geological Survey. The latest list is on the inside of the back page. **David Redmayne** amplifies the brief comments of the list in a summary of the year's significant earthquake activity.*

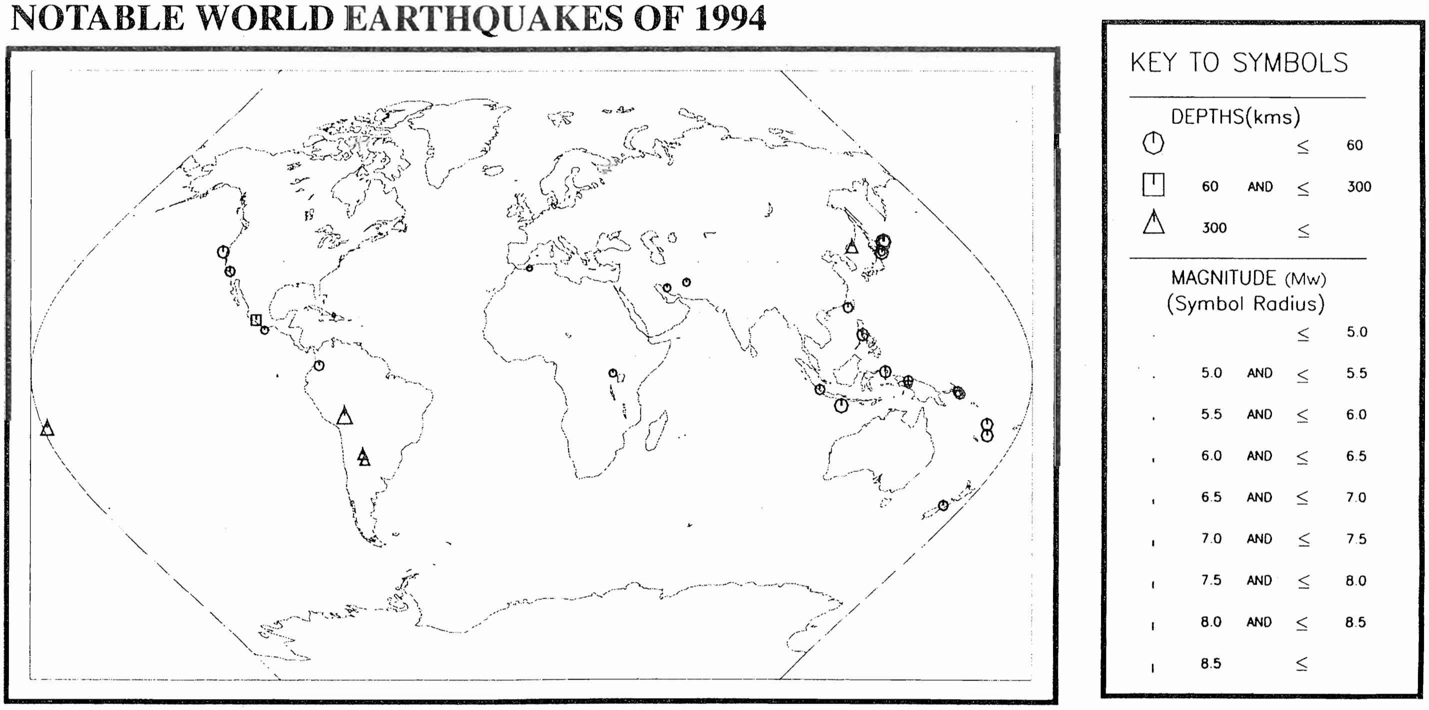
Despite the continued public misconception that "earthquakes are on the increase", 1994 proved not be exceptional for earthquakes. Nevertheless there was one "great earthquake", with a magnitude over 8.0 Ms and a number of severely damaging earthquakes with catastrophic human and economic consequences.

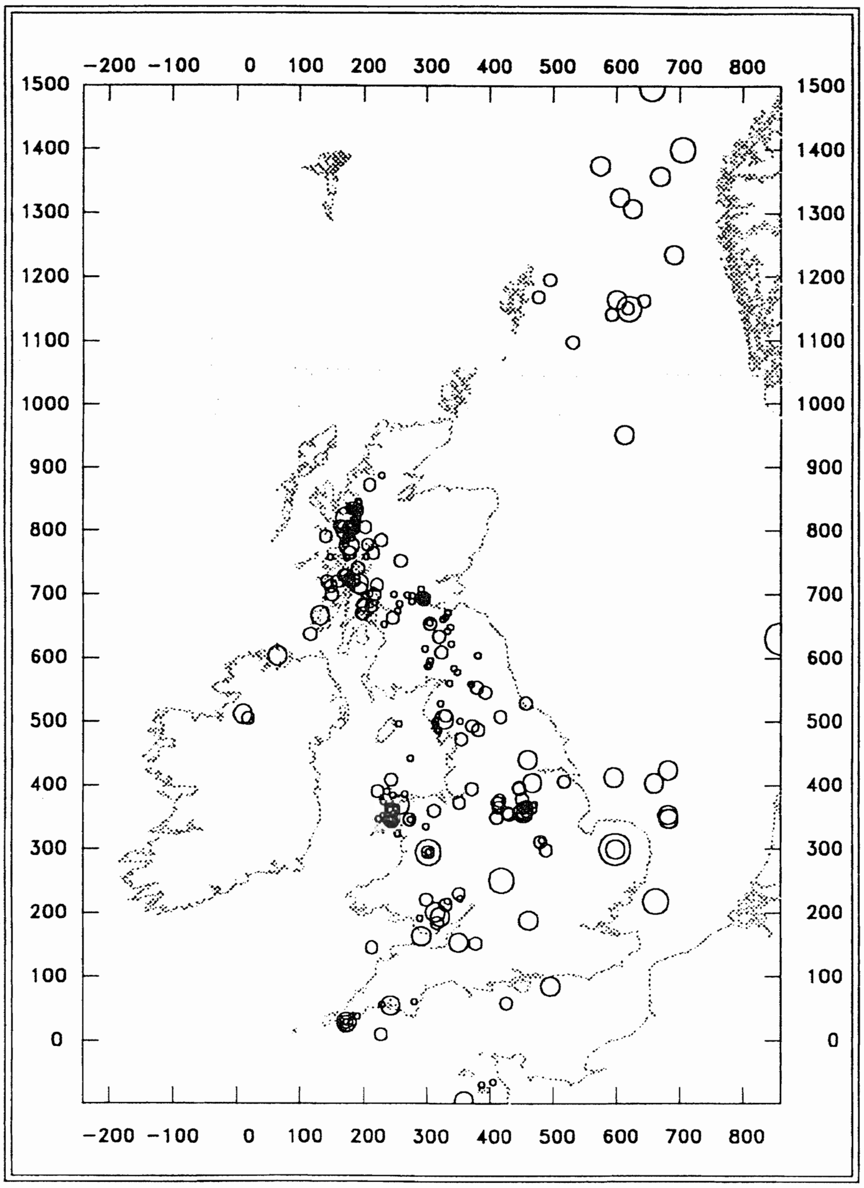
The occurrence of one "great earthquake" is consistent with the normal annual average for earthquakes over 8.0 Ms. There were also 11 "major earthquakes", with magnitudes (the greater of Mb and Ms) between 7.0 and 7.9, which compares with a long term average of 18 per annum. Ninety-two "strong earthquakes", with magnitudes between 6.0 and 6.9, occurred, which again was lower than the long term average of 120 per annum. The number of people reported killed by earthquakes during 1994 was 1,098, well down on the long term average of 8,700 per year. However, this was because most of the major earthquakes occurred in remote, sparsely populated areas, rather than to improved protection against earthquakes.

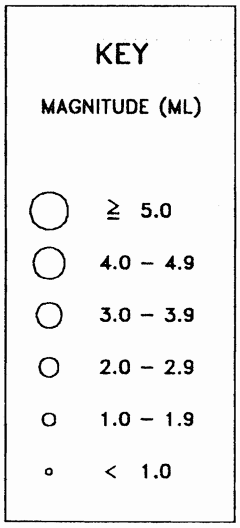
Most of the severely damaging earthquakes of 1994 were in the major or strong categories. There were, however, a number of notable exceptions, proving again that a relatively small earthquake with a shallow depth of focus in a highly populated area can be disastrous. The magnitude 5.9 Ms Algerian earthquake of 18 August (described later) was the most notable example of this, killing some 159 people. The Fort Portal area of Uganda suffered the effects of a magnitude 6.0 Ms earthquake on 5 February which resulted in four fatalities. The smallest earthquake of 1994 to cause fatalities occurred on 2 March in the St Luis du Nord area of Haiti. This magnitude 5.0 Ms earthquake damaged houses and killed four people. Several events with magnitudes around 6.0 Ms caused damage and some fatalities in parts of Iran early in the year and Mexico also suffered damage and two fatalities from a magnitude 6.1 Ms earthquake on 4 July.

Northridge in Los Angeles was the

NOTABLE WORLD EARTHQUAKES OF 1994







Epicentres of all UK earthquakes located in 1994 (from the BGS Bulletin of British Earthquakes for 1994)

first area to be struck by a damaging earthquake in 1994. With a magnitude of 6.8 Ms, the Northridge earthquake of 17 January was by no means the largest that Los Angeles could expect; however, it proved to be severely damaging and caused the deaths of sixty people and injury to 7,000 others, in an area that prides itself in earthquake preparedness. Indeed, the relatively low death toll probably owes much to the implementation of earthquake building codes and standards.

The earthquake, which occurred on a previously unknown thrust fault close to Northridge, resulted in severe damage in the San Fernando Valley with a maximum Modified Mercalli Intensity of 9 in the Northridge and Sherman Oaks areas. Freeway overpasses collapsed and many fires were started. In all, 40,000 buildings were damaged in Los Angeles and 20,000 people left homeless. A remarkable feature of the earthquake was the high peak ground accelerations experienced close to the epicentre: 1.8 g was recorded at Tarzana, 7 km south of the epicentre, and 1.0 g was exceeded at several locations. The cost of the earthquake damage has been estimated to be between $13 billion and $20 billion.

On 15 February, Sumatra, Indonesia, was struck by a major earthquake. The magnitude 7.0 Ms event killed 207 people, over 2,000 were injured and 75,000 were left homeless in Lampung Province. Much of the damage resulted from landslides, mudslides and fires in Liwa where over 6,000 buildings were damaged. The damage was estimated at US$169 million.

Indonesia again suffered the effects of a major earthquake on 2 June. The magnitude 7.2 Ms earthquake struck south of Java and killed at least 250 people and injured 423 others. Much of the damage was caused by the earthquake induced tsunami which inundated areas along the eastern part of the south coast of Java with tsunami run-ups reaching 500 m in places. The earthquake was also felt strongly in eastern Java, on Bali and on the islands of Lombok and Sumbawa.

A few days later, on 6 June, the highest individual death-toll for a 1994 earthquake occurred when a magnitude of 6.6 Ms earthquake struck a mountainous area of Colombia. At least 295 people were killed, 500 were left missing and 13,000 were made homeless. There was extreme damage and landslides in the Cauca, Huila, Tolima and Valle Departments of Colombia. In addition an avalanche from Huila Volcano blocked the Paez River and resulted in severe flooding.

A remarkable earthquake occurred on 9 June with an epicentre in northern Bolivia. It had a focal depth of 631 km and a magnitude of 7.0 Mb. The moment magnitude of 8.2 Mw calculated for this event gives a better indication of its size, indicating that the energy release was equivalent to a great earthquake, although strictly speaking it does not qualify as a "great earthquake" on grounds of magnitude. As a result of its extreme depth and great energy release it was felt in many parts of South America, with isolated parts of Brazil and Peru suffering damage. Furthermore, this earthquake was also felt in many locations in North America including Los Angeles, Chicago, Boston and Toronto in Canada, over 6,000 km from the epicentre! It is believed to be the first earthquake in this area to have been felt in North America. There were reports of five people being killed in Peru by this earthquake.

Northern Algeria was struck on 18 August by a relatively small, but deadly, earthquake with a magnitude of 5.9 Ms. At least 159 people were killed, 289 injured and over 8,000 left homeless by this earthquake, which destroyed thousands of houses in Mascara Province.

The great earthquake of 1994 occurred on 4 October in the Kuril Islands, to the north of Japan. The magnitude was 8.1 Ms and it was felt throughout the Kuril Islands and northern Japan, including the Tokyo area. Ten people were killed on the island of Iturup and severe damage and injuries occurred on other islands of the Kuril chain and on the eastern coast of Hokkaido. A tsunami contributed to the damage with peak-to-trough wave heights up to 3.5 m, recorded in parts of Hokkaido. An immediate tsunami warning was given throughout northern and eastern Japan following the earthquake, in time for low lying areas to be evacuated.

On 14 November another earthquake accompanied by a tsunami caused damage in the Philippine Islands. The magnitude was 7.1 Ms. Seventy-eight people were killed and 225 were injured on the islands of Luzon and Mindoro from the combined effects of the earthquake and tsunami.

Other areas of the world that experienced major earthquakes during 1994 were Halmahera in Indonesia, the Vanuatu Islands, South Island, New Zealand, northern California, the Kuril Islands and Honshu, Japan. Most of the events that occurred in these areas were either offshore or in remote locations, limiting the resultant damage and casualties. There were also a number of strong earthquakes at exceptional depths, greater than 450 km, in the Fiji Islands, in north-western Argentina and in the Sea of Japan.

The British Geological Survey detected and located 357 earthquakes in the British Isles and surrounding continental shelf areas during 1994. Of these, 42 had magnitudes of 2.0 ML and over and 23 events were felt by people. Twenty-six of the earthquakes of 2.0 ML and over were onshore or near-shore and included two events in Ireland. The remaining 16 were located offshore in the North Sea and Norwegian Sea areas.

Earthquake activity in the offshore areas was about average during 1994. Four events exceeded magnitude 3.0 ML and one of these equalled 4.0 ML. This magnitude 4.0 ML earthquake occurred on 18 October and was felt as a "shaking" on a production platform in the Dan oil field of the central North Sea.

Only one other offshore earthquake was felt during the year: a magnitude 3.3 ML Norwegian Sea event on 27 July, which was felt in parts of Norway.

UK earthquake activity was a little more than average during 1994, with one onshore earthquake with a magnitude between 4.0 and 4.9 ML, as against an average occurrence of one every two or three years. There were four events between 3.0 and 3.9 ML against an average of three per annum. In the magnitude range 2.0 to 2.9 ML there were 21 events recorded on land or near shore in the British Isles, including two in Ireland, which is only slightly less than the long-term annual average of 23.

The largest UK event occurred on 15 February in the Norwich area. The magnitude was 4.0 ML and it was felt over an area of 31,000 km^2 in Norfolk and Suffolk and in parts of Cambridgeshire and Essex. A maximum intensity of 5 MSK was assessed close to the epicentre where very minor damage occurred. This was the largest onshore British earthquake since the magnitude 5.1 ML Bishop's Castle earthquake of 2 April 1990. There was a magnitude 2.8 ML aftershock on the same day which caused moderate shaking in the epicentral area.

Constantine in Cornwall was affected by a swarm of earthquake activity during June 1994 during which 68 events were recorded. The largest two, with magnitudes of 2.2 and 1.6 ML, occurred on 11 June and were felt by people in Constantine, Helston and Penryn.

The coalfield areas of central Scotland, south Wales, Yorkshire and Nottinghamshire continued to experience earthquake activity of a shallow nature which is believed to be mining-induced. Seventy-four such events were recorded and seven of these were felt by people. The two strongest of these events occurred at Bargoed, Mid Glamorgan, on 17 August and at Stillingfleet, North Yorkshire, on 5 December with respective magnitudes of 2.1 and 2.2 ML. Each of these earthquakes was felt in the epicentral area.

Other notable UK earthquakes of the 1994 include the magnitude 2.8 ML Bristol Channel earthquake of 1 January which was felt in parts of north Devon. The Bangor earthquake of 10 February, with a magnitude of 2.9 ML, was felt throughout Gwynedd and caused some slight damage in Bangor. A magnitude 3.1 ML earthquake in Powys on 17 March caused moderate shaking in the Newtown area. Stratford-upon-Avon experienced a magnitude 3.0 ML earthquake on 12 May, which was felt from Leamington Spa to Worcester and some minor damage occurred in the Stratford-upon-Avon area. A magnitude 3.2 ML event was felt in southern parts of the Isle of Skye on 8 August and another magnitude 3.2 ML earthquake, offshore from Harwich, was felt at Walton-on-the-Naze on 15 September.

***David Redmayne** is a member of the Global Seismology Research Group of the British Geological Survey.*

The "Bulletin of British Earthquakes 1994" edited by A B Walker was published in March 1995. Copies of this and previous years' reports can be obtained from the Global Seismology Research Group secretary and from BGS bookshops. For further details contact: The Global Seismology Research Group, British Geological Survey, Murchison House, West Mains Road, EDINBURGH EH9 3LA, Scotland, UK.

Modelling Train Collisions

Neil Kirk

Any moving vehicle has the potential to collide with another structure and bridges are a common feature of such collisions. A collision between a vehicle and a bridge is a highly non-linear event involving plasticity, large deflections, variable contact, bolt, weld and material failure.

Trying to understand all these complex interactions is a daunting prospect, but tools do exist to analyse these processes. The most common and well validated approach is to use an explicit finite element method such as DYNA3D. DYNA3D has been in use at Frazer-Nash Consultancy for about 12 years. In this time the code has been validated for a number of analysis types, one of which is vehicle crashworthiness and, in particular, rail vehicle collision. Typical features of a finite element model of a train carriage used to predict its collapse performance are:

- The very refined mesh in areas where collapse will occur, and a coarser mesh elsewhere (NB since a coarse FE model is over-stiff and is less able to collapse, care must be taken over the use of coarse meshes or the model will only confirm existing prejudices).
- Self-contact modelled only over carefully prescribed areas (due to the computational cost of such an analysis).
- The use of the largest element size possible, which still leads to very computationally large models compared with implicit static or linear analyses.

The mesh densities of the collapsing components are arrived at using two methods:

(i) Considering a component in isolation and modelling it with increasingly refined meshes until the results converge. This method then yields the mesh density required to provide acceptably accurate answers.

(ii) Considering a component in isolation, build and test a prototype. In parallel, analyse the FE model of the same component and refine the model to achieve correlation.

Method (i) is quick and simple and usually yields good results. Method (ii) is slower and more expensive, but does not rely so heavily on modelling assumptions (e.g. material data).

Once a suitable mesh density has been determined for the components under reasonably realistic loadings, these can be assembled into a model of the complete structure and subjected to a test load case. If the agreement is very close, the method is validated for this case.

In September 1994 SECED and the IStructE Study Group on Modelling Motorway Bridges held a joint meeting entitled Impact on Bridges. This and the following article are based on presentations at that meeting.

Train/bridge collision loads

The explicit finite element method (and in particular DYNA3D) can be extended to cover the collision of trains with bridge structures. For example the upper figure shows an aluminium train in collision with a steel bridge pillar, prior to impact. In this case the vehicle structure was modelled in full, but the bogies and their suspension were neglected. The model was previously designed for static and linear dynamic analysis and has not been optimised for crashworthiness analysis. It is representative in weight (including non-structural mass) and low deflection stiffness, but is likely to be inadequate for very high deformations of the bodyshell.

Fortunately the initial analysis does not indicate large deformations (but note the above comments about coarse meshes confirming prejudices). The bridge model is quite simple, consisting of a vertical steel column, the bottom of which was considered to be fixed, and the top constrained laterally with respect to the vehicle.

To simulate a derailment at moderate speed, the vehicle model was given an initial forward velocity of 20 m/s (45 mph) and an initial lateral velocity of 5 m/s (11 mph). The analysis was run for 100 ms.

The lower figure shows the end of the run. Most of the visible deformation in the vehicle is in the roof, but this is not significant to the analysis. The most significant aspect of the impact occurs much closer to the floor level, at the point of contact with the door pillar. Deflections here are small, but forces very large due to the comparatively high local vehicle stiffnesses. A second feature is that the bodyshell is slewing around the pillar as well as sliding along it.
Modelling shows the pillar at the end of the analysis shows that the maximum elastic strain seen in the pillar is of the order of 1.2%. This value is well below the failure strain of steel (typically 20%-50%). However the deformations of the pillar are of the order of 70mm which may be adequate to cause it to buckle under the vertical load of the deck and what it is carrying.

Of particular interest are the lateral and longitudinal forces exerted on the pillar. Modelling indiactes a peak force of around 1 MN at around 50 ms. It should be noted that these are the initial force peaks, and that there may be a larger peak later when the vehicle slews right around and more of its mass acts directly on the pillar.

This example demonstrates the capabilities of the technique. But at what cost?

The costs of using the technique can be broken down into a number of key areas:

(i) **Time to build the model**
Building a finite element model of a vehicle and bridge takes days or weeks, rather than hours. The example given above is a simple one using models from other sources, and hence it only took a day or so to set up and about the same time to run. However building the train model from scratch is likely to take a month (or more) and the "bridge" structure, practically nothing. So in this case the time is in the vehicle model. Manufacturers of vehicles routinely subject their designs to examination by finite element analysis, and using existing models (if available) would give a head start to building a suitable collision model. A more complex bridge model (particularly if

constructed of pre-stressed concrete) could take a couple of weeks to build by a skilled crashworthiness engineer.

(ii) **Computers to run the models** Most design offices now make extensive use of Computer Aided Design software run on networked work station computers. The type of analysis described above would fit easily on to a fairly powerful work station and thus the incremental cost is unlikely to be significant. The power of the computer is only really important in reducing the run times and therefore even a powerful PC might be acceptable if you were willing to wait for the results.

(iii) **Time to run the model** Run times can be significant. A one or two day run is not unusual, and in some cases, it may take a week. This ties up the computer but costs little in terms of staff time.

(iv) **Training** Training can be quite costly. Cost effective model building and analysis requires a good understanding of the tools being used and the principles behind the analysis. A good linear finite element analyst has to "unlearn" some rules associated with implicit analysis and learn new ones in order to become proficient at non-linear collapse analysis.

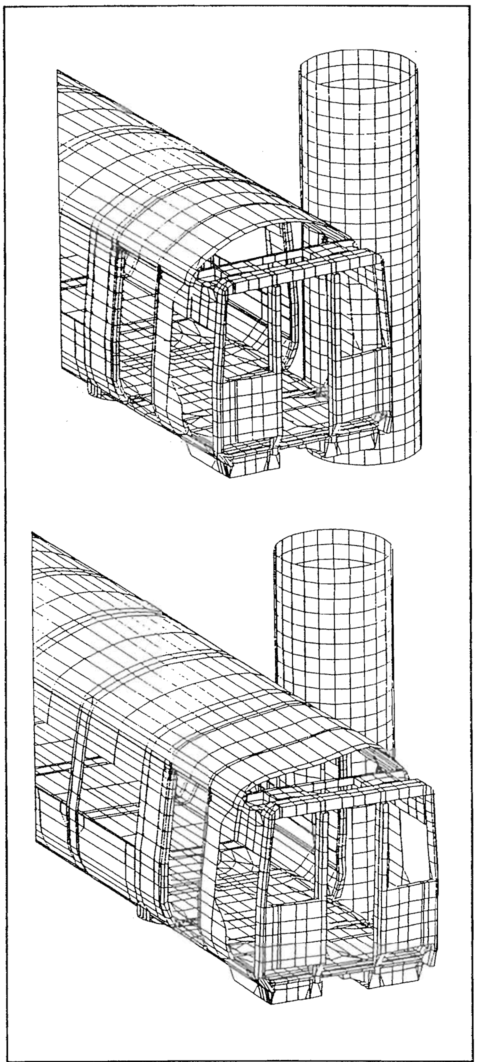
(v) **Quality control** Quality control of finite element modelling is a topical and significant issue. Suffice it to say that the type of analysis described here is no less in need of close quality control than more traditional FEA methods.

Use of the method

The approach to the modelling of bridge bashing described here has a number of uses, given the power of the technique:

- **Design** The key to the efficient use of the technique for the design of bridges is to have a suitable vehicle model prepared and validated. This model can then be impacted onto any design of bridge construction chosen in order that bridge responses or loadings can be determined. The bridge structure itself is usually of a relatively simple construction in comparison with the impacting vehicle, therefore the time taken to build a bridge model may be minimal.

An alternative approach to the problem would be to perform a number of empirical tests using various bridge structure and vehicle models to determine generic loadings for any given construction type. These guidelines could then be used in the normal design process. This approach is likely to be quite costly initially, but will yield long term benefits when designing numerous bridges.



Models of carriage and bridge pier before (top) and after (bottom) impact

- **Forensic investigation** At Frazer-Nash Consultancy we use the techniques described above in a forensic capacity to determine the circumstances surrounding an incident. The great strength of the modelling method is that once the model has been built, a variety of scenarios can be investigated to evaluate theories and possibilities. Thus the root cause of a problem may be determined. Examples of this type of work include accident investigation and support of litigation.
- **Safety case development** The collision of vehicles is an undesirable consequence of failure of a system and it is not possible to make any complex system (such as a railway) 100% safe. However the techniques described here can provide supported evidence of the consequences of a potential system failure. For example the failure of a set of signals causing a derailment or collision at a busy junction (Clapham type incidents) or the failure to brake coming into a terminus (Cannon Street type incidents). In these situations, analysis supports the detailed safety case which has identified the risks (being a combination of probability and possible severity).

***Dr Neil E Kirk** works for Frazer-Nash Consultancy Limited*

Vehicle Impact on Masonry Parapets

T C K Molyneaux

Much research has been undertaken into the behaviour of brickwork under the action of static distributed loading and some (military) research into the response of masonry to high velocity impacts. The behaviour of masonry walls under low velocity impacts characteristic of vehicle collisions appears not to have been studied.

This article describes the development of analytical modelling techniques that have been used to predict the behaviour of masonry parapet walls under impact loading. The study has included brickwork walls and stone walls with a range of mortar mixes including the limiting case of drystone walls. The analytical approach involves the direct representation of individual blocks of masonry and their interface joints. Experimental results obtained from pendulum impact tests on panel walls and full size vehicle impact tests on parapet walls are presented and compared with the analytical predictions. Static and dynamic material tests are described.

The work described in this presentation comprises part of a parapet research project being undertaken by Parkman Consulting Engineers on behalf of the County Surveyors Society. The Finite Element software used throughout is Oasys DYNA3D version 5.1(a).

Material tests

In all, over 300 small specimen tests have been conducted. The most striking finding was the degree to which the shear strength of mortar joints is sensitive to strain rate. The shear strength of brick triplets measured at typical impact speeds was over three times greater than values obtained in "static" tests. This finding was reinforced by the outcome of the study of the panel walls where it was shown that for the observed failure modes to occur it is necessary for the joints to exhibit this enhanced strength.

Pendulum and vehicle impact tests

Three types of panel wall were constructed and tested in a purpose built pendulum rig. The walls were constructed on concrete bases that could be lifted into position in the pendulum rig. Restraints were applied at the two vertical edges so as to prevent lateral movement in the direction of the impact. The walls were not restrained against movement in their own plane or against rotation about a vertical axis at these two edges. Mortared specimens were permitted to cure for a minimum of 28 days. The bricks used in the construction of all specimens at Liverpool were perforated Class B engineering bricks. The following panel walls were tested (4 tests of each). Each panel was 2m wide and approximately 1m high.

(i) Concrete block panels, stretcher bond, 1:2:8 mortar mix.

(ii) Concrete block panels, stretcher bond, 1:4 mortar mix

(iii) One brick thick brick panels, English garden wall bond, 1:1:6 mortar mix.

(iv) Mortar filled brick cavity wall, two single skin stretcher bond panels with a 50mm filled cavity, 1:4 mortar mix.

A test programme of vehicle impact tests was undertaken at MIRA (Motor Industry Research Association) to validate the analytical model. The data obtained from the material testing and the experience gained in modelling the panel walls were used in modelling each of the MIRA impact tests and producing predictions of the expected outcome.

Finite element modelling

The performance of the masonry structures of interest in this study is dominated by the behaviour of the joints. These joints will fail at a critical combination of shear and tensile loading and then either slide with friction or separate. Under increasing compressive stresses, either direct or due to bending, the bricks/blocks and mortar will initially behave in an elastic manner and eventually crush.

The approach adopted in modelling the masonry is to sub-divide the structure into representative cuboid units each "connected" to the adjacent unit by interface equations. The configuration of the representative units was chosen with a view to potential failure modes and the overall size and feasibility of the model created. For the block models and many of the smaller brick models each brick/block was represented individually, while in the case of the large brick structures each unit represented several bricks. The solid elements are prescribed bilinear elasto-plastic material properties reflecting the material represented (mortar/brick or mortar/block). The interface equations employed to represent the (mortar) joints between units hold the surfaces fixed together until a limiting combined tensile and shear force is exceeded, after which the surfaces are free to move apart or slide with a prescribed friction. The failure criterion takes the form:

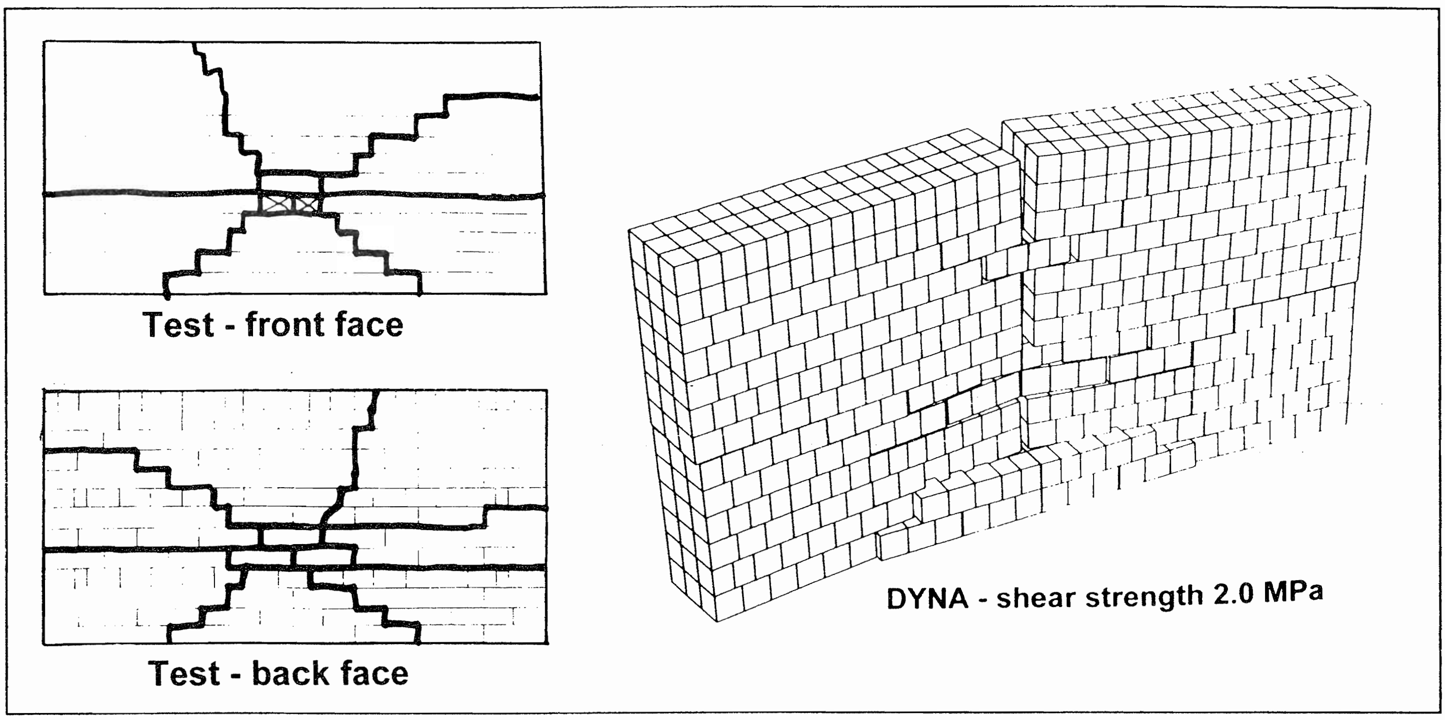
$$\left(\sigma/\sigma_{\text{limit}}\right)^2 + \left(\tau/\tau_{\text{limit}}\right)^2 = 1$$

In addition to the interfaces between blocks, there are interface equations employed between the bottom course and the ground and between the impactor and the front surface. It is essential that the structures are in a state of static vertical compression under gravity at the start of the impact if friction is to be represented adequately. Consequently a dynamic relaxation analysis is conducted first. It was necessary to exclude the initial velocity of the impactor (pendulum or vehicle) from this preliminary calculation.

The test format at MIRA involved a 1500kg car impacting a 30m length of wall at 20° (between the direction of travel of the car and the length of wall). Although in the automotive industry detailed models of vehicles are developed, the main purpose of these is to study the effect of impacts on the components of the vehicle. Such models take hundreds of hours to develop and are considered unnecessary for this type of analysis where a simpler model will suffice. The model developed comprises solid elements of elasto-plastic material properties that have been adjusted to produce the required mass and collapse characteristics. The vehicle is not constrained vertically and has no wheels or interaction with the ground. The timing of the vent and the magnitude of the impact forces are such that interaction with the ground will have little effect during the primary impact. In the test, the behaviour of the car after the impact will be governed very much by the wheels rolling on the ground - no attempt has been made to predict this behaviour using the finite element model.

Vehicle Impacts

- **Ashlar Block Wall** The centre 10m length of the (simulated) ashlar wall was modelled in a similar way to the block panel walls. The concrete blocks plus mortar were 506mm long, 336mm high and 400mm thick and were modelled individually by 12 solid elements. The outer two 10m lengths were modelled more coarsely.
- **English Garden Wall (215mm thick)** A one brick thick English garden wall bond exhibits horizontal (bedding) and vertical (perpend) joints that pass directly through the wall. Consequently it was possible to adequately mesh such a wall employing cuboid blocks that represented double bricks. This had the advantage that the interfaces between units represented actual mortar joints. Again, as for the



The cracking pattern from a test specimen of English garden wall and the results from a DYNA analysis

previous wall model only the middle third was meshed in detail.

• **Drystone Wall (450mm)** A drystone wall of roughstone blocks presents many problems when attempting to produce a finite element model as the size, shape and contact points of the blocks vary greatly throughout the wall. A considerable contribution to the resistance a masonry wall can offer comes from the horizontal arching mechanism. This behaviour results in large panels of wall being mobilised as the vehicle impacts. The arching mechanism would be expected to be limited in a rough block drystone wall and hence a lower bound model was developed that would exhibit no arching whatsoever. This model employed cuboid blocks as in the model of the ashlar wall but in this case there was no interaction between adjacent units - hence no arching. There was of course interaction between the vehicle and each individual block impacted. Hence, the wall represented by this model resisted penetration by virtue of its mass along - a conservative model.

In addition to the model described above a second approach was investigated in order to explore the importance of arching and the sensitivity to stone and wall quality. This model adopted the same cuboid blocks but employed inter-block contact equations that allowed for a gap to exist between adjacent blocks. This gap had to be closed before compressive and frictional interaction could occur.

The finite element approach adopted has been shown to successfully represent both the behaviour of the masonry parapet wall and the impacting vehicle. In walls where the strength of the mortar is significant it is essential to assess the dynamic strength parameters of the mortar. The dynamic strength of mortar joints in walls is significantly greater than the static strength.

***T C K Molyneaux**, works in the Department of Civil Engineering, University of Liverpool, Brownlow Street, Liverpool L69 3BX*

The Society for Earthquake and Civil Engineering Dynamics

The Fifth Mallet-Milne Lecture

Professor Bruce A Bolt

University of California at Berkeley, Berkeley, California, USA

FROM EARTHQUAKE ACCELERATION TO SEISMIC DISPLACEMENT

A PUBLIC LECTURE

Wednesday 24 May 1995
at 5.00pm

The Institution of Civil Engineers
1-7 Great George Street
London SW1P 3AA

Sponsored by: British Geological Survey
Non-members are invited to attend. Following the lecture there will be an informal reception, for which tickets are available from the Secretary (0171 839 9827)
An associated exhibition will be mounted in the week preceding the lecture.

The Mallet-Milne Lectures, a series of public biennial lectures, have been established by the Society for Earthquake and Civil Engineering Dynamics in honour of the pioneering British scientists Robert Mallet (1818-1883) and John Milne (1850-1913).

Technology Exchange now under way: Call for contributions

Robin Adams, International Seismology Centre

Early last year I reported in the Newsletter on an initial meeting called by the World Meteorological Organisation (WMO) in Geneva to discuss the setting up of a System for Technology Exchange for Natural Disasters (STEND). STEND is an information exchange programme aimed at increasing awareness of available technology. It is particularly targeted at developing countries, and has been approved as an INDR Demonstration Project. It is being developed by the Hydrology and water Resources Department of the world Meteorological Organisation in Geneva, and is closely modelled on a similar scheme that they have been successfully operating for hydrology for the last thirteen years.

The STEND Advisory Committee, which includes representatives of international seismological and volcanological bodies, as well as meteorologists and hydrologists, recently held its first meeting. SECED interests were watched by Robin Adams (Chairman), and Chris Browett. The Committee approved the immediate establishment of STEND in the fields of hydrology, seismology and volcanology, and stressed that related engineering topics should be included. Later extension to include disciplines such as meteorology, tsunamis and landslides have been envisaged.

The technology involved could be in the form of instruments, software or publications in the fields of data acquisition, analysis, interpretation and methodologies. Both new and established submissions are welcome, from laboratories, research establishments and the commercial sector. The description of each "component" should be brief enough to fit on two pages, and should comprise details of purpose, a description of exactly what is offered, how it is presented, from where it is available and any cost involved.

After review by the Advisory Committee, components will be classified according to topic and included in a "STEND Reference Manual", which will be available in a computer-readable form as well as a printed version. Copies of the manual will be made available at national centres such as INDR focal points and national seismological and volcanolocical agencies, and regional scientific and engineering centres. Those interested in obtaining an item or service offered in the manual should contact the supplier directly, with a copy to WMO. WMO has agreed to act a Secretariat for the scheme, and to be responsible for maintaining and updating the Reference Manual, with UNESCO also acting as sponsor.

In the field of interest of SECED, submissions are welcome, not only on seismological topics such as earthquake recording, data analysis, cataloguing and hazard estimation, but also in the field of earthquake engineering where there is much available expertise in planning, and earthquake-resistant design and construction techniques. Techniques to help simple low-cost construction would be particularly welcome, as would advice on retrofitting and re-construction following disaster.

A major publicity and collection effort will be aimed at geophysicists at the IUGG Assembly at Boulder in July 1995, and it is hoped that enough components will have been submitted for the first issue of the STEND Reference Manual to be published by the end of 1995. Contributions of components, including those on engineering topics, are welcome at any time, and *there is no reason why those wishing to have software or equipment listed in the STEND Reference Manual should not submit them now.*

For further information, and detailed instructions on the preparation and submission of information on components, please contact: The STEND Project, Hydrology and Water Resources Department, World Meteorological Organisation, 41 ave Giuseppe-Motta, Case postal No 2300, CH-1211 Geneva 2, SWITZERLAND Tel:+41-22-730-8407 Fax:+41-22-734-8250 e-mail: jmiller@ties.itu.ch.

Information on STEND is now available on the World-Wide Web. Connect to http://www.wmo.ch/ and follow references to Hydrology and Water Resources Programme, HOMS and STEND. As the project evolves, this will be the most up-to-date source of information.

Notable Earthquakes April - December 1994

			Lat	Long	Dep	Magnitudes			Location
	Date	UTC			kM	ML	Mb	Ms	
8	APR	01:10	46.61N	143.68E	13		6.0`	6.3	E OF HONSHU, JAPAN
			Felt in Obihiro, Tomakomai, Hokodate and Kutchan areas, Hokkaido. Also felt in the Hachinohe, Akita and Sendai areas, Honshu						
13	APR	22:22	3.14S	135.97E	29		6.0	6.3	IRIAN JAYA, INDONESIA
			Felt in the Enarotali and Nabire areas						
18	APR	17:29	6.47S	154.92E	26		6.6	6.7	SOLOMAN ISLANDS
			Felt strongly on Bougainville, Papua New Guinea. Felt on New Island and at Rabaul, Papua New Guinea. Felt on Choiseul, Santa Isabel and at Honiara, Soloman Islands						
19	APR	21:52	53.13N	1.13W	1	1.2			MANSFIELD NOTTS
			Felt in Mansfield, Nottinghamshire						
21	APR	03:51	5.70S	154.12E	28		5.9	6.6	NEW ISLAND
			Felt at Rabaul, Papua New Guinea.						
10	MAY	06:36	28.50S	63.10W	601		6.4		NW ARGENTINA
			Felt at La Rioja and Mendoza						
12	MAY	01:08	52.15N	1.73W	16	3.0			STRATFORD-UPON-AVON
			Felt at Statford on Avon, Leamington Spa, Worcester and Evesham						
02	JUN	18:17	10.48S	112.83E	18		5.7	7.2	S OF JAVE, INDONESIA
			At least 250 people killed, 27 missing, 423 injured, about 1,500 houses damaged or destroyed leaving many people homless and 278 boats sunk by the tsunami along the south east coast of Java						
06	JUN	20:47	2.92N	76.06W	12		6.4	6.6	COLOMBIA
			At least 295 people killed, 500 missing, 13,000 homeless and severe damage from landslides. Felt in much of southwestern Colombia from Tunja to Pasto.						
09	JUN	00:33	13.84S	67.55W	631		7.0		NORTHERN BOLIVIA
			Five poeple reported killed in Peru, and numerous injured. Minor structural damage also reported at Cochabamaba, Las Paz and Oruro, Bolivia; Brasilia, Camp Grande, Port Velho and Manaus, Brazil; Arica, Chile and Tacna, Peru. Felt throughout much of South America, in the Caribbean and it was also felt in many parts of North America including Los Angeles, Chicago, Boston and Toronto. (Moment magnitude: 8.2Mw)						
11	JUN	03:16	50.10N	5.18W	7	2.2			CORNWALL
			Felt at Constantine, Helston, Penryn and Four Lanes						
11	JUN	06:18	50.10N	5.18W	8	1.6			CORNWALL
			Felt at Constantine						
18	JUN	03:25	42.96S	171.66E	14		6.2	7.1	S ISLAND, NEW ZEALAND
			Some structural damage at Christchurch. Landslides blocked Highway 73 between Artjur's Pass and Christchurch. Felt throughout South Island and the southern part of North Island.						
13	JUL	02:35	16.63S	167.51E	33		6.3	7.4	VANATU ISLANDS
			Felt at Port-Villa. Felt on Ambrym, Aoba, Eftate, Erromango, Espiritu Santo, Maewo, Malakula and Pentecost						
14	JUL	01:23	56.29N	5.36W	7	2.1			KILMELFORD, S'CLYDE
			Felt on Seil Island and Lerags, Strathclyde						
18	JUL	12:29	54.41N	3.12W	13	2.2			CONISTON, CUMBRIA
			Felt at Coniston, Elterwater and Torver, Cumbria						
21	JUL	18:36	42.30N	132.89E	473		6.4		SEA OF JAPAN
			Felt at Onahma, Tokyo, Aomari, Sapparo and Tottori, Japan						
09	AUG	06:57	60.16N	1.95E	13	3.6			NORTHERN NORTH SEA
17	AUG	04:57	57.18N	5.73W	3	3.1			ISLE OF SKYE, HIGHLAND
			Felt in the Duisdalemore area in the southern part of the Isle of Skye						
17	AUG	23:50	51.69N	3.25W	2	2.1			BARGOED, M. GLAMORGAN
			Felt at Bargoed, Mid Glamorgan and Blackwood, Gwent.						
18	AUG	01:13	35.56N	0.11W	9		5.5	5.9	NORTHERN ALGERIA
			At least 159 people were killed, 289 injured, 8,000 to 10,000 left homeless and thousands of houses destroyed in Mascara province.						
19	AUG	10:02	26.65S	63.38W	565		6.4		NW ARGENTINA
			Felt at Antofagasta, Chile.						
01	SEP	15:15	40.41N	125.65 W	10		6.6	7.0	NORTHERN CALIFORNIA
			Felt at Rio Dell and at Miranda. Felt throughout much of northern California, as far south as Frenso and as far north as southern Oregon.						
15	SEP	06:36	51.79N	1.80E	8	3.2			SE OF HARWICH
			Felt at bWalton-on-the-Naze. This earthquake had an epicentre 62 km east of Colchester where one of the most damaging UK earthquakes occurred in 1884. It is in an area where very few earthquakes are recorded.						
16	SEP	06:20	22.55N	118.74E	12		6.5	6.7	TAIWAN REGION
			One person was killed and at least 400 were injured in the Guangdong and Fujian Provinces, China. Structural damage occurred in Fujian and Guangdong provinces, China. Felt in Hong Kong.						
04	OCT	13:22	43.71N	147.33E	33		7.4	8.1	KURIL ISLANDS
			At least 10 people killed or missing and extensive damage on Iturup; considerable damage and possibly some deaths and injuries on Kunashi. Shikotan and other islands in the Kuril chain from the earthquake and tsunami. One person died from a heart attack, and at least 340 people injured and extensive damage occurred along the east cost of Hokkaido, Japan. Felt strongly in northern Honshu and also felt in the Tokyo area, Japan.						

Notable Earthquakes April - December 1994 (continued)

	Date	UTC	Lat	Long	Dep kM	ML	Mb	Ms	Location
09	OCT	07:55	43.90N	147.91E	23		6.5	7.0	KURIL ISLANDS
			Felt on Iturup. Felt in the Kushiro area and Hokkaido, Japan						
13	OCT	21:50	56.81N	5.67W	4	2.2			LOCHAILORT, HIGHLAND
			Felt at Kentra, Highland.						
18	OCT	18:38	55.35N	5.25E	15	4.0			CENTRAL NORTH SEA
			Felt in the Dan oilfield						
02	NOV	14:57	56.81N	7.35E	10	3.8			SKAGERRAK
14	NOV	19:15	13.53N	121.09E	33		6.1	7.1	MINDORO, PHILIPPINES
			At least 78 people were killed and 130 injured on Luzon and Mindoro. A local tsunami contributed to extensive damage in the Calapan and Perto Galera areas. Felt at Batangas, Manila and Tagaytay City.						
20	NOV	16:59	2.00S	135.93E	24		5.7	6.3	IRIAN JAYA, INDONESIA
			Twenty-eight people were injured and many buildings damaged at Serui and Yapen. Also felt on Biak.						
25	NOV	17:10	53.10	1.21W	1	2.1			MANSFIELD, NOTTS
			Felt at Mansfield, Nottinghamshire.						
05	DEC	22:05	53.85N	1.09W	0.1	2.2			STILLINGFLEET, N. YORKS
			Felt in the villages of Stillingfleet and Riccall.						
10	DEC	16:17	18.24N	101.35W	67		6.5		GUERRERO, MEXICO
			Felt strongly in the Mexico City area.						
28	DEC	12:19	40.45N	143.49E	33		6.4	7.5	E OF HONSHU, JAPAN
			This earthquake was felt strongly at Hachinohe, Honshu and in parts of Hokkaido. It was felt throughout central Honshu, including the Tokyo area. Two people are reported to have been killed and over 200 have been injured. Localised structural damage and widespread non-structural damage occurred in northern Honshu coastal communities from Hachinohe to Senda.						

Compiled by: Bennett Simpson, Global Seismology Research Group, British Geological Survey

Forthcoming events

26 April 1995
Analysis & testing of bridges, Joint SECED & IStructE group on Management & Maintenance of Bridges, IStructE London

4-8 September 1995
18 Seminaire Regional European de Genie Parasismique, L'Ecole Centrale Lyon

26-27 October 1995
SECED Conference - European Design Practice, Chester, UK

20-22 November 1995
Pacific Conf. on Earthquake Engineering PCEE'95, Melbourne, Australia

14-16 November 1995
1st Int. Conf. on Earthquake Geotechnical Engineering, Tokyo, Japan

15-17 May 1995
SEE: The 2nd Int. Conf. on Seismology and Earthquake Engineering, Tehran, Iran

5-8 June 1996
EURODYN '96, Florence, Italy

23-28 June 1996
11WCEE: 11th World Conf. on Earthquake Engineering, Acapulco, Mexico

SECED

SECED, The Society for Earthquake and Civil Engineering Dynamics is the UK national section of the International and European Associations for Earthquake Engineering and is an affiliated society of the Institution of Civil Engineers. It is also sponsored by the Institution of Mechanical Engineers, the Institution of Structural Engineers, and the Geophysical Society. The Society is also closely associated with EEFIT, the UK Earthquake Engineering Field Investigation Team. The objective of the society is to promote cooperation in the advancement of knowledge in the fields of earthquake engineering and civil engineering dynamics including blast, impact and other vibration problems.

For further information about SECED contact The Secretary, Institution of Civil Engineers, Great George Street, London SW1P 3AA, UK.

SECED Newsletter

The SECED Newsletter is published quarterly. Contributions are welcome and manuscripts should be sent typed on one side of the paper only. Copy on a PC compatible disk is also acceptable. Diagrams should be sharply defined and prepared in a form suitable for direct reproduction. Photographs should be high quality (black and white prints are preferred).

Diagrams and photographs are only returned to authors on request.

Articles should be sent to Dr A Blakeborough, Editor SECED Newsletter, University of Oxford, Department of Engineering Science, Parks Rd, Oxford, UK.

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