VALIDATION STUDIES ON THE EERC (BRISTOL) SHAKING TABLE

A Blakeborough[1], R T Severn[2] and C A Taylor[3]

İNGİLTERE DEPREM MERKEZİ SARSMA TABLASININ DOĞRULANMASI

ABSTRACT

With EC funding, a European Consortium of Shaking Tables (ECOEST) has been formed with a first aim of comparing the performance of the facilities at Athens, Bristol, ISMES and Lisbon. As a precursor to this, the EERC at Bristol has been subjecting its own table to rigorous testing, and this paper describes two aspects. First, is a description of the parameters constraining performance of shaking tables, with an extensive assessment of the performance of the Bristol table (with and without payload) against its design specification. Second, is a comparison of the table's performance, against commonly accepted software, in the response to the 1985 Mexico earthquake record of a 10-tonne model building made up of moment-resisting frames and eccentrically-braced frames.

SHAKING TABLE PERFORMANCE VALIDATION

The 6-axis, 3 x 3 m shaking table at the EERC has been in operation since 1988, and during that period every opportunity has been taken to ensure that its actual performance meets the design specification, whether in reproducing recorded earthquake time-histories, response spectra, sine sweeps or random or multi-sine excitation. Such validation is essential, of course, for commercial equipment qualification tests for nuclear power stations for example, but it is equally important in research programmes, particularly those which involve collaboration with others, as in the current European Community activities reported in a separate paper. A variety of standards exist which give guidance on general and specific requirements for seismic qualification of equipment. IEEE 344 for example, which deals with general issues, whereas IEEE 382 specifies acceleration levels and frequency values for qualification of valve actuators.

In the UK, specifications for Sizewell B nuclear power station describes testing arrangements without giving particular levels, and the Lloyds type approval

[1] Dr, Earthquake Engineering Research Centre (EERC), Bristol, UK
[2] Prof, Earthquake Engineering Research Centre (EERC), Bristol, UK
[3] Dr, Earthquake Engineering Research Centre (EERC), Bristol, UK

scheme specifies a severe resonance search and vibration ageing test such as would be applied for equipment used in offshore installations.

Where specific excitation levels are not given, they might be provided by the client as 'site specific' response data for particular installations. Sometimes 'all-sites' spectra are designed to envelope spectra from different sites and thereby reduce the number of qualification tests required, but this can lead to significant over testing.

Whilst the above standards give some detail about arrangements for, and levels of, testing, they relate to only one part of the whole seismic qualification operation which has to be project managed within an organised laboratory environment, and this organisation is effected as part of a quality system. The organisation for which qualification is conducted generally make the provision of quality assurance (QA) a contractual requirement. In the UK BS5750/ISO9000 are adopted as basic QA standards, but seismic standards are nearly always more onerous. In Bristol, the EERC has developed its own quality system, which incidentally, has become the University norm for research laboratories. It conforms to BS5882 for activities related to nuclear installations, and to BS6460 and BS5781 which relate to testing laboratories.

Figure 1 shows (Ref 1) the original performance specification for the table which serves to illustrate, in a simplified analysis, the principle limitations on capability. In the lowest range, up to 0.5 Hz, the performance is displacement limited due to the stroke (L) of the actuators;

$$\ddot{x}_{max} = (2\Pi f)^2 L/2 \quad \text{where } f = \text{frequency} \tag{1}$$

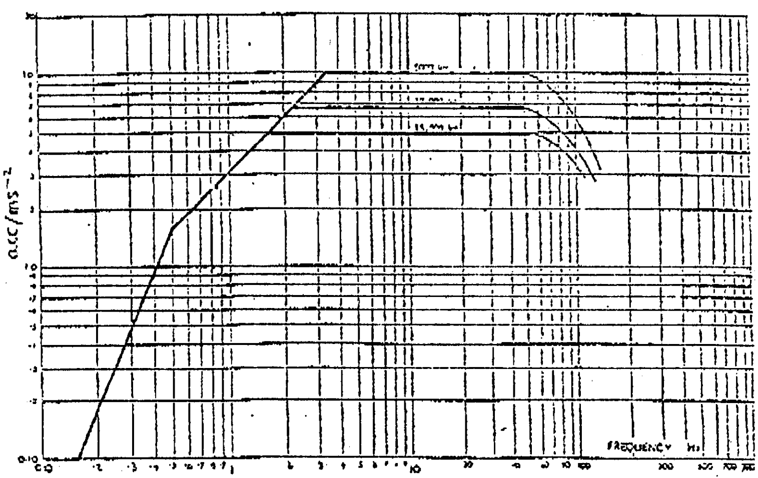


Figure 1 EERC Earthquake Simulator: specification for maximum sinusoidal acceleration

In the middle range, between 0.5 - 3Hz, the performance is velocity limited since the pipework and actuator valves restrict the maximum oil flow rate (Q).

$$\ddot{x}_{max} = 2\Pi \, fQ / A \tag{2}$$

where A is the cylinder cross-sectional area. The capacity of the hydraulic pump is the final limit on performance if high velocities are to be sustained for several cycles of motion. Here, hydraulic accumulators are introduced into the system; they act like capacitors, smoothing out transient demands and overcoming restricted pump output.

In the range 3 - 50 Hz and beyond, the performance is acceleration limited due to system pressure (P) and actuator area (A)

$$\ddot{x}_{max} = \frac{PnA}{M + m} \tag{3}$$

where n is the number of actuators - 8 in our case; m is the mass of the moving parts and M is the payload mass.

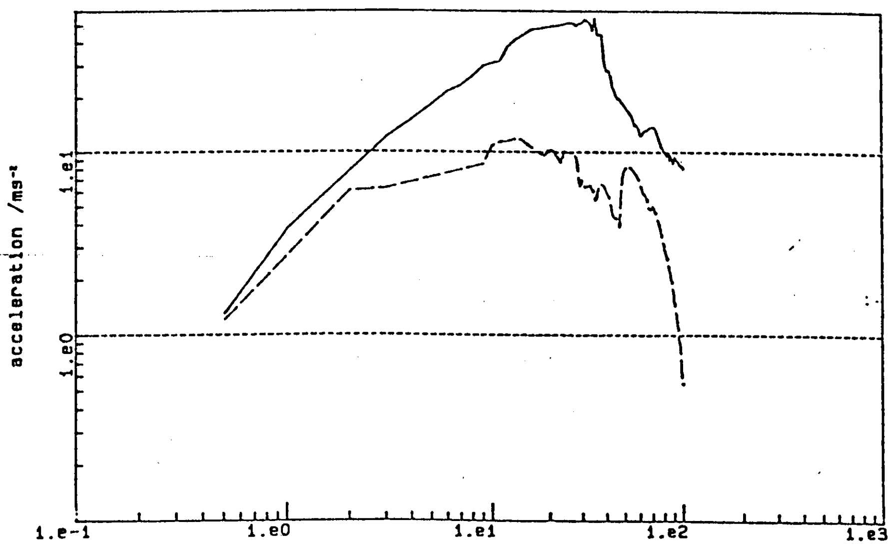


Figure 2 EERC Earthquake Simulator: measured sinusoidal acceleration response

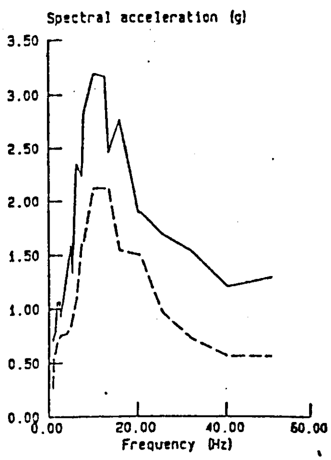
Figure 2 is the actual performance curve for the EERC table with swept since input. There is some resemblance to Figure 2, but other factors are at work, particularly above 10 Hz. A servo-hydraulic simulator is a complex mixture of electrical, hydraulic and mechanical systems. The electrical part is the easiest to control, but resonances and non-linearities elsewhere are harder to cope with. The most obvious is the 'oil-column-resonance', involving the mass of the platform and the compressibility of the oil in the actuators, and occurring at a frequency of approximately:

$$f_h = \frac{A}{\Pi}\left\{\frac{Nn}{(M+m)^V}\right\}^{1/2} \tag{4}$$

where V is enclosed volume of cylinder and N is bulk modulus of oil. For the EERC table f_h occurs between 15 - 20 Hz, depending on direction. Resonance of the platform itself usually occurs above the seismic range. Even with careful design the mechanical connections have flexibility and backlash and this may result in further resonance or performance dropout as well as harmonics. Harmonics of the fundamental driving frequency can also result when striving for maximum performance: here, the servo valves are either fully open or fully closed, resulting in a square force wave form.

Some shaking tables have effectively a three-variable control system which uses feedback of acceleration, velocity and displacement signals to improve the level of control; even so, it cannot be assumed that the table response will faithfully reproduce the input signal. The EERC table has a relatively simple analogue electronic control system, and for time-history signals relies heavily on iterative procedures to obtain the drive signal giving the closest match to the required earthquake. This is called 'time-history matching'. A similar process is used to obtain drive signals for a given response spectrum and is called 'signal shaping'. Figure 3 gives a successful enveloping of a required response spectrum (RRS) by the test response spectrum (TRS) in a seismic qualification test.

In view of recent advances in digital electronics, a new digital system is under development for the EERC table.



Freq (Hz)	RRS (g)	TRS (g)	TRS/RRS
1.00	0.25	0.70	2.70
1.25	0.59	0.75	1.25
1.58	0.59	0.79	1.34
2.00	0.70	1.06	1.52
2.52	0.74	1.07	1.45
2.78	0.76	0.93	1.22
3.17	0.76	1.03	1.36
4.00	0.77	1.29	1.67
5.04	0.84	1.58	1.89
5.41	0.92	1.33	1.45
6.35	1.10	2.35	2.14
7.64	1.63	2.23	1.37
8.00	1.63	2.83	1.74
10.08	2.12	3.19	1.51
12.70	2.12	3.17	1.49
13.59	2.12	2.46	1.16
16.00	1.54	2.77	1.80
20.10	1.50	1.83	1.26
20.73	1.49	1.89	1.27
25.40	0.95	1.69	1.76
32.00	0.72	1.53	2.13
40.22	0.56	1.29	2.15
50.56	0.56	1.30	2.32

RSPA v1.05

Figure 3 Successful enveloping of required response spectrum (RRS) by test response spectrum (TRS) in seismic qualification test

VALIDATION OF SOFTWARE FOR STRUCTURAL FRAME DESIGN

One of the recent uses of the EERC table has been in the validation of commercially available software used for seismic design. Although such software is based upon sound principles, it had not been subjected to practical verification either in the field or the laboratory. The total programme includes both structural and geotechnical seismic software, but only the first of these has reached a stage where useful results have been obtained. The particular software considered is the PAFEC suite for linear behaviour, and Oasys-DYNA3D for the non-linear seismic response at ductilities of 4 and 6. These studies are still in progress.

Model Frame

The model (Figure 4) used borrows its concept from the Century tower in Tokyo in that it consists of a perimeter steel-framed structure, square on plan, with two opposite sides being moment-resisting frames (MRF) and the other two eccentrically-braced frames (EBF). But table-size, scaling laws and costs meant that whereas the actual Century tower has 26 storeys, our model had only 10, each of 0.3 m, with plan dimensions of 1.2 m and a scale of 1:15. Because the budget price for the model was £10k, standard square and round bar and plate sections had to be used, not I-sections or hollow sections as would be used in the prototype. Thus, the model sacrificed geometric similarity for practicality of

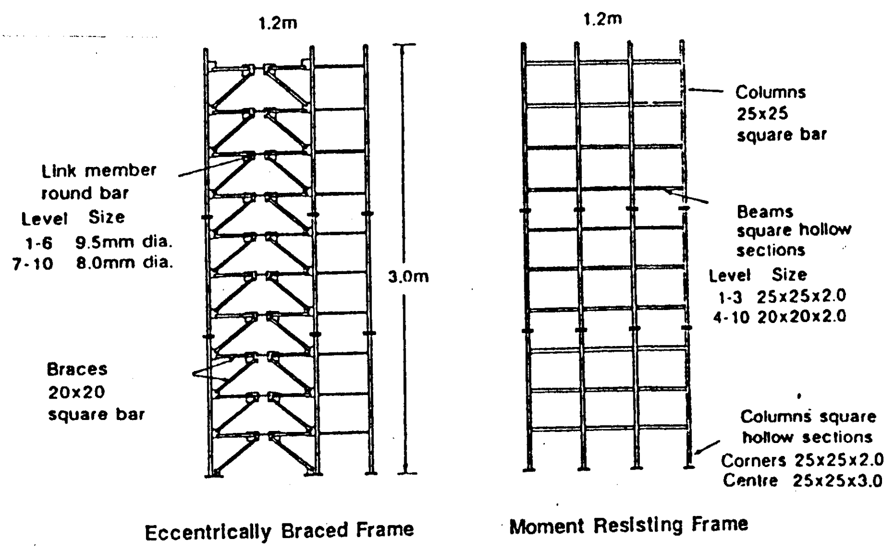


Figure 4 10-Storey Model details: Eccentrically-Braced Frames and Moment Resisting Frames construction, but the use of steel ensured similarity of elastic and post-yield behaviour. In order to achieve similarity of gravity forces and P-Δ effects, it was necessary to add considerable lead mass at each floor level; in fact, 9 of the total 10 tonnes total mass were added lead.

For the MRF, columns were solid 25 mm square, except at ground level where hollow sections were used to provide connection to the fully-fixed connection to the table. The solid columns were approximately twice as stiff in bending, and three times as stiff in compression as corresponding 2 mm thick hollow section. But column stiffness becomes less important as the frame is excited beyond yield. All MRF connections were full penetration butt welds. For the EBF, columns were again hollow at ground level and solid elsewhere; diagonal and horizontal braces were square solid bar. The link element was a solid circular bar welded to end plates. At prototype scale the link element is normally a stiffened I-section and forms a continuous member with the horizontal brace; it is usually designed to fail in shear along its full length, or in bending with plastic hinges at each end. This arrangement was not possible in the model, where the circular bar which yielded in bending was used. For these links, bolted connections were used so as to allow replacement of severely damaged elements. Elsewhere in the EBF fully welded connections were used.

The floor diaphragms were 2 mm mild steel plates, which maintained the square shape of the frame during excitation and helped to distribute the lateral load. They were welded to the centrelines of the MRF beams and EBF horizontal braces, but cut back near the links.

Seismic design

The prototype structure corresponding to the model was designed according to UBC 88; seismicity zone 4 and a hard rock site were assumed. The static analysis method advocated by the code was used, and PAFEC software used for modal properties and member forces. The calculated fundamental period resulted in a lower base shear than the Code allowed, and so the Code minimum was used in design. Because the conventional strong column/weak beam approach was used for the MRF design, the governing factor was limitation on inter-storey drifts, and this require an increase in member sizes beyond minimum requirements.

EBF design followed accepted rules, with yielding limited to link elements. The calculated fundamental period from PAFEC here resulted in a base-shear greater than that given by the Code. The former was used for design.

Testing Programme - (i) Subframe Tests

Cyclic-load tests were performed on single storeys of both MRF and EBF to measure elastic and yielding properties, during which some fabrication faults were discovered. For MRF, beam-column fillet welds were inadequate, resulting in softening under cyclic deformation; these were replaced by full penetration butt welds. For EBF, link detail had to be modified so as to move the plastic hinge away from the weld point.

(ii) Instrumentation

Figure 5 shows the general positioning of accelerometers displacement gauges and strain gauges; for any test the maximum number of channels available was 48. The transducers were arranged in one of four configurations, and because of symmetry only one MRF or EBF was instrumented comprehensively; the other two were instrumented only to check for torsion. In all tests table horizontal accelerations were measured with checks on vertical acceleration. In the first configuration one EBF was instrumented for excitation in its own plane. Accelerations were measured at all 10 levels, and also at level 10 on the opposite EBF. Absolute displacements were measured at the top and bottom, and relative floor displacements (drifts) by transducers along the diagonal. Axial strains were recorded in diagonal braces for the lowest 5 levels, and bending strains measured in the lowest 5 link elements. The second measurement configuration repeated the first, but on one MRF with excitation in its own plane.

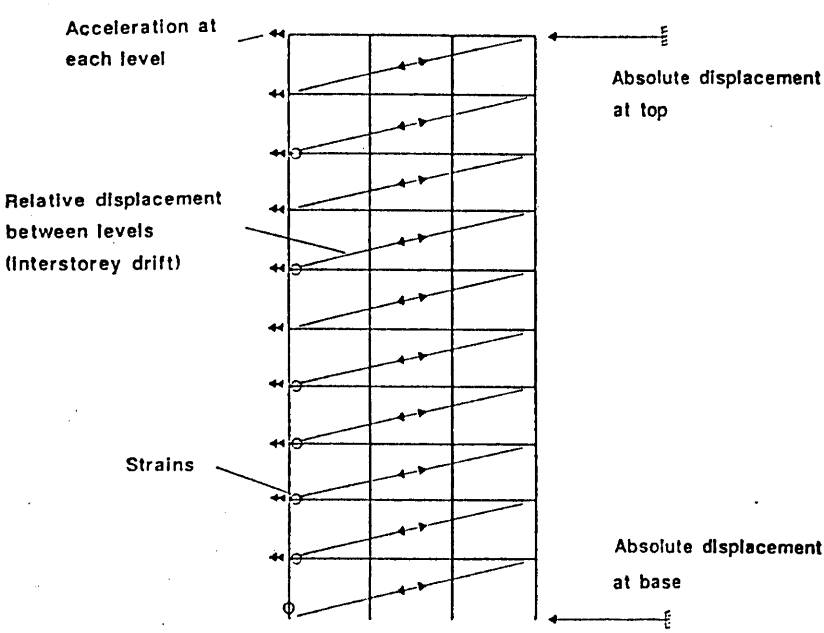


Figure 5 10-Storey Model: Typical Experimental Measurements

The third and fourth configurations monitored the response for excitation applied in two horizontal directions simultaneously. In the third, most of the measurements related to the MRF with a few on the EBF, whereas the reverse was true for the fourth configuration. In all cases, permanent sets measured by displacement transducers were checked with independent measurements using dial gauges and theodolite readings.

(iii) Dynamic Tests

Harmonic tests were made first by sine sweeps in both horizontal directions in the range 0.1 - 2.0 Hz so that natural frequencies, modal shapes and damping could be obtained from power spectra of floor accelerations using a spectrum analyser. Table rotational accelerations were also monitored.

For linear earthquake tests the 1985 Mexico record was used, speeded-up according to the necessary scaling factor of $(15)^{1/2}$. In addition its frequency was excited in its two directions separately and also in these two directions simultaneously, in all cases at about 50% of its yield capacity.

For the non-linear earthquake tests a similar single-direction and two-direction pattern was followed, with the force level initially up to the predicted yield point and then later to a maximum ductility of 6 in the MRF direction and 8 in the EBF direction. The modification of the Mexico record frequency components previously referred to was necessary in order to excite the frame beyond yield within the capacity of the table.

Some Results

A full report on this work is given in Ref 2; here, only a few salient findings are reported. In the linear studies, the natural frequencies and modal shapes were predicted accurately from the start for the MRF, but only for the EBF after a re-assessment of its stiffness based upon a more careful study of the subframe tests, where it was noticed that after the first yielding cycle the stiffness was reduced, most likely because of the link element. The revised link stiffness produced good agreement with PAFEC calculations

The non-linear tests are probably more interesting, and Figures 6 and 7 show first a check on instrumentation by comparing the velocity at the top of MRF and EBF frames, respectively, as obtained separately from accelerations and displacement transducers during the ductility 4 tests. In like manner, Figure 8 gives a comparison for the same tests, between the sum of the measured storey drifts and the absolute displacement between the top and the base of the MRF, whilst Figure 9 compares base shear with the sum of storey inertia forces for the EBF. Here, the shear-force was obtained from measured brace axial strains whereas the storey inertia forces were obtained from storey accelerations.

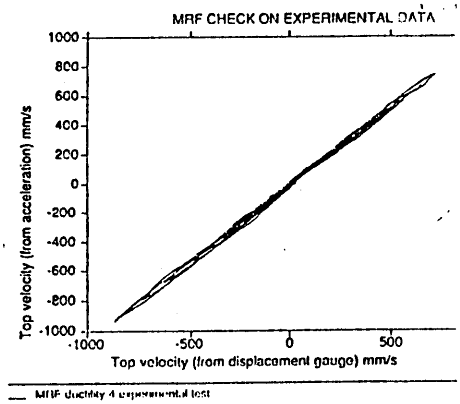


Figure 6
MRF Ductility 4 Test:
Top Velocity Check

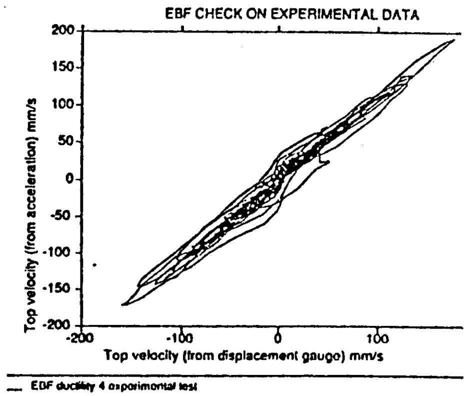


Figure 7
EBF Ductility 4 Test:
Top Velocity Check

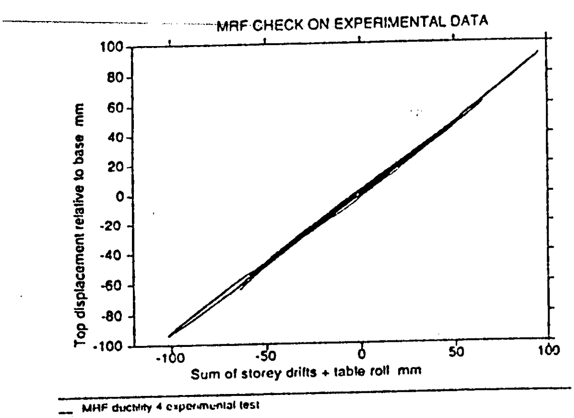


Figure 8
MRF Ductility 4 Test
Displacement Check

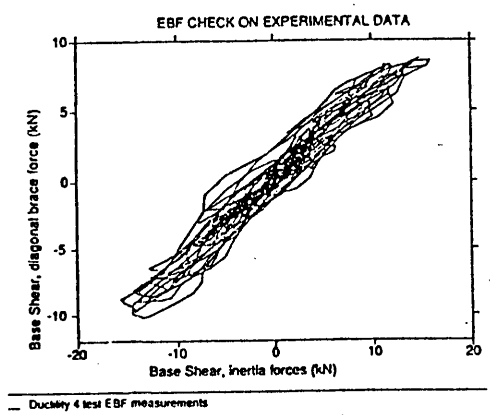


Figure 9
EBF Ductility 4 Test
Base Shear Check

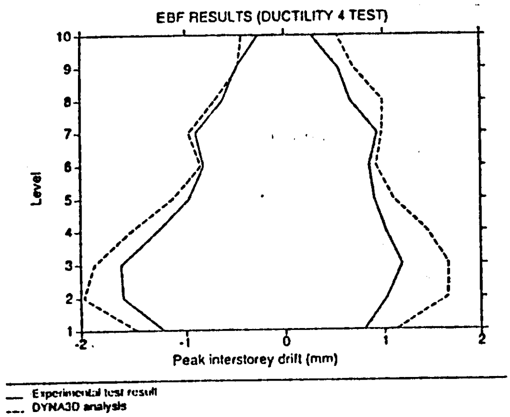


Figure 10 EBF Peak Interstorey Drifts, Ductility 4 Test

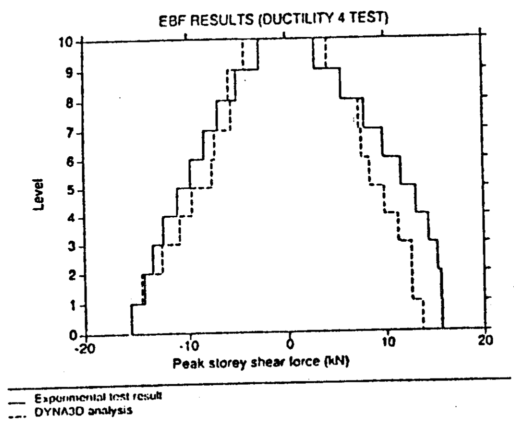


Figure 11 EBF Peak Storey Shears, Ductility 4 Test

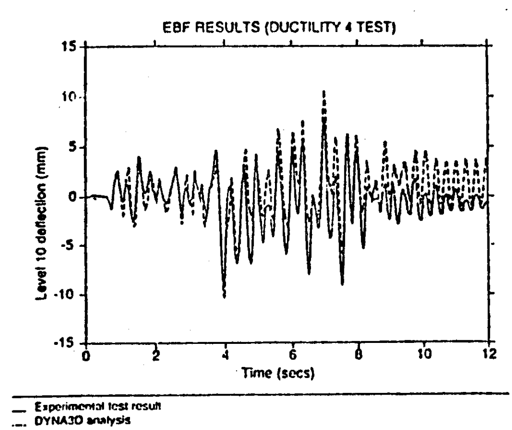


Figure 12 EBF Top Deflection (ductility 4 test)

The essential purpose of the non-linear tests was, of course, to validate the DYNA3D software and Figure 10 compares the peak interstorey drifts for the EBF, ductility 4. The peak measured drift was 1.61 mm between levels 2 and 3; this is 0.5% of storey height and a ductility of about 3.5. The corresponding analytical result was 1.97 mm between levels 1 and 2. It is to be noted that for the same level of ductility the MRF gives a peak drift of 17.5 mm.

For the EBF, ductility 4 tests, Figure 11 compares peak shear forces, which at 15.7 kN for both experiment and analysis is 15.7% of the model weight. For the same tests, Figure 12 compares top deflection for the experiment with corresponding DYNA3D calculations. Finally, for the EBF ductility 6 tests, Figure 13 compares experimental peak interstorey drifts with those from DYNA3D.

Finally, it should be said that in the analytical studies sensitivity analyses in beam yielding characteristics were carried out for both MRF and EBF; these are fully reported in Ref 2.

REFERENCES

1 Equipment Qualification Using the SERC Earthquake Simulator. Brownjohn J M W, Taylor C A, Blakeborough A and Severn R T. CEE-Mexico Workshop on Seismology and Earthquake Engineering, Mexico City, 22-26 April 1991.

2 Ove Arup and Partners/University of Bristol Teaching Company Scheme: Report on the Structural Project. Ove Arup and Partners, Consulting Engineers, Fitzroy Street., London, 1992.

İNGİLTERE DEPREM MERKEZİ SARSMA TABLASININ DOĞRULANMASI

A. BLAKEBOROUGH, R. T. SEVERN, C. A. TAYLOR

İngiltere'nin Bristol Üniversitesi Deprem Mühendisliği Araştırma Merkezi'nde 1988 yılından beri çalışmakta olan 3x3 m boyutunda altı serbestlik dereceli sarsma tablası üzerinde, tablanın öngörülen işlevini doğrulama amacıyla önceki depremlerin benzerlerini yaratma veya tekil ya da katlı sinüs dalgası ya da tümüyle rastgele yer hareketleri oluşturma yoluna gidilmekte, aynı tabladan çerçeve boyutlandırmasında kullanılan yazılımların da geçerliliğini doğrulama amacıyla yararlanılmaktadır.