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# NON-LINEAR TIME HISTORY SEISMIC STRUCTURAL ANALYSIS USING LS-DYNA3D

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## ABSTRACT

This paper describes the use of the non-linear explicit time history analysis code LS-DYNA3D for the seismic response analysis of building and civil engineering structures.

A number of recent developments to LS-DYNA3D to facilitate analyses of this type are summarised. These include algorithms to simulate the cyclic hysteretic response of steel, concrete and soil elements, and of seismic isolators. The use of these features is illustrated by reference to a number of recent seismic design and retrofit projects undertaken by the authors.

## KEYWORDS

Seismic response analysis, finite element analysis, building structures, non-linear dynamic analysis, soil structure interaction, LS-DYNA3D

## INTRODUCTION

Major seismic events around the world continue to demonstrate the destructive power of earthquakes. Buildings, bridges and other structures are damaged or destroyed, often with great loss of life and great economic loss.

Economic design accepts that inelastic deformation, or damage, will occur in severe earthquakes, but that the extent should be limited and if possible repairable, and the structure should not collapse. Increased computer power permits structures to be modelled in detail, and non-linear dynamic response simulations to be performed as part of the design process to predict a structure's response to the required design earthquake motions. Such simulations allow the designer to understand the seismic performance of structures with greater detail and confidence than traditional design methods, and enable him to assess the likely locations and degree of damage. Designs can thereby be improved.

These computer simulation techniques can be applied not only to the design of new structures, but also to the assessment (and retrofit design where necessary) of existing structures, which were often not designed to modern standards of safety.

The paper illustrates the use of the explicit non-linear dynamic analysis code LS-DYNA3D for the simulation of seismic response in the design of a number of projects performed by the authors.

## SOFTWARE REQUIREMENTS FOR SEISMIC ANALYSIS OF STRUCTURES

Software for the simulation of the non-linear seismic response of structures must be able to cater for the following features.

- Earthquake loadings are relatively long duration transients lasting typically 20-40 seconds.

- The duration and frequency content of the earthquake loading can in many cases bring about near-resonant response for a large class of structures. Structural damping therefore has a significant influence on seismic response.

- Most buildings tend to be framed structures in which coarse discretizations of lumped mass, stiffness and plasticity are reasonable assumptions. (Inelastic demand is often concentrated in local areas of a structure e.g. beam ends). Full 3D models are therefore typically discretised as assemblages of 1D beam elements, springs, dampers and masses.

- Earthquakes impose cyclic inelastic demands on elements of structures. Complex mechanisms of concrete crushing and cracking, reinforcing steel yield, fracture and bond slip, and structural steel buckling and tearing, often result in complex progressive degradation of stiffness and strength as the number of cycles increases. Material models must therefore monitor prior loading history. Element formulation therefore tends to be highly empirical with the material constitutive relationships introduced at a "high level". Phenomenological formulations of material hysteresis are therefore typically used in the form of non-linear springs, or beam post-yield moment-rotation relationships.

- Due to the nature of the seismic problem, (i.e. structures modelled with a relatively small number of degrees of freedom comprised of relatively complex phenomenologically formulated elements, subjected to long duration transients), implicit time integration methods have traditionally been used. However, there is a growing need to develop more rational models of component parts of structures and systems. Therefore solid finite elements (e.g. 2D and 3D plates and shells) are utilised to model steel plates, soils, etc. Explicit time integration techniques such as those of LS-DYNA3D then begin to become more attractive.

## LS-DYNA3D SEISMIC ANALYSIS DEVELOPMENTS

LS-DYNA3D was originally developed by Livermore Software Technology Corporation (LSTC) to simulate short timescale highly non-linear events, and the program has been used extensively in the modelling of blast and impact response of structures and vehicles.

In order to meet the specific needs of seismic design, Ove Arup and Partners (Arup) working in collaboration with LSTC have made a number of enhancements to LS-DYNA3D over the past two years. These have been validated by comparison with experimental results, and are briefly discussed in the following sections.

In seismic response, inelastic axial and flexural interactions can be significant on frame members, particularly in the form of inelastic brace buckling. Although fibre element models are rational, they can be computationally intensive relative to simplified phenomenological beam elements. Therefore an elastic beam element has been developed with plasticity lumped at the ends. The element takes account of the interaction between axial force and biaxial bending on hinge formation, through a user-defined yield surface. Elastic and inelastic buckling of compression members in a frame can be simulated by subdividing the member into a number of beam elements. Fig. 1 demonstrates the classical "pinched" hysteretic behaviour exhibited by braces undergoing cyclic inelastic buckling. The observed degradation of tensile and compressive capacity under repeated cyclic loading of a steel brace can thus be simulated in this way.

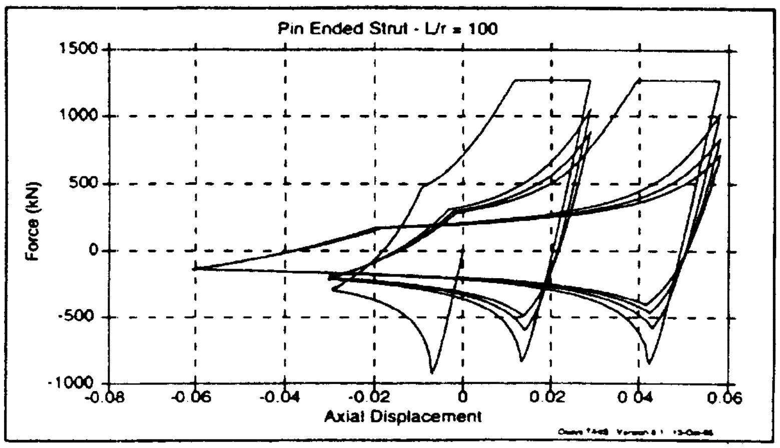



**Fig. 1 : Steel brace buckling simulation**

A "Fibre" model beam element has been developed for the simulation of inelastic flexural behaviour of reinforced concrete. This model superimposes or overlays different material models corresponding to the confined concrete, unconfined concrete, and the reinforcing steel. Fig. 2 shows the results of a simulation of full scale test data for a tall reinforced concrete shear wall modelled with vertical "fibre" beam elements.

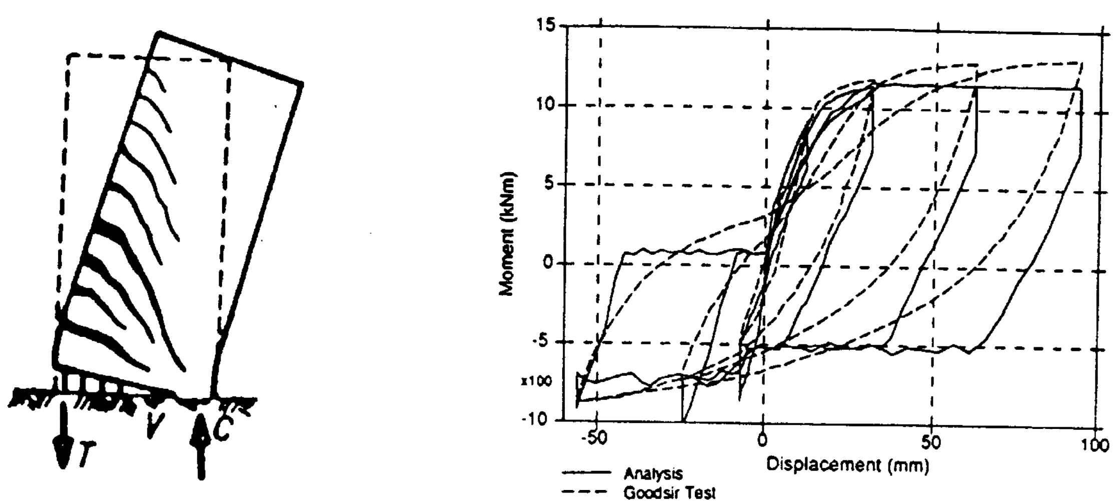
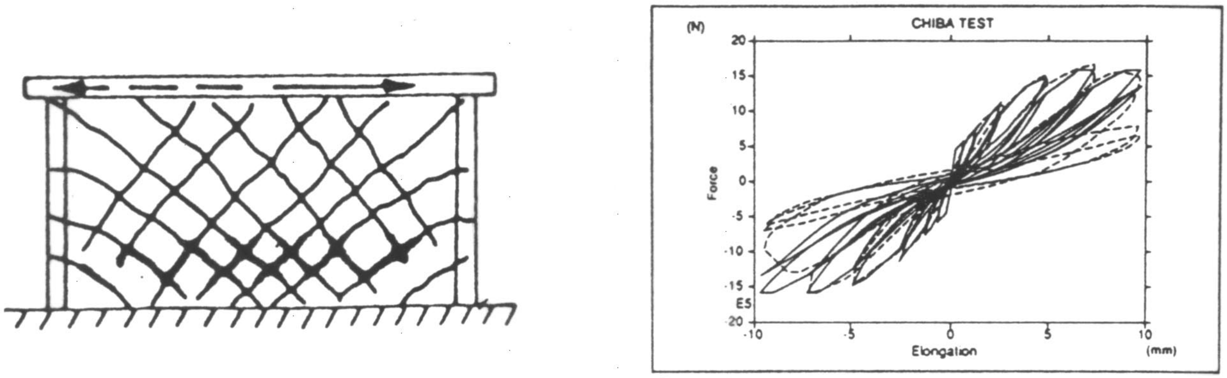



**Fig. 2 : Tall flexural shear wall modelled with fibre beam element**

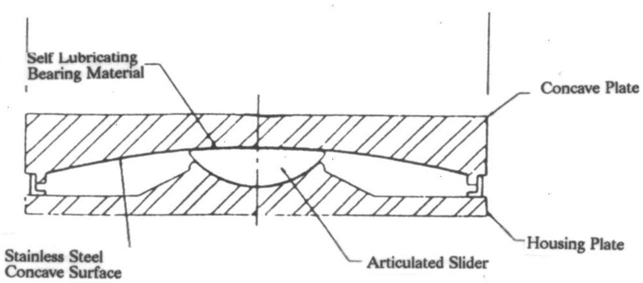
A squat reinforced concrete shear wall model has been developed. The complex seismic behaviour involving factors such as loss-of-bond, bar slip and plane sections not remaining plane is captured phenomenologically by incorporating hysteresis rules based on typical measured cyclical force-deflection behaviour. Fig. 3 shows the results of a simulation of a cyclically loaded squat shear wall.



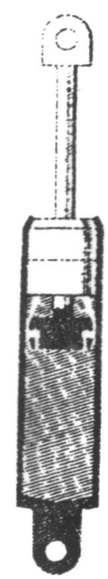

Calculated behaviour
Measured behaviour

**Fig. 3 : Simulation of squat reinforced concrete shear wall**

Modern aseismic design often considers the incorporation of supplemental damping and/or seismic base isolation to reduce the forces and inelastic demands on the structure. Such energy-absorbing devices are constructed using non-linear springs and dashpots as shown in fig. 4.




F.P.S Isolator



Viscous Damper

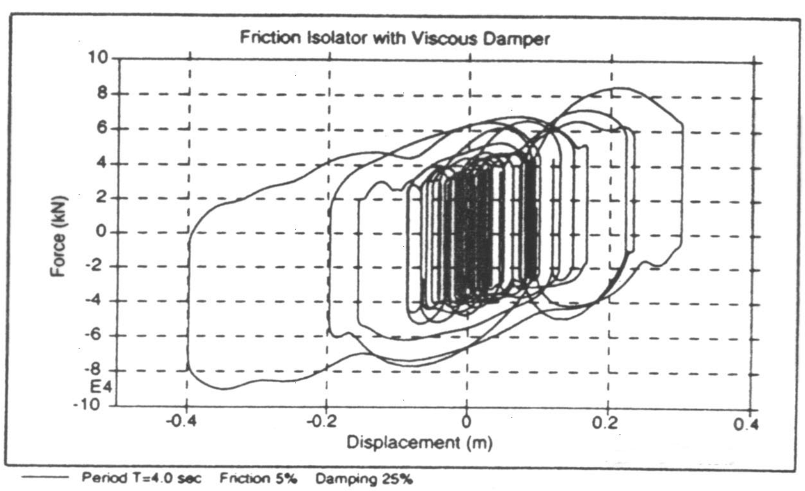



**Fig. 4 : Seismic isolators and supplemental damping**

Dynamic interaction between the structure and the soil on which it is founded is often significant. An enhanced dynamic soil material model, incorporating stress-strain hysteresis typical of cyclically loaded soil has been developed. Typical results are shown in fig. 5.

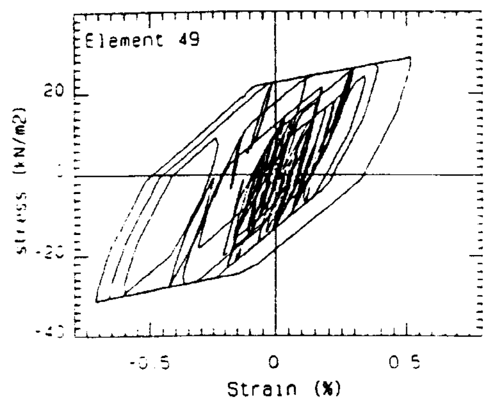



**Fig. 5 : Simulated soil stress-strain hysteresis**

Simulation of structural damping has been made possible by the use of a damping matrix constructed from modal damping parameters obtained from a linear elastic analysis (performed on the same model by a linear elastic analysis code).

## REQUIREMENTS FOR POST PROCESSING

One of the principal purposes of non-linear seismic analysis is to identify the ductility demands on individual components of a structure, and then to check that the capacity for this deformation to occur exists without brittle material fracture or unstable buckling. Facilities to extract this type of information in the form of force/deflection hysteresis diagrams, plastic hinge rotation diagrams and energy absorption with time are available using the programs Oasys D3PLOT and Oasys T/HIS developed by Arup. In addition, D3PLOT has facilities for animation of the deflection of a structure through an earthquake. It is possible to superimpose on this animation the variation of element force or plastic deformation indicated by changing colours during the event. These animations are instructive not only to the design engineers but also to lay clients.

## EXAMPLES OF USE

### (1) Soil/Pile/Structure Interaction

Arup performed a study for Mitsubishi Estates to assess the effect of seismic action on the piles supporting a multi-storey warehouse facility in Japan. The ground conditions at the site comprised varying layers of soft soil and landfill to a depth of some 70m. The steel piles on which the building was to be supported would be subjected not only to inertia forces from the accelerations of the building, but also to the kinematic effect of the significant deformations within the soil itself during a seismic event.

The problem was analyzed with LS-DYNA3D using a 2D model of a vertical slice through the building and soil. The piles were represented as elastic-plastic beam elements connected to the non-linear soil elements by springs representing the non-linear local interaction between a pile and the soil.

The time history analyses identified the deflection, shear force and bending moment demands on the piles. The most critical location was not immediately beneath the building but near the base of the piles where they pass through a very soft soil layer. Typical results at one timestep are shown in figs 5, 6 and 7.

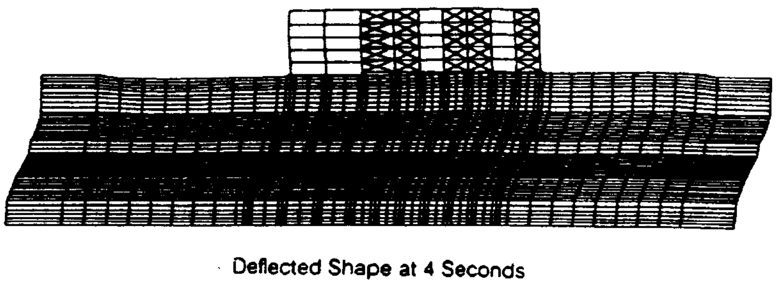



**Fig 6 : Deflected shape (magnified)**

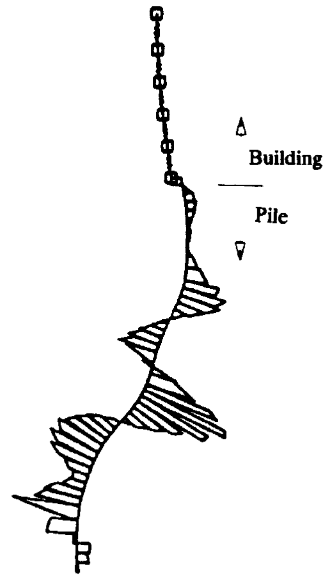


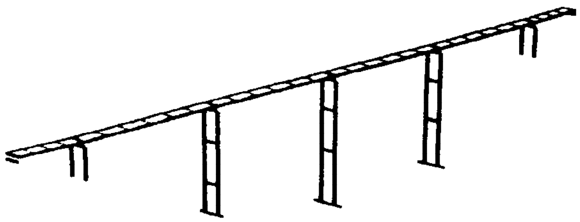

**Fig 7 : Pile bending moment on magnified displaced shape**

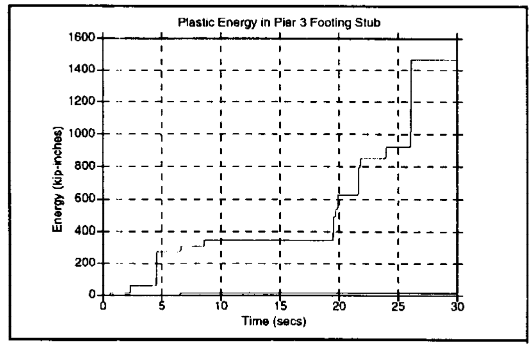
(2) Bridge Retrofit Using Damping Devices

Arup performed a study for the retrofit of an existing highway bridge in California. The bridge deck was supported on concrete frame towers in deep water which had not been designed to modern standards of strength and ductility.

Preliminary analysis had shown that there were several areas of concern - the inadequate ductility of the concrete frames, the likely failure of the footings by the concrete column punching through, and uplift of the footings. Conventional retrofit schemes involving strengthening of elements would be difficult to accomplish since many of critical areas were under deep water. LS-DYNA3D was used to analyse a simple 3D model of the bridge to examine the existing seismic response and evaluate various alternative retrofit options.

A scheme in which the deck was isolated from the concrete frames using sliding bearings together with supplemental viscous damping at the bearings was shown to reduce the seismic demands on the inaccessible concrete elements and foundations to an extent that strengthening these elements would not be required. Fig 8 shows typical response output from the analysis. (Fig. 4 showed the seismic energy absorbing bearings and the hysteresis that they produce.)






Finite Element Model of Bridge

Isolated vs Non-Isolated Comparison of Damage in Footings

**Fig 8 : Putah creek bridge retrofit study**

(3) Kobe earthquake, Japan, Bridge Damage Simulation

Arup conducted field investigations of the Kobe earthquake, and analytically simulated the damage observed on certain elevated expressways using LS-DYNA3D. The bridge under consideration was constructed of multi-cellular steel box column piers. The Kobe earthquake caused local plate buckling at the base as is shown in Fig 9. A 60,000 element non-linear finite element model was created. A cyclic pseudo-static pushover analysis was performed to capture and quantify the post-elastic behaviour.

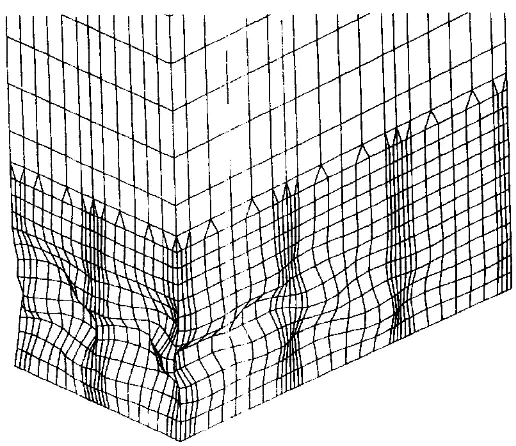


**Fig 9 : Kobe bridge damage simulation**

(4) High Rise Building in Osaka, Japan

Arup are currently carrying out the structural design for the Osaka International Conference Centre. The building comprises a large steel braced structure of 90 m height above ground and four levels of basement. Extensive use is made of unbonded braces in the superstructure.

As the building exceeds 60m in height it will be subject to a special approval procedure

As the building exceeds 60m in height it will be subject to a special approval procedure from the Tall Buildings Committee of the Ministry of Construction, requiring non-linear seismic analysis.

The conventional approach in Japan for such projects is firstly to perform a quasi-static non-linear lateral push-over analysis up to "failure" of the structure to determine the force-deflection characteristics of each storey of the building. Non-linear dynamic analysis for appropriate ground motion records is then be performed on a simplified vertical cantilever model where the storey masses are connected by non-linear shear springs representing the inter-storey force deflection characteristics, as calculated from the earlier pushover analysis.

LS-DYNA3D has been used for the pushover analysis and the non-linear time history analyses on the simplified models.

It is also now feasible to perform full 3-D non-linear seismic response analysis on a detailed model of the building as a whole and the use of this technique is adopted for more precise checking of the seismic response of the structure. Fig. 10 shows the architect's conception, as well as the 3D structural analysis model.

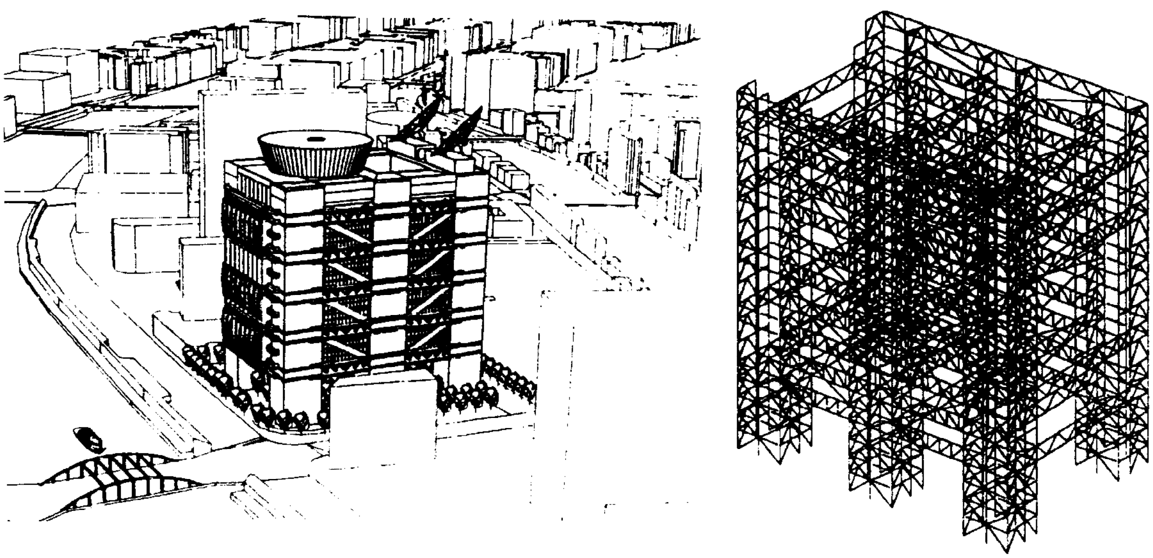


**Fig. 10 : Osaka International Convention Centre**

## CONCLUSIONS

Although an explicit code such as LS-DYNA3D is at first sight not an obvious choice for the seismic analysis of structures, it can be used effectively for this purpose, particularly as the traditional phenomenological models give way to the more rational introduction of material models at the fibre level. It is robust in dealing with material and geometric non-linearity, and its structure enables special element or material types to be developed and incorporated relatively easily. LS-DYNA3D has been enhanced with a number of features essential to the effective performance of seismic response analysis, and further developments are under way.