International Scientific Advisory Committee

Paul Acker, Paris, France
George Y. Baladi, Albuquerque, USA
Ben I.G. Barr, Cardiff, Wales
Ignacio Carol, Barcelona, Spain
Alberto Carpinteri, Torino, Italy
Luigi Cedolin, Milano, Italy
Vladimir Cervenka, Prague, Czechoslovakia
Jenn-Chuan Chern, Taipei, Taiwan
Ken P. Chong, Washington, USA
Dave Darwin, Lawrence, USA
Rene de Borst, Delft, The Netherlands
John W. Dougill, London, England
Eduardo N. Dvorkin, Buenos Aires, Argentina
Lennart Elfgren, Lulea, Sweden
Manuel Elices, Madrid, Spain
Rolf Eligehausen, Stuttgart, Germany
Dominique Francois, Chatenay Malabry, France
Pietro Gambarova, Milano, Italy
Kurt H. Gerstle, Boulder, USA
Vellore S. Gopalaratnam, Columbia, USA
Neil M. Hawkins, Seattle, USA
Arne Hillerborg, Lund, Sweden
Hubert K. Hilsdorf, Karlsruhe, Germany
Hideyuki Horii, Tokyo, Japan
Anthony R. Ingraffea, Ithaca, USA
Jeremy Isenberg, Los Altos, USA
Hamlin M. Jennings, Evanston, USA
Bhushan L. Karihaloo, Sydney, Australia
Michel G. Katona, Tyndall, USA
Jin-Keun Kim, Seoul, Korea
Albert S. Kobayashi, Seattle, USA
Dusan Krajcinovic, Tempe, USA
Victor C. Li, Ann Arbor, USA
Herbert N. Linsbauer, Wien, Austria
Yiu-Wing Mai, Sydney, Australia
Herbert A. Mang, Wien, Austria
Sheng-Taur Mau, Houston, USA
Jacky Mazars, Cachan, France
Hirozo Mihashi, Sendai, Japan
Sidney Mindess, Vancouver, Canada
Zenon Mroz, Warsaw, Poland
C. Dean Norman, Vicksburg, USA
Byung-Hwan Oh, Seoul, Korea
Hajime Okamura, Tokyo, Japan
Josko Ozbolt, Stuttgart, Germany
Phillip A. Pfeiffer, Argonne, USA
Gilles Pijaudier-Cabot, Cachan, France
Jaime Planas, Madrid, Spain
Pere C. Prat, Barcelona, Spain
Hans W. Reinhardt, Stuttgart, Germany
Jan G. Rots, Delft, The Netherlands
Victor E. Saouma, Boulder, USA
Surendra P. Shah, Evanston, USA
Robert L. Sierakowski, Columbus, USA
Stein Sture, Boulder, USA
Stuart E. Swartz, Manhattan, USA
Jan van Mier, Delft, The Netherlands
Richard N. White, Ithaca, USA
Kasper Willam, Boulder, USA
Folker H. Wittmann, Zurich, Switzerland
Spencer T. Wu, Washington, USA
Yuri V. Zaitsev, Moscow, USSR

Sponsors

The Conference is organized by

Northwestern University

in collaboration with the

NSF Science and Technology Center for Advanced Cement-Based Materials (ACBM)

and the

ACI Committee 446 on Fracture Mechanics

under the auspices of the

International Association for Bridge and Structural Engineering (IABSE)

and the

American Concrete Institute (ACI)

and sponsored by the

U.S. National Science Foundation (NSF)

FRAMCOS 1

First International Conference on Fracture Mechanics of Concrete Structures

organized by

NORTHWESTERN UNIVERSITY

June 1-5, 1992
Beaver Run Resort
Breckenridge, Colorado

Conference Chairman:
Zdeněk P. Bažant

Organizing Committee:
Surendra P. Shah (Assoc. Chairman)
Victor E. Saouma (Coordinator)
Gustavo Gioia (Program Manager)
Kurt H. Gerstle
Vellore S. Gopalaratnam
Phillip A. Pfeiffer
Stein Sture
Kasper Willam

11:00 Is the Dynamic Behaviour of Concrete Influenced by the Presence of Free Water? (p.644)
by P. Rossi, J. G. M. van Mier and F. Toutlemonde

11:15 Fracture of Concrete Under Torsional Impact Load Conditions (p.622)
by N. J. S. Gorst and B. I. G. Barr

11:30 Fracture Characterization in Blast-Loaded Concrete Structures (p.628)
by F. B. A. Beshara and K. S. Virdi

11:45 Concrete Slab Tests Using a Shock Tube: How to Quantify Concrete Dynamic Fracture? (p.634)
by F. Toutlemonde, C. Boulay and C. Gourraud

12:00 Nonlinear Dynamic Analysis of Damage in Concrete (p.650)
by M. P. Luong and H. Liu

12:15 Nonlinear Dynamic Analysis of Impact Failure Modes in Concrete Structures (p.565)
by A. Miyamoto, M. W. King and M. Fujii

12:30 The Transient Solution of Mode-I Crack Propagating with Transonic Speed (p.638)
by Y. L. Chung

12:45 Conference adjournment

11:00 Simulation of Cycling Bond-Slip Behavior (p.918)
by J. Ožbolt and R. Eligehausen

11:15 R-Curve Modeling of Rate Effect in Static Fracture and Its Interference with Size Effect (p.924)
by Z. P. Bažant and M. Jirásek

11:30 Time-Dependent Fracture of Concrete: Testing and Modeling (p.912)
by F. Zhou and A. Hillerborg

11:45 Probabilistic Modelling of Brittle Fracture Strengths and Load Duration Effects for Concrete (p.288)
by S. G. Reid

12:00 Material Model for High Strength Concrete Exposed to Cyclic loading (p.900)
by T. Kanstad and G. Petkovic

12:15 Stiffness Degradation of Tension Softening Behavior in Concrete (p.906)
by N. Nomura and H. Mihashi

12:30 A Study on Fatigue Life of Reinforced Concrete Beam with Multiple Tension Reinforcing Bars (p.936)
by N. Matsumoto

12:45 Conference adjournment

FRACTURE CHARACTERIZATION IN BLAST-LOADED CONCRETE STRUCTURES

Dr F B A Beshara and Prof K S Virdi
Structures Research Centre
Department of Civil Engineering
City University
Northampton Square, London EC1V 0HB, UK

ABSTRACT

The paper describes a finite element based analysis of reinforced concrete plane and axisymmetric structures under blast loading conditions. The method provides the possibility of activating different fracture mechanisms and failure modes characteristic of reinforced concrete structures. The rate sensitivity effects are also accounted for in the constitutive relations adopted for the materials in both tension and compression. The significance of history and rate dependent characterization is illustrated by means of examples.

INTRODUCTION

An understanding of the structural behaviour under blast loading is of concern in many aspects of military and civil engineering. For more realistic analysis of two dimensional reinforced concrete structures exposed to blasts, the nonlinear finite element method offers many advantages, especially in spatial discretisation. The method lends itself to convenient modelling of material nonlinearities and different fracture mechanisms. The paper briefly describes the method, but a fuller description of the theory and implementation can be found in [1-4].

MODELLING OF CONCRETE FRACTURE IN COMPRESSION

Concrete is idealized as a rate and history dependent elasto-viscoplastic strain hardening-softening material. The dynamic fracture of concrete in compression is modelled by generalizing the failure stress concept within the viscoplasticity theory by means of a set of variables, the values of which can be determined from empirical data. The viscoplastic behaviour is controlled by two bounding rate dependent surfaces in the stress space, the initial yield surface F_o and a failure surface F_f. The failure surface predicts failure if the state of stress satisfies the following condition

$$F_f\left(I_1, J_2, \sigma_{cd}\right) = f\left(I_1, J_2\right) - \sigma_{cd} = 0 \tag{1}$$

where $f\left(I_1, J_2\right)$ is the failure function which is assumed to be a function of the first stress invariant I_1 and the second deviatoric stress invariant J_2. In the above equation, σ_{cd} is the dynamic compressive strength of concrete and is a function of its static strength and of the effective strain rate dependent magnification factor [1]. The following function has been developed for the representation of the failure surface of concrete in the principal stress space:

$$f\left(I_1, J_2\right) = a\, I_1 + \sqrt{b\, I_1^{\,2} + 3\, c\, J_2} \tag{2}$$

where a, b, c are material constants which have been evaluated elsewhere [1], using Kupfer's test results [5]. In the above formulation, the initial yield surface defines the onset of viscoplastic behaviour. When the stress state lies within this surface, concrete response is assumed to be linear elastic. Once concrete has been stressed beyond the elastic limit, a subsequent new loading surface develops. The new loading surface is assumed to have the same shape in stress space as that of the failure surface. Thus, the general form of the loading surface is proposed as

$$F_o\left(I_1, J_2, \tau\right) = f\left(I_1, J_2\right) - \tau = 0 \tag{3}$$

in which τ is the effective stress which is assumed to be a function of the effective viscoplastic strain ε_{vp}, and the effective strain rate, $\dot{\varepsilon}_{eff}$.

Concrete crushing

To model the crushing mechanism for concrete, its ultimate deformation capacity under biaxial stress state is defined as a strain controlled phenomenon. This is achieved by converting the failure function described in terms of stresses to that in terms of strains such that

$$C\left(I_1', J_2', \varepsilon_{cu}\right) = a\, I_1' + \sqrt{b\, I_1' - 3cJ_2'} - \varepsilon_{cu} = 0 \tag{4}$$

where I_1' is the first invariant of strain, J_2' is the second deviatoric strain invariant, and ε_{cu} is concrete ultimate strain (0.003-0.005).

Degradation of concrete compressive strength

To include the plastic stiffness degradation effects in the pre- and post-failure regimes, the parameter τ in Eqn (3) is derived as function of a history dependent plastic damage variable, effective viscoplastic strain, to fit quasi-static experimental results. Based on empirical rate sensitivity factors, this function is extended for dynamic problems. For the prefailure range, an isotropic hardening rule is developed which assumes the uniform expansion of the loading surface to be rate and history dependent. In Ref [1], the normalized effective stress is defined by the following hardening function

$$\frac{\tau}{\sigma_{cd}} = -\frac{2}{C}\left[1 - C + \frac{2C}{\varepsilon_{cd}}\varepsilon_{vp}\right]^{1/2} - \frac{2}{C}\left[1 - C + \frac{C}{\varepsilon_{cd}}\varepsilon_{vp}\right] \quad (5)$$

in which ε_{cd} is the dynamic peak compressive strain and C is a constant derived as a function of concrete elastic limit. In the postfailure range, the loading surface shrinks with the increase in viscoplastic strain. A rate dependent softening rule has been defined [1] in which the effective stress is assumed as a function of the dynamic compressive strength and the postfailure viscoplastic energy, κ, such that

$$\tau = \sigma_{cd}\, e^{-\beta\kappa} \quad (6)$$

in which β is a concrete softening constant. Excellent agreement [1] has been obtained with Kupfer's results [5] for both the hardening and softening functions. To evaluate the viscoplastic strain rate vector, $\dot{\varepsilon}_{vp}$, the classic flow rule is modified to include rate dependence of inelastic deformations. The evolution law for the internal variable of associated rule, the fluidity parameter γ, is derived as a semi-empirical function of the effective strain rate.

$$\dot{\varepsilon}_{vp} = \gamma\left(\dot{\varepsilon}_{eff}\right) < \phi\,(F_o) > \mathbf{a} \quad (7)$$

where $\phi\,(F_o)$ is the flow function and **a** is the flow vector. From the governing uniaxial elasto-viscoplastic stress strain relation [1], and the curve fitting of experimental results, the fluidity parameter is found as a function of the effective strain rate and the concrete compressive strength.

IDEALIZATION OF CONCRETE TENSILE FRACTURE

Tensile fracture is modelled here by treating concrete as a linear elastic strain softening material [1, 4] with smeared fixed crack formulation.

Crack initiation criterion

The onset of tensile cracking is assumed to be governed by a rate sensitive strain criterion. The influence of deformation velocity is considered by raising the cracking strain to relative the static condition using a rate dependency factor.

$$\varepsilon_{cr} \geq \varepsilon_{td} \quad (8)$$

where ε_{td} is the dynamic cracking strain of concrete which is defined [1] as a function of the corresponding static strain and an empirical effective strain rate dependent magnification factor.

Degradation of tensile strength of cracked concrete

Upon cracking the gradual loss of tensile strength of concrete is governed by a nonlinear reversible tension softening rule based on the concrete fracture energy G_f, the crack characteristic length L_c, the static tensile strength σ_{ts} and static cracking strain ε_{ts}

$$\sigma = \sigma_{ts}\, e^{\frac{-\varepsilon + \varepsilon_{ts}}{\psi}} \quad , \quad \psi = \left(G_f - 0.5\, \sigma_{ts}\, \varepsilon_{ts}\, L_c\right) \; / \; \sigma_{ts}\, L_c \tag{9}$$

The fracture energy concept leads to a nonlocal format of the equivalent softening relation necessary to meet objectivity of analysis with respect to mesh elements size.

CHARACTERIZATION OF CONCRETE FRACTURE IN SHEAR

Degradation of shear strength of cracked concrete

Considerable shear can be transferred across cracks due to aggregate interlock and dowel action of steel bars. In the smeared crack approach, the shear modulus of cracked concrete is obtained by using a reduction factor, which depends on the tensile strain ε across the crack.

$$\beta_c = 1 - \frac{\varepsilon_t}{0.004} \; ; \; \beta = 0 \text{ if } \varepsilon_t \geq 0.004 \tag{10}$$

Detection of fracture localization and diagonal shear cracks

Under blast conditions, sudden and extensive diagonal cracking occurs within a few time steps. Some recommendations on computational strategies to be adopted are now given, based on numerical results [1]. First, displaying only full cracks, i.e. cracks for which the normal strain is beyond the ultimate strain of the tensile softening branch, is necessary to reveal any fracture localization in the structure behaviour as well as to uncover the shear-type cracks in the predicted crack patterns. Second, the use of Gaussian quadrature with a reduced 2x2 order for the integration of stress fields proves to be a successful means of avoiding stress-locking phenomena associated with strain localization mechanism [1]. This results in a partial release of the continuity requirements imposed by shape functions assumed for the finite elements.

MODELLING OF YIELDING OF STEEL REINFORCEMENT

Steel is modelled as a uniaxial strain rate dependent elasto-viscoplastic material in tension and compression in which the yield stress σ_{yd} is rate dependent. Beyond yield, the effective stress level is governed by a linear strain hardening function such that

$$\tau = \sigma_{yd} + H\, \varepsilon_{vp} \tag{11}$$

where H is the hardening modulus of steel. To calculate the viscoplastic strain rate, the associated flow rule is modified in a similar fashion to concrete where the fluidity parameter is derived as a semi-empirical function of the strain rate [1].

FINITE ELEMENT IMPLEMENTATION AND NUMERICAL APPLICATIONS

For the spatial discretisation of the nonlinear dynamic equilibrium equations, 8-node isoparametric elements have been employed for concrete with embedded bars to simulate reinforcement. Perfect bond is assumed between steel and concrete. Explicit central difference scheme has been used for temporal discretisation of dynamic equations while explicit Euler integration has been adopted for time rate constitutive relations [1, 4]. To implement the proposed fracture models, a versatile computer program, FEABRS, has been developed for linear and nonlinear dynamic analysis of two dimensional concrete structures. The program has been used to study the response characteristics of several structures under impulsive and blast loading [1-4]. In Figs 1-4, comparisons are made with test results of Ref [6] where many aspects of concrete fracture and the generality of the proposed models are well demonstrated by the analysis.

CONCLUSION

For the finite element analysis of concrete structures, a numerical model is presented for characterization of fracture mechanism under blast loading. The proposed rate and history elasto-viscoplastic constitutive model which includes strength degradation effects in the pre- and post-failure regimes, is suitable for modelling the concrete dynamic fracture in compression. For idealization of concrete tensile fracture, the adopted rate sensitive cracking condition in conjunction with fracture energy dependent tension softening rule proved to be a powerful numerical tool. In addition to a fracture strain based-shear retention factor, some recommendations are described for detecting diagonal shear cracks and fracture localization mechanisms. Steel yielding is considered by a modified viscoplasticity theory. An illustrative example is included.

REFERENCES

1. Beshara, F B A, Nonlinear finite element analysis of reinforced concrete structures subjected to blast loading, *PhD Thesis*, Structures Research Centre, Department of Civil Engineering, City University, London, June 1991.

2. Beshara, F B A and Virdi, K S, Nonlinear finite element dynamic analysis of two dimensional concrete structures, *Computers and Structures*, 1991, **41**, pp 1281-1294.

3. Beshara, F B A and Virdi, K S, A computational strategy for the cracking process in concrete structures under shock and earthquake loading conditions, *Proceedings of Int. Conf. on Earthquake, Blast and Impact*, SECED, held at University of Manchester Institute of Science and Technology, Manchester, 1991, pp 249-263.

4. Beshara, F B A and Virdi, K S, Time integration procedures for finite element analysis of blast-resistant reinforced concrete structures, *Computers and Structures*, 1991, **40**, pp 1105-1123.

5. Kupfer, H, Hilsdorf, H K, and Rüsch, H, Behaviour of concrete under biaxial stresses, *ACI Journal*, 1969, **66**, pp 656-666.

6. Seabold, R H, *Dynamic shear strength of reinforced concrete beams, Part 2*, Naval Civil Engng. Lab., Port Hueneme, Calif., AD 644823, 1967.

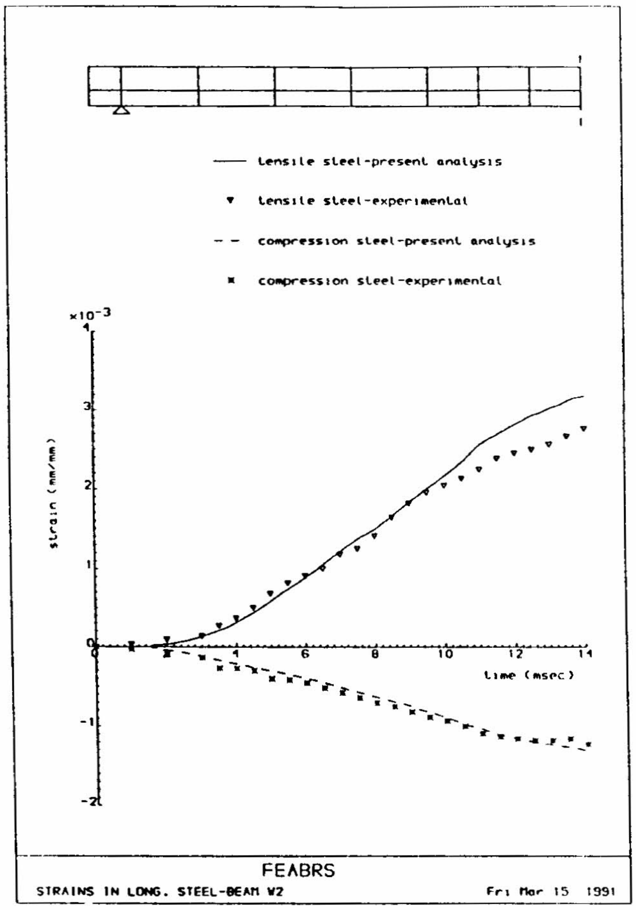

Fig 1: Strain history of steel

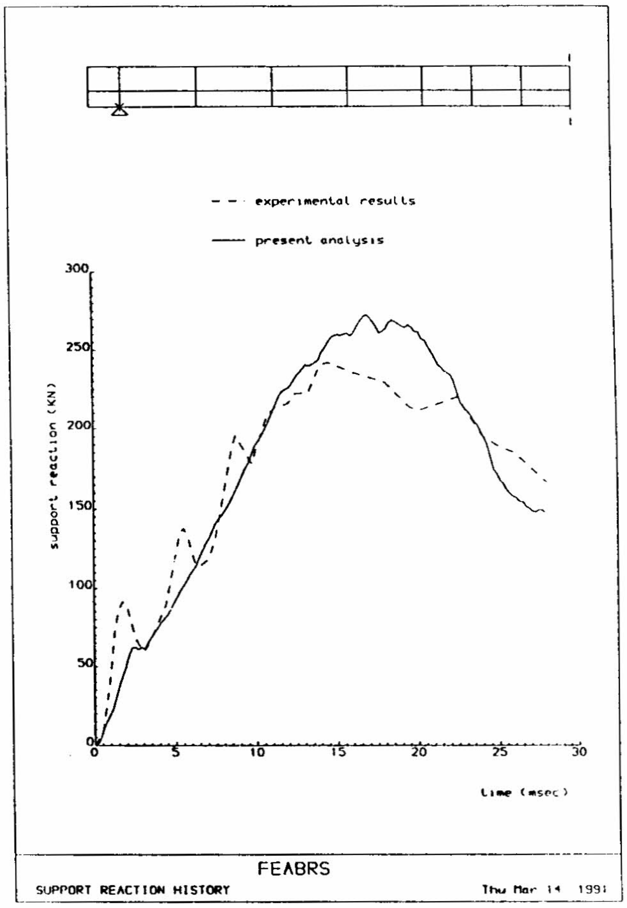

Fig 2: End reaction history

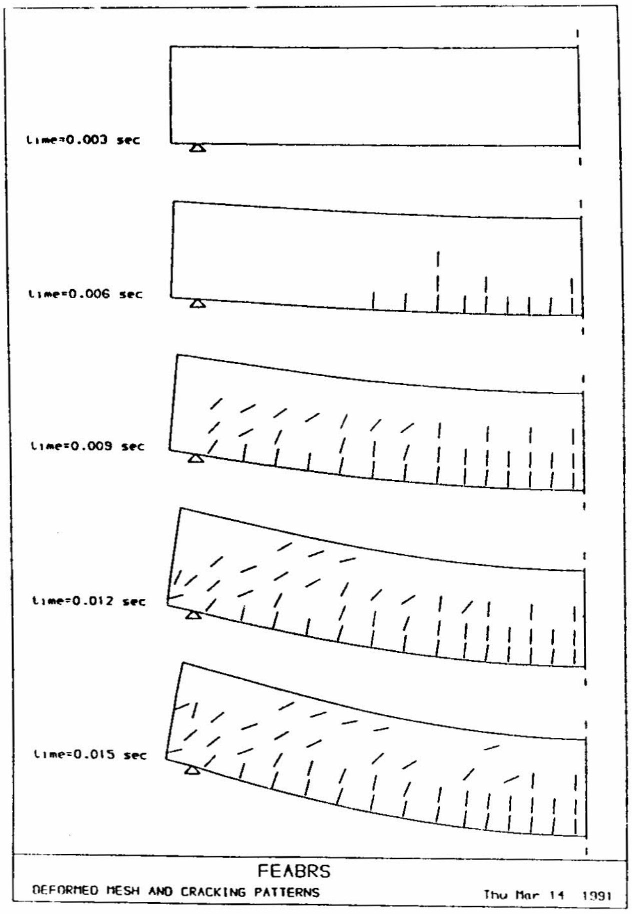

Fig 3: Cracking patterns

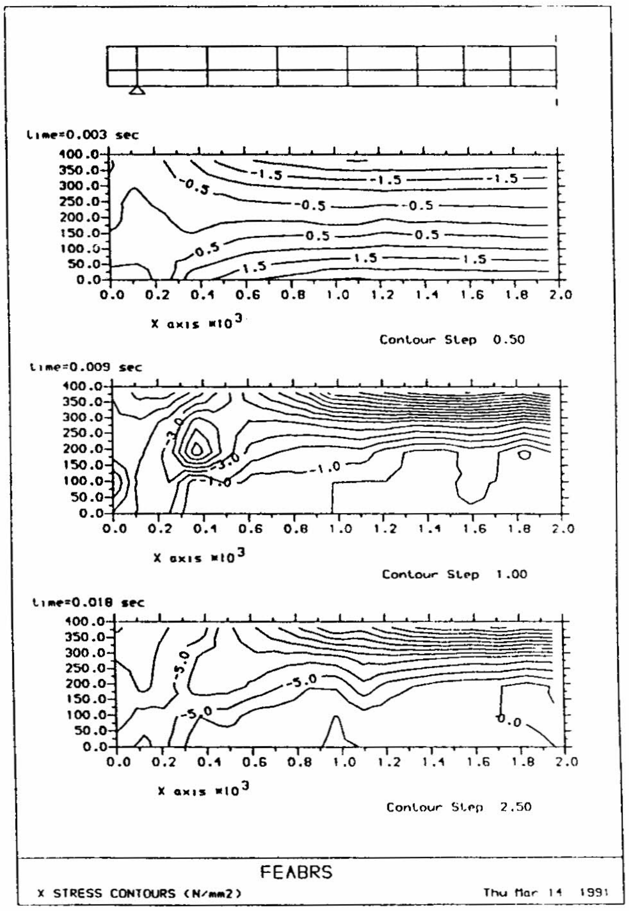

Fig 4: Longitudinal stress