SPD/D(95)363

AEA Technology

The Winfrith Concrete Model in LS-DYNA3D

B J Broadhouse

February 1995

	Name	Signature	Position	Date
Author	B J Broadhouse	[signature]	PMG2	22/2/95
Checked	J B Wintle	[signature]	PMG1	8/4/95
Approved	J C Duthie	[signature]	PMG1	8/4/95

Structural Performance Department
AEA Technology
Winfrith Technology Centre

THE WINFRITH CONCRETE MODEL IN LS-DYNA3D

B J Broadhouse

SUMMARY

The three-dimensional finite element code LS-DYNA3D is used in many industries world-wide for analysis of the response of structures to dynamic loadings. Analysis of the response of reinforced concrete structures to severe dynamic loadings such as impact and blast, requires a constitutive material model that covers all aspects of concrete behaviour, including cracking.

The Winfrith Concrete Model, now available in LS-DYNA3D, has been developed over the last decade, and validated against a wide range of impact and blast tests. It has been used to determine the response of, and damage to structures such as reactor containment buildings subject to impact from aircraft and plant generated missiles, floors subject to dropped loads, civil structures subject to impact from vehicles and falling buildings, and protected and unprotected buildings subject to blast loading.

The theoretical basis of the constitutive model is described, the input parameters for the model are defined, and the results of an example case are given.

Structural Performance Department
AEA Technology
Winfrith Technology Centre

February 1995

CONTENTS

1. INTRODUCTION

The Winfrith Concrete Model was originally developed in response to the requirement of the Nuclear Industry for a finite element analysis capability to predict the local and global response of reinforced concrete structures to accidental impact loadings. In the past decade, data from a wide range of impact and blast experiments have been used to develop improvements to the constitutive model, and to demonstrate its validity for analysis of the dynamic response of structures.

The model has recently been implemented in LS-DYNA3D [1], and is available in the form of add-on subroutines that can be linked with the standard LS-DYNA3D code.

The theoretical basis of the constitutive material model is described; the input parameters for the model are defined, and the results of an example case are illustrated.

2. THEORETICAL BASIS

The Winfrith Concrete Model is a smeared crack (sometimes known as pseudo crack), smeared rebar model, implemented in the 8-noded single integration point continuum element.

The hydrostatic stress state in the concrete is determined from a typical non-dimensionalised volume compaction curve shown in Figure 1, which originated from Reference [2]; or alternatively may be input by the user as a Pressure -v- Volumetric Strain curve.

The deviatoric stresses are incremented elastically, using a locally rate dependent modulus, and are limited by the yield surface shown in Figure 2, which is due to Ottosen [3]. The form of this yield surface is typical of the response of most concretes, and has been fitted to data from a number of sources quoted by Ottosen. The yield surface expands with increasing hydrostatic stress, and its radii at the compressive and tensile meridia are determined by the locally rate sensitive compressive and tensile strengths. The rate dependence of the elastic modulus and compressive and tensile strengths follow data given in Reference [4], and shown in Figure 3.

The flow stress is determined by radial return to the yield surface, and tensile failure is indicated if the maximum principle stress at yield is greater than half the value of the current tensile strength. If tensile failure is indicated, a special post-failure treatment is invoked, which decays the crack-normal tensile strength as the crack develops. Up to three orthogonal cracks may be initiated in any element. If failure is indicated in tri-axial compression, the concrete is deemed to be crushed, and three instantaneous (closed) cracks are generated so that the material has no tensile capacity on unloading.

Typical stress-deformation curves for tensile failure are given in Reference [5], and illustrated in Figure 4. This type of post-failure behaviour has been studied in Reference [6], and the average non-dimensionalised bi-linear crack stress decay function shown in Figure 5 has been developed for the model. The rate of stress decay depends on the local fracture energy G, which itself is rate dependent. Softening in failed elements is also accounted for by decay of the shear modulus as the crack develops.

The reinforcement is defined as up to three orthogonal tensile stiffeners in the global coordinate directions. The rebars take their strain from the concrete element strain, implying full bonding in non-cracked elements, and full de-bonding within the element for cracked elements. The rebar stress is determined from a bi-linear stress-strain relationship input by the user, with strain hardening and failure.

3. MODEL INPUT PARAMETERS

The strain rate dependent version of the model in LS-DYNA3D is Material Type 84. (There is an earlier non-rate dependent version, Type 85, which is retained for compatibility with previous work, but is not now recommended). The parameters for the constitutive model are as follows:

COLUMNS	QUANTITY		FORMAT
1 - 10	Card 3	Tangent Modulus (concrete)	E10.0
11 - 20		Poisson's ratio	E10.0
21 - 30		Uniaxial compressive strength	E10.0
31 - 40		Uniaxial tensile strength	E10.0
41 - 50		Fracture energy	E10.0
51 - 60		Aggregate size	E10.0
1 - 10	Card 4	Young's modulus (steel)	E10.0
11 - 20		Yield stress	E10.0
21 - 30		Hardening modulus	E10.0
31 - 40		Ultimate elongation	E10.0
	Cards 5 to 8 may be left blank		
1 - 10	Card 5	Volumetric strain (concrete)	E10.0
11 - 20		Pressure	E10.0
21 - 30		Volumetric strain	E10.0
31 - 40		Pressure	E10.0
	. . .		
1 - 10	Card 8	Volumetric strain (concrete)	E10.0
11 - 20		Pressure	E10.0
21 - 30		Volumetric strain	E10.0
31 - 40		Pressure	E10.0

Pressure is positive in compression; volumetric strain is given by the natural log of the relative volume, and is negative in compression. The tabulated data are given in order of increasing compression, with no initial zero point.

If the volume compaction curve is omitted, the following scaled curve is automatically used; where P1 is the pressure at uniaxial compressive failure, from $P1 = \sigma_c/3$ and K is the bulk unloading modulus, from $K = E_s/3(1-2\mu)$; and E_s is half the input tangent modulus, μ is Poisson's ratio.

Volumetric strain	Pressure (MPa)
P1/K	1.00xP1
0.002	1.50xP1
0.004	3.00xP1
0.010	4.80xP1
0.020	6.00xP1
0.030	7.50xP1
0.041	9.45xP1
0.051	11.55xP1
0.061	14.25xP1
0.094	25.05xP1

The reinforcement disposition is defined at the end of the LS-DYNA3D input data file. Reinforcement may be defined in specific groups of elements, but it is usually more convenient to define a two-dimensional mat in a specified layer of a specified material. Reinforcement quantity is defined in terms of the cross-sectional area of steel relative to the cross-sectional area of concrete in the layer.

To specify the three reinforcement quantities in groups of elements, input the following data for each group of elements.

COLUMNS	QUANTITY	FORMAT
1 - 10	First element in group	I10
11 - 20	Last element in group	I10
21 - 30	Element increment	I10
31 - 40	X-Reinforcement quantity	E10.0
41 - 50	Y-Reinforcement quantity	E10.0
51 - 60	Z-Reinforcement quantity	E10.0

The immediately preceding group of elements may be repeated using a global increment, if the first two numbers are defined as negative.

To specify two-dimensional layers of reinforcement, input the following data for each layer.

COLUMNS	QUANTITY	FORMAT
1 - 10	Zero	I10
11 - 20	Material number	I10
21 - 30	Axis normal to layer	I10
31 - 40	Coord where plane cuts axis	E10.0
41 - 50	Reinforcement quantity (A)	E10.0
51 - 60	Reinforcement quantity (B)	E10.0

Axis = 1: A and B are in the Y-Z plane
Axis = 2: A and B are in the Z-X plane
Axis = 3: A and B are in the X-Y plane

4. EXECUTION

The Winfrith Concrete Model generates an additional binary output file, containing information on crack locations, directions and widths. In order to invoke the model, and generate this file, the execution line is modifed by adding:

q=crf where crf is the name of a crack file (e.g. q=D3CRCK)

5. LS-TAURUS

The graphical post-processing code LS-TAURUS has been modified to read the crack file, and display the cracks on the deformed mesh plots. The execution line is again modified by adding:

q=crf where crf is the name of the crack file(e.g. q=D3CRCK)

Then, the command:

cracks w

entered after a "time" or "state" command, will cause the crack information to be read at that time, and all subsequent "view" or "draw" commands will cause cracks to be superimposed on the mesh plot.

The parameter "w" causes all cracks greater than width = w to be plotted, thereby permitting selective crack plotting, and estimation of crack sizes. If w = 1 then all cracks are plotted, regardless of size.

6. EXAMPLE

The example is a case of a square reinforced concrete slab built into heavy reinforced concrete side beams; the slab is impacted in the centre by a dropped solid steel cylinder. The finite element mesh for the example case is shown in Figure 6; only a quarter of the geometry is modelled, as it has two-fold symmetry. The top of the long cylinder has been cut off in the figure for clarity.

Figure 7 shows a sketch of the crack pattern from the impact test, and indicates that a through-thickness crack up to 0.5mm wide was formed in the concrete slab.

Figure 8 shows crack patterns predicted by the model; when all cracks are plotted, a broad failure zone is observed, but when cracks greater than 0.5mm wide are plotted, the predicted crack is very similar to the observed crack. Figure 9 shows the transient displacements for selected nodes along a symmetry plane; they indicate the abrupt change of displacement at the boundary of the displaced cone.

7. CONCLUSIONS

The Winfrith Concrete Model is available from AEA Technology, as add-on source routines to be linked with the standard LS-DYNA3D code which can be obtained from LSTC. The post-processing code LS-TAURUS, also available from LSTC, has the crack plotting capability built in.

Data files and results for the example are available for verifying the new users' implementation of the concrete model.

8. REFERENCES

[1] Hallquist J.O. LS-DYNA3D Theoretical Manual. LSTC Report 1018. June 1991.

[2] Green S.J., Swanson S.R. Static Constitutive Relations for Concrete. AFWL-TR-72-2, Kirtland Airforce Base. 1973.

[3] Ottosen N.S. Failure and Elasticity of Concrete. RISO-M1801. July 1975.

[4] CEB Information Bulletin No.187. Concrete Structures under Impact and Impulsive Loading. 1988.

[5] John R. Shah S.P. Constitutive Modelling of Concrete under Impact Loading: Effects of Fast Transient Loadings; Ed W.J.Ammann, Pub A.A.Balkema. 1988.

[6] Wittmann F.H et al. Fracture Energy and Strain Softening of Concrete as Determined by means of Compact Tension Specimens. Materials and Structures Vol 21, pp21-32. 1988.

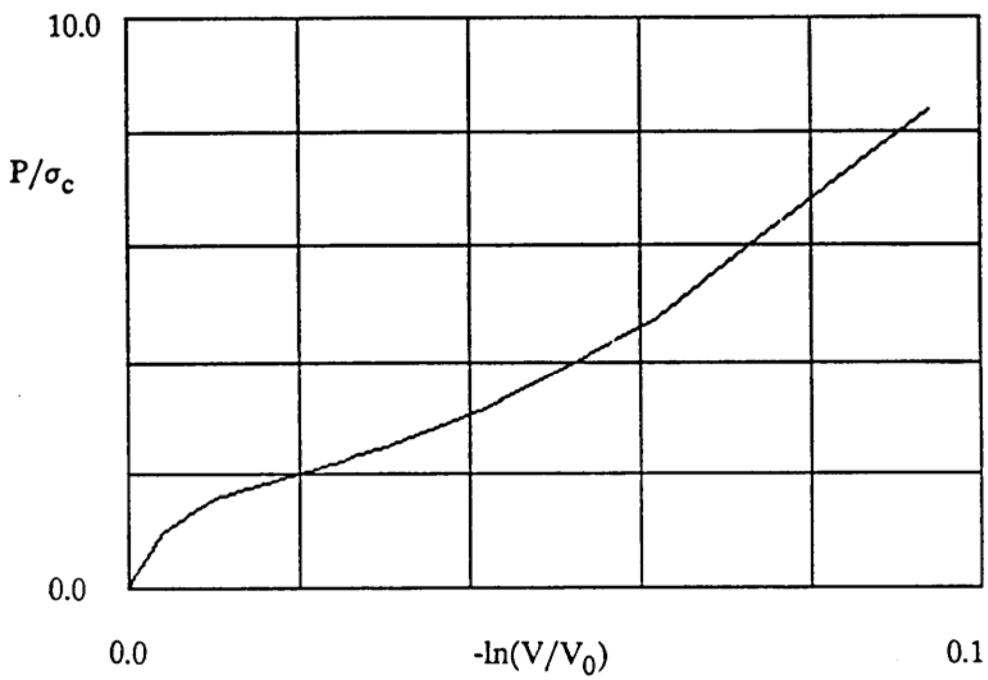
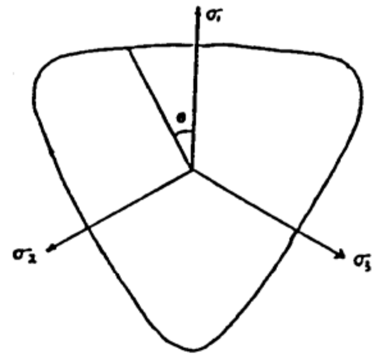


FIGURE 1. VOLUME COMPACTION CURVE FOR CONCRETE
(Green & Swanson, 1973)



DEVIATORIC SECTION

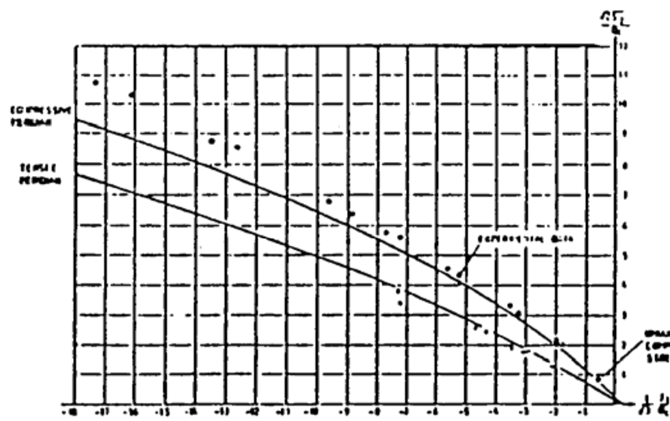
$$A\frac{S_2}{\sigma_c^2} + \lambda\frac{\sqrt{S_2}}{\sigma_c} + B\frac{J_1}{\sigma_c} - 1 = 0$$

where $\lambda = K_1 \cos\left[\frac{1}{3}\cos^{-1}(K_2 \cos 3\theta)\right]$ for $\cos 3\theta \geq 0$

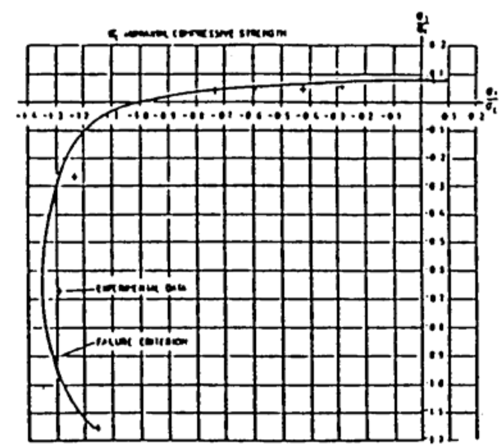
$\lambda = K_1 \cos\left[\frac{\pi}{3} - \frac{1}{3}\cos^{-1}(-K_2 \cos 3\theta)\right]$ for $\cos 3\theta \leq 0$

$\cos 3\theta = \frac{3\sqrt{3}}{2}\frac{S_3}{S_2^{1.5}}$

and A, B, K_1, K_2 are functions of $\frac{\sigma_t}{\sigma_c}$



RENDULIC SECTION



BI-AXIAL SECTION

FIGURE 2. OTTOSEN YIELD SURFACE FOR CONCRETE

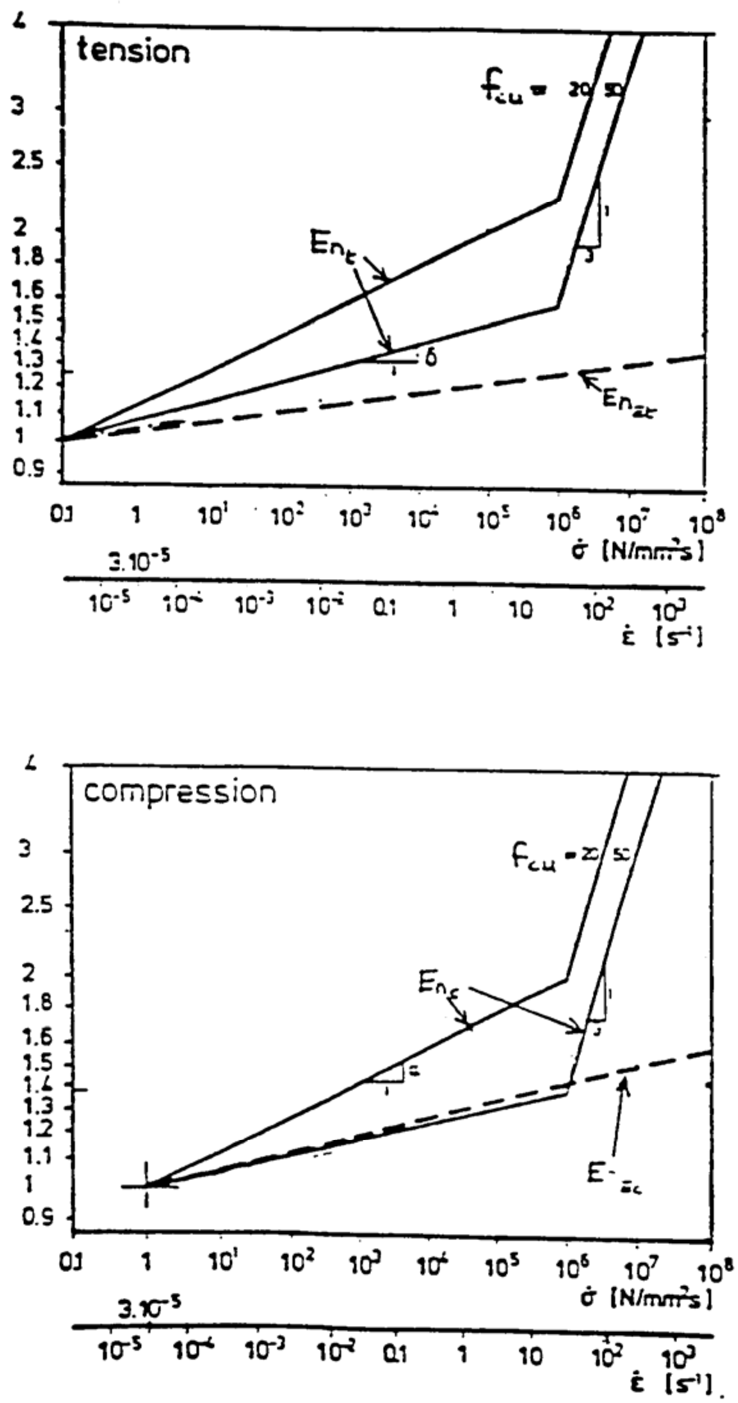


FIGURE 3. STRAIN RATE ENHANCEMENT FACTORS
(CEB Information Bulletin No.187, 1988)

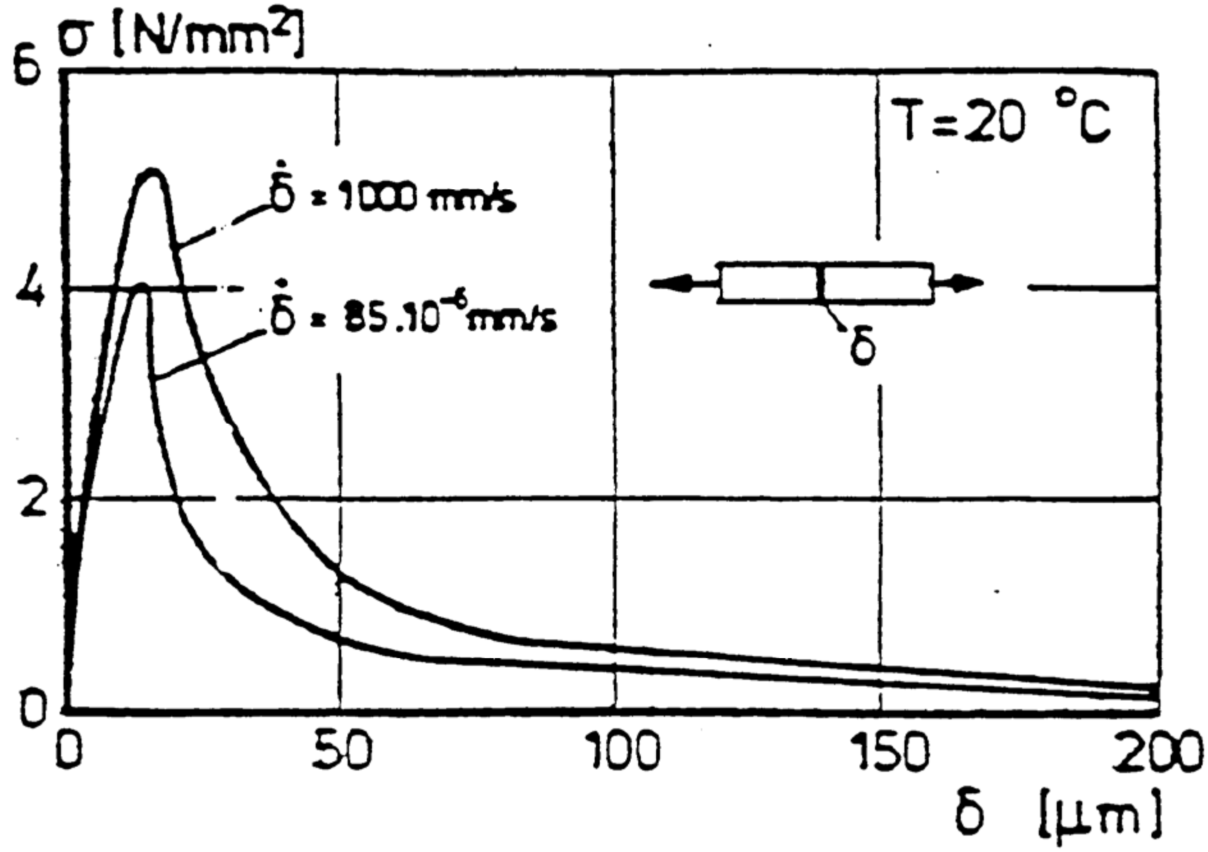


FIGURE 4. TYPICAL STRESS-DEFORMATION CURVES IN TENSION
(John & Shah, 1988)

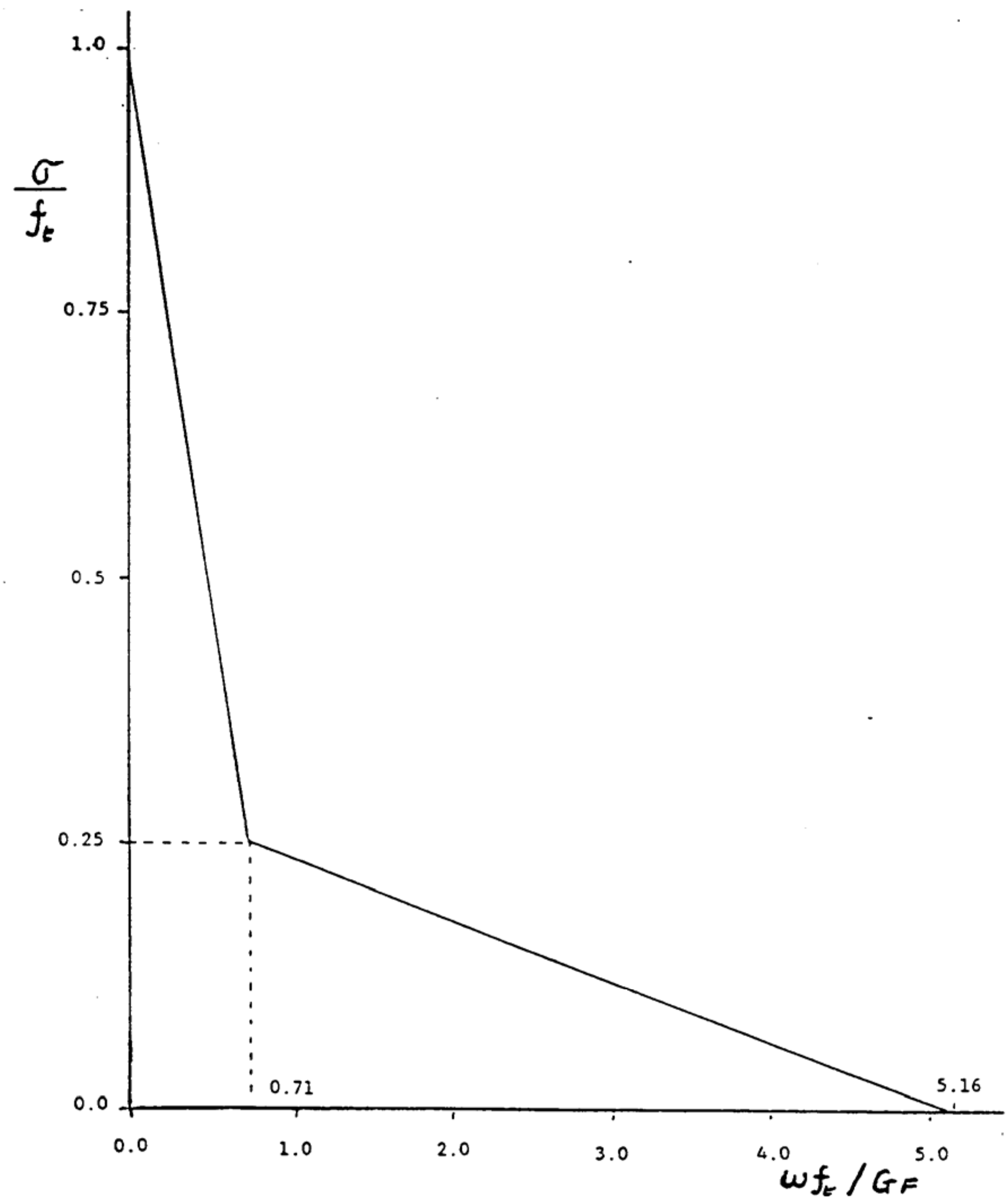


FIGURE 5. NON-DIMENSIONALISED CRACK STRESS DECAY FUNCTION
(Average results from Wittmann, 1988)

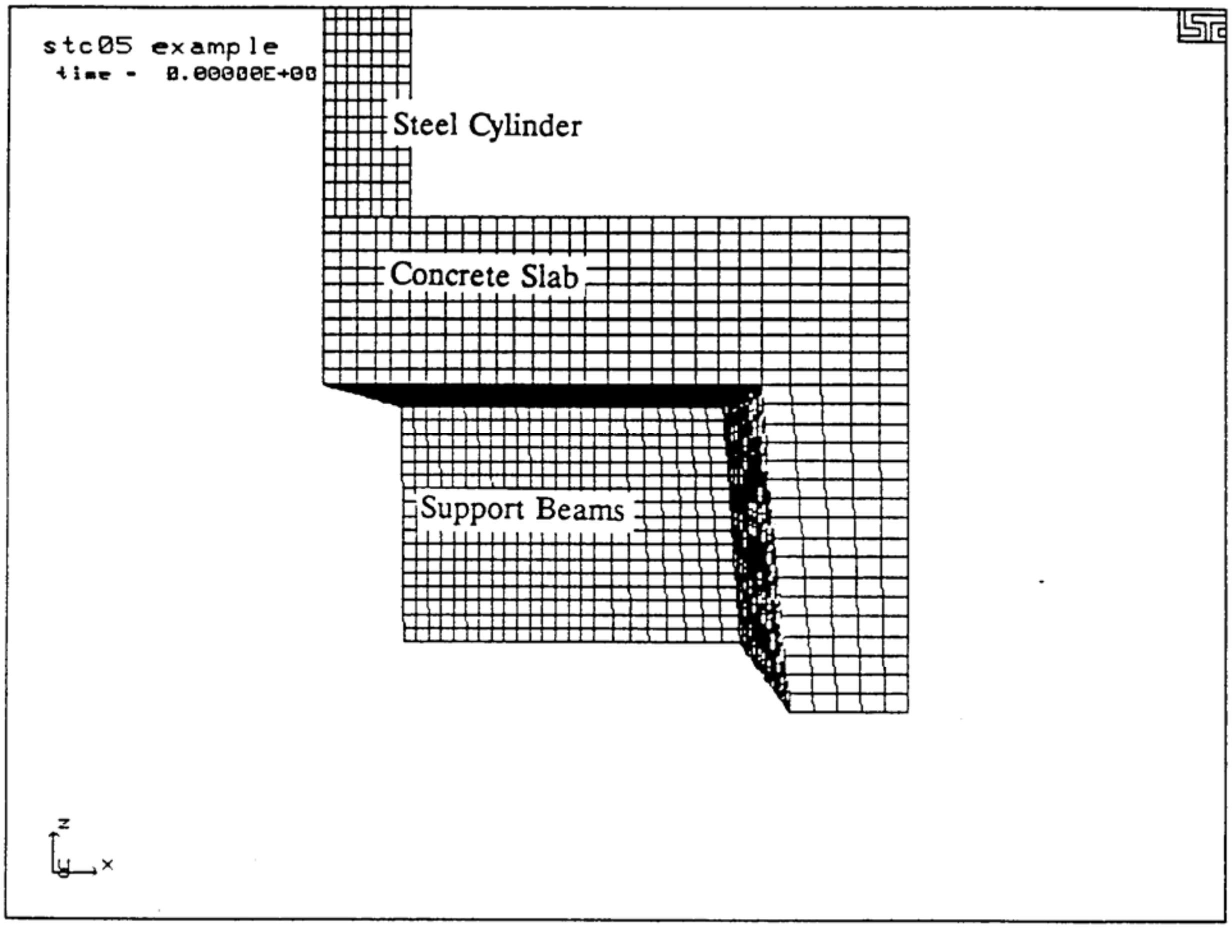


FIGURE 6. FINITE ELEMENT MESH FOR EXAMPLE CASE

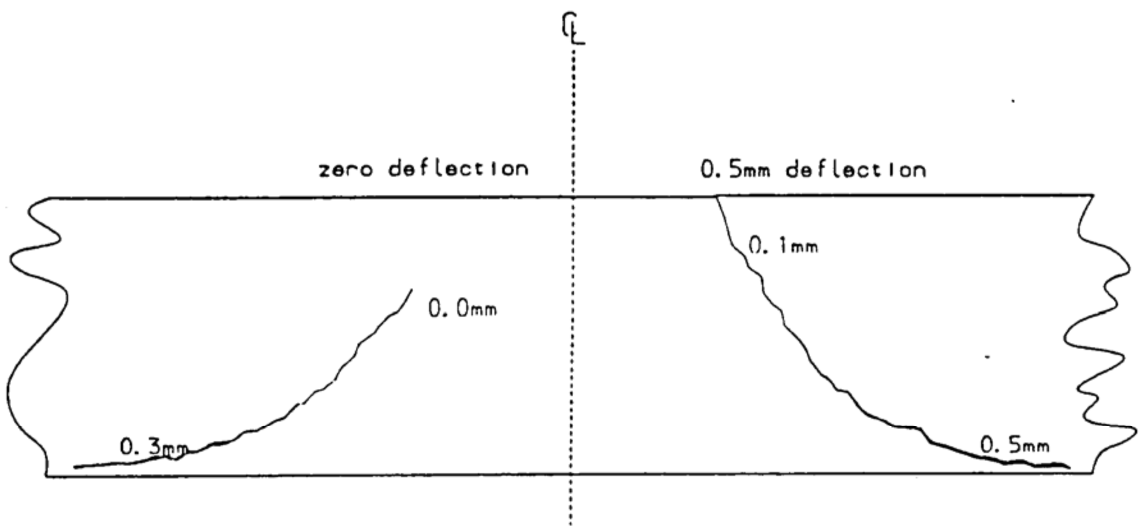
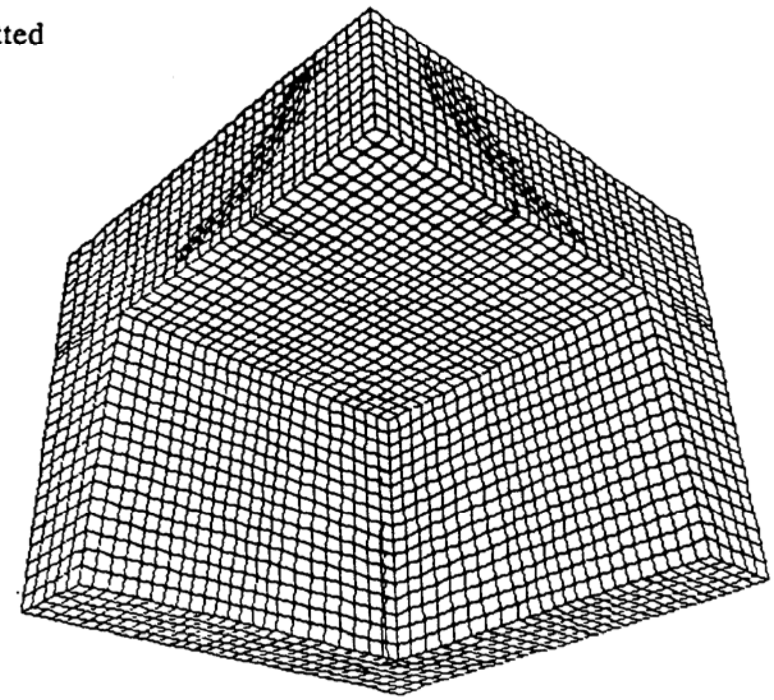


FIGURE 7. SKETCH OF CRACK PATTERN ON SECTIONED SLAB

All Cracks Plotted



Cracks > 0.5mm Plotted

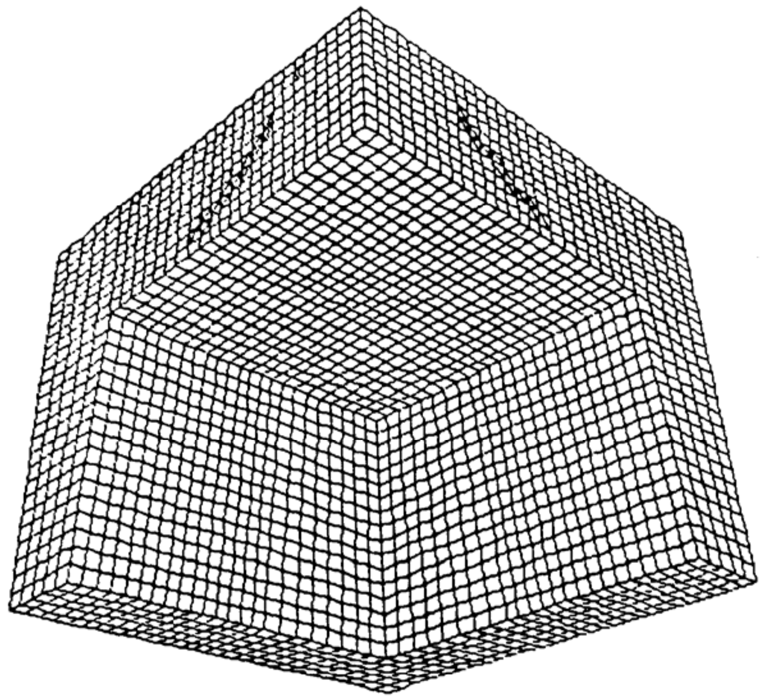


FIGURE 8. CRACK PATTERNS PREDICTED BY LS-DYNA3D

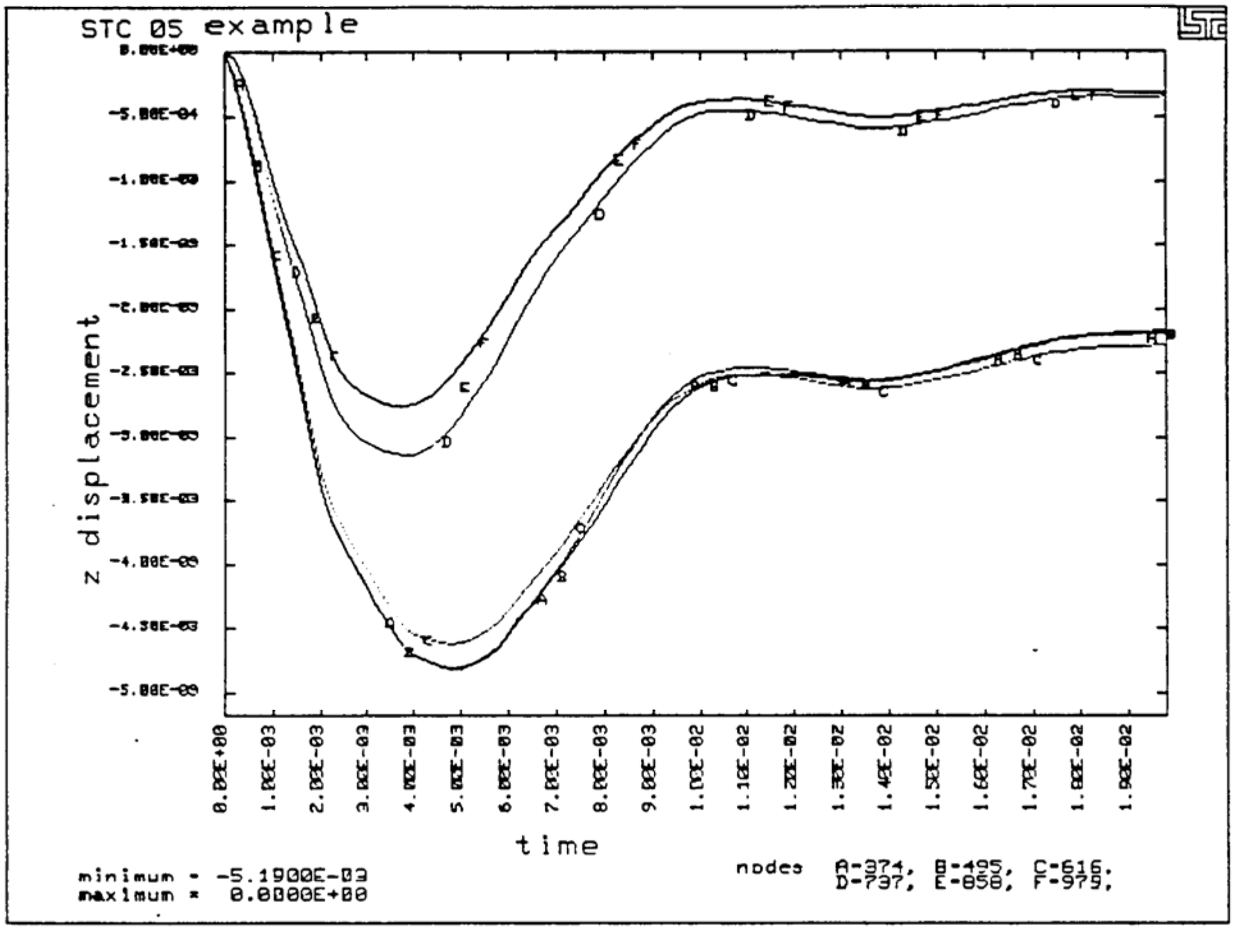


FIGURE 9. TRANSIENT DISPLACEMENTS FROM LS-DYNA3D