THE AUTOMATED THREE-DIMENSIONAL ANALYSIS OF STEEL PLATE TO SHOT PEENING MECHANICS

Y. F. AL-OBAID
Faculty of Technological Studies, PAAET
P.O. Box 42325, 70654, Shuwaikh, Kuwait

ABSTRACT

An automated dynamic finite element analysis is presented in which provision is made for three-dimensional isoparametric element existing in the target metal plate. A steel plate with nine layers is chosen. The plate is idealised using 20 noded isoparametric elements and is subjected to steel shots with varying velocities. On the basis of this analysis, the computer program has been developed to dynamic loading due to impinging shot. The analysis presented herein includes facilities for loading and unloading phenomena and automatic production of residual stresses. The residual stresses from the analysis are in a good agreement with those obtained from others.

KEYWORDS

Shot-peening, Residual stresses, mesh generation, Three-dimensional Dynamic Finite Element, Isoparametric Element.

INTRODUCTION

In general the process of shot-peening by throwing many small hard balls at metal parts, is tend to establish many dents on the target plate.

The indentation at each point of impact on the target is the result of local plastic deformation. As the deformed regions tend to expand, they are restrained by adjacent, deeper metal that was not plastically deformed by the shot impact. Since the plastically deformed surface layer seeks to occupy more space it is compressively strained, i.e. it is residually stressed in compression. This compressively stressed layer is extremely effective in preventing premature failure under conditions of cycling loading since the fatigue failure generally propagates from the free surface of a target and starts in a zone that is subjected to tensile stresses. This phenomenon is fully explained by several researches.

In principle when on rebound of the shot, the balanced system of residual stresses are trapped in the target, the plastically deformed zone recovers only some part of the elastic portion of its total strain. The resulting trapped compressive stresses assume their positions in a thin sub-surface layer with tensile residual stresses distributed throughout the lower region as shown in Figure 1.

A hugh literature is available for this paper. References exist [5,6] which describe a simplified approach to the process. The finite element analysis has been carried out by the author [1-4] which is concerned with development of a 3-D finite element analysis which cope with complex target geometry and allows for dynamic loading due to an impinging shot. Here only brief details of the 3-D finite element analysis ispresented For more details concerning this paper, the reader is advised to consult [1-10]

FINITE ELEMENT FORMULATION

An attempt is to employ three dimensional finite element analysis to the process; which cope with steel target geometry and allows for dynamic loading due to an impinging shot. The steel target plate is considered to be elastoplastic and the analysis allows for strain and work hardening.

The three-dimensional elements which have been used in this analysis are 20 noded isoparametric elements (Fig 2). by using strain-displacement relations and particular constitutive laws, the stresses and strains are evaluated in terms of nodal displacements. The strain energy of the entire target already descritized is then obtained by adding the contribution to all its elements using the principle of minimum potential energy, linear equations are initially produced relating the generalised nodal displacements and generalised externally applied loads in the form given by

$$[K]\,(U) = (P) \tag{1}$$

where [K] is the overall stiffness matrix, (U) are generalised displacements and (P) are the nodal loads caused by internal and external loads on a target. The paper then proceeds to establish a criterion for a three-dimensional analysis of the target. It is followed by a step-by-step analysis for computing incremental stresses, total stresses and strains using a standard transformation. Stresses are converted into nodal loads and the residual forces are examined and checked at the end of each iteration and finally the iteration terminates.

The computer program [9] has the options for the solution of equations using Blocking Technique and DIRECT ELIMINATION. The convergence of the iterative solution is closely related to a uniform acceleration [8, 10]. The target elements are simultaneously examined for shot peening. The analytical results for residual stresses are plotted in three dimensions. These results are in a good agreement with others [5,6].

STEEL PLATE FINITE ELEMENT MESH GENERATION

The finite element mesh scheme for the given target plate of the size shown in Fig 3 and Fig 4. In order to produce accurate residual stresses, it has been decided to divide the thickness of the target steel plate into nine layers (in Y-direction). The plate thickness below the neutral axis is divided into two equal layers each has 0.0079m. Immediately above the neutral axis, the thickness of the first layer is 0.00397m. Above this layer there are six equal layers each of 0.00198m thickness. A flexibility exists for various plane meshes of variable dimensions. A one-quarter of the actual size of the target plate is chosen for the shot peening analysis based on the finite element technique. A mesh, hence, contains 81 elements of 20 noded isoparametric shapes as shown in Fig 5.

The finite element mesh generation FEM GEN version 7 [11] has been adopted for this paper. The steel target plate is meshed with a sequence of commands which can be either typed directly into the prgram or read from a file. FEMGEN will automatically link up the subregions to give continuity of node and element numbering. A typical steel target plate mesh is shown in Figures 6 and 7.

DYANAMIC FINITE ELEMENT ANALYSIS

The dynamic equilibrium at the nodes of a system of structural elements is formulated at a given time t as

$$[M](\ddot{\delta}_t)+[C_t](\dot{\delta}_t)+[K_t](\delta_t)=(R_t) \quad (2)$$

where (δ) and (R) are the vectors of displacement and specified load, respectively, $[M]$ represents the mass matrix which is regarded as constant; $[C]$ and $[K]$ are the damping and stiffness matrices, respectively, which, inasmuch as material non-linearities are taken into consideration, depend on the state of strain and stress reached and thus vary with time. The subscript t is used for quantities at time t; a dot denotes a derivative with respect to time.

To formulate equation 2 a discretisation with respect to space, using isoparametric finite elements, is performed. As far as the time domain is concerned, the only applicable method is the numerical step-by-step integration of the coupled equations of motion, equation 2. The response history is divided into time increments Δt which are of equal length. The system is calculated for each Δt for a linear system with properties determined at the beginning of the interval. Only one matrix based on [M], [K] and [C] at time t = 0 has to be partially inverted. The change of the initial load in each time step representing the non-linearities occurring during a specific time step depends on the state at the end of the time interval and is determined iteratively. It is then added to the initial load present at the beginning of the specific time step, thus forming the initial load for the next time step. In addition, the direct-integration procedure allows a general damping matrix [C], which has to be specified explicitly, to be used without resorting to complex eigenvalues. Non-proportional damping arises in many dynamic problems such as plates and beams under vibration and machine components.

For shot peening, the influence of the damping matrix [C] on maximum response is small, and therefore [C] is neglected.

The general steps of flow calculations are:

1. Apply a load increment, (ΔP_n),

where n is the load increment.

2. Accumulate total load $(P_n)=(P_{n-1})+(\Delta P_n)$ and $(R)=(\Delta P_n)$ where (R) is the residual load vector.
3. Solve $(\Delta U_i)=[K]^{-1}(R)$, where i is the iteration.
4. Accumulate total displacements $(U_i)=(U_{i-1})+(\Delta U_i)$
5. Calculate strain increments as $(\Delta \varepsilon_i)=[B](\Delta U_i)$ and strains $(\varepsilon_i)=(\varepsilon_{i-1})+(\Delta \varepsilon_i)$
6. The stress increments are calculated using the current non-linear constitutive matrices. For steel target plate elasto-plastic relations are considered. They are expressed in the general form:

$$(\Delta \sigma_i) = (f(\sigma)) \quad (\Delta \varepsilon)$$

Accumulate stresses as

$$(\sigma_i) = (\sigma_{i-1}) + (\Delta \sigma_i)$$

7. All calculations for stresses and strains performed at the Gauss points of all elements. The initial stress vector is

$$(\sigma_o(t+\Delta t))_i = f(\varepsilon(t+\Delta t))_i - [D_T](\varepsilon(t+\Delta t))_i$$

8. Using the principle of virtual work, the change of equilibrium and nodal loads $(\Delta P(t+\Delta t))_i$ is calculated as

$$(\Delta P(t+\Delta t))_{iTOT} = \int_{-1}^{+1}\int_{-1}^{+1}\int_{-1}^{+1}[B]^{T''}(\Delta \rho_o(t+\Delta t))_i \, d\xi d\eta d\zeta$$

$$\sigma_o(t) - (\sigma_o(t+\Delta t))_i = 0$$

$d\xi$, $d\eta$, $d\zeta$ are the local co-ordinates.
The integration is performed numerically at the Gauss points

9. Effective load vector P(t) is given by

$$(\Delta P(t+\Delta t))_{iTOT} = -[\Delta C(t)_{in}]((U(t+\Delta t))_i - (U(t)))$$
$$-[\Delta C(t+\Delta t)]_i (U(t+\Delta t))_i - [\Delta K(t)_{in}]((U(t+\Delta t))_i - (U(t))_i)$$
$$-[\Delta K(t+\Delta t)]_i (U(t+\Delta t))_i$$

10. Von Mises criteria is used together with transitional factor f^*_{TR} form the basis of the plastic state, see Fig 8
11. The elasto-plastic stress increment will be $(\Delta \sigma_i)=[D]_{ep}(\sigma(t+\Delta t)_{i-1}(1-f^*_{TR})(\Delta \varepsilon)$
If $\sigma(t+\Delta t)_i < \sigma_y(t)$, it is an elastic limit and the process is repeated. The equivalent stress is calculated from the current stress state where stresses are drifted they are corrected from the equivalent stress-strain curve.

12. The residual load vector is calculated as
$(R)=(P_n) - \int [B]^T \sigma(t+\Delta t)_i d\,\mathrm{vol}$

The convergence of the iterative scheme is reflected in the above diminishing residual force vector (R). A new scheme based on accelerating the displacements through out the domain by the same factor is fully explained in [4].

RESULTS

All points have been plotted in three dimensions, and graphs have been produced for the X-Y, X-Z and Y-Z planes The mesh containing 81 elements and 544 node points has a grid lettering as shown in Fig 9. All elements have been numbered with element numbers at their centres on faces F_1 to F_3 and node points at their edges. Graphs have been drawn only on those faces shown in Fig 9, i.e. faces F_1 to F_4 and centres C_1 to C_3. Horizontal and vertical readings have been plotted on these faces looking in the X-Y plane only.

Due to space limitation, only one increment (increment No 2) has been plotted. One can see mesh grading system under Increment 2 both static and dynamic residual stresses looking at X-Y plane portions DEF (Fig 10), portion DFG (Fig 11) and portion DGH (Fig 12) have been plotted. The magnitudes and positions of such stresses vary in both cases. Similarly under Increment 3.

Such information is better visualized in the form of a distribution at the central plane through the thickness as shown in Figure 13. For comparison, the distribution is shown as predicted from other models [5,6]

It is concluded that the real plot of three-dimensional residual stresses can be plotted on the three-dimensional mesh as and when viewed in specific planes they would, in general, form a distribution curve of a cosine function.

CONCLUSION

An automated three-dimensional analysis of steel plate to shot-peening mechanics has been carried out. The steel target plate is considered to be elasto-plastic and the analysis allows for strain and work hardening. Descritization process is implemented in which a provision is made to descritized the plate into a series of solid isoparametric elements having nine layers within the plate thickness. An automatic production three dimensional forms of displacements velocities, accelerations, plasticities and residual stresses have been obtained.

Only residual stresses are reported.

ACKNOWLEDGEMENTS

The author is indebted to Dr Y. Bangash and Dr S. T. S. Al-Hassani for their valuable comments and suggestions. This work acknowledges Mrs Anne Smith for typing this manuscript.

REFERENCES

[1] Al-Obaid, Y.F., "Finite Element Approach to Shot-Peening Mechanics" International Conference on Steel Structure, Yugoslavia. November 1986

[2] Al-Obaid, Y.F., "A Three-Dimensional Dynamic Finite Element Technique for Indentation Problems as Applied to Shot-Peening Mechanics", 2nd International Conference on Shot-Peening, Chicago U.S.A. 1984.

[3] Al-Obaid, Y.F., "A Three-dimensional Dynamic Finite Element Analysis for Improving Fatique Life of Metal by Shot-Peening", Fourth International Conference on mechanical production and design, Dec 27-29 1988 Cairo Eygpt.

[4] Al-Obaid, Y.F., "Three-dimensional Residual Stresses of Target Metal to Shot-Peening Mechanics" CSME Mechanical Engineering Forum 1990, June 3-9, Toronto, Canada

[5] Al-Hassani, S.T.S., "Mechanical Aspects of Residual Stress Development in Shot-Peening". First International Conference on Shot-Peening, Paris, 14-17 September 1981. Pergamon Press

[6] Flavenot, J.F. and Nikulari, A., "La Measure des contraintes Residuelles: Methode de la (Fleche) Methode de la (Sourse de Contraintes)". Les Memories Technique due CETIM (31), 1977

[7] Branes, K. H., "Current use of Shot-Peening", Aero Digest, Vol 50, 1945

[8] Horwath, J.A., "Effect of Shot-Peening Variables on bending fatigue". First International Conference on Shot-Peening, Paris 14-17 September 1981. Pergamon Press.

[9] Al-Obaid, Y.F., "Numerical Analysis of the Laterally Loaded Piles in the Kuwait Off-shore Environment" International Journal of Ocean Engineering 13 (1), 85-92, 1986.

[10] Bathe, K.J., Wilson, E.L. "Stability and Accuracy Analysis of Direct Integration Method". Int J. of Earthquake Engineering and Structural Dynamics, 1, 283-291, 1977.

[11] FEMGEN, Version 7, SERC Package,
Rutherford Lab, 1981

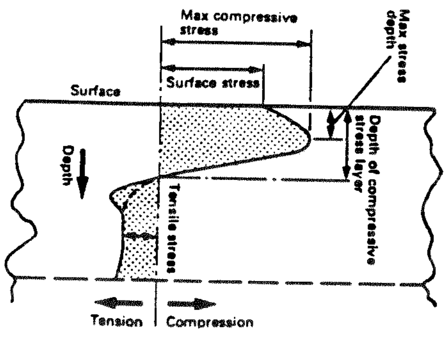


Fig. 1 Typical residual stresses distribution

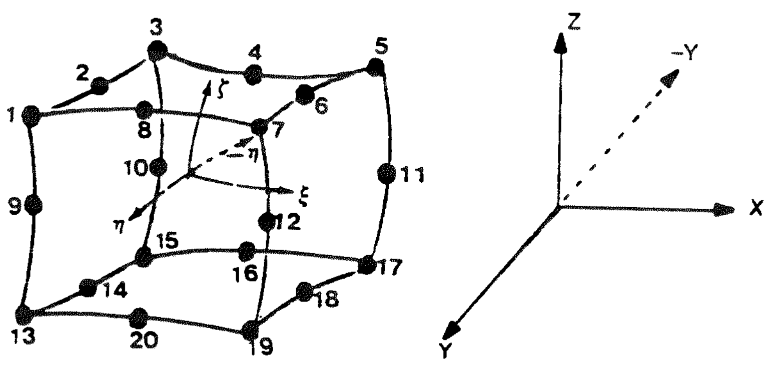
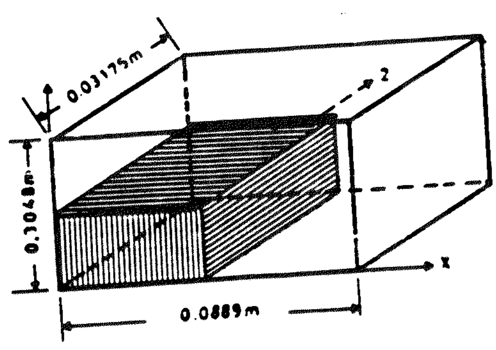


Fig. 2 Three-dimensional isoparametric element



Shaded Area (i.e. $\frac{1}{4}$ of plate size) Containing 81 elements

Fig. 3 Actual Plate Size

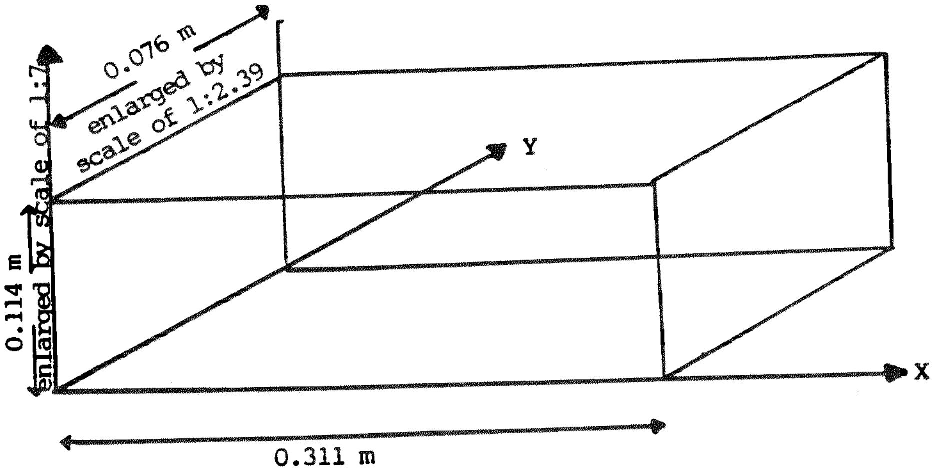
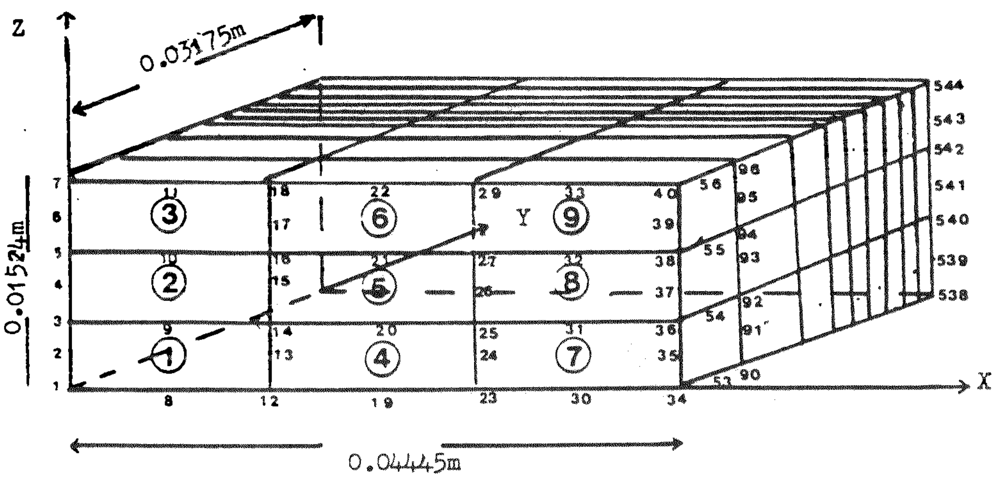


Fig. 4 enlarged by scale of 1:7



Note: True Dimensions of mesh containing 81 elements
Elements are numbered as shown.

Fig. 5 Basic Layout

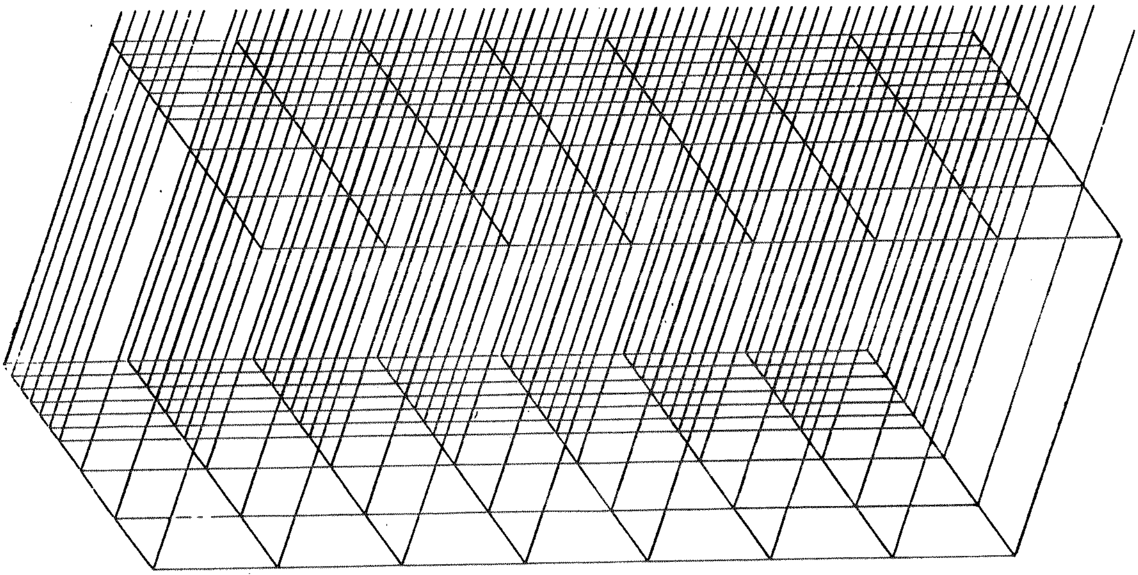


Fig. 6 Three-dimensional target plate

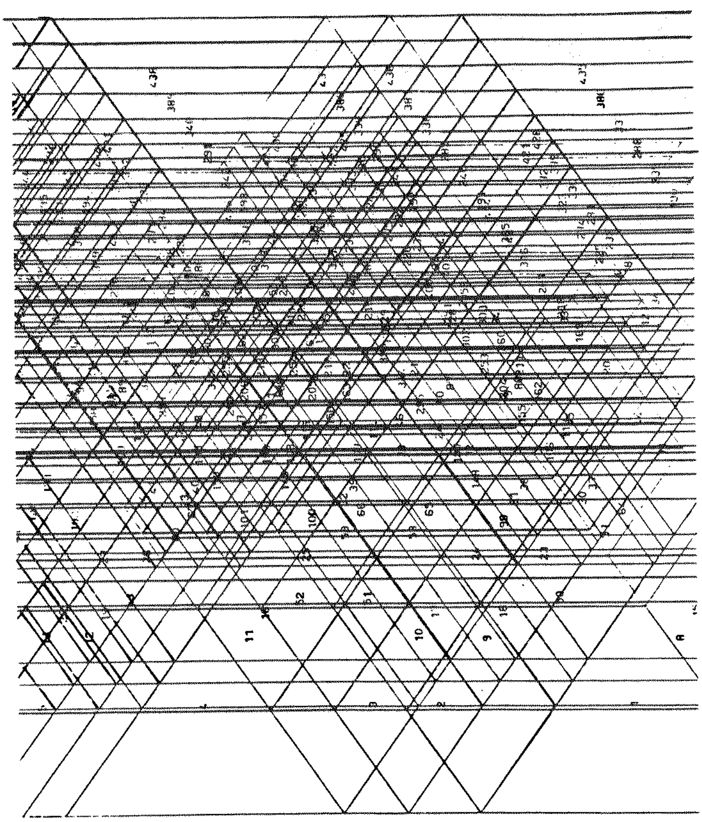
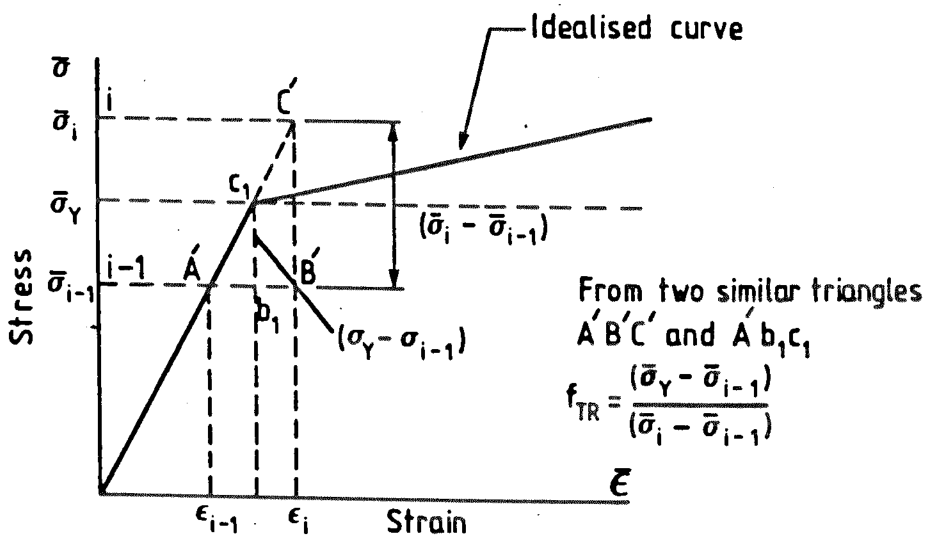
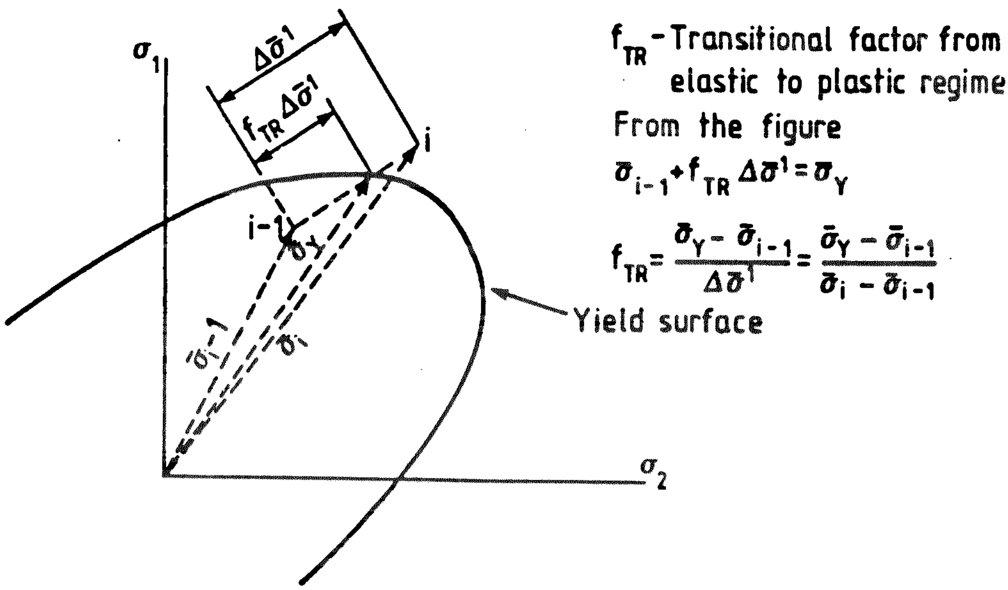


Fig. 7 Three-dimensional target plate



(a) Equivalent stress-strain curve for steel



(b) Yield surface in the principal stress axes

Fig. 8

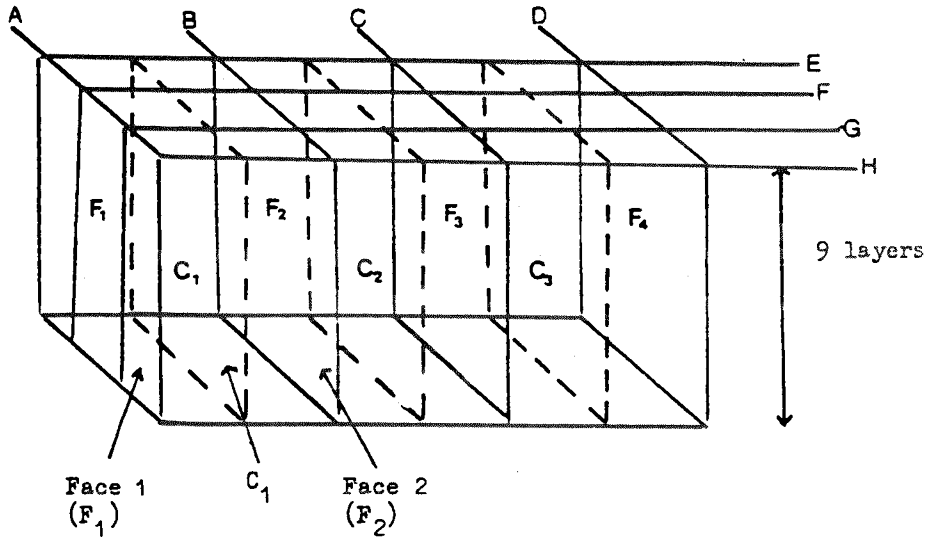


Fig. 9 Grid Lettering

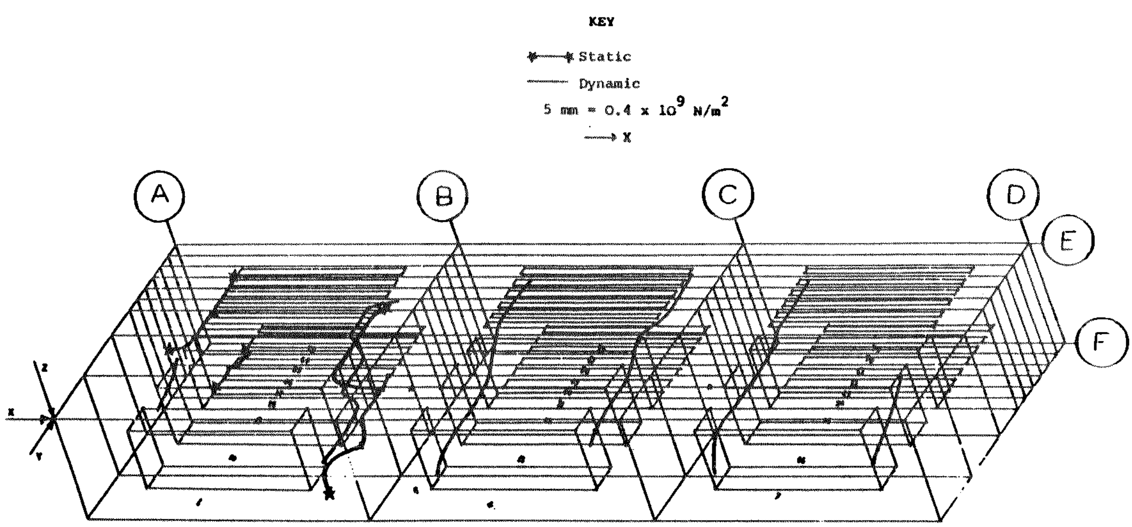


Fig. 10 Increment 2. Normal residual stresses at G-points X-Y plane. Portion EF.

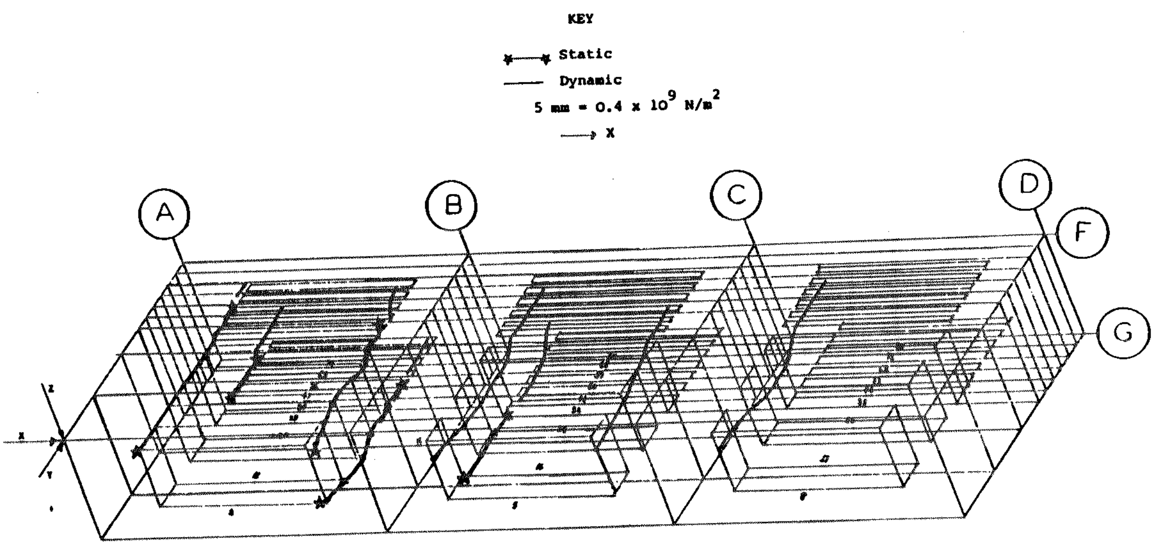


Fig. 11 Increment 2. Normal residual stresses at G-points in the X-Y plane. Portion FG.

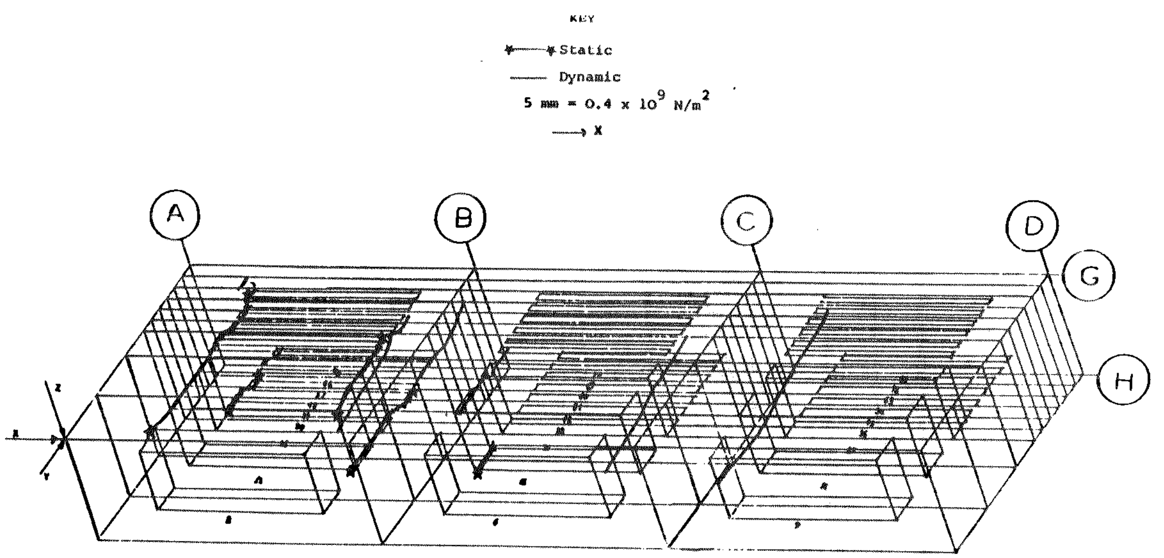


Fig. 12 Increment 2. Normal residual stresses at G-points in the X-Y plane. Portion GH.

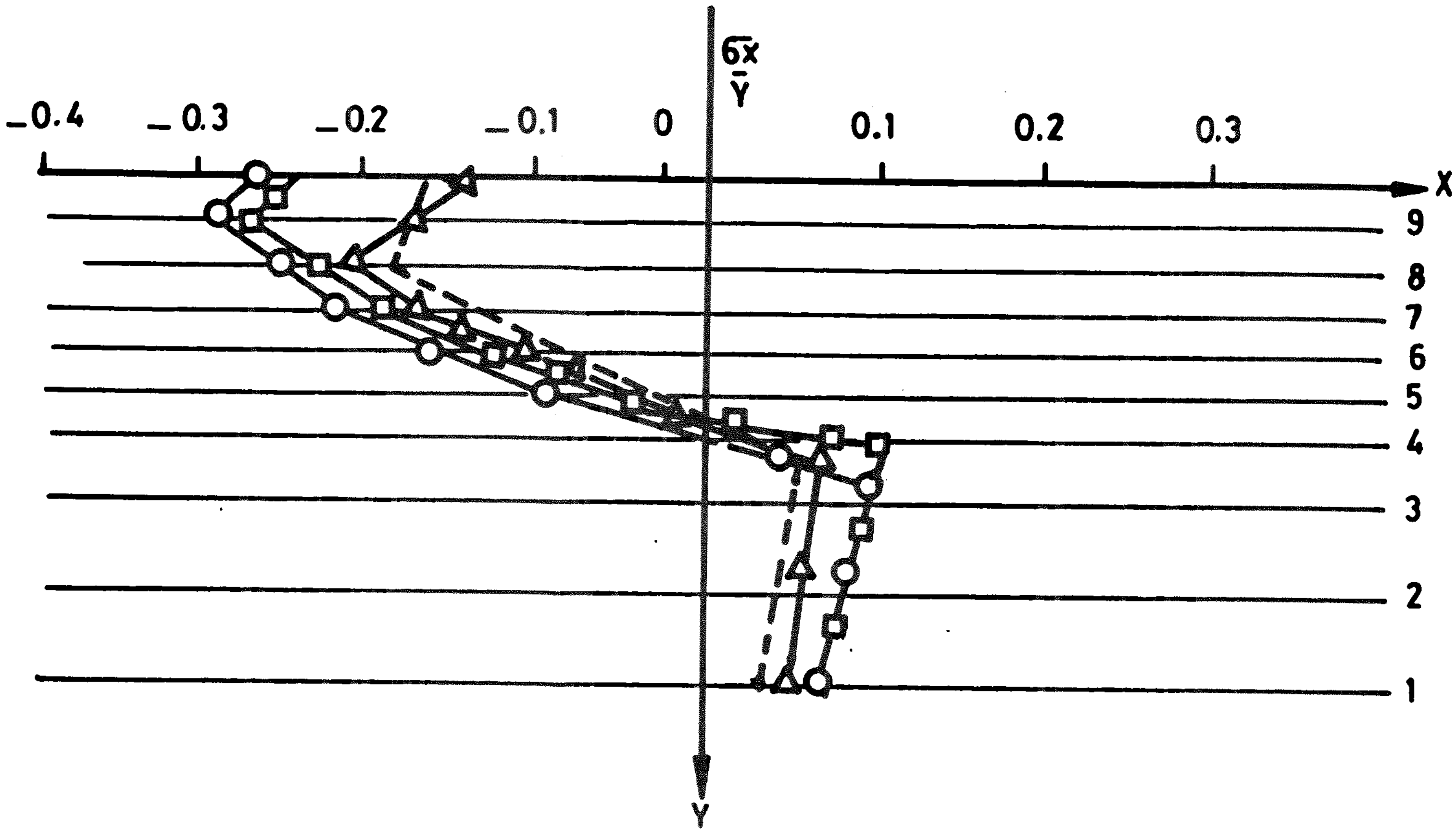


Fig. 13 Residual stress distribution in x-y central plane through the thickness. Finite element with O-V = 100 m/sec. □-v = 70 m/sec and △-V = 60 m/sec. The dotted line is from others [5, 6], shot size 0.7 mm dia.