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AIRCRAFT CRASH UPON A CONTAINMENT STRUCTURE OF A NUCLEAR POWER PLANT

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1. INTRODUCTION

The reinforced concrete outer containment of a Nuclear Power Plant (NPP) is required to be designed to withstand the impact of aircraft and aircrash debris etc. The problem is of strategic significance because the damage caused to the structure by these missiles may lead to the leakage of nuclear radiations. The safety design of NPP against aircraft crash requires the evaluation of crash probability. If the probability is smaller than the allowable value then the aircraft crash is neglected as design basis item. Otherwise adequate measures are taken to bring the released radioactive material within the permissible limit. The aircrafts and their striking velocity to be considered in the design of a structure are decided by the accident analysis. The probabilistic aspect of the problem has not been covered in the present work.

The non-affordability of coupled analysis of large problems like aircraft crash on NPP, automobile impact on a structure etc. due to the requirement of excessive amount of manual as well as computer time and storage compels us to switch over to the uncoupled analysis. Moreover, the results of coupled analysis are heavily influenced by the analyst's modelling technique and choice of increment size. It is uncoupling of the missile and the target which converts the impact load to the impulse load. This impulse can be found by taking into consideration only the inertial and stiffness properties of missile and considering the target to be rigid. Though the impulse load so obtained disregards the inertial and stiffness characteristics of the target but its effect can be incorporated by modifying it for the inertial and stiffness properties of target at different time steps as we march in time domain during the analysis of the target.

2. FORCING FUNCTION

As a projectile strikes a target, a part of it close to the target gets crushed and the remaining portion of projectile undergoes elastic deformation, which, from the point of view of deformation, may be regarded as rigid with not much error [Riera(1980)]. So, considering a soft missile to consist of a thin deformation zone and a rigid zone within control volume S as shown in Fig. 1. The aircraft is assumed as a one dimensional model. Therefore this model can yield only total force, it will not give variation of force on the contact area. It is assumed that the projectile axis and its flight trajectory coincide and the impact is normal.

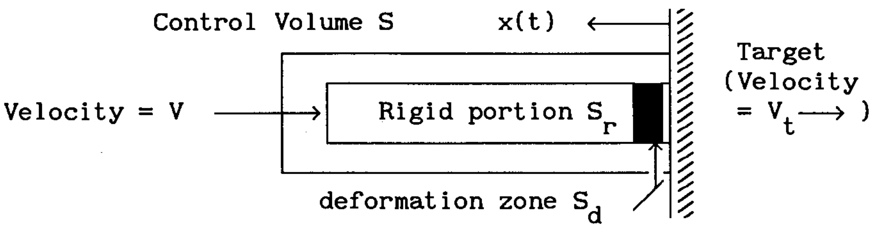


Fig. 1 Missile Striking a Target

Assuming no torn-off wreckage pieces, no momentum crosses the boundary of control volume. Therefore particle mechanics approach can be applied to it. Application of momentum equation to the projectile yields

$$F[x(t)] = \frac{d}{dt}(m V - m_c V_t) \qquad .....(1)$$

where, F[x(t)] = reaction from the target. If, the mass entering the deformation zone remains confined without any further change, we can write

$$F[x(t)] = V \frac{dm}{dt} + m \frac{dV}{dt} - m_c \frac{dV_t}{dt} \qquad .....(2)$$

where, V = velocity of the rigid portion of the missile at time t; V_t= velocity of the target at time t; m = mass of the rigid portion of the missile; m_c= crushed mass of the missile; (dm/dt) = rate at which mass enters the deformation zone = $-\mu[x(t)]$ V; $\mu[x(t)]$ = mass per unit length of the missile at a distance x(t) from the nose of the missile. Therefore,

$$F[x(t)] = P_c[x(t)] - \mu[x(t)] V^2 - m_c \frac{dV_t}{dt} \qquad .....(3)$$

where, $P_c[x(t)]$ is the load necessary to crush or buckle the projectile. The Eqn. (3) has been employed for evaluating the reaction from the target at different time steps.

3. MATERIAL MODEL FOR REINFORCED CONCRETE

The material model employed in the study is a strain rate sensitive elasto visco-plastic model. It is a two surface model in which the failure and yield surfaces are represented by a five parameter model which is non circular as well as non-affine on deviatoric plane. The curve meridians of the model are described by cubic and the non circular trace on the deviatoric plane is represented by an ellipse.

Smeared crack approach with fixed crack angle is adopted for tensile cracking. Initiation of cracks depends upon maximum principal strain. Closing and reopening of cracks is allowed following the secant path. The shear transfer across crack due to aggregate interlock and dowel action is also considered by taking a reduced value of the shear modulus. Degradation in the material strength due to accumulated damage is also considered.

4. DYNAMIC EQUILIBRIUM EQUATIONS AND SOLUTION STRATEGIES

The non linear equilibrium equations can be written as

$$\underline{M}\,\ddot{\underline{d}} \pm \underline{C}\,\dot{\underline{d}} \pm \underline{p}(\underline{d}) = \underline{f} \qquad .....(4)$$

where, $\underline{d}$, $\dot{\underline{d}}$, $\ddot{\underline{d}}$ are the vectors of nodal displacements, velocities and accelerations respectively. $\underline{M}$ and $\underline{C}$ are the mass and damping matrices, $\underline{p}(\underline{d})$ is the vector of internal resisting forces and $\underline{f}$ is the vector of external applied force.

Using the finite element procedure, the discrete equations governing the nonlinear behaviour of a structure can be derived from the principle of virtual work. The resulting nonlinear equations of equilibrium at an instant of time t can be written as

$$\psi(\underline{d}) = \underline{f} - \underline{p}(\underline{d}) = 0 \qquad .....(5)$$

where, $\psi(\underline{d})$ is the residual force vector. Due to nonlinear nature of Eqn. (8), an incremental solution procedure is usually adopted in order to trace the response of the structure. But pure incremental method is very much unreliable because no check is performed on the global equilibrium, and the method can lead to a progressive drift off from the true equilibrium path. Its performance gets improved when iteration is performed at the end of increment for balancing the residual forces. During the typical load increment, the linearised equations to be solved for each iteration (say i), have the form

$$\underline{K}_i\ \delta\underline{d}_i = \underline{\psi}_i \qquad .....(6)$$

where, $\delta\underline{d}_i$ is the incremental nodal displacement during the ith iteration and $\underline{K}_i$ is the tangential stiffness matrix in ith iteration.

Table 1 Material Properties for Reinforced Concrete

S.no.	Properties	
1.	Young's modulus of concrete (MPa)	30000
2.	Young's modulus of steel (MPa)	200000
3.	Poisson's ratio of concrete	0.20
4.	Yield stress of steel (MPa)	460
5.	Crushing strength (MPa)	35
6.	Crushing strain	0.0035
7.	Mass density (Kg/m^3)	2400
8.	Fracture Energy (Kg/cm)	0.1
9.	Fluidity parameters for concrete	0.30 5, 0.76
10.	Fludity parameters for steel	1.53 0, 0.97
11.	Factor for end of elasticity	0.4
12.	Biaxial strength (MPa)	40.6
13.	Ultimate tensile strain x10^{-6}	180
14.	High Compression along $\theta = 0^\circ$ (σ_{m1} MPa)	128
	(τ_{m1} MPa)	20.6
15.	High Compression along $\theta = 60^\circ$ (σ_{m2} MPa)	128
	(τ_{m2} MPa)	26.6
16.	Strain softening parameter	10
17.	Failure surface functions β_o, β_1	1.84, 1.09

5. AIRCRAFT CRASH PROBLEM

A containment of Nuclear Power Plant (NPP) is analysed for the crash of Boeing 707-320 striking with a velocity of 230 mph (i.e. 102.8 m/s). The variation of crushing strength and linear mass density of the aircraft is shown in Fig. 2.

Damping is neglected in the analysis as it does not affect the maximum response for impulse loading [Rebora *et al.*(1976)]. The soil structure interaction has been neglected and the base of the containment shell has been assumed to be fixed at the foundation level. The reaction from the target i.e. $\underline{f}$ required for the analysis is calculated for each time step using Eqn. 3. The displacement configuration of the structure at previous time step has been considered in the evaluation of the last term of the equation.

The structure is considered to have failed when sufficient number of Gauss points get cracked and analysis indicated successively increasing iterative displacement accompanied by a growth of residual forces and dissipated energy. The model is not able to predict the penetration, scabbing or perforation.

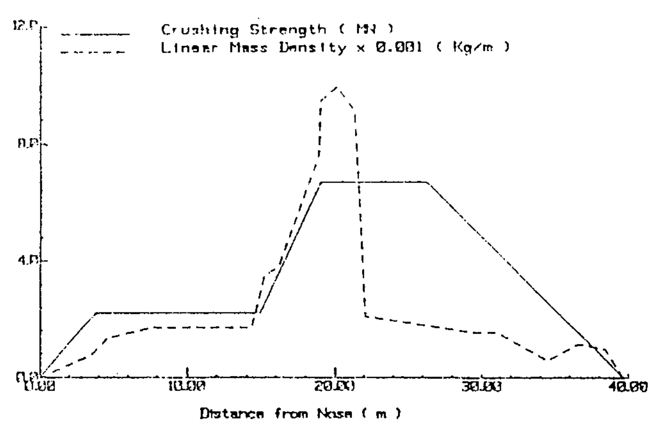
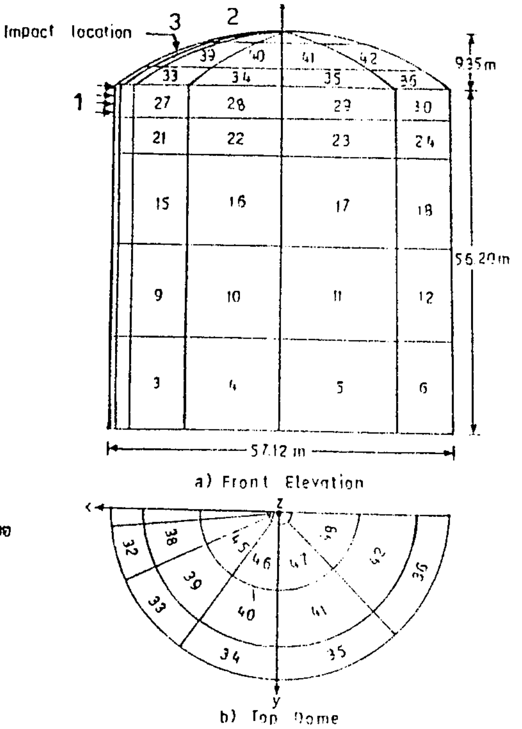


Fig. 2 Linear Mass Density and Crushing of Boeing 707-320



a) Front Elevation

b) Top Dome

Fig. 3 Dimensions, Discretisation and Impact Location

5.1 Geometry and Material Properties

The geometry of containment with dimensions, discretisation and impact locations is shown in Fig. 3. Three cases have been considered. (i) The containment with varying wall thickness and 0.61 m dome thickness, (ii) constant wall thickness of 1.2 m and 0.61 m thick dome, and (iii) constant wall thickness of 1.2 m and 1.2 m thick dome. Three locations are considered for impact of aircraft as shown in Fig. 3.. These cases are analysed for the horizontal impact of Boeing 707-320. The material properties listed in Table 1 are used in the analysis.

5.2 Analysis for Aircraft Crash

Linear analysis is carried out for each case with gravity loads. The containment configuration for case (i) is found to be unsafe to resist the impact of the aircraft at any of the three locations. The 120 cm wall and 61 cm thick dome (case ii) is sufficient to resist the horizontal crash of Boeing at location no.1, but unsafe to resist the impact at location no.2 or 3. The nonlinear response for case (iii) at two impact locations no. 1 & 2 are presented below.

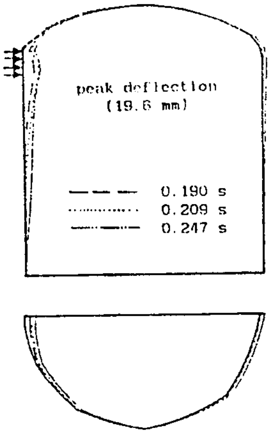


Fig. 4 Deflected Shape Along the Plane of Symmetry

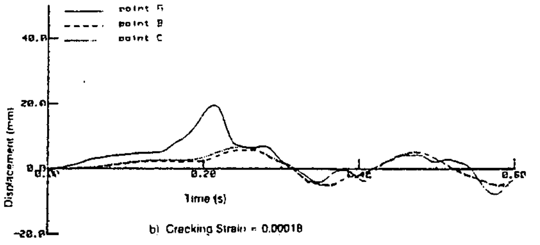


Fig. 5 Horizontal Displacement

The nonlinear displacement for location no. 1 along the plane of symmetry is plotted in Fig. 4. The nonlinear horizontal displacement history of the three monitored nodal points is shown in Fig.5. The propagation of cracks at different times are shown in Fig.6. The stress variations along the plane of symmetry at the outer surface of containment are shown in Fig.7. Due to segmental dome, considerable stresses are observed near the junction of wall and dome. The cracking is quite low due to larger diameter of cylindrical shell and it is localised near the junction of wall and dome.

6. CONCLUSIONS

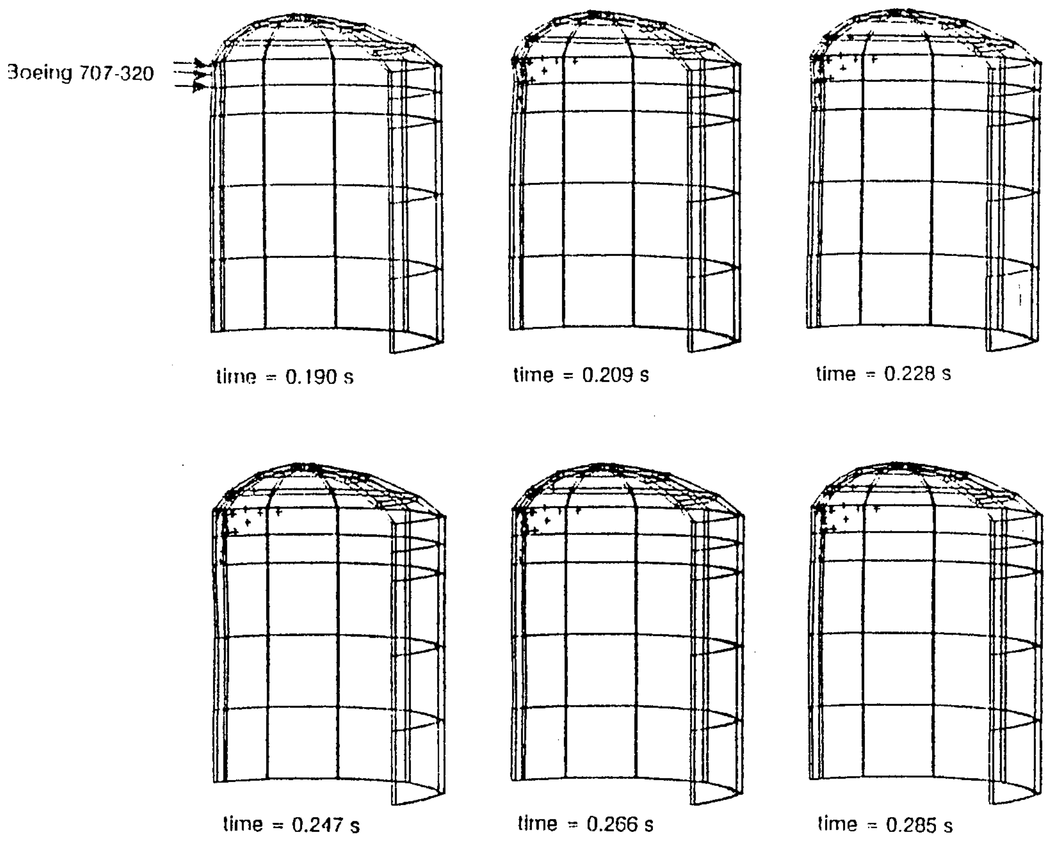
There is no requirement of prior knowledge of reaction time response for the analysis of the structure hit by an aircraft. The reaction time response can be calculated simultaneously with the analysis of the target.

7. REFERENCES

1. CERVERA, M., E. HINTON, J. BONET and N. BICANIC(1987),'Numerical Methods and Software for Dynamic Analysis of Plates and Shells', Pineridge Press, Swansea, U.K., pp. 320-504.

2. REBORA, B., Th. ZIMMERMANN and J.P. WOLF(1976),'Dynamic Rupture Analysis of Reinforced Concrete Shells',Nucl. Engg. & Design, Vol. 37, pp. 269-297.

3. RIERA, J.D.(1980),'A Critical Reappraisal of Nuclear Power Plant Safety Against Accidental Aircraft Impact', Nucl. Engg. & Design, Vol. 57, pp. 193-206.



time = 0.190 s

time = 0.209 s

time = 0.228 s

time = 0.247 s

time = 0.266 s

time = 0.285 s

Fig. 6. Propagation of Cracks for Containment
(Cracking Strain = 0.00018; Wall = 1.2m; Dome = 1.2m)

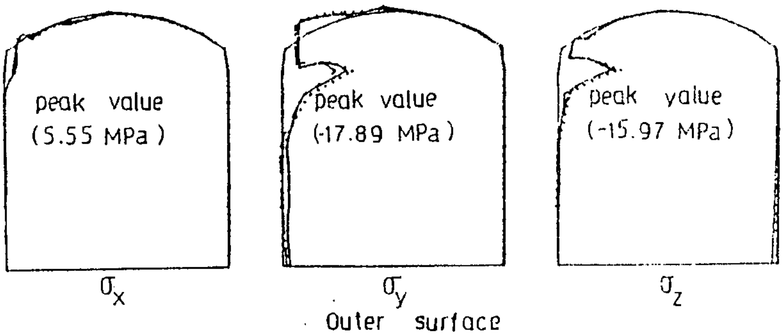


Fig. 7 Stress Variation in Concrete Along the Plane of Symmetry
(Cracking Strain = 0.00018; Wall = 1.2m; Dome = 1.2m)