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Nonlinear transient analysis of Indian PHWR reinforced concrete containments under impact load - A case study

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Abstract: The safety analysis of modern nuclear containments requires that dynamical loads, such as aircraft crashes, beyond design basis severe accident induced shock loads and earthquake, etc. be taken into consideration. The main object of this work is to study the behaviour of reinforced concrete containment under accidental aircraft crash. A three dimensional nonlinear dynamic finite element computer code ARCOS3D is developed. Analyses have been performed for two benchmark problems and one Indian PHWR outer containment.

1 INTRODUCTION

The safety analysis of nuclear reactor containment requires the accurate prediction of strength limits in extreme load and beyond design basis severe accident conditions. The problems included in the category are energy release events of various scales, transients due to pressure releases in the primary piping loop, shock analysis for assessment of response to aircraft impact, pipe whip, hydrogen detonation and seismic analysis. Damage caused by these missiles may follow a number of hypothetical abnormal events. It is desirable to demonstrate that even in such conditions the containment integrity is able to provide proper radiation shielding to the public. This requires that the actual response of structures to severe loads, be predicted with a higher degree of accuracy than is typically the case with other conventional loading conditions.

The object of this investigation is to study the effect of impact loading on the surface of containment which serves as a biological shielding and as a protection against exterior missiles or explosions. The Indian PHWRs have double containments, wherein the inner containment is made of prestressed concrete and outer containment is made of reinforced concrete construction. This design is able to withstand any extreme load and adequate margin is available for severe accidents.The analysis of NPP structure subjected to aircraft impact can be performed by uncoupling the problem[Riera(1968)]. This work uncouples the missile and target structure and hence the impulsive load is generated from the impact energy. In this work , three dimensional finite element method ARCOS3D using 20-noded solid elements is developed to capture all possible local and global failure modes in a realistic manner which also overcomes inherrent approximations with shell formulations.

2 COMPUTATIONAL FEATURES OF ARCOS3D

The analysis of nuclear containment needs a very high degree of accuracy for impact loading conditions to assess local damage and global structural behaviour. The finite element method developed in this work accounts reinforcement and concrete in a single 20-noded solid element assuming perfect bond. Each set of reinforcing bars is smeared as a two-dimensional layer which is assumed to resist only axial stresses.

2.1 Material Model

The material model used for reinforced concrete is a strain-rate sensitive elasto-viscoplastic model suitable for transient analysis. This model accounts for the triaxial state of stress which is needed to capture a wide range of failure modes. In the present elasto-viscoplastic model the fluidity parameter is not constant, and it is assumed to be dependent on the elastic strain rate. A variable strength limit surface is adopted to monitor the damage caused by viscoplastic flow. The degradation of the yield surface is assumed to be initiated if the stress at a point reaches the strength limit surface.

The yield and strength limit surface are expressed in terms of the first and second stress invariants only. During inelastic straining both yield and failure surfaces change depending upon the amount of accumulated damage. In this work, hardening is not considered for concrete and an exponential function is used to describe the post-failure behaviour. The failure stress is assumed to be a function of the viscoplastic energy density. The rate of viscoplastic straining is expressed in terms of rate of elastic strain and on the position of the yield surface. The fluidity parameter is related to the elastic strain rate through an exponential function of an effective elastic strain rate which are the deviatoric strains that cause most damage to concrete..

The main feature of plain concrete material behaviour is its low tensile strength, which results in tensile cracking at a very low stress compared with the failure stress in compression. This work adopts smeared crack model wherein the stiffness of the cracked gauss point is modified and the cracked concrete is assumed to remain a continuum. To fully describe this smeared crack model, a craking criterion, a strain-softening(or tension stiffening) rule and a model for shear transfer are used.

The crack is assumed to form in a plane orthogonal to the stress if the maximum principal strain exceeds a limiting value. A maximum of two cracks are allowed to form at each sampling point. In order to make the constitutive model objective with regard to the size of the finite elements used in the mesh, the softening curve is related to the fracture energy of the concrete. In this work an exponential function is used to simulate the strain-softening effect.

A simplified approach is used to take account of the shear transfer capacity of cracked concrete. This leads to the reduced value of shear modulus corresponding to the crack plane. The generalised elasto-viscoplastic model discussed for concrete is valid for reinforcing steel with appropriate material parameters.

2.2 Solution of Dynamic Equations of Equilibrium

The nonlinear dynamic equilibrium equation can be written as

$$[\,M\,]\{\,\ddot{u}\,\} + [\,C\,]\{\,u\,\} + [\,K_T\,]\{\,u\,\} = \{\,f\,\} \qquad (1)$$

where [M], [C] and [K] are mass, damping and tangent stiffness matrices respectively,and $\{\ddot{u}\}$, {u} and {u} are nodal accelerations, velocities and displacements respectively. The mass matrix is lumped by scaling the diagonal term of the consistent mass matrix so that the total mass is preserved. The Rayleigh damping is used since it leads to a computationally attractive banded structure same as the stiffness matrix. The predictor-corrector form of Newmark method is used in this work which is most suitable for nonlinear transient analysis. A residual force based convergence criterion is selected to terminate the equilibrium iterations.

3 NUMERICAL RESULTS

The behaviour of reinforced concrete structures under dynamic loading is studied by analysing one simply supported beam and two containment buildings using the finite element code ARCOS3D. The results are discussed in the following sections. In this study damping effects are assumed to be negligible due to short duration transient loadings..

3.1 Simply Supported ADINA Beam under Two Point Loading.

One half of the simply supported beam[ADINA(1983)] shown in fig.1 is modelled with five 20-noded solid elements to study the linear and nonlinear dynamic behaviour using ARCOS3D under a step loading of 30KN. Linear dynamic analysis was performed with a time step of 0.0005 secs and the peak displacement of 5.86mm occurs at 0.0095sec which is in good agreement with 5.8mm at 0.0097sec as reported by Cervera et al.(1988). Nonlinear dynamic analyses have been performed for α (ratio of stress at elastic limit to the ultimate compressive strength) = 1.0,0.4 and 0.3 for a cracking strain of 0.000075. The deformed shape for α = 0.3 at 0.010sec is plotted in fig.2 and displacement-time history is presented in fig.3.The peak displacement of 8.09mm at 0.012sec for α=0.4 agrees well with 8.08mm at 0.012sec as reported by Cervera et al.(1988). The peak displacements for α=0.3 and 0.4 are 8.7mm and 8.34mm at 0.013 and 0.0125 secs respectively. For α=1.0, the total number of cracked gauss points are 22 within 25 time steps and no further cracking has been observed. For α=0.4, 40 gauss points have cracked within 170 time steps and no further cracking is observed. For α=0.3,36 gauss points have cracked within 68 time steps and therefore the solution does not proceed because of the progressive cracking of many gauss points.It is seen from fig.4 that the vibration period is elongated and the amplitude is reduced as the value of α varies from 1.0 to 0.3 due to energy dissipation by concrete cracking.

3.2 General Electric Mark3 Containment under Aircraft Impact

This containment is subjected to a horizontal impact of Boeing 707-320[Rebora et al.(1976)] over an area of 28m^2 near dome-wall junction. Due to symmetry one half of the containment is analysed using ARCOS3D with 81 solid elements[Fig.4].The deformed shape of the containment for nonlinear(α=0.4) dynamic case at 0.26 secs is presented in fig.5. The displacement-time history at points A, B and C are plotted in figs.6-8 respectively for linear and nonlinear(α=0.4) dynamic cases with a time step of 0.00475secs. The peak displacement at point A for linear dynamic case is 40mm(at 0.252 secs) and for nonlinear dynamic case is 42mm(at 0.252secs). This value is in close agreement with Rebora et al.(1976) for a linear case as 36.3mm(at 0.276 secs) and for nonlinear case as 42.9mm(at 0.276secs). The number of gauss points that have cracked at upto 40, 50, 60 ,120 and 171 th time steps are 8, 28, 41, 43, 44 respectively. No further cracking has been observed after 0.812sec.The maximum of 44 number of cracked gauss points is very less compared to a total of 1215 and hence the difference between linear and nonlinear results is not significant. The present results match well with that reported by Rebora et al.(1976).

3.3 Indian PHWR Outer Containment Building under Aircraft Impact

An Indian PHWR outer containment building[Fig.9] is analysed for a horizontal aircraft impact of Boeing 707-320[Rebora et al.(1976)] over an area of 28sq.m just below the ring beam. The reinforcement and details of cross section are presented by Gupta et al.(1993). Due to symmetry one half of the containment is modelled with 126 solid elements[Fig.10] Half mass of the cellular slab of inner prestressed containmentis lumped on nodes at that elevation. Linear and nonlinear(α=0.4) dynamic analyses have been performed using ARCOS3D. The deformed shape at 0.2secs for nonlinear dynamic case is presented in fig.11 which shows a localised effect of the aircraft impact on containment. The displacement-time histories at points A,B and C are shown in figs.12-14 respectively. The peak displacement for linear dynamic case is 62mm at 0.252secs and for nonlinear dynamic case is 146mm at 0.232secs. It is seen that the Indian PHWR outer containment undergoes local damage near the location of aircraft impact. Moreover the locations B and C are not undergoing large deformations compared to the deformation at location A. The consequences of this local damage of the outer containment will not affect safe operation of the nuclear containment system, since the Indian PHWR has inner prestressed concrete containment which can provide adequate safety.

4 CONCLUSIONS

The linear and nonlinear dynamic responses of a reinforced concrete beam and two nuclear containment buildings have been studied using the finite element code ARCOS3D. The results of analysis of ADINA beam and Mark3 containment building agree very well with the reported results in the literature. Having vaidated with these two examples, the outer containment building of Indian PHWR has been analysed. The response shows that the outer containment will undergo only local damage. This damage of outer containment will not affect the safety of the Indian containment system, since the inner prestressed concrete containment can provide adequate protection of the nuclear reactor systems against aircraft impact.

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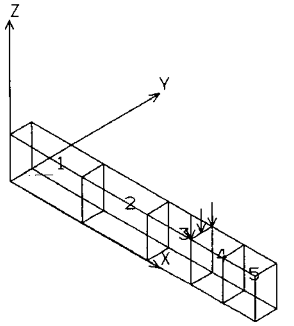


FIG.1 FINITE ELEMENT MESH OF ADINA BEAM -HALF MODEL: 5 ELEMENTS-

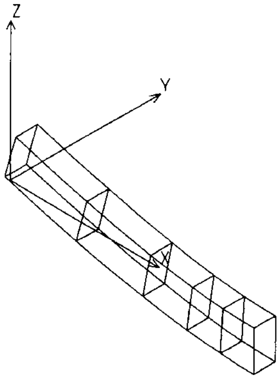


FIG.2 DEFORMED SHAPE OF ADINA BEAM AT 0.01 SECS

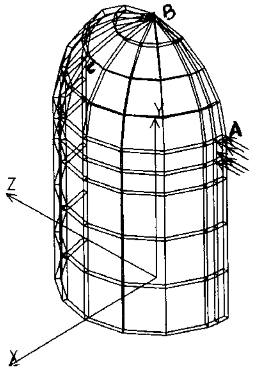


FIG.4 MARK3 CONTAINMENT - FE MESH -HALF MODEL: 81 ELEMENTS-

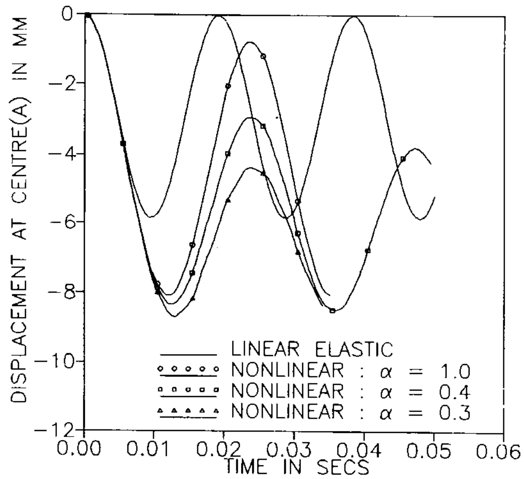


FIG.3 DISPLACEMENT HISTORY OF ADINA BEAM

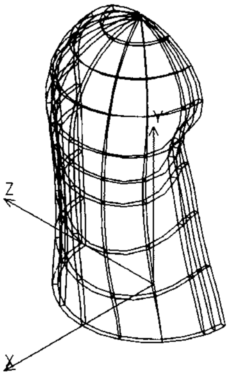


FIG.5 DEFORMED SHAPE OF MARK3 CONTAINMENT AT 0.26 SECS

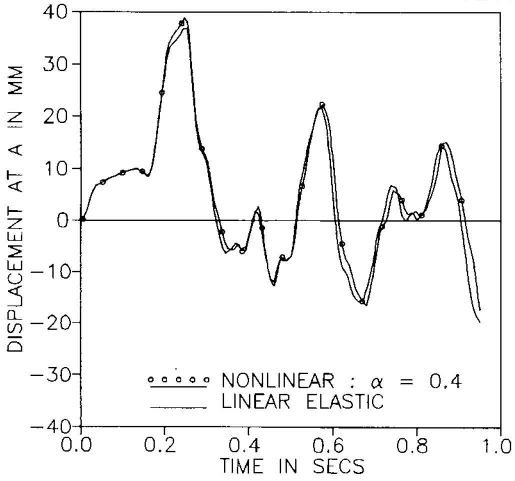


FIG.6 DISPLACEMENT HISTORY AT A OF MARK3 CONTAINMENT

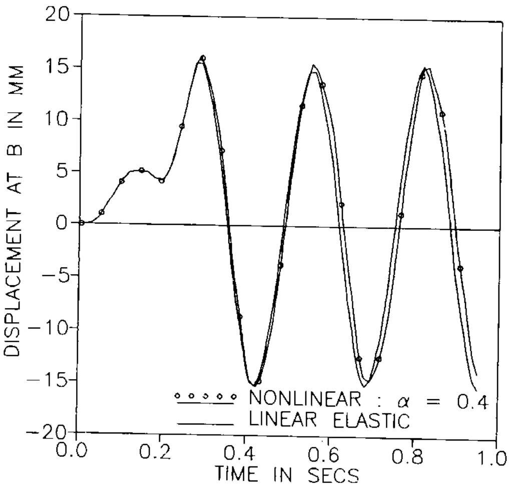


FIG.7 DISPLACEMENT HISTORY AT B OF MARK3 CONTAINMENT

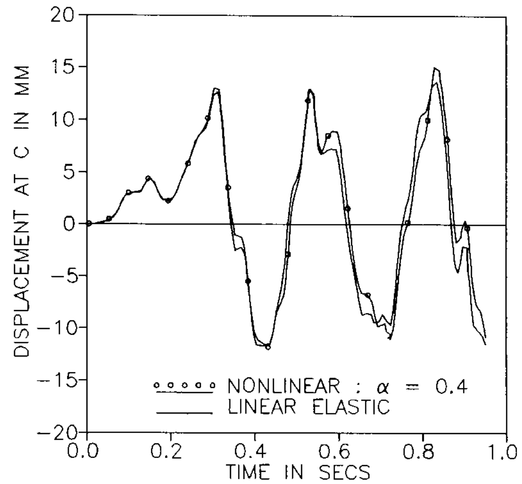


FIG.8 DISPLACEMENT HISTORY AT C OF MARK3 CONTAINMENT

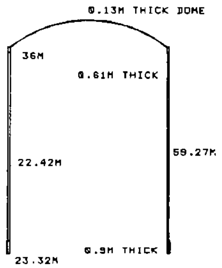


FIG.9 INDIAN PHWR OUTER CONTAINMENT
-CROSS SECTIONAL ELEVATION-

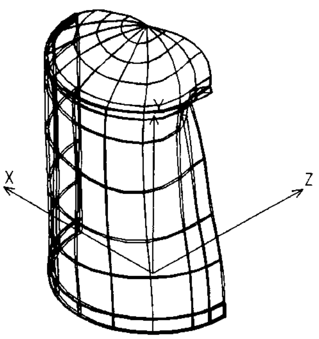
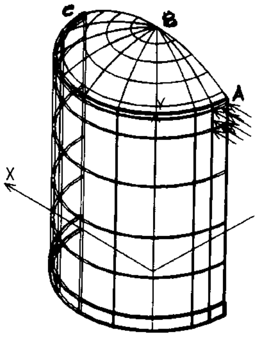


FIG.11 DEFORMED SHAPE OF INDIAN PHWR CONTAINMENT AT 0.2 SECS



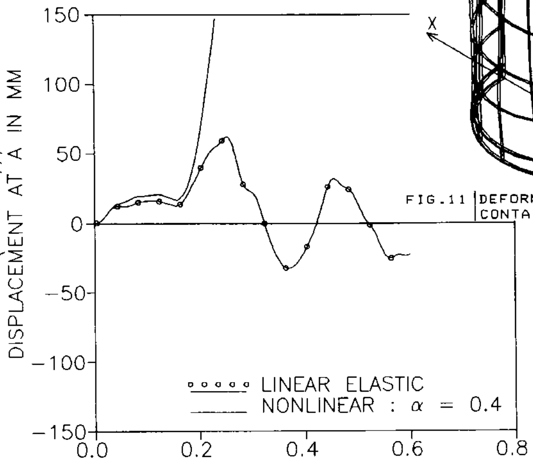


FIG.12 DISPLACEMENT HISTORY AT A OF INDIAN PHWR CONTAINMENT

FIG.10 INDIAN PHWR OUTER CONTAINMENT
-HALF MODEL: 126 ELEMENTS-

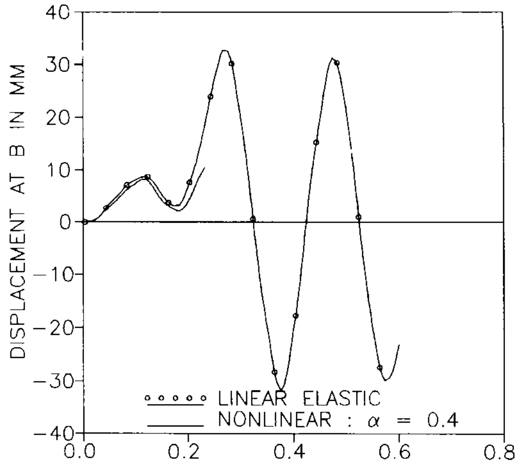


FIG.13 DISPLACEMENT HISTORY AT B OF INDIAN PHWR CONTAINMENT

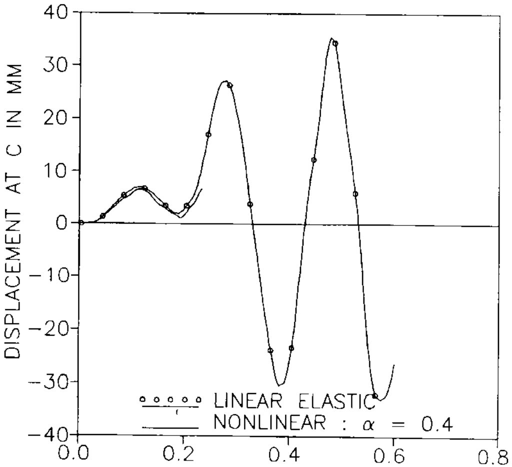


FIG.14 DISPLACEMENT HISTORY AT C OF INDIAN PHWR CONTAINMENT