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Reinforced Concrete Modeling for Protective Structure Analysis

Modèles pour l'analyse d'éléments de protection en béton armé

Modellbildung für Stahlbeton bei der Berechnung von Schutzbauwerken

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SUMMARY
A major limitation in 3D dynamic finite element analysis of protective structures is reinforced concrete modeling. The requirements of such a model and the approaches currently used are outlined in this paper. The advantages and consequences of using a simple composite continuum model are studied through a representative example. Promising directions of further research in this area of reinforced concrete modeling are also indicated.

RESUME
Une limite importante à l'analyse tridimensionelle dynamique d'éléments de protection en béton armé est posée par le choix d'un modèle convenable. On montre les exigences posées à un tel modèle et on présente quelques modèles souvent utilisés. Les avantages et les conséquences de l'adoption d'un modèle continu simple sont étudiés à l'aide d'un exemple typique. Des possibilités de recherches sont indiquées.

ZUSAMMENFASSUNG
Eine Hauptschwierigkeit, die bei der dreidimensionalen, dynamischen Finite Elemente Berechnung von Schutzbauwerken auftritt, besteht in der Modellbildung für Stahlbeton. Anforderungen an derartige Modelle und heute übliche Vorgehensweisen werden dargestellt. Die Vorteile und Konsequenzen der Anwendung eines einfachen Kontinuummodells werden an einem Beispiel erläutert. Mögliche Richtungen weiterer Forschungstätigkeit werden angedeutet.

1. INTRODUCTION

Major advances have been made in dynamic, three-dimensional, nonlinear finite element methods in recent years[1] which enable the design of protective structures to be based on more rational estimates of structural response than was previously possible[2]. Simulation of geometric details using up to 20,000 constant strain hexahedral finite elements is possible and the cost of time-marching analyses is of the order of one to three hours. Work in simulating the nonlinear multiaxial properties of soil surrounding the structure has resulted in complementary advances [3]. Nonlinear models of reinforced concrete structures have been proposed (e.g. [4-6]) but their application to analysis of protective structures has lagged with the result that concrete modeling is the weakest aspect of the analysis.

The requirements for a reinforced concrete model of protective structures include its validity for short-time, monotonically-increasing deformation. There is occasionally a need to represent one or two cycles of load or deformation, but seldom more. The model must be valid for deformations up to and beyond those associated with the maximum load. It must be compatible with integration algorithms commonly used in dynamic, nonlinear analyses which include, at a minimum, guarantees of uniqueness, continuity and stability of solution. In addition, the algorithms for computing the properties must be economical of computer execution time and storage so as not to penalize overall execution time. Finally, the model should be expressed in terms of a few empirical parameters (order of 10) which can be defined by a limited experimental effort.

The types of concrete models which meet these criteria may be termed the continuum and structural element approaches. The continuum approach includes all models expressing multiaxial stress-strain relationships. Examples include models based on plasticity and endochronic theories and a variety of variable moduli models. The structural element formulation of concrete properties in terms of stress resultants (moments, membrane forces and shears) is attractive from the standpoint of describing structural properties in natural structural terms. Problems such as describing combined flexural and membrane behavior in terms of composite stress-strain relations, whose solution in the continuum approach requires through-the-thickness integration [8], are avoided. The same types of theoretical frameworks, including plasticity theory, can be used for the stress-resultant formulation [9].

The purpose of this paper is to illustrate by an example the advantages and disadvantages of the plasticity theory, continuum approach to reinforced concrete modeling. The example is a horizontal shelter which is subjected to airblast and local airblast-induced ground motion. The response of this hypothetical structure, which has complicated reinforcing patterns, is simulated with a three-dimensional, nonlinear finite element analysis using the TRANAL computer program developed by Weidlinger Associates [10].

2. EXAMPLE OF STRUCTURE TO BE ANALYZED

Methods of analyzing protective structures will be illustrated by means of the example shown in Fig. 1. This structure is made up of a rectangular headworks section, including stiff frame,

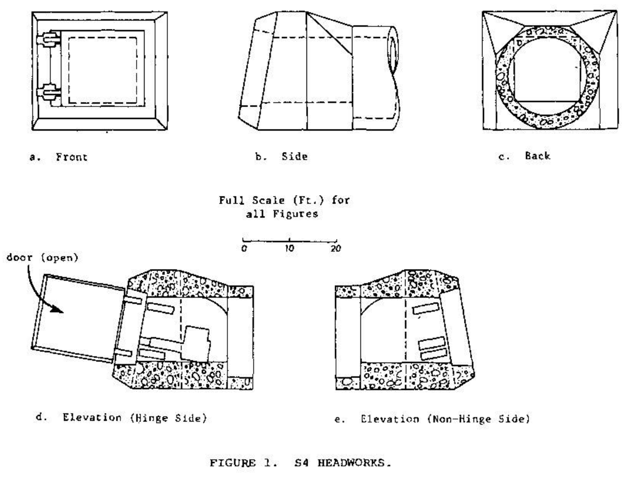


FIGURE 1. S4 HEADWORKS.

bearing surface and closure of door; and a transition section, which connects the headworks to a long horizontal tube. The main detail to be represented in the headworks frame is the circumferential reinforcing, including liner plate around the jamb of the door opening. The door is composed essentially of plain concrete poured into a steel tub; dowels connected to the interior of the tub act as connectors. At the transition region the cross-section changes from rectangular (headworks) to circular (tube). Both circumferential and longitudinal reinforcement are especially heavy in the transition section, whose cross-sectional area is significantly less than that of the front face of the closure which receives the direct load.

The loads on the structure derive from airblast applied to the front face and to the berm which covers the tube. The direct airblast on the front is amplified by dynamic reflection effects such that a high frequency pressure peak of about seven times the overpressure is applied to the door. The result is that direct airblast on the front of the closure is the dominant load in this example.

3. MODELING AND TEST OF STRUCTURE

3.1 Finite Element Discretization

Both the structure and soil media are represented by 3D continuum finite elements. The finite element model, consisting of about 20,000 hexahedrons, is shown in Fig. 2. Symmetry is assumed about the center vertical plane of the tube so that only half (the hinge side) of the shelter and berm is included. Special attention is given to details in the closure and in the headworks and transition region (Fig. 3). The dynamic analysis is performed using TRANAL, an explicit 3D nonlinear dynamic program for soil-structure interaction analysis developed especially for large-scale 3D problems [10]. On a CDC 7600, approximately 20,000 elements can be used with a solution time of 2500 element-time step per CP second. The subcycling feature permits different integration time steps in structural and soil elements; the penalty usually imposed on explicit integration methods by stringent requirements on time step is thereby imposed only where it is actually required, rather than on all equations of the system. The total computation time for the

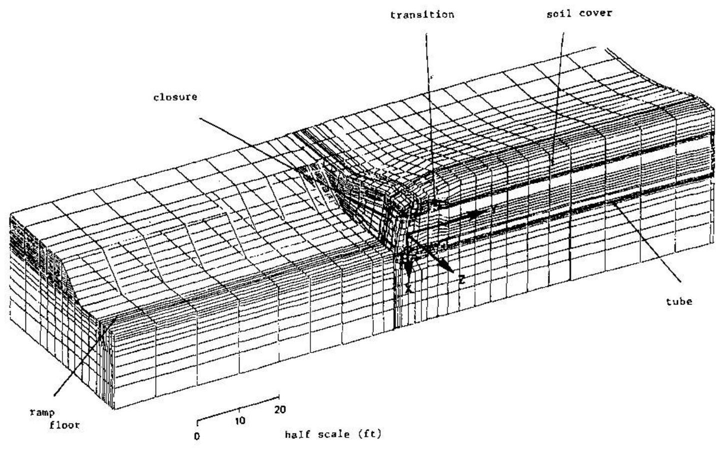


FIGURE 2. FE MODEL OF S4 TEST, COORDINATES SYSTEM.

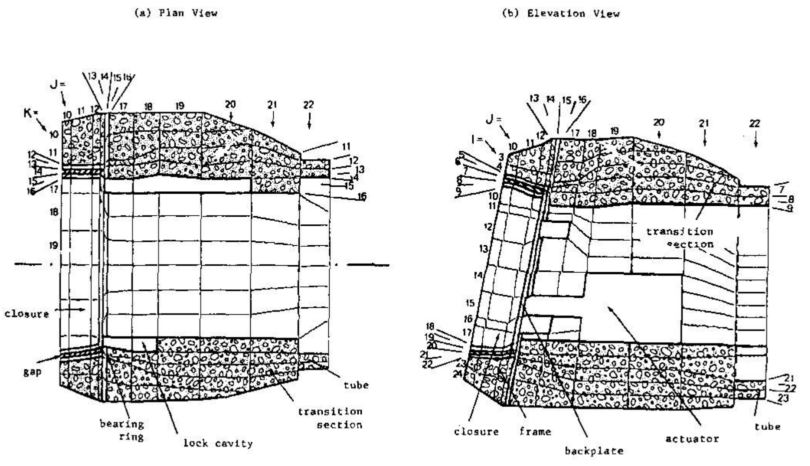


FIGURE 3. S4 HEADWORKS MODEL (IJK ARE FOR ELEMENT/NODE ACCOUNTING).

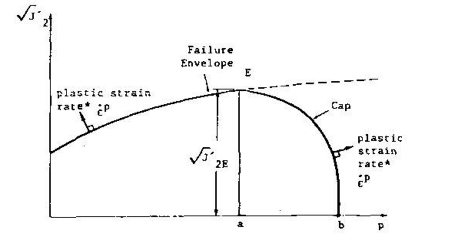
example is 50 CPU seconds for 0.1 msec of simulation time.

3.2 Soil Model

The in-situ soil and backfill are modeled as elastic-plastic materials defined by a modified Drucker-Prager yield function and a work-hardening cap (see Fig. 4 and also [7]) together with an associated, plastic potential flow rule. This formulation has been found to represent properties of a variety of soil and rock types [11, 12].

3,3 Structural Model

Both the plain concrete and structural steel are modeled as elastic, perfectly plastic materials, with associated flow rule (see failure envelope in Fig. 4). The concrete has a yield surface based on the dynamically enhanced compressive strength and the steel a von Mises' yield surface corresponding to A36 steel. The concrete strength is 10,000 psi for concrete in the closure and 6000 psi for concrete in other parts of the structure. The continuum elements which model the steel plates in the closure and bearing frame impose a stringent penalty on the local integration time step because of the dimension of the steel plate (5 in.) and because of the need to use a minimum of two elements across its thickness. The effect of the reinforcing steel in different parts of the structure, i.e. headworks, frame, tube, etc., is modeled by adjusting the amount of tension that the plain concrete model can accommodate. The basic yield surface is otherwise unchanged.



Failure envelope: $\sqrt{J'_2} = A - C \exp(-3Bp)$

cap: $\sqrt{J'_{2E}} = (p_b - p_a)/R = f(\dot{\varepsilon}^p_v)$

*The plastic strain rate $\dot{\varepsilon}^p$ is governed by the associated flow rule whereby the plastic strain rate vector is normal to the yield surface when plotted to the appropriate scale parallel to the p-axis (plastic volumetric strain rate) and the $\sqrt{J'_2}$ axis (plastic deviatoric strain rate)

FIGURE 4. TYPICAL YIELD SURFACE IN THE CAP MODEL FOR COMPRESSIVE STRESSES.

3.4 Test Description

The test program involved subjecting a half-size structure to blast loading using a high explosive simulation technique (HEST). Pressure generated within two HEST cavities and applied to the entire width of the front-face, wingwalls and soil berm covering the headworks is designed to match the prescribed loading.

The structure and its neighboring areas are heavily instrumented. There are approximately 400 channels of measurements, including concrete/rebar strain measurements, interface stress measurements, airblast pressures, accelerometers and velocity gages as well as pretest and posttest surveys. Some of the test data will be presented in Section 4 where they are compared with results obtained from the finite element analysis. The analysis was performed prior to the test event, based on predictions of airblast loading and estimates of soil properties.

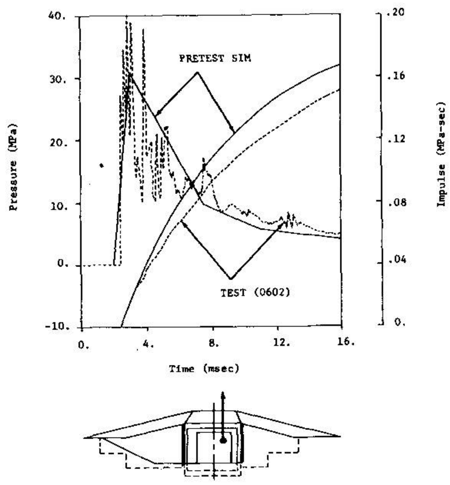


FIGURE 5. COMPARISON OF FRONT-FACE LOADING USED IN ANALYSIS AND ACHIEVED IN TEST.

4. STRUCTURAL RESPONSE AND PERFORMANCE OF MODEL

Due to inherent vibrations in the HEST cavity, the front load developed in the test differs from that assumed in the finite element analysis. An indication of this difference is given in Fig. 5, which compares the measurement of a pressure gage on the upper right corner of the closure front face with its design value. While the peak HEST load is higher than the design value due to cavity vibrations, the impulse in the physical test is 10% low at 6 msec after detonation.

A comparison of the motion of the center of the closure backplate is given in Fig. 6. The initial peak is due to the front load and is higher for the test structure due to the higher peak load realized in the test. Consequently, the rebound is more severe in the test. There is also strong indication that the closure frequency for the test structure is less than that simulated, probably due to the support condition assumed in the analysis. Subsequent motion is dominated by the relatively rigid motion of the support or headworks given in Fig. 7. The spike at 11 msec coincides with the sudden failure of the transition section described later, and is absent in the analysis results. Despite these differences, however, both the test data (measurement and posttest observations) and analysis support the fact that the closure/headworks remains elastic, that the transient response of the closure is short-lived, and that the closure/headworks then moves as a rigid body.

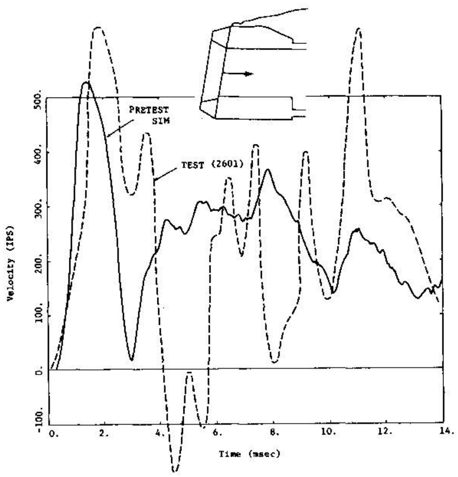


FIGURE 6. COMPARISON OF VELOCITY/TIME HISTORIES AT CENTER OF CLOSURE BACKPLATE.

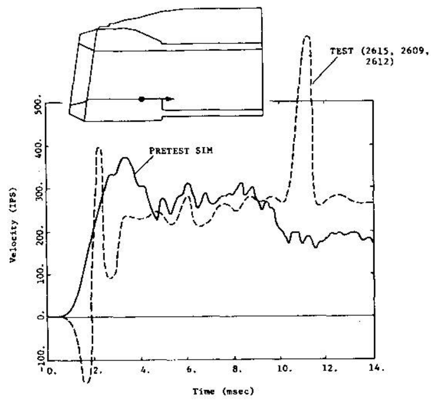


FIGURE 7. COMPARISON OF MOTION AT HEADWORKS FLOOR (LONGITUDINAL COMPONENT).

A comparison of the longitudinal tube concrete strain/time history immediately behind the headworks is given in Fig. 8. The correlation between analysis and test is in general quite good. Comparison of the circumferential strain at the same location as given in Fig. 9 is less favorable. Whereas dilatancy is dictated by the reinforced concrete model, test data seem to indicate the opposite.

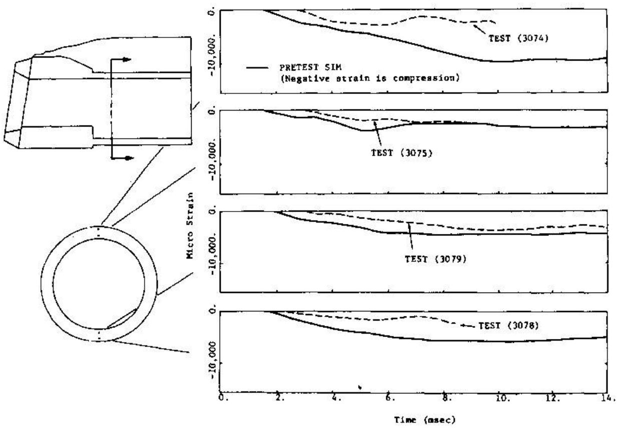


FIGURE 8. COMPARISON OF LONGITUDINAL STRAIN/TIME HISTORIES AT TUBE CROSS-SECTION BEHIND HEADWORKS.

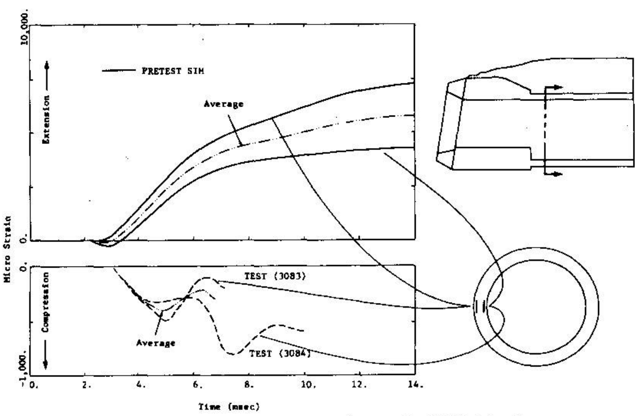


FIGURE 9. COMPARISON OF CIRCUMFERENTIAL STRAIN/TIME HISTORIES AT TUBE CROSS-SECTION BEHIND HEADWORKS (x = 2.995 m).

Both test and analysis indicate crushing failure of concrete at that location, and posttest survey such as that reproduced graphically in Fig. 10 certainly confirms this finding. The present plasticity model does not simulate strain softening with resulting redistribution of load. Consequently, the longitudinal stress in the concrete is maintained at 9000 psi as shown in Fig. 11. This results in higher computed strains. Furthermore, this load is transmitted to the remainder of the tube section so that overall, a length of the tube from the transition to about one tube diameter behind is shown by the analysis to undergo significant plastic deformation. Physically, crushing failure of the concrete at the transition practically isolates the tube portion from the headworks, protecting the tube from further damage except for several major cracks along construction flaws (Fig. 10), and allowing the headworks to move impulsively as the spike in the velocity-time histories of Figs. 6 and 7 show.

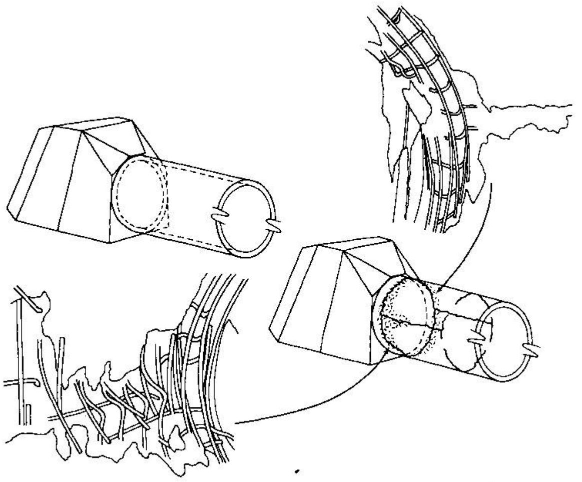


FIGURE 10. DAMAGE PATTERN OF TUBE, POSTTEST OBSERVATION.

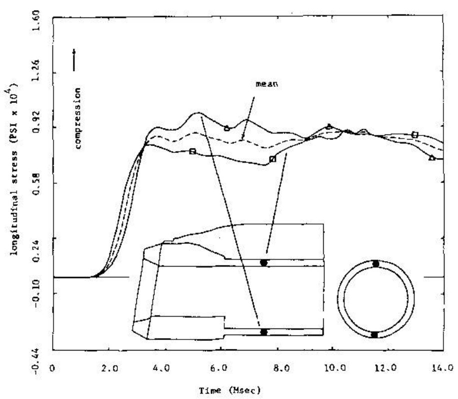


FIGURE 11. LONGITUDINAL STRESS/TIME HISTORIES FOR POINTS AT TUBE SECTION HALF-TUBE DIAMETER BEHIND HEADWORKS.

5. SUMMARY AND RECOMMENDATIONS

A major limitation in 3D dynamic finite element analysis of protective structures is reinforced concrete modeling. In this paper, we have outlined the requirements of such a model and approaches currently used. The performance of a simple composite continuum model is then studied, using a modified Prager-Drucker yield surface with the associated flow rule, and a tension region determined by the proportion of steel reinforcement. The advantages and consequences of using such a model are examined through a representative case study.

The simple plasticity model performs quite well when the inelastic deformation is minor. In the case study presented, good qualitative and quantitative agreements between test and analysis are obtained in portions of the structure which remain basically elastic. The performance of the analysis model is not as good in portions of the structure where extensive concrete failure occurs. Although the analysis results succeed in identifying areas of extreme distress in the structure, the concrete model is unable to reproduce some important features of failure and post-failure. Specifically, the absence of strain softening and load redistribution features in the model result in spreading out the zone of inelasticity. Since the major objective of protective structure design (and hence analysis) is not only its survivability and vulnerability in hostile environments, but also to strike a delicate balance between hardness and cost, it is essential that the reinforced concrete model used be able to discriminate conditions of near-failure from failure, and to reproduce the effect of different amounts of reinforcements and changes in reinforcement orientation.

Two directions of research in the area of reinforced concrete modeling for protective structure applications appear most promising. One approach is to refine the continuum representation of plain concrete in the tensile cracking, compressive failure and post-failure regions, which is then used in conjunction with an explicit representation of the reinforcement. In this approach, the dual-element strain-compatible finite element concept appears promising 4 . The disadvantages of this approach are the additional input data required, numerical stability, and possible difficulty in the interpretation of results so obtained.

Alternately, structural elements can be used to model the structure. This is a natural representation of inelastic flexural properties of the structure and has an added advantage in that the model properties are easy to define experimentally. This approach requires careful implementation in order to maintain the efficiency required for large dynamic analyses 1 .

ACKNOWLEDGMENT

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