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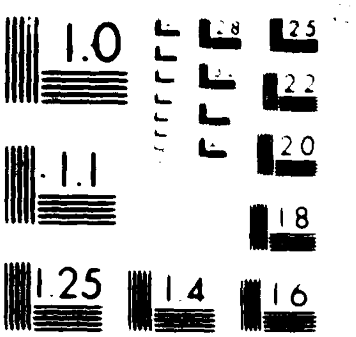
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DEVELOPMENT OF ADVANCED CONSTITUTIVE MODELS FOR PLAIN AND REINFORCED CONCRETE

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ANNUAL REPORT

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This is the first annual report under the referenced contract. The objective of the research is to develop a new and advanced approach to modeling the constitutive behavior of reinforced concrete that provides substantial improvement over existing approaches, especially in the nonlinear response regime. To accomplish this, the research has been partitioned into two major tasks, which are being pursued concurrently. One task consists of formulating a procedure (mixture theory) for analytically mixing reinforcing steel and plain concrete, so that the interaction between the two is properly modeled. The other task consists of developing a model of plain concrete, which accurately portrays its nonlinear, multiaxial behavior and is also computationally feasible for use in conjunction with the mixture theory. The mixture theory is designed to synthesize the global constitutive properties of reinforced concrete from the properties of plain concrete, steel, interfaces and reinforced geometry. The progress made during the first year's effort toward achieving these objectives is described.

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FOREWORD

This is the first Annual Report under AFOSR Contract F49260-84-C-0029, summarizing the research performed by S-CUBED during the period from March 1, 1984 to February 29, 1985. Partial support for portions of the research was provided by the Defense Nuclear Agency under Contract DNA001-84-C-0127. The Co-principal Investigators for the project are Dr. G. A. Hegemier and Dr. H. E. Read. The AFOSR Contract Technical Monitor is Lt. Col. L. D. Hokanson.

Drs. Hegemier and Murakami, consultants to S-CUBED, are also Professors of Applied Mechanics at the University of California, San Diego. Dr. Valanis, an S-CUBED consultant, is also Professor of Mechanics at the University of Cincinnati, Cincinnati, Ohio.

The authors express their appreciation to Dr. D. H. Brownell and Mr. R. G. Herrmann, who provided excellent computational support throughout the course of the research.

I. INTRODUCTION

1.1 BACKGROUND

During the past several years, the Air Force has been deeply involved in an extensive effort to develop, and assess the feasibility and relative effectiveness of, various candidate modes for basing the MX strategic weapons system. One of the candidate modes that has received considerable attention is the so-called superhard silo, which is conceived as a large buried reinforced concrete structure designed to protect a missile from the shock loads prescribed by the design attack scenarios. The enormous costs involved in constructing the large number of such structures required by the system dictates that their design be not only safe but cost-effective as well.

In the event that the enemy threat changes, it is also important for the strategic system designer to know the ultimate hardness of the concrete protective structures, so that the survivability of the system with regard to the new threat can be readily assessed. The most expeditious and economical way to do this is through the use of validated analytical models of the structure's behavior. There is, accordingly, a need to have reliable analytical models that can predict the loading environments for which complex reinforced concrete structures will collapse, or incur sufficient damage to render them functionally inoperable.

The current methods for designing silos are largely empirical, with heavy reliance upon engineering experience gained from the design of structures for prior defense systems, and insight obtained from the results of pertinent field tests conducted on small scale structures. Full scale testing of silos under simulated explosive environments is extremely rare due to the enormous costs involved. Analytical studies with finite element codes are often performed, but because of the crudeness of the material models for the plain and reinforced concrete used, little confidence is placed in the results so obtained, especially when nonlinear effects dominate the behavior. At best, relatively simple elasto-plastic models of plain concrete, developed from quasi-static, low pressure laboratory data, are combined with simple overlay approaches to account for the steel reinforcement. The resulting model of reinforced concrete is unable to account for the interaction that occurs between plain concrete and rebar during deformation. Inasmuch as such models are generally developed on the basis of quasi-static, low pressure data, they are not capable of describing the response of concrete to the high pressure, impulsive loading environments of interest. It is therefore not surprising that, at present, the collapse (failure) load of a missile silo cannot be analytically predicted to within a factor of 2. Clearly, there is a crucial need to understand how complex reinforced concrete structures fail under complex loads applied at high loading rates.

The inability of the current constitutive models to adequately describe the nonlinear behavior of plain and reinforced concrete is the main reason for the lack of confidence in numerical simulations of structural response. Without a valid numerical simulation capability, there is little hope of arriving at a cost-effective design. The inaccuracies associated with the current constitutive models of reinforced concrete stem from two main sources; namely, (1) inadequate models of plain concrete behavior, especially for high pressures and high rates of loading and (2) overly simplified methods used in mixing plain concrete and steel rebar to obtain a model of reinforced concrete. In both cases, the nature of the problem requires research at a fundamental level, since the basic technology is missing. Although extensive research has been conducted over the past fifty years on reinforced concrete, the emphasis has not been on the high pressure, dynamic response regime. Therefore, if we are to develop methods which can lead to cost-effective, reliable designs for concrete defense structures, improved modeling of the response of plain and reinforced concrete to high pressure loading environments is needed, as well as corresponding experiments to validate the modeling. This requires a significant advancement in current technology.

1.2 IMPORTANCE OF STEEL-CONCRETE INTERACTIONS

Over the response regime of interest to the DoD, the behavior of reinforced concrete is dominated by complex nonlinear interactions between the steel and concrete. In particular, it is well known that such interactions can have a major effect on global structural characteristics such as stiffness, strength, damping and ductility. In addition, steel-concrete interactions can have a primary influence on damage accumulation and failure modes.

To illustrate the above statement, consider the example of reinforced concrete in direct tension. Practical steel percentages (in the direction of loading) range from 3 percent ("dense" layout) to 0.5 percent ("sparse" layout). If one examines the unload-reload tangent modulus associated with the global stress and strain in the direction of loading, then one finds that the initial (uncracked concrete) modulus drops by approximately 65 percent for 3 percent steel, as damage in the form of progressive cracking and steel-concrete bond degradation, accumulates with increasing global deformation (extension). For 0.5 percent steel, this number becomes approximately 95 percent! For the global deformation domain of practical relevance, the initial modulus is too high for computational purposes and the asymptotic (steel only) modulus is too low. The required modulus lies in the transitional region between the two extremes. However, behavior in this transitional domain can be predicted only if steel-concrete interactions are considered. For the example cited, the problem of predicting the appropriate stiffness is a classical problem known as "tension stiffening".(1)

Thus, it is evident that a model of reinforced concrete must, in some sense, reflect steel-concrete interactions. In the past, practitioners have attempted to account for some of these interactions, in an effort to fit test data, by "adjusting" the constitutive relations of either the steel or the concrete (usually the latter). However, such an empirical approach requires a myriad of costly experiments -- costly since the specimen size must be "large" when compared to the typical steel spacing (material "microstructural" dimension) if a continuum description of reinforced concrete is to be used. In the final analysis, the empirical method does not furnish the simulation accuracy and capability that are needed for the proper treatment of current DoD problems concerning the design and analysis of reinforced concrete protective structures.

1.3 OBJECTIVES

The ultimate objective of the research described here is to construct an advanced, nonlinear, multiaxial, nonphenomenological constitutive model of reinforced concrete that will provide simulation accuracy that is superior to existing models in the *nonlinear response regime. The term 'advanced nonlinear multiaxial'* implies a model that will provide greater accuracy to existing models in the inelastic, nonlinear response regime and for arbitrary paths in multiaxial stress or strain space. The term 'nonphenomenological' implies a model that is capable of synthesizing the global properties of reinforced concrete from a knowledge of the plain concrete and steel properties, the concrete-steel interface properties, and the geometry of the steel reinforcement.

The specific research objectives of the work performed during present reporting period were as follows:

- Validation of General Mixture Theory. Complete the validation of the basic mixture framework. For this purpose, exercise the mixture model in the following fundamental modes: (1) the steel-concrete bond mode, (2) the dowel action model and (3) the dowel plus interface shear transfer mode. For modes 1 to 3, compare numerical simulations using the mixture theory with available experimental data in an effort to assess the accuracy of the modeling procedures.

- Variational Principles. Develop the mixture variational principles necessary for proper boundary condition formulations, and for construction of the finite element method.
- Endochronic Theory. Continue the effort, initiated under the previous contract, to explore the potential of using the new endochronic theory to describe the behavior of plain concrete. Consider various methods for incorporating shear-volumetric coupling which are compatible with the observed behavior of concrete.
- Strain Softening. Conduct a study of strain softening. Based upon the outcome, propose a general approach for modeling plain concrete wherein the microlevel behavior is non-softening, but may crack, while the macrolevel response may exhibit softening.

1.4 SCOPE

The scope of the research described here is presently limited to modeling the nonlinear behaviors of plain and reinforced concrete to low pressure, quasi-static loading. The reasons for this are twofold, namely, (1) there is, in general, a much larger data base available on the quasi-static, low pressure behavior of plain and reinforced concretes to guide the modeling effort although there is still a critical deficiency in the knowledge of how these materials behave under arbitrary load paths, and (2) rate-effects add further complexity to the models, with little credible data currently available to calibrate these effects. Overall, the basic plan is to, first, develop and apply the proposed approach to the quasi-static, low pressure behavior of reinforced concrete and, if successful, to then extend the resulting model to the high pressure, high rate of loading response regime, using the sparse data base presently available.

II. CURRENT STATUS OF RESEARCH

The progress made during the past year toward achieving the research objectives described earlier is summarized in this section. First, the basic technical approach being followed to meet these objectives is outlined. Then, the progress made toward developing and validating an advanced mixture theory with microstructure for reinforced concrete is described. Next, the effort to develop a realistic constitutive model of plain concrete for use in conjunction with the mixture theory is summarized. Finally, the progress made in understanding strain softening and other related issues is discussed.

2.1 APPROACH

The nonlinear response of reinforced concrete is largely dominated by complex interactions between the steel and the concrete. Consequently, an accurate model of reinforced concrete must be capable of accounting for such interactions. Further, in an effort to minimize the number and type of tests necessary to define the parameters of a given model, it is highly desirable that it be nonphenomenological, i.e., that the global properties of reinforced concrete be synthesized from the constitutive properties of the steel and concrete, the steel-concrete interface physics, and the steel ageometry.

A candidate modeling approach that satisfies the above objectives is the "mixture theory with microstructure." As was noted previously, this modeling concept is a result of previous successful attempts to describe the nonlinear behavior of fibrous composites.(2-6) According to the mixture concept, the composite constituents (steel and plain concrete) are modeled at each instant of time as superposed continua in space. Each continuum is allowed to undergo individual deformations. The microstructure of an actual composite of steel and concrete is then simulated by specifying the nature of the interactions between the continua. With respect to reinforced concrete, previous "smearing" or "homogenizing" techniques may be viewed as a mixture theory in which each component is constrained to have the same deformation gradient at the same spatial point. Relaxation of this constraint through an improved mixture framework obtained by micromechanical considerations regarding the interactions of the components leads to a marked improvement in the simulation of real material behavior.

The key to the development of mixture models for reinforced concrete is an asymptotic procedure called "multivariable asymptotic expansions." This mathematical technique, together with a "smoothing" operation, leads to the desired mixture forms. The methodology is applicable to both dense and sparse steel layouts.

Construction of an improved nonlinear model of reinforced concrete has necessitated research in two basic areas: (1) the development of appropriate analytical procedures for "mixing" or "homogenizing" the steel and concrete and (2) the development of an advanced nonlinear multiaxial description of plain concrete. Additional important subsidiary tasks include the determination of steel-concrete interface physics, the performance of validation studies, and the development of finite element methods (FEM) associated with numerical computations. The current status of research in area (1) is outlined below; area (2) is covered in Section 2.3.

2.2 REINFORCED CONCRETE MODELING

To-date, candidate reinforced concrete models have been formulated for both dense and sparse unidirectional steel layouts. In addition, variational principles have been formulated which serve as the basis for conversion of the analytical descriptions to numerical (finite element) form.

In the case of the dense steel layout, the model construction technique is based on the use of multivariable asymptotic expansions, a variational principle, and certain smoothing operations. The resulting model has been cast in the form of a binary mixture which resembles an overlay of two continua: steel and concrete; these continua interact via "body forces" which are functionals of the relative global displacements of the continua.

In the case of the sparse steel layout, a variational method is used to generate the desired model. Here the description takes the form of a new FEM rebar element. The latter includes a description of the steel, a certain amount of concrete cover, and the interaction between the two. In practice, this element is to be used in place of the usual rebar element overlay.

During the last research period, the primary effort concerning reinforced concrete model development has been directed toward the validation of the basic mixture framework, and to modifications of this framework where necessary. For this purpose a number of fundamental test problems were defined, associated experimental data were collected, and comparisons were made between numerical simulations and test data.

The test problems selected were designed to exercise various modes of steel-concrete interaction. After initial cracking of a reinforced concrete structure, three basic steel-concrete interaction (load transfer) mechanisms are activated. These are, in general, interdependent and are associated with: (1) steel-concrete bond action (BA); (2) dowel action (DA), and (3) DA and interface shear transfer (IST).

Problems selected for initial study were designed to separate BA and DA. For this purpose pull-out and tension tests were adopted for validating the BA mode, and shear tests with lubricated, smooth crack surfaces were considered for DA. Shear tests with normal (to the rebar) crack surfaces, including aggregate interlock, were subsequently used to evaluate combined DA and IST. The foregoing cases included both scaled and full-scale specimens, and both monotonic and hysteretic deformation-time histories.

The BA and DA problems have revealed excellent simulation capability and accuracy well into the highly nonlinear range of deformation. Combined DA and IST studies also exhibited proper model behavior, the experimental data base is sparse for this case however.

Other validation problems are under current study. One such problem concerns reinforced concrete in direct compression, with and without confinement stress. This important case is theoretically complex since the crack field generated is, in general, oblique to the principal steel directions. As a consequence, all major steel-concrete interaction mechanisms are activated. Modification of the mixture model to incorporate more general concrete crack distributions was found to be necessary in order to adequately simulate material behavior under general multiaxial stress histories. The necessary modification is in progress. In addition to theoretical complexity, validation of this case has been rendered difficult by a paucity of accurate and complete test data.

In addition to the above studies, which are directed toward nonlinear steel-concrete interaction effects, several test problems have been examined which were intended to validate certain dynamic response phenomena such as geometric dispersion. The latter is important in cases involving intense loads over short time intervals. The results of this effort led to a revision of the mixture formulation to reflect more accurate microstructural fields in the steel and concrete. The modification rendered the mixture framework unchanged, but resulted in new model parameters which furnish more accurate phase velocity spectra.

Future work will include completion of the validation studies noted above and initiation of new test problems. As part of this effort, the reinforced concrete model will be further generalized to include more complex concrete crack fields and failure modes

Once model validation is sufficiently complete, it is planned to undertake a parameter study of certain important loading conditions, such as direct compression, to ascertain the effectiveness of various steel confinement layouts. Of special interest is the dependence of global ductility on rebar layout.

In addition to validation and parametric studies, efforts will be made to develop the methodology necessary to utilize the mixture model within the context of the finite element method (FEM). The main problem here is the development of efficient numerical algorithms.

Documentation

Details of the general theoretical developments concerning model construction and associated variational principles can be found in References (7-9). In-depth studies of the steel-concrete bond problem can be found in Reference (8) for monotonic deformation and Reference (10) for hysteretic deformation. The steel-concrete dowel problem and combined IST and dowel problems are treated in Reference (11). A brief summary of the validation tests conducted thus far is contained in Reference (12).

2.3 PLAIN CONCRETE MODELING

In recent years, a variety of nonlinear constitutive models has been proposed in the literature for describing the response of plain concrete to short-term loads, but, as noted by Chen and Suzuki,(13) a general constitutive relation capable of describing both pre- and post-failure behavior of plain concrete simply does not exist today. The present models have been based upon nonlinear elasticity, classical plasticity, hypoelasticity, endochronic plasticity, bounding surface plasticity continuous damage theory and plastic fracture theory. In almost all cases, the models were developed from, and validated against, data from standard laboratory tests in which at least two of the principal stresses were equal.

Some true triaxial experiments have also been performed on concrete, but these have been largely limited to proportional, monotonically-increasing loading to failure. The results from these tests, while useful for calibrating and validating models for relatively simple load paths, are inadequate for identifying and characterizing the salient constitutive features of concrete under arbitrary load paths, unloading, stress reversals and reloading, which are generally encountered in practice.

To fill the existing need for data on the response of plain concrete to complex, multiaxial loading paths, Scavuzzo, Stankowski, Gerstle and Ko(14) recently conducted an extensive laboratory testing program, using a true triaxial test device designed specifically for use in studying the multiaxial behavior of geomaterials. This device independently applies three normal stresses of up to 15,000 psi to the sides of 4-inch cubical specimens. The focus of this experimental study was confined to the range of load levels below that at which significant cracking of the plain concrete would occur. A total of 47 different non-standard stress paths were investigated. Of these, a number of paths were chosen to provide insight into possible stress-path independence. From the results of this study, it was found that plain concrete exhibits behavior under complex loading which appears to be not well represented by the current models.

In an effort to analytically represent the results from the experimental study, Stankowski and Gerstle(15) developed a simple, hypoelastic-type constitutive model that is an extension of a previous model by Gerstle.(16) The model was applied to several of the complex axisymmetric stress paths studied experimentally and, considering the simplicity of the model, it showed remarkable predictive capability. Several other more complex concrete models(17,18) were also exercised around the same paths by Gerstle and Willam,(19) but failed to show comparable predictive capabilities. While the simple model has shown its ability to capture many of the response features of plain concrete under several axisymmetric stress histories, it has not, to date, been extended to, nor validated against, more general loading conditions. In order to capture certain features of behavior that are beyond the scope of the simple theory, and to have a theory that is applicable to general multiaxial loading states, we explored the potential offered by the new endochronic theory for describing the extensive experimental results given by Scavuzzo, et al.(14)

The new endochronic plasticity theory was developed by Valanis,(20) and has since been applied with remarkable success to various problems of metal plasticity(21,22) and geomaterials.(23) The theory is based upon the hypothesis that the current state of stress in a material is a linear functional of the entire history of deformation, with the history defined with respect to a time scale, called intrinsic time, which is itself a property of the material at hand. Such an approach does not require the notion of yield surface nor the specification of unloading-reloading criteria, and these unique features make the theory particularly *attractive for describing the behavior of concrete*, which does not exhibit a well-defined yield point. It should be noted that the new endochronic plasticity theory considered herein is substantially different from those versions of the older theory used to develop the concrete models described by Bazant and Bhat(24) and Bazant and Shieh.(25) Proper closure of hysteresis loops is guaranteed in the present theory, so that artifices, such as the jump-kinematic hardening introduced by Bazant and Shieh,(25) are not required. Some of the basic inelastic response features of this new theory have recently been discussed by Trangenstein and Read(26) and Murakami and Read.(27)

During the past year's effort, a new endochronic plasticity theory for plain concrete was developed to describe its behavior over the stress range where significant cracking does not occur. The theory is isotropic and exhibits the important features of concrete behavior, including shear-volumetric coupling, effect of hydrostatic pressure on shear response, hardening, hysteretic effects and stress-path dependence.

This new endochronic concrete theory has been proof-tested with remarkable success against the extensive set of complex load path data recently obtained by Scavuzzo, et al. at the University of Colorado,(14) using a true triaxial device. These data cover a range of pressures from 2,000 to 12,000 psi, and consist of arbitrary load paths, unloading, stress reversals and reloading; they represent one of the most extensive set of data on concrete behavior that currently exists.

An analytical procedure for reducing the linear hereditary constitutive integrals to a system of coupled linear ordinary differential equations has been developed, and a numerical approach has been devised for treating the resulting system of differential equations that govern the model under very small load steps for either load- or deformation-controlled conditions.

As noted earlier, the scope of the new model is presently limited to stress levels in plain concrete which do not produce significant cracking. The model is isotropic and therefore unable to describe stress-induced anisotropy produced by significant cracking with preferred orientation. For many practical applications, this limitation may not prove to be overly restrictive, since there are obviously many instances where a concrete structure is driven into the nonlinear regime during service, but not to the extent where substantial cracking occurs. In the case of defense structures, however, where there is a need to predict the loads for which substantial cracking (failure) occurs, a more general model is required. In view of the very impressive predictive capability provided thus far by the new endochronic theory for concrete, we will be extending the model in our future work to cover more general behavior, including cracking.

Documentation

Complete details of the development, application and validation of the new endochronic model for concrete are given in Reference (28). Two papers on the subject have also been prepared and accepted for publication (see References (6) and (9) of Sec. 3). In addition, one of the papers (Ref. (9) is scheduled for presentation at the Second Symposium on the Interaction of Non-Nuclear Munitions with Structures in April 1985 at Panama City, Florida.

2.4 STRAIN SOFTENING

Until recently, strain softening has been generally viewed as a true material property and routinely incorporated into constitutive models. As a result, the literature abounds with advanced, complex constitutive models for materials such as concrete, rock and soil which contain strain softening. The notion of a local constitutive model is fundamentally a continuum concept in which stress, strain, density, etc., are assumed to exist at every point of a continuum and no characteristic dimensions are present. If such a local approach is valid, the constitutive behavior of an infinitesimal material element will be the same as that of a finite volume of material, provided that the stress and strain fields within the finite volume are homogeneous. When this is the case, the constitutive behavior of an infinitesimal element can then be determined from finite specimens tested under conditions of homogeneous stress and strain. As the stress and strain fields increasingly deviate from homogeneity, tests on finite specimens become increasingly inappropriate for determining material properties. The basic issue, then, is as follows: Is the strain softening inferred in the usual manner from conventional laboratory tests on concrete, rock and soil a true material property or is it simply a manifestation of the effects of progressively increasing inhomogeneity of deformation.

We have continued the study of strain softening in concrete, which was initiated under the previous AFOSR contract. A comprehensive review paper, listed as Reference 1 in Section 3, was prepared during this reporting period and has been accepted for publication. In this paper, a variety of evidence pertaining to strain softening of rock, soil and concrete is presented and carefully examined for the purpose of determining whether strain softening is a true property of these materials or simply a structural effect. The subject is approached from the experimental, theoretical and numerical viewpoints.

Without exception, the evidence leads to the conclusions that strain softening, as inferred in the usual manner from conventional laboratory tests, is not a true property of these materials, but is simply a manifesttation of the effects of progressively increasing inhomogeneity of deformation. In tests on concrete and rock, the development of internal cracking of material caused by imperfect boundary conditions between the test specimen and the loading plates was found to be the source of strain softening while, for soils, strain softening was found to arise from either stable inhomogeneous deformation caused also by imperfect boundary conditions or through unstable deformation modes which can occur irrespective of the nature of the boundary conditions. In all cases where strain softening was reported for these materials, the measured force-displacement data from laboratory tests was transformed to a stress-strain curve by simply using original values of the length and cross-sectional area of the specimens; little or no attention was given to the physical condition of the specimen during a test. In some cases, it was reported that the specimen had "virtually disintegrated" by the end of the test.

Since the existing evidence indicates that strain softening is not a true material property of concrete, rock and soil, it therefore follows that it is not appropraite to incorporate it into constitutive models for these materials intended for use within a local continuum mechanics framework. A new, rational approach for treating macroscopic "softening" of materials, such as concrete and rock, within a finite element framework is urgently needed and is the subject of considerable discussion and study within the continuum mechanics community. We are currently exploring a number of approaches to this problem under the present program.

The results of our investigation of strain softening revealed that, in many instances, theoreticians had unknowingly developed advanced constitutive models with strain softening on the basis of experimental data that was inappropriate for this purpose. The reasons for this appear to be twofold; namely, (1) there has been insufficient interaction in the past between theoreticians and experimentalists to detect a problem, and (2) experimentalists have not been aware of the need to provide greater details of the states of the specimens during tests. As a result, there has been an apparent propagation of misinformation in the literature regarding certain features of response. This observation prompted us to extend our investigation to include other features of the behavior of brittle solids besides strain softening, such as strain hardening, failure states, failure modes and strain rate effects.

The results from this study are documented in Reference (29) of Section 3, and were presented as a General Lecture to the Workshop on Inelastic Deformation and Failure Modes, Northwestern University, Evanston, Illinois, November 18-21, 1984. Also, a paper on this topic (Reference (7) of Sec. 3) has been prepared and accepted for publication.

III. PUBLICATIONS

The following papers were prepared, and submitted for publication, during the reporting period covered by this report:

1. Read, H. E., and G. A. Hegemier, "Strain Softening of Rock, Soil and Concrete," Mechanics of Materials (1985), to appear.
2. Read, H. E., Discussion of "Hysteretic Endochronic Theory for Sand," by Z. P. Bazant, R. J. Krizek and C.-L. Shieh, Journal of Engineering Mechanics, Vol. III(1), Jan 1985, 103.
3. Hegemier, G. A., H. Murakami and L. J. Hageman, "On Tension Stiffening in Reinforced Concrete," submitted to Mechanics of Materials.
4. Murakami, H., and G. A. Hegemier, "On Simulating Steel-Concrete Interaction in Reinforced Concrete. Part I: Theoretical Development," submitted to Mechanics of Materials.
5. Hageman, L. J., H. Murakami and G. A. Hegemier, "On Simulating Steel-Concrete Interaction in Reinforced Concrete. Part II: Validation Studies," submitted to Mechanics of Materials.
6. Valanis, K. C., and H. E. Read, "An Endochronic Plasticity Theory for Concrete," Mechanics of Materials (1985), to appear.
7. Hegemier, G. A., and H. E. Read, "On Deformation and Failure of Brittle Solids: Some Outstanding Issues," Mechanics of Materials (1985), to appear.
8. Hegemier, G. A., and H. Murakami, "A Nonlinear Theory for Reinforced Concrete," Proc. Second Symp. on the Interaction of Non-Nuclear Munitions with Structures (1985), to appear.
9. Valanis, K. C., and H. E. Read, "An Endochronic Plasticity Theory for Concrete," Proc. Second Symp. on the Interaction of Non-Nuclear Munitions with Structures (1985), to appear.

IV. INTERACTIONS

The following is a list of the interactions (coupling activities) by the contract staff members which occurred during the reporting period on issues related to the research done under the present contract:

5.1 ORAL PRESENTATIONS AT MEETINGS, CONFERENCES, SEMINARS AND WORKSHOPS

1. Murakami, H., "Some Basic Inelastic Response Features of the New Endochronic Theory," Oral presentation at the 21st Annual Meeting of the Soc. Engrg. Sci., VPI, Blacksburg, VA, October 15, 1984.

2. Hegemier, G. A., "On Deformation and Flow of Brittle Solids," General Lecture presented at the Workshop on Inelastic Deformation and Failure Modes, Northwestern University, Evanston, Illinois, November 18-21, 1984.

3. Valanis, K. C., "An Endochronic Plasticity Theory for Concrete," Oral presentation at the Workshop on Inelastic Deformation and Failure Modes, Northwestern University, Evanston, Illinois, November 18-21, 1984.

4. Read, H. E., "Inelastic Response Characteristics of the New Endochronic Theory with Singular Kernel," Oral presentation at the Workshop on Inelastic Deformation and Failure Modes, Northwestern University, Evanston, Illinois, November 18-21, 1984.

5. Read, H. E., "On Modeling the Dynamic Behavior of Plain Concrete," oral presentation at DNA Concrete Material Properties Meeting, Terra Tek, Salt Lake City, Utah, March 7, 1984.

6. Hegemier, G. A., "Development of an Advanced Constitutive Model for Reinforced Concrete," oral presentation at DNA Concrete Material Properties Meeting, Terra Tek, Salt Lake City, Utah, March 7, 1984.

5.2 CONSULTING AND ADVISORY FUNCTIONS TO OTHER LABORATORIES AND AGENCIES

G. A. Hegemier - Member of DARPA Advisory Committee for Large Scale Computations of Nonlinear Material Behavior (1984 to present)

H. E. Read - Member of DNA Concrete Material Properties Steering Committee (1983 to present)
- Consultant to U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, (June 1984).

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