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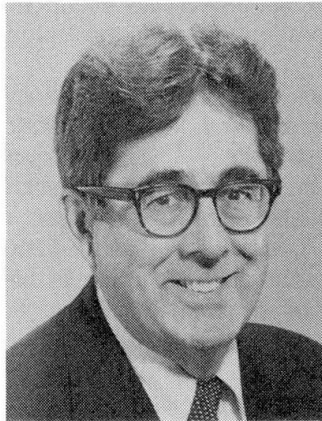
## Analysis of Structural Concrete Systems

Analyse des structures en béton

Berechnungsmethoden von Stahlbetontragwerken

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### SUMMARY

A review of the analysis of structural concrete systems is presented with respect to analytical models, linear elastic analysis, static and dynamic analysis, segmental analysis, and nonlinear analysis. Past history, present status, future trends, and the role of the computer are discussed. Several examples are presented to illustrate points made.

### RÉSUMÉ

Un compte rendu des méthodes d'analyse des structures en béton est présenté où l'on tient compte des modèles analytiques, de l'analyse linéaire élastique, de l'analyse statique et dynamique, de l'analyse concernant des éléments de construction discrétisés ainsi que de l'analyse non-linéaire. L'évolution passée, l'état actuel et les tendances d'avenir vues à travers le rôle de l'ordinateur sont successivement discutés. Plusieurs exemples illustrent les points abordés.

### ZUSAMMENFASSUNG

Diese Arbeit gibt einen Überblick über Berechnungsmethoden von Stahlbetontragwerken. Der Überblick umfasst analytische Modelle, linear elastische sowie statische und dynamische Berechnungsmethoden, Berechnungen von Tragwerken in Segmentbauweise, sowie nichtlineare Berechnungsmethoden. Die Entwicklungsgeschichte, gegenwärtige Fortschritte, zukünftige Tendenzen und der Beitrag des elektronischen Rechners werden vorgestellt. Mehrere Beispiele veranschaulichen die vorgetragenen Argumente.



## 1. INTRODUCTION

A structural concrete system may be defined as any structural system made up of structural concrete in combination with any amounts of reinforcing steel, prestressing steel, and rolled steel sections. Thus, structures constructed of plain concrete, reinforced concrete, prestressed concrete, partially prestressed concrete, composite concrete-steel sections, or any combination thereof, and built cast-in-place, precast, nonsegmentally, or segmentally, are all included in the above definition.

Structural concrete systems have been widely used for buildings, bridges, dams, tanks, cooling towers, nuclear containment vessels, offshore oil platforms, and many other structures. The ultimate goal of the designer of these structures is to produce a structure which satisfies the functional, structural, construction, esthetic, and cost requirements for the completed structure.

The overall design of these structures must insure their safety and serviceability throughout their construction and service life history under normal and abnormal loading and environmental conditions due to dead loads, live loads, construction, winds, earthquakes, floods, temperature variations, support movements, and other effects. In the past the analysis of these structures to determine internal forces, moments, and displacements have been based on simplified analytical models, generally assuming a linear, homogeneous, uncracked material. The designs for the required reinforcement or prestressing to resist these internal forces and moments have then generally been based on empirical procedures prescribed in codes or recommended practices for each particular type of structural concrete system.

Considerable research and effort have been exerted in recent years to develop improved methods of analysis and design of individual members and joints using strut and tie models (Schlaich [1], Marti [2]), truss models (Hsu [3]), truss models and compression field theory (Collins et al. [4,5]), and plasticity theory (Thurlimann [6]). Many other authors have contributed to the above research on individual members and joints. A smaller number of researchers have studied the analysis and design of total structural concrete systems composed of concrete, reinforcing steel, and prestressing tendons. Scordelis [7,8] has presented finite element models, methods of analysis, and computer programs for these systems, built nonsegmentally or segmentally, and loaded through their elastic, cracking, inelastic, and ultimate ranges.

With the increased complexity of structures and the greater computational power and speed available today, there is a need to develop a unified approach for the analysis and design of the entire spectrum of these structural concrete systems which takes advantage of the latest analytical and experimental research, materials, computers, and practical design and construction experience.

The purpose of this introductory report is to present the author's views on some considerations to achieve the above goal primarily with respect to structural analysis. Structural design and structural analysis will be discussed with respect to their past history, present status, future development, and the role of the computer. Several examples will be described to illustrate points to be made. It is hoped that this report will stimulate other authors to present their views on these subjects so as to have a useful discussion at the Stuttgart Colloquium.

## 2. STRUCTURAL DESIGN

The total structural design process involves many aspects, but for purposes of discussion it can be simplified to the following three stages: (1) conceptual design, (2) preliminary design, and (3) final design. Within these three stages the structural system selected must be considered from a global, regional and local analysis, design, and response standpoint to insure its satisfactory performance. The term "satisfactory performance" must be defined with respect to the criteria in existence at the time of the original design and specified for external loads and other actions, as well as displacements, cracking, etc. Changes in these criteria over the years due to any reason must be recognized and may require what has come to be known as "retrofitting" to insure satisfactory performance under the new criteria.

In all aspects of the structural design process, the designer must apply a good knowledge of structural behavior, mechanisms of failure, materials and analysis, and continuously ask himself the question "what if?" to insure that his structure has redundancy and that progressive failure can be avoided. Let us now consider the three design stages and the role of the individual designer, the computer, and education in each of them.

### 2.1 Conceptual Design

The conceptual design stage is perhaps the most important. However, it is not sufficient by itself without the second and third stages. The selection of the correct design criteria and structural system for a particular structure such as a building, bridge, dam, etc. which satisfies functional, esthetic, structural, and construction requirements is certainly dependent on the designer's creative ability, experience, and judgment. The question is: how does he develop these? The author believes that they are developed to a large extent by the detailed analyses and designs that the designer has previously performed and the subsequent observations that he has made of his and other creative designers' structures during construction and after completion over a long period of time.

As in art, music, or in the sciences, the creative ability of structural designers will vary greatly even after a long period of time. Only a few will become truly great designers. One of the biggest challenges to engineering educators is how computers can be brought into the educational process to nurture, rather than destroy, the development of this creative conceptual design ability of structural engineering students. Some educators believe interactive computer graphics will provide the key, where the student will sit in front of his user-friendly-oriented personal computer and communicate with it much as he would with a friendly teacher who has all the answers to all of the questions he has. Other computer advocates believe that expert systems development will provide the link between the expert, knowledgeable engineer, expert system, and the novice user. The author does not personally believe that these can replace the human personal link of a good teacher or contact with a good designer who can provide the enthusiasm and examples for the student to aspire to.

Other necessary components of structural engineering education are personal experience and observation of the behavior of real engineering materials and real structures in the laboratory and in the field, both during and after construction. In the opinion of the author, computer simulations can never replace this experience.

### 2.2 Preliminary Design

Once the conceptual design has been completed and one or more structural systems and materials have been selected, a preliminary analysis and design takes place to determine and compare the general dimensions, proportions, and costs of the structural systems selected. In the past, this was often done using approximate methods on simplified analytical models based on experience and simple calculations using statical control. Most of the great designers of the past and present were and are experts at doing this type of preliminary design by hand without the aid of a computer. In the context of today's availability of personal computers, every engineer with stronger and more powerful interactive computer graphics programs can study simplified or final analytical models of a structural system. The author believes that every designer in the future will use his personal computer as a powerful tool in every phase of the design, including the preliminary design stage.

### 2.3 Final Design

The final stage in the design process is the detailed global, regional, and local analysis and design of the selected structure using accurate analytical models to determine the displacements and internal forces and moments needed to design and proportion the structural elements and joints and to check the strength, stiffness, and stability of the structure as a whole. It is at this stage of final analysis and design where the computer has traditionally played its most dominant role since the beginning of its use in structural engineering. Computer programs which each year have increasing capabilities, speed, versatility, and ease of use are being used for final analysis, design, and even drafting. This trend is bound to continue.





While the computer can play an important role in the final design stage, it is imperative that experienced and qualified structural engineers be involved in the interpretation of the results using their judgment and knowledge of structural behavior to insure that the final design meets all of the design criteria for the particular structure throughout its construction and service load history and under increasing live loads, environmental loads, or other effects throughout its elastic, cracking, inelastic, and ultimate ranges.

Of particular importance in the final design is a final review of the design drawings by an experienced structural designer to insure that the structural system and the concrete dimensions and detailing for reinforcement and prestressing of the members and joints are reasonable and no obvious omissions have been made. It should always be remembered that, finally, only what goes on the drawings is what will be built.

### 3. STRUCTURAL ANALYSIS

#### 3.1 General Remarks

The objective of any structural analysis can be defined in general and simple terms as follows: *Given:* a defined analytical model of some real total structural system or portion thereof, subjected to a prescribed load and environmental history; *find:* the external reactions and displacements and the internal forces and deformations in the system at any location and time. The analytical model may be "global," such as the total structure; "regional," such as a particular rigid frame, beam, or column; or "local," such as a joint or anchorage.

Depending on the design criteria, importance, and complexity of the structure, as well as other factors, a variety of assumptions may be made for the analytical model and the type of analysis to be used. These may involve (1) linear or nonlinear analysis, (2) static or dynamic analysis, (3) time-dependent analysis, and (4) segmental analysis, as well as other analyses.

For many structures considered in present design codes, strength design is based on a linear elastic static analysis of the structural concrete system subjected to factored loads to determine internal forces and moments from which concrete dimensions and reinforcing and prestressing requirements are determined based on ultimate strength design procedures. Past practice often used hand calculations on simplified analytical models, design tables, charts, graphs, and other published aids to carry out this procedure. These have been and are rapidly being replaced by computer aids such as programs, spread sheets, etc. geared to the personal computer which many engineers now possess and utilize. This trend is bound to continue.

While many of the analyses and designs described above can be accomplished by following approximate or empirical procedures prescribed in codes or recommended practices, it is desirable to have refined analytical models and methods of analysis which can trace the structural response, as necessary, throughout the construction, service, and environmental load history and under increasing loads through their elastic, cracking, inelastic, and ultimate ranges.

A unified analytical approach and model is needed which, as necessary, can be used for linear or nonlinear analysis, static or dynamic analysis, time-dependent analysis, segmental analysis, and other analyses. Inherent in such an approach is the use of the computer as a powerful computational tool. Versatility in application should be an important feature of such an approach so that global, regional, or local analyses of a structural concrete systems can be performed as desired. One such unified approach is described below and several examples of its application are given later to stimulate useful discussion at the Stuttgart Colloquium.

#### 3.2 Analytical Models

For the purposes of structural analysis, a structural concrete system can be modelled analytically as a system of joints (nodal points) interconnected by discrete structural elements made up of concrete, reinforcing steel, and prestressing steel. In general, the total structure may be idealized by one or more of the following types of structural systems (Fig. 1):

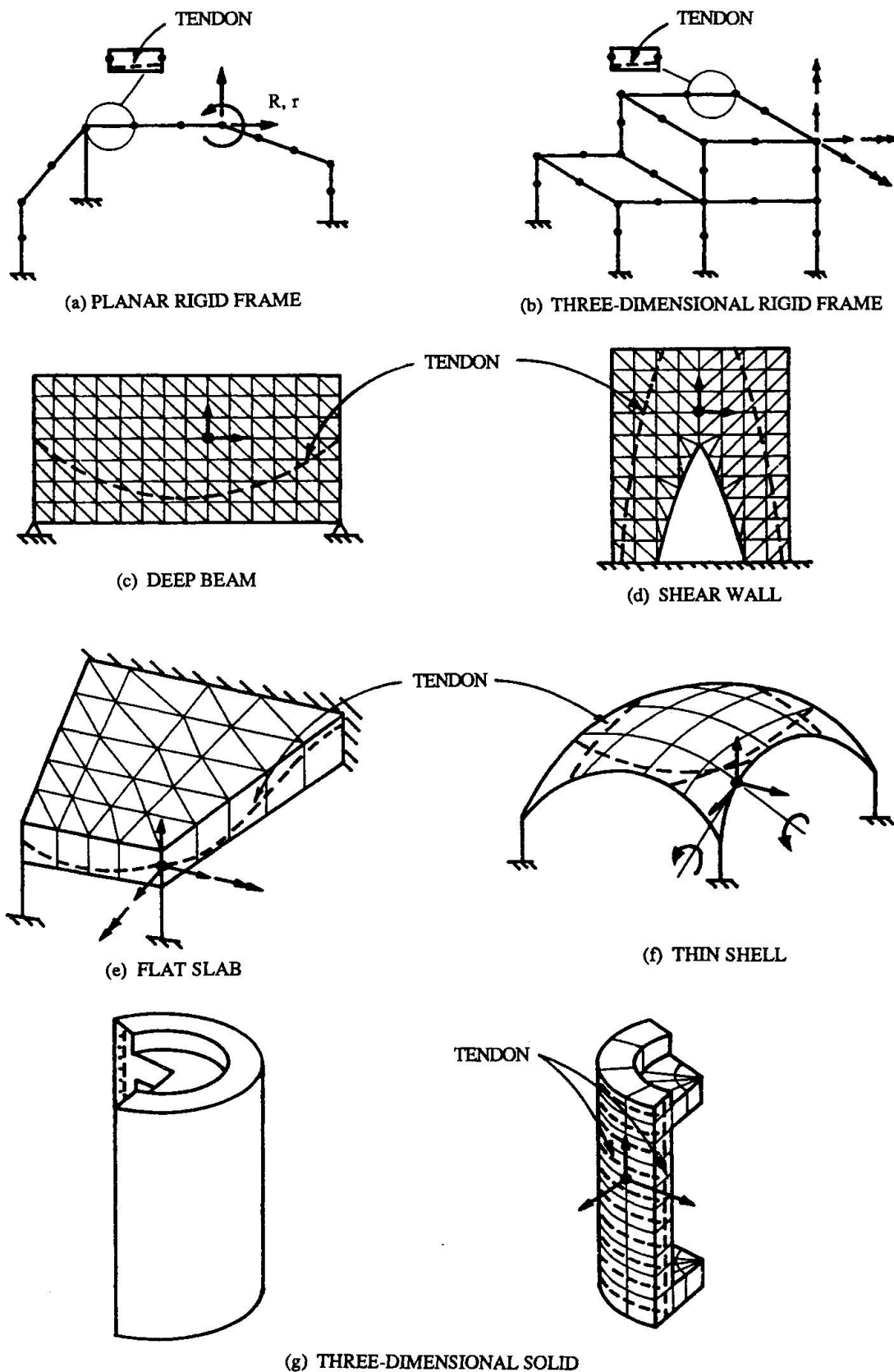


FIG. 1 - FINITE ELEMENT ANALYTICAL MODELS



1. Planar or three-dimensional rigid frames made up of one-dimensional (1D) elements;
2. Panels or slabs made up of two-dimensional (2D) triangular or quadrilateral flat finite elements;
3. Thin shells made up of two-dimensional (2D) flat or curved finite elements or axisymmetric thin shell elements; and
4. Solids made up of three-dimensional (3D) solid finite elements or axisymmetric solid elements.

If desired, a regional or local portion of the total structure also can be modelled as a refined subset of the total global structure, as desired. With such a unified analytical model, various types of analysis can be performed. The selection of an appropriate analytical model to represent an actual structure or portion thereof is a key step in the analysis process and is influenced by many factors. This is illustrated later in Example 1.

### 3.3 Linear Elastic Analysis

Numerous general purpose programs have been developed for personal microcomputers (PC) to perform linear elastic analyses for the above systems. For structural concrete systems the elements usually are assumed to be homogeneous uncracked gross concrete members. The rapid development of the PC during the past few years at decreasing cost has put at the personal command of the individual engineer, at his desk, and at any time, the computational power of the mainframe computers used in the 1970's. The available structural engineering PC software employs computer graphics in color, improved pre- and post-processing, computer-aided analysis and design, database systems, and the use of spreadsheets to simplify and speed up many of the tasks confronting the structural engineer.

A typical example of such a PC computer program available commercially in the U.S. today with which the author is familiar is the SAP90 program developed by Wilson and Habibullah [9]. Many others also exist. The SAP90 computer program consists of five modules which can be linked as desired:

1. Basic statics module for pre-processing and checking of input data, plus the static analysis of 2D and 3D structures made up of 1D frame elements;
2. Finite element module for the analysis of continuum structures made up of plate, membrane, shell, axisolid, or 3D finite elements;
3. Dynamics module for eigenvalue, Ritz, response spectrum, or time history dynamic analysis of structures;
4. Graphics module for plotting and display of undeformed and deformed shapes; mode shapes; axial force, shear, and moment diagrams; and stress contours; and
5. Design module for using the results found in 1. to 4. in post-processor modules to design members to satisfy existing steel or concrete design codes.

It is the author's conclusion that the linear static analysis of any structural system that can be modelled as shown in Fig. 1 can be accomplished today quickly and economically. However, useful and correct results can be obtained only by careful and proper interpretation of the input and output.

### 3.4 Static and Dynamic Analysis

Either or both a static or/and dynamic analysis may be required depending on the nature of the design criteria, loading, and environmental history. Static loadings, analytical procedures, and design criteria are usually well defined and understood. On the contrary, these are more difficult to define and understand for dynamic effects due to earthquakes. For example, the principles used in the development of seismic guideline provisions for bridges in the United States [10] (1981) were:

1. Small-to-moderate earthquakes should be resisted within the elastic range of the structural components without significant damage;
2. Exposure to shaking from large earthquakes should not cause collapse of all or part of the bridge; and
3. Realistic seismic ground motion intensities and forces should be used in the design procedure.

Item 3. is difficult to define for a particular geographical location and is highly dependent on soil conditions. Depending on the complexity and importance of the structure, the analysis may be based on an equivalent static force method, a dynamic response spectrum method, or a dynamic time history method. For structural concrete systems subjected to large earthquakes, a linear elastic dynamic analysis is often used. Dynamic analyses usually indicate internal forces and moments well above the linear elastic range. Concepts of "ductility demand" and "ductility factors" based on engineering judgment and research must be introduced to justify the safety of the structure based on these analytical results. Inherent in their justification is the use of properly detailed reinforcement and confinement of concrete in the joints and members.

Seismic analysis and design of structural concrete systems should be based on the latest knowledge and state of the art in this rapidly changing field of study. Analytical and experimental research, together with field observations of damage during earthquakes during the past thirty years, has resulted in a tremendous change and improvement in rational seismic analysis and design for this complex problem. Computer tools are now available to assist in this process, but the basic methods used in them should be clearly understood by the user. Example 2 illustrates some of the problems associated with seismic analysis and design in an actual structural failure during an earthquake.

### 3.5 Segmental Analysis

Another important consideration in the analysis of certain structural concrete systems such as segmentally erected prestressed concrete bridges, cable-stayed bridges, tall buildings, dams, and other structures is to be able to trace the response of the structure during each stage of its construction. For example, an analysis of a segmentally erected prestressed concrete bridge might use a plane frame model consisting of 1D elements made up of concrete and prestressing tendons. During construction, possible changes in structural configuration or loading can occur at any time and could include restraining and releasing of support conditions, installing and removing frame elements, stressing and removing prestressing tendons and form traveller loadings, and applying or removing external loads. All of these should be considered in a segmental analysis which often is performed considering the structure to be made up of linear elastic uncracked concrete elements and prestressing tendon elements.

Of particular importance in a segmental analysis is its ability to trace the time-dependent response through construction and under service loads, providing a record of stresses in the concrete and the prestressing tendons and displacements of the structure during this history. The time-dependent effects of creep, shrinkage, and aging of the concrete and relaxation of the prestressing steel should be included in the analysis, which is generally based on a step-forward integration in the time domain. Because of its complexity, special purpose computer programs for segmental analysis must be utilized. Such a computer program, SFRAME, has been developed by Ketchum [11]. Others are also available, generally on a proprietary basis. Care must be exercised in selecting the input parameters for creep and shrinkage of the concrete and relaxation of the prestressing steel because of the sensitivity of the final results to this selection. Example 3 demonstrates the implication of some of these factors in the deflection analysis of a 195-meter-span prestressed concrete segmental bridge.

### 3.6 Nonlinear Analysis

The capability for nonlinear material, geometric, and time-dependent analysis of reinforced and prestressed concrete systems of all types has been the goal of research at Berkeley for the past fifteen years. Methods of nonlinear analysis and computer programs, described in some detail in references 7 and 8, have been developed for 2D and 3D frames, slabs, panels, and thin shells

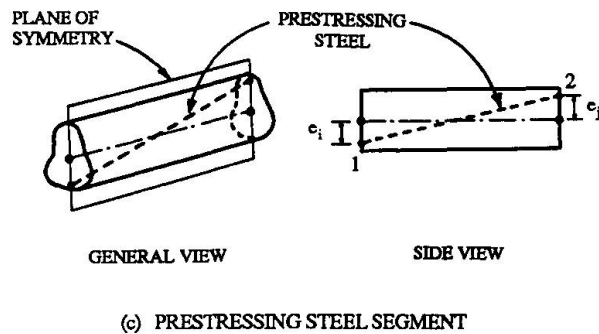
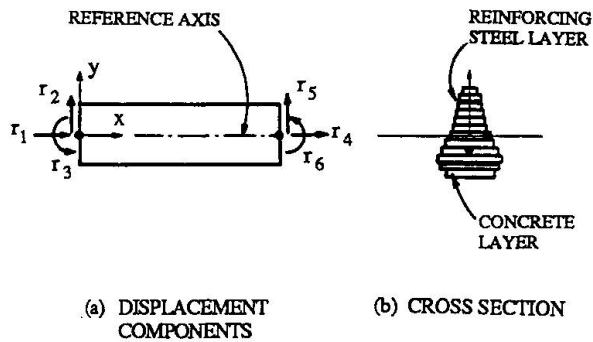


FIG. 2 - ONE DIMENSIONAL ELEMENT FOR PLANAR FRAMES

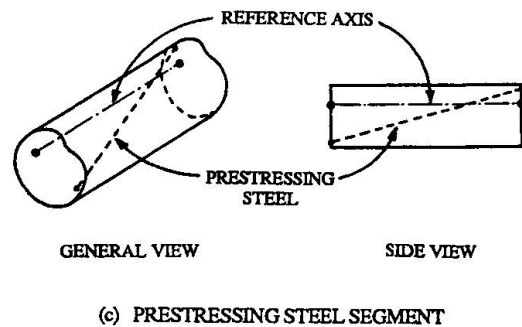
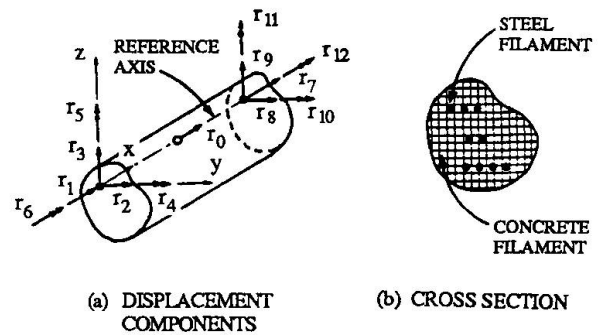


FIG. 3 - ONE DIMENSIONAL ELEMENT FOR 3D FRAMES

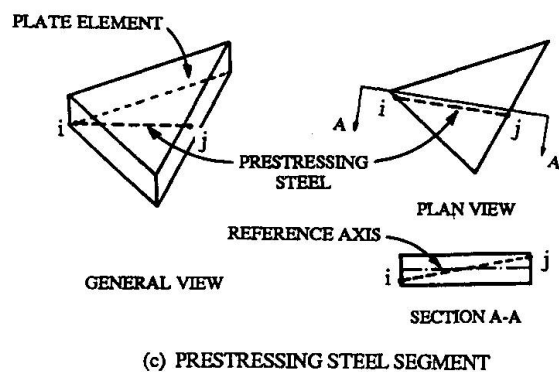
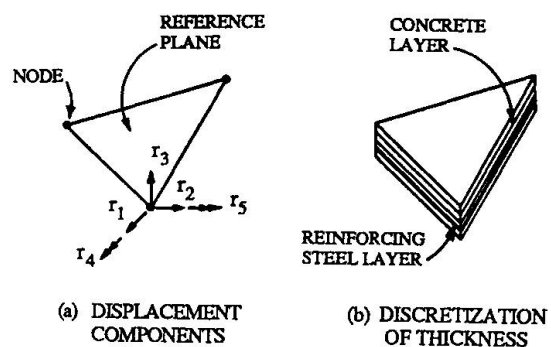


FIG. 4 - TWO DIMENSIONAL ELEMENT FOR PANELS AND SLABS

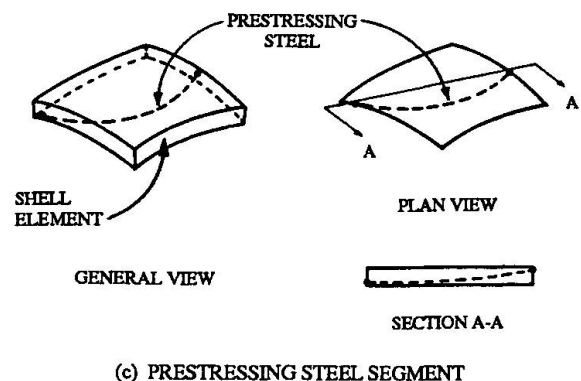
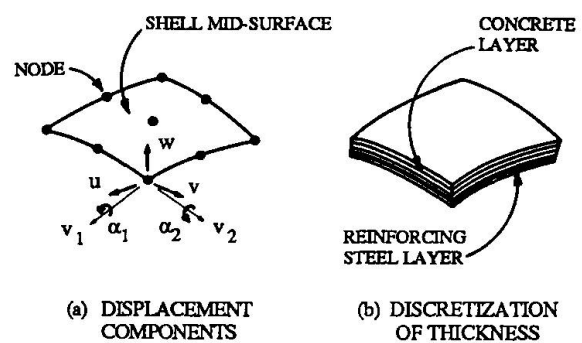


FIG. 5 - CURVED ISOPARAMETRIC ELEMENT FOR THIN SHELLS

(Fig. 1), as well as for straight and curved box girder bridges. Segmental analysis capabilities have been added recently for planar and three-dimensional frames.

Time-dependent effects due to load history; temperature history; creep, shrinkage, and aging of the concrete; and other prestress losses due to anchor slip, friction, and relaxation are all included in the analysis. Any combination of nonprestressed and prestressed reinforcement may be specified so that partial and fully prestressed cases may be analyzed through their elastic, cracking, inelastic, and ultimate ranges.

For 2D or 3D rigid frames (Figs. 2, 3) a series of 1D longitudinal finite elements with layered or filamented cross-sections of concrete and reinforcing steel are used to model the systems. For slabs, panels, and thin shells (Figs. 4, 5) an assembly of flat or curved 2D layered finite elements are used to model the concrete and multidirectional reinforcement systems. In all of the above, within each finite element the prestressing steel segment is assumed straight or curved and can be defined by vectors in space using its element boundary coordinates.

In the nonlinear analysis of all of the above structural systems, a unified finite element tangent stiffness formulation, coupled with a time-step integration scheme, is used to trace their quasistatic response up to ultimate failure. Nonlinear material stress-strain relationships are used for the concrete, reinforcing steel, and prestressing steel throughout the nonlinear finite element analysis to determine the displacements; crack patterns; and strains and stresses in the concrete and reinforcing and prestressing steel at any time up to failure, under any load or environmental history.

With the increasing computational power and speed of computers every year, these methods of analysis and computer programs can be used for global analysis, where deemed necessary and applicable, in an economical way. Example 4, given later, illustrates one such example involving a nonlinear material, geometric, and time-dependent analysis of a reinforced concrete shell.

While the analytical models for 1D elements accurately model the nonlinear longitudinal stress response due to axial force and bending moments (Figs. 2, 3), additional research needs to be done to represent the nonlinear response due to shear and torsion more accurately without going to 2D or 3D solid elements (Figs. 1c to 1g). These solid elements with reinforcement and prestressing can also be used for the local analysis of joints or portions of members from planar or 3D frames loaded to failure.

At the basic research level, work must continue on how best to model analytically in detail, especially at the "local level," the nonlinear effects up to failure of the structural concrete system made up of a combination of concrete, reinforcing steel and prestressing steel under combined stress, creep, shrinkage, cracking, aggregate interlock, dowel action, bond, tension stiffening, stress relaxation, cyclic loading, and dynamic loading. These are not simple problems to answer, but the best available analytical tools must be developed and utilized whenever needed and necessary.

#### 4. EXAMPLES

Four examples are presented to illustrate some of the capabilities and problems in the use of the methods of analysis which have been described. The structures considered are: (1) a multicell, multispan, curved, prestressed concrete bridge on skew supports, (2) a multispan double deck viaduct structure, (3) a 195-meter-span prestressed concrete segmental bridge, and (4) a gabled hyperbolic paraboloid (HP) shell roof.

##### 4.1 Example 1 - Highway Bridge, San Juan, Puerto Rico

A three-span, multicell, curved, prestressed box girder bridge (Fig. 6), proposed as part of the highway connection to the airport in San Juan is chosen to illustrate the possible selection of analytical models for a linear elastic analysis. Complete details of this study have been presented by Scordelis et al. [12]. The general plan, typical panel tendon profile, and cross-sectional dimensions of the constant depth bridge are shown in Fig. 6.





Several analytical models of increasing complexity were possible:

1. A planar grid, hereinafter termed the "SAP4 model," consisting of a single line of 1D beam elements, with six degrees of freedom at each end, along the longitudinal axis of the total bridge cross-section, rigidly connected and supported by transverse 1D elements at the supports oriented in the direction of the skew end abutments and interior support bents;
2. A planar grid consisting of six lines of 1D beam elements with six degrees of freedom at each end along the six longitudinal axes of the girder webs, supported by transverse 1D elements at the skew end supports and interior support bents, and also connected transversely at specified intervals in each span by 1D elements simulating the transverse bending stiffness of the bridge or diaphragms between longitudinal girders;
3. An orthotropic slab having the plan geometry and support conditions of the actual bridge, with appropriate bending and torsional stiffnesses assigned to the slab in the longitudinal and transverse direction to simulate the actual bridge;
4. A finite element model, hereinafter termed the "CELL4 model," in which the top and bottom slabs, the longitudinal webs, and the transverse diaphragms or supports are modelled with 2D finite elements incorporating both in-plane membrane stiffnesses and plate bending stiffnesses.

Typical of many modern designs today, the selection of the analytical model to use is highly dependent on the computer programs available and their pre- and post-processing and automatic generation capabilities for input of nodal point coordinates, element properties, dead loads, live loads, and prestressing loads, and for output of displacements, internal forces, and moments. Based on these criteria and the availability of a general purpose program for the SAP4 model and a special purpose program for the CELL4 model, only these models were chosen for the analysis. The same mesh layout (Fig. 6a) was used for both models. For the CELL4 model, automatic generation of dead loads and equivalent prestress loads was performed internally in CELL4 from a minimum of necessary of input data. Such a capability was not available for the SAP4 model, and extensive calculations had to be carried out externally for the prestressing load input data into SAP4.

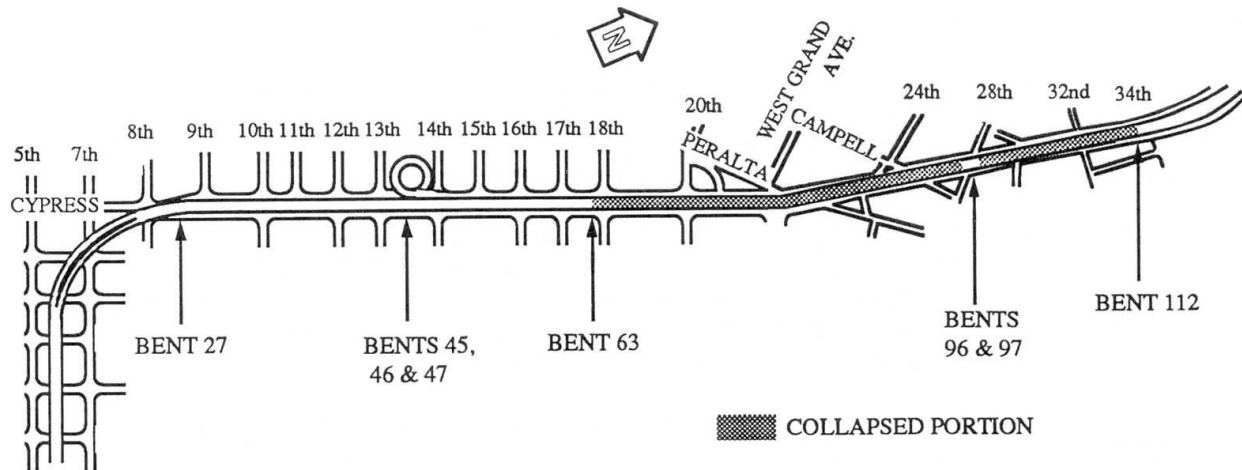
The SAP4 beam model had the advantage of simplicity of output since, as a single longitudinal member, it yielded results for the longitudinal variation of centerline displacements and total sectional forces and moments. However, it had the disadvantage that it did not give any information on the transverse distribution of these quantities. On the contrary, the CELL4 finite element model gave a voluminous output of stresses in all elements and displacements throughout the width and length of the model. For use in interpretation and design, automatic stress integration routines in CELL4 provided results for internal forces and moments in six prescribed individual longitudinal girders and for the total section. Time required for external calculation of these quantities from element stresses would have been prohibitive. Thus, the CELL4 model gave a complete output of the distribution of individual girder forces, moments, and displacements over the entire structure with about the same external effort used for the SAP4 model.

This illustrates the importance of available software and their capabilities in selecting the analytical model to be used.

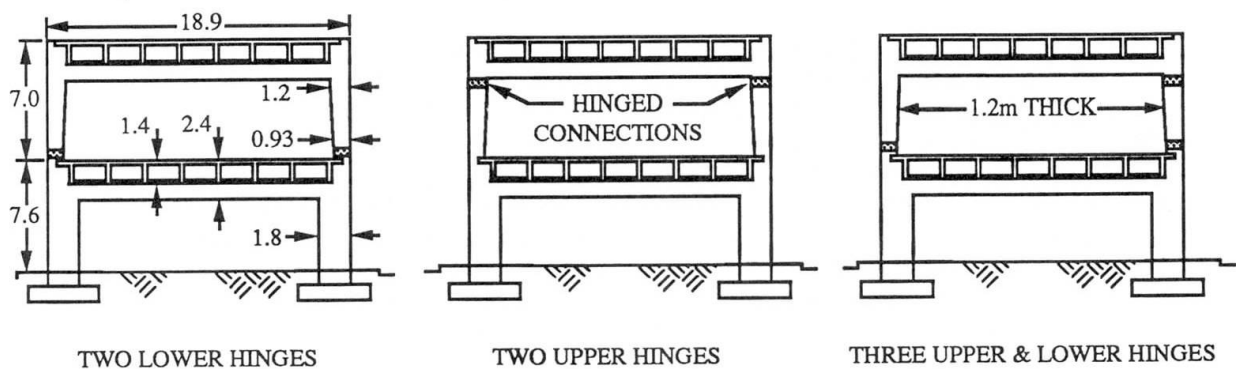
#### 4.2 Example 2 - I880 - Cypress Viaduct, Oakland, California

The Cypress Street Viaduct (Fig. 7) was a 2.5 km long concrete double deck freeway carrying four lanes of traffic on each deck. It consisted of a series of eighty-three two-story bents extending from bent 29 through bent 111 (Fig. 7a), monolithically connected to and supporting seven-cell box girder bridge spans on two levels. Several transition bents also existed at each end. Typical transverse dimensions are shown in Fig. 7b. Typical longitudinal spans varied from 21 to 24 meters. A variety of bent types and hinge combinations were utilized in the upper story columns, with the three most common shown in Fig. 7b.

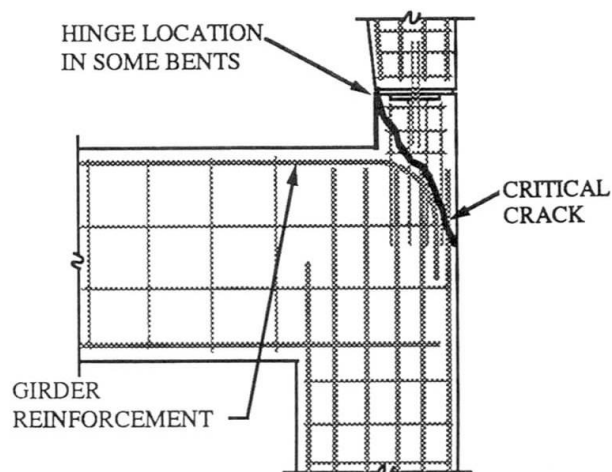
Preliminary design of the structure by CALTRANS (California Department of Transportation) began in 1949 and construction took place between 1955 and 1957. During the magnitude 7.1 Loma Prieta



a) PLAN OF CYPRESS STRUCTURE WITH DAMAGED BENTS



b) TYPES OF BENTS WITH TYPICAL BENT DIMENSIONS (IN METERS)



c) DETAIL OF FAILED CONNECTION



d) PHOTO OF COLLAPSED STRUCTURE

FIG. 7 - EXAMPLE 2 - I 880 - CYPRESS VIADUCT - OAKLAND, CALIFORNIA

earthquake of October 17, 1989, a large portion of the structure collapsed, extending from bent 63 through bent 112, with only bents 96 and 97 remaining standing (Fig. 7). Forty-two persons were killed and 108 injured in the collapse.

The analysis and design of the viaduct between 1949 and 1955 were performed without the benefit of the knowledge gained in seismic design during the past thirty years and without the aid of computers. It is believed that the structural system was designed with many hinges to simplify its analysis and interpretation of behavior, as well as provide for movements due to creep, shrinkage temperature and prestressing, and future construction additions. This, coupled with the minimum seismic design criteria and forces existing in the early 1950's made the structure highly susceptible to damage or collapse under a strong earthquake.

After the 1971 San Fernando earthquake, CALTRANS's seismic design criteria were upgraded for new construction to include more realistic forces, ground motions, and dynamic analyses using computers. However, it was decided as a first priority that the limited available funds for retrofitting only be used to install longitudinal restrainers at transverse expansion joints existing in every third span of the box girder bridge system to prevent failures of the types experienced during the 1971 San Fernando earthquake. Unfortunately, no detailed global, regional, and local analyses of the entire structural system were made, at that time or up until the failure of the viaduct on October 17, 1989, to determine if other weaknesses existed.

The typical failure mode for most of the bents, between bents 63 and 112, is shown in Figs. 7c, d. The heavy lateral shears generated by the earthquake ground motions, which had to be transferred through the hinge joint together with the vertical gravity load of the structure above, caused a critical diagonal crack below the joint and along a plane of weakness above the bent-down girder reinforcement (Fig. 7c). The vertical gravity and lateral seismic forces then pushed the upper column down and away from the joint, causing the collapse of the upper deck onto the lower deck. A lack of sufficient transverse confinement reinforcement in the joint region, as is recommended today, was a key factor in the failure.

Subsequent to the earthquake a number of analytical and experimental investigations have been made which predict the failure as it occurred. These have included static and dynamic analyses at a global, regional, and local level, as well as ambient and forced vibration tests and quasistatic cyclic load tests on an undamaged three-bent (45, 46, 47) portion of the viaduct. A decision to demolish and remove the entire viaduct was made, and this was completed in January, 1990.

This example illustrates the importance of using the latest research findings and the best analytical tools in the design of new structures and the retrofitting of old structures.

#### 4.3 Example 3 - Parrotts Ferry Bridge, California

This example is used to illustrate the importance of basic input parameters and refined analytical models in time-dependent computer analyses of prestressed concrete segmental bridges. The Parrotts Ferry Bridge (Fig. 8) is a segmentally erected, three-span, post-tensioned, single-cell box girder bridge with a center span of 195 meters supported by 68-meter-high bridge piers. The bridge was constructed of cast-in-place lightweight concrete segments using the balanced cantilever method and was completed in 1979.

During design, prior to construction, analyses were performed including the time-dependent effects of creep and shrinkage using simplified analytical models. During and after construction, deflections have been monitored over the past ten years. Both the magnitude and the current rate of the measured midspan deflection have been larger than analytically predicted (Figs. 8c, d). Measured deflections below the predicted closure elevation were 10 cm at closure in March, 1979, 38 cm in September, 1979, and 66 cm in July, 1988. While the bridge is not in any structural distress, its present appearance with a pronounced midspan sag (Figs. 8c, d) is disconcerting to riders and viewers.

Recent detailed segmental analyses of the bridge using the computer program SFRAME [11], with refined analytical models for the structure and for creep, together with analyses and tests of the

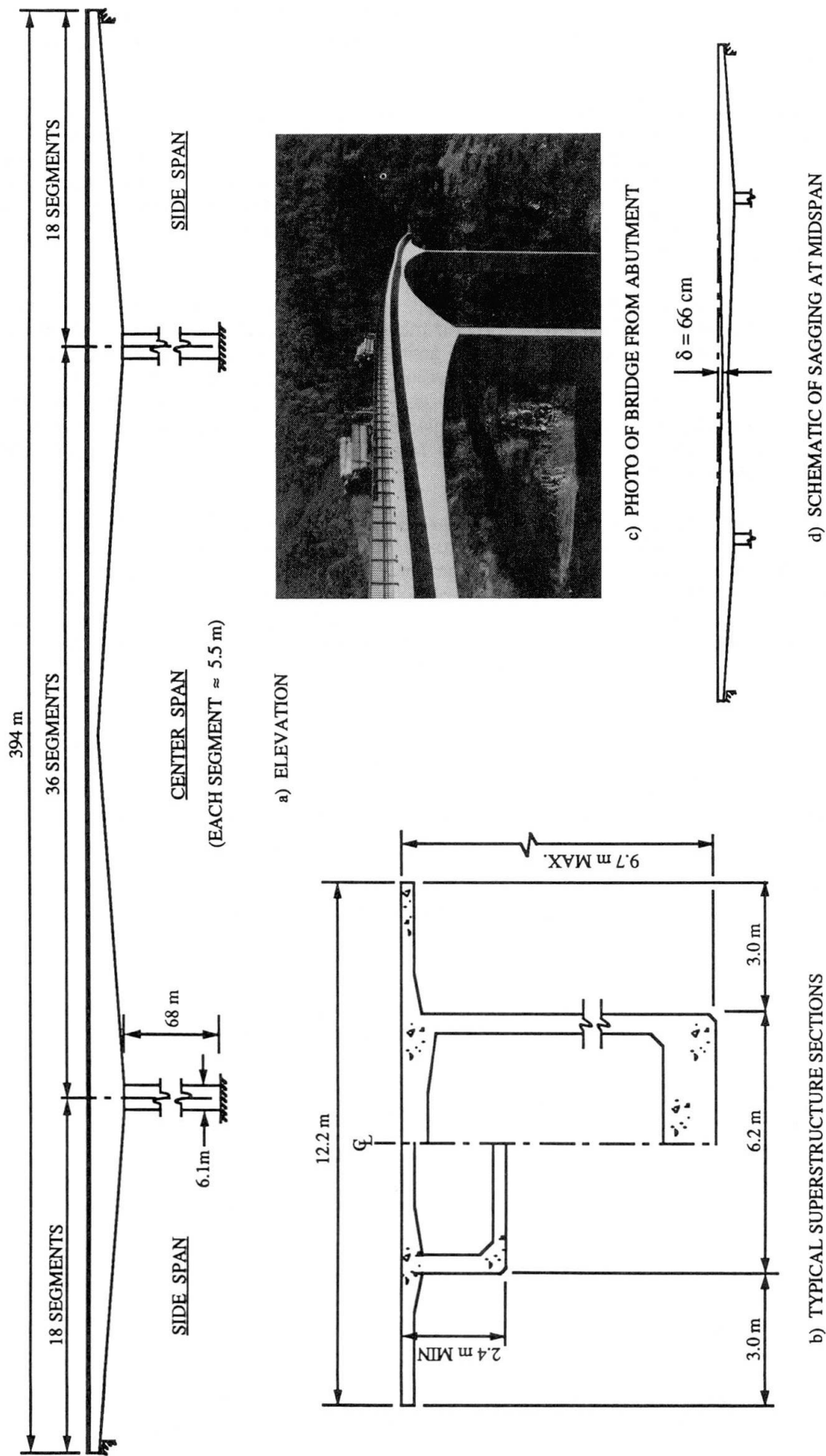
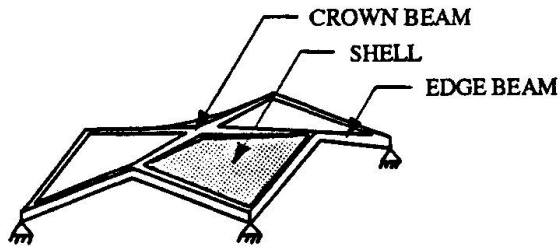
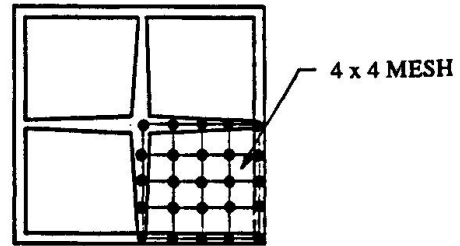


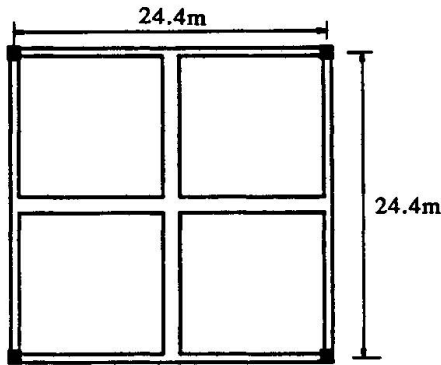
FIG. 8 - EXAMPLE 3 - PARROTTS FERRY BRIDGE, CALIFORNIA



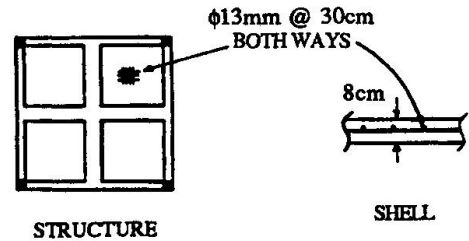
(a) GENERAL VIEW



(b) FINITE ELEMENT MESH

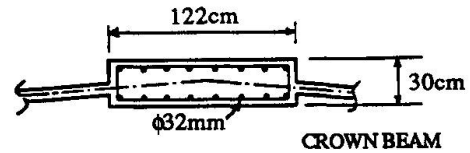


(c) PLAN DIMENSIONS

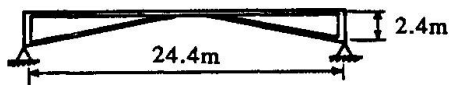


STRUCTURE

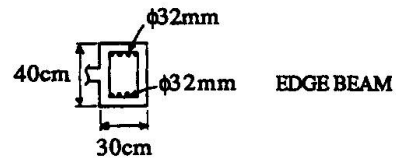
SHELL



CROWN BEAM

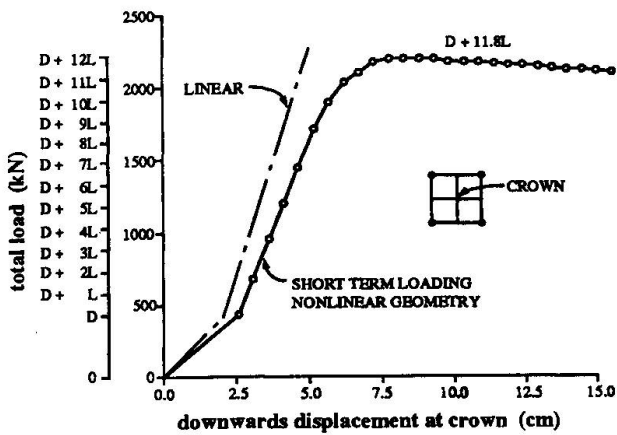


(d) ELEVATION DIMENSIONS

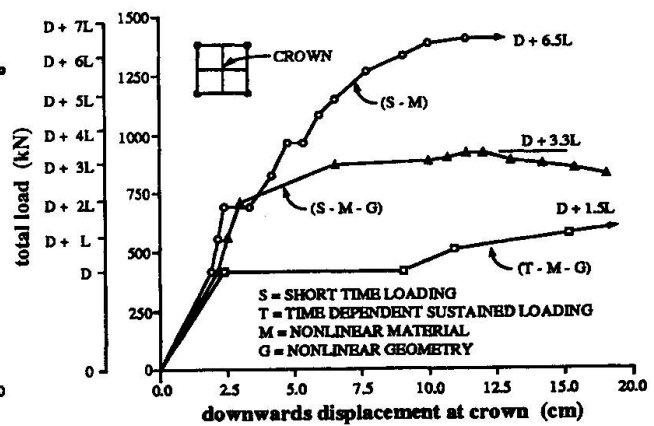


EDGE BEAM

(e) TYPICAL REINFORCEMENT LAYOUT



(f) LOAD VS. DISPLACEMENT FOR UNCRACKED MODEL



(g) LOAD VS. DISPLACEMENT FOR CRACKED RC MODEL

FIG. 9 - EXAMPLE 4 - GABLED HYPERBOLIC PARABOLOID (HP) SHELL ROOF





material properties of the lightweight concrete actually in the bridge, indicate that the probable causes of the higher deflections were that the actual modulus of elasticity is lower than that used in the original design, and the actual creep factor is higher than that used in the original design. This demonstrates that input material properties must be determined carefully and that the sensitivity of final results to variations in input parameters should be considered in analyses of this type to establish upper and lower bounds, if necessary. With the greater computational power and available computer analysis programs, this can be done today efficiently and economically using refined analytical models.

#### 4.4 Example 4 - Gabled Hyperbolic Paraboloid (HP) Shell Roof

Many shell roofs of this type (Fig. 9a) were designed in the 1960's using only simple membrane theory, and several of them suffered large increasing deflections with time. In one such shell a collapse occurred ten years after it had been completed.

In this example selected analytical results are presented from a detailed study by Chan [13] of a gabled HP shell with crown and edge beams, having the dimensions and reinforcement shown in Figs. 9c, d, e, to demonstrate the dramatic decrease in the ultimate load which can occur when nonlinear material, geometric, and time-dependent effects are included in the analysis. The structure was designed, based upon membrane theory, for dead load (D) plus a live load (L) of  $958 \text{ N/m}^2$ .

A number of nonlinear finite element analyses were then carried out using the mesh layout in Fig. 9b and the computer program NASHL [13] in which the reinforced concrete shell and beam elements were modelled as shown in Figs. 1f, 5. All the nonlinear analyses were performed by first applying the total dead load (D) of the shell plus beams and then adding multiples of the  $958 \text{ N/m}^2$  live load (L) until failure occurred. Only the results for a case using an oversized crown beam (Fig. 9e) are presented here in Figs. 9f, g to show the undesirable effects of doing so.

Crown displacement results shown in Fig. 9f from the analysis of a homogeneous uncracked concrete model without (linear) and with nonlinear geometry effects included indicate that the ultimate load in the latter case is  $D+11.8L$ . The response is almost linear up to a load of  $D+10.0L$  after which the continuous change in geometry causes local instability in the vicinity of the crown where the curvatures of the shell are smallest and the axial force is the largest.

Figure 9g shows the results of three analyses for a reinforced concrete analytical model of the HP gable shell which included nonlinear material effects such as cracking, etc. First, for a short time, loading with only nonlinear materials, the ultimate load was  $D+6.5L$ . Second, for a short-time loading with nonlinear material and geometry, the ultimate load drops to  $D+3.3L$ . Finally, for a case in which the dead load is first applied and then left on for five months, during which time creep and shrinkage take place, resulting in increased deflections and redistribution of stresses, and then increments of live load are applied on the structure with nonlinear material and geometry, the ultimate load drops to  $D+1.5L$ . This illustrates the large decrease in the ultimate load that can occur in shells of this type as each nonlinearity is included in the analysis.

#### 5. SUMMARY AND CONCLUSIONS

A review of the analysis of structural concrete systems has been presented with respect to analytical models, linear elastic analysis, static and dynamic analysis, segmental analysis, and nonlinear analysis. Past history, present status, and the role of the computer in analysis have been discussed. It can be concluded that tremendous progress has been made during the past thirty years in our analytical capability to predict the response of structural concrete systems. This is due to the development and understanding of more accurate and realistic analytical models and the increasing computational power and speed of computers to perform the necessary analyses accurately, economically, and efficiently. This trend is bound to continue in the future. Of course, the ultimate goal of this improvement in analytical capability is its intelligent implementation in design so as to produce better, safer, and more economical structures, regardless of their complexity. This should be a continuing, unending, and exciting challenge for all structural engineers.

## 6. ACKNOWLEDGEMENTS

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