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ELASTIC-PLASTIC, AND VISCOELASTIC CONCRETE MODELS

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COMPUTATIONAL EXPERIENCES WITH VARIABLE MODULUS, ELASTIC-PLASTIC,  
AND VISCOELASTIC CONCRETE MODELS

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This morning we heard four talks on what a sad state of disarray the constitutive theory of concrete is in. After lunch Professor Bazant showed that numerical prediction of cracking in concrete is on questionable foundation and illustrated examples that support his claim. Finally Professor Gerstle illustrated that you cannot measure concrete strength properties reliably--even under the best of laboratory conditions. Now what I am expected to do is to show you how to calculate the inelastic response of a complex concrete structure within 10 percent of its actual behavior!

Six years ago the Reactor Safety Research Division of the Nuclear Regulatory Commission (NRC) approached the Los Alamos National Laboratory to develop a comprehensive concrete structural analysis code to predict the static and dynamic behavior of Prestressed Concrete Reactor Vessels (PCRVs) that serve as the containment structure of a High-Temperature Gas-Cooled Reactor. The PCRV is a complex concrete structure that must be modeled in three dimensions and possesses other complicating features such as a steel liner for the reactor cavity and woven cables embedded vertically in the PCRV and wound circumferentially on the outside of the PCRV. The cables, or tendons, are used for prestressing the reactor vessel. In addition to developing the computational capability to predict inelastic three dimensional concrete structural behavior, we were to verify the code response against documented experiments on concrete structural behavior. My presentation is directed at relating to you our part experiences in this code development/verification effort.

The code I am going to discuss is called NONSAP C and is a greatly modified version of the NLSAP code developed in the Civil Engineering Department of the University of California at Berkeley. The modifications to the code that have been made over the past six years include:

(1) Implementation and verification of three concrete constitutive models: two time independent models--an orthotropic, variable modulus reinforced concrete model developed by the Air Force Weapons Laboratory and the Chen and Chen model discussed this morning--and the aging viscoelastic creep model of Bazant.

(2) Incorporation of a multi-node tendon element and a membrane element for representing prestressing cables and steel liners in reactor vessels in addition to 3D isoparametric elements for representing concrete behavior.

(3) Development of pressure and gravity loading capability, cylindrical coordinates options and incorporation of an out-of-core solver for the NONSAP code, which makes possible the analysis of complex concrete structural problems.

I will discuss the constitutive models in a little more detail. The variable modulus model smears together representation for steel reinforcing and concrete behavior and forms a composite stiffness model for the concrete element. It is often called an orthotropic variable stiffness model. What it does, effectively, is that when you strain the concrete, it changes the stiffness of the element according to a nonlinear elastic type model. It also calculates composite stiffness of the steel and concrete and it does cracking based on a stress criterion that Professor Bazant was talking about. The model also accounts for bond interactions between steel and concrete.

The Chen and Chen model is one of the code models also. Initially the elastic-plastic model for concrete was very attractive to us. The reason is that one of the disadvantages of the variable-modulus model is that you have to store a lot of variables at each integration point. For a three-dimensional analysis using isoparametric elements and using the minimum of eight integration points per element with 32 variables to store per integration point, it just takes up a lot of time and a lot of storage to spool things in and out onto a storage disc. Whereas for the elastic-plastic model, you're getting down to a smaller numbers of variables (14) that you must store per integration point and the time and storage requirements are that much less restrictive.

The other model we put in the NONSAP code was a creep model based on the Kelvin chain that Professor Bazant has developed. This model is an aging viscoelastic creep model. It was felt to be important when we started this program to put this creep capability in because prestressed concrete reactor vessels are prestressed over a long period of time and if the concrete creeps, then the tendons which have effected the prestressing will relax and some of the capability of the vessel will be lost. It was felt important to be able to predict these effects reliably.

Once you get into three-dimensional analysis, one of the things that you have to do is to develop a way to represent (a) the structure that you're modeling and (b) all the data you get back from an analysis. We developed or imported a preprocessor code and a post-processor code for NONSAP-C. The former develops three dimensional meshes of complex configurations. Finally NONSAP-C stands for Nonlinear Stress Analysis Program-Concrete. Not very original, but it reflects the fact that it's basically the NONSAP code with extensive modifications.

I now want to show you some of the capabilities of the NONSAP-C code. Figure 1 illustrates a tendon element. With it you can take a structure and wrap through nodes a tendon of arbitrary--well not arbitrary--as many as 20 nodes and tie various parts of the structure together. It was not a particularly theoretically cumbersome thing to develop. It's a free-slip element although we have modified it to do certain types of bonding also. It's a unique feature of this code.

Figure 2 illustrates a membrane element that supports, for thin metal sheets, only a plane stress state (no bending stresses) and it can undergo elastic-plastic material behavior.

Figure 3 shows the three-dimensional isoparametric continuum element used in NONSAP-C which can be used with the three concrete material models discussed previously. This element can be combined with the tendon and membrane elements to produce the composite element shown in Fig. 4, and which will be used in an analysis that will be shown later. Shown is a concrete element with a liner on the inside of the element, and some post tensioning tendons on the outside.

We did a set of test problems and I want to talk to you about these because I think they are important. Figure 5 shows a reinforced concrete plate--simply supported on three sides and free on the remaining side. It is a square plate, 10 meters on a side and half a meter thick and it was reinforced inside and outside. Now we did this problem early on in the game since the computer results for the ultimate load can be compared with the results of the yield line theory.

Figure 6 illustrates the result of our calculation. The limit load is shown, and here the curve comes right up to the limit load. The code very closely predicts the limit load. In this kind of code development exercise we wanted to concentrate on the calculations that you cannot do with other codes,

and one area that is up in the air is predicting failure loads. Presumably many codes could predict an elastic behavior of these reinforced concrete structures, but we wanted to be able to predict their nonlinear behavior reliably. Figure 7 illustrates the crack pattern that was developed in the plate and it looks pretty good as far as the yield line deformation mode is concerned.

At the University of Illinois Structural Engineering Research Laboratory, Professor Sozen did an extensive series of experiments on model concrete vessels. The length to height of each cylinder was a factor of about two, and each had a flat head. Some of them were penetrated in the head region. All were internally pressurized and then tested to failure. These vessels have no reinforcing in the head area, and that is where they failed. So if you want to test out a constitutive law for concrete, it makes sense to try to simulate the behavior of these experimental vessels using your constitutive model. If you mask the response with steel (presumably codes can calculate the behavior of steel), it is not as good a test as doing a calculation on a pure concrete structure. We calculated the cracking of one of the vessels (PV-27) and the crack pattern appears in Fig. 8a. The vessel failed--it was loaded to failure--and a portion of the head blew out. Our crack patterns, if you took a limit, simulates how it actually failed in the experiment. Figure 8b illustrates the crack pattern looking down on the top of the vessel (and here you can see the penetration). Again the top is almost completely cracked.

In Fig. 9 we plotted the pressure versus the central deflection. This was the disconcerting part of the whole exercise. We calculated the elastic behavior correctly, but we could calculate very little change in the slope of the curve until at this point (about 10 megapascal) the vessel failed. By failure I mean the code ceases to converge when it does its nonlinear calculations. When Professor Sozen did the experiments the load continued to increase until at about 16 megapascals the vessel failed. There was a large amount of apparent ductility in the actual vessel behavior. Unfortunately, we have not been able to resolve this problem. We tried the calculation with other codes such as the ADINA and we get basically the same result--an under-prediction of the ultimate load capability and the observed ductility of the unreinforced vessel. It appears that there is something going on to give the appearance of much more ductility in the unreinforced vessel and that you can not get a basic agreement with code calculations that employ the commonly accepted constitutive models.

I will now show you some creep calculations. Figure 10 illustrates a section out of the cylindrical part of a concrete reactor containment building. It is a sector of the building and on the outside it is post-tensioned with cables. In the calculation we post tensioned the cables at time = 90 days and then let the structure creep. Figure 11 illustrates how well the code calculation agrees with a hand calculation based on shell theory. Good agreement is seen. Now the creep model in the code is aging so that if you apply a load at 90 days, you get a different response than if you apply a load at 10 days or at 200 days.

How do we do analysis of complex concrete structures? Figure 12 illustrates a model of a real structure--the Zion containment building. There is a steel liner on the inside and the tendons on the outside. Figure 13 shows our model of the tendons laid out on the dome. They arc on a triangular grid, and they tie into the side wall vertical tendons which are also prestressed.

With a mesh generator you can generate your mesh and take a look at it. If nodes are out of place, you can move them around. Figure 14 gives you an idea of what comes out of a mesh generator before you do the analysis on the structure. Figure 14 does not show the steel tendons. Figure 15 shows the response of the dome to initial post tensioning after 90 days, and Fig. 16 shows a deformed configuration of the dome.

At this point I'd like to summarize our findings. The Nuclear Regulatory Commission sponsored this work. I'll use one of their now pet expressions "lessons learned" and discuss the lessons we learned from this code development exercise.

1. Nonlinear computational analysis of complex concrete structural behavior is very difficult, time-consuming, and expensive when the effects of concrete cracking and crushing and reinforcing yield are taking place.

2. Ultimate load behavior observed on tests on unreinforced concrete pressure vessels are not predicted by the usual concrete constitutive models, although crack patterns were predicted adequately.

3. In addition to spending a lot of time on doing basic experiments to determine constitutive properties of concrete, I think it's important that somebody puts together a series of experiments on real concrete structural models where the structure is in biaxial or triaxial stress and where at least you have several different percentages of reinforcing. It would be necessary

to test the structures to failure. The structure should be carefully instrumented and the response carefully measured. Then contracts should be let to all the brave souls who want to calculate the inelastic response of the structures with their own code or constitutive models. Then we can see who can predict the inelastic behavior most accurately. Until we do something like that we are going to be threshing around for years and years and not be any closer to the solution of practical concrete structural problems.

Thank you.

#### QUESTIONS

Scheyer: I was wondering about the numerical algorithm. Do you have any trouble when you're solving problems over days, hundreds of days?

Anderson: Are you referring to the creep problem? (Yes). We have not had any problem with that. We take fairly large time steps and the numerical algorithm performs stably. I'm sure that this algorithm is in other codes also.

Question: In your attempt to replicate experiments did you change your mesh size?

Anderson: Yes, we did it on one of the unreinforced axisymmetric vessels without the penetrations. Paul Smith did many of these calculations.

Smith: We played all of the games in mesh size and the problem remains in modeling the postfailure behavior of the concrete. The mesh size seemed not to help us very much as we refined it. As we refined the mesh it had no effect on the ductility of the vessel.

Anderson: Because we are so far from the observed ductility, there's got to be some other physical mechanisms that are going on that are not correctly modeled by that constitutive model.

Question: Did you have a strain-softening range?

Anderson: No. We did not have a softening portion in the curve. The curve goes up and approaches an essentially flat response.

Shah (U. of Il, cc): Would cracking have helped?

Anderson: I don't think so. What happens in an unreinforced vessel is that once you start cracking you're essentially removing material from the structure, and I would expect that you should have early catastrophic failure because your competent sections are getting smaller. You're not going to get much more material strength--enhanced capability as with Professor Bazant's problem discussed earlier. Only if you have reinforcing can you get significant stress readjustment and then further calculate upwards along the failure curve.

Bazant: What I would like to point out is that with a strength model (which is very difficult to do in a code but not in theory) one should check the incremental stiffness matrix for many combinations of loading and unloading. As for example, in a certain model, let's say cracks propagate to the right. One element in front is cracked and now the one above is also cracked in parallel. So if you never check the possibility of stiffness changes with loading or unloading you may think everything is okay but you may find out that everything concentrates into one crack with a sharp edge. However, this requires the code to check many combinations of loading and unloading and the number of combinations is preposterous, but a code that doesn't check this actually misses these unstable rearrangement effects which happens in practice of course.

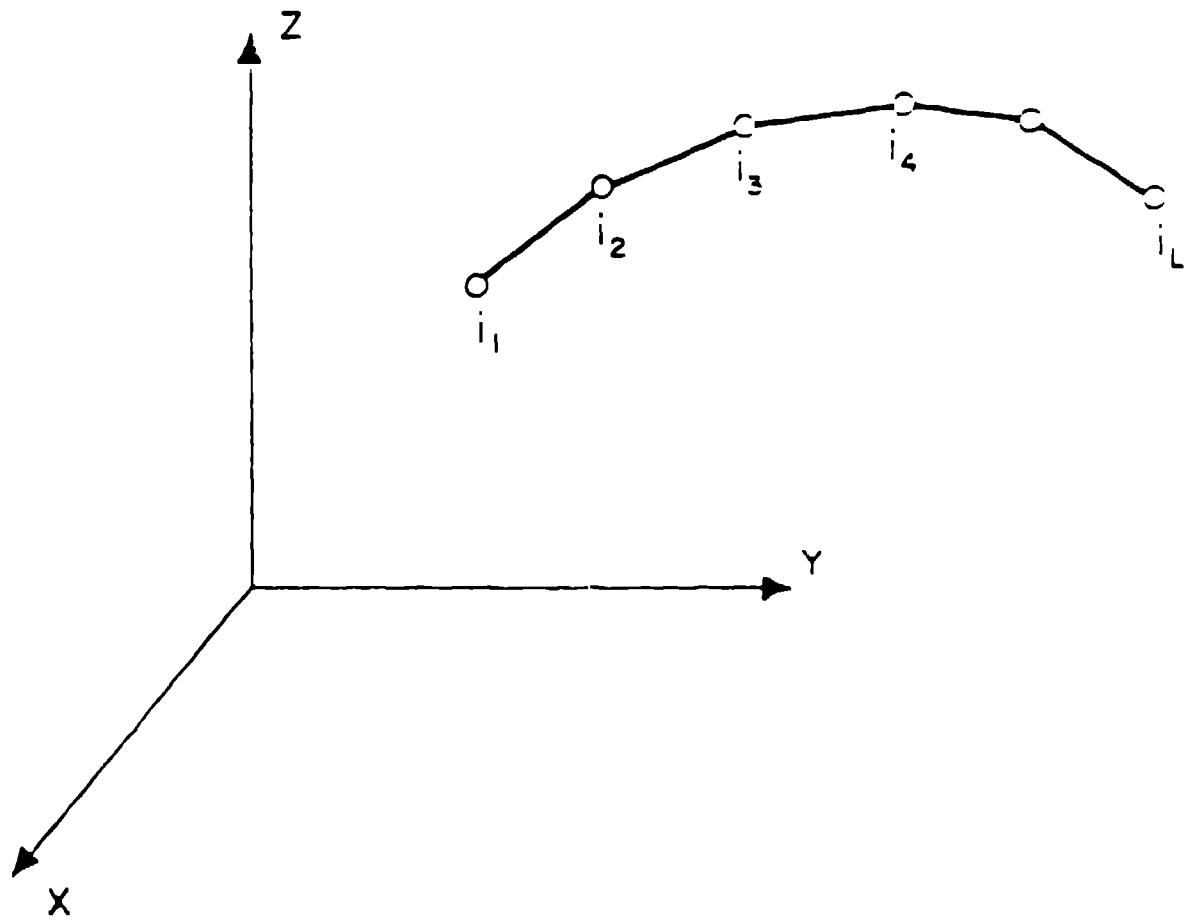


Fig. 1. Multi-node tendon element.

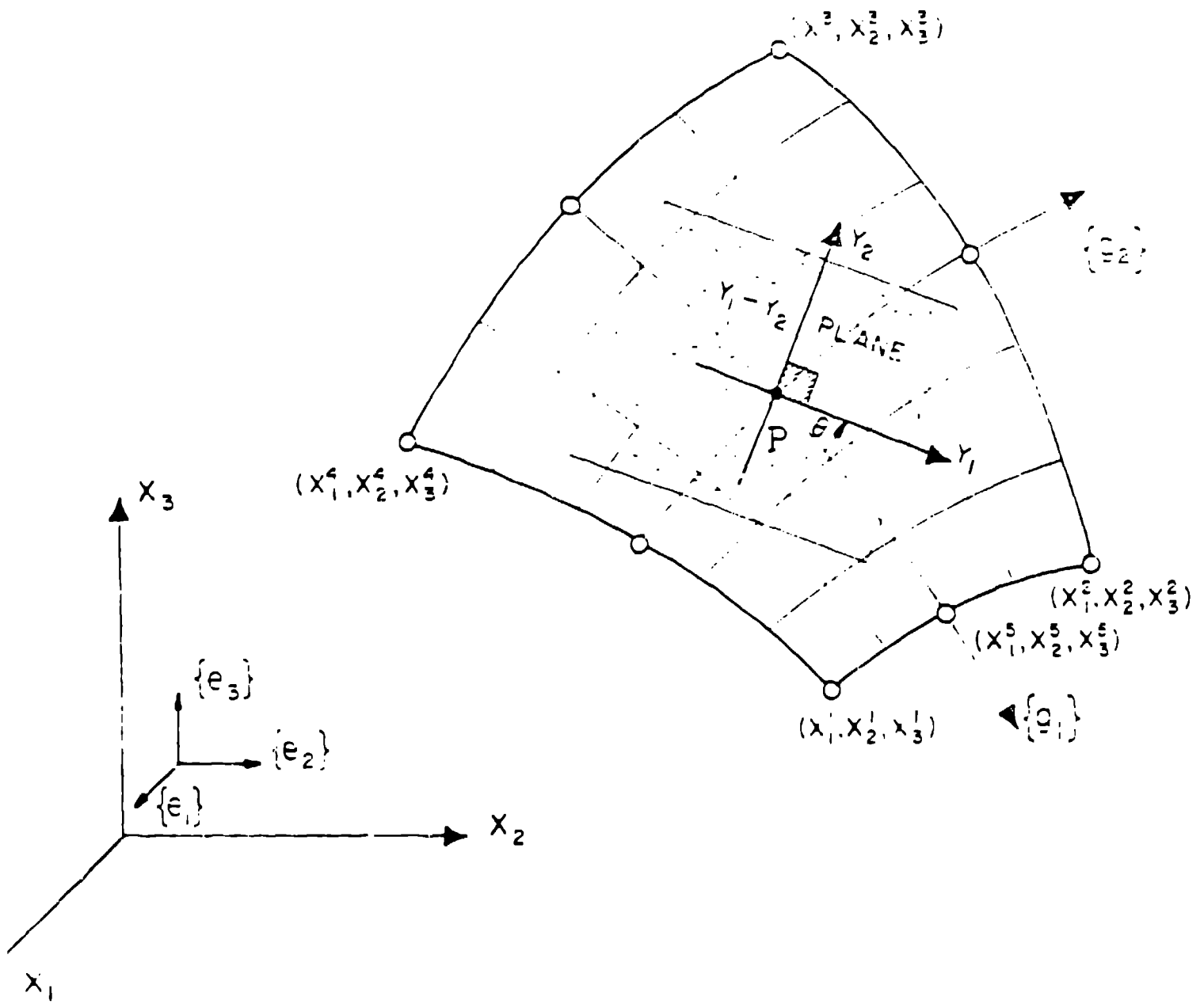


Fig. 2. Membrane finite element and local and global coordinate systems.

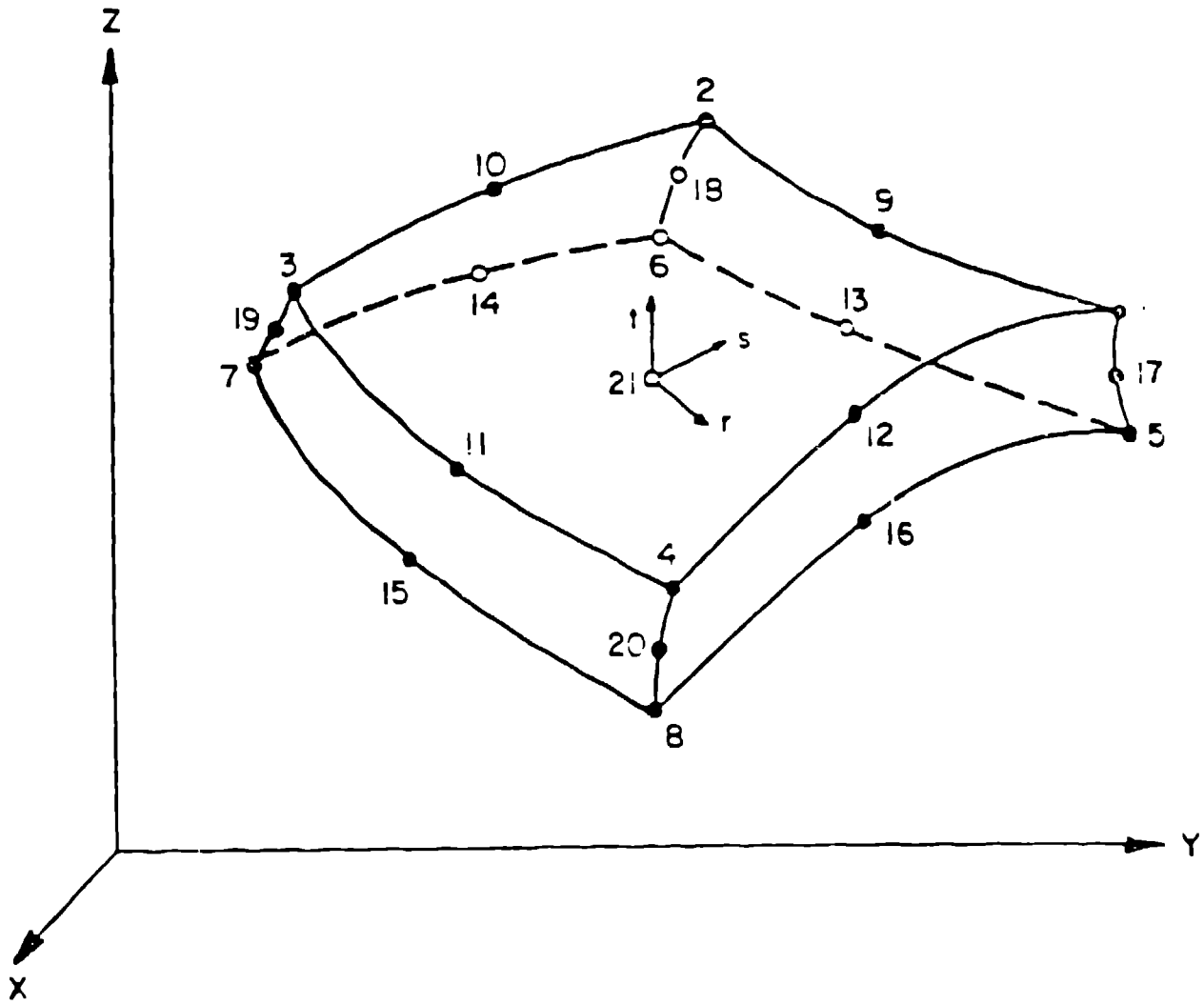


Fig. 3. Three-dimensional brick or thick shell element.

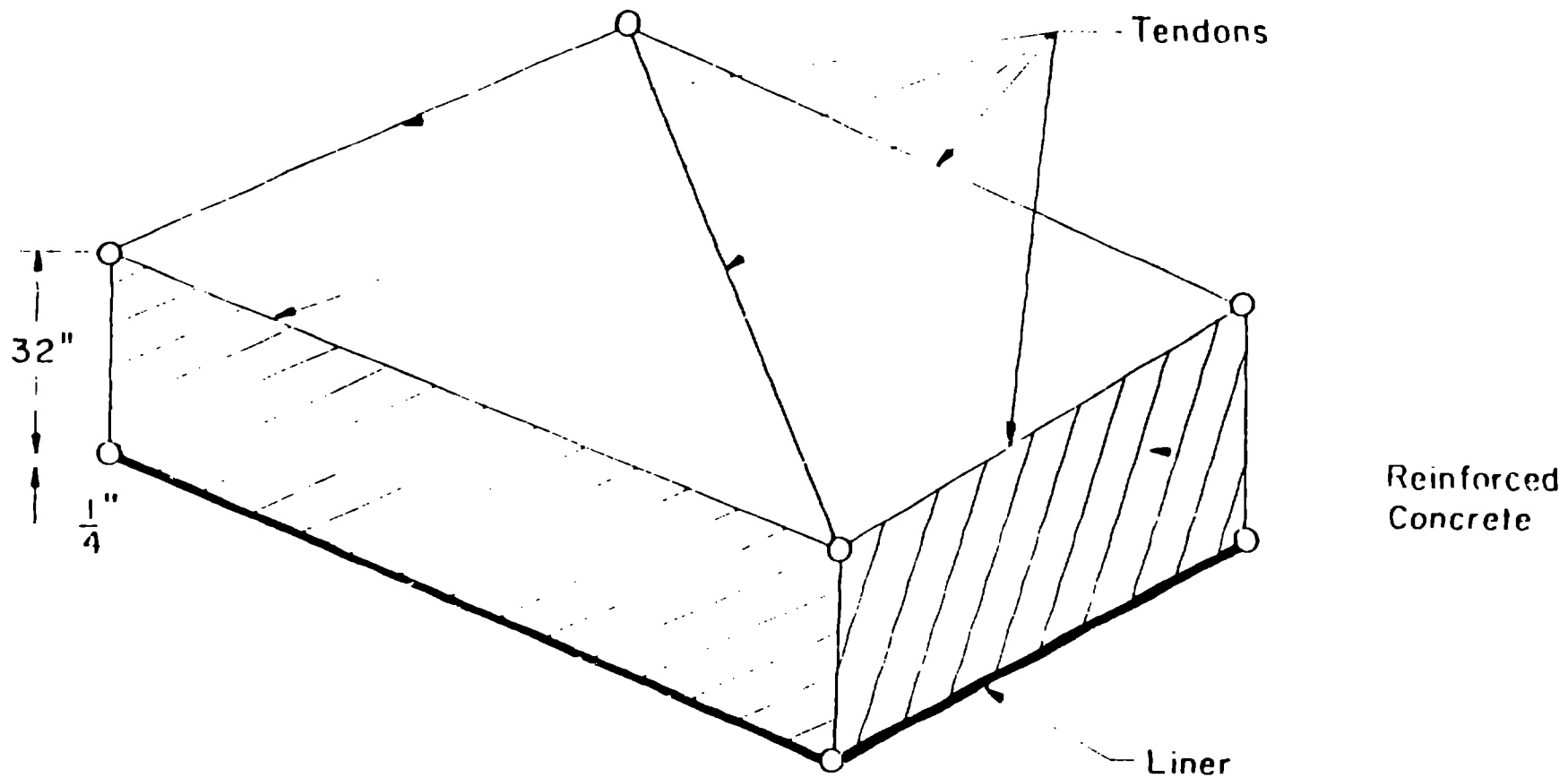


Fig. 4. Containment building schematic.

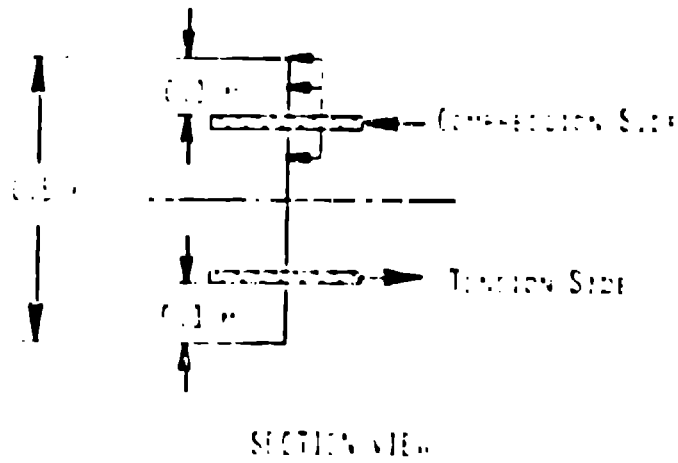
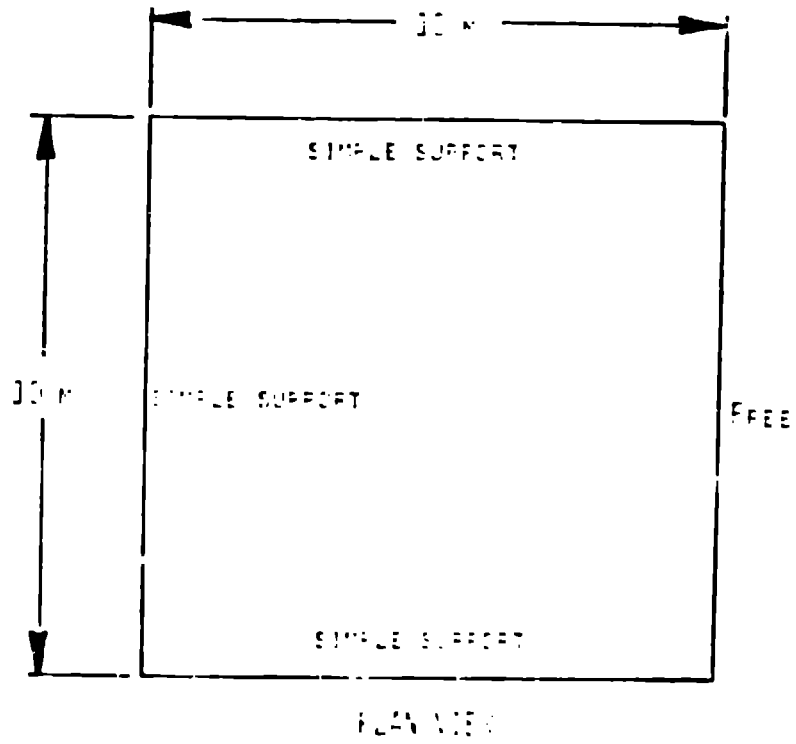


Fig. 5. Concrete plate showing reinforcement.

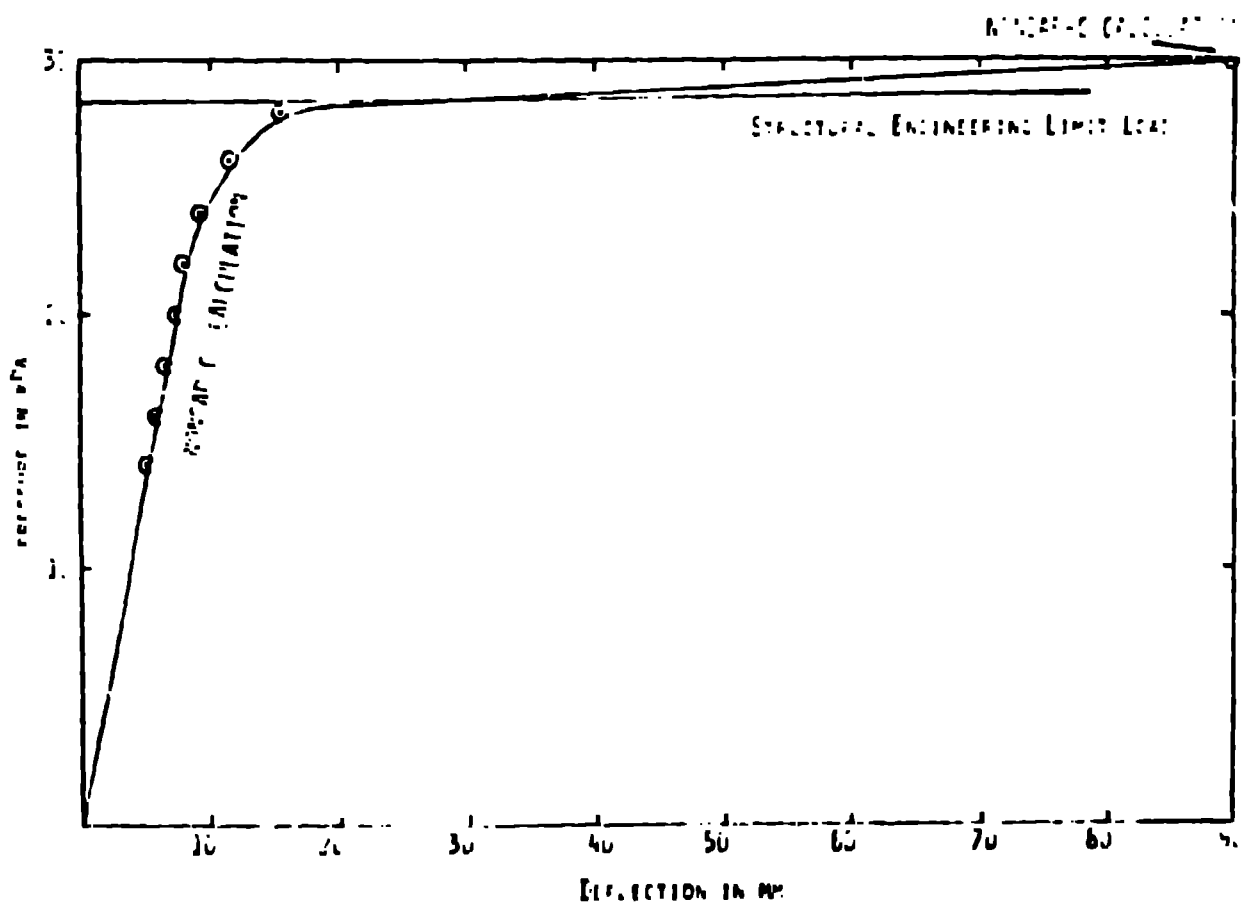


FIG. 6. Response of the concrete plate.

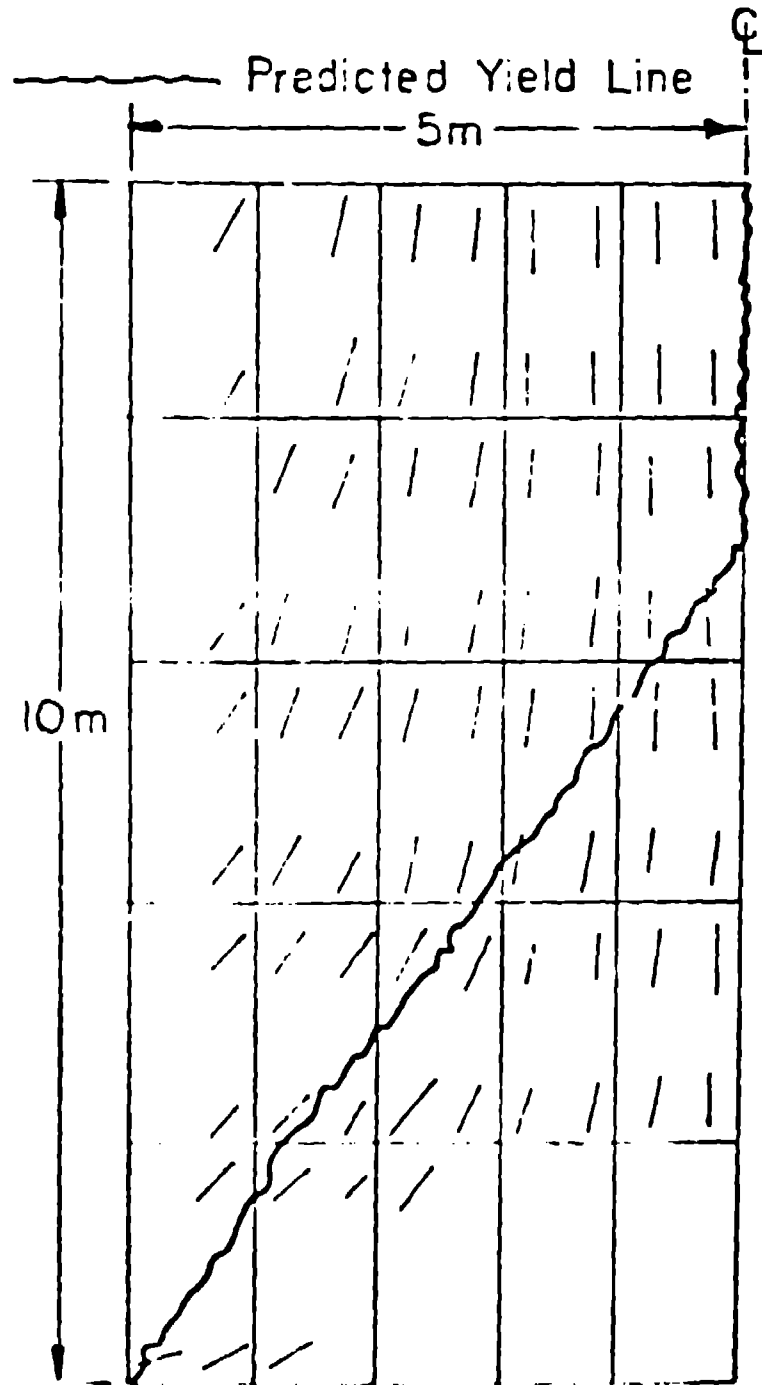


Fig. 7. Crack pattern in the reinforced concrete plate.

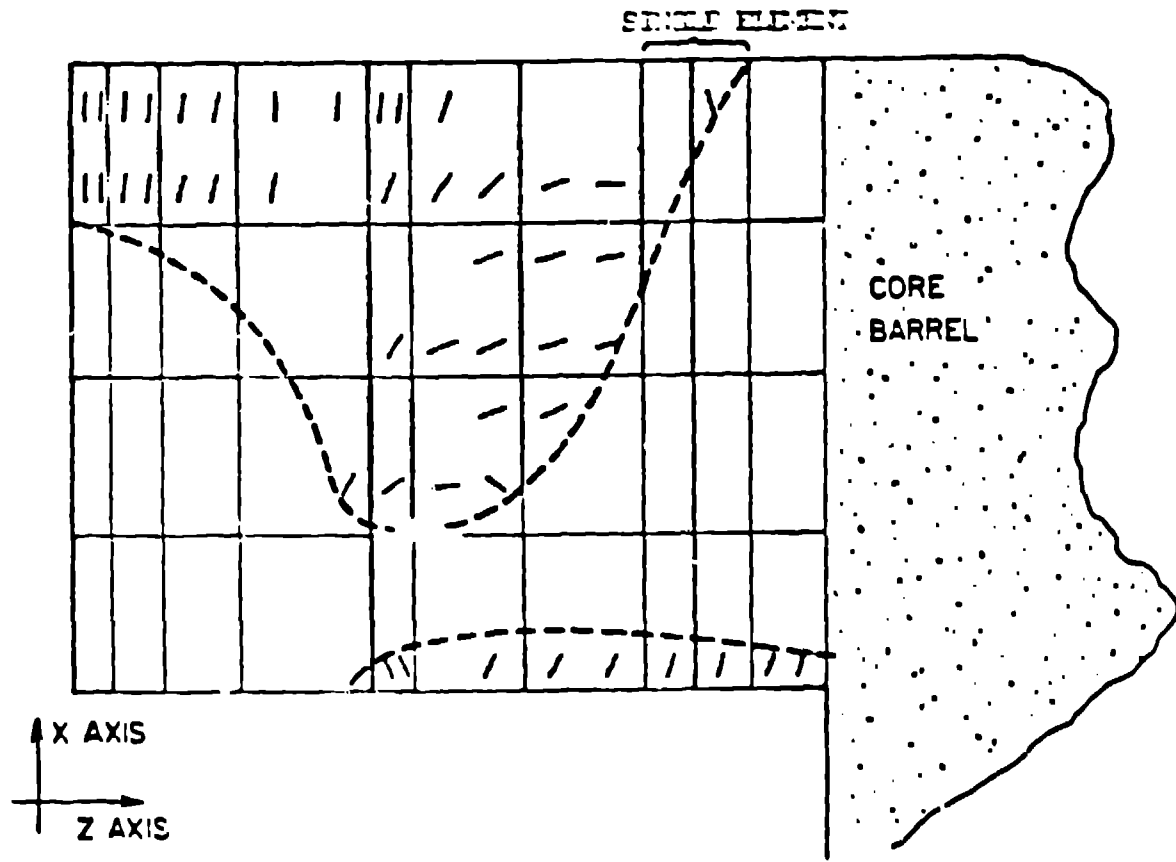


Fig. 8a. Crack pattern on the penetration face of the end slab of PV-27 as computed by NONSAP-C.

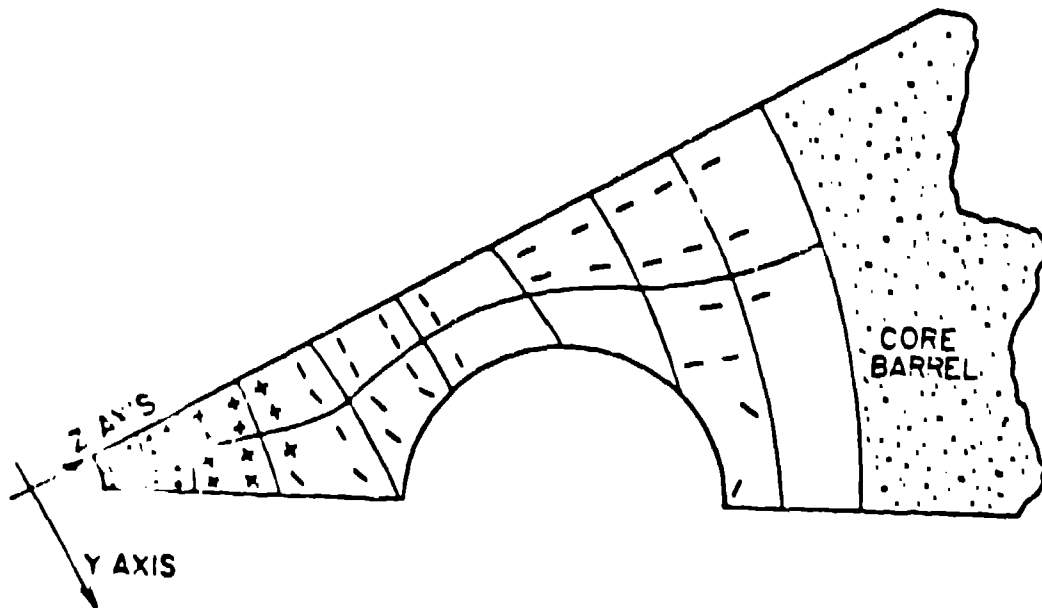


Fig. 8b. Crack pattern at the outer surface of the end slab of PV-27 as computed by NONSAP-C.

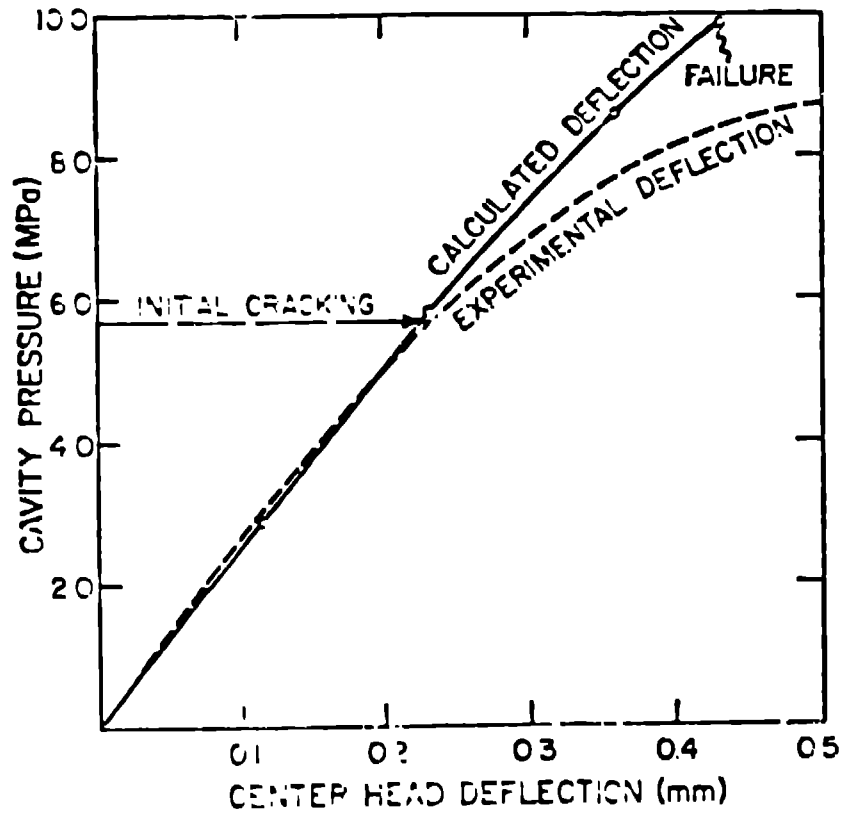


Fig. 9. Experimental and computed pressure-deflection curves for PV-27.

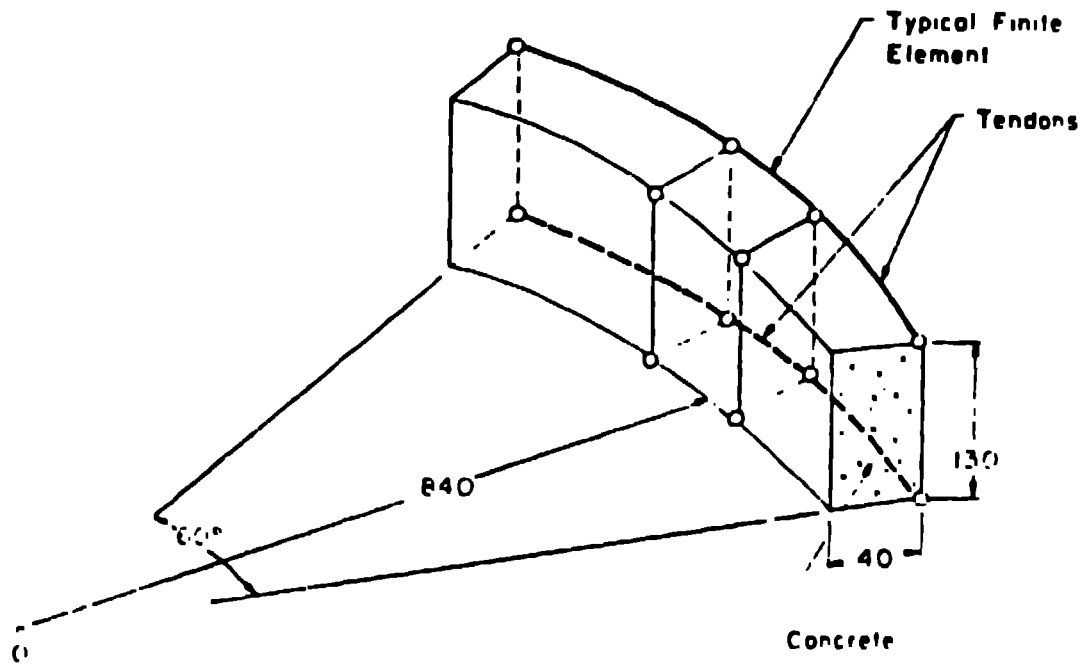


Fig. 10. Fast-tensioned concrete ring.

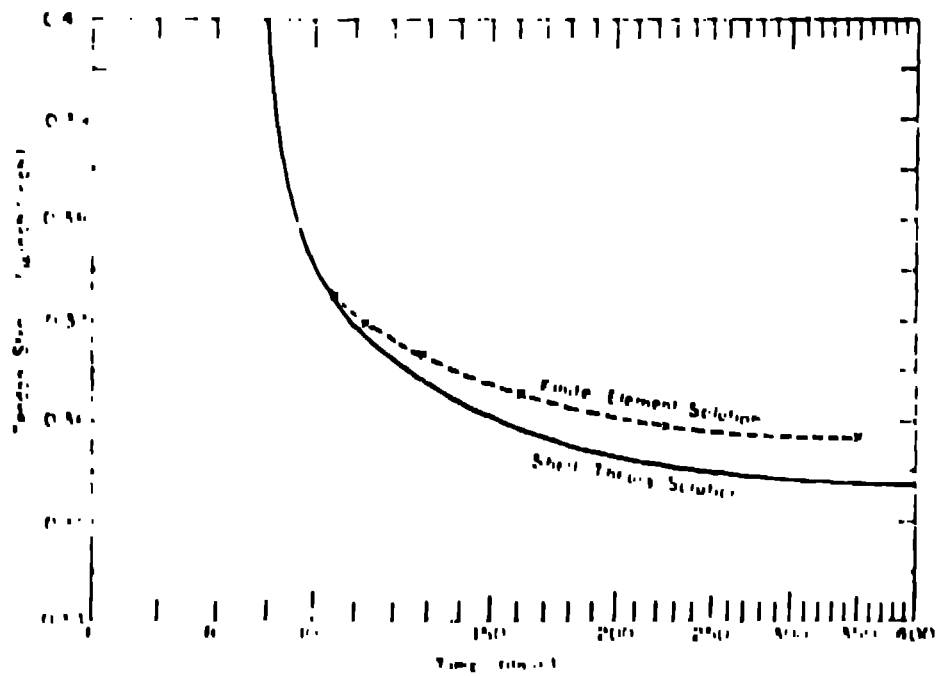
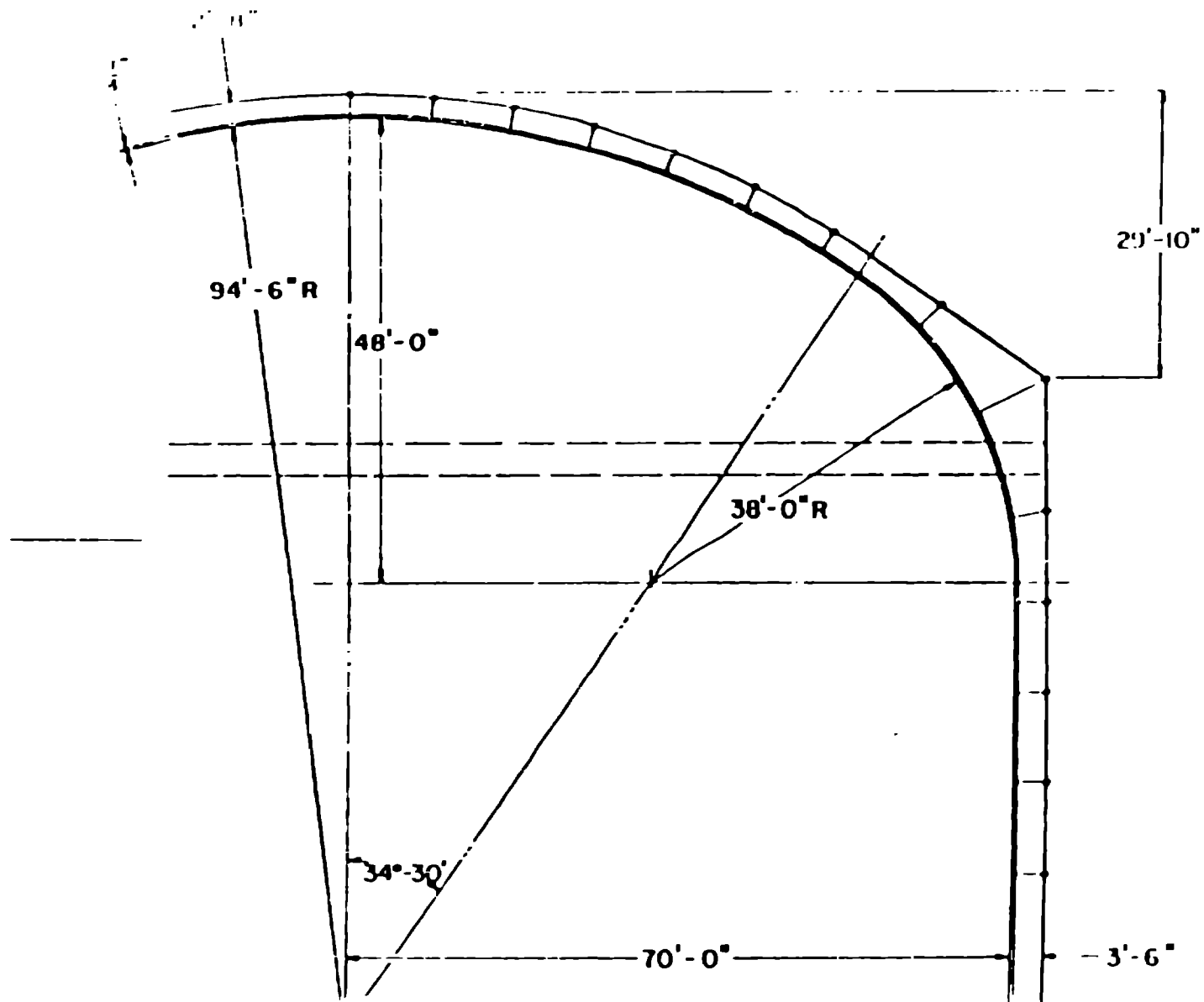


Fig. 11. Decay of post-tensioning strain for concrete ring problem.

Fig. 12. Thermal cylinder hoop strain-time results and the inner surface.



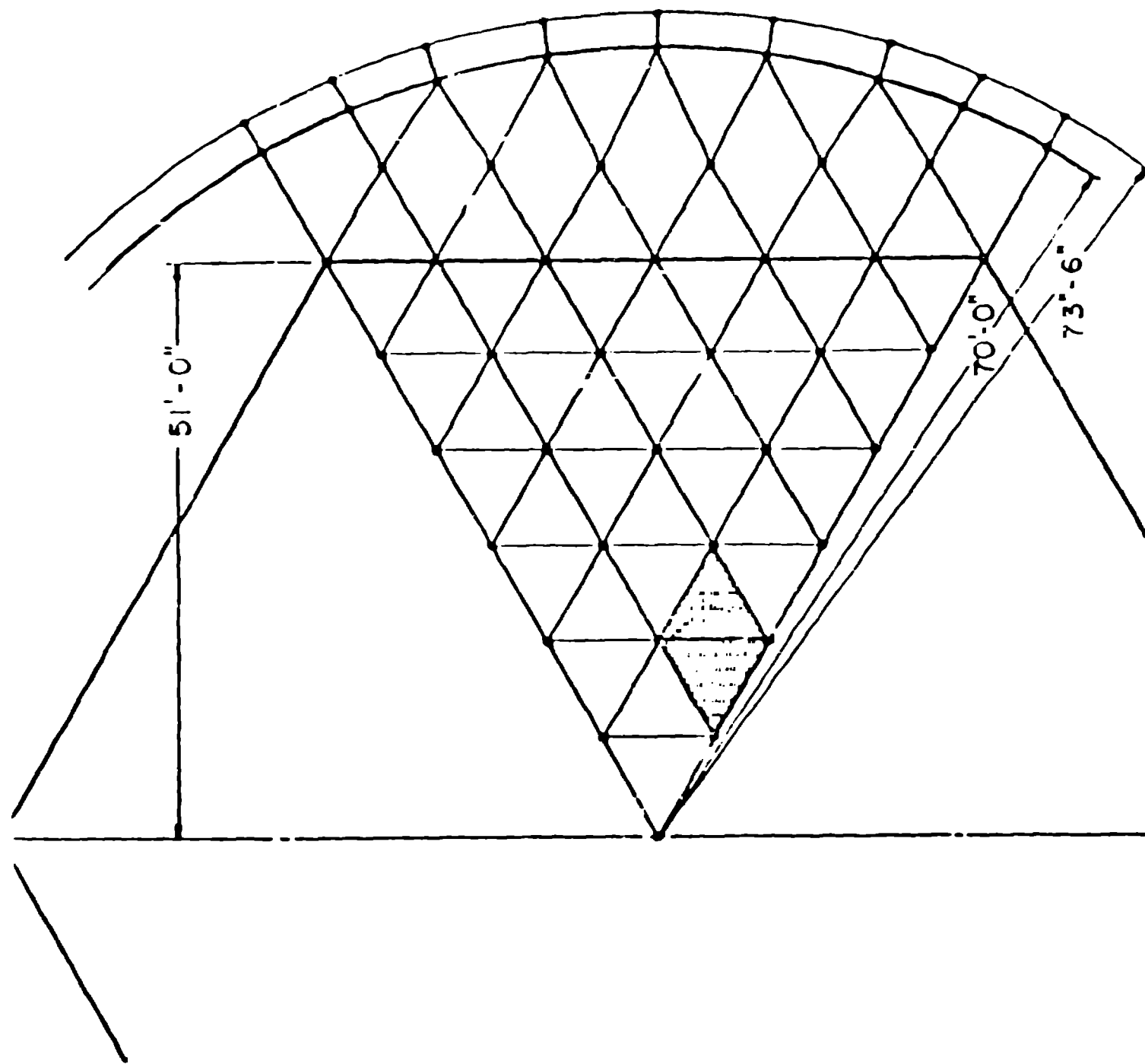
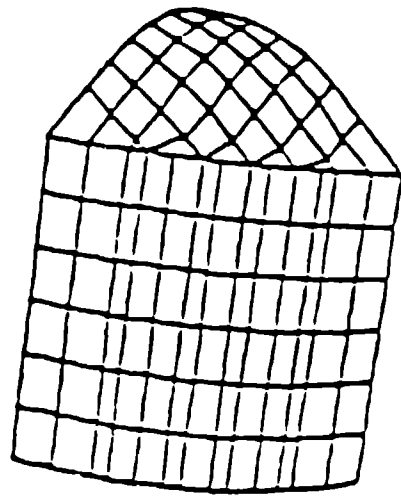
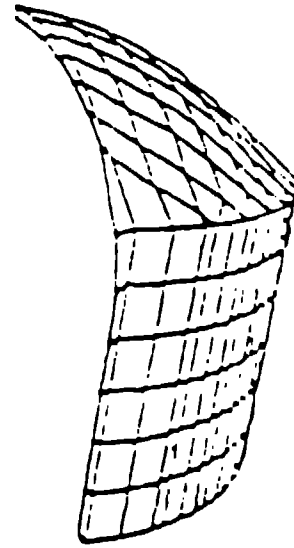


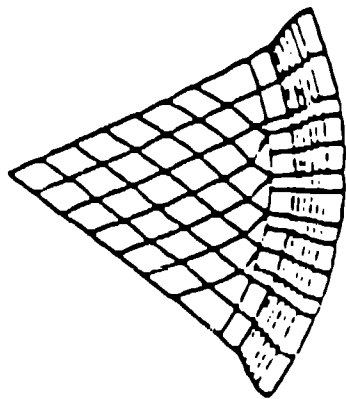
Fig. 13. Thermal cylinder hoop strain-time results at the outer surface.



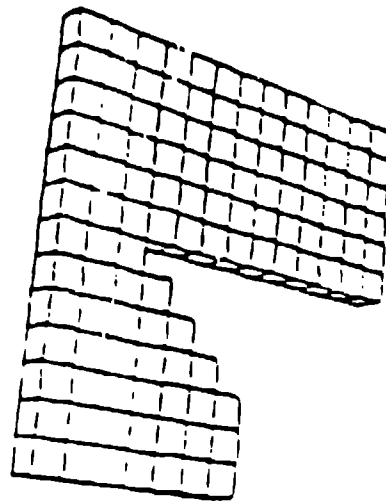
BACK VIEW



SIDE VIEW



BOTTOM VIEW



LOGICAL MESH

Fig. 14. Tendon arrangement on the dome of the containment building.

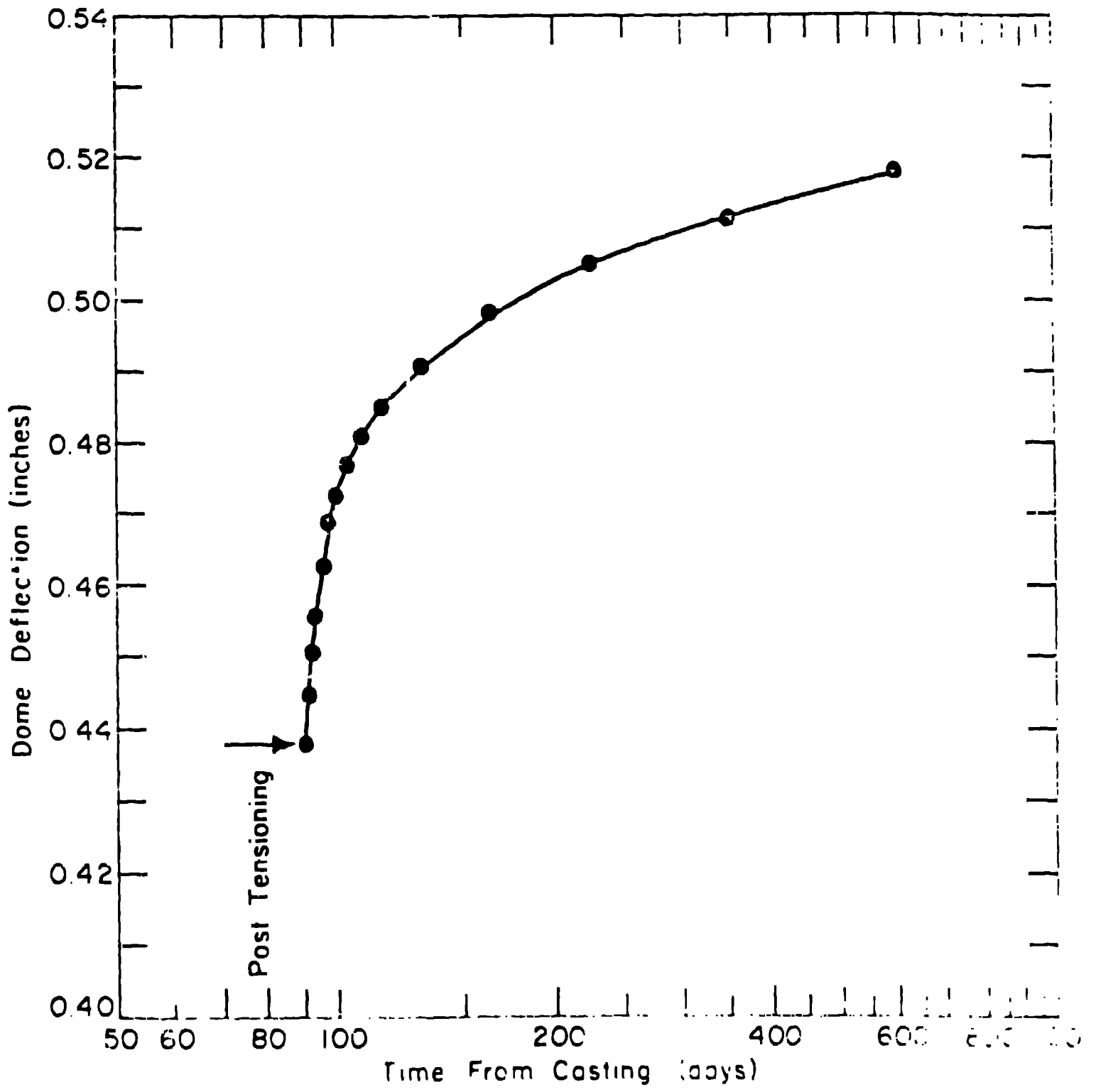


Fig. 15. Dome deflection as a function of time.

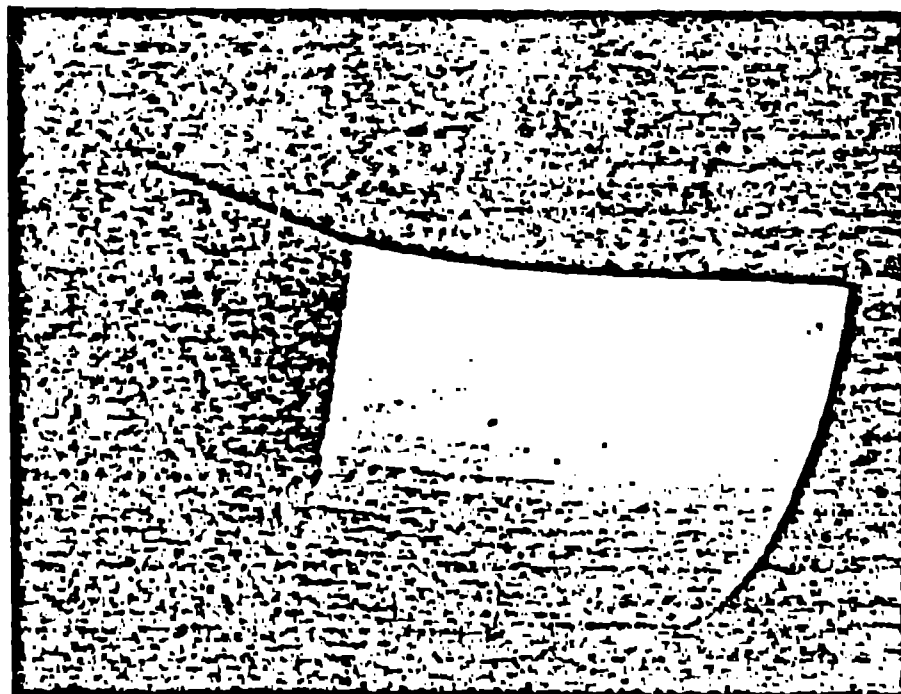
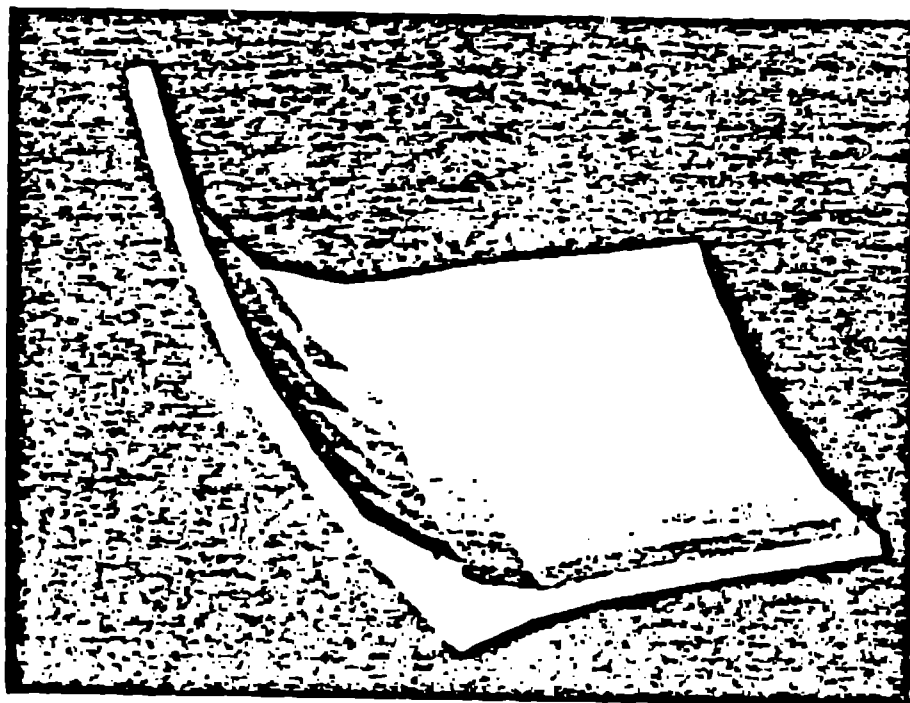


Fig. 16. Color tone views reconstructed from the finite element mesh.