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EXPERIMENTS ON CONCRETE CONICAL SHELLS FOR OTEC STRUCTURAL SYSTEMS

By

H. C. Mehta
T. Y. Chang
W. F. Chen

Department of Civil Engineering
Fritz Engineering Laboratory
Lehigh University
Bethlehem, Pa. 18015

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Experiments on Conical Concrete Shells for OTEC Structural Systems

ABSTRACT

Described herein are tests of thirteen conical concrete shells under monotonically increasing axial load conditions. The load-deformation response, internal stresses and crack propagation through the elastic, inelastic and ultimate stress ranges are presented. The properties of concrete and the behavior of the shells are varied by (1) polymer impregnation; (2) steel reinforcement as ring stiffening and (3) general wire mesh reinforcement. The stress-strain behavior of concrete for both reinforced and unreinforced specimens is tailored to range from strong linear elastic but brittle to tough and ductile by the combination of rubbery and brittle polymers like butyl acrylate and methyl methacrylate, respectively. The behavior of such composite specimens is ideal for the purpose of comparison with various material models now available in the extended NONSAP finite element analysis program which includes, among others, the nonlinear concrete constitutive relations developed recently at Fritz Engineering Laboratory.

Data from these experiments will be used to demonstrate the general validity of the proposed material model for concrete in the regime of tension-compression state of stresses. In-depth, interpretative studies of the experiments and analytical predictions based on the extended NONSAP program will be presented in a later report. Preliminary comparisons for plain concrete specimens indicate a close agreement between the experiments and the proposed theory. Extensive correlation studies in the future shall provide final confirmation of the proposed concrete constitutive relations which have been implemented as a subroutine in a nonlinear general purpose finite element program.

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1. FOREWORD

General

A constitutive relation and failure criterion for concrete material under general three-dimensional stress states has been developed using the work-hardening theory of plasticity. The formulation has all the required properties of concrete and gives a close estimate to experimental stresses for complete general stress states.

In order that the results of research be readily usable in the analysis of suboceanic structures such as the large shells proposed for adoption in the Ocean Thermal Energy Conversion program (OTEC), corresponding computer codes have also been developed to reflect this material response.

The proposed material model has been applied to several selected concrete and reinforced concrete shell structures. The finite-element subroutine for the NONSAP program has been modified and applied to analyze plain and reinforced concrete shell specimens of cone-, cylinder- and dome-shapes under monotonically increasing axial load condition. The finite-element solid program (EPFFEP) has also been developed and applied to study the behavior of concrete cylindrical hulls under hydrostatic loading conditions. The analytical results will be compared with a few selected well-controlled experiments, providing final confirmation of the validity of the computer model. This report presents the experimental phase of the research program.

Objectives

The overall objective of the program is to devise the means and capability necessary to achieve a satisfactory analysis of the OTEC structures. In particular, we attempt to satisfy the following two requirements: to assess their true safety against failure and to insure their serviceability at the working load.

More specifically, the work is to include the following phases:


3. writing a corresponding computer code in the form of a subroutine which can be adaptable for use in an existing or postulated large finite element analysis computer program. ERDA report No. COO-2682-7 entitled "Extended NONSAP Program for OTEC Structures" in preparation; ERDA report No. COO-2682-8 entitled "EPFFEP Program for OTEC Structures" in preparation


5. verifying the contemplated constitutive relationships by comparing the analytical solution with experimental results.

This report summarizes the results of well-controlled tests on conical concrete shells. Preliminary comparisons of plain concrete specimens support the general validity of the FEL approach. The critical next step is to compare extensively these and other available experimental data with the computer solutions developed in item (3), providing final confirmation of the computer model.
2. INTRODUCTION

Large submersible shells and other components of reinforced concrete whose dimensions will be many times greater than such elements studied previously have been envisioned as a part of a total concept to utilize the solar energy available in the oceans [1-6]. The analysis and design of these structural components pose a challenge due to several factors, some of which are entirely novel due to location of the plant. Since most of these structures consist of a series of ring stiffened cylindrical or conical shaped reinforced concrete shells covered with spherical caps, analysis of such structures requires the availability of nonlinear general purpose computer programs based on either finite difference method or finite-element method. To further extend the existing computer programs so that they can handle both plain and reinforced concrete materials in a generalized manner, inclusion of elastic-plastic-strain hardening-fracture material model and kinematics of concrete fracture and crushing is required [7]. To test if such a postulated theory will reasonably predict the strength and behavior of OTEC structures during construction and in operation, well-controlled tests on thin conical concrete shell specimens under monotonically increasing axial load conditions are required.

The objective of the experimental phase of this program is, therefore, to test conical concrete shell specimens with widely varying material properties and to trace their load-deformation response, internal stresses and crack propagation through the elastic, inelastic and ultimate stress ranges. It has been possible to vary the stress-strain properties of concrete and the behavior of conical concrete shells by (1) polymer impregnation; (2) steel reinforcement as ring stiffening and (3) general mesh reinforcement. The detail of this test program is described here. The stress-strain and fracture behavior for both reinforced and unreinforced concrete is tailored here to range from strong linear elastic but brittle to tough and ductile by various combinations of rubbery and brittle polymers like butyl acrylate and methyl methacrylate, respectively [9]. Such composite specimens are found ideal for the purpose of comparison with various material models now available in the extended NONSAP program [8].
3. PREPARATION AND FABRICATION OF SPECIMENS

The conical concrete specimens were cast in two sizes, the big cone and the small cone, the nominal dimensions and details of which are shown in Figs. 1 and 2. In total, seven batches were made using the same concrete mix shown in Table 1 with a uniaxial compressive strength of approximately 6000 psi and a splitting cylinder strength of approximately 600 psi. The mold comprised of outer and inner thin steel sheet cones spaced at the top and bottom by circular spacers (Fig. 3). Each specimen was cast in three layers with sufficient intervals in between to allow the mix to settle in the mold and bleed water if any. Eight 3x6 in. cylinders were also cast with each of the first four batches to measure the stress-strain properties. Batches 5, 6 and 7 were cast with the same mix as above but included wire reinforcement or one ply of wire mesh as shown in Table 2 and Figs. 1 and 2. All the specimens were removed from the mold after 72 hours and kept in moisture room (90-100% RH) for 28 days.

Four of the specimens were impregnated with polymers using the following procedure. Specimens from the same batch were dried in the oven at 260°F for 72 hours and then soaked at atmospheric pressure in a monomer bath contained in 55 gallon drum for 45 hours. The excess monomer was then drained from the tank and hot water was poured in to polymerize the monomer in the concrete. The water was kept hot for 8 hours (80-90°C) by bubbling steam into the water. The specimens were then taken out from the tank and dried and temperature annealed at 210°F for 5 hours in the oven. The details of the polymer treatment for the four specimens from the same batch are given in Table 3 and the drying, impregnation and percent loading data in Table 4. A summary of the design information for all specimens is given in Table 2.
4. TESTS ON 3x6 IN. CYLINDERS

Compression (ASTM C39-66) and split tensile (ASTM C496-66) tests were conducted on the 3x6 in. cylinders. The cylinders in compression were capped with hydrostone to give a smooth and level surface. Two clip gages (averaging 8 strain gages) were attached on either side of the rings fastened 3 in. apart onto the middle portion of the cylinders as shown in Fig. 4. The readings were fed to an automatic plotter which plotted the load versus the deformation at a constant hydraulic flow rate. This setup enables the tracing of the entire load-deformation relation including the post-ultimate load deformation characteristics. It also enables the reuse of the clip gages which would not be possible with traditional deformation measuring devices. The tensile load-strain curves were plotted similarly as the cylinders were loaded in splitting test with gages attached on one side as shown in Fig. 5.

The strength and secant modulus of elasticity result from the 3x6 in. cylinders are summarized in Table 5. Typical stress-strain curves in compression and load-strain curves in split tension are shown in Fig. 6 and Fig. 7, respectively.

It is obvious from Figs. 6 and 7 and Table 5 that the modulus, strength, ultimate strain and energy to break are increased dramatically by impregnation with MMA. The stress strain curves show a high degree of linearity with only a slight tendency to yield at high strains. This is in agreement with data reported previously [10,11]. With the incorporation of rubbery polymer like butyl acrylate (BA) with the composition shown in Table 3, the compressive strengths, tensile strengths and modulus of elasticity decrease from those obtained by MMA impregnated samples in agreement with previous work [9]. Two points are evident for MMA/BA specimens: 1) the drop in tensile strength beyond peak point is not as high as in compression and 2) the strains at rupture in both compression and tension range between 3-4 times that of plain concrete strains. The failure is no longer sudden and as explosive as MMA impregnated samples. This also confirms the previous study that by controlling the percent of BA in the mixture, a wide range of stress-strain behavior from brittle to ductile may be obtained [9].
5. TESTS ON CONICAL SHELLS

5.1 Test Procedures

The same procedure was used for both small cone and big cone. The big cones were tested in 800 kips constant movement type of machine and the small cones in 120 kips constant movement universal testing machine, except cones 10 and 11 (Table 2) which were tested in 300 kips Baldwin constant loading rate machine.

The cones were strain gages with 0.5-0.67 in. electrical resistant strain gages in two directions (vertical and circumferential) at top, center and bottom. The locations and distances for gages on each of the cones are given in Appendix. The strain gages were attached both inside and outside of the wall. The wires attached to the inside gages were taken out from two 1/2 in. diameter holes drilled on opposite sides in the middle height of the specimen. Since the compressive stress and hoop tension were low in this region and cracks always initiated in hoop tension at the lower edge which rarely passed through these holes, they did not materially effect the results.

The test setup is shown in Fig. 8. A thin polyethylene sheet was placed on the base, and hydrostone compound of the right consistency was spread on the sheet. The cone was lowered and centered on the hydrostone ring. Hydrostone was then spread on top of the cone and a plastic sheet was placed on top. The loading head was lowered to cap the cone in place under a load of 2000 lbs. for the big cone and 500 lbs. for the small cone. The capping compound was then allowed to set over night before the test. This procedure gave very consistent results and minimized the friction at both top and bottom.

Cone 7, when cast using the above procedure, gave a lower strength than cone 8 as the lower base was highly uneven and could not be cast satisfactorily using the above procedure. Cone 8, having the same problem, was therefore cast on a thick layer of cement and hydrostone, the thickness varying to fill up the uneveness. As seen from the results (Table 2), cone 8 gave almost twice the ultimate load than that of cone 7.
The strain gages were wired to a B&F multi-channel recorder and the readings from the load cell and the strain gages were recorded automatically on paper tape for each load increment ranging from 3-10 kips. The readings from the paper tape were transferred onto cards or magnetic tape and the data was stored in the computer. A computer program was written for each cone to get actual load-strain data at different load increments and plotted automatically for various combinations of strain gage readings versus loads. A typical calibration of load cell is shown in Table 6.

5.2 Test Results and Observations

Unreinforced Specimens

Failure of unreinforced concrete cones A, B, 1, 2 and 3 were semi-brittle. The failure started at the lower end as the maximum hoop tension was attained. This is evident from the failure modes shown in Figs. 9 and 10. Unreinforced, polymer impregnated cones 4 and 5 also failed in a similar manner but much more explosively. These cones shattered into many pieces at failure (Fig. 11) which made it impossible to locate the initial point of failure. This type of failure mode is representative of material failure.

Figures 12 and 13 show the load-hoop strain relations for plain concrete cones 1 and 2. The analytical predictions based on linear elastic material model are also shown in the figure. The analytical solutions are based on the general purpose nonlinear finite-element analysis NONSAP program which was developed originally by the University of California at Berkeley and extended recently at Fritz Engineering Laboratory [8]. The superimposition of the test data as shown in Figs. 12 and 13 are the solutions obtained for up to 10% fixity at both ends. There is quite a variation in test data observed, probably due to variations in thickness and surface defects but, in general, the data tend to follow the roller supports as the end conditions. Further analysis and verification of the data will be carried out and reported later to see if the extended NONSAP program could correctly predict the behavior and strength of polymer impregnated and/or steel reinforced specimens.
The load-strain curves for unreinforced control and polymer impregnated cones 3, 4 and 5 are shown in Figs. 14 and 15. The increase in load carrying capacity for impregnated specimens is approximately three times that of regular specimens. This is consistent with the results observed on 3x6 in. cylinders. In all cases, BA incorporated cones show a ductility of approximately twice that of only MMA impregnated cones. It is interesting to note that both cones 4 and 5 achieved about the same ultimate load even though the material strengths were quite different (Figs. 6 and 7). This is due to more straining ability of BA-rich cone. The failure initiating in hoop tension was curtailed by the increasing straining ability of the ductile material of cone 5 so that the cone was able to redistribute this high tensile stress and thus be able to take more load. On the other hand, cone 4 achieved such high stiffness and strength, primarily through its higher material stiffness and strength.

Reinforced Specimens

Since the failure initiates in hoop tension at the bottom, specimens 6 and 11 were wire reinforced with several loops of 0.142 in. diameter wire up to 4.5 in. and 3 in from the bottom level, respectively. Specimens 7 through 10 were reinforced with 1-ply, 18 gage wire mesh 1/2 in. center to center. The details are given in Fig. 1. Figures 16 and 17 show the load strain curves for reinforced concrete cones 6, 7 and 8. Due to uneven nature of bottom surface for cone 7, it attained only about half the ultimate load of cone 8. The wire reinforced cone 6 shows the similar load strain characteristics as mesh reinforced cone 8 and achieved slightly higher ultimate load.

The characteristics of failure for wire reinforced specimen are quite different from mesh reinforced specimen as shown in Figs. 18 and 19. Extensive shelling off of outer layer near bottom and nonuniformly spaced cracks are observed for wire reinforced cone (Fig. 18) as compared to very uniformly spaced longitudinal cracks as observed in mesh reinforced case (Fig. 19), presumably due to uniform reinforcement provided by the mesh. The strength obtained for both the wire reinforced and mesh reinforced specimens was almost three times the unreinforced specimens.
The load-strain curves for polymer impregnated wire and mesh reinforced specimens are shown in Figs. 20 and 21. Mesh reinforced plain concrete cone 9 failed prematurely to give about the same strength as unreinforced cone B and cone 3. However, the failure was somewhat ductile with gradual drop in load as compared to total collapse for unreinforced cones. Polymer impregnated mesh and wire reinforced cones 10 and 11 attained the strength of 120-122 kips as compared to 84-90 kips for polymer impregnated unreinforced cones 4 and 5, or 27-33 kips for unreinforced plain concrete cones B and 3. Thus, there is a strength additive effect for both polymer impregnation and wire reinforcement.

The failure characteristics for reinforced, polymer impregnated cones 10 and 11 as shown in Figs. 22 and 23, respectively, lie intermediate between polymer impregnated unreinforced cones 4 and 5 (Fig. 11) and wire and mesh reinforced cones 6 and 8 (Figs. 18 and 19). Many more cracks are observed for reinforced polymer impregnated concrete cones than reinforced plain concrete cones due to higher strains achieved at failure, but the failure modes are similar. In all wire reinforced cones (polymer treated and non-treated), bond failure with no breakage of wire was observed in contrast to typical necking failure observed for steel mesh in all mesh reinforced cones.
6. CONCLUSIONS

The following conclusions are drawn from the current experiments:

1. The load carrying capacities for polymer impregnated concrete shell specimens are approximately 2 to 3 times that of plain concrete control specimens.

2. Ductility for MMA/BA shell specimens is approximately twice that of MMA specimens and 2 to 4 times that of plain concrete control specimens.

3. The MMA/BA shell specimens reach about the same ultimate strength as MMA specimens even though the cylinder strengths for MMA/BA materials are much lower than that of MMA materials.

4. Polymer impregnated, mesh and wire reinforced shell specimens attain a strength approximately 40% more than that of polymer impregnated unreinforced specimens and about four times that of unreinforced plain concrete specimens. There is a direct strength additive effect for both polymer impregnation and wire reinforcement.

5. Preliminary analytical study shows that the end conditions for plain concrete shell specimens are very near roller support conditions.
7. REFERENCES


Table 1 Mix Proportions for Concrete

<table>
<thead>
<tr>
<th>Component</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement type 1, air entrained</td>
<td>94 lbs</td>
</tr>
<tr>
<td>Water</td>
<td>42-44 lbs</td>
</tr>
<tr>
<td>Sand, washed granite</td>
<td>179 lbs</td>
</tr>
<tr>
<td>Coarse aggregate, crushed granite 3/8&quot; maximum</td>
<td>154 lbs</td>
</tr>
<tr>
<td>Slump</td>
<td>3-4 in.</td>
</tr>
<tr>
<td>Entrained air</td>
<td>5%</td>
</tr>
<tr>
<td>Approximate uniaxial compressive strength</td>
<td>6000 psi</td>
</tr>
<tr>
<td>Approximate splitting cylinder strength</td>
<td>600 psi</td>
</tr>
</tbody>
</table>

Table 2 Description of Specimens and Strength

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Size</th>
<th>Batch Number</th>
<th>Type of Treatment</th>
<th>Maximum Load (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>big cone</td>
<td>1</td>
<td>control</td>
<td>76</td>
</tr>
<tr>
<td>B</td>
<td>small cone</td>
<td>1</td>
<td>control</td>
<td>33</td>
</tr>
<tr>
<td>1</td>
<td>big cone</td>
<td>2</td>
<td>control</td>
<td>55</td>
</tr>
<tr>
<td>2</td>
<td>big cone</td>
<td>4</td>
<td>control</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>small cone</td>
<td>4</td>
<td>control</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>small cone</td>
<td>2</td>
<td>MMA</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>small cone</td>
<td>3</td>
<td>MMA/BA (40/60)</td>
<td>84</td>
</tr>
<tr>
<td>6</td>
<td>big cone</td>
<td>5</td>
<td>control, wire reinforced</td>
<td>190</td>
</tr>
<tr>
<td>7</td>
<td>big cone</td>
<td>6</td>
<td>control, mesh reinforced</td>
<td>89.5</td>
</tr>
<tr>
<td>8</td>
<td>big cone</td>
<td>7</td>
<td>control, mesh reinforced</td>
<td>175</td>
</tr>
<tr>
<td>9</td>
<td>small cone</td>
<td>5</td>
<td>control, mesh reinforced</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>small cone</td>
<td>6</td>
<td>MMA/BA (60/40) mesh reinforced</td>
<td>120</td>
</tr>
<tr>
<td>11</td>
<td>small cone</td>
<td>7</td>
<td>MMA/BA (60/40) wire reinforced</td>
<td>122</td>
</tr>
</tbody>
</table>
Table 3 Details of Polymer Treatment

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Monomer Mixture</th>
<th>Catalyst</th>
<th>Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>MMA + 10% TMPTMA</td>
<td>0.5% Azobisobutyronitrile</td>
<td>None</td>
</tr>
<tr>
<td>5</td>
<td>MMA/BA (40/60%) + 10% TMPTMA</td>
<td>&quot;</td>
<td>None</td>
</tr>
<tr>
<td>10</td>
<td>MMA/BA (60/40%) + 5% TMPTMA</td>
<td>&quot;</td>
<td>0.142 in diameter wire reinforced base to 3 in. (see Fig. 2)</td>
</tr>
<tr>
<td>11</td>
<td>MMA/BA (60/40%) + 5% TMPTMA</td>
<td>&quot;</td>
<td>1-ply, 18 gage wire mesh 1/2 in $\phi$ to $\phi$ (see Fig. 2)</td>
</tr>
<tr>
<td>7, 8, 9</td>
<td>None</td>
<td>None</td>
<td>Same as specimen No. 10</td>
</tr>
<tr>
<td>6</td>
<td>None</td>
<td>None</td>
<td>Two intertwined 0.142 in. diameter wires reinforced base to 4-1/2 in. (see Fig. 1)</td>
</tr>
</tbody>
</table>

Table 4 Drying-Impregnation Data for Small Specimens

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Type</th>
<th>Dry Wt.</th>
<th>Saturated Wt.</th>
<th>% Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>small cone</td>
<td>40.45 lbs.</td>
<td>42.90 lbs.</td>
<td>6.06</td>
</tr>
<tr>
<td></td>
<td>cylinder</td>
<td>1600 gms.</td>
<td>1700 gms.</td>
<td>6.20</td>
</tr>
<tr>
<td>5</td>
<td>small cone</td>
<td>38.6 lbs.</td>
<td>40.9 lbs.</td>
<td>5.96</td>
</tr>
<tr>
<td></td>
<td>cylinder</td>
<td>1547 gms.</td>
<td>1660 gms.</td>
<td>7.30</td>
</tr>
<tr>
<td>10</td>
<td>small cone</td>
<td>48.9 lbs.</td>
<td>51.75 lbs.</td>
<td>5.83</td>
</tr>
<tr>
<td>11</td>
<td>small cone</td>
<td>49.0 lbs.</td>
<td>51.6 lbs.</td>
<td>5.30</td>
</tr>
</tbody>
</table>

Treatment Steps
1. Dried in oven for 72 hrs. @ 260°F.
2. Soak impregnation in a monomer tank for 45 hrs.
3. Hot water-steam polymerization for 8 hrs.
4. Dried and temperature annealed at 210°F for 5 hrs.
<table>
<thead>
<tr>
<th>Batch Number</th>
<th>Type</th>
<th>Splitting Tensile Strength $f'_t$ (psi)</th>
<th>Compressive Strength $f'_c$ (psi)</th>
<th>Secant Modulus of Elasticity $E(x10^6$ psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control</td>
<td>624</td>
<td>6,578</td>
<td>4.60</td>
</tr>
<tr>
<td>1</td>
<td>Control</td>
<td>-</td>
<td>6,932</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Control</td>
<td>530</td>
<td>6,437</td>
<td>2.56</td>
</tr>
<tr>
<td>2</td>
<td>Control</td>
<td>-</td>
<td>6,437</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Control</td>
<td>554</td>
<td>4,916</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Control</td>
<td>835</td>
<td>5,305</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Control</td>
<td>493</td>
<td>5,517</td>
<td>3.00</td>
</tr>
<tr>
<td>4</td>
<td>Control</td>
<td>495</td>
<td>5,057</td>
<td>-</td>
</tr>
<tr>
<td>2 MMA</td>
<td>1,851</td>
<td>17,400</td>
<td></td>
<td>6.11</td>
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<td>2 MMA</td>
<td>1,521</td>
<td>19,663</td>
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<td>-</td>
</tr>
<tr>
<td>3 MMA/BA (40/60)</td>
<td>1,583</td>
<td>10,787</td>
<td></td>
<td>3.93</td>
</tr>
<tr>
<td>3 MMA/BA (40/60)</td>
<td>1,026</td>
<td>11,565</td>
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</table>
Table 6  Typical Calibration of Load Cell for Cone #4 Test

<table>
<thead>
<tr>
<th>Load P(kips)</th>
<th>Strain Increment (Δe, micro-in/in)</th>
<th>Note: Full Bridge Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Red +P</td>
</tr>
<tr>
<td>5</td>
<td>196</td>
<td>White -P</td>
</tr>
<tr>
<td>10</td>
<td>187</td>
<td>Black -S</td>
</tr>
<tr>
<td>15</td>
<td>192</td>
<td>Green +S</td>
</tr>
<tr>
<td>20</td>
<td>195</td>
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<td>25</td>
<td>183</td>
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<td>80</td>
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<tr>
<td>85</td>
<td>196</td>
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<tr>
<td><strong>Average</strong></td>
<td><strong>189.12</strong></td>
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</table>

Strain Δe(micro in/in)/kip = [189.12/5] = 37.8234
Sec. B-B Details Of Reinforcement - Mesh Reinforced

Fig. 1 Dimension and Reinforcement Details of Big Concrete Cone

Sec. B-B Details Of Reinforcement - Mesh Reinforced

Fig. 2 Dimension and Reinforcement Details of Small Concrete Cone
Fig. 3 The Outer and Inner Molds to Cast the Concrete Cones
Fig. 4 Setup for Compression Test on 3x6 in. Cylinders to Measure the Stress-Strain Behavior for Polymer Impregnated Specimens.

Fig. 5 Setup for Measurement of Load-Strain Behavior in Splitting Cylinder Test
Fig. 6 Typical Compressive Stress-Strain Curves for 3x6 in. Cylinders
Fig. 7 Typical Split Tensile Load-Strain Curves for 3x6 in. Cylinders
Fig. 8(a) Cone Capping and Setup in the Testing Machine

Fig. 8(b) Test Setup for Big Cone in 800 kip, Constant Displacement Machine. Note the Cast in Place Cap and Polyethylene Sheets at Top and Bottom to Minimize Friction.
Fig. 9 Uniform Longitudinal Cracking Pattern in Unreinforced Big Cone

Fig. 10 Cracking Pattern in Unreinforced Small Cone; Note the Failure Mode is Same as in Big Cone, Fig. 9.
Fig. 11 Total Collapse is Observed at Ultimate Load for all Unreinforced Polymer Impregnated Cones
Fig. 12 Load-Strain Curves for Horizontal Gages at Base for Plain Concrete Cones 1,2. The Support Conditions are Close to Roller Type Support.
Fig. 13 Load-Strain Curves for Horizontal Gages at Center for Plain Concrete Cones 1, 2
Plot Number B-5
A = MMA Small, Cone 4
B = MMA/BA Small, Cone 5
C = Control Small, Cone 3

Fig. 14(a) Load-Strain Curves for Two Horizontal Gages at Center for Polymer Concrete Cones 4 and 5
Fig. 14(b) Load-Strain Curves for Two Vertical Gages at Center for Polymer Concrete Cones 4 and 5
Plot Number B-9
A = MMA Small, Cone 4
B = MMA/BA Small, Cone 5
C = Control Small, Cone 3

2 Horizontal Gages
Lower Level

Fig. 15(a) Load-Strain Curves for Two Horizontal Gages at Base for Polymer Concrete Cones 4 and 5
Fig. 15(b) Load-Strain Curves for Two Vertical Gages at Base for Polymer Concrete Cones 4 and 5

Plot Number B-10
A = MMA Small, Cone 4
B = MMA/BA Small, Cone 5
C = Control Small, Cone 3
Fig. 16(a) Load-Strain Curves for Two Horizontal Gages at Center for Reinforced Concrete Cones 6, 7 and 8
Fig. 16(b) Load-Strain Curves for Two Vertical Gages at Base for Reinforced Concrete Cones 6, 7 and 8
Fig. 17(a) Load-Strain Curves for Two Horizontal Gages at Base for Reinforced Concrete Cones 6, 7 and 8

Plot Number B-9
A = Big Cone Wire, Cone 6
B = Big Cone Mesh, Cone 7
C = Big Cone Mesh, Cone 8
Plot Number B-10
A = Big Cone Wire, Cone 6
B = Big Cone Mesh, Cone 7
C = Big Cone Mesh, Cone 8

Fig. 17(b) Load-Strain Curves for Two Vertical Gages at Base for Reinforced Concrete Cones 6, 7 and 8
(a) In-Plane Shell Cracking with Falling Off of Outer Shell is Observed

(b) Other side of cone shown in (a). Due to eccentric loading, some longitudinal cracks are observed.

Fig. 18 Failure of Wire Reinforced Cone
Fig. 19 Failure mode of mesh reinforced cones. Very uniformly spaced longitudinal cracks beginning at bottom are observed.
Plot Number B-5
A = Mesh 1 Control, Cone 9
C = Mesh 2 MMA/BA, Cone 10
B = Wire 1 MMA/BA, Cone 11

Fig. 20(a) Load-Strain Curves for Two Horizontal Gages at Center for Reinforced Polymer Concrete Cones 10 and 11
Plot Number B-6
A = Mesh 1 Control, Cone 9
C = Mesh 2 MMA/BA, Cone 10
B = Wire 1 MMA/BA, Cone 11

Fig. 20(b) Load-Strain Curves for Two Vertical Gages at Center for Reinforced Polymer Concrete Cones 10 and 11
Plot Number B-10
A = Mesh 1 Control, Cone 9
C = Mesh 2 MMA/BA, Cone 10
B = Wire 1 MMA/BA, Cone 11

Fig. 21(a) Load-Strain Curves for Two Horizontal Gages at Base for Reinforced Polymer Concrete Cones 10 and 11
Fig. 21(b) Load-Strain Curves for Two Vertical Gages at Base for Reinforced Polymer Concrete Cones 10 and 11
Fig. 22 Total collapse (Fig. 11) is prevented by wire reinforcement of polymer impregnated cones; extensive cracking observed before substantial load drop.

Fig. 23 Total collapse (Fig. 11) is prevented by mesh reinforcement of polymer impregnated cones; failure mode is quite similar to mesh reinforced plain concrete cones (Fig. 19).
APPENDIX

Locations and distances for strain gages on each of the eleven conical shell specimens listed in Table 2 are given in Figs. 24 through 34.

**Figure**

24 Cone #1, Big Cone, Control
25 Cone #2, Big Cone, Control
26 Cone #3, Small Cone, Control
27 Cone #4, Small Cone, MMA
28 Cone #5, Small Cone, MMA/BA
29 Cone #6, Big Cone, Control Wire Reinforced
30 Cone #7, Big Cone, Control Mesh Reinforced
31 Cone #8, Big Cone, Control Mesh Reinforced
32 Cone #9, Small Cone, Control Mesh Reinforced
33 Cone #10, Small Cone, MMA/BA-Mesh Reinforced
34 Cone #11, Small Cone, MMA/BA-Wire Reinforced
Cone #1, Big Cone, Control

**Vertical Gages**

- x4
- x3
- 16x x15
- 7x x8
- x11
- Level 3
- Level 2
- x20
- x19
- 32x x31
- 23x x24
- x27
- x28
- Level 2
- Level 1

**Horizontal Gages**

- x2
- x1
- 14x x13
- 5x x6
- x9
- Level 3
- Level 2
- x18
- x17
- 30x x29
- 21x x22
- x25
- Level 2
- Level 1

**Fig. 24 Location of Gages**

Note: Measurements along face of wall not vertical.
**Cone #2, Big Cone, Control**

**Vertical Gages**

- Level 3
  - x10
  - x12
- Level 2
  - x6
  - x8
- Level 1
  - x4
  - x2

**Horizontal Gages**

- Level 3
  - x23
  - x21
- Level 2
  - x9
  - x11
- Level 1
  - x15
  - x13
  - x3

**Fig. 25 Location of Gages**

Note: Measurements along face of wall, not vertical.
Cone #3, Small Cone, Control

Vertical Gages

Horizontal Gages

Note: Measurements along face of wall, not vertical.

Fig. 26 Location of Gages
Cone #4, Small Cone, MMA

**Vertical Gages**

- x3
- x4
- x8
- x7
  Level 3
- x11
- x12
  Level 2
- x16
- x15
  Level 2
- x19
- x20
- x24
- x23
  Level 1

**Horizontal Gages**

- 1x+31
- 2x+28
- 6x+25
- 5x+34
  Level 3
- 9x+32
- 10x+29
  Level 2
- 14x+26
- 13x+35
  Level 2
- 17x+33
- 18x+30
- 22x+27
- 21x+36
  Level 1

**Fig. 27 Location of Gages**

Note: Measurements along face of wall, not vertical.

Level 1 x = 1/2" long, + = 1" long
Cone #5, Small Cone, MMA/BA

Vertical Gages

Level 3
- x14
- x4
- x16

Level 2
- x18
- x6
- x8
- x20

Level 1
- x22
- x10
- x12
- x24

Horizontal Gages

Level 3
- x13
- x3
- x15
- x17
- x5

Level 2
- x19
- x7
- x11
- x21
- x9

Level 1
- x23

Note: Measurements along face of wall, not vertical.

Fig. 28 Location of Gages
Cone #6, Big Cone, Control Wire Reinforced

Vertical Gages

Level 3
\[\times 4 \quad \times 2 \quad \times 6 \quad \times 8\]

Level 2
\[\times 12 \quad \times 10 \quad \times 14 \quad \times 16\]

Level 1
\[\times 20 \quad \times 18 \quad \times 22 \quad \times 24\]

Horizontal Gages

Level 3
\[\times 3 \quad \times 1 \quad \times 5 \quad \times 7\]

Level 2
\[\times 11 \quad \times 9 \quad \times 13 \quad \times 15\]

Level 1
\[\times 19 \quad \times 17 \quad \times 21 \quad \times 23\]

Note: Measurements along face of wall, not vertical.

Fig. 29 Location of Gages
Cone #7, Big Cone, Control Mesh Reinforced

Vertical Gages

Level 3
- x4
- x2
- x6
- x8

Level 2
- x12
- x10

Level 1
- x14
- x16

Horizontal Gages

Fig. 30 Location of Gages

Note: Measurements along face of wall, not vertical.

Level 3
- x3
- x1
- x5
- x7

Level 2
- x11
- x9
- x13
- x15

Level 1
- x19
- x17
- x21
- x23
Cone #8, Big Cone, Control Mesh Reinforced

Vertical Gages

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>x4</td>
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</tr>
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<td>x7</td>
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<td>x20</td>
<td>x11</td>
</tr>
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<td>x18</td>
<td>x9</td>
</tr>
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<td>x13</td>
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Horizontal Gages

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<td>x21</td>
<td>x11</td>
</tr>
<tr>
<td>x23</td>
<td>x9</td>
</tr>
</tbody>
</table>

Note: Measurements along face of wall, not vertical.

Fig. 31 Location of Gages
Cone #9, Small Cone, Control Mesh Reinforced

**Vertical Gages**

- 
- Level 3
  - \( x_2 \)
  - \( x_4 \)
  - \( x_6 \)
  - \( x_8 \)

- Level 2
  - \( x_{10} \)
  - \( x_{12} \)
  - \( x_{14} \)
  - \( x_{16} \)

- Level 1
  - \( x_{18} \)
  - \( x_{20} \)
  - \( x_{22} \)
  - \( x_{24} \)

**Horizontal Gages**

- Level 3
  - \( x_{11} \)
  - \( x_{13} \)
  - \( x_{15} \)
  - \( x_{17} \)

- Level 2
  - \( x_{19} \)
  - \( x_{21} \)
  - \( x_{23} \)

- Level 1
  - \( x_{1} \)
  - \( x_{3} \)
  - \( x_{5} \)
  - \( x_{7} \)

---

**Fig. 32 Location of Gages**

- Note: Measurements along face of wall, not vertical.
Vertical Gages

Level 3

x4
x2
x6
x8

Level 2

x12
x10
x14
x16

Note: Measurements along face of wall, not vertical.

Level 1

x20
x18
x22
x24

Horizontal Gages

Level 3

x3
x1
x5
x7

Level 2

x11
x9
x13
x15

Level 1

x19
x17
x21
x23

Fig. 33 Location of Gages
Cone #11, Small Cone, MMA/BA-Wire Reinforced

**Vertical Gages**

<table>
<thead>
<tr>
<th>Level 1</th>
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<tbody>
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**Horizontal Gages**

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<td>x7</td>
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<tr>
<td></td>
<td>x15</td>
<td>x9</td>
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</table>

1/2" x 14" Level 1

6-1/2" x Level 2

6-1/2" x Level 3

Note: Measurements along face of wall, not vertical.

Fig. 34 Location of Gages
Project Publications

1. ERDA Report No. C00-2682-1

2. ERDA Report No. C00-2682-2

3. ERDA Report No. C00-2682-3

4. ERDA Report No. C00-2682-4

5. ERDA Report No. C00-2682-5

6. ERDA Report No. C00-2682-6

7. ERDA Report No. C00-2682-7

8. ERDA Report No. C00-2682-8

9. ERDA Report No. C00-2682-9