PLASTER MODELS USED TO PREDICT FAILURE PATTERNS IN CONCRETE SLABS

By

HORACE THOMAS KORNEGAY

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PATTERNS IN CONCRETE SLABS

Thesis Approved:

Thomas Scott Dean
Thesis Adviser

T. Gilbert Palmer

J. H. Boggs
Dean of the Graduate College

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CHAPTER I

INTRODUCTION

The purpose of this investigation is to study the feasibility of determining the yield-line pattern for concrete slabs subjected to a uniform load. K. W. Johansen (3) has developed a method of analysis for such slabs. The only variables needed to use this method are strength of concrete, magnitude and distribution of load, strength of steel, support conditions, and size and shape of the slab. The method is based on the assumption that the correct failure mechanism can be found through a trial and error procedure using a mathematical model. This process may become involved if the general shape of the yield-line pattern is unknown. The proposed method shows the yield pattern which should be considered in the design of the slab. With some small revisions, it can be used to find the actual failure load and displacements which are normally found by using a mathematical model as suggested by Johansen.

Tests were conducted to find a suitable material to represent the reinforcement commonly used in slabs. These tests were performed on slabs of simple configuration in order that the resultant yield lines could be predicted. Hardware cloth was found to be the best reinforcement.

It is not the purpose of this paper to be a handbook of failure patterns for different sizes and shapes of slabs, but only to show a method by which these failure patterns can be readily obtained.

CHAPTER II

YIELD-LINE THEORY

Many publications have discussed the analysis of slabs by yield-line theory. Only a brief explanation of the method is presented here. If more detailed information is desired, it may be obtained from books written by K. W. Johansen (3), L. L. Jones (4), or others.

Two methods are used to solve problems in yield-line theory, the work method and the equilibrium method. If both methods are extended to produce an exact solution, they will give identical solutions. Only the work method is described in this paper because the slab shapes and support conditions studied are best suited to this method.

Basic Assumptions

The basic assumption of yield-line theory is that a reinforced concrete slab will develop yield hinges when in overload conditions (loads above working loads) but will not collapse until a mechanism is formed. The yield lines begin forming where the bending moment per unit width is maximum. Once the tensile portion of the concrete in this section reaches its capacity, tension cracks form, thus reducing the stiffness of the portion. The reduction in stiffness causes a redistribution of moments. The process continues until the load is increased sufficiently to cause a yield of the steel in the region of maximum moment. With a further increase in moment, the section which has yielded will continue to deform but will not sustain any more moment; therefore, the section adjacent to the yielded section will support the additional load. This process continues until the yield lines reach the slab boundary. Any further increase in load will cause unstable equilibrium; thus, the slab is supporting its maximum load when the yield lines reach the boundary. If the structure is loaded so that unstable equilibrium exists, the slab elements will continue to rotate until the concrete along the yield lines crushes. Obviously, this causes failure.

The basic concept of the response of the slab being understood, some other assumptions can be made to facilitate the analysis. The curvature at the yield line is due to plastic deformation and is large compared to the elastic deformations between the yield lines. Consequently, the elastic deformations are ignored, and the segments between the yield lines are considered as planes. It follows that the yield lines are straight because they are the intersection of two straight inclined planes.

The following statements summarize the foregoing discussion:

(a) Yield lines end at a slab boundary.

(b) Yield lines are straight.

(c) A yield line, or extension of a yield line, passes through the intersection of the axes of rotation of adjacent slab elements.

(d) Axes of rotation generally lie along lines of supports and pass over any columns.

Analysis

The first step in analyzing a slab is to assume a failure mechanism. Without the use of model studies, this assumption must be made from the use of the statements previously discussed and more refined theorems set forth by Johansen (3). Next some convenient point at which to give the slab a virtual displacement, δ, is chosen. The deflection of all points in the slab are now determinable in terms of δ, and the amount of external work done on the system can be computed.

In calculating the internal work, the elastic deformations may be neglected as stated previously; therefore, all of the work is absorbed in the plastic deformation or yield lines.

The solution is obtained by setting the internal work equal to the external work as shown in the following equation.

$$\int\int w\delta\, dx\, dy = \sum m_b \ell \Theta \tag{1}$$

where:

(a) w is the load per unit area.

(b) δ is the virtual displacement.

(c) dx and dy are differential lengths in the x and y directions respectively.

(d) m_b is the ultimate bending moment along a yield line.

(e) Θ is the rotation of a slab element with respect to its original position.

Note that Θ can be found in terms of the virtual displacement and the known dimensions of the slab; therefore, the bending moment can be found in terms of the load per unit area, w. The amount of steel required for a given slab size and load or the allowable load for a given slab and area of steel can be determined by conventional methods.

When a yield line intersects the steel at an angle other than zero or ninety degrees, a change in the allowable moment must be considered. Consider a yield line which intersects cd at an angle Θ as shown in Figure 1. The allowable unit moment along cd is m (reinforcement perpendicular to cd). The component of the moment, m, along the direction of the yield line is $\ell_{cd} \cdot m \cdot \cos \Phi$, and the component of m_b in the same direction is $\ell_{ab} \cdot m_b$. If these two terms are equal, the result is the following equation:

(2) $$\ell_{cd} \cdot m \cdot \cos \Phi = \ell_{ab} \cdot m_b$$

Solving for m_b and noting the ℓ_{cd}/ℓ_{ab} is equal to $\cos \Phi$, the result is as follows:

(3) $$m_b = m \cos^2 \Phi$$

If there is capacity to resist bending moment in several directions, then m_b is the sum of the components of the moments along the direction of m_b, that is

(4) $$m_b = \sum_{i=1}^{n} m_i \cos^2 \Phi_i$$

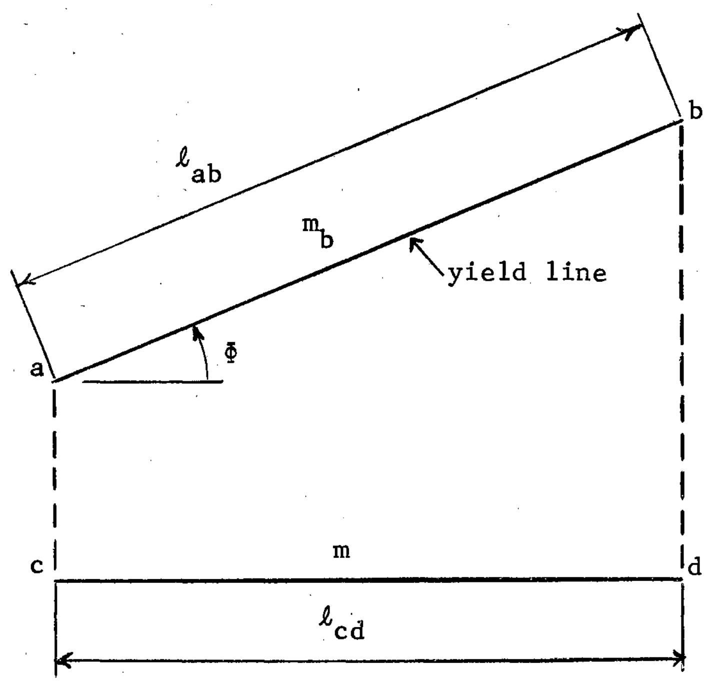


Figure 1. Relationship of Allowable Moment to Yield-Line Moment.

In slabs the steel is usually placed in an orthogonal grid. This placement yields a special case of the above equation. In Figure 2, the reinforcing in one direction is a known function of the reinforcing in the other direction. Thus, equation (4) becomes:

$$(5) \qquad m_b = m \cos^2\Phi + \mu m \cos^2(\pi/2 + \Phi)$$

or

$$(6) \qquad m_b = m \cos^2\Phi + \mu m \sin^2\Phi$$

Another special condition occurs when the reinforcing in both directions is equal ($\mu = 1$); the moment per unit length is constant regardless of the direction considered.

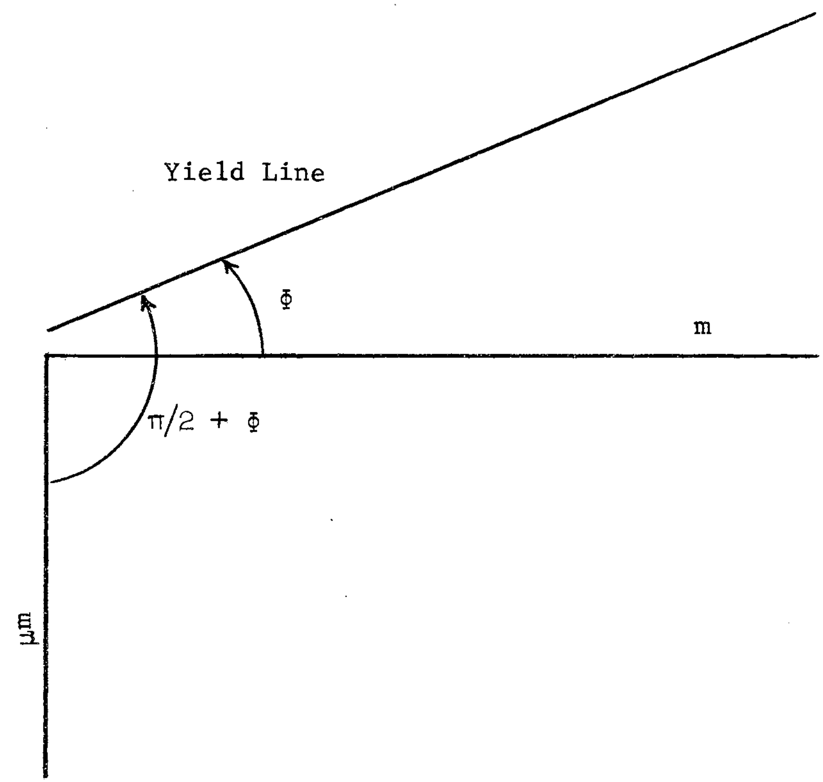


Figure 2. Relation of Perpendicular Allowable Moments to Yield-Line Moment.

CHAPTER III

DESIGN AND PREPARATION OF MODELS AND LOADING FRAME

Plaster models were chosen for this investigation because of their ability to represent a brittle material such as concrete (7). The size of the slab and the reinforcement were chosen so that only small loads would be necessary to test the slabs. Dimensions of the slabs are unimportant since dimensional analysis is not involved in the model studies. However, the elastic and plastic properties of the materials chosen should be similar to those used in constructing reinforced concrete slabs. The materials used in the tests described in this paper conform with the above conditions.

Molds

The forms used for preparation of the models were made of pressed hardboard attached to a plywood base with three-eighths inch molding attached with screws. These models are not refined, but they are reasonably accurate and inexpensive. Steel or plexiglass would be more suitable when great precision is required; however, for the type of models studied, masonite forms were very satisfactory.

Reinforcement

The reinforcing used in the models was steel hardware cloth. It consists of 0.02 inch diameter wires spaced 0.125 inch on center in perpendicular directions and welded at each intersection. The wire is not deformed as steel reinforcing rods are; however, the welded intersections help develop bond between the steel and plaster. This is not the same type of bonding found in actual slabs, but it simulates this effect. Other types of reinforcements used in preliminary tests included monofilament nylon fishing line, twenty-four gauge copper wire, twenty-four gauge galvanized steel wire, twenty-eight gauge steel wire coated with green paint (used by florists), twenty-six gauge lacquer-coated copper wire (used for winding electromagnets), one-fourth inch hardware cloth, fourteen-by-eighteen mesh steel screen wire. Only the nylon and lacquered copper wire reinforcements showed poor bonding characteristics. The other reinforcements showed varying degrees of bond strength with the best results obtained from the ones which were woven and/or welded at the intersection of each wire, i.e., screen wire and hardware cloth, which are shown in Figures 3 and 4.

Plaster

The plaster mix used for this investigation was 0.9 water/plaster ratio by weight. This ratio was used for several reasons: (1) it is slow setting, giving ample time to pour and smooth the plaster; (2) it is a thin mixture which will not disturb the reinforcement when it is poured into the mold; (3) it is weak enough that only small pressures are required to crack the slabs. A seven-tenths water/plaster ratio will work if pressures larger than three pounds per square inch are available for testing the slabs. Stress-strain, strength-time as well as other pertinent relations are available for both of the above mixes (5).

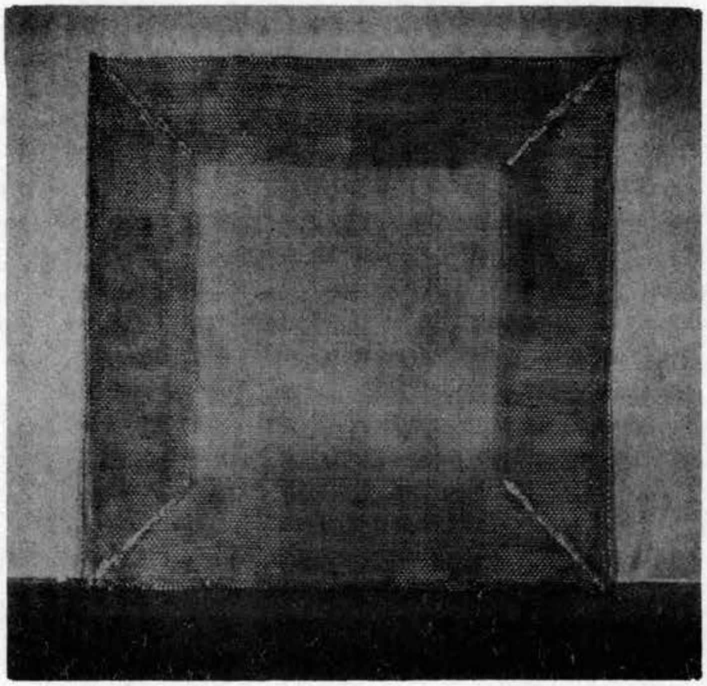


Figure 3. Copper Screen Wire Used as Reinforcement.

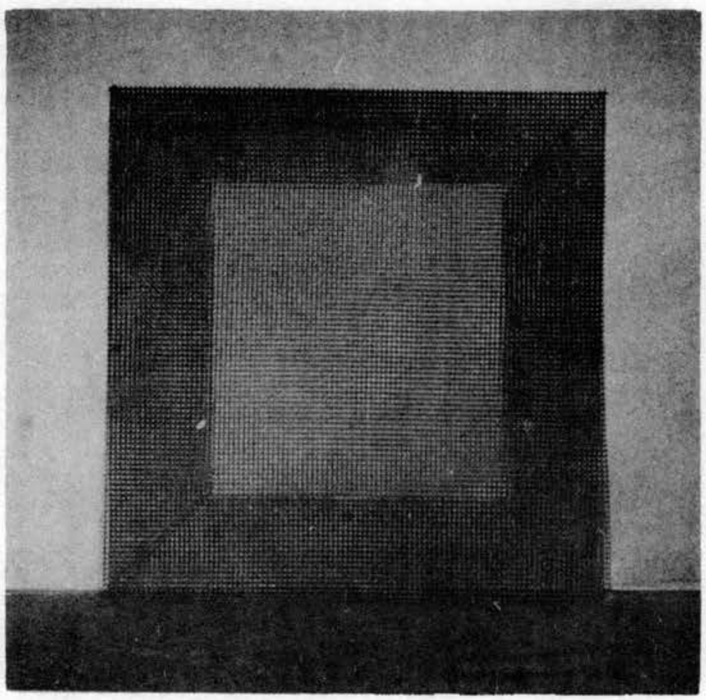


Figure 4. Hardware Cloth Used as Reinforcement.

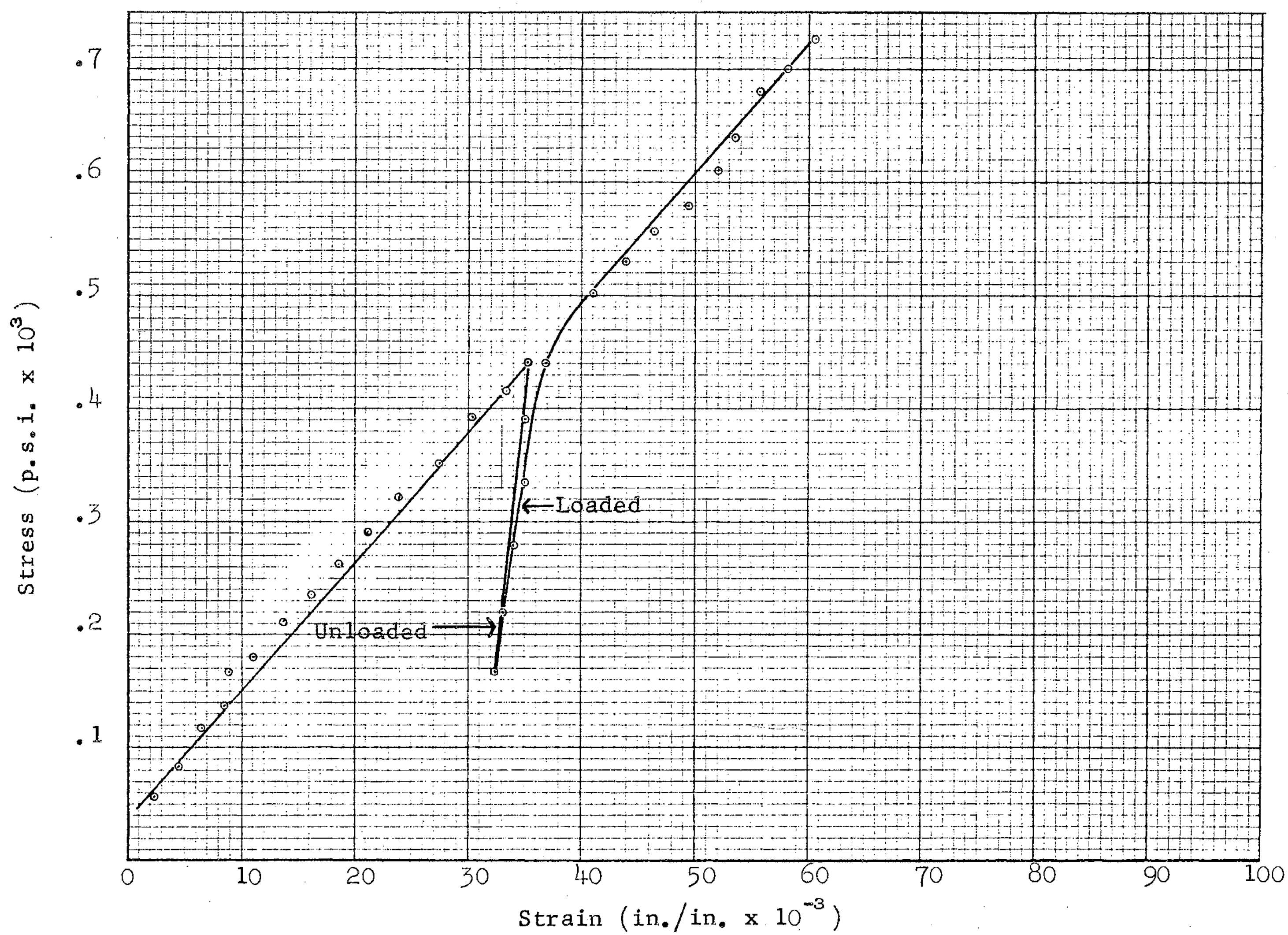


Figure 5. Stress-Strain Relationship for Copper Screen Wire.

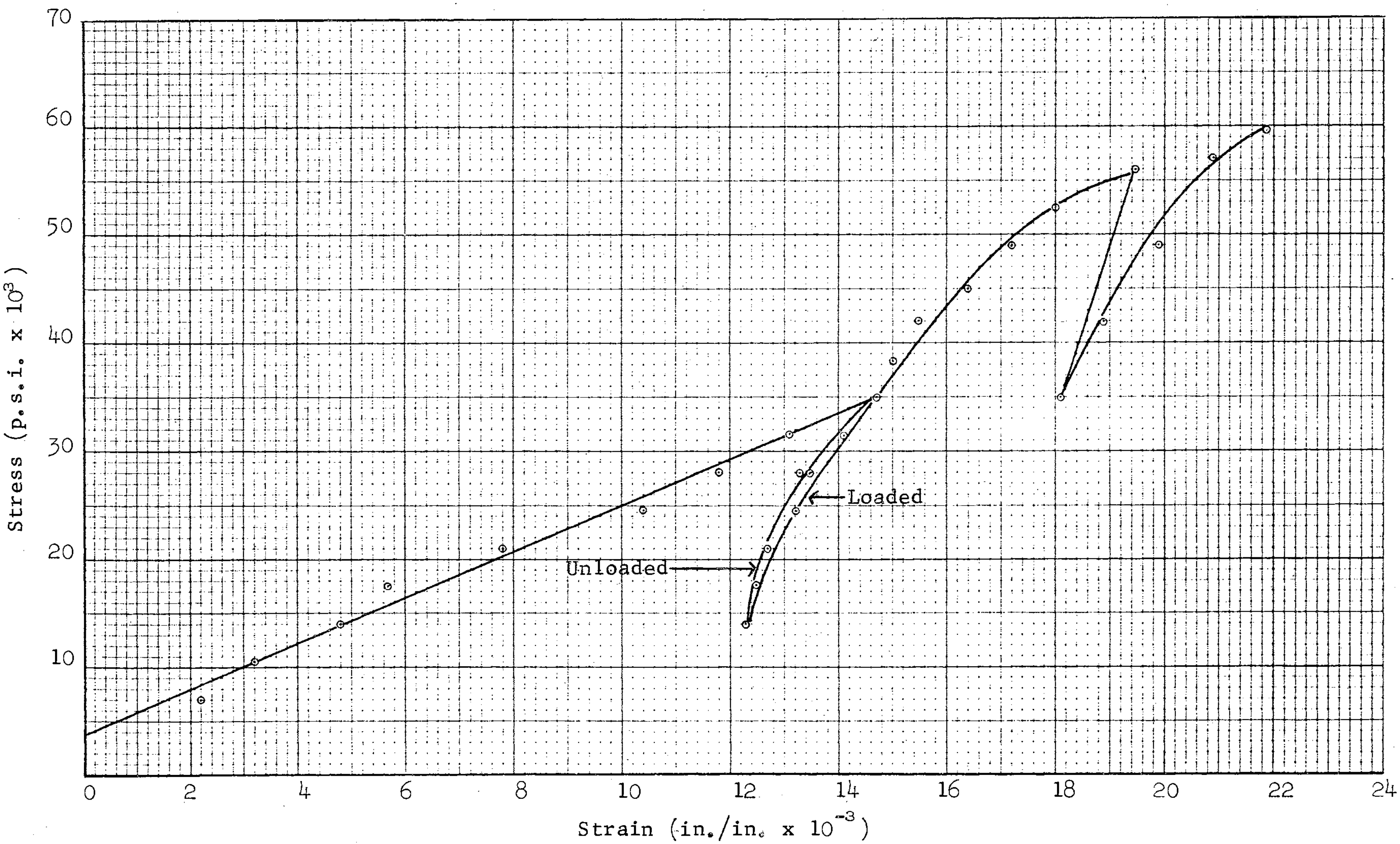


Figure 6. Stress-Strain Relationship for 1/8" Hardware Cloth.

Preparation of Models

The preparation of the models was one of the most important steps in the procedure for making plaster-model tests. The reinforcement must be bent into shape with great accuracy. In this investigation the total distance from the top face of the reinforcement to the bottom face of the reinforcement was one-fourth inch with a one-sixteenth inch layer of plaster used to cover the steel. Therefore, if the reinforcement was made too deep by one-sixteenth inch, the reinforcement was exposed at the top of the slab. The most accurate method found for placing the reinforcement was to lay the reinforcement mesh on taut strands of twenty-six gauge lacquered copper wire. As noted previously, the lacquered wire has a negligible amount of bonding capacity and, therefore, adds no strength to the slab. Four strands of copper wire sufficiently supported the hardware cloth. Another method of supporting the mesh was tried, but it was too inaccurate to hold the reinforcing in its proper position. A "gel" coat of plaster equal to the thickness required for the bottom cover layer was poured into the mold. After the plaster had thickened enough to support the weight of the reinforcing (about fifteen minutes), the mesh was placed in the mold, and the remaining volume of plaster was mixed and poured into the form. Two problems arose when the above method was used. One difficulty was getting the "gel" coat even or level so that it could support the reinforcement properly. The second problem was that the thickened plaster showed a tendency to dissolve or wash out from under the mesh allowing the reinforcement to rest on the bottom of the form.

The mixing of the plaster should be undertaken with care. The best method was to pour the powdered plaster into the proper amount of water and to saturate each granule of plaster. The powder and water should set for about five minutes to allow all of the powder to become thoroughly moistened, and then the mixture should be stirred gently by hand. It should not be mixed vigorously because this will cause air bubbles to form. All of the lumps should be removed. If hand mixing is used, the problems of lumps can be eliminated, and a consistent mix is almost assured (1).

After the plaster was poured into the mold, it was allowed to stand for about five minutes so that excess water and any tiny air bubbles, which might have formed during the pouring, could rise to the surface. The surface was then leveled with a straight bar.

Curing

After the plaster had taken its initial set, the slab was removed from the form and marked, and pertinent data was recorded. A special drying rack was constructed in which the slabs were cured. This device is shown in Figure 7. It was necessary to cure the slabs in this manner to prevent warpage which occurs because of the difference in moisture content of opposite sides when they are dried in a flat position.

The slabs were cured from twenty-four hours to three days depending upon the support conditions to be used and the reinforcing material. The actual curing time of each slab was recorded and is shown in Tables I, II, and III.

Loading Frame

All of the tests on yield-line theory have considered only uniform loads, but the uniform loads have been simulated by a series of sixteen, thirty-two, or sixty-four point loads (3, 4, 8). It was felt that the tests to be made for this investigation should try to simulate the uniform load more accurately than the tests mentioned above. To obtain the wanted simulation, a square balloon was constructed of three mil polyethylene and butyl rubber. The balloon was housed in a cube constructed of three-fourths inch plywood. One side of the cube was left open so that the loading platform could be placed there. The platform was constructed so that simple, fixed, and column support conditions could be simulated. The testing apparatus is shown in Figure 8.

Testing Procedure

After the slabs cured, they were removed from the drying rack and placed on the loading platform. The balloon was then inflated until the slab rested lightly against all supports. This pressure was held constant until the slab was positioned exactly on the supports. The pressure should have been increased at a uniform rate, but in the tests conducted this was difficult because of small leaks in the balloon. However, it has been shown that if the plaster models are tested within four minutes and not less than one minute from the first application of load, the change in loading rate does not seriously affect the results (1). These limits were followed in the tests recorded in this investigation.

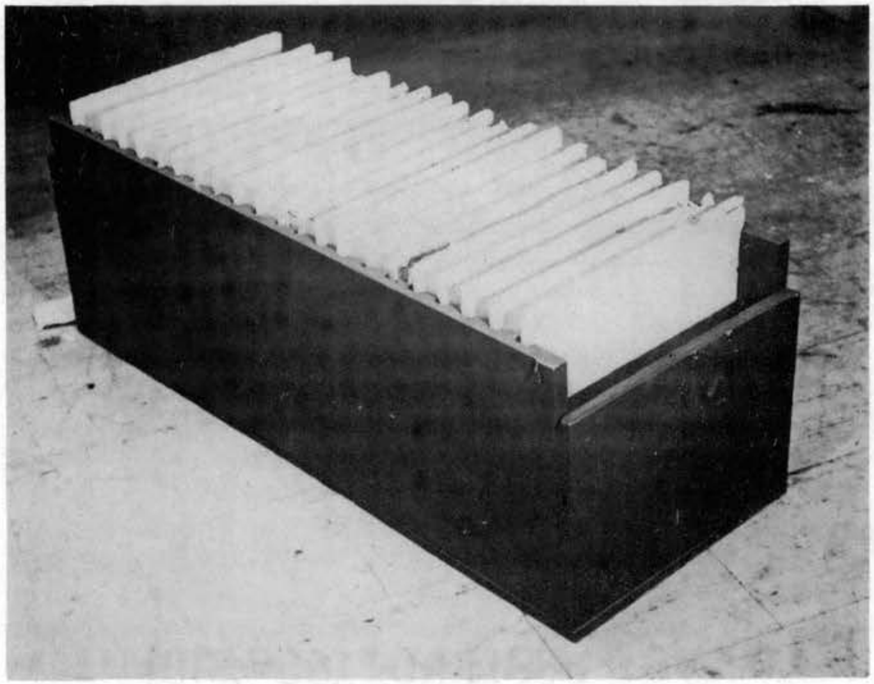


Figure 7. Curing Rack.

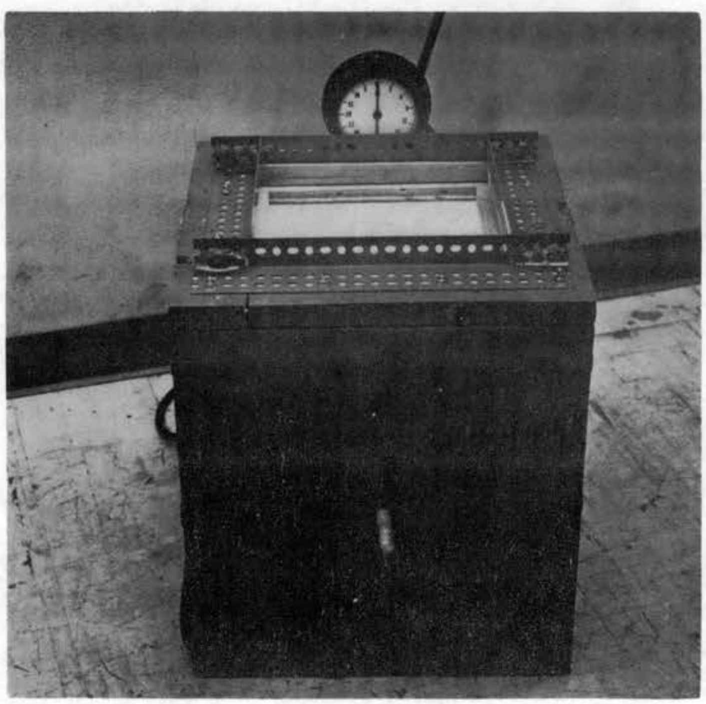


Figure 8. Testing Apparatus.

CHAPTER IV

TEST RESULTS

Three series of tests were made in this investigation. Each series was conducted under different support conditions. These three conditions--simple, fixed, and column supports--represent the ones encountered most frequently in concrete construction.

Simple Support Conditions

Simple support tests were conducted first for several reasons: (1) other test results are available for these conditions, and (2) this seemed to be the easiest condition to simulate.

A plywood platform with a hole cut to the exact size of the span in each direction was made. Some models were tested while resting directly on the plywood, but this was inaccurate since any slight roughness in the wood or models prevented full contact between the two. An adhesived cork strip was attached to the platform to overcome this difficulty. The situation was improved by the cork, but full contact between the two surfaces was still not achieved. A one-half inch thick strip of foamed plastic, similar to rubber foam, was found to allow full support along the edge of the slab. If the foamed plastic is too thick, it will allow large deflections at the center of the support and cause the slab to crack as if it were simply supported only at the corners. Slab number twenty-three, shown in Figures 9 and 10, illustrates this type of failure.

Table I gives the pertinent data for each slab. The slabs are shown in Figures 9 through 24. The lines of failure are marked in ink; therefore, the final small cracks are shown the same size as the large initial cracks. In some cases the full failure mechanism was not produced because pressures above three pounds per square inch were unavailable.

Fixed Support Conditions

Fixed supports were simulated by clamping the edge of the slab to the simple support condition. This was accomplished by placing a sized two-by-four over the edge of the slab and putting bolts through the two-by-four and plywood platform. Two rows of bolts were used to assure that the two-by-four was level along the edge of the slab. Only two models were tested in this manner. It was found that the edges of the slabs rotated between the two-by-four and the plywood platform regardless of the pressure exerted by the bolts. Both models failed along lines indicating simple support, as discussed previously. Only one crack formed along the fixed support in either slab. These models are shown in Figures 25 through 28 with pertinent data given in Table II.

Column Support Conditions

Four methods of representing column supports were used. First, a three-sixteenth inch dowel was placed at each corner. The model failed in "punching shear" at the point of support.

Second, to spread the reactive forces over a larger area than used previously, one-half inch square blocks were used. As shown in Figure 29, one corner failed in bending which caused large deflections; the corners were then supported only at the edge of the block supports. The plaster again failed in "punching shear."

Third, three-fourths inch square blocks were placed on spherical supports. With large reactive forces, approximately twenty pounds at each support, it was found that the wooden block would not rotate on the spherical support. The model failed in the same manner as the models before had failed.

The last tests were made without the wooden blocks; the model was placed directly on the spherical support. The slab did not fail in "punching shear." Five slabs were tested in this manner. Four contained one-eighth inch hardware cloth, and the other contained fourteen-by-eighteen mesh copper screen. All of the slabs in this group failed in the same way. A yield line would form across the corner, and with further increases in load, the reinforcing separated from the plaster; therefore, the slab was supported only by the upper and lower layers of steel and that portion of the plaster bounded by these two layers.

The results of these tests are shown in Figures 29 through 36 with pertinent data recorded in Table III.

TABLE I

TEST RESULTS FOR SLABS WITH SIMPLE SUPPORTS

Slab Number	Date Cast	Kind and Size Reinforcement	Date Tested	Support Conditions	Expected Failure	Actual Failure	Remarks
22	2-28-66	14 x 18 mesh copper screen	3-3-66	12" x 12"			Reinforcement not extended into supports
23	2-28-66	26 gauge copper wire	3-3-66	11" x 11"			Rubber foam too thick
24	3-2-66	14 x 18 mesh copper screen	3-3-66	11" x 11"			Rubber foam support
25	3-2-66	1/8" hardware cloth	3-3-66	11" x 11"			Rubber foam support Cured too long
26	3-6-66	1/8" hardware cloth	3-7-66	11" x 11"			Rubber foam support Cured too long
27	3-6-66	1/8" hardware cloth	3-8-66	11" x 11"			Rubber foam support Cured too long
28	3-6-66	1/8" hardware cloth	3-8-66	12" x 12"			Cork strip support
29	3-6-66	1/8" hardware cloth	3-8-66	12" x 12"			Rubber foam support
30	3-6-66	1/8" hardware cloth	3-8-66	12" x 12"			Cured too long, not enough pressure to complete test
42	3-13-66	1/8" hardware cloth	3-14-66	12" x 12"			Reinforcing in center section too low
43	3-13-66	1/8" hardware cloth	3-14-66	12" x 12"			

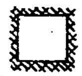
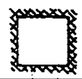
——— Yield Line

— — — Hidden Yield Line

Simple Support

TABLE II

TEST RESULTS FOR SLABS WITH FIXED SUPPORTS

Slab Number	Date Cast	Kind and Size Reinforcement	Date Tested	Support Conditions	Expected Failure	Actual Failure	Remarks
40	3-13-66	1/8" hardware cloth	3-14-66	 12" x 12"			Unable to restrain edges from rotating
41	3-13-66	1/8" hardware cloth	3-14-66	 12" x 12"			Unable to restrain edges from rotating

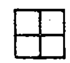
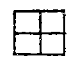
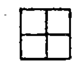
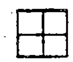
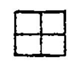
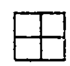
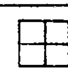
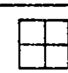
Yield Line

Hidden Yield Line

Fixed Support

TABLE III

TEST RESULTS FOR SLABS WITH COLUMN SUPPORTS

Slab Number	Date Cast	Kind and Size Reinforcement	Date Tested	Support Conditions	Expected Failure	Actual Failure	Remarks
44	3-15-66	1/8" hardware cloth	3-16-66	o o 12" x 12" o o			3/16" dowels, failed in punching shear
45	3-15-66	1/8" hardware cloth	3-16-66	o o 12" x 12" o o			1/2 x 1/2 wooden blocks on spherical supports, punching shear
46	3-15-66	1/8" hardware cloth	3-16-66	o o 12" x 12" o o			Spherical supports, bending moment crack, failed in shear
47	3-15-66	1/8" hardware cloth	3-17-66	o o 12" x 12" o o			Bending moment crack, failed in shear
48	3-15-66	1/8" hardware cloth	3-17-66	o o 12" x 12" o o			Failed in shear
49	3-15-66	1/8" hardware cloth	3-17-66	o o 12" x 12" o o			Yield line at one corner, failed in shear
50	3-16-66	1/8" hardware cloth	3-17-66	o o 12" x 12" o o			Failed in shear
51	3-16-66	1/8" hardware cloth	3-17-66	o o 12" x 12" o o			Failed in shear

——— Yield Line

— — — Hidden Yield Line

o Column Support

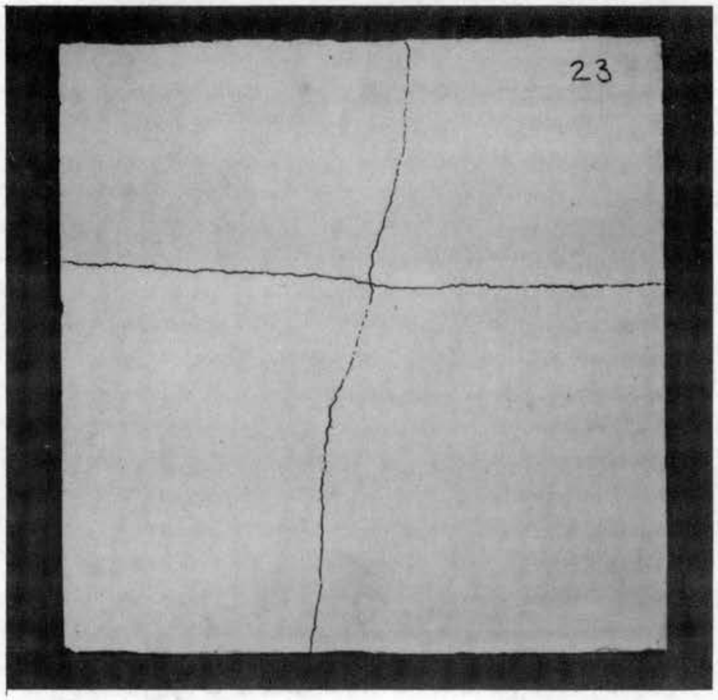


Figure 9. Top View of Model Number 23.

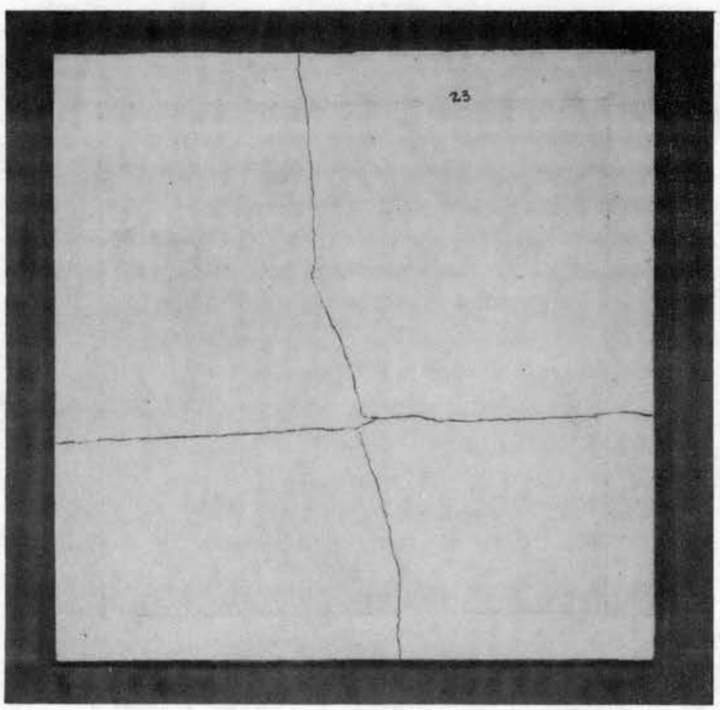


Figure 10. Bottom View of Model Number 23.

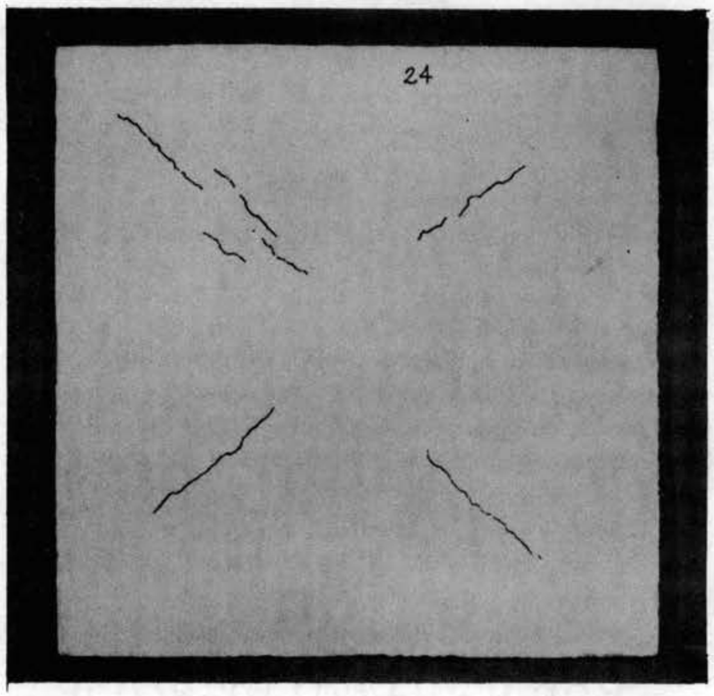


Figure 11. Top View of Model Number 24.

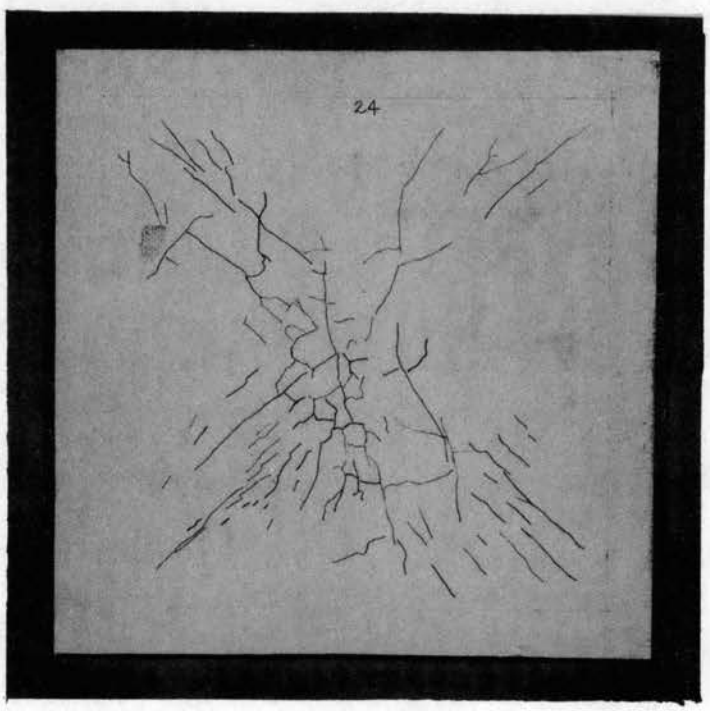


Figure 12. Bottom View of Model Number 24.

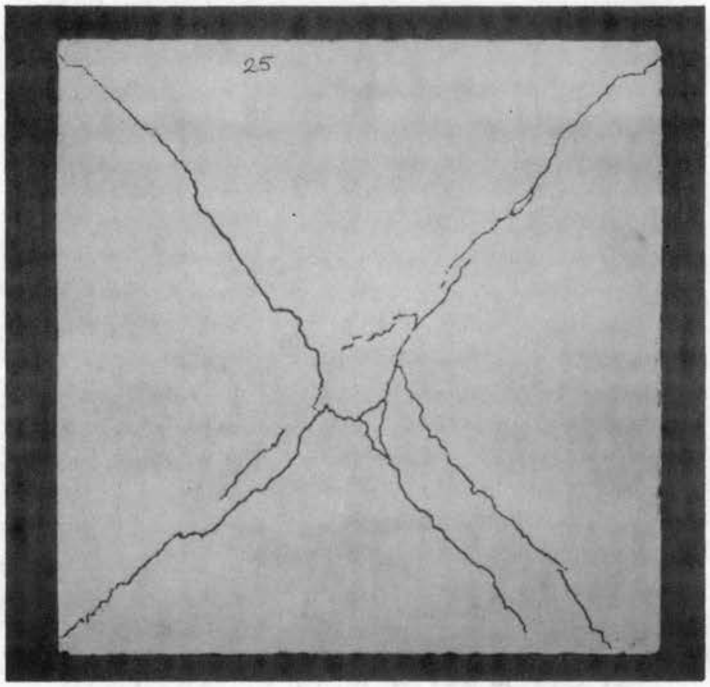


Figure 13. Top View of Model Number 25.

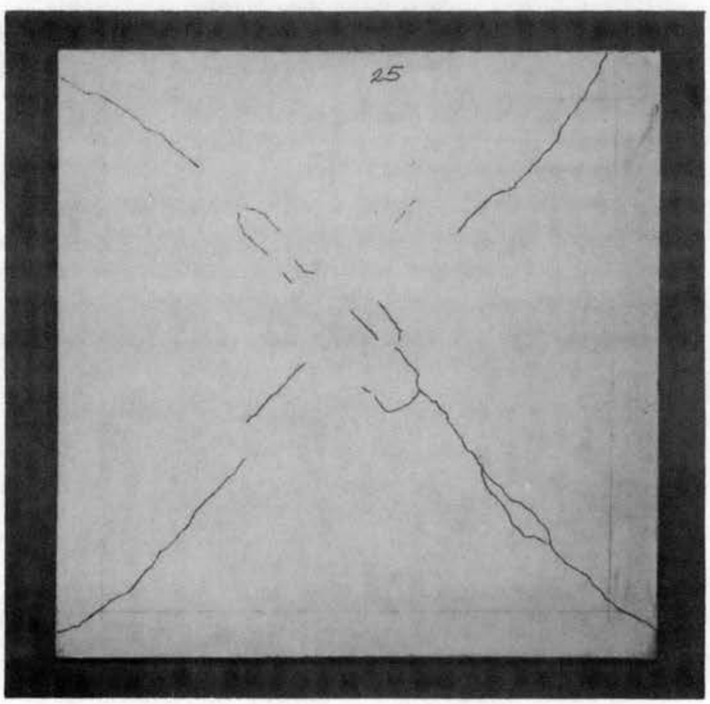


Figure 14. Bottom View of Model Number 25.

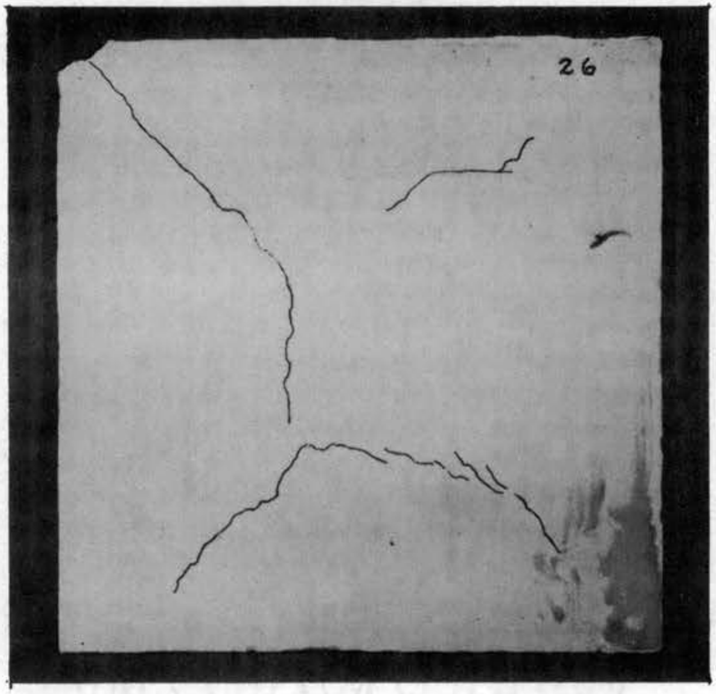
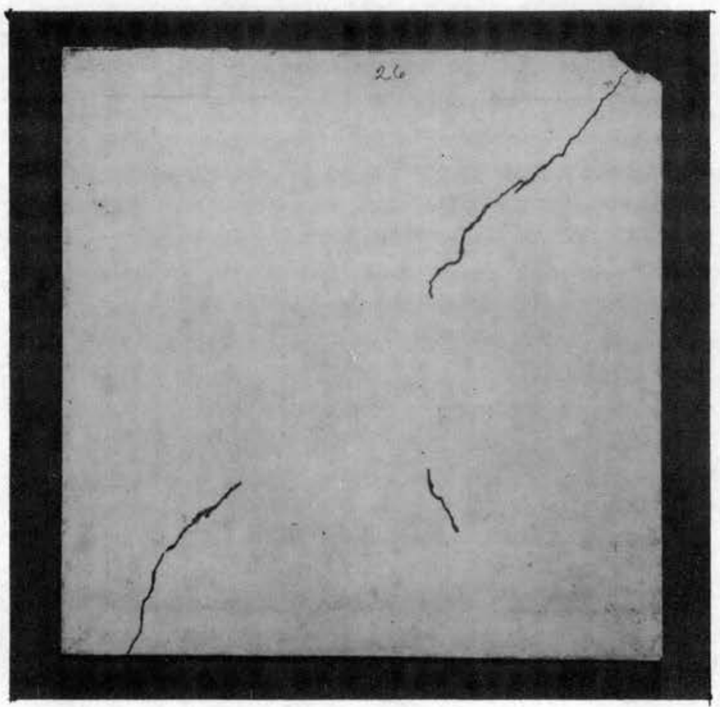


Figure 15. Top View of Model Number 26.



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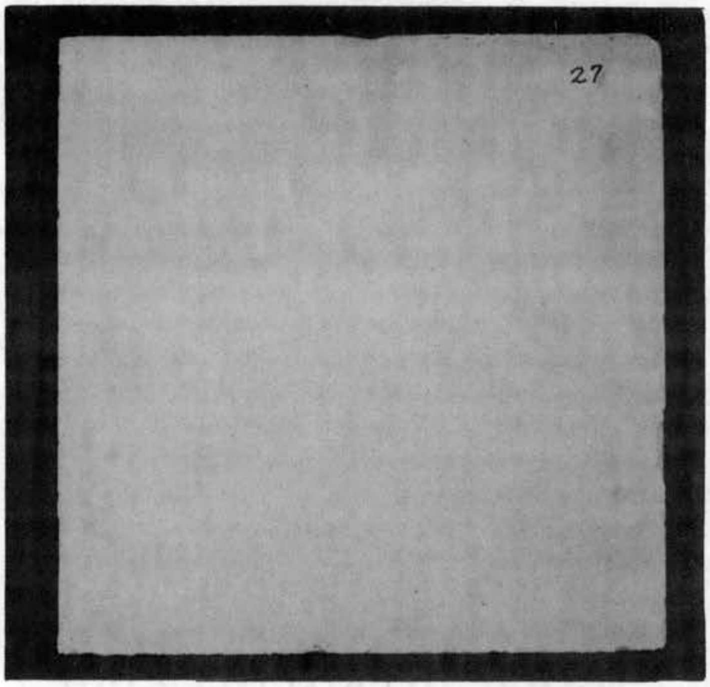

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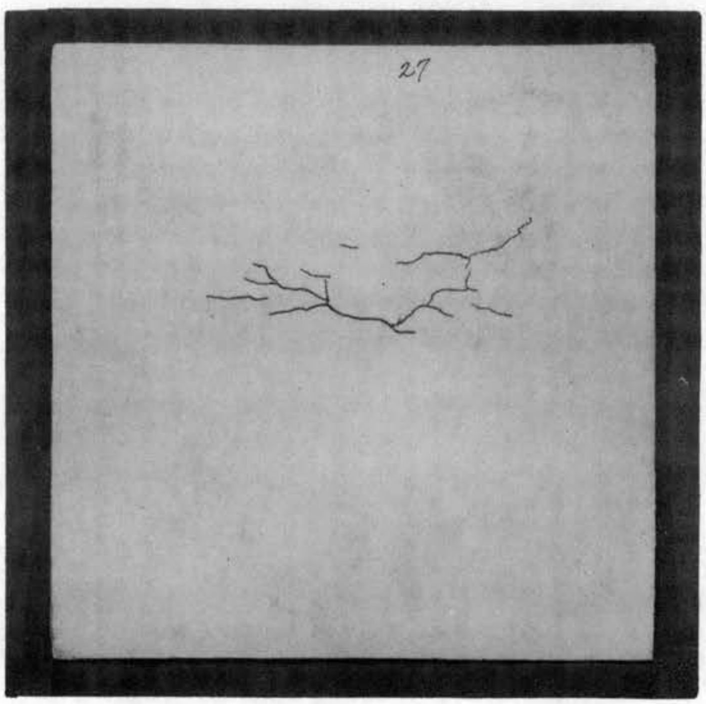

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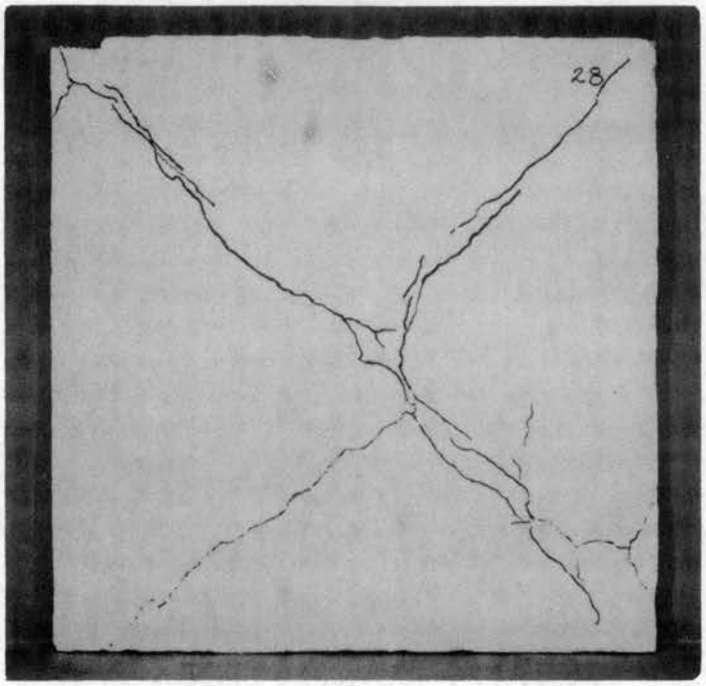

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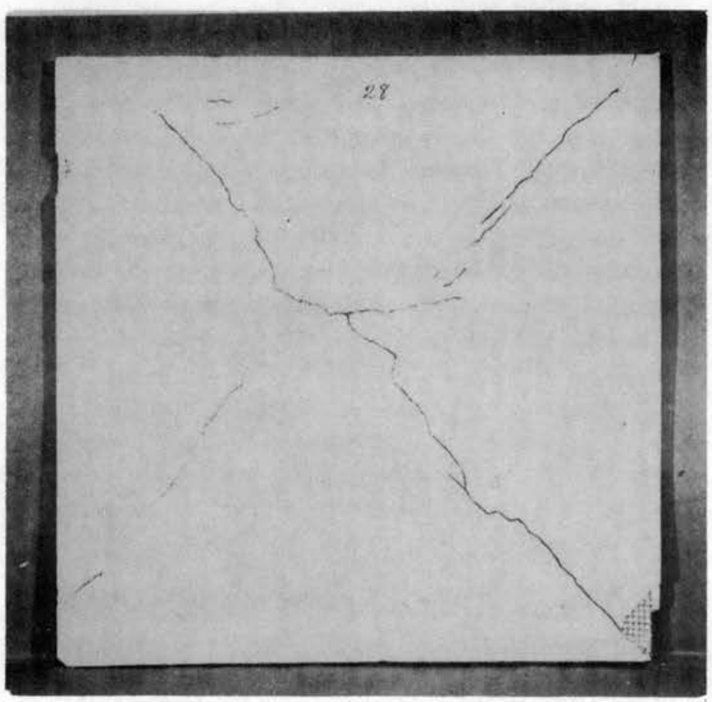

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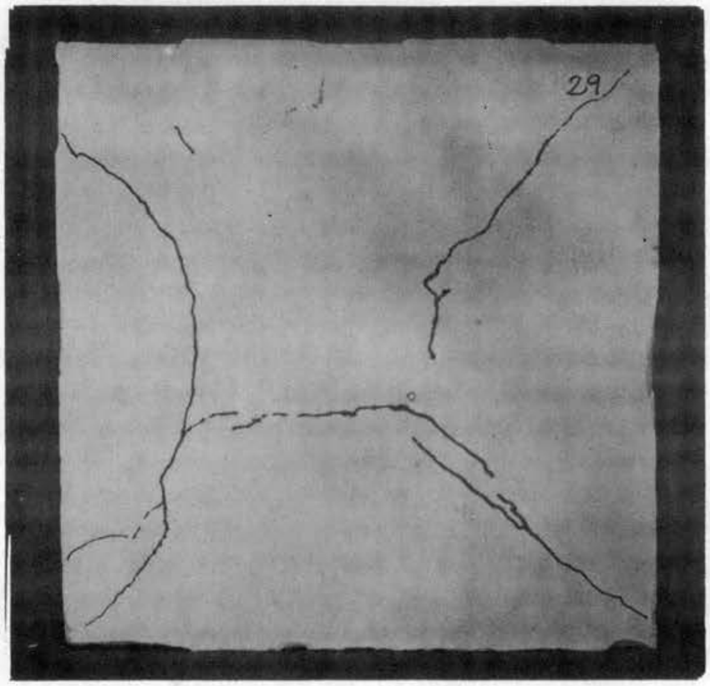

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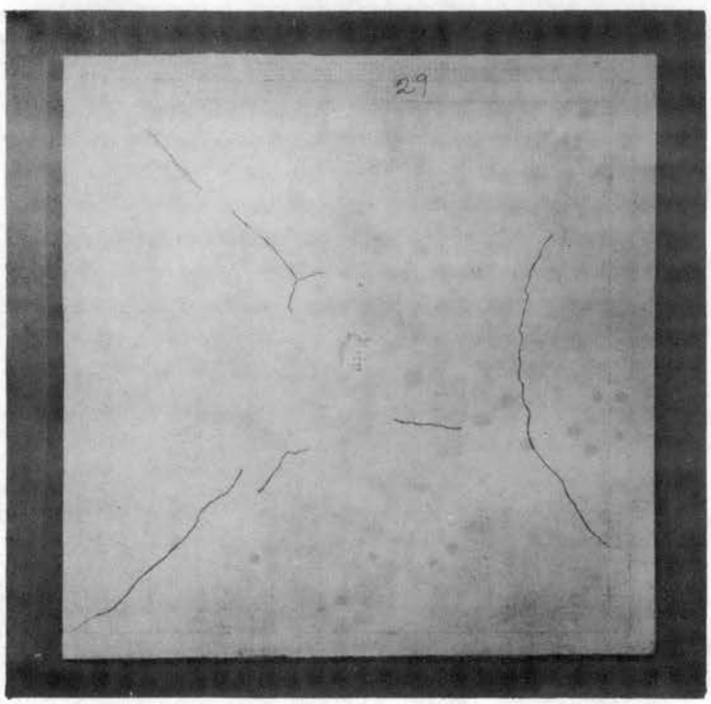

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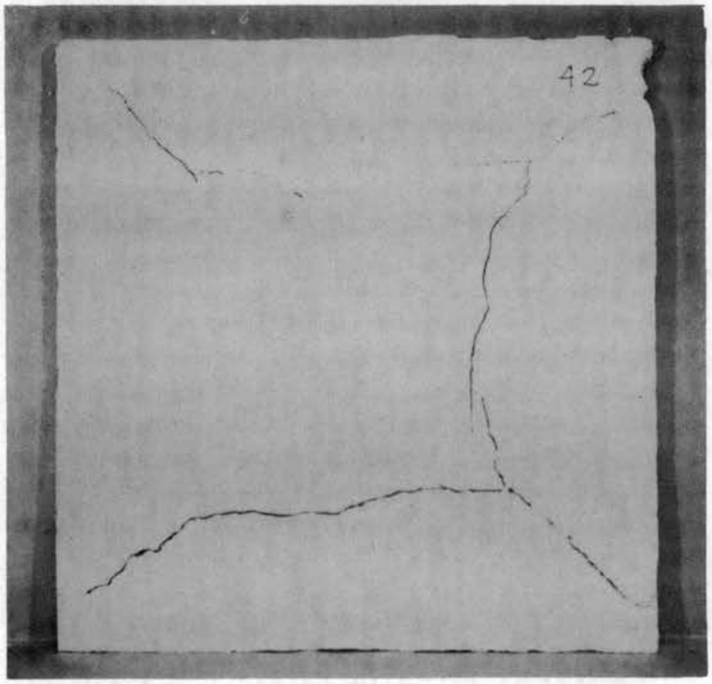

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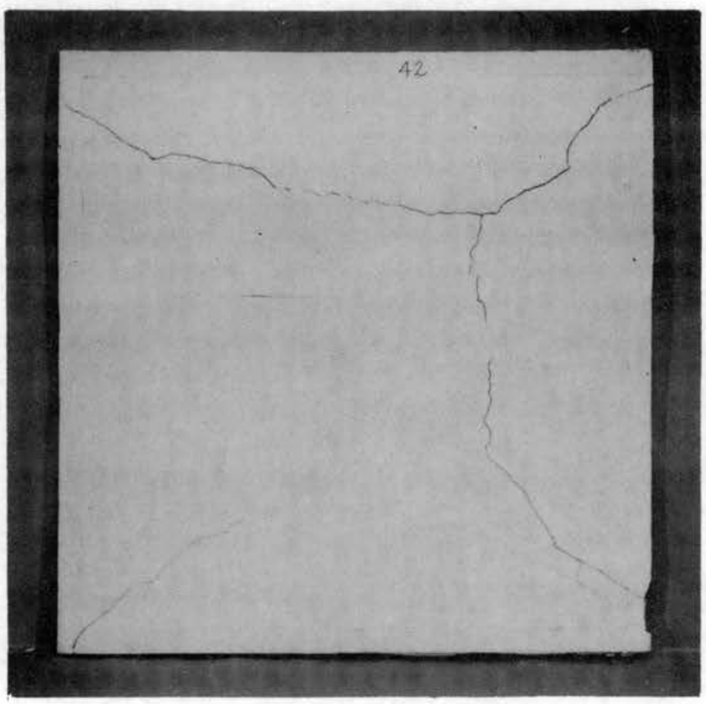

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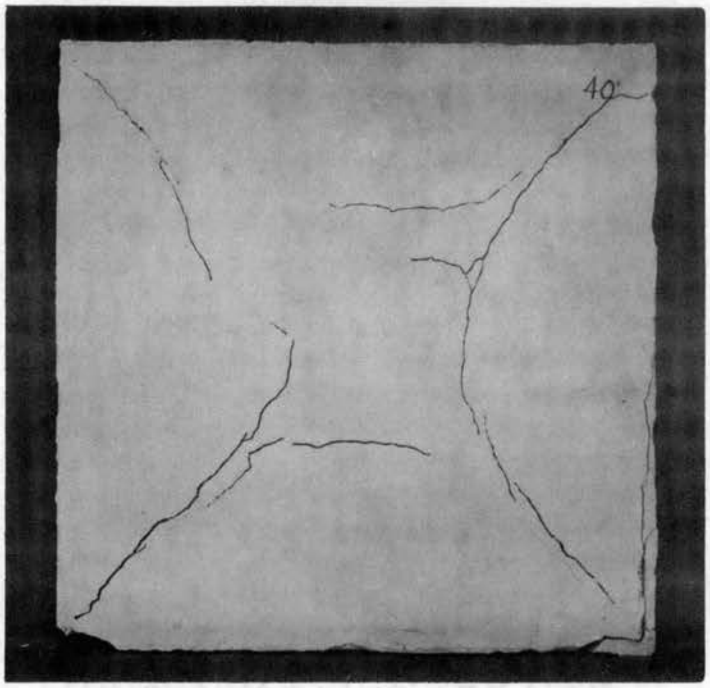

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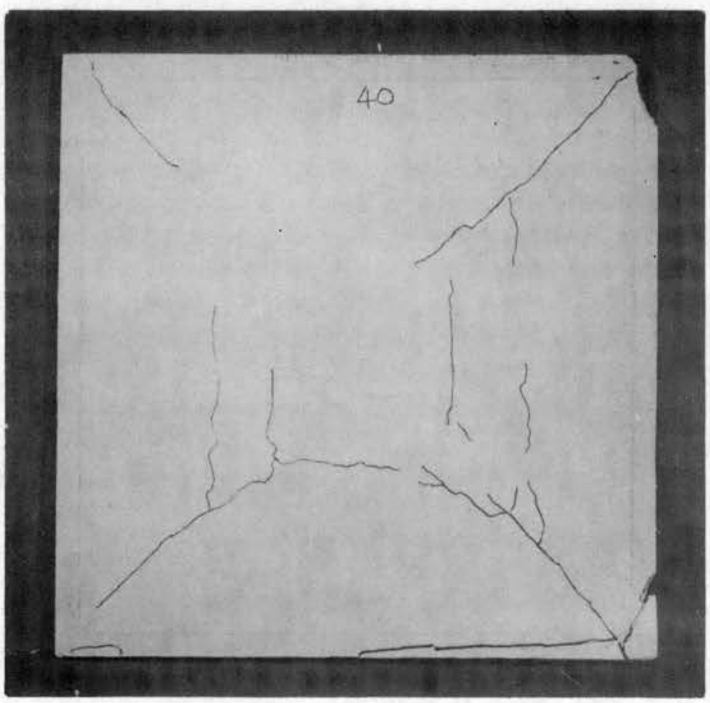

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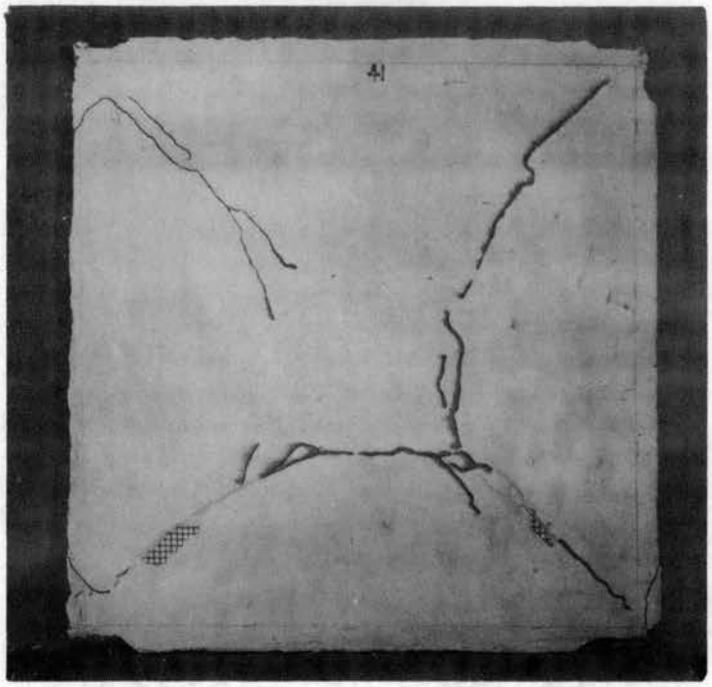

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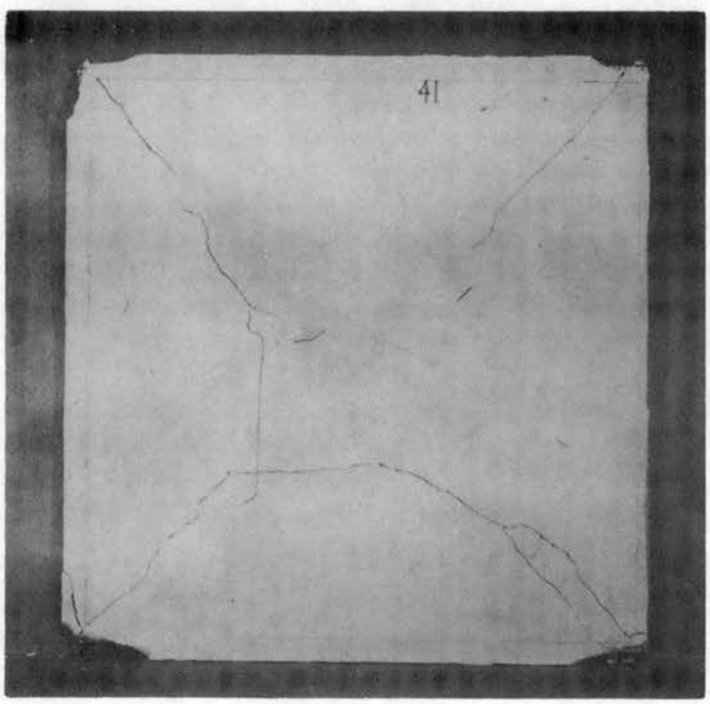

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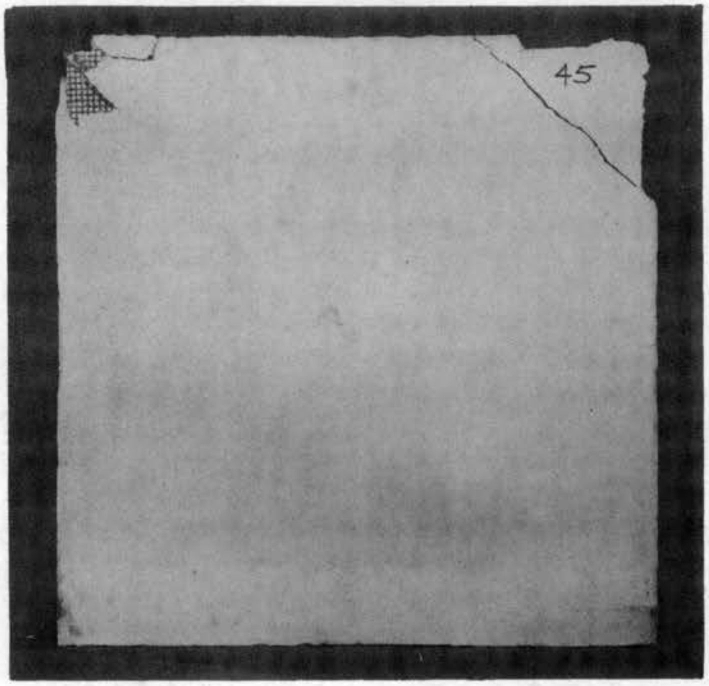

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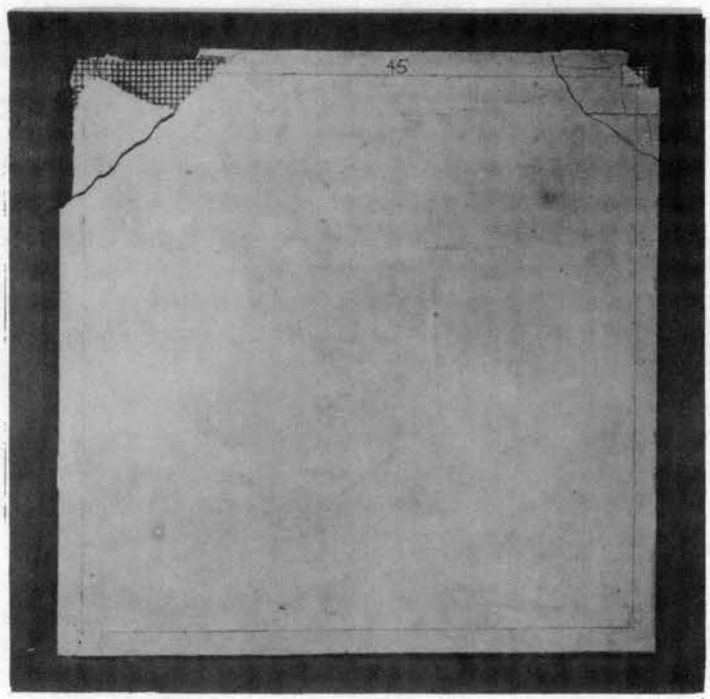

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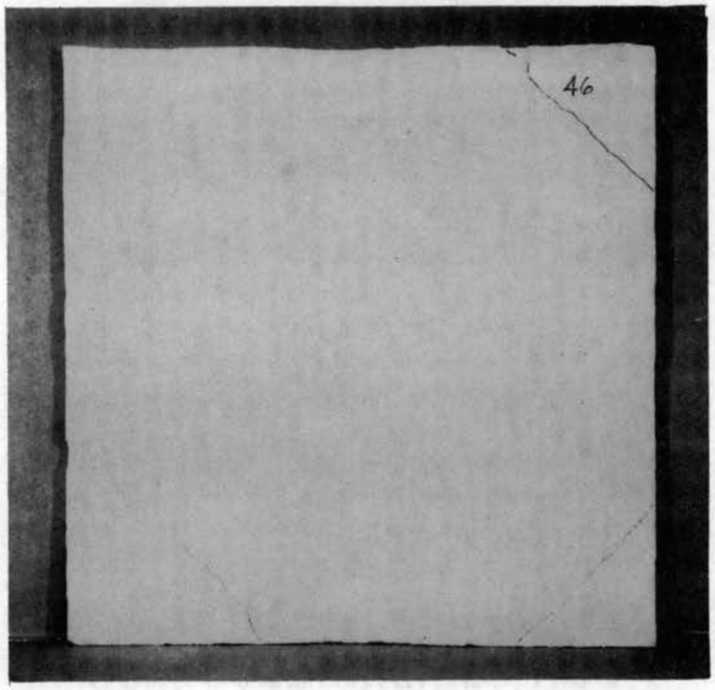

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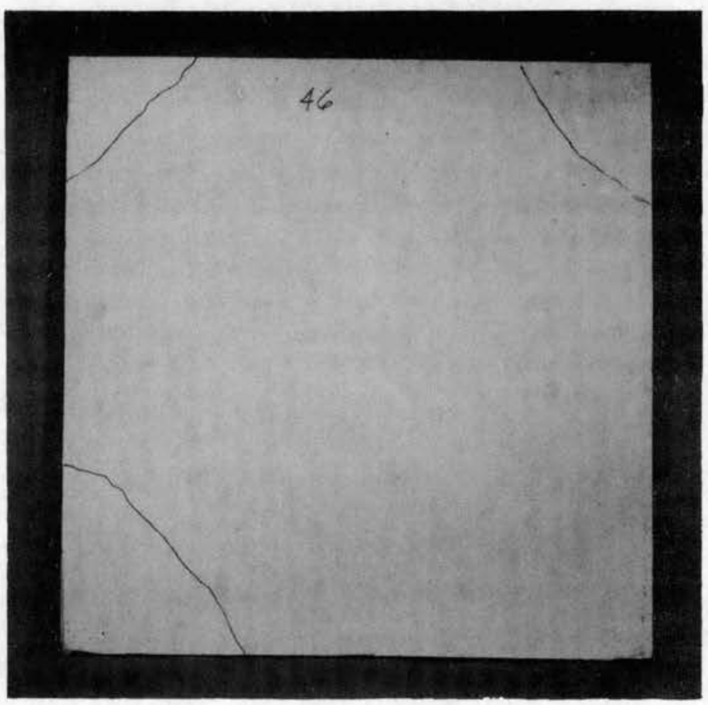
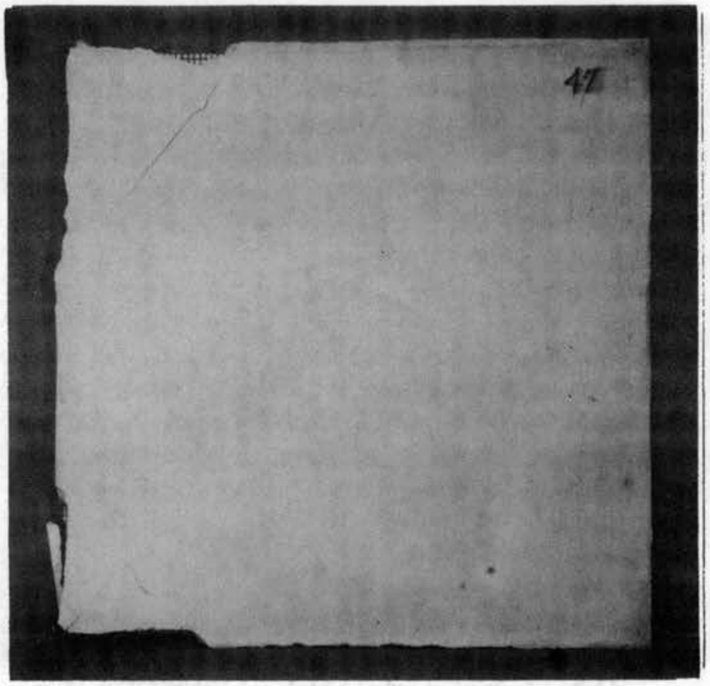


Figure 32. Bottom View of Model Number 46.



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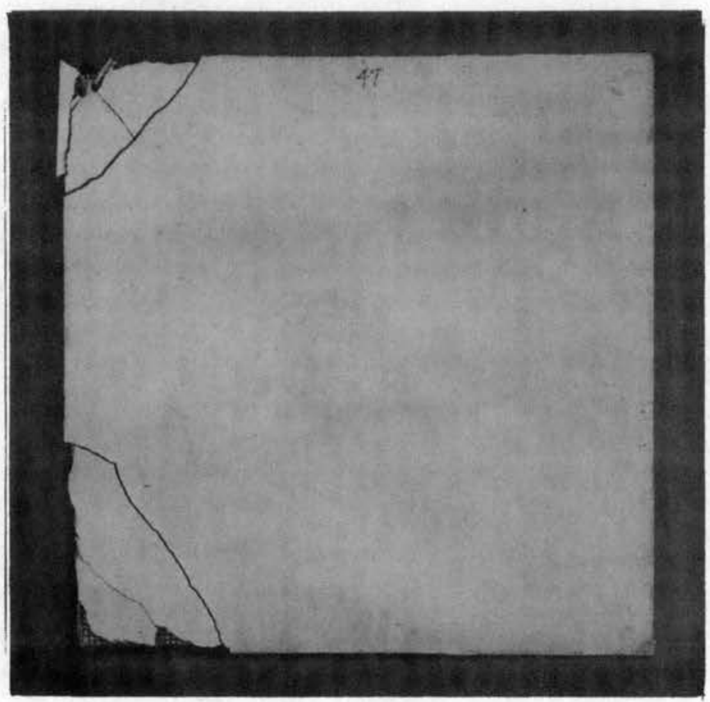

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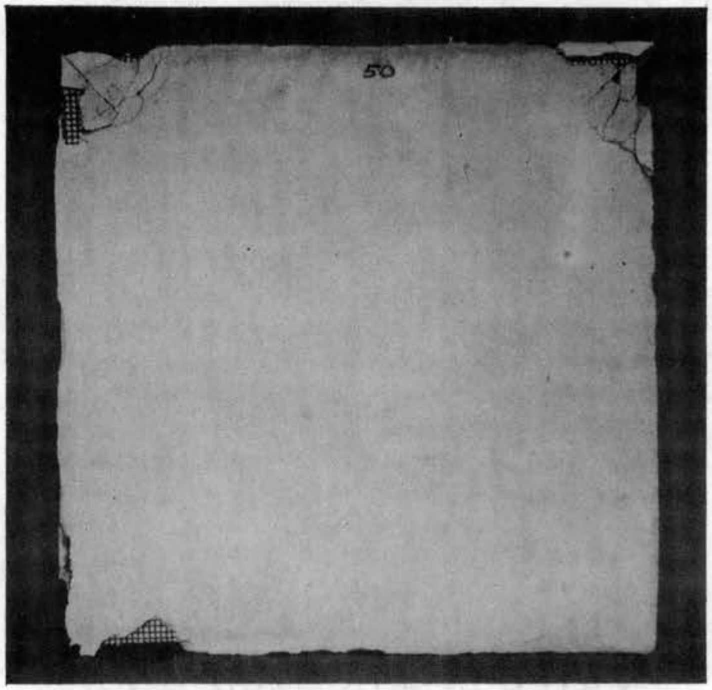

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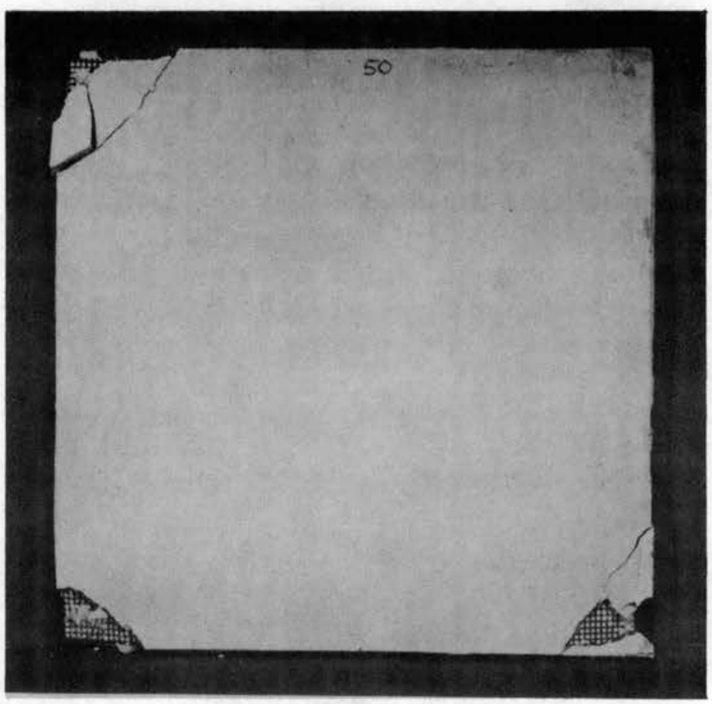

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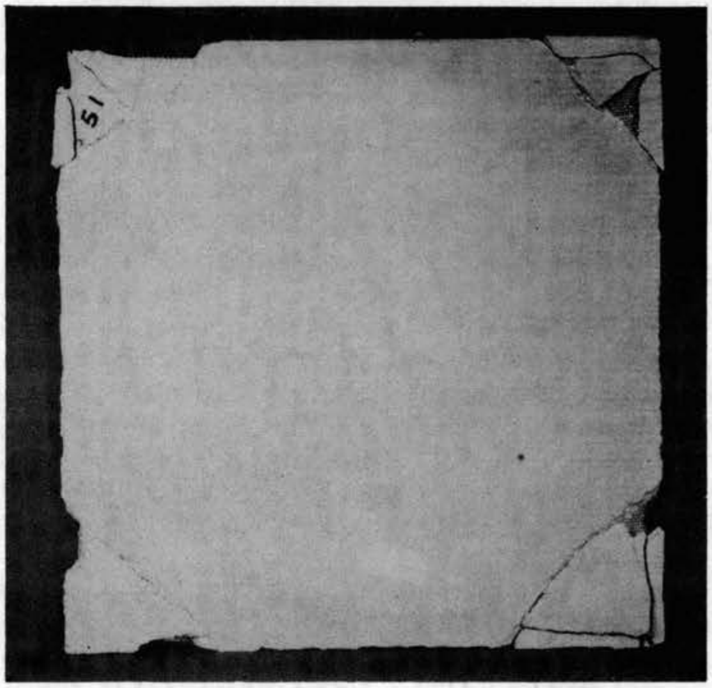

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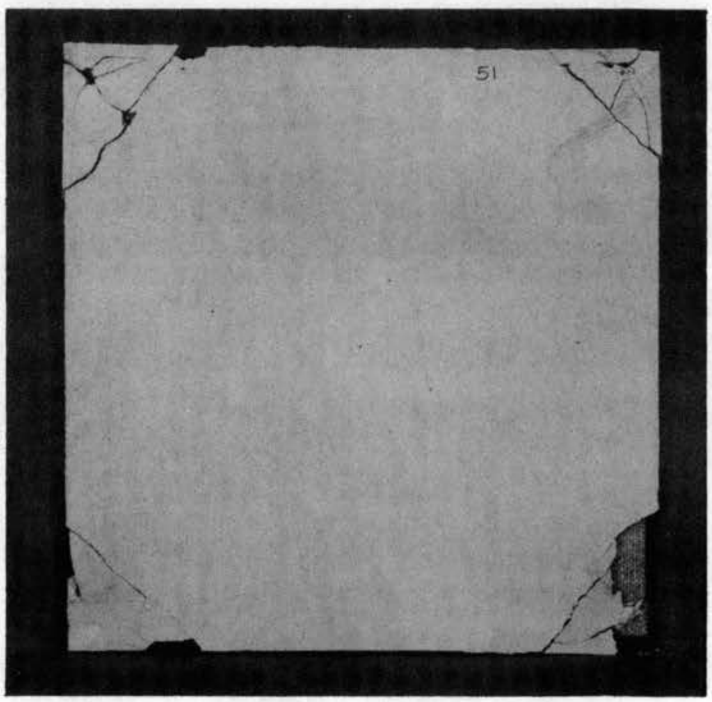

Figure 38. Bottom View of Model Number 51.

CHAPTER V

SUMMARY AND CONCLUSIONS

Several types of wire were tested to find a material which would simulate the steel reinforcing used in concrete slabs. Hardware cloth and copper screen were found to have the correct properties. The main advantage of these two materials is their ability to bond to plaster. The plaster used for the investigation was molding plaster, mixed in a 0.9 water/plaster ratio by weight. This mix was suitable because it is low in tensile strength and slow setting.

The testing apparatus consisted of a square balloon constructed of three mil polyethylene and butyl rubber. The balloon produced a satisfactory uniform load. However, pressures above three pounds per square inch were unattainable because of small, unavoidable leaks.

Three types of support conditions were tested: simple, fixed, and column supports. The simple support condition was easily obtained by the use of a plywood platform. The yield-line patterns formed under this condition were not exactly the same for all of the slabs tested, but the general pattern was readily recognizable.

Fixed supports were not produced by the method used. Regardless of the clamping pressure applied to the edges of the slabs, there was some rotation at the support which did not allow the correct yield pattern to form.

Column supports were effectively simulated by spherical supports, but all of the slabs tested in this manner failed in shear. Since yield-line theory considers only bending moment failure, these tests gave no valid yield pattern.

As expected, very slight variations in placement of the reinforcing caused the yield pattern to deviate from the correct pattern. This problem can be solved by the method used, but it is a tedious process. It was found unnecessary to cure the models for five days as suggested in other papers. Even though relatively large elastic deformations occur, the correct yield pattern can be obtained. It was also noted that the reinforcement used did not necessarily need to have the same stress-strain relation as that of the steel reinforcing used in concrete slabs.

Suggestions for Future Study

It has been shown that model analysis of yield-line theory is feasible, but there is a need for further study. Methods for simulating fixed and column supports are areas which require attention. Research should be extended to include combinations of different support conditions, e.g., two fixed edges and two simply supported edges, two fixed edges and one column support. Irregular slab shapes, such as L-shapes, would provide an interesting study. The type of research presented in this paper should also be extended to encompass folded plate and thick-walled cylindrical shell structures. Dimensional analysis should be applied to models similar to those tested in this investigation as well as to other combinations such as those mentioned previously.

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VITA

H. Thomas Kornegay

Candidate for the Degree of

Master of Architectural Engineering

Thesis: PLASTER MODELS USED TO PREDICT FAILURE PATTERNS IN CONCRETE SLABS

Major Field: Architectural Engineering

Biographical:

Personal Data: Born in Elgin, Texas, January 2, 1942. Parents, Mr. and Mrs. Maxie L. Wright and the late H. T. Kornegay.

Education: Attended grade school in Houston and Groesbeck, Texas; was graduated from Longview High School, Longview, Texas in 1959; received the degree of Bachelor of Science of Architectural Engineering from the University of Texas in August, 1964; completed the requirements for the Master of Architectural Engineering in May, 1966.

Professional Experience: Allen and Guinn, A.I.A., Longview, Texas, from June, 1962 to September, 1962, and from June, 1963 to September, 1963. Graduate Assistant, School of Architecture, Oklahoma State University, from September, 1964 to April, 1966.

Organizations: Chi Epsilon, American Society for Testing and Materials.