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AN INVESTIGATION OF CERAMICS AS STRUCTURAL MATERIALS

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Prepared by
UNIVERSITY OF CALIFORNIA
Los Angeles, Calif.
for

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FOREWORD

The research described in this report, "An Investigation of Ceramics as Structural Materials," was carried out under the technical direction of F. R. Shanley and W. J. Knapp, and is part of the continuing program in Analytical and Experimental Investigations of Ceramic Materials for Use as Structural Elements.

This study is supported by the Office of Advanced Research and Technology of the National Aeronautics and Space Administration, Washington, D. C.

Submitted under Contract No. NsG-427.

ACKNOWLEDGMENTS

Most of the experimental work of this project was carried on by graduate students, who used portions of the results in their theses. We wish to express our appreciation to the following former members of the project staff for their contributions while graduate students: M.A. Ali (M.S. June 1964), C-P Chen (M.S. expected September 1966), George Nikolaychik (M.S. June 1965), A.P. Raju (M.S. June 1965), and David Weiss (LL.B. June 1964).

The interest and assistance of the International Pipe and Ceramics Corporation, Los Angeles, in fabricating and donating ceramic plates for this research, are gratefully acknowledged. Earlier support also was provided by Interpace (then Gladding McBean and Company) for the study of a biaxially prestressed ceramic slab.

We also are appreciative of the encouragement and advice of a number of staff members of the Materials Science Laboratory, Aerospace Corporation.

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I. INTRODUCTION

Experimental work has been carried on for some years, in several engineering fields, which is directed to increased applications of ceramics as structural elements. Impetus for such research arises largely from the growing need for structural materials that may be used at elevated temperatures. In particular, aerospace structures commonly encounter severe operating environments involving high temperatures and the presence of oxygen. Although ceramics characteristically are brittle, they are outstanding in their refractoriness and oxidation – resistance.

Research on prestressed ceramic structures has been carried on in the Department of Engineering, U. C. L. A., since about 1952 (Reference 1). These early experiments were intended to evaluate the possibility of using prestressing techniques with ceramics, and the results were encouraging. However, reference to the literature will reveal that there is limited information available on ceramics which may be used by the structural designer for immediate application. This lack of information is understandable, of course, in view of the previously limited use of ceramics as structural elements in which sizable stresses are developed.

The general purpose of the research carried on under this grant (NsG-427), therefore, was to carry on some basic experiments with typical ceramics to obtain information needed for the successful utilization of ceramics in structural applications. An additional objective was to design, fabricate and test some original structural members comprised of prestressed ceramic elements.

II. RESEARCH PROGRAM

In view of the objectives mentioned above, the following studies were undertaken:

1. <u>Prestressed Ceramic Members</u>

   (a) Load-bearing characteristics of prestressed ceramic members. Uniaxially prestressed ceramic beams and biaxially prestressed ceramic plates were tested.

(b) Bending-stiffness characteristics of prestressed segmented ceramic plates. Two plates were designed and fabricated: one comprised of square segments, and the second comprised of triangular segments.

(c) Fabrication of prestressed segmented ceramic domes. Several attempts were made to design and fabricate segments for ceramic domes. Several domes were fabricated.

(d) Behavior of biaxially prestressed ceramic plates subjected to thermal stresses.

2. Lightweight Ceramic Members

(a) Effects of directional cellulation on the strength of a ceramic material.

(b) Strength of some ceramics containing hollow glass spheres.

III. RESULTS

Brief summaries of the results of the several studies are given here. In most cases, the study was completed, and the results given either in a publication or in a report.

1(a) Load-Bearing Characteristics of Prestressed Ceramic Members

The purposes of this experimentation were to determine how the static load-bearing capacity of prestressed ceramic members changes with the level of prestressing, and how much improvement may be realized by prestressing.

Ceramic beams, 3/8" x 1/2" x 4" in size, were uniaxially preloaded to various levels of prestress. In each case, the prestressed beam was loaded in bending (using four point loading) to failure. Deflections were measured during bending. This study is almost complete, and a report will be written to summarize the results.

Biaxially prestressed ceramic plates were subjected to transverse loading until failure occurred. The plates were 1/2" x 6" x 6" in size, and the transverse load was applied normal to the center of a plate face over a 1-1/2" circular area. The load-bearing characteristics of ceramic plates, under the conditions of this study, were greatly improved by biaxial prestressing, giving an optimum increase of almost 700%. An analysis of the loading of a hypothetical uniaxially prestressed beam was presented to explain the main features of the variation of load-bearing capacity with prestress. The stiffness of prestressed plates increased with level of prestress. The failure occurring in a biaxially prestressed plate, by the loading used, was characterized by the formation of a hole by the penetrating ram.

A complete report of this work was published as a NASA Contractor Report (CR-188, Reference 2).

1(b) Bending-Stiffness Characteristic of Prestressed Segmented Ceramic Plates

These investigations were concerned with the bending behavior of prestressed segmented ceramic plates. Two types of plates were studied: one comprised of square ceramic segments, and another comprised of triangular segments.

The plate comprised of square segments was 1 inch thick and 4 feet x 4 feet in overall dimensions. Biaxial prestressing was accomplished with steel wire ropes. The structural properties of interest were the bending, twisting and Poisson stiffnesses.

The experimentation involved two cylindrical bending tests for the determination of the flexural stiffnesses D_x and D_y, an anticlastic bending test to find the Poisson stiffness D_1 and two twisting tests to determine the twisting stiffness D_{xy}. The experimental results were as follows: D_x was 28,550 lb-in.^{2}/in., D_y was 13,450 lb-in.^{2}/in., and D_{xy} was 62,000 lb-in.^{2}/in. on the average. D_1 was very small, being 305 lb-in.^{2}/in. These stiffnesses were different at various plate locations because of nonuniformities of the plate prestress.

The stiffness constants D_x D_y, D_{xy}, and D_1 also were derived analytically from the geometries of the cross section and an effective elastic modulus E and an effective Poisson ratio μ of the composite plate. The flexural stiffnesses D_x and D_y were calculated to be 37,300 lb-in ^{2}/in., and 13,300 lb-in.^{2}/in., respectively, whereas D_{xy} was calculated to be 156,00 lb-in.^{2}/in. The Poisson stiffness D_1 was calculated to be 5,560 lb-in.^{2}/in. The agreement between the experimental and analytical stiffnesses is considered to be good in view of the assumptions involved in the calculations.

A complete report on this investigation has been prepared (Reference 3).

The second plate, comprised of triangular segments, is in the final stages of fabrication. "Three-way" prestressing will be applied, in the plane of the plate, with wire ropes placed along the recessed edges of the segments. After fabrication, this plate will be loaded to determine its bending-stiffness behavior. Completion of this study is estimated by September, 1966.

1(c) Fabrication of Prestressed Segmented Ceramic Domes

The objective of this work is the fabrication of prestressed ceramic elements with double curvature, with particular emphasis on the utilization of such elements as building units for larger structures.

A hemispherical dome about 18 inches in diameter was chosen as a structure to be fabricated with ceramic units having double curvature.

The successful fabrication of segmented ceramic domes in the university laboratory has proved to be a difficult task in view of the limited facilities and lack of skilled ceramic technicians. However, considerable experience has been attained in this work, and the following summary may be helpful in designing and fabricating future segmented structures with double curvature.

a. Fabrication and testing of single-piece (monolithic) ceramic domes.

It was considered desirable to fabricate and test several single-piece ceramic domes, inasmuch as the results would be useful for comparison with those to be obtained with prestressed segmented domes. The slip-casting process was chosen for fabrication; suitable plaster-of-Paris molds were designed and fabricated by a commercial mold shop. An alumina-containing ceramic body (50% alumina, 20% feldspar, and 30% clay, by weight) was prepared in slip form (dispersed with sodium silicate), and about five hemispherical domes were successfully formed and fired. After firing, these domes were about 17 inches in outside diameter and approximately 1/2 inch thick.

Some local interest was expressed in testing such a dome hydrostatically. With the approval of NASA, two domes were provided to the U. S. Naval Ordnance Test Station, Pasadena, California, for hydrostatic testing.

Before testing, each dome was sealed by inverting it onto a metal plate and evacuating the air from the dome through a hole in the plate. This vacuum was sufficient to hold the dome onto the plate when the assembly was placed under water and subjected to buoyancy forces. External hydrostatic pressure was then applied to the dome at a rate of 130 psi/minute until the maximum of 1200 psi (machine capacity) was reached; after remaining at 1200 psi for one hour, the pressure was released at the same rate. Failure of the ceramic did not occur at any time. Strain-gauges were attached to the dome surface to permit an evaluation of deformations.

Although the first test demonstrated that the domes could withstand the pressure to which they were subjected, it was noted that the porosity of the ceramic enabled water to enter the dome. In subsequent tests, the domes were externally coated with an epoxy film, and water seepage did not reappear.

The complete results of the above testing, and the use of such information in the design of underwater structures, are given in a thesis by S. H. Brand (Reference 4).

b. Fabrication of prestressed segmented domes

Two steps were involved in this fabrication: first, the design of segments to be used for generating a dome, and second, a forming procedure for making ceramic segments.

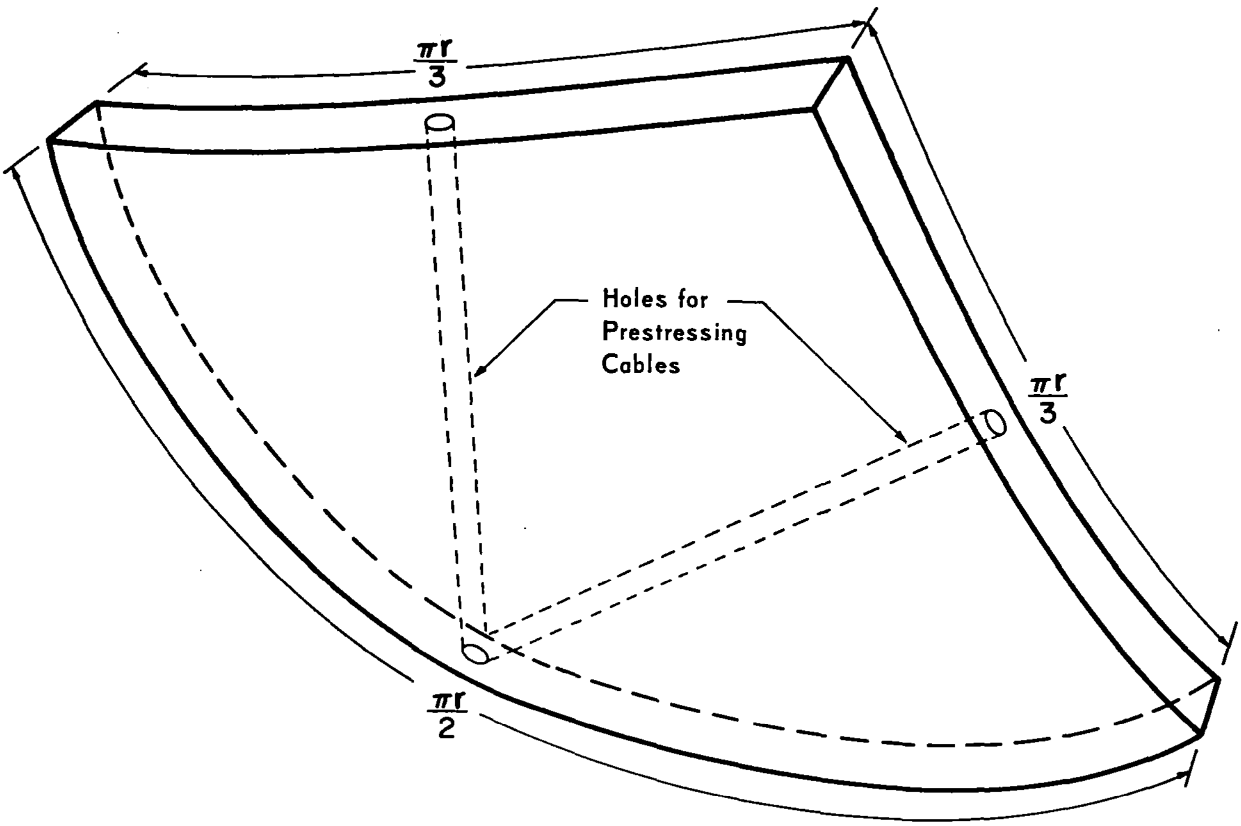
1. Design of Segments

It was felt that segments of triangular shape are particularly well-suited for generating members with double curvature. The first design was of a hemispherical dome that could be fabricated by assembling 12 segments of equal size and shape. It is considered that this segment design is unique, in that it allows for the generation of the dome with the assembling of segments of a single type. The shape of this segment is shown in Figure 1. It may be seen that a hemispherical dome may be fabricated by assembling 12 segments (Figure 2). Each segment contained two holes for prestressing cables; another unique feature of this design is that the path of a hole is that of a great circle.

A strong interest has developed in the use of smaller segments for fabricating prestressed ceramic domes. At present, a method developed by Meyer and Bellifante[5] is being studied, with the intent of designing several small triangular segments which may be used to generate a dome. This design also will require the design of the network of prestressing cables.

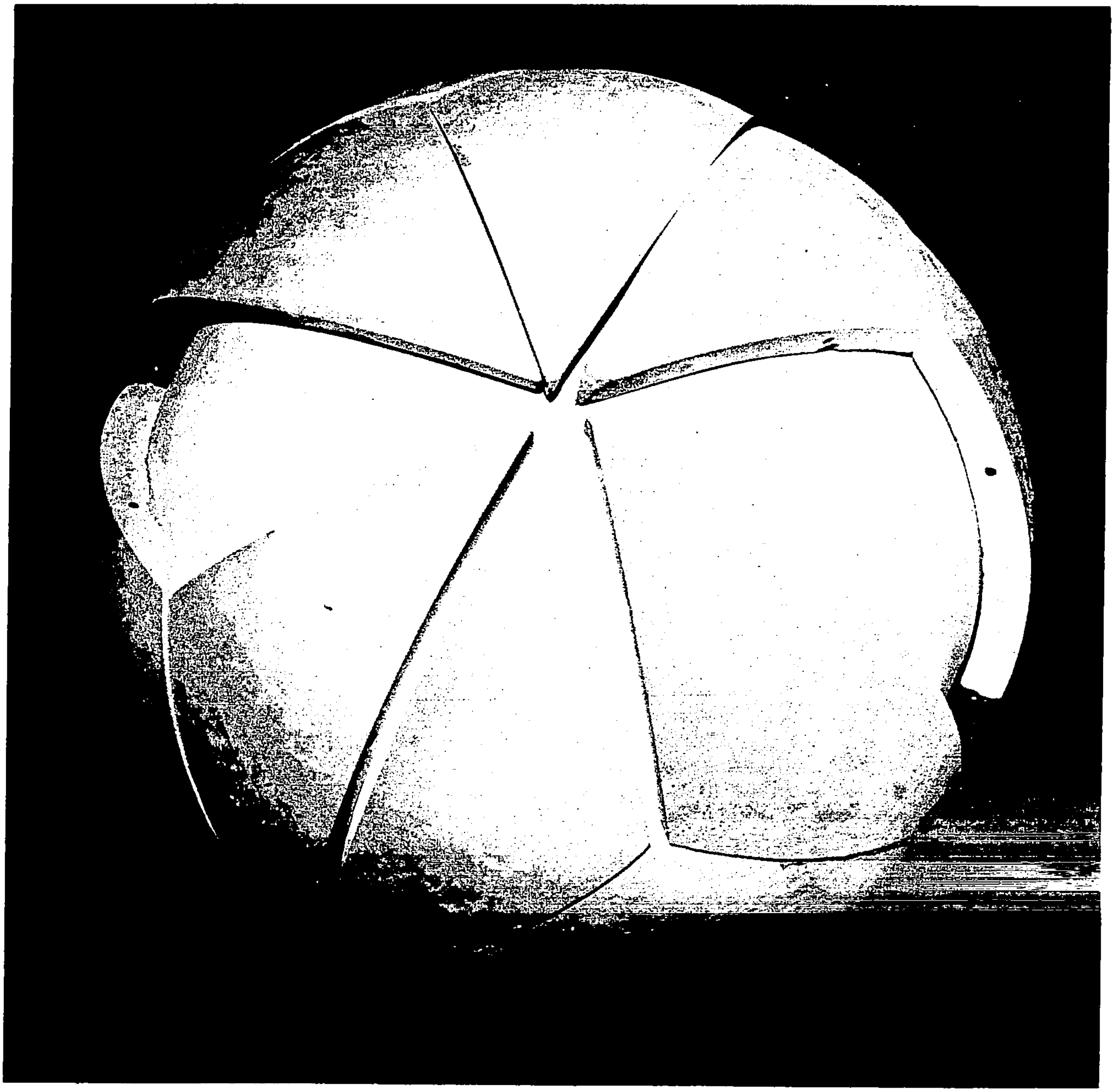
2. Fabrication Methods

Several fabrication methods were tried, in anticipation of their use in making segments of the type shown in Figure 1, or smaller.



TRIANGULAR SEGMENT FOR FABRICATING A HEMISPHERICAL DOME

FIGURE 1



TRIANGULAR SEGMENTS

FIGURE 2

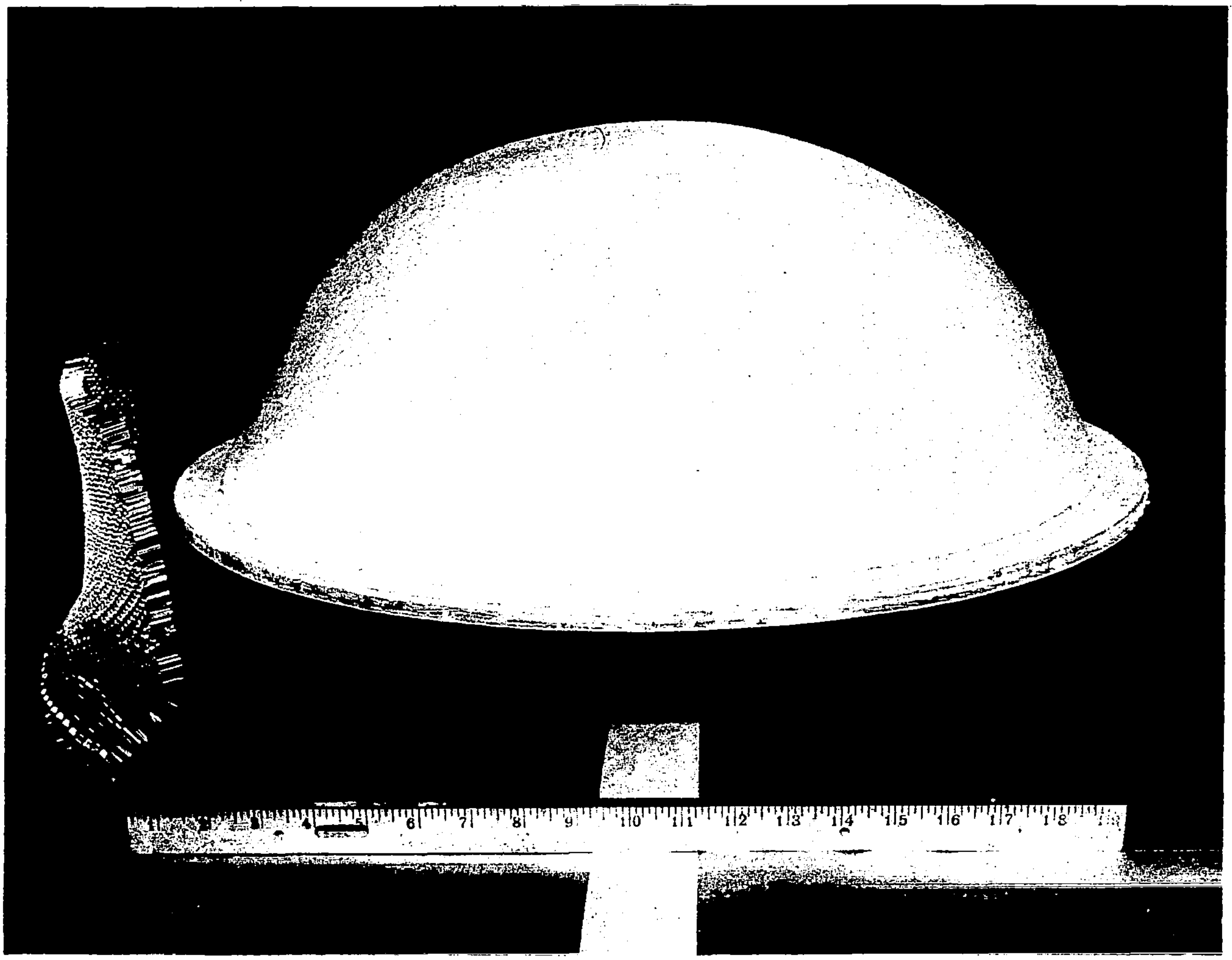
a. Slip-casting a single hemispherical element: While the element was still soft, it was cut with a knife into triangular segments. The segments so formed were to be dried and fired. This method proved difficult.

b. Plastic-forming individual triangular elements: A plastic mixture of the body was rammed into a mold shaped to form elements of the type of Figure 1. After drying, the element was removed from the mold and fired.

c. Ramming a ceramic body into a preformed refractory metal "honeycomb:" This is a method used by the Boeing Company to fabricate the refractory nose-cap for an aerospace vehicle. Our experimentation involved the fabrication of a hemispherical dome by ramming an air-setting material into the meshes of a preformed metal (aluminum alloy in this trial) honeycomb. The shape of the individual segment was not significant in this experiment, but was chosen because of the availability and easy-forming character of the honeycomb material (see Figure 3).

To summarize the results of experiments with fabrication methods, it would seem feasible to use either slip-casting or plastic-forming for forming individual segments. However, it was clear that shrinkages occurring in drying and firing make it difficult to maintain close size tolerances and shape. Undoubtedly grinding of fired segments would be required in order to produce good fitting and well-mated surfaces. The ramming of a ceramic material into a preformed honeycomb is an attractive method for forming and assembling small segments.

As a final observation, it is difficult to successfully manufacture closely-sized segments (for generating elements with double curvature) with the limited facilities and staff of a university



HEMISPHERICAL DOME FABRICATED BY RAMMING A CERAMIC
MATERIAL IN THE MESHES OF A METAL HONEYCOMB

FIGURE 3

laboratory. Such a fabrication task may be accomplished most successfully by a manufacturer of technical ceramics.

1(d) Behavior of Biaxially Prestressed Ceramic Plates Subjected to Thermal Stresses

Ceramics are well-known for their sensitivity to rapid temperature changes. However, earlier work has indicated that prestressing may be an important means of protecting ceramics against thermal shock.

The use of biaxial prestressing as a means of reducing or preventing damage to ceramic specimens under thermal stress was studied. The extent of structural damage of the ceramic material, after thermal stressing, was evaluated by determing the degradation in its bending strength. The experimental results indicated that the residual bending strength of the thermally stressed plates increased linearly with increasing level of pre-compression, until a level of prestress was reached which was equal to the bending strength of the virgin material. Prestress levels of this value, or greater, for the conditions of this experimentation, appeared to provide full protection against damage under the imposed thermal load.

A paper on this study has been prepared (Reference 6). A revision of this paper has been submitted to The American Ceramic Society for publication.

2(a) Effects of Directional Cellulation on the Strength of a Ceramic Material

Experimentation has been carried on for many years on the development of light-weight, strong ceramics. One approach commonly used is to introduce pores into the material; however, randomly distributed pores of the usual type radically reduce the strength of the ceramic.

In our work, ceramic specimens containing parallel cylindrical holes, arranged in symmetrical configurations, were loaded in compression to failure in the axial direction of the holes. The strength/weight characteristics of these specimens exceeded markedly those normally shown by ceramic specimens in which the corresponding porosity is uncontrolled as to pore shape and distribution. In general, the reduction in load-bearing capacity was directly proportional to the reduction in the cross-sectional bearing area, excepting in the low-porosity portion of the strength-porosity curve, where a larger strength reduction was shown.

A paper (Reference 7) on this study has been accepted for publication by The American Ceramic Society.

2(b) Strength of Some Ceramics Containing Hollow Glass Spheres

This research is concerned with the strength of ceramic specimens made by incorporating thin-walled silica glass spheres in a glassy matrix These spheres produce a pore structure which should give a light-weight ceramic processing improved strength.

In these tests the glassy matrix component used was powdered glass of a commercially-available soda-lime type (screened to give particles below 200 mesh). Mixtures of these hollow spheres, powdered glass, and a small amount of organic binder, were prepared. The experimental mixtures were dried in an oven, hand-crushed and screened through a 60 mesh sieve. The sieved mixture was charged into a mold and cold pressed, using a forming pressure of 2000 psi, to form beam-specimens about 1/4" x 3/8" x 3-1/2" in size. The specimens then were sintered; after sintering, they were tested for their mechanical strength in bending.

Experimentation is continuing and several additional matrix components are being investigated. They include an epoxy-plastic, and white Portland cement. It appears desirable to use several matrix components to confirm the effect of the hollow spheres. Preliminary results indicate that the strength characteristics of these specimens are good considering their pore contents.

This study will be completed by about August, 1966.

IV. SUMMARY

The research carried on under this grant (NsG-427) has been directed to an increased utilization of ceramics as structural members, particularly for aerospace applications. The investigations carried on were concerned with three general objectives, as follows:

(1) Studies of several characteristic of prestressed ceramic members.

(2) Development of fabrication methods for prestressed segmented ceramic members.

(3) Development of strong lightweight ceramics.

V. PUBLICATIONS AND/OR REPORTS RESULTING FROM THIS RESEARCH PROGRAM

"Ceramics as Structural Materials," F. R. Shanley and W. J. Knapp, Journal of Structural Div., A. Soc. Civil Engineers, Vol. 91, No. ST4. Proc. Paper 4429, 47-55, August 1965.

"Load-Bearing Characteristics of Biaxially Prestressed Ceramic Plates," M.A. Ali, R.D. Chipman, Peter Kurtz, and W.J. Knapp, NASA Contractor Report CR-188, March 1965.

"Bending-Stiffness Properties of a Prestressed Ceramic Plate," G. Nikolaychik, R.B. Matthiesen, and W.J Knapp. Department of Engineering, UCLA, Report No. 65-26, June 1965.

"Behavior of Biaxially Prestressed Ceramic Plates under Thermal Loading," A.P. Raju, Peter Kurtz and W.J. Knapp, paper submitted to The American Ceramic Society for publication, December 1965.

"Strength of Ceramic Specimens Containing Parallel Cylindrical Holes," David Weiss, Peter Kurtz and W.J. Knapp, paper accepted for publication by The American Ceramic Society, 1966.

VI. GRADUATE THESES RESULTING FROM THIS RESEARCH PROGRAM

The following theses were presented to the University of California, Los Angeles, in partial fulfilment of the requirements for the degree of Master of Science:

"Load-Bearing Characteristics of Prestressed Ceramic Plates," M.A. Ali, June 1964.

"Bending-Stiffness Properties of a Prestressed Segmented Ceramic Plate," George Nikolaychik, June 1965.

"Behavior of Biaxially Prestressed Ceramic Plates Subjected to Thermal Stresses," A.P. Raju, June 1965.

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1. (a) Shanley, F. R., "Preliminary Investigation of a Prestressed Ceramic Wing," RAND Research Memorandum, No. RM-598, RAND Corp., Santa Monica, California, January 24, 1951.

   (b) Johnston, R. D., Chipman, R. D., and Knapp, W. J., "Prestressed Ceramics as a Structural Material," Journal Amer. Ceramic Soc., Vol. 36, No. 4, 121-126, 1953.

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3. Nikolaychik, G., Matthiesen, R. B., and Knapp, W. J., "Bending-Stiffness Properties of a Prestressed Ceramic Plate," Department of Engineering UCLA Report No. 65-26, June 1965

4. Brand, S. H., "Analysis and Design Considerations of Underwater Ceramic Capsules," M. S. Thesis, University of California, Los Angeles, June 1965.

5. Meyer, R. R., and Bellifante, R. J., "Fabrication and Experimental Evaluation of Common Domes having Waffle-like Stiffening," Douglas Report SM-47742, November 1964. Submitted under NASA Contract NAS 8-11542.

6. Raju, A. P., Kurtz, Peter, and Knapp, W. J., "Behavior of Biaxially Prestressed Ceramic Plates under Thermal Loading," paper submitted to The American Ceramic Society for publication, December 1965.

7. Weiss, David, Kurtz, Peter, and Knapp, W. J., "Strength of Ceramic Specimens Containing Parallel Cylindrical Holes," paper to be published by The American Ceramic Society, 1966.