VAULTED BRICK CONSTRUCTION IN GUADALAJARA

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ARCHITECTURE AT RICE UNIVERSITY is a series of reports on thoughts and investigations from the School of Architecture of the University. The series is published in the belief that architectural education can best be advanced when teachers, practitioners, students, and laymen share what they are thinking and doing.

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VAULTED BRICK CONSTRUCTION IN GUADALAJARA

I. FOREWORD

BY CAREY CRONEIS
CHANCELLOR, RICE UNIVERSITY

Introducción
por
Carey Croneis

Desde mediados de 1963 la Universidad de Rice ha tenido el placer y honor de formar parte de un grupo de universidades Norteamericanas quienes, a través de sus representantes, se han asociado con el objeto de cooperar con el desarrollo académico y físico de la Universidad Autónoma de Guadalajara.

Profesores y funcionarios administrativos de varias universidades importantes—Arizona, California, Colorado, Colorado State, Dallas, Denver, Kansas, New Mexico, Rice, Southern California, Texas, y Tulane—se reunieron desde el 28 de junio al 1°. de julio de 1963 en Guadalajara, México. A ellos se les unió un grupo especial de invitados que incluían al Lic. Luis M. Farías, el Director General de la Oficina de Información del Gobierno Mexicano, el Doctor Saxton Bradford, quien representaba a Su Excelencia, Thomas C. Mann, Embajador de los Estados Unidos en esa época en México, el Sr. John Nagel, representante de la Fundación Ford para México y América Central, el Sr. Thomas Linthicum, Cónsul General de los Estados Unidos en Guadalajara, el Ing. Salvador Ochoa Montes de Oca, Presidente de la Junta de Directores de la Universidad de Guadalajara, representantes de las compañías Bacardi y Nestle de México, junto a un grupo de distinguidos profesores y administradores de la Universidad Autónoma de Guadalajara, incluyendo al Rector, Dr. Luis Garibay G., el Vice-Rector, Lic. Antonio Leano A. de Castillo, el Secretario General, Lic. Carlos Pérez Vizcaíno, y el Proboste, Dr. Angel Morales Castro,

Since mid-1963 Rice University has had the honor and pleasure of being one of a group of American universities which, through their representatives, have banded together as a consortium whose purpose it is to assist in the academic and physical development of the Universidad Autonoma de Guadalajara.

Professors and administrative officers of a number of major universities—Arizona, California, Colorado, Colorado State, Dallas, Denver, Kansas, New Mexico, Rice, Southern California, Texas, and Tulane—met in Guadalajara, Mexico, on 28 June to July 1, 1963. They were joined by a group of special guests including Lic. Luis M. Farias, the Director General of the Mexican Government Office of Information, Dr. Saxton Bradford, who represented His Excellency, Thomas C. Mann, then Ambassador of the United States to Mexico, Mr. John Nagel, the representative of the Ford Foundation for Mexico and Central America, Mr. Thomas Linthicum, the Consul General of the United States for Guadalajara, Ing. Salvador Ochoa Montes de Oca, president of the Patrons of the University of Guadalajara, representatives of the Bacardi and Nestle companies of Mexico, together with a group of distinguished professors and administrators from the Universidad Autonoma de Guadalajara, including the Rector, Dr. Luis Garibay G., the Vice-Rector, Lic. Antonio Leano A. de Castillo, the Secretary-General, Lic. Carlos Perez Vizcaino, and the Provost, Dr. Angel Morales Castro, as como asimismo el Dr. Oscar F. Wiegand de la Universidad de Texas, coordinador de los planes de desarrollo para la UAG. Estos señores han sido muy cordiales y una gran ayuda a los miembros del cuerpo docente de la Universidad de Rice, quienes, de varias maneras, han participado en este programa cooperativo.

Durante el curso de la conferencia inicial del año 1963, se plantearon los objetivos del programa cooperativo, fueron consideradas las posibilidades de ayuda y de iniciativa privada vis-a-vis a un desarrollo tradicional de las universidades en México, y se llegaron a acuerdos con respecto a las distintas áreas de colaboración por establecerse con cada una de las universidades Americanas representadas. Al término de las sesiones se planteó a la asamblea una resolución dirigida a la Fundación Ford y a la UAG, cuyo borrador original fué preparado por el autor.

Esta resolución fué adoptada, y ha formado la base principal para los diversos propósitos cooperativos que han sido puestos en marcha con excelentes resultados. Como consecuencia de ello, fondos para funcionamiento y construcción han sido recibidos de varias instituciones, incluyendo a la Fundación Ford, al programa US-AID y al Departamento de Estado de los Estados Unidos.

well as Dr. Oscar F. Wiegand of the University of Texas, the coordinator of the development plans for the UAG. All of these gentlemen have been most cordial and helpful to members of the Rice University faculty who, in various ways, have taken part in the cooperative program.

During the course of the 1963 initial conference, the objectives of the envisaged cooperative program were spelled out, private initiative and support possibilities vis-a-vis orthodox university development in Mexico were considered, and agreements were reached with reference to the various areas of collaboration to be established with each of the American universities represented. At the close of the sessions, a resolution directed to the Ford Foundation and to the Universidad Autonoma de Guadalajara was put before the assembly, the original draft of the proposal having been prepared by the present writer. This resolution was adopted, and it has formed a principal basis for the various cooperative arrangements which subsequently have been put into effect with a gratifyingly high degree of success. As a consequence, development, operating and construction funds have been forthcoming from various agencies, including the Ford Foundation, the US-AID program, and the U. S. Department of State.

En la adjudicación de las áreas academicas de la UAG a las distintas universidades Norteamericanas, Ingeniería y Arquitectura fueron las disciplinas asignadas a la Universidad de Rice, y además, a Rice le fué entregada la responsabilidad de desarrollar el plano regulador del nuevo campus de la UAG. Durante la conferencia inicial, William Caudill, Director de la Escuela de Arquitectura de la Universidad de Rice, y el autor consideraron junto a los funcionarios de la UAG posibilidades potenciales de sitios para el nuevo campus de la Universidad, comparado esto con las posibilidades prácticas de desarrollar una institución de tal envergadura en el terreno actual, en el cual en esa época ya habían varios edificios nuevos. En última instancia, se llegó a la decisión de seguir adelante con el desarrollo del sitio actual de la UAG.

Cuando los deseados fondos necesarios para situar el proyecto de la UAG en su primera etapa de planeamiento llegaron, le fué posible a la Universidad de Rice enviar al profesor Harry Ransom de la Escuela de Arquitectura a Guadalajara a trabajar bajo la égida del Departamento de Estado de los Estados Unidos. El proyecto comenzó en octubre de 1964 con tres arquitectos y cuatro estudiantes, sin embargo, el 1°. de enero de 1966 participaban 30 estudiantes, 3 arquitectos y 4 ingenieros. A través de todo el programa, a la Universidad de Rice y al profesor Ransom les ha sido útil no sólo la eficaz cooperación

In the apportioning of areas of academic concern to the various U. S. universities of the UAG consortium, engineering and architecture were disciplines assigned to Rice University, and, in addition, Rice was given the responsibility for developing the master plan of the new Autonoma campus. At the time of the original conference, William Caudill, Director of the Rice School of Architecture, and the writer spent some time with the officials of the UAG in considering potential sites for a new campus for the University, as compared with the practicality of developing a major institution on the present University campus which at that time was already occupied by several new buildings. Ultimately, a decision was reached to go ahead with the development of the present site of the UAG.

When the hoped-for funds necessary to put the entire UAG project into its detailed planning stage became available, it was possible for Rice University to send Professor Harry Ransom, of the School of Architecture, to Guadalajara to work under the aegis of the United States Department of State. The project began in October, 1964, with three architects and four students. On January 1, 1966, however, there were 30 students, three architects and four engineers involved. Throughout the entire program, Rice University and Professor Ransom have profited not only from the effective cooperation de la administración de la UAG sino que además, la ayuda directa que han recibido de las facultades de Arquitectura e Ingeniería de dicha Universidad. Rice está especialmente agradecida al arquitecto Francisco Camarena, Director de la Escuela de Arquitectura y al Ingeniero José Luis Amezcua S., Director del Instituto de Ciencias Exactas y Terrestres. El dibujo de los cientos de planos fue hecho por un enorme grupo de alumnos avanzados, sin cuya valiosa ayuda este proyecto no podría haberse completado.

Muy pronto en el trabajo de coordinación del diseño del campus, el profesor Ransom quedó particularmente intrigado con la vieja costumbre local de construir sistemas de techumbre con bóvedas de ladrillo. Como en ello había ciertos problemas de orden estructural invitó al profesor Nat Krahl de la Universidad de Rice, a visitar la UAG con el propósito de estudiar esta técnica en profundidad y especialmente para iniciar una serie de pruebas y experimentos a fin de determinar la gama de posibilidades estructurales inherentes a este sistema de construcción local.

El informe que sigue, documenta el procedimiento arquitectónico-estructural e ilustra como, en este caso en particular, la unidad ladrillo se transformó en la determinante de diseño de un campus universitario completo. Pruebas y análisis estructurales tuvieron éxito al demostrar la gran resistencia propia al sistema de bóvedas de ladrillo convencionales. Una serie de pruebas hechas en construcciones de tamaño natural determinaron con éxito las dimensiones de la trama estructural

of the UAG administration, but from the direct assistance of the Autonoma's Architectural and Engineering faculties. Rice is particularly indebted to Arq. Francisco Camarena, Director, UAG School of Architecture, and to Ing. Jose Luis Amezcua S., Director, Institute of Exact and Terrestrial Sciences. The drafting of the hundreds of drawings was done by a large force of advanced architectural students, without whose valued assistance the project could not have been completed.

Early in Professor Ransom's work in coordinating the campus design of the University, he became particularly intrigued with an ancient local practice of constructing roof systems of vaulted brick. Because there were certain engineering problems involved, he invited Rice Professor Nat Krahl to visit the UAG for the purpose of examining the technique in depth, and, in particular, to initiate a series of engineering tests and experiments to determine the actual range of engineering possibilities possessed by this local construction system.

The following report documents the architectural-engineering procedure and illustrates how, in this particular circumstance, a unit of brick became the design determinant for the architecture of an entire university campus. The structural tests and structural analysis were successful in demonstrating the great inherent strength of the conventional brick vaults. A range of full-size construction tests was successful in determining the que puediese permitir la construcción de bóvedas de ladrillo de doble curvatura sin el uso de moldajes, y que como resultado final se consiguió un método más sofisticado de construcción de bóvedas, una vez más, sin moldajes. Resulta que el método no sólo es práctico, sino que permite una rápida construcción de bóvedas soportadas por una trama de vigas y pilares de hormigón armado. Además, no es únicamente un proceso relativamente barato sino que su resultado es estéticamente agradable. Esto se debe en parte a que el cielo de la bóveda puede ser dejado a la vista dado el extraordinario color y la interesantísima textura de los ladrillos utilizados.

Al hablar en la conferencia original en Guadalajara, el autor hizo notar lo relativamente mucho que la UAG había realizado con el relativo poco apoyo financiero, a tal punto de situar en una posición incómoda a varias de las universidades Americanas allí representadas que comunmente se quejan de la suficiencia de sus mayores recursos. Con respecto a esto, se hizo notar que la edad de una persona u organización se puede determinar por la cantidad de dolor que el individuo u organización experimenta al enfrentar una nueva idea. UAG es joven y vigorosa, y no ha experimentado dolor, por lo menos de esa naturaleza. Ha experimentado audazmente y con éxito desarrollar una institución privada e independiente, apoyada por particulares y corporaciones y especialmente por

dimensions of a supporting structural network that would permit doubly curved brick vaults to be constructed without the use of forms and eventually resulted in a more sophisticated method of building such vaults, again without forms. It turns out that the method is not only practical but that it permits rapid construction of vaults which can be supported on a network of reinforced concrete beams and columns. Moreover, not only is the process relatively cheap but its results are also aesthetically pleasing. This is true in part because the underside of the vaults can be exposed advantageously owing to the unusually attractive color and interesting surface texture of the bricks employed.

Speaking at the original conference at Guadalajara, the writer observed that the UAG had accomplished relatively so much with relatively little financial backing that it put many of the U. S. universities represented in an embarrassing position because they commonly complain about the adequacy of their much greater resources. In this connection, it was also pointed out that the age of a person or an organization can be determined by the amount of pain the individual or the institution experiences when encountering a new idea. UAG is young and vigorous, and experiencing no pain, at least of this sort. It has boldly and successfully experimented by developing an independent private institution, supported by "recibos de educación," procedimientos que son "nuevos" y heterodoxos en la educación superior Latinoamericana. Es por lo tanto propio y adecuado entonces, que en su moderno y futuro desarrollo UAG tome ventaja de un "nuevo" concepto arquitectónico-estructural, que sin embargo está firmemente enraizado en un antiguo y atractivo procedimiento de construcción característico del estado de Jalisco.

La Universidad de Rice está orgullosa de haber tomado parte en el desarrollo de UAG, particularmente a través de los proyectos de arquitectura e ingeniería dirigidos por los profesores Ransom y Krahl, delineados someramente en esta publicación. Su agradecimiento a las otras universidades Norteamericanas que forman parte del consorcio es grande, pero a la de los líderes de la Autónoma es aún mayor. Entre ellos los Drs. Luis Garibay G. y Angel Morales Castro merecen especial mención por su dedicación eficaz e incansable a una causa extraordinaria.

El esfuerzo cooperativo entre Rice y UAG se refleja en la mejor forma quizás en el símbolo integrado de diseño que aparece en todos los planos. Representa el apropiado, mas biológicamente imposible, matrimonio de las águilas Mexicanas de la Universidad Autónoma de Guadalajara y los buhos Atenienses de la Universidad de Rice—colofón que orgullosamente presentamos en esta publicación.

individuals and corporations, and particularly by tuition receipts, all of which procedures are "new" and unorthodox in Latin American higher education. It is altogether proper and fitting, therefore, that in its modern and future development the UAG should take advantage of a "new" structural and architectural concept which is nonetheless firmly rooted in an ancient and most attractive building procedure characteristic of the state of Jalisco.

Rice University is proud to have been connected in several material ways with the development of the UAG, particularly through the architectural and engineering projects directed by Professors Ransom and Krahl, which are briefly outlined in this publication. Its indebtedness to the other U. S. universities of the consortium is great, but its obligation to the leaders of the Autonoma is even greater. Among them Drs. Luis Garibay G. and Angel Morales Castro deserve special mention for their tireless and effective dedication to an unusually worthy cause.

The cooperative effort between Rice and the UAG is perhaps best characterized by the integrated design symbol which appears on all of the production drawings. It represents the appropriate, if biologically improbable, wedding of the Mexican eagles of the Universidad Autonoma de Guadalajara and the Athenian owls of Rice University—a colophon we are pleased to display in the present publication.

II. STRUCTURAL EVALUATION

BY NAT W. KRAHL
ASSOCIATE PROFESSOR OF STRUCTURAL ENGINEERING

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Part II is the text of an engineering report submitted to the campus design team at the Universidad Autonoma de Guadalajara for their use in designing the new campus buildings.

LIST OF FIGURES

FIGURE 1. Vaulted brick floor and roof systems under construction on steel framework.

FIGURE 2. Vaulted brick roof system under construction on precast concrete framework.

1. PURPOSE

For some time now the School of Architecture at Rice University and the architectural firm of Caudill, Rowlett, and Scott have been assisting representatives of the Autonomous University of Guadalajara in the preparation of a Master Campus Plan for the development of their university. One concept which has found favor with the planners is that of using an indigenous construction system—namely, roofs and floors of very flat barrel vaults of brick, supported on a structure of contemporary design—as an architectural and structural feature of the campus buildings. This report is an outgrowth of a trip by the writer to Guadalajara for the purpose of observing this unique construction system and is based in part on a continuing series of tests which have been performed at the Autonomous University since that time. The purpose of this report is to present an evaluation of this construction system to the campus planning team for their use in the preparation of their plans.

2. ORIGIN AND DESCRIPTION OF VAULTED BRICK CONSTRUCTION IN GUADALAJARA

2.1 ORIGIN

This construction system, known in Guadalajara as "techo de bóveda," is essentially a structural system whereby a roof or floor is constructed of brick multiple barrel vaults, almost flat, which are supported on a framework of steel (Fig. 1), or sometimes concrete (Fig. 2). The system is apparently unique to a portion of central Mexico and reaches its fullest expression in the state of Jalisco and its principal city, Guadalajara.

This method of construction is an outgrowth of centuries of experience and experimentation with this and similar methods.

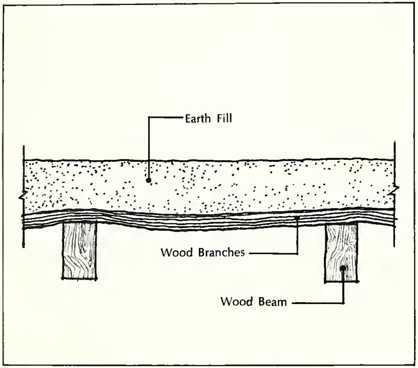

FIGURE 3. Terrado construction.

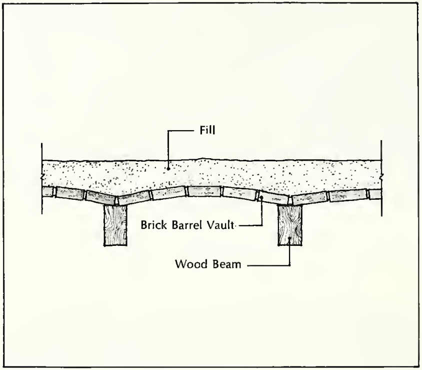

FIGURE 4. Primitive Catalán vaulting.

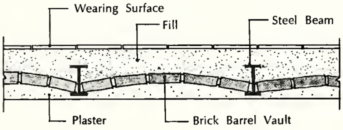

FIGURE 5. Techo de bóveda.

It apparently stems originally from the Terrado system of building (Fig. 3) in which the Indians of Mexico used wood beams to support tree branches which were covered with earth. This method was modified by the Spanish to the Catalan system (Fig. 4), in which wood beams supported short-span multiple brick vaults which, in turn, supported an earth or concrete fill and wearing surface.

With the introduction of structural steel, some builders used rolled steel beams in lieu of wood beams to support the brick vaults, and examples of this are to be seen in Guadalajara. Then someone observed that the shape of the steel beam would allow it to be placed between two adjacent vaults, thereby containing the depth of the arch rib and being virtually concealed itself, and the final step in the evolution of the method had been taken (Fig. 5).

2.2 DESCRIPTION

Any description, analysis, or evaluation of this construction system must first recognize that this system is a combination of two separate structures: first, the brick vaults, which support the floor and the loads imposed on the floor and carry these loads to the supporting structure; and second, the supporting framework of steel or concrete beams, girders, and columns which directly support the vaults.

a. *Vaults*

A typical cross-section through this type of construction is shown in Fig. 5. Typically, the supporting beams are placed 80-130 cm. (32-51 in.) center-to-center, and this distance becomes the span of the barrel vault. The bricks comprising the barrel vaults are laid without formwork, each successive row of bricks in itself becoming an arch rib spanning between steel beams. The vaults themselves are almost flat, the rise usually being only 3-8 cm. (1.5-3 in.). The bricks are handmade mud bricks of local manufacture, are very light in weight and are laid with the large side flat against the adjacent arch rib. The bricks are laid dry, and the suction of the mortar against the side of each brick helps keep it in place until its arch rib has been completed. Also, the vertical axis of each brick is tilted slightly so that each brick is partly supported by the newly-completed adjacent arch rib until its own rib is completed. The mortar in which the brick is laid is made from lime and sand.

A level surface above the vaults and beams is achieved by filling with a lightweight concrete made from hydrated lime and "Jal," which is a local pumice sand and gravel and is the volcanic material from which the State of Jalisco takes its name. The thickness of the fill varies, particularly on roofs, which are usually sloped for drainage. For example, a variation of fill thickness from 5 to 20 cm. (2 to 8 in.) over a roof would not be unusual.

A wearing surface of burnt clay brick or tile is usually placed on top of the concrete fill. On roofs a waterproofing layer of asphalt or cement is placed between the concrete fill and wearing surface.

Finally, the underside of the vaults is almost always covered with a plaster made from lime and sand to give a perfectly flat ceiling which conceals the vaults and beams. In some cases a wire mesh is attached to the beam flange to support the plaster below the flange. In a few cases the brick vaults and steel beams have been left exposed to view from below and achieve a dramatic architectural effect because of the varying colors of the brick and the apparent daring of the flatness of the vaults.

The brick vaults described above are widely used in Guadalajara to support the typical floor loads and roof loads encountered in houses and office buildings. The floor live load used locally for design of dwellings is 150 kg./m.^{2} (30.8 lb./ft.^{2}), and maximum office floor live load for which this type of construction would be considered suitable by local engineers is about

350 kg./m.^{2} (71.8 lb./ft.^{2}). In addition, the brick vaults themselves are not considered suitable for resisting heavy, concentrated loads. If such loads are anticipated in buildings of this type of construction, it is customary to support these loads on small beams of steel or reinforced concrete, which replace the arch ribs in that immediate location and carry their loads directly to the supporting framework of beams, girders, and columns.

The allowable loads and the practices stated above are based primarily on accumulated experience. Prior to the series of tests described in this report, there were apparently no test data available to aid in an evaluation of this structural system.

Apparently the only criticism of this system by local architects and engineers is that a few buildings employing this system have floors which will vibrate noticeably when excited by such factors as nearby truck traffic, a person jumping on the floor, etc. Some floors which can be excited to vibrate noticeably during construction show no objectionable vibration after completion of the building. The writer believes this behavior to be primarily dependent upon the supporting structure and discusses the point further in Chapter 5.

b. Supporting structure

As mentioned above, the beams which directly support the vaults are usually steel beams placed 80-130 cm. (32-51 in.) apart. Typical beam sizes range from 4-inch to 8-inch I-beams, depending on their span and their supported load. Usual spans are in the range of 4-6 meters (13-20 ft.). Most often the steel beams are supported by steel girders which, in turn, are supported by steel columns. Occasionally, small precast concrete beams of I-section are used in lieu of steel beams to support directly the brick vaults (Fig. 2), and the remainder of the supporting structure may then become reinforced concrete.

At an interior beam under uniformly distributed load, the lateral thrust from the vault on one side balances that from the other side; but at edge beams under any loading and at interior beams under unsymmetric loadings there are unbalanced thrusts to be resisted. For this purpose, it is the common practice to use tie rods between adjacent beams at intervals along the length and to extend the lines of rods all the way across the building. The rods are eventually concealed within the floor construction.

Individual members of the supporting structure are, of course, designed according to the live and dead loads, the conditions of support, and the span or length of members.

3. TEST PROGRAM

In order to aid in the evaluation of this structural system, a series of tests was performed at the Autonomous University of Guadalajara. The original reports of these tests, in Spanish, and an English translation are presented in Appendix A of this report. The tests themselves can be classified into two groups: first, tests of individual materials used in this structural system; and, second, a test of full-scale vaults.

3.1 TESTS OF MATERIALS

The brick used in Guadalajara for vault construction is made by hand in the countryside nearby, and is trucked into the city for use. The primary ingredient is a mud made from water and Jal, which is readily available throughout the entire area. In addition, certain amounts of manure and maguey fiber are used in the mixture. The bricks are formed in wood molds, dried in the open air (Fig. 6), then stacked in large piles and fired with mesquite logs, which are placed in slots left in the piles. (Fig. 7). The resulting brick is light in weight, very porous, and has beautiful variations in color, which depend largely upon the degree of firing. Predominant colors range through various shades of yellow, ocher, orange, red and brown. Appendix A contains the quantitative measurements of certain mechanical properties of samples of brick coming from the brickyards of Tateposco and Las Pintas.

In addition to tests of the brick used for the barrel vaults, certain mechanical tests were also performed on representative samples of the mortar used in the vault construction, the Jal concrete fill placed above the vaults, and the burnt clay brick used for the wearing surface. Specifically, the samples of each of these materials corresponded to those particular materials used in the construction of the full-scale vaults that were load tested. Results are given in Appendix A.

FIGURE 6. Handmade mud brick drying in the open air at Tateposco.

FIGURE 7. Handmade mud brick stacked for firing at Tateposco.

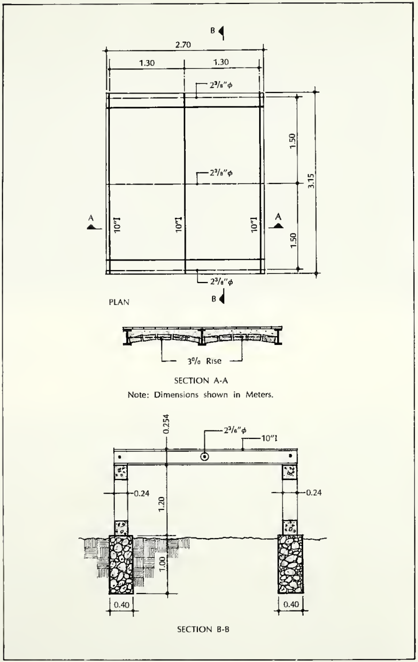

FIGURE 8. Test vaults.

3.2 TEST OF VAULTS

Appendix A contains the report of the load test of full-scale brick vaults performed on the campus of the Autonomous University of Guadalajara. A sketch of the structure which was tested is shown in Figure 8 and photographs of the test are shown in Figures 9-16. The basic aim of the test was to observe the behavior and the strength of the brick vaults under uniformly distributed load. As mentioned above, the structural system under consideration has two separate components, the brick vaults and the supporting structure. It was felt that a supporting structure of steel or reinforced concrete could be readily analyzed with confidence because of the wealth of research information which is available concerning such structures. However, no test data were available for the brick vaults, since they seem to be unique in several respects. What was desired, therefore, was a measure of the strength of the vaults themselves, without a premature failure on the part of the supporting structure. To achieve this end, the steel beams supporting the test vaults were made arbitrarily oversize, 10-inch I-beams on a 3 meter (9 ft. 10 in.) span, while the vaults were constructed of conventional proportions and materials.

Sacks of river sand were used to simulate a uniformly distributed load on the structure. The sacks failed before the structure, but the test was successful in demonstrating that the structure was capable of sustaining a superimposed uniformly distributed load of 1893 kg./m.^{2} (388 lb./ft.^{2}) without appreciable damage and without excessive deflection. Based on the maximum live load in current use for this type of construction, which is 350 kg./m.^{2} (71.8 lb./ft.^{2}), we find a factor of safety which must be greater than 5.4. Additional details of the vault load test are found in Appendix A.

FIGURE 9. Brick arches constructed for original tests.

FIGURE 10. River sand bags being placed for uniform loading tests.

FIGURE 11. Arch end view during early loading.

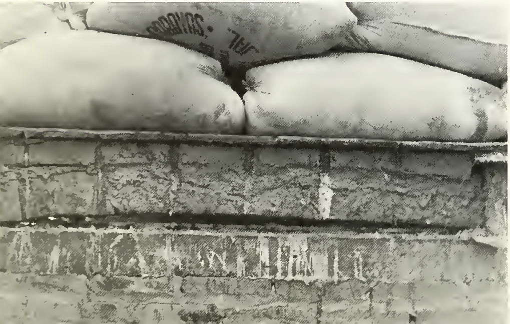

FIGURE 12. Deflection meter placed at center of beam span.

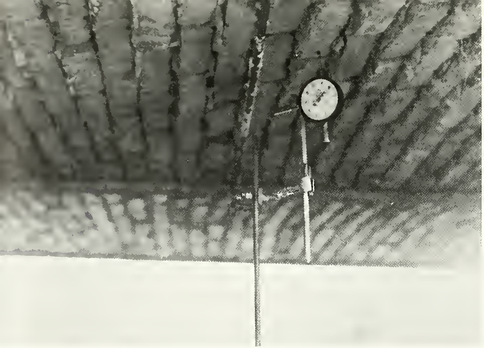

FIGURE 13. Instrumentation reading of vault deflection.

FIGURE 14. Partially loaded test.

FIGURE 15. At this point of loading the vault is supporting 388 pounds per square foot.

FIGURE 16. With no appreciable damage to any structural element, vaults supporting 388 pounds per square foot. This is 5.4 times design live load.

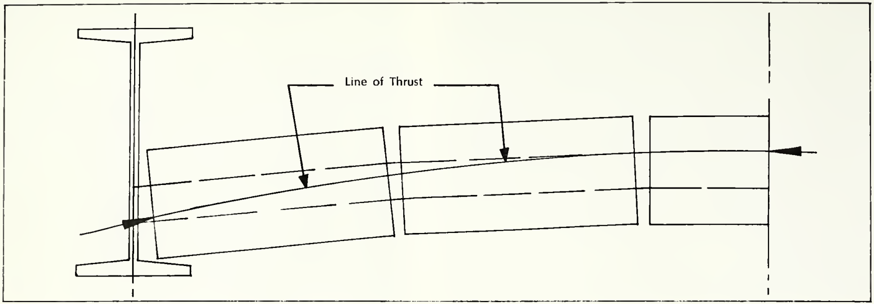

FIGURE 17. Line of thrust of test vaults.

FIGURE 18.

CALCULATIONS FOR: HORIZONTAL THRUST,
MAX. COMPRESSIVE STRESS,
TENSILE STRESS IN TIE RODS

Span: 1.30 m.

Dead Load:	Paving Brick	15 kg./m^2....	3 lb./ft.^{2}
	Jal Concrete Fill.......	70 kg./m^2....	14 lb./ft.^{2}
	Brick Vault	145 kg./m^2....	30 lb./ft.^{2}
		230 kg./m^2	47 lb./ft.^{2}

For Design Live Load of 350 kg./m.^{2} (72 lb./ft.^{2}):

Total Load = 230 + 350 = 580 kg./m.^{2} (119 lb./ft.^{2})

$$\text{Horizontal Thrust} = \frac{wL^2}{8h} = \frac{580 \times 1.30^2}{8 \times 0.075}$$

Horizontal Thrust = 1,630 kg./m. (1,097 lb./ft.)

$$\text{Max. Compressive Stress} \doteq \frac{2H}{bd} = \frac{2 \times 1{,}630 \times 1}{100 \times 11.2}$$

Max. Compressive Stress = 2.91 kg./cm.^{2} (41 lb/in.^{2})

$$\text{Tensile Stress in Tie Rods} = \frac{H}{A_s} = \frac{1{,}630 \times 1.50}{2 \times 0.71}$$

Tensile Stress in Tie Rods = 1,720 kg./cm.^{2} (24,500 lb./in.^{2})

For Max. Test Live Load of 1,893 kg./m.^{2} (388 lb./ft.^{2}):

Total Load = 230 + 1,893 = 2,123 kg./m.^{2} (435 lb./ft.^{2})
Horizontal Thrust = 5,960 kg./m. (4,010 lb./ft.)
Max. Compressive Stress = 10.64 kg./cm.^{2} (151 lb./in.^{2})
Tensile Stress in Tie Rods = 6,290 kg./cm.^{2} (89,500 lb./in.^{2})

4. ANALYSIS OF VAULTS

Figure 17 shows a scale drawing of a cross-section of the barrel vault used in the load test. If we consider a unit thickness of vault perpendicular to the plane of the paper, we can analyze the vault as an arch rib. Since these vaults in practice are constructed without formwork, it must be realized that the actual curve of the underside, or intrados, of the rib will vary somewhat from one cross-section to another. But, since the rise of the arch is so small, only about 3% of the span, all smooth curves of this rise and span will lie very close to one another. Hence the small variations in construction are likely to be unimportant. For simplicity, the placement of bricks in Fig. 17 is shown approximating the curve of a second-degree parabola. Because this arch is of relatively short span and, in practice, supports a relatively light, uniformly-distributed load, the so-called "line of thrust" analysis is considered to be the most suitable basis for analysis.* According to this analysis, the line of thrust under uniformly distributed load becomes parabolic, the crown thrust is horizontal, and its resultant lies at the upper extremity of the middle third of the arch rib, while the resultant thrust at the skewback lies at the lower extremity of the middle third of the arch rib.

The line of thrust following these restrictions is shown in Fig. 17. Since this line of thrust lies entirely within the middle third of the bricks making up the arch rib, no tensile stress will be developed in any part of the rib regardless of the magnitude of the applied load, and hence we can conclude that the arch is stable against failure by rotation of one section of the arch about the edge of a joint. Other possible modes of failure to be investigated include the sliding of one section of the arch on another, crushing of the masonry, and failure of an abutment to provide adequate thrust resistance.

As a measure of sliding stability we examine Fig. 17 and find that the maximum angle between the line of thrust and the normal to the joint between arch sections is about 6 degrees. The significance of this number is evaluated in the next chapter.

The rise of the arch itself is only 3.9 cm. (1.5 in.), but we see from Fig. 17 that the rise of the thrust line is 7.5 cm. (3.0 in.). Fig. 18 shows the calculations for horizontal thrust, maximum compressive stress in the arch, and tensile stress in the tie rods for two separate conditions: first, a design live load of 350 kg./m.^{2} (72 lb./ft.^{2}); and, second, the maximum test live load of 1893 kg./m.^{2} (388 lb./ft.^{2}). The significance of these stresses is evaluated in the next chapter.

*Harry C. Plummer, *Brick and Tile Engineering*, Structural Clay Products Institute, Washington, D.C., 2nd ed., 1962, pp. 199-214.

5. EVALUATION

5.1 VAULTS AND COMPONENT MATERIALS

Two aspects of vault construction and behavior are worthy of comment here: first, the unique construction method whereby the brick vaults are laid without formwork; and, second, the ability of the vaults to carry uniformly distributed loads of considerable magnitude without damage or excessive deflection, despite their flatness.

The handmade bricks used in constructing the vaults are extremely porous because of the materials and methods used in their manufacture. This high porosity is reflected in the absorption percentages reported in the test results of Appendix A. In addition, the bricks are very light in weight, being about one-third less in unit weight than the usual machine-made brick used in the United States. Thus, when a brick is laid dry in mortar against an adjacent, newly-completed arch rib, the suction generated on the contacting large face is sufficient to hold the light brick in place until its own arch rib is completed. The naturally low humidity of the Jalisco climate contributes to this process, of course. Also contributing to the support of the new rib is the fact that the vertical axis of each brick is slightly tilted toward the existing construction so that the newly-completed arch rib actually provides some positive mechanical support for the rib under construction.

In order to evaluate the load-carrying capacity of the vaults, we shall combine the results of the load test described in Chapter 3 and the mathematical analysis reported in Chapter 4. Modes of failure to be considered can be listed as follows: rotation of one section of the arch about the edge of a joint, the sliding of one section of the arch on another, crushing of the masonry, and failure of an abutment to provide adequate thrust resistance. We shall examine each of these possibilities in turn.

First, we see from Fig. 17 that the line of thrust under uniform load lies entirely within the middle third of the bricks making up the arch rib, regardless of the magnitude of the applied load; and this precludes the possibility of a tensile stress developing in any part of the masonry. Hence, we can state that the arch is stable against failure by the rotation of one section of the arch about the edge of a joint.

Next, from Fig. 17 we see that the maximum angle between the line of thrust and the normal to the joint between arch sections is about 6 degrees. The coefficient of friction between the units is at least 0.50, without counting the additional resistance to sliding provided by bond between the mortar and the masonry units. This coefficient of friction corresponds to an angle of friction of about 27 degrees; and, since 6 degrees is much less than 27 degrees, the arch is quite stable against sliding.

Concerning the possibility of masonry crushing, we should be able to conclude that since the test vaults sustained no appreciable damage under a superimposed live load of 1893 kg/m.^{2} (388 lb./ft.^{2}), the stresses produced by this load must be lower than the failing stresses for the component materials. Maximum compressive stress in the vault is calculated in Fig. 18 to be 10.64 kg./cm.^{2}, well below the compressive strength of Tateposco brick, 65.5 kg./cm.^{2}, and even well below the compressive stress at first crack, 20.8 kg./cm.^{2} The calculated stress of 10.64 kg. /cm.^{2} is slightly greater than the measured compressive strength of the mortar, 8.8 kg./cm.^{2}; but we should recognize that the mortar strength was measured in an unconfined compression test, whereas the mortar in the vault is stressed in a confined condition in which its strength is likely to be much greater than in the unconfined condition. Thus the arch rib is seen to be safe against crushing with a large factor of safety for a design load of 350 kg./m.^{2}, and this is seen to be true by both analytical and experimental considerations.

Thrust resistance is provided by the steel beams and tie rods. The only question concerning the adequacy of the thrust resistance arises in the case of an unbalanced thrust, as on an edge beam. The edge beam transfers this thrust to the tie rods, which tie the two edge beams together across the width of all the vaults. Fig. 18 indicates a calculated tensile stress of 6290 kg./cm.^{2} (89,500 lb./in.^{2}) in the tie rods of the test vaults at maximum load. The test results give no data concerning the yield strength of the particular grade of steel from which the tie rods were manufactured; but for most grades of structural steel rods, the yield strength would be well below 6290 kg./cm.^{2} If the tie rods had yielded, this would likely have been reflected in a sudden increase of vault deflection; and, since no such increase was observed, it is likely that the tie rods did not yield and that the calculated stress in the tie rods is too high. Several factors help to explain this situation. First, the entire test structure was only 3 meters long between centers of end supports. Through friction at the bearings of the steel beams on the end supports, some force may have been transferred into the supports so that they participated with the tie rods in providing thrust resistance. Also, the Jal concrete and paving brick are considered to be only dead weight, and the only load-resisting masonry element in the floor construction is assumed to be the brick arch. Actually, the Jal concrete and the paving brick have structural strength in themselves and may well participate with the brickwork in supporting the loads. If so, the line of thrust would have a much greater depth available for its equilibrium position, the magnitude of the thrust would be reduced, and the resulting stresses would thereby be reduced. This is to say that the line of thrust analysis illustrated in Fig. 17 is conservative for design, but may be overconservative for the evaluation of test results when applied to this particular structure. It would seem prudent, however, to provide tie rods in accordance with the requirements of the line of thrust analysis for any construction contemplated on the UAG campus.

It would seem unnecessary to check the ability of the edge beam to withstand the bending produced by the horizontal thrust between tie rods, since the great stiffness of the vaults in the horizontal plane would make possible a horizontal arching between tie rods even if the beam were relatively flexible in this direction.

A word of caution should be mentioned concerning the proper elevation of the tie rods. In order to avoid eccentricities which could produce secondary moments and stresses in the structure, it will be desirable to keep the elevation of the tie rods as close as possible to the intersection of the line of thrust with the web of the steel beam. According to Fig. 17, it looks as if this requirement can be satisfied and still keep the tie rods concealed in the depth of the arch rib.

A final word of caution concerns the handling of concentrated loads. The test program did not investigate concentrated loads, nor is the line of thrust analysis recommended for treating concentrated loads. Unless further investigations are made into this type of loading, it is recommended that the limitations on the use of this structural system which have been accumulated through experience be strictly followed where concentrated loads are involved. In general, this would mean leaving out arch ribs in the immediate location of the concentrated loads and replacing them with beams of steel or reinforced concrete.

5.2 SUPPORTING STRUCTURE

As mentioned above, a great deal of research information is available concerning the behavior of a structural framework of steel or reinforced concrete when subjected to a known loading condition. Therefore, the design of such a framework to resist certain specified loads is, to some extent, a straightforward matter. However, two special conditions pertaining to the structures supporting brick vaults in Guadalajara deserve special consideration.

The latest specifications of the American Institute of Steel Construction recommend* that the depth of fully stressed beams and girders in floors be not less than $F_y/800{,}000$ times the span; and, where subject to shock or vibration, not less than $F_y/650{,}000$ times the span. In their notation F_y is the specified minimum yield point of the type of steel being used, in pounds per square inch. If members of less depth are used, the unit stress in bending should be decreased in the same ratio as the depth

*Section 1.13, "Commentary on the Specification for the Design, Fabrication and Erection of Structural Steel for Buildings," April 17, 1963, American Institute of Steel Construction.

is decreased from that recommended above. These specifications also require† that the depth of beams and girders supporting flat roofs be not less than $f_b/600{,}000$ times their span length whether designed as simple or continuous spans, where f_b is the computed bending stress in pounds per square inch. These specifications are mentioned because apparently some of the beams used in Guadalajara to support the vaulted brick construction are too shallow to meet these standards. The excessive flexibility of some of these beams is the most likely source of the noticeable vibration which is occasionally present in a structure of this sort, and which was mentioned in Chapter 2. It is recommended that all of the AISC Specifications be strictly followed in the detailed design of structural steel for the buildings of the UAG campus, and that the latest specifications of the American Concrete Institute be followed in the detailed design of any concrete framework.

The second special condition worth mentioning is the fact that Guadalajara lies in a region where earthquake activity is frequent and, occasionally, severe. It has been some time since a major earthquake was felt in this area, but such earthquakes are a matter of historical record here. Earthquake engineering has advanced to the point where it is perfectly feasible for a building to be designed to pass through a minor seismic disturbance without appreciable damage and to survive a major seismic disturbance. Proper design for these conditions requires a consideration of the overall configuration of the building in addition to individual member sizes, connections, etc. It is recommended that due attention be given to seismic considerations in the design of the UAG buildings.

†Section 1.13, "Specification for the Design, Fabrication and Erection of Structural Steel for Buildings," adopted April 17, 1963, American Institute of Steel Construction.

6. CONCLUSIONS

Based on the considerations outlined in the first five chapters of this report, the following conclusions are offered:

1. It has been demonstrated by load test and by mathematical analysis that multiple barrel vaults of handmade brick, when constructed of the proportions and the materials customary in Guadalajara, can be used with a high factor of safety to support their own dead weight plus a uniformly distributed live load up to 350 kg./m.^{2} (72 lb./ft.^{2}). For a live load of 350 kg./m^2. the factor of safety is greater than 5.4.

2. In any use of these brick vaults in the new buildings on the UAG campus, it is recommended that tie rods between supporting beams be designed to resist the thrust obtained by making a line of thrust analysis (or similar analysis) on the vaults themselves.

3. Since no tests have been made to determine the behavior of the brick vaults under concentrated loads, it is recommended that any use of the vaults strictly observe the limitations which have been accumulated through experience regarding the support of concentrated loads. In general, this would mean leaving out brick arch ribs in the immediate location of the concentrated loads and replacing them with beams of steel or reinforced concrete. If any modification of this recommendation is desired, additional tests should be performed to justify such modification.

4. It is recommended that any steel members, in the structural framework which supports the vaults, be designed in accordance with the latest specifications and recommendations of the American Institute of Steel Construction. Special attention is called to Section 1.13 of the Specifications and the Commentary on the Specifications concerning limitations on depth of flexural members, since apparently some steel beams used in Guadalajara to support brick vaults are shallower than these provisions recommend.

5. It is recommended that any concrete members, in the structural framework which supports the vaults, be designed in accordance with the latest specifications of the American Concrete Institute.

6. It is recommended that due attention be given to seismic considerations in the design of the UAG buildings.

APPENDIX A

TEST RESULTS

Facultad de Ingeniería Civil

Universidad Autónoma de Guadalajara
Incorporada a la Universidad
Nacional de México
Ciudad Universitaria Autónoma
Tel. 5-95-36

REPORTE DE ANALISIS DE MATERIALES EFECTUADOS EN EL LABORATORIO DE LA FACULTAD DE INGENIERIA U.A.G.

MATERIAL ENSAYADO:

Ladrillo de lama hecho a mano procedente de las ladrilleras de "Tateposco".

Muestra	1	2	3	4	5	Prom.
Peso Volumétrico Seco Kg/M3	1260	1255	1200	1210	1370	1259
Módulo de Ruptura. (Kg/cm2)	15.4	9.41	16.7	15.6	25	16.42
Resistencia a la compresión (Kg/cm2)	50.35	55.5	37.00	66.0	118.5	65.47
Primera Grieta (Kg/cm2)	16.9	30	17.2	20	19.8	20.78
Absorción (24 hs.)	27.6%	32%	32.8%	31.6%	27.5%	30.3%
Absorción (5 hs. ebullición)	36.5%	38.7%	33%	38.2%	32%	35.68%
Coeficiente de Saturación	0.75	0.83	1.0	0.83	0.86	0.854

NOTA: Temperatura del Agua para saturación en 24 hs., 17.5 °C.

Fórmula Módulo de ruptura $\frac{3}{2}\ \frac{PL}{bd}\ 2$

Fórmula compresión $\frac{P}{A} = f$

Absorción $\frac{Ph-Ps}{Ps}\ 100 = W$

Coeficiente de saturación $= \frac{Ph2 - Ps}{Ph - Ps}$

REPORT OF ANALYSIS OF MATERIALS PERFORMED IN THE LABORATORY OF THE SCHOOL OF ENGINEERING U.A.G.

MATERIALS TESTED:

Handmade mud brick coming from the brickyards of "Tateposco."

Test	Units	Sample 1	2	3	4	5	Average
Volumetric Weight, Dry	kg/m^3 lb/ft^3	1260 78.6	1255 78.4	1200 75.0	1210 75.5	1370 85.5	1259 78.6
Modulus of Rupture	kg/cm^2 lb/in^2	15.4 219	9.41 134	16.7 237	15.6 222	25 356	16.42 234
Compressive Strength	kg/cm^2 lb/in^2	50.35 716	55.5 789	37.0 526	66.0 939	118.5 1,685	65.47 931
First Crack	kg/cm^2 lb/in^2	16.9 241	30 427	17.2 245	20 285	19.8 281	20.78 296
Absorption (24 hours)	%	27.6	32	32.8	31.6	27.5	30.3
Absorption (5 hrs. boiling)	%	36.5	38.7	33	38.2	32	35.68
Coefficient of Saturation	-	0.75	0.83	1.0	0.83	0.86	0.854

NOTE: Temperature of the water for saturation in 24 hours, 17.5° C (63.5° F).

Formula for Modulus of Rupture $\frac{3}{2}\frac{PL}{bd^2}$

Formula for Compressive Strength $\frac{P}{A} = f$

Absorption $\frac{P_h - P_s}{P_s} \cdot 100 = W$

Coefficient of Saturation $= \frac{P_{h_2} - P_s}{P_h - P_s}$

Facultad de Ingeniería Civil

Universidad Autónoma de Guadalajara
Incorporada a la Universidad
Nacional de México
Ciudad Universitaria Autónoma
Tel. 5-95-38

Reporte de análisis de materiales efectuados en el Laboratorio de la Facultad de Ingeniería de la U.A.G.

Material ensayado:
Ladrillo de lama hecho a mano procedente de las ladrilleras de "Las Pintas".

Muestra	1	2	3	4	5	Prom.
Peso volumétrico Kg/m^3 seco	1180	1070	1180	1180	1180	1158
Módulo de ruptura (Kg/cm^2)	11.4	11.9	13.55	16.50	11.35	12.94
Resistencia a la compresión	33.15	43.2	72.2	61.2	14.6	44.87
Primera grieta Kg/cm^2	12.3	14.7	15.7	30.3	9.9	16.58
Absorción (24 Hrs.)	37.8%	31.4%	36.35%	30.8%	38.8%	35.03%
Absorción (5hs. ebull.	37.4%	44.2%	45.5%	41%	46%	42.82%
Coeficiente de saturación	1	0.71	0.79	0.75	0.84	0.818

Encargado del Laboratorio

Ing. Carlos Trujillo del Río

Jefe del Depto. de Física

Ing. Francisco Núñez Farías

REPORT OF ANALYSIS OF MATERIALS PERFORMED IN THE LABORATORY OF THE SCHOOL OF ENGINEERING U.A.G.

MATERIALS TESTED:

Hondmade mud brick coming from the brickyords of "Los Pintos."

Test	Units	Sample 1	2	3	4	5	Average
Volumetric Weight, Dry	kg/m^3 lb/ft^3	1180 73.7	1070 66.8	1180 73.6	1180 73.6	1180 73.6	1158 72.3
Modulus of Rupture	kg/cm^2 lb/in^2	11.4 162	11.9 169	13.55 193	16.50 235	11.35 161	12.94 184
Compressive Strength	kg/cm^2 lb/in^2	33.15 472	43.2 615	72.2 1,026	61.2 870	14.6 208	44.87 638
First Crack	kg/cm^2 lb/in^2	12.3 175	14.7 209	15.7 223	30.3 431	9.9 141	16.58 236
Absorption (24 hours)	%	37.8	31.4	36.35	30.8	38.8	35.03
Absorption (5 hrs. boiling)	%	37.4	44.2	45.5	41	46	42.82
Coefficient of Soturotion	-	1	0.71	0.79	0.75	0.84	0.818

Director of the Loborotory — Head of the Deportment of Physics

Engineer Corlos Trujillo del Rio — Engineer Francisco Nunez Forios

Facultad de Ingeniería Civil

Universidad Autónoma de Guadalajara
Incorporada a la Universidad
Nacional de México
Ciudad Universitaria Autónoma
Tel. 5-95-38

LABORATORIO DE RESISTENCIA DE MATERIALES
FACULTAD DE INGENIERIA U.A.G.

Informe de las pruebas de Resistencia de bóveda de ladrillo de lama apoyada en viga de fierro.

Datos de Construcción.- La bóveda se construyó con ladrillo de lama prosedente de "Tateposco" con un claro de 1.30 mts. y una flecha de 3.9 cms. (3% claro) sobre- la bóveda se colocó un hormigón de Cal y Jal hidratada- de un espesor promedio de 7 cms. y por último se colocó en la parte superior un enladrillado consistente de ladrilla de barro cocido con dimensiones 20 X 20 X 1 cms. Las dimensiones totales de las bóvedas fueron: 3.15 X - 2.69 mts. dando una superficie de 8.4735 M2. Se usó mortero de Cal y arena amarilla en proposiciones comunes.

Prueba.- Se cargó la bóveda con sacos de arena de- río que se fueron pesando independientemente, y colocando en la bóveda para dar una carga uniformemente repartida en toda la superficie; se midieron las deformaciones de los arcos de bóveda así como las de las viguetas de apoyo, llegando a tener una carga total de 16.033 Kg y una deformación de 6.98 milimetros sin tener fallas - considerables en todo el elemento estructural.

Resultados:

Resistencia de la bóveda sin llegar a la ruptura.

1892.92 Kgs/m2.

Deformación de toda estructura.

6.98 milimetros.

No hubo fallas de consideración.

Resistencia del mortero 8.8 Kgs./cm2. a la compresión.

Guadalajara, Jal. 10 de Diciembre de 1964.

El Encargado del Laboratorio.

Ing. Carlos Trujillo del Río.

STRENGTH OF MATERIALS LABORATORY
SCHOOL OF ENGINEERING U.A.G.

Report of the strength tests of a vault of mud brick supported on steel beams.

Construction data.- The vault was constructed of mud brick from "Tateposca" with a span of 1.30 meters (4 feet 3.2 inches) and a rise of 3.9 centimeters (1.5 inches), 3% of the span. Over the vault was placed a concrete of Jal and hydrated lime of an average thickness of 7 centimeters (2.8 inches), and last, on the upper part was placed a firm paving of burnt clay brick with dimensions 20 x 20 x 1 centimeters (7.9 x 7.9 x 0.4 inches). The total dimensions of the vaults were: 3.15 x 2.69 meters (10 feet 4.0 inches x 8 feet 9.9 inches) giving an area of 8.4735 square meters (91.2 square feet). A mortar of lime and yellow sand in the usual proportions was used.

Test.- The vault was loaded with sacks of river sand which were weighed independently and were placed on the vault in order to give a load uniformly distributed over the whole surface; the deformations of the arches of the vault were measured as well as those of the supporting beams, reaching a total load of 16,033 kilograms (35,350 pounds) and a deformation of 6.98 millimeters (0.27 inch) without appreciable damage in any structural element.

Results:

Strength of the vault without reaching failure
1,892.92 kilograms/square meter
(388 pounds/square foot)

Deformation of the whole structure
6.98 millimeters
(0.28 inch)
There was no damage of importance.

Compressive strength of the mortar
8.8 kilograms/square centimeter
(125 pounds/square inch)

Guadalajara, Jalisco

December 10, 1964
Director of the Laboratory
Engineer Carlos Trujillo del Rio

Facultad de Ingeniería Civil

Universidad Autónoma de Guadalajara
Incorporada a la Universidad
Nacional de México
Ciudad Universitaria Autónoma
Tel. 5-95-36

Oficina de Planeación de
Ciudad Universitaria Autónoma.
Atte. Arq. Ransom.

Informe de las pruebas de Resistencia de Materiales solicitada por esa H. Oficina.

1.-

A.- Peso volumétrico del hormigón de Jal usado en bóvedas de la prueba realizada en Diciembre próximo pasado.

DOSIFICACION EN VOLUMEN.

JAL____________	2
ARENA AMARILLA__	1
CAL ____________	0.75
AGUA____________	0.50

Peso volumétrico a la edad de
10 días 938.89 Kgs/M^3
6 días 1047.60 Kgs/M^3

B.- MODULO DE RUPTURA.
2.535 $Kgs/cm.^2$

C.- RESISTENCIA A LA COMPRESION
1a. grieta: 3.52 Kgs/cm 2
Ruptura: 4.35 Kgs/cm.2

2o.- Peso volumétrico del ladrillo de barro recocido usado como impermeabilisante de bóvedas.

PESO VOLUMETRICO.
1464.29 Kgs/cm2

Office of Planning of the
Autonomous University City
Attention: Architect Ronsom

Report of the strength of materials tests requested by that Honorable Office.

1.-
A.- Volumetric weight of the Jal concrete used in the vaults in the test performed last December.

PROPORTION BY VOLUME

JAL	2
YELLOW SAND	1
LIME	0.75
WATER	0.50

Volumetric weight at

10 days	938.89 kg./m.^{3}	(58.5 lb./ft.^{3})
6 days	1047.60 kg./m^3	(65.5 lb./ft.^{3})

B. MODULUS OF RUPTURE

2.535 kg./cm.^{2} (36.1 lb./in.^{2})

C. COMPRESSIVE STRENGTH

Cracking:	3.52 kg./cm.^{2}	(50.0 lb./in.^{2})
Rupture:	4.35 kg./cm.^{2}	(61.9 lb./in.^{2})

2.- Volumetric weight of the burnt clay brick used to make the vaults impermeable.

VOLUMETRIC WEIGHT

1464.29 kg./m.^{3} (91.4 lb./ft.^{3})

Facultad de Ingeniería Civil

Universidad Autónoma de Guadalajara
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Ciudad Universitaria Autónoma
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3.- DEFLEXION TOTAL DE LA BOVEDA
6.98 mm.

DEFLEXION DE LA VIGA DE ACERO
2.446 mm.

DEFLEXION RELATIVA DE LA BOVEDA.
6,98-2.446= 4.534 mm.

PERALTE DE LA VIGA - 10"
CLARO DE LA VIGA - 2.67 Mts.

A t e n t a m e n t e
" CIENCIA Y LIBERTAD "
Guadalajara, Jal., Abril 9 de 1965.

Encargado del Laboratorio de Resistencia de Materiales.

ING. CARLOS TRUJILLO DEL RIO.

3.- TOTAL DEFLECTION OF THE VAULT
6.98 mm. (0.28 inch)

DEFLECTION OF THE STEEL BEAM
2.446 mm. (0.10 inch)

RELATIVE DEFLECTION OF THE VAULT
6.98 - 2.446 = 4.534 mm. (0.18 inch)

DEPTH OF THE BEAM - 10 inches

SPAN OF THE BEAM - 2.67 meters (8 feet 9.2 inches)

Sincerely,

"SCIENCE AND LIBERTY"

Guadalajara, Jal., April 9, 1965

Director of the Strength of Materials Laboratory

Engineer Carlos Trujillo del Rio

APPENDIX B

CONVERSION FACTORS BETWEEN METRIC AND ENGLISH UNITS

METRIC UNITS TO ENGLISH UNITS

1 meter	=	39.37	inches
1 square meter	=	10.76	square feet
1 kilogram	=	2.205	pounds
1 kilogram/meter	=	0.6721	pound/foot
1 killogram/square centimeter	=	14.22	pounds/sq. inch
1 kilogram/square meter	=	0.2049	pound/sq. foot
1 kilogram/cubic meter	=	0.06243	pound/cu. foot

ENGLISH UNITS TO METRIC UNITS

1 inch	=	0.02540	meter
1 square foot	=	0.09290	square meters
1 pound	=	0.4536	kilogram
1 pound/foot	=	1.488	kilogram/meter
1 pound/square inch	=	0.07031	kilogram/square centimeter
1 pound/square foot	=	4.883	kilograms/square meter
1 pound/cubic foot	=	16.02	kilograms/cubic meter

III. DESIGN EVOLUTION

BY HARRY S. RANSOM
ASSOCIATE PROFESSOR OF ARCHITECTURE

LIST OF FIGURES

The preceding sections of this report technically document the structural capacity of a traditional regional building technique: the building of brick barrel vaults.

In the architectural programming for all of the proposed new buildings for the Universidad Autonoma de Guadalajara it became evident that a system of architectural flexibility must be an integral part of the structural skeleton. It is imperative that, with relative ease, walls may be relocated, modules added, spaces rearranged. Versatility is essential. The barrel brick vault system satisfied these requirements to a workable degree. But it was recognized as basically a one-way growth system with the opportunity to expand or move in only one direction. For example, partitions can be only reasonably relocated at the supporting beams, framing in the same direction (Fig. 1).

A two-way directional system was therefore desired so that expansibility could occur in either of two directions. Such a system can be seen today (Fig. 2) in one building in Guadalajara, "La Casa de las Artesanias." In this handsome structure two-way doubly curved brick vaults are employed, spanning approximately 16 feet and supported upon square steel-framed bays. But elaborate formwork was necessary to achieve this striking result.

Consequently, a subsequent series of tests was undertaken by the architectural design group in Guadalajara to discover that dimension of supporting structural network that would permit the doubly curved brick vaults to be constructed without the use of forms; and to retain a low rise of the vault capable of inclusion within a normal ceiling-floor thickness (Fig. 3).

Several trial-and-error, full-size tests were conducted; calculations reviewed and refined; and visual details studied. To transcribe all of the testing procedures would make this investigation a purely text oriented writing. Suffice to say that the original tests acted as a springboard for the development of a more sophisticated method of building vaults of brick; in this instance, doubly curved brick vaults—built without the use of forms—spanning 5′-2³/₈″ (1.60 meters) rising 3.9″ (10 centimeters). These vaults are in turn supported upon an aggregate network of reinforced concrete beams and columns. The underside of the brick vaults will be exposed to take advantage of their rich color and textural surface (Fig. 4-11).

This evolved system then becomes the structural design determinant for all of the architecture of the new campus of the Universidad Autonoma de Guadalajara—a system rich in both the past and the present (Fig. 12).

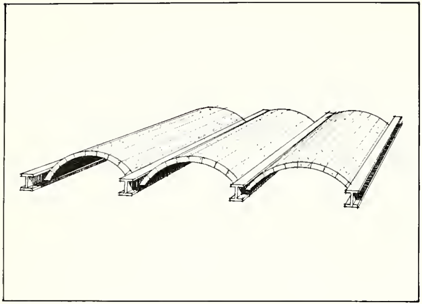

FIGURE 1. One way growth system.

FIGURE 2. View of ceiling of "La Casa de las Artesanias" in Guadalajara, ▷ showing doubly curved, two way vaults.

FIGURE 3. Two way growth system.

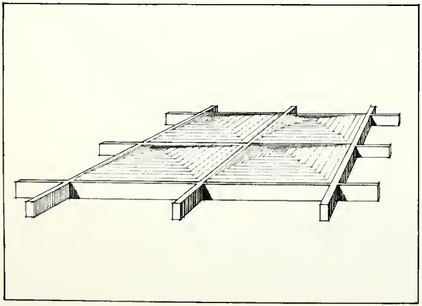

FIGURE 4. Forming of test structure, December 1965. Note small wood pieces used for forms. Plywood is quite expensive.

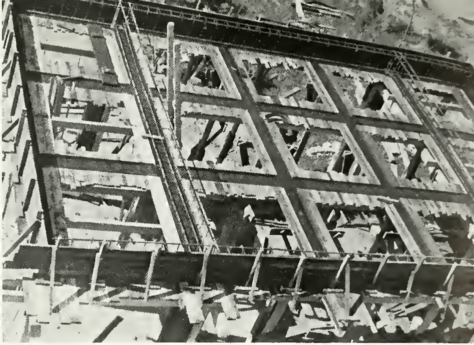

FIGURE 5. Reinforcing being placed in the test structure, 3 modules by 5 modules, two end modules cantilevered.

FIGURE 6. Concrete being placed.

FIGURE 7. Diagonal and circular doubly curved vaults constructed for study purposes.

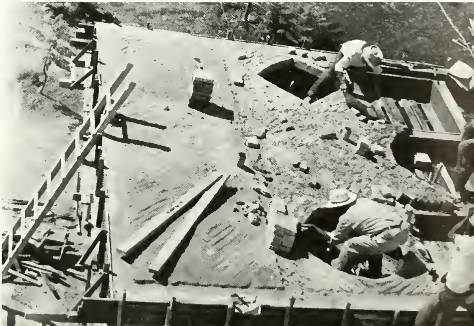

FIGURE 8. Diagonal vault completed. Labor time; 3 hours, 45 minutes. Labor time for circular vault; 7 hours.

FIGURE 9. Forms removed; the effect of the concrete coffered ceiling.

FIGURE 10. The diagonal vault system. Electrical outlet box fully recessed in brick depth.

FIGURE 11. Rectangular brick vault. Labor time; 1 hour, 10 minutes. This is the vaulting system that will be used in the new university buildings.

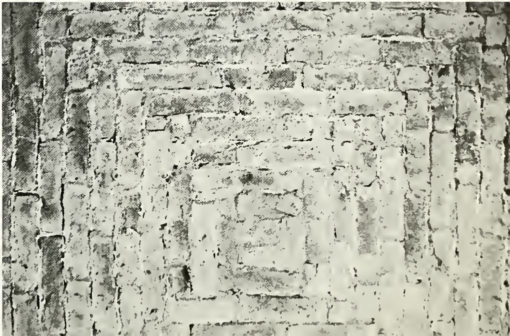

FIGURE 12. Aerial view of model of the proposed campus.

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