Geometry and Mechanics, Inescapable Tools of Architectural and Structural Design

La geometría y la mecánica, herramientas ineludibles en el diseño arquitectónico y estructural

Juan Gerardo Oliva Salinas
Research Center of Architecture, Urbanism and Landscape Architecture
Graduate School of Architecture, National Autonomus University of Mexico
jgos@unam.mx

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Abstract

The aim of this paper is to describe some teaching procedures that have been applied in the education on structures for architecture students at the National Autonomous University of Mexico (UNAM). Even though most of the architecture curricula at Mexican higher education institutions include the subjects of mechanics and geometry, they are taught separately and are not applied to architectural concepts and structural design. In order to mitigate these undesirable teaching conditions, a group of professors has attempted to simultaneously incorporate mechanics and geometry into the conception and design of structures. In response to the aforementioned circumstances, 'Mechametry' was created as a new subject in the UNAM architecture curriculum. Mechametry has been offered for 10 years to undergraduate students, as well as to students in the Design of Lightweight Structures specialization course. Nowadays, many former students are working for companies in Mexico and around the world and are directly involved in the design and construction of shells and other spatial structures, primarily tensile surface structures. Some selected projects by these students will be shown and described in this paper, as will projects that have received awards in international contests for architecture students.

Keywords: teaching of structures, tensile surface structures, mechanics, geometry, mechametry, sustainability

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Resumen

El objetivo de este artículo es describir algunos procedimientos que han sido aplicados en la enseñanza de las estructuras con estudiantes de arquitectura de la Universidad Nacional Autónoma de México (UNAM). A pesar de que en México la mayoría de los planes de estudio de las instituciones de educación superior incluyen las materias de mecánica y de geometría, se enseñan de manera independiente una de la otra y no se aplican directamente a la concepción arquitectónica ni al diseño estructural. Para mitigar estas condiciones indeseables en la enseñanza, un grupo de profesores ha intentado incorporar a la mecánica y a la geometría, simultáneamente, en la concepción y en el diseño de estructuras. Como respuesta a las circunstancias antes descritas, se creó una materia en los planes de estudio de la UNAM denominada 'Mecametría'. Ésta ha sido impartida durante más de diez años a estudiantes de la Licenciatura, así como a alumnos de la Especialización en Diseño de Cubiertas Ligeras. Hoy varios exalumnos trabajan para compañías, en México y en otros países del mundo, que están directamente involucradas con el diseño y construcción de cascarones y otras estructuras espaciales, principalmente estructuras velarias. En este artículo, se mostrará y describirá la selección de algunos proyectos de estos exalumnos, así como proyectos que han recibido reconocimientos en concursos internacionales de estudiantes de arquitectura.

Palabras clave: *enseñanza de las estructuras, velarias, mecánica, geometría, mecametría, sostenibilidad*

Introduction

In current attempts by structural designers to produce sustainable architecture and engineering, lightweight structures become relevant, as they meet environmental criteria, such as maximum efficiency with minimum materials and making better use of natural resources.

The conception, design and construction of lightweight structures should therefore be carried out by architects and engineers with the greatest possible knowledge of the handling of the form, through deep knowledge of geometry, and the best possible understanding of structural behavior, through deep knowledge of mechanics. Certainly, the ability of each structural designer to conceive and design a new structure is measured through their personal ability, a skill with which they were born and which is augmented by the training they have acquired in universities or other higher education institutions. An architect or an engineer with a deep knowledge of geometry and mechanics can therefore properly conceive and design a better sustainable structure, which must not lack that characteristic that was defended countless times

by the architect Felix Candela, that great builder of reinforced concrete shells in Mexico: beauty.

Since the last century, we can add the names of many other renowned designers and builders in addition to Felix Candela: Vladimir Schuchow, Antonio Gaudí, Eduardo Torroja, Pier Luigi Nervi and Frei Otto are some of the most outstanding individuals that represent a common conception, design and construction of sustainable architecture and engineering. It is curious that, in the 60's and 70's, the term sustainability was not used; however, all of the efforts of these builders were aimed at conceiving and designing sustainable architecture and engineering. All of them, architects or engineers, can be considered to be the earliest defenders of what we now identify as sustainable architecture or engineering.

Mechanics and geometry

After many years of teaching separate courses on structural geometry and mechanics to undergraduate architecture students, the author of this paper came to the conclusion that, if the contents of both subjects were taught simultaneously, explaining the close relationship between form and structural behavior, students would obtain a clearer and more objective view of how structures work and behave and consequently would be able to conceive, design and construct better structures. Students would thus understand that a form resulting solely from the designer's formal whims can become beautiful and shocking, even if it is totally unsustainable. The author is convinced that future architects and engineers must acquire, at the university level, the sufficient and necessary knowledge to practice professionally in a responsible fashion and with the conviction to propose and produce sustainable architecture and engineering.

Based on the above, the author proposed the creation of a single subject in the architecture curriculum called "mechametry" – mechanics and geometry – where students simultaneously learn and exercise these two fields of knowledge and come to understand how they complement each other. There was strong resistance on the part of the university administration to the acceptance of this term, but over time, and given the program's results, they have officially accepted the term mechametry.

Several architects and engineers who took the mechametry course offered to undergraduate students in the Faculty of Architecture, as well as to graduate students taking the Design of Lightweight Structures specialization course, are currently working in Mexico and around the world as freelancers or for agencies dedicated to the design and construction of lightweight structures, mainly tensile surface structures. Many of them have received national and international awards.

Didactic methodology

Below is a description of the general sequence of one semester of the elective course on mechametry. Each course consists of 16 two-hour sessions, giving a total of 32 hours per course. It is important to note that an average of 45 students enroll in the course each semester. With more than 300,000 students, the UNAM is one of the largest universities in the world and the main campus in the south of Mexico City is called University City.

Session 1: The professor starts out by inviting the students to reflect on the importance and the close relationship that exists between the shape and the mechanical behavior of a structure, presenting and discussing examples of past and contemporary buildings in which this relationship is emphasized. The professor also shows examples of finished buildings where form was conceived without considering the importance of adequate and sustainable structural behavior.

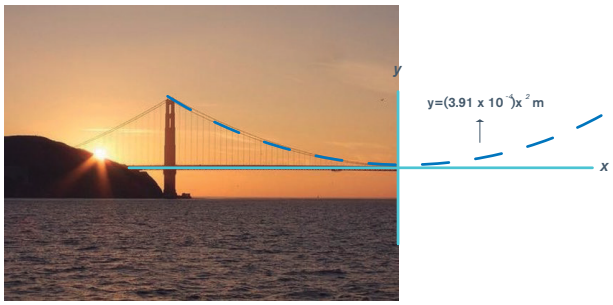
Session 2: Mechametry students have already studied statics and strength of materials. However, some fundamental concepts –force, stress, tension, inertia– are repeated again with a focus on the conception and design of a lightweight structure. Students also simultaneously conduct analytical exercises.

Session 3: The students have already studied descriptive and analytic geometry in previous semesters. Here we discuss the relationship between form and structural behavior for conical sections and catenaries and their application to the conception and design of a lightweight structure. Once again, the students conduct analytical exercises.

Learning about minimal surfaces at the mechametry workshop, 2017.
Image: UNAM - Structures Laboratory archive

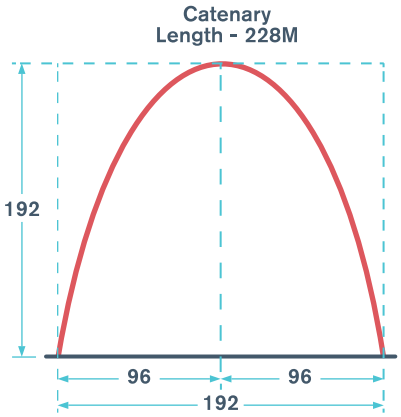
Comparing soap surfaces with membrane surfaces at the mechametry workshop, 2017.
Image: UNAM- Structures Laboratory archive

Example of the relationship between form and structural behavior.
Image: Marin Headlands, *The Golden Gate Bridge*, projectrich.com.



Graphic: UNAM - Structures Laboratory archive.

Example of the relationship between form and structural behavior.
Image: Sam Valadi, *Gateway Arch*, flickr.com.



Graphic: UNAM - Structures Laboratory archive.

Sessions 4: to 13 During the 10 subsequent sessions, students form teams of no more than five students each, with each team developing three lightweight structures. They can apply any lightweight structural system: tensile sur-face structures, grid shells, tensegrity systems, pneumatic structures, structures with nodes and bars, etc. Each team presents its project with a physical model and evaluates its successes and failures while looking for solutions that could improve its structur-al design. The students consider all the observations made during their evaluation and then, they redesign an improved version of their project.

Models made by mechametry students.
Image: UNAM - Structures Laboratory archive

Model made by a team of UNAM students.
Image: UNAM - Structures Laboratory archive

Student model placed on the UNAM campus.
Image: UNAM - Structures Laboratory archive

Sessions 14 to 13: During the last three sessions of the mechametry course, each team designs a final lightweight structure and builds a physical model that will be placed on the grounds of the Faculty of Architecture. In this case, the model has to be large enough to demonstrate the knowledge they have acquired during the 16 sessions of the course.

At the end of the course, the students are evaluated on attendance, participation, individual and group work.

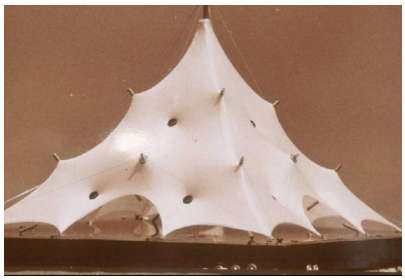
International recognition

Many architects and engineers who took the mechametry course as undergraduate architecture students or as graduate students in the Design

of Lightweight Structures specialization course are currently working, in Mexico and abroad, as freelancers or employees of companies dedicated to the design and construction of lightweight structures, primarily tensile surface structures. Many of them have also won national and international awards for their work.

The recognitions and awards given to former students of the mechametry course that has been taught by the author over the past 15 years are listed below. Many of these students have also collaborated on the ongoing research projects of the UNAM Faculty of Architecture's Lightweight Structures Laboratory under the direction of the author.

1999 – Industrial Fabrics Association International (IFAI), USA.
Students Centre at the Millennium Dome in Greenwich, U.K.
1st Place: Víctor Hugo Roldán
Honorable Mention: Mauricio Cortés, Cinthya Echave, Miguel del Río



Students Centre at the Millennium Dome in Greenwich, U.K. Image: UNAM - Structures Laboratory archive

Students Centre at the Millennium Dome in Greenwich, U.K. Image: UNAM - Structures Laboratory archive

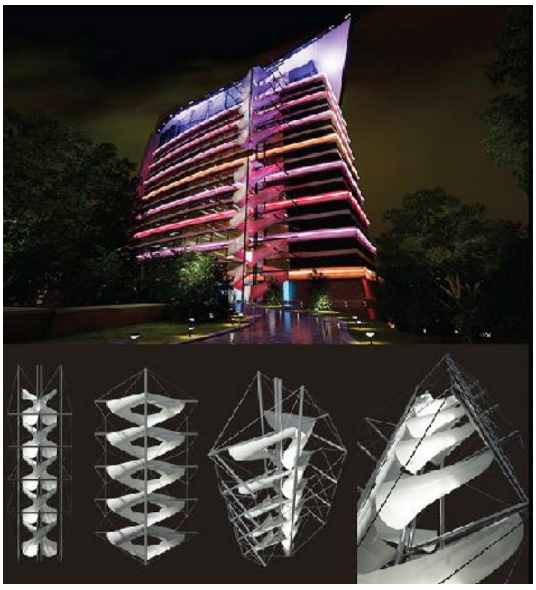
2006 – Contest, Micro-Architecture category, Germany.
Exhibition Pavilion in Coyoacan, Mexico City
2nd Place: Jesús Flores Hernández

Exhibition Pavilion in Coyoacan, Mexico City. Image: UNAM - Structures Laboratory archive

2008 – Hangai Medal: Papers presented at the IASS-SLTE 2008 International Symposium, Acapulco, Mexico.
"Computational Methods in the Teaching of Complex Forms, Case Study: The Hyperbolic Paraboloid": Carolina Carmona Aparicio.
Design and Development of a Convertible Dome for the Patio of a Historic Building.
Honorable Mention: Carlos Zetina Gargollo.

Students awarded the Hangai Medal, 2008. Image: UNAM - Structures Laboratory archive

2012 – V Latin American Symposium on Tensile Structures TENS-SCH 2012, Santiago de Chile, Chile.
Emergency Evacuation Systems in High-Rise Buildings.
1st Place: Diego Abraham Calixto Chávez, Alejandro Montes González, Pedro Ortiz Fernando, Alberto Robles Rodríguez.



Emergency Evacuation Systems in High-Rise Buildings. Image: UNAM - Structures Laboratory archive

Award-winning projects by former students

Over 20 former students of the mechametry course are currently working as architects or engineers, either as freelance professionals or at companies dedicated to the design and construction of lightweight structures.

Some of these projects are listed below:

2006 – *Playa Mia Beach Club Pavilion*, Cancun, Mexico
Marcos Ontiveros
IFAI Outstanding Achievement Award.

Playa Mia Beach Club, Cancun, Mexico.
Image: UNAM - Structures Laboratory archive

2008 – *Los Danzantes Restaurant*, Oaxaca, Mexico
Marcos Ontiveros
IFAI International Achievement Awards in Exterior Shades.

Los Danzantes Restaurant in Oaxaca, Mexico.
Image: UNAM - Structures Laboratory archive

2008 - *Trajinera: Traditional Gondola in Xochimilco*, Mexico.
Marcos Ontiveros
IFAI Outstanding Achievement Award

Trajinera in Xochimilco, Mexico City.
Image: UNAM - Structures Laboratory archive

2012 - *Restaurant at the University of Leon*, ENES, UNAM, Leon, Mexico.
Fernanda Gómez, Eric Valdez, Juan Ramírez
IFAI Award of Excellence.

Restaurant at the University of Leon, Mexico.
Image: UNAM - Structures Laboratory archive

Conclusion

This paper presents a methodology for teaching structures to students of architecture and/or civil engineering, both at the undergraduate and postgraduate levels, through mechametry, which is the simultaneous teaching of mechanics and geometry. It emphasizes the close relationship that exists between these two disciplines, that is, between the

mechanical behavior of a structure and its form. Students carry out a series of exercises in which they must conceive and design lightweight structures, both individually and in groups, constructing physical models that are discussed in front of the class and in which successes, failures and possible solutions are discussed. Students then present a final project that incorporates all of the observations made in their partial evaluations, thus designing an adequate and logical lightweight structure in terms of its form and its structural behavior. Finally, students have submitted their projects to international student competitions, many of them receiving prizes that demonstrate the effectiveness of the teaching strategies shown herein. The author is confident that this is a good methodology for teaching structures to architecture and civil engineering students, but this strategy does not aim to be the only or the best way to achieve these objectives.

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Juan Gerardo Oliva Salinas
jgos@unam.mx

Born in 1950 in Mexico City. In 1975, he Graduated from the architecture program at the National Autonomous University of Mexico (UNAM) and was awarded a Doctorate in Engineering from the University of Stuttgart, Germany in 1982. Since 1983, he has been a professor and the director of the Structures Laboratory at the UNAM, a visiting professor of technology in Argentina, Guatemala and Ecuator and a guest lecteur in the United States, Spain, India, Singapore and Peru. Since 1992, he has been a member of the International Association for Shell and Spatial Structure (IASS): since 2007, a member of its executive council; and since 2015, its vice president. Chairman of the 6th International Seminar on Structural Morphology, 2008 and of the IASS-SLTE 2008 Symposium in Acapulco, Mexico (IASS - III Latin American Symposium on Tensile Structures). Chairman of the Structural Engineers World Congress (SEWC), 2017, Cancun, Mexico. Member of the Editorial Board of the International Journal of Space Structures. In 1999, he was the winner of the national contest to design and construct lightweight structures for the UNAM. Students under his direction have been awarded with international prizes: IFAI 1999, TensiNet 2007 and the V Latin American Symposium on Tensile Structures. He primarily works with lightweight structures and mechametry- mechanics and geometry- applied to architectural and structural design, teaching structures to architecture students and collaborating with architects and engineers. He has designed and built several grid-shells and tensile surface structures. In 1997, he was awarded with the National University Prize in Architecture and Design and, in 1999, with the Mexico City Engineering Prize.

Arquitecto por la UNAM, 1975 y Doktor-Ingenieur por la Universität Stuttgart, 1982. Desde 1983, investigador en la Facultad de Arquitectura, UNAM. Desde 1983 pertenece al Sistema Nacional de Investigadores (SNI). Conferenciante magistral en Estados Unidos, España, India, Singapur y Perú. Profesor invitado en Argentina, Ecuador, Guatemala y Turquía. Vicepresidente de la International Association for Shell and Spatial Structures. En 2007 recibió el Premio Universidad Nacional, en 2009 el premio de Ingeniería de la Ciudad de México y en 2014 el Reconocimiento al Mejor Investigador por la U. Autónoma de Aguascalientes.