

Teaching Structures with Models: Experiences from Chile and the Netherlands

Mauricio Morales Beltran¹, Andrew Borgart²

¹ PhD Researcher, Architectural Engineering, Delft University of Technology, The Netherlands, m.g.moralesbeltran@tudelft.nl

² Assistant Professor, Structural Mechanics, Delft University of Technology, The Netherlands, a.borgart@tudelft.nl

Summary

This paper states the importance of using scaled models for the teaching of structures in the curricula of Architecture and Structural Engineering studies. Based on 10 years' experience working with models for different purposes, with a variety of materials and constructions methods, the authors will address the advantages and possible approaches for a methodology of working with models.

Keywords: *scale models; materials; construction methods; work methodology*

1. Introduction

Using scale models in the teaching of structures has many advantages. As an approach to the reality of a building, the models allow to test in a more controlled environment the translation from the design plan into material world. Also they are helpful where a physical demonstration is needed to explain the mechanical behaviour of certain structural systems or configurations. However, as any other tool, the use of models requires firstly the clear definition of the goals or purpose for what an model-based exercise will be develop for, and secondly, of an adequate framework in which the students can effectively get the knowledge derived from the construction, developing or testing a model. This paper points out the importance and necessity of the work with models, as a teaching tool for students of Architecture and Structural Engineering, based on a classification of the use of models regarding different goals on how the knowledge is delivered. The paper is organized from a description of important cases from the author's experiences in Chile and The Netherlands in teaching with models during the last 10 years, followed by of a comparison between the context and the use of computational backup as support for the process of construction of the models. Finally, some guidelines and keys will be addressed for the work with models, depending on the objectives that has the process within the models will be built. The conclusions summarize the advantages in using models for different purposes within design approach of structures or for testing a predefined performance.

2. Description of cases

We have set four questions which should be answered before plan an exercise based on the use of models: why, what, how and when.

Why? Understanding the use of models as a tool for allow to students getting knowledge, a first classification has been made considering basically the nature of this knowledge and how it should be deliverer: through discovering (knowledge is already there); through the creation (knowledge could be created), and through transfer (knowledge is translating). Basically this different purposes are addressed by means of three types of models – the What?: *Studying*,

which mainly refers to the construction of scaled-down model from a “real” building (Candela, Fuller, etc.) to explore the geometrical relationships between structure and shape; *Exploring*, which getting start from some predefined design, the model is developed as a tool to check the feasibility of constructing “complex” shape or for understanding the inherent complexity of its assembly; and *Testing*, where the models are used to explain either structural behaviour (columns, beams, walls, truss, shells, etc.); or mechanical properties of materials.

Since the kind of model chose has great influence in the further methodology to be develop, the sequence of actions involved in this methodology also can be defined globally as Repeating – the sequence is based in understanding the original work while we repeat or adapt the process to build it; Inventing/Solving – the sequence is based on an exploration of possible ways to solve the problem, therefore we “invent” the solution; Performing – the sequence is based on a controlled experience with the models since we already know how it behaves. Locally, each methodology is defined due a particular exercise – the cases- whose are explained further on. These particular methodologies are based on the scale or size of the model, definition of the constructive process/system, the organization of team work, schedules and the use of supportive tools (machinery or software for instance).

As a point for later; the “when”. Will be explained for each case, and it makes reference to the most appropriate time –within certain timeline or schedule, in which exercise with models could be settled down properly.

Table 1: classification of the cases regarding the main objective proposed

	why	what	How	
			methodology	cases
1	Discover knowledge	Studying models	Repeating	1.A Bend & Break: Tensegrity 1.B Geodesic Dome
2	Create knowledge	Exploring models	Inventing/solving	2.A Morpharchitecture 2.B Shape in Nature
3	Transfer knowledge	Testing models	Performing	3.A Physical Experiments 3.B Trussed Beams



Fig. 3: The Tensegrity models designed and built during the 2011 Minor Bend & Break.

1.A Bend & Break: Tensegrity – minor 2011: Bachelor 3, students Architecture and Civil Engineering, TUD, NL.

A way of achieving insight in the structural behaviour of structures is by studying well known structural typologies. This can be done by sketching, using a computer and building and testing a model. Building different variations of a structural typology enables students to compare their various geometries and structural behaviour, and thus give them insight in the general characteristics of that specific structural typology to be able to apply them satisfactory in an architectural design. In the minor Bend and Break different groups of students work as teams to design, build, calculate and test a Tensegrity structure (Fig.1) Small models, scale 1 to 20, made from wooden sticks and elastic wire are made in the preliminary design stage for exploration. Then each team chooses one of these designs to be scaled up to a 1 to 1 model. This 1 to 1 inexpensive model is made of hollow steel tubes and prestressed steel cables.

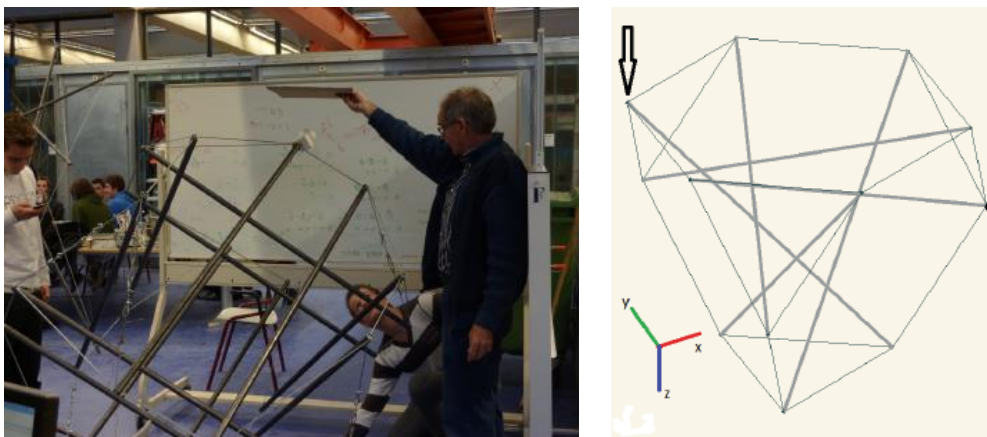


Fig.4: Load testing and calculating the Tensegrity models.

The model is then tested; measuring the vertical and horizontal deflections as result of a singular load suspended on one of the ends of a compression rod and is brought into a state of vibration so to be able to measure the structures Eigenfrequencies. These results are then compared to finite element (FEM) calculations of a computer model of the structure with the same loads applied with a finite element programme. This gives the students the opportunity to discuss the differences in results of the physical test and the computer calculations and the differences between their respective designs. Students must have basic skills of using FEM programmes. In this approach students learn to investigate the structural behaviour of well established typologies, to build and test them and to compare this with numeric simulations.

1.B Geodesic Dome – Structural Systems 2006: Bachelor, students Architecture, UCN, CL.

This exercise was proposed with the primary objective of to solve how to build a geometrical-shaped structure based on the characteristics and properties of a certain material. For that reason we chose the Geodesic Dome, designed by Buckminster Fuller for the Expo'67. The approach developed by the students, led them to the understanding the relationship between the conception of certain design and its final materialization as a real object. Although the geometrical pattern of the geodesic dome was based on a double layer of tetra- and octahedrons, this was simplified to one layer of penta- and hexagons. To achieve this level, the structure was treated as a truncated icosahedron with a frequency of range 6, meaning an assembly of 8 kind of different triangles.

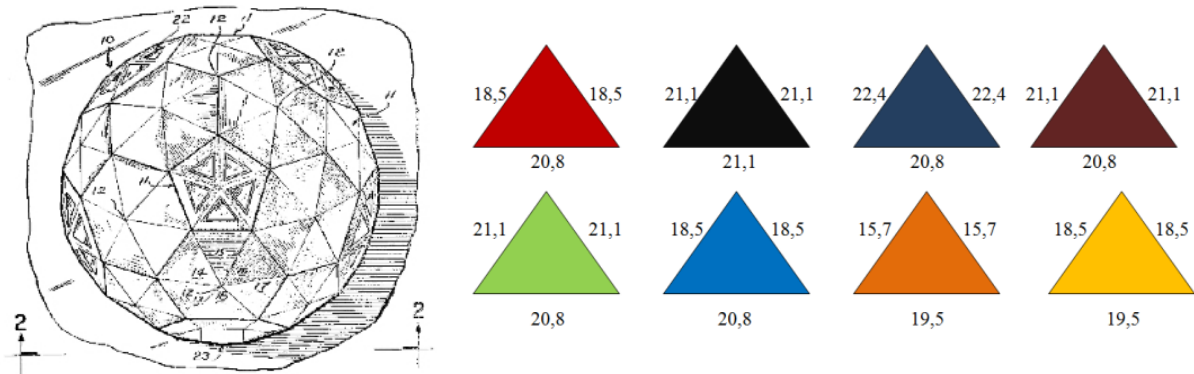


Fig.5: Original reference[3] and display of triangle-based modules.

Due the size of the model (2m of diameter), wooden sticks with rectangular cross-section were used to construct the triangles, which in turn were precisely combined to form pentagons.



Fig.6: First scaled-down model in cardboard and final model assembled .

Table 2: Timeline of the process of constructing de geodesic dome model.

1st stage	2nd stage	3rd stage	4th stage	5th stage	6th stage	7th stage	8th stage
Research and compilation of data, drawings update	Measurements for the molding test	Decision-making in basis on geometrical relationships	Construction of the scaled down model (truncated icosahedron) as reference	Definition of connection and inclination angles in the wooden sticks	Construction of triangles and hexagon's assembly	Fitting the molds	Final Model Assembly

The methodology for the whole exercise is based on the study of a real as reference: 6 assignments for 6 teams, 6 different constructive systems or at least, 6 combinations from known materials as steel, RC, wood, etc. This allow for further discussions based on comparisons. All works should be regarded as geometry-based shapes, whilst this will first

help with the understanding of the structure, afterwards it will be very useful for the practical process of drawing, cutting and sizing of the pieces for the model.

2.A. “Morpharchitecture” – Workshop 2011: Bachelor 3 students Architecture and Master 1 students, Building Technology and Architectural Engineering, TUD, NL

In the chain from design to engineering and finally to production and construction all steps influences each link in the process. A design decision has repercussion for the way of construction and a choice for the fabrication method will give constraints on the design. These issues are especially important for complex geometry structures.

Another important aspect concerning the design of complex geometry structures is exploration. This enables the designer to come up with unorthodox solutions by searching for different options within certain constraints such as a particular fabrication method. Computational methods can support such an integral design process, and link all the different stages and enable bi-directional design decisions.

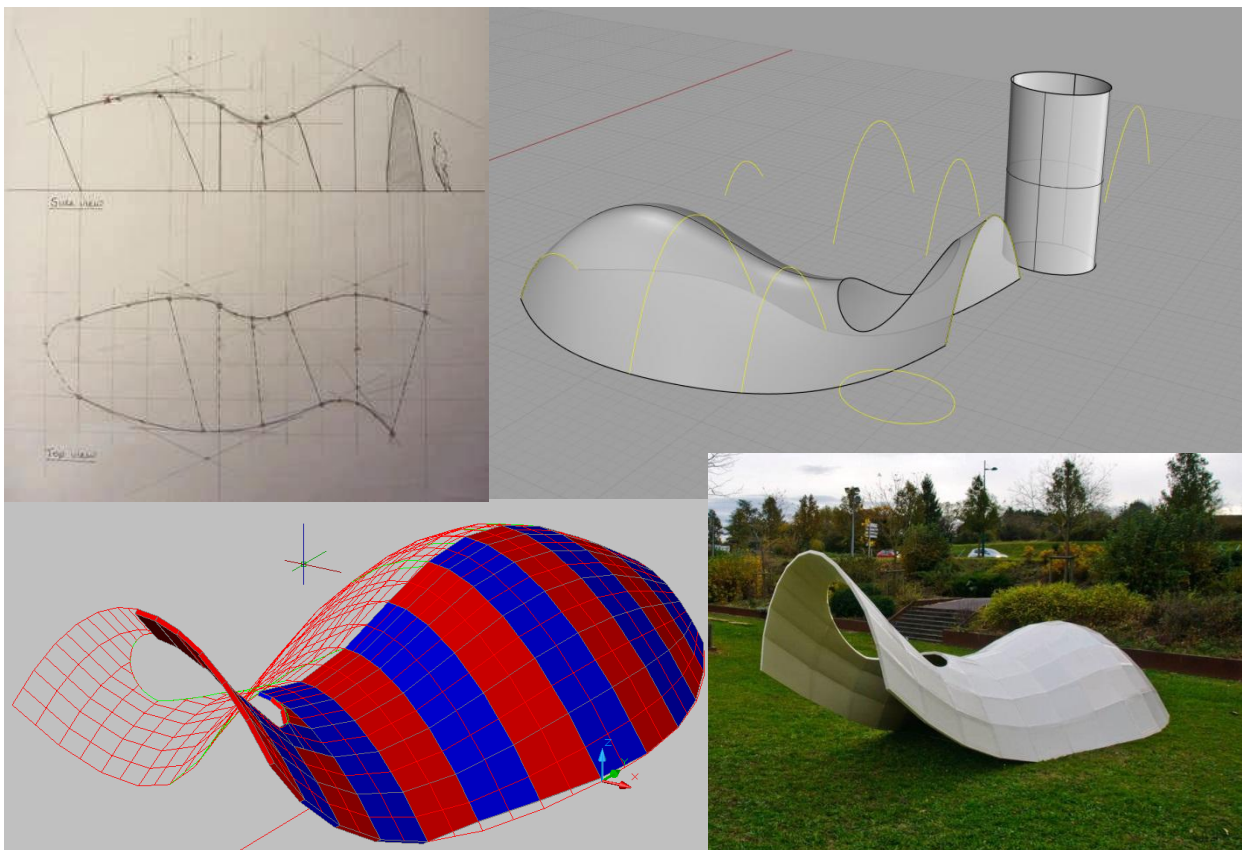


Fig. 7: The shell designed, engineered and built in the 2011 Morpharchitecture workshop, using the “de Casteljaou” algorithm.

Teaching such an integral design approach to students can be done with the aid of structural morphology; exploring the relationship between form and structural behaviour, material and constructability. An example is designing and constructing a complex geometry is the annual “Morpharchitecture” workshop, in which one group of students work together to produce a model of a complex geometry structure as output. The scale of these models is 1 to 5, which results in a size of approximately 4 by 8 meters floor area and 3 to 4 meters high.

The method used to control the design and production process is by using a simple algorithm, the “de Casteljaou” algorithm [2]. It is an easy way to construct a Bezier curve; this can be

done by hand or by using a computer. Because of the simplicity of the algorithm by its recursive nature it gives insight in the way a complex geometry is controlled and can be constructed. The shape is next panelised into a selection of flat quadrangular panels which are hand cut joined together to form the complex geometry. The material used for the panels is foam and tape is used for the joining, thus making such an object inexpensive. The use of 3D computer programmes is essential in this process; students must have basic skills of working with this kind of software to be able to participate in this kind of workshop. The benefit to students of such an approach is to learn to control the entire process from design to construction and to learn the appropriate tools to do so and conclude in making a large model by working together.

2.B. Shape in Nature – course Structures in Nature: Bachelor, students Architecture, UCN, CL.

Structure can be defined as any arrange of elements configured to resist environmental forces. In Nature, an extra value is added to this definition: the configuration is always optimized – through evolution – to use the less amount of energy available. Therefore, we set a particular approach for understanding structures from the principles which organizes and rules the configuration of shapes in Nature. This approach get start with simple drawings of a selected case of study – a natural form, but focused in to discover the basic set of components and the rules or pattern that allow to build the shape, through geometrical relationships.

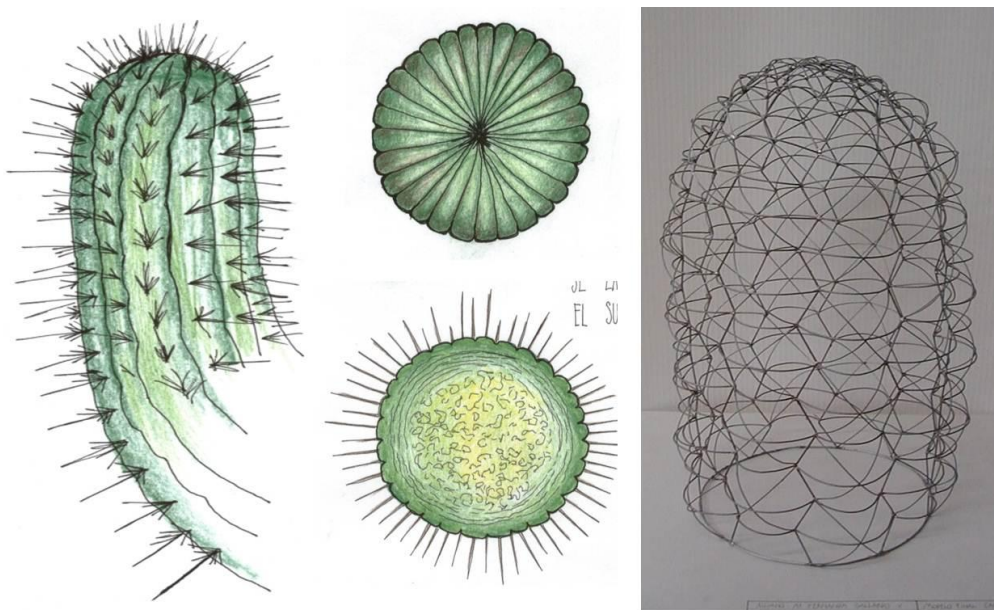


Fig. 8: From initial drawings to the geometric-based model of a cactus.

Once these geometric-based rules are defined, the construction of the models arises as an empirical proof on how the shape can be build, attending this principles but constrained on the use of different materials. Thus, the main conclusion addresses the fact that structure is basically a geometrical organization of elements which in turns depends mainly in the nature of the forces applied.

A further strategy, already based on the development of a sequential model, is focused in the understanding of the structures in Nature from its ability to adapt or change its shape as a response for the environmental variations. While in Nature, the organisms should adapt for

grow up, move on, reproduce, etc., in the exploring with the models, the need of adaption is defined as a response for an applied load. Based on this simplification, the mechanisms or moveable joints are also solved using the case study as reference but relying on the geometrically three-dimensional pattern already settled up. And moreover, the movement (adaptation) is also driven in a predictable way, depending on the geometrical constraints of the shape and allowable degrees of freedom in the connections. In practical terms, the process of adaptation is geometrically controlled by the structure itself.

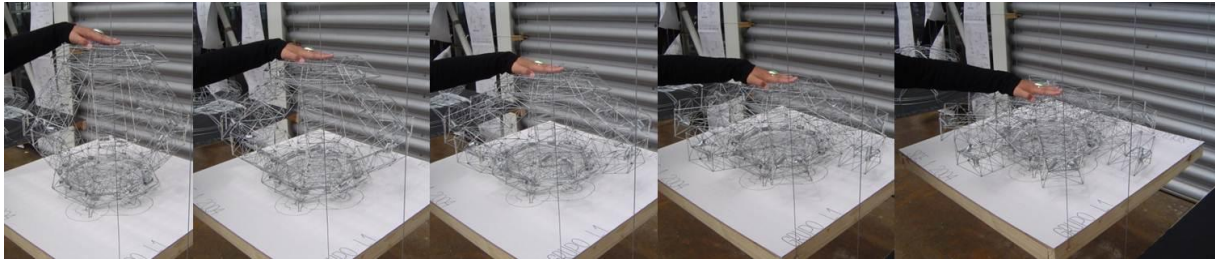


Fig. 9: Adaptation sequence of an geometric-based model.

This method allows the exploration of several shapes based on geometrical principles. Furthermore it also allows exploring and understanding how the structures behave while depending on the nodes or connection constraints.

3.A. Physical Experiments – course Structural Mechanics: Master 1 students, Building Technology and Architectural Engineering, twice every Academic year, TUD, NL.

Teaching students of architectural educations theory of structures poses quiet a challenge for tutors. The theory of structural mechanics is abstract and difficult to learn. The biggest challenge is to make the theory thus understandable that it is applicable for designing structures which fits the architectural concept. A way to support the teaching of the basic theoretical framework is by using models in the way of physical experiments [1].

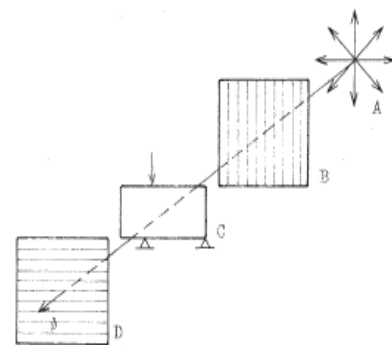
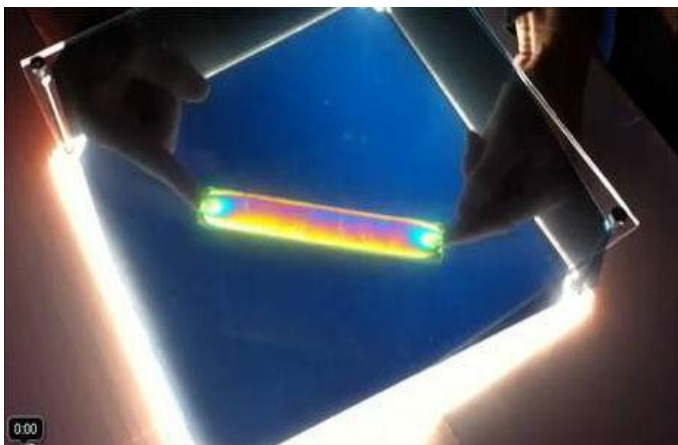


Fig. 10: Showing stresses by deforming a photoelastic material between two polaroid sheets.

Structural mechanics describes physical phenomena relating the structures in a mathematical setting. These physical phenomena can be visualised by doing experiments, which used alongside the theory can highly improve the understanding of the behaviour of structures. Students can perform these experiments themselves and discuss among each other what they see and what the rules are.



Fig.11: Moiré patterns showing deflections of an out-of-plane loaded plate

Different experiments suitable for teaching the theory of plates and slabs are; photoelasticity for visualising stresses in beams and plates, moiré patterns for showing deflections of slabs and the “sand hill” model for examining the load distribution of slabs. The different materials used for these experiments can be easily purchased; the models themselves do not take up a lot off space and are thus ideal for hands-on use by students. These physical models are used in the structural mechanics class in the master course Building Technology / Architectural Engineering. The results are compared to finite element (FEM) calculations of the same structures used in the physical experiment; this gives a better understanding of interpreting the results of the FEM calculation.

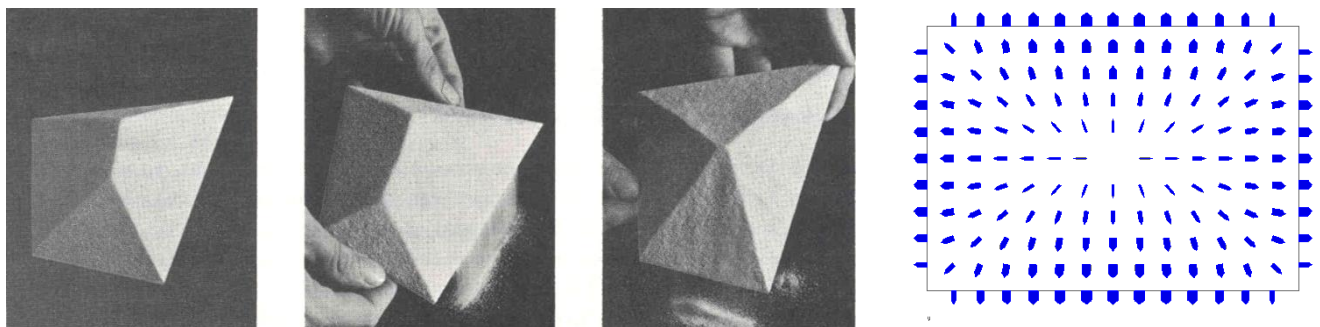


Fig.12: Sand hill models (physical and numeric) visualizing the load distribution of out-of-plane loaded plates

The different mentioned models (physical and computational) are used as tools for teaching students theoretical principles of structural mechanics individually with knowledge and understanding as output. This can be used for successfully designing structures.

3.B. Trussed Beams – course Structural Systems: Bachelor, students Architecture, UCN, CL.

Theory of structures has been developed through years and years of experiences, implying both mistakes and successful results. Although in nowadays there is a deep knowledge based on structural mechanics mainly, the fact of all those knowledge was first observed in real-time experiences and then translated into formulas, definitions and statements is the basic premise to develop a methodology based on experimental models. In the case described, the exercise is about to design and build a trussed beam, spanning 60cm while it should resist 3kg applied on the middle of the span. Further requirements are given (for instance the mandatory use of

wooden sticks or paper) in order to set a fixed framework for the constraints, while there is a great freedom to define the number, size and geometry of the beam itself.

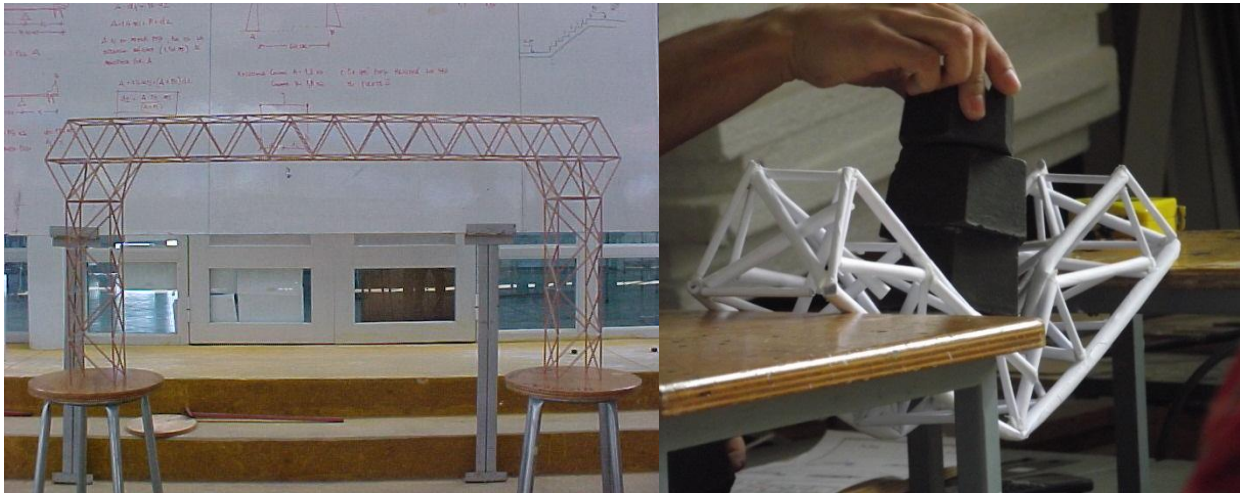


Fig.13: Different strategies are applied on the construction of beams: changes of material, variation in the support conditions and connections.

Since the exercise is realized by a reduced number of students, at the moment of testing the structures, there are several ‘good’ solutions for the same problem. Beside the advantages for the students is to observe how their own structure behaves whilst loaded, the comparison between different solutions gives them a more broad insight about the general behaviour of beams. This insight is complemented with extensive theoretical explanations.

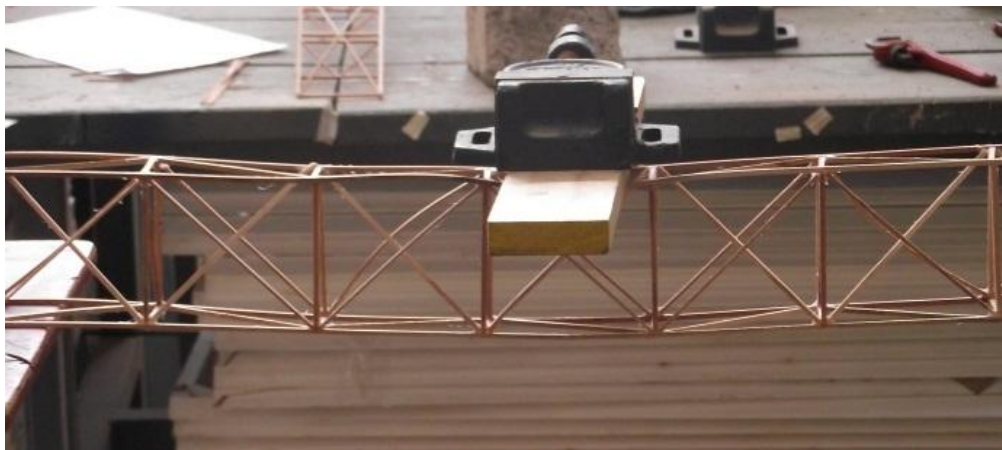


Fig.14: Test performed on a 70cm trussed beam, to evaluate the distribution of stresses in the elements when the load is applied outside from nodes.

To avoid the oversizing in the design of the structures, the ratio Load/Weight is considered as the main parameter to evaluate the configurations proposed: the higher, the better. This also contributes to create a sort of internal contest among the teams what –in a controlled way, is a motivation in the search of more challenging designs. Finally, the exercise is repeated a couple of times in order to introduce the concept of weight-optimized structures.

3. Comparison Matrix

Understanding the use of models as a tool for getting or delivering knowledge, a classification has been made on basis in the main objective of using this tool, in the context of teaching structures.

Table 3: comparison of cases considering different parameters

classification	Studying		Exploring		Testing	
case	1.A	1. B	2.A	2.B	3.A	3.B
country	NL	CL	NL	CL	NL	CL
year/frequency	2011	2006	2011	once per year	twice per year	twice per year
scale/size	1:20, 1:1	2x2x1.5	3x3m; 2-5m height	< 0.5m3	400x400mm	< 0.8x0.5x0.3
materials	steel tubes, steel cable, cable clamps, rigging screws, strain gauge	paper, cardboard, glue, tape, wooden sticks	foam panels, tape	wire, welding wire, tin	2 glass panes with polaroid's, photoelastic material, light, transparent glass panes with thin black lines, silver sand, plates and boxes with holes	paper, wooden sticks, glue, tape
students	24	60	20	35	40	40
groups	8	6	1	12	1	20
tutors	2	4	2	1	1	1
hours	100	80	40	80	8	40
level	bachelor	bachelor	bachelor master	bachelor	master	bachelor
cost (approx.)	1000	200	500	100 - 200	300 - 400	100
Computational support?	yes	no	yes	no	yes	no

4. Conclusions

Chile / The Netherlands: Based on the author's experiences in teaching with models, there are not clear differences between the results obtained in both countries, in terms of the assimilation of contents by the students, which could be attributed to the dissimilar culture background. Therefore, we can state that using models as it is described in the cases, is a powerful tool to deliver knowledge about structures, no matter in what kind of cultural context they could be applied on.

Primary assumptions: The problem of to construct the model is unequivocally associated to the understanding of how to solve the building process. Therefore, the learning occurs when the students experiment, develop or assemble the model. To focus this learning process towards the subjects regarding Theory of Structures, any other relationship between the original work studied and its context, cultural environment or function shall not be taken into account, during this process. Thus, the work with models implies a simplification of the reality of the structure.

Scale: In the cases described, the scale is defined for the size of the model. And the size in turn, is defined depending of complexity of geometry (configuration), the properties of the materials applied and mainly rely on the proposed objectives. However, a good approach for testing models is 1:25 as a maximum. 1:10, 1:5 and 1:2 while 1:1 is the best of course, exploration models might cover a similar range (between 1:20 and 1:1). For studying models, the range could be even higher between 1:20 – 1:200, with an average of 1:50.

Materials: As mentioned before the election of the materials for the models depends fundamentally on for which purpose these will be developed. Nevertheless depending on the addressed size, the question about how much could cost a model becomes important. Moreover at some cases, especially when certain features are very similar among different materials (for instance mechanical properties) the final election used to rely on this variable. Also a definition of the construction system, implying the way and time involved of making the connections assemble and building process must to be considered.

Organization: Beside the general definition of the course/workshop framework, including the timeline for the exercise of build the model (or set up the experiments), a plan should be settled in terms of how much time the students will spend on that part of the process. An approach for a definition of the number of members in the work teams and their own organization of tasks also is required.

Computational Backup: The main advantage of using it comes from on how fast becomes the process. Speeding up the sizing of pieces/elements, or delimiting the possible outcomes from a structural test through simulation of performance. Also compared parallel calculations obtained through the use of an appropriate software increase the reliability (robustness) of a test results made in basis on models. Especially when results are evaluated, regarding to some specific performance.

Acknowledgements

The authors would like to thank to the students involved in all those academic experiences above described. The first author would like to thank to the School of Architecture, Universidad Catolica del Norte - UCN (Chile). The second author would like to thank to the Faculty of Architecture and Faculty of Civil Engineering and GeoSciences, Delft University of Technology – TUD (The Netherlands).

References

- [1] Beranek, W. *Bereking van Platen*. Delft University of Technology. Delft, 1976
- [2] Marty, A., *Pascalian forms, essay on curved shapes*, Editions de l'esperou, 2006.
- [3] Fuller, R.B., *Building Construction*. United States Patent Number 2,682,235, Issue Date: June 29, 1954