



Teaching geometric modeling and analysis of tensegrity structures

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Abstract

Purpose:

This paper will present an efficient methodology for teaching geometric modeling and analysis of spatial grids and tensegrity structures through a guided design experience. Tensegrity is a non-conventional kind of framework very interesting from a structural, geometrical and aesthetical point of view.

Method:

The methodological principles of these teaching and learning experiences are based on four main pillars: 1) Learning by doing, 2) Teaching by doing, 3) Learning by thinking and 4) Teaching by suggesting. From an engineering point of view, a geometrical approach to these structures is essential for their structural analysis.

Result:

By using a methodology based on learning by doing (building virtual and physical models), students are able to gain a quick and effective knowledge not only in structural concepts about tensegrity spatial frames, but also in the different software tools used during the course: AutoCad, Autodesk Inventor, ToyGL, MS Excel, VBA, GNU Octave, etc.

Discussion & Conclusion:

Learning by doing is a very effective way of acquiring knowledge, because students can practice continuously with different academic tools for research, design, analysis, construction, etc. Moreover, it is also a more dynamic and engaging method, which makes the course easier and more entertaining, according to the opinions of teachers and students of the MSc Research in Civil Engineering at the University of Cantabria.

1 Introduction

This paper will present an efficient methodology for teaching geometric modeling and analysis of spatial grids in general and tensegrity structures in particular, through a guided design experience. One of the main *mottos* of this course is “learning by doing”, as will be explained further on, so the course is eminently practical and empirical, with only a few theoretical hours. More than that, the aim of the course is to encourage the students to complement the limited time of the program by engaging themselves in a personal research about any of the subjects, ideas or tools experimented during the course. Related to this idea, Ramón y Cajal, the Spanish Nobel Prize, used to quote Ostwald, who said that especially gifted students never appear satisfied with what ordinary instruction offers them [1].

The vehicular theme of the course is spatial grids in general. However, Tensegrity, a non-conventional kind of framework, will be especially explored because of its interest from a structural, geometrical and aesthetical point of view. However, it is uncommon and rarely included among the structural typologies studied in the curriculum of Civil Engineering or other engineering degrees / postgrads. This is due to the fact that their applications are limited at the moment, and it is a relatively new line of research in the field of Engineering, Architecture, etc.

In this work, the authors explain the way in which these incredible structures are the vehicle to learn from several experiences, concepts and tools that could also be applied to many other areas of engineering, applied science or research in general.

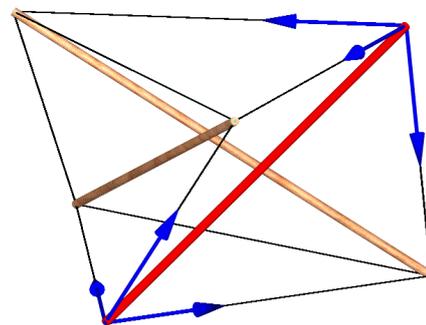


Figure 1. Tensegrity "Simplex". Arrows in blue represent the tension in the cables acting on the red compressed strut.

1.1 Definition of Tensegrity

Definition of Tensegrity has always been very ambiguous and controversial [2]; for that reason, important differences about this concept arise depending on the consideration of different authors. In this paper, tensegrities will be considered as self-stressed and auto-

stable structures composed by isolated components in compression inside a net of continuous tension, in such a way that the compressed members (usually bars or struts) do not touch each other and the pre-stressed tensioned members (usually wires or even tensile membranes) delineate the system spatially [3]. Figure 1 shows the "Simplex", the most basic tensegrity structure.

1.2 Tensegrities: peculiar structures

Tensegrity spatial frames are very particular because, contrary to conventional frameworks, geometry of the structure depends completely on the internal stresses and external forces supported by the system as a whole. Therefore, geometrical definition and structural analysis must be approached unifying both concepts in practice from the draft. This fact converts the approach to design tensegrities in an iterative method that can be optimized as much as desired.

2 Academic context

2.1 Scope of the course

Engineering design and research have not, usually, a formal, quantifiable, teachable core body of knowledge; therefore, it is not very common to find pure design or research courses in undergraduate curricula, even though their importance in any field of science. As a substitute, engineers are expected to learn research or design during their professional career [4]. Certainly, the development of a formalized approach to both subjects persists to be a challenge to the teaching of engineering, which can be achieved in postgraduate courses.

The research and design of tensegrity structures is contained within a broader frame program, because it is included in the course of "Geometrical Design of Spatial Grids". This course is attended by students enrolled in the MSc Research in Civil Engineering of the University of Cantabria, which gives access to the Doctoral Program of Civil Engineering.

As can be stated in the title of the course, the subject is not tensegrity structures in particular, but spatial grids in general. However, as tensegrities are an innovative and promising structural system and it is one of the several lines of work of the research group EGICAD, responsible for the teaching of this course, it was highly recommended to focus on them especially for doctrinal purposes.

2.2 Competences and objectives of the course

The aim of the course is that students acquire methodological basis to launch their instruction as researchers in the field of spatial structures. If this is achieved, they would have normally developed different kinds of competences, which are classified in two main groups as follows:

General Competences:

- Looking deeper into the exhaustive and detailed knowledge of the field of study.
- Development of critical analysis of existing knowledge and tools, their applicability and limits.
- Making original and innovative proposals for the development of knowledge extending its depth and applicability.

Specific Competences:

- Acquisition of knowledge of the basic subjects that comprise the field of engineering.

- Knowing the technologies, tools and techniques in the field of engineering which may constitute a specialty or a specific line of in-depth study.
- Capacity to identify, measure, state, analyze, diagnose, model and describe scientifically and technically a problem in the field of engineering.
- Capacity to develop explanatory models and original and innovative instruments of analysis consistent with the nature of the problems characteristic of engineering and based on observable experience and a critical analysis of the available proposals, both one's own and those of others.
- Capacity for integrated analysis of engineering problems.

3 Methodology

Designing effective courses can be achieved by succeeding in developing the following aspects [5]:

- 1) articulation of course objectives;
- 2) creation of instructional/learning activities;
- 3) design of effective assessments.

In the precedent section, a description of the course objectives and competences to develop have already been exposed. In section 4, explanations of the learning activities will be proposed. Finally, the evaluation of the students' work will be summarized in section 5. The methodological approach will be established attending to the most relevant aspects of the teaching and learning experience.

3.1 Organization and distribution of times

Currently, the course of "Geometrical Design of Spatial Grids" requires 3 ECTS Credits, which means 75 hours in total. An extended description of the distribution of these hours is presented in Table 1.

Activities "on campus"	Hours	Total
Theory sessions	4	24
Practical sessions	20	
Follow-up Activities	Hours	75 hours
Tutorials	3	
Evaluation	3	
Activities "off campus"	Hours	
Team work	15	
Individual work	30	

Table 1. Distribution of activities and times ("on campus" and "off campus").

3.2 Methodological philosophy of the course

The methodological principles of the course are based on four main pillars:

- 1) Learning by doing
- 2) Teaching by doing
- 3) Learning by thinking
- 4) Teaching by suggesting

As can be stated in the distribution of hours, some traditional face-to-face "seat time" has been replaced by autonomous (but guided) learning activities, either individual or collective. Besides, 80% of the "on campus" course is dedicated to practical sessions, which verifies the purpose of aiming on "learning by doing". Confucius exemplified this wisely: "I hear and I forget. I see and I remember. I do and I understand".

Research on cognition openly points out that students learn best by doing: by recognizing types of data, articulating real-world problems, discussing and assessing

options, choosing among formulas and tools, justifying choices, etc. [5]

Related to this point, it could also be interesting to explain that, as important as “learning by doing” is, so too is **“teaching by doing”**. It is far too obvious that “one can only teach effectively those things that one actually does” [1]. This is the reason, among others, why tensegrity structures, which belong to a line of research of EGICAD, is one of the vehicular subjects of this course.

However, “doing” is not always enough to acquire new knowledge, because it can be based on the mechanical repetition of certain tasks. It is essential to achieve that students, when dealing with a specific problem, do not merely repeat the procedures explained in the classroom, but apply the acquired knowledge to analyze and solve any similar exercise. This method will develop the skill of the students to seek for suitable solutions to the challenges that they will find during their professional careers [6].

Therefore, the other pillar of the course is supported by the **“learning by thinking”** idea. Eduardo Torroja, one of the most important Spanish engineers of the last century, said that there was so much to learn at the School of Civil Engineering that there was little time to think [7]. He also mentioned Confucius, again, saying that it is as useless to learn without thinking as it is dangerous to think without having first learnt from others. This is the reason why, during this course, once and again, students are asked to stop, turn off the screens of the computer, put aside books or papers and meditate about some concept or question.

Finally, the course is also participating in the philosophy of **“teaching by suggesting”**. This idea is magnificently expressed by Ramón y Cajal when he said that *“the master has the responsibility of shortening this preparation, orienting the pupil, showing him roads open to investigation, guiding him in literature searches, and finally, suggesting to him how to acquire all of the accessory knowledge and abilities that are useful”* [1].

3.3 Development of the tasks

The procedure to develop the different activities is sensitively homogenous during the four main blocks (see point 4) in which the course is organized. There are mainly two types of activities:

1) Research tasks

The first half of each block is dedicated to a brief explanation about the general concept to deal with, after which the students have to do some research about the key points of the subject. Of course, this work of investigation is guided through a set of questions, suggestions and comments that will address the pupils to the main issues and sources of interest. Not all the questions will have to be replied in the classroom, as some of them should be analyzed and answered as individual or team homework.

At the end of the research task of every block, students are asked to implement an entry of Wikipedia, related to the studied subjects, that they think is incomplete or can be improved. This task is oriented to let them understand that information and knowledge are the consequence of the efforts of many people, and that their small contribution, in any field, can be useful to fulfill the gaps in different areas or topics.

Among this category, a different kind of activity is included, such as visiting buildings, civil works, roofings, shelters or current work sites where spatial grids are the

fundamental support of the structure. The best known and most accessible places around the city (Santander, in Cantabria, Spain) are facilitated in the course guide, as well as their exact location, although there is also the possibility of visiting some other interesting examples out of the list.

2) Applied tasks

After finding out the main answers to the questions and comments proposed in the course guide, the students are invited to apply some of those concepts to develop practical exercises. Several empirical activities are proposed in order to be started in the classroom and, if not completed, to be finished in “off campus” hours. Most of the time, these exercises are related to the presentation of a software tool (AutoCad 2D and 3D, Autodesk Inventor, ToyGL, VBA for AutoCad and Microsoft Excel, GNU Octave / Matlab, etc.).

4 Organization in blocks and workflow

4.1 Block 0 – Preliminary test

In order to measure the effectiveness of the teaching methodology, a survey is conducted before and after the execution of the course project. In this preliminary test, students have to evaluate, from 1 to 5, the knowledge they have about several subjects, competences in different areas, general skills and technical skills.

At the end of the course, the same test is carried out to compare the results with the initial inputs. Since we are talking about cognitive abilities, the students should be able to evaluate what they can do with the knowledge they have just acquired.

4.2 Block 1 – Knowledge and sketching

The first block is designed as an introduction to the general topic of spatial frames and spatial grids. At the start of the research task, a basic and introductory lecture serves as an explanation of the most basic concepts, principal ideas and main sources of information and research that they could need. After this session of theory, students are required to do a deeper exploration on those subjects; this is done by finding out more information linked by some conducting questions that are gathered in the course guide. It has been proved that anecdotic or contradictory inquiries have a positive effect in acquiring some of the concepts, as they are deeply remembered due to their appealing character. As an example: “What is the relationship of Alexander Graham Bell with space frames? Is the same person that invented the telephone?”

The first applied task is focused on exercising design expression skills and visual communication skills by means of manual sketching. Graphics is a universal language for communicating among applied and research engineering and technology. Training the ability to express an idea by means of a simple sketch is basic and fundamental for any engineer. Thus, students are asked to represent their first spatial grid in 2D and 3D using a pencil and a piece of paper as their only tools.

4.3 Block 2 – Design and drafting

During the second session, some more profound concepts are introduced to the students, like tensegrity structures. At the same time, the research tasks are carried out by using more sophisticated means; apart from the basic bibliography and conventional web searches (e.g. Google Scholar), students are introduced to the

specific tools provided by the university to search in special databases, like Web of Science, Scopus, Engineering Village, etc.

The best way to learn how to read drawings is to learn how to prepare drawings [8]. Therefore, the applied task of this second block is dealing with the technical drawing of a certain tensegrity grid with AutoCad 3D. At this stage, students are not able to design a tensegrity structure, because its geometry and topology is totally interconnected with its structural behavior. Hence, they will reproduce an existing double-layer tensegrity grid, which will help them to understand better the geometrical configuration of this kind of construction (Figure 2).

Drawing a large spatial grid can be time consuming and, in some occasions, ineffective, due to the fact that some substructures are widely replicated. Thus, students are introduced to the powerful and useful tool of programming for AutoCad in VBA. Even though this utility is not shown in extension, all those pupils that are interested in knowing more about it have the possibility of enjoying intensive instructions during personal or collective tutorials.

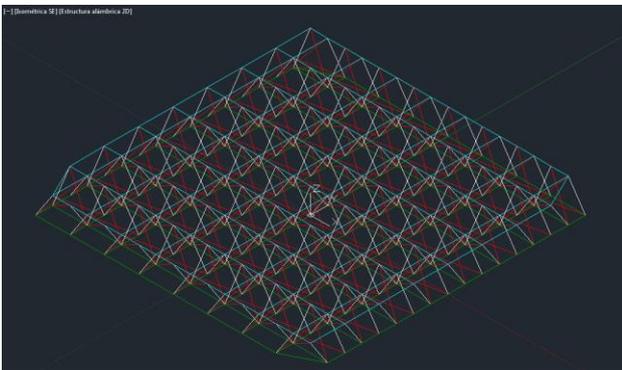


Figure 2. Double-Layer Tensegrity Grid defined in AutoCad 3D represented by lines

4.4 Block 3 – Modeling and representation

Research tasks of the third block are focused on finding out more about some of the most important elements of a space frame: the knots. Historical and currently used knots are considered in order to acquire valuable knowledge that could be applied to the detailed design of the grids.

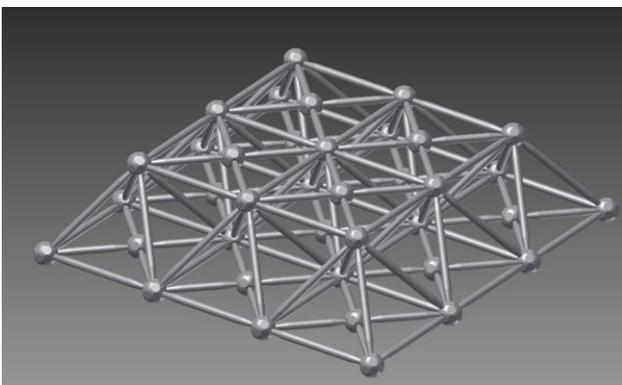


Figure 3. Double-Layer Grid defined in Autodesk Inventor

Students are also familiarized with some new software tools. The first one is a commercial and well-known program, Autodesk Inventor (freely available in student version). Importing data from model made during the

precedent task, developed with AutoCad, will lead them to generate a realistic model of the bars, wires and knots that configure a tensegrity grid (Figure 3).

Furthermore, a second program developed by Julien Averseng [9], ToyGL, is used to model directly reticulate space structures, simple first and more complicated later. ToyGL is a real time implementation of a discrete element method with applications in interactive design and dynamic nonlinear analysis of lightweight structures (Figure 4). Thus, it is possible to “play” with the structures and to see their behavior when changing their parameters in real time. Even though it performs a calculation on the structure, which corresponds to the next and last block of the course, its performance and easiness to model three-dimensional structures makes it very suitable to be introduced at this stage.

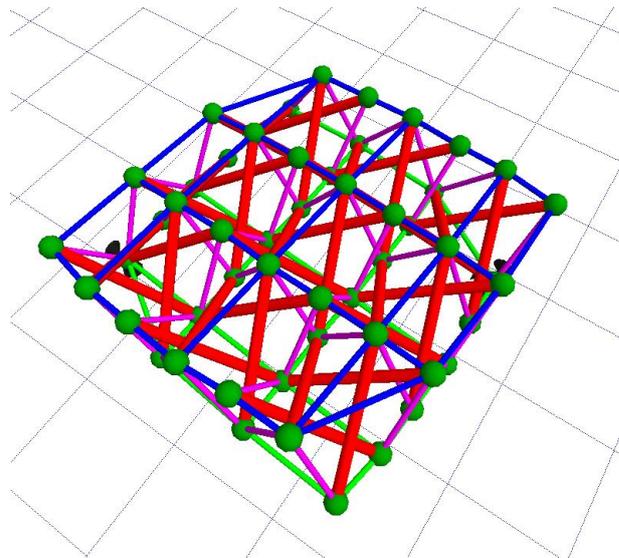


Figure 4. Double-Layer Tensegrity Grid defined and loaded under self-weight in ToyGL.

In order to take advantage of the models generated previously in AutoCad, it is advisable to create a method to process the raw data from the dwg file. By means of implementing a short code in VBA for MS Excel, it is possible to import the geometrical data, analyze it and export it to the source file that ToyGL uses for loading the parameters of the structure. As in the previous case, only some hints are explained here, with the hope that curious and attentive students would query some more about these techniques during the tutorials.

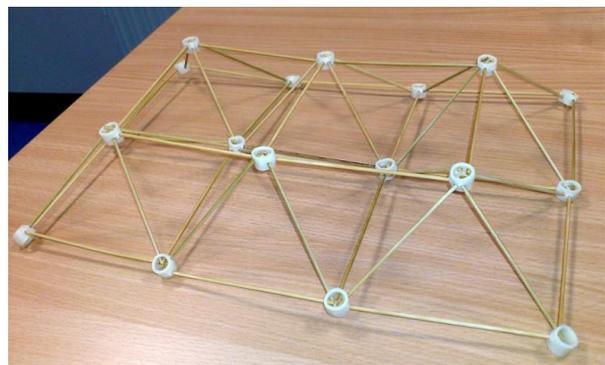


Figure 5. Model of a spatial grid built by the students

Finally, during this session the students are provided with materials to build physical models of spatial

frameworks (Figure 5); later on, a brief workshop is dedicated to tensegrity structures, which requires more time and manual skills. The models are proposed to be started to build in the classroom, finishing them as individual homework.

4.5 Block 4 – Analysis and calculation

In the last session of the course, the structures defined geometrically in precedent activities are subject to a structural analysis, by means of three different tools, one of them not mentioned until now.

Initially, the double-layer tensegrity grids modeled with ToyGL are now studied in terms of loads, forces and stresses. This approach will teach the students to understand the response of the structure to the external loads, obtaining for instance maximum tensions or slack cables.

In order to analyze locally the most critical and sensitive points, Autodesk Inventor is again used, in particular its module of simulation for modal analysis. The practical task is dedicated to load a knot with the forces in the struts that have been identified by means of ToyGL. Results are easily achieved and understandable, as well as visually eye-catching (Figure 6).

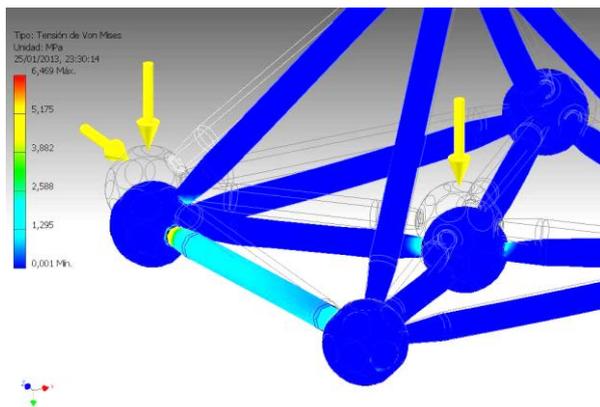


Figure 6. Modal analysis of the knot of a spatial grid by means of the simulation module of Autodesk Inventor.

Finally, a powerful and useful software is presented to the students in the same terms as the other programming tools, e.g. explaining some hints about it in order to ignite the flame of curiosity among the pupils. GNU Octave is a high-level programming language, primarily intended for numerical computations. It is also a free software, mass collaboration project and the perfect substitute (mostly compatible) of Matlab (another numerical computing environment and fourth-generation programming language, widespread among industry and academia). Interested students are invited to follow the procedure to import data from AutoCad geometry, analyze it by means of several programming codes in Octave and export it again to a text file that could be read again by AutoCad (as a script file) or other programs. This output file could contain all the information of the structure in such a way that could be visualized easily in real or augmented scale depending on the deformation, color gradient depending on internal stresses, thickness scale depending on internal forces, etc.

The inclusion of this software in the table of contents of the course is not an unjustified addition, as for instance the only way of calculating the number of infinitesimal mechanisms and states of self-stress (characteristic of

any tensegrity structure) is by means of matrix calculation [10], which can be easily and efficiently done with GNU Octave or Matlab.

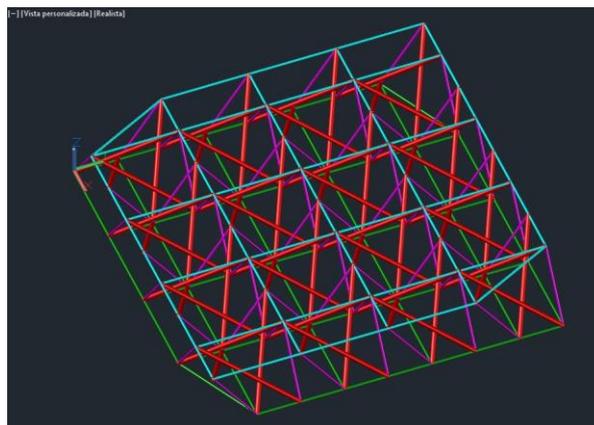


Figure 7. Double-Layer Tensegrity Grid modeled in AutoCad 3D with solids (cylinders) by means of a script.

5 Evaluation

The assessment of the work of the students is divided in three main parts:

1) Assistance and participation.

Obviously, attitude of the students during the “on campus” sessions is one of the most important factors to estimate the final evaluation of their work.

2) “Off campus” work

The research and applied tasks proposed during the sessions in the classroom are rarely able to be finished there. Therefore, individual or team work is programmed in order to accomplish the completion of this “homework”. Special attention is made to those activities that are resolved further than the strictly demanded enunciate, filling the gaps between questions and analyzing the subjects from additional points of view.

3) Tutorials

As commented along this exposition, the teachers in charge of this course pay special attention to those pupils that take advantage of the planned times to query the professorate about the subjects that, more than explained, have been slightly hinted during the different sessions. Those students, full of curiosity and keen on learning more and better, are always rewarded in a special academically manner.

6 Conclusion

An ambitious and so far efficient methodology for teaching geometric modeling and analysis of tensegrity structures has been presented in this work. It is based on the philosophy of learning by doing (with continuous guided and applied tasks), teaching by doing (with contribution of self-experience), learning by thinking (with recursive oriented questions, research tasks and times for reflection) and teaching by suggesting (with some hints to be fathomed rather than full explanations)

By means of defining a logical, understandable, practical and iterative workflow, students will be able to acquire sequentially the different concepts and procedures needed to accomplish the design of a spatial grid or a tensegrity structure.

At the end of the course, students will not be able to use with expertise all the software tools used during the course. However, they will be aware of their existence and

will be able to exploit them as basic users, which will give them the chance, in the future, to apply them for a more deep and professional usage if necessary.

Finally, the fact of giving freedom to decide which ideas, concepts, actions, tools or programs are most suitable or appealing for each student, is a key factor to reinforce the involvement of each one of them in the development of the course.

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