Teaching Spatial Structures:

Who to Teach, What to Teach and How to Teach

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Abstract
The Space Structures Research Centre of the University of Surrey, UK, has been active in offering
courses on spatial structures since its establishment in 1963. The courses vary from a day workshop
on ‘Design, Assemble and Dismantle a Full-scale Prefabricated Lattice Spatial Structure’ for
secondary school students to a core module of the master degree course in structural engineering
entitled ‘Space Structures’. Specifically, details about this Space Structures module are discussed in
the paper. However, brief explanations about some other courses organised by the Centre are also
included.

Keywords: Teaching Spatial Structures, Space Structures Research Centre, Model Base Teaching,
Structural Morphology, Conceptual Design, Hands-on Project.

1. Background
Architects and structural engineers, usually, are the people who deal with design and construction of
spatial structures and they need to learn the principles of these structural systems. However, experts
from other fields may also get involved in the area of spatial structures in one way or the other as
shown in Figure 1. The figure represents a spatial structure, namely, a sculpture consisting of two
concentric single layer geodesic domes based on icosahedron, with the smaller dome being suspended
inside the larger one. The structure called the Rise, designed by Wolfgang Buttress, an artist who won
an international competition heralding a new dawn for Belfast, Northern Ireland [1]. Although
architects and structural engineers including Emmanuel Verkinderen (a Surrey graduate) were
involved in the design and construction of the Rise, the initial idea was proposed by Buttress who is an artist.

![The Rise](image_url)

**Figure 1**: The Rise, a sculpture consisting of two concentric geodesic domes designed by Wolfgang Buttress, Belfast, Northern Ireland, 2011.

The aim of the present paper is to discuss methods of teaching spatial structures to students of architecture or civil/structural engineering. Some experts including Tim Ibelling believe that it would be a great opportunity to have students of architecture and structural engineering working together on basics of structural concepts [2]. There are also some concerns about the challenges in teaching a group consisting of students from the two disciplines [3]. All in all, it is believed that in teaching a mixed group, more attention should be paid to the basic principles of design rather than the design details. Examples of short courses designed for such mixed groups will be referred to later.

Design of structures, in general, and spatial structures, in particular, can be considered as an integrated process involving the following main steps:

- Arrangement of the main structural components to satisfy the needs of a structural project referred to as the ‘Conceptual Design’, which may also be considered as the stage that the key decisions about the project are made [4],
- Sizing of the structural components based on the modelling, calculations and structural properties of the chosen material, referred to as ‘Structural Analysis’,
- ‘Detailing’ of the structure including the design of shape, size and material of the supports, connections and any additional parts to the main structure, and
- ‘Practical Considerations’ including the assembly strategy, temporary loading during construction, durability and maintenance.

The above points, as well as background and level of participants of a course need to be taken into consideration in designing curriculum for teaching spatial structures. Moreover, choosing appropriate teaching method(s) to deliver the course may help the students to benefit more from the course.
The Space Structures Research Centre of the University of Surrey has been organising a number of courses in the past 50 years. In what follows, a few examples of such courses will be discussed.

2. Space Structures, A Core Module of the Master Degree in Structural Engineering

A postgraduate MSc course on structural engineering was established at the University of Surrey in 1965. At the present, the course consists of 8 modules including 4 core modules on structural engineering and other 4 modules on either civil or bridge engineering, as well as a dissertation. The subject of 'Space Structures' has been one of the core modules of the course since its establishment. The module content and teaching methods of this module will be discussed in the sequel. The students in this module usually have a civil/structural engineering background and the course is offered in three different styles, namely, full time, part time and distance learning.

2.1. Introduction to Spatial Structures

A series of lectures being delivered in around 8 hours to introduce the popular spatial structural systems including lattice structures, tensile structures (membrane, tensegrities, cable domes, suspendomes) and deployable structures. In the lectures, some 200 outstanding projects from around the globe will be discussed in terms of form and function, structural morphology and main structural components, as well as giving some general information (designer, material, construction, etc). These lectures give an overview of a wide range of application of spatial structures with particular attention to the importance of structural morphology in conceptual design of the projects. Study the excellence and success may be considered as a key component to develop creativity in a curriculum design for structural engineering [5]. To support the students in this part of the module, the lectures will be videoed and the videos together with the presentation files will be available to the students via the virtual learning environment of the University, 'SurreyLearn'. Also, using models to demonstrate structural concepts has been an interesting method of teaching structural behaviour [6] and [7]. Therefore, a number of physical models of different structural systems are available in the Centre for a more effective demonstration of structural behaviour to the students. A rather interesting historic picture shows an occasion for demonstrating the 'unexpected' strength of a wire model, Figure 2 (left). The figure shows a wire model of a double layer lattice dome which has been used since 1965.
2.2. Configuration Processing

Although structural morphology of spatial structures is being discussed in the introductory lectures of the ‘Space Structures’ module, it would be beneficial to the students to understand how to create spatial structural configurations in a convenient manner. This is due to the key role of configuration processing in creating morphology in conceptual design. A new algebra, namely, formex algebra, and its programming language Formian were developed at the Centre for configuration processing of spatial structures [9]. Teaching the fundamentals of formex algebra and creating some basic configurations in Formian is another part of the module. This part is being done in around 6 hours of interactive sessions during the semester. Also, the students should provide formex formulations for a number of configurations in the first assignment of the module, Figure 3. The figure shows a single layer diaphragm dome configuration together with its parametric formex formulation. Detailed information about formex configuration processing and Formian is available in several publications. In particular, an earlier paper presented at the IASS-CSCE International Congress in Toronto, Canada, describes the manner in which configuration processing has been taught at the University of Surrey [10].
2.3. Structural Analysis

It is believed that a good structural design, at present, is more about producing a structural concept which deals with satisfaction of a holistic set of requirements including efficiency, beauty and sustainability, in a creative manner, rather than focusing on structural analysis to satisfy issues like economy of sizing structural members and following codified rules [2], [3] and [4]. However, there are some analytical aspects in structural design which are covered in the module. Considering the background of the students, they are capable of using a FEM package to create a model and design the main structural elements of an ordinary structure. Structural analysis in this module will give them more in-depth knowledge about the following aspects:

- Fundamentals of collapse analysis of lattice structures,
- Comments on modelling lattice structures in FEM packages, and
- Available methods for static analysis of tensile structures.

The above aspects are being discussed in 6 hours of lecture. Regarding the collapse analysis, subjects like modes of instability, structural behaviour in progressive collapse and how to use a FEM package in structural collapse analysis is being discussed. Also, fundamentals of the Newton-Raphson Algorithm and the Dynamic Relaxation Method are being covered in connection with static analysis of tensile structures. The students should use their structural analysis knowledge, later in the semester, to analyse a spatial structure of their own design in the second assignment of the subject.
2.4. Construction of Spatial Structures

To bridge the gap between theory and practice, the construction of lattice spatial structures has been a key element of the module. Also, this is a good medium to involve the students more in the teaching process which helps them to understand the subject better. It is quoted from Confucius (450 BC), that "Tell me and I will forget, show me and I may remember, involve me and I will understand". Full scale physical models of a number of lattice structural connecting systems are available in the Centre, Figure 4. Particulars of each system, as well as examples of their application are being discussed within around 4 hours of interactive sessions. Preparing a couple of preliminary designs in groups of 3-5 students creates an active learning environment in this part of the module. Besides the importance of the connecting systems, assembly of lattice spatial structures, in particular, is being discussed. To cover this aspect, the students should come up with a strategy for assembling an existing project, while brief information about the morphology, connecting system and site of construction is provided. Each group should present their solution to the class and discuss the pros and cons of it. Finally, a short video of construction (5-10 mins) of the project is being shown, followed by a concluding discussion. More videos of construction of lattice spatial structures are available to the students on SurreyLearn. Also, relevant lecture notes including detailed information about the lattice structural systems, as well as their manufacturing process is being given to the students.

Recently, a hands-on project has been designed for further development of the module regarding construction of spatial structures. The project is about the Design, Assemble and Dismantle (DAD) of a lattice structure. In this project, around 150 prefabricated tubular steel members in 3 different lengths (105-145 cm), as well as relevant connections (bolts, washers and nuts) are provided to the
students (in groups of 7-12). The ArchiVision Company from Iran assisted the Centre in designing the structural components of this full scale lattice structure and the tubular members were manufactured in the University Workshop. Each group of students has to design a configuration using the members and check the practicality of their design in the laboratory, Figure 5. To facilitate the design process, a set of magnetic bars together with steel balls are available to make a small scale structural model. Also, the full scale structural members are available to the students to assemble a part of the structure in the lab. This would give them confidence about the practicality of the design. By the end of the meeting, the following documents should be submitted by each group:

- Sketches to introduce the structure,
- Role allocation to specify, at least, the project manager and the safety officer,
- List of requirements for assembly including the structural components (tubular members and connections) and tools, and
- Completed risk assessment form considering the nature of the project and the chosen assembly strategy.

Later in the semester, each group has 2 hours to assemble and dismantle their structure, Figure 6. The figure shows two groups of students with the assembled structures. Finally, the students should deliver a short group presentation (around 5 mins) in the class to introduce their configuration choice and discuss the highlights of the project including what went well and what can be improved. The groups will be assessed based on the attractiveness of their structure (40%), management skills (30%) and health and safety considerations (30%). The percentages represent the proportions of the allocated marks in the DAD Project. The videos of the presentations, as well as the time lapse of the construction are being available to the subsequent students as a source of information.
2.5. Workshop on Tension Structures

A one day workshop is designed to discuss tension structures including an introduction to tensile materials (membranes, films, etc), form finding and fundamentals of specific software for designing tensile structures (Easy). The software is a product of Technet GmbH and students have the chance of creating a model of their own structure using the software. This workshop has been very effective in providing practical information about the design and construction of tensile structures from the start of modelling to the design of the structural components and preparing the cutting pattern of the membrane. A further step to progress this part of the course would be construction of a full scale membrane structure using the provided information.

2.6. Assignments, Feedback and Assessment

The final mark for the course consists of the following parts (with the weighting of each part):

- Assignment 1 (15%) including a theoretical part, as well as a practical part. The theoretical part focuses on configuration processing of lattice structures and students should provide formex formulations for some lattice structural configurations including flat grids, barrel vaults and domes. The practical part of the assignment is the DAD Project which was explained earlier.

- Assignment 2 (10%), deals with the preliminary design of a large span structure including a 3000 word report about a collapsed lattice structure to discuss the reasons for the failure, as well as preparing a preliminary design for a relatively large span structure. This gives a chance for the students to apply their knowledge on configuration processing, structural analysis and practical considerations in the design process.

- The final part to assess the progress of the students in the module is a 2 hour written exam (75%) which examines the students’ understanding of the key elements of the course.

The two assignments will receive written feedback and to pass the module, one needs to achieve a minimum of 50% in each and all of the above components.

3. Short Courses

A number of short courses have been organised by the Centre at the University of Surrey, as well as some other universities around the globe. The focus of these courses has been on some elements of the mentioned module in Section 2. In what follows, examples of such courses are introduced.

3.1. Introductory Courses

The 1-3 day courses aim to introduce fundamentals of different spatial structural systems. The participants, usually, have architectural and/or structural engineering background at different levels, namely, university students, lecturers, professionals from the industry, etc. The courses are mostly lecture based and focus on spatial structural morphology and discussing some outstanding projects. Also, 3 day courses on the introduction to formex configuration processing have been organised several times. This is an interactive course and helps the participants (usually a mixed group) to get familiar with the fundamentals of configuration processing in Formian. This course is a prerequisite for other advanced configuration processing courses.
3.2. Advanced Courses
The 3 day advanced interactive courses are focused on more specific subjects using a project based approach. These include courses on formex configuration processing of ‘Polyhera’, ‘Geodesic Domes’ and ‘Free Structural Forms’. Also, courses on design and construction of ‘Tensegrity Structures’, ‘Cable Domes’ and ‘Suspen-domes’ have been organised. These courses are mainly designed for university researchers, as well as experts from the industry to give them more in-depth knowledge about the subject.

3.3. DAD (Design, Assemble and Dismantle) Project
The hands-on project was discussed in detail in Section 2.4. A more general version of the project also has been organised for secondary school students attending introductory programmes at the University of Surrey, Figure 7. The figure shows two groups of students participating in the DAD Project in 2015 as a part of the Young Persons University and the Headstart Programmes.

3.4. Assessment of Short Courses
The participants are being assessed based on their performance during the courses. The main objective of such courses is to educate and promote innovative thinking of the students in the context of spatial structures. The ‘process’ in the short course is much more important comparing the ‘product’ in the course, namely, the solutions that the participants develop during the course. Therefore, the course would just be a highlight in the learning journey of the participants and aims to encourage them to undertake further studies.

4. Conclusion
It is beneficial for architects and structural engineers to understand the fundamentals of spatial structures. The subject can be taught to these experts in either mixed or separate groups and this needs to be considered when designing a course. Teaching spatial structures, mostly, concerns the conceptual design and structural morphology. However, some aspects of structural analysis also need to be covered in a specific course for structural engineers.

To study the success is a nice approach in teaching spatial structures, so that, having a databank of outstanding spatial structures would facilitate the introduction to the subject. An example of such databank is the ALOSS; Album Of Spatial Structures, [11]. Also, it would be beneficial for the
Instructors to share their teaching experiences which can lead to an overall improvement in the quality of teaching.

Of course, individuals differ in regard to what mode of instruction or study is most effective for them, which is referred to as the ‘Learning Style’ [12]. However, Ji and Bell (2008) claimed that students show a greater interest in topics which are demonstrated physically, than in topics that are explained using the so called ‘chalk and talk’ method, that is, by words and blackboard/OHP/PowerPoint presentations. Also, students are motivated by hands-on experience and by linking concepts and models to real engineering problems [7] and [13]. Moreover, working with physical models has been used as a powerful tool for exploration of spatial structures [14]. Also, it would help the students to understand the subject better when experts from the industry are involved in teaching. An example of this involvement is a guest lecture at the closing session of the DAD Project by the Engineering Manager of Novum Structures UK.

The discussed teaching methods in this paper are aimed to create an interactive learning environment to sustain the knowledge for the students. Although the methods are highly effective, there are some challenges including the time of organisation for each course and safety considerations in practical activities.

References
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