



Benefits of Full-scale Physical Models in Civil Engineering Education

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Abstract

Engineering students, usually, show a greater interest in topics which are demonstrated physically rather than those that are explained using the so called ‘chalk and talk’ methods, that is, by oral presentations and blackboard/whiteboard/OHP. Also, students are motivated by hands-on experience and by linking concepts and physical models to real engineering problems. A hands-on project has been designed by the Author for civil engineering students to improve their practical considerations in designing structures. The project is about Design, Assemble and Dismantle (DAD) of a full-scale lattice structure. A specific teaching kit including prefabricated full-scale tubular steel members, as well as required connectors has been designed and manufactured for the DAD Project and the participants should design a structure using (all or part of) the provided structural components. The project is modified to suite the participants at different levels, i.e. postgraduate or undergraduate levels. Also, a simpler version has been offered as a part of the ‘University Promotional Programmes’ for secondary school students.

This paper provides further information about the background of the DAD Project and discusses the Project in more detail. Also, relevant literature is reviewed and a methodology is proposed to assess the potential benefits of using full-scale physical models as a part of a master degree module offered in the academic year 2015-16. Finally, the outcomes of the research, as well as further recommendations are provided.

1. Background

The Author, as a practicing architect and the director of an architectural firm, has been involved in the design and construction of around 150 ‘Spatial Structures’ in different projects since 1999. An example of these projects is a 40 metre span geodesic dome shown in Figure 1. Also, to maintain the relationship between the industry and academia, a series of 1-3 day courses on design and construction of spatial structures was organised by the Author in different universities. The earlier courses in the series were mainly delivered using chalk and talk methods while in the latter ones a combination of lecture base sessions and practical activities were implemented. Figure 2 shows a group of participants of a two day course assembling a full-scale lattice structure in the Azad University of Shiraz, Iran. Based on the feedback from the participants and local course organisers, as well as personal observation, the Author realised the positive impact of the additional practical activities. This experience was a starting point for the Author to develop the idea of using full-scale physical models in engineering education. More information about this idea and the focus of the present work is being discussed in the sequel.



Figure 1: A geodesic dome with glass cladding having around 40 m span designed and constructed by ArchiVision Company in Mashhad, Iran ¹.



Figure 2: A group of participants assembling a full-scale prefabricated lattice structure as a part of a two-day course on design and construction of spatial structures organised by ArchiVision Company in Shiraz, Iran ¹.

2. Introduction

Design of structures, in general, and that of 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 ²,
- Sizing of the structural components based on the virtual models, calculations and structural properties of the chosen material, referred to as ‘Structural Analysis’,
- ‘Detailing’ of the structure including the shape, size and material of the supports, connections and any additional parts of the structure, and
- ‘Practical Considerations’ including the assembly strategy, temporary loading during the construction, durability and maintenance.

As far as engineering education is concerned, the above points, as well as background and level of participants of a course need to be taken into consideration in the curriculum for

teaching spatial structures. Moreover, choosing appropriate teaching method(s) will help the students to benefit more from the course.

Physical model based teaching is a particular method that the Author is quite comfortable with and feels confident to use. This method can be applied in engineering education in various situations and for different purposes. For example:

- a. Using physical models to demonstrate structural concepts as an effective method of teaching structural behaviour ^{3,4}. A rather interesting historic picture shows an occasion for demonstrating the ‘unexpected’ strength of a wire model, Figure 3 (left). It shows a steel wire model of a double layer lattice dome which has been used at the University of Surrey since 1965.

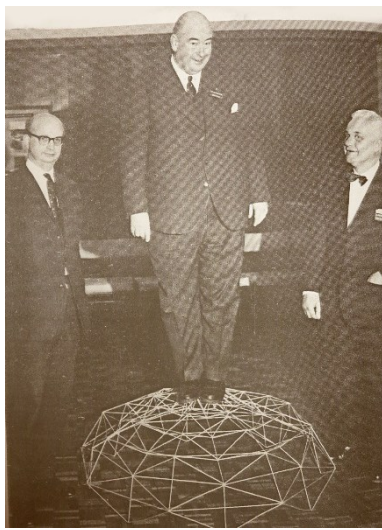


Figure 3: Amusing load test of a steel wire model of a double-layer dome in two events. Left figure: Dr J S Blair, of Stewarts and Lloyds Ltd, with Professor Z S Makowski (on the left) and Professor S du Chateau (on the right) during the conference on tubular structural engineering, Corby, UK, 1965 ⁵. Right figure: Mr Joe Chilvers, an undergraduate student during a lecture at the University of Surrey, Guildford, 2014.

- b. Using physical models in a ‘making and learning process’ which implies that students will learn about structural concepts during the process of making physical models. In this case, the scale and the material used to make the models are some key factors of the method. Making small scale models is an effective way to visualise and study the fundamentals of the structural concepts. However, full-scale models are preferred to concentrate on practicing real engineering problems.

Considering the potential benefits of physical models, a hands-on project has been designed by the Author for further development of teaching the design and construction of spatial structures. The project is about the Design, Assemble and Dismantle (DAD) of a full-scale lattice structure. In this project, around 150 prefabricated tubular steel members in 3 different lengths (105-145 cm), as well as relevant connectors (bolts, washers and nuts) are provided to the students. Over 200 students in groups of 5-19 have already participated in the Project at the University of Surrey since 2014. Incidentally, the ArchiVision Company from Iran assisted the design of the structural components of this full-scale teaching kit and the tubular elements were manufactured in the University Workshops. Each group of students has to design a configuration using (all or part of) the available structural components and check the practicality of their design in the laboratory, Figure 4. To facilitate the design process, a set of magnetic bars together with steel balls are available for making small scale models. Also, the

full-scale structural components are available to the students for assembling the structure, or parts of it, in the lab. This would give them confidence about the practicality of the design. After the group meeting in the lab, the following documents should be submitted by each group:

- Sketches/drawings to show the configuration of the structure,
- Role allocation to specify the responsibility of each group member, in particular, the project manager and the safety officer,
- List of requirements for assembly, including the structural components (tubular members and connectors), tools, etc and
- Completed risk assessment form considering the nature of the project, as well as the chosen assembly strategy.

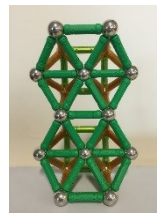


Figure 4: DAD Project group meeting in the teaching lab. Left figure: A group of students designing their structure and examining the practicality of the design. Right figure: An example of a small scale structural model with magnetic bars and steel balls.

Later in the Project, each group has 2-3 hours to assemble and dismantle their structure,

Figure 5. The figure shows two groups of students with the assembled structures. Finally, each group should deliver a short presentation (5-7 minutes) in the class to introduce their configuration choice and discuss the highlights of the project including ‘what went well’ and ‘what can be improved’. Also, each student should submit a three page report to discuss their personal findings during the Project. The groups will be assessed based on the attractiveness of their structure, management skills and health and safety considerations. Also, the individuals will be assessed based on their report. 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. A five minute introductory video entitled ‘DAD Project 2015’ is also available on YouTube ⁶.



Figure 5: Two groups of students participating in the DAD Project, after assembling their structures.

The DAD Project has been offered to participants of different background and various level of studies. Since June 2014, eighteen groups of students have participated in the Project as a part of the following programmes at the University of Surrey:

- Promotional activities for year twelve secondary school students, namely, ‘Young Persons University’ and ‘Headstart’ (names of promotional activities),
- Undergraduate module entitled ‘Integrated Design I’ offered to the first year students in Civil Engineering, and
- Master degree module entitled ‘Space (Spatial) Structures’, that is a core module for the MSc Course in ‘Structural Engineering’ and an optional one for the students in ‘Civil Engineering’ and ‘Bridge Engineering’ courses.

A main aim of the Project is to involve students in an active learning environment. Also, the structure designed by the students is not as important as the process of the design and construction. In other words, the project is ‘process based’ rather than ‘product based’. So, the attention of the present paper is on the potential benefits of the DAD Project as an example of the use of full-scale physical models in engineering education. The benefits may be grouped into the following two categories:

- General benefits of a group design project such as the development of team-working and communication skills to solve engineering problems. As a group project, peer learning ⁷ is a key factor in the project and participants seem to be happy to have constructed their own structure, which is (for most of them) the very first experience as such.
- Particular benefits of using full-scale physical models to improve the practical considerations in the design and construction of structures.

The focus of this research is to assess the benefits of the DAD Project on the above two categories for the master degree students participating in the Project in the academic year 2015-16. Detailed information about the research methodology will be given in Section 4.

3. Literature Review

Froyd et al ⁸ have identified five major shifts in the past 100 years of engineering education, two of which have already occurred, namely:

- i. A shift from hands-on and practical emphasis to engineering science and mathematical modelling. Although the focus of engineering education has been moved from the practical activities, the importance of making a balance between theory and practice is still a challenge in the field.
- ii. Another shift to ‘outcome-based’ education and accreditation as a quality control system for engineering education. Although, a number of experts believe ⁹ that all the necessary skills for performing a job in practice, specially in the field of construction, cannot be provided with just the formal education and training ⁹⁻¹².

Also, latter three shifts have been identified by Froyd et al ⁸ which are still in process:

- iii. A shift to emphasising ‘Design’ as a distinctive element of engineering. A reason for this necessary shift was the earlier overemphasis on science, engineering science and mathematics. It is argued by a number of experts that a good structural design, at

- present, is more about producing a structural concept which deals with satisfying a whole 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 elements and following codified rules ^{2, 13, 14}.
- iv. A shift to apply education, learning and social behavioural science research to engineering education. To support this, Hithcock & Hughes also argue that reflecting, criticising and putting forward a more informed view to the educational process would be possible by doing research in education. Consequently, the educational practice could benefit from the outcomes of such research. Also, there has been strong links between research in education and the research traditions of the social sciences which both are complex and complicated themes ¹⁵.
 - v. The final shift entitled the influence of ‘Information, Computational and Communication Technology (ICCT)’ on engineering education.

Having the above shifts in engineering education in mind, it is believed that individuals differ in regard to what mode of instruction or study is most effective for them, which is referred to as the ‘Learning Style’ ¹⁶. However, Ji and Bell claim that engineering 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 oral presentation and blackboard/whiteboard/OHP ⁴. Also, the students are motivated by hands-on experience and by linking concepts and models to real engineering problems ^{4, 17}. Hands-on activities have been implemented not only in engineering education but also in provisional programmes of the Science, Technology, Engineering and Mathematics (STEM) fields. An example of such programmes is discussed in a paper entitled ‘Attracting Girls to Civil Engineering through Hands-On Activities That Reveal the Communal Goals and Values of the Profession’ ¹⁸. Incidentally, the DAD Project also has been organised as a part of the provisional programmes of the University of Surrey, as mentioned earlier. Moreover, working with physical models has been used as a powerful tool for exploration of spatial structures in other academic institutions ¹⁹.

On the other hand, it is also crucial that the practical experience gained from the world of work being supported by the theoretical knowledge ^{9, 20}. A balance combination of both theory and practice makes the educational curriculum more relevant and this combination may result in higher retention rates of students within the construction and engineering field ⁹. Gillie states that ‘structural engineers produce real things and yet structural engineering education is dominated by the theory’ ²¹. Also, a constant challenge in structural engineering education is to ensure that practical/real-world engineering skills are embedded in the university degree programmes ^{22, 23}. Laboratory sessions in engineering education provide a forum to discuss practical aspects in universities. However, such sessions are usually becoming focused on displaying specific concepts in structural mechanics, rather than tackling the real world engineering problems. Also, realistic connection details, material selection, cost and construction problems are either absent or not being considered seriously enough in small-scale exercises ^{22, 23}.

To bridge the gap between theory and practice, some universities have been organising practical courses, one of which is the Constructionarium. The course has been running by the

Imperial College London since 2003 and different learning methods have been utilised in the course such as experiential learning, role play, reflective learning and project-based learning. In this course, groups of students will attend a week long residential project in the north of the UK to design and construct a full-scale structure. The aim is to make the students able to apply theory in practice, specifically, by construction of miniature projects based on real life structures²³. The following points are claimed as the potential benefits of the Constructionarium:

- Providing an educational setting to bring industry and academia together.
- Keeping academic staff in touch with construction practice.
- Providing a safe way for large groups to gain site experience as a team.
- Offering a broad body of knowledge including technical, practical and academic information with an integrated nature.

Although the constructionarium project is very effective at introducing the practical challenges of construction, the creativity factor involvement in design and construction is being limited due to the scale and required resources of the project^{21, 23}. Also, a small proportion of civil engineering students in the UK are lucky enough being able to attend the constructionarium.

Another example of practical activities to provide experience for the students is a series of construction competition organised at the University of Edinburgh. Martin Gillie, the organiser and the Head of Civil Engineering claims that the participants of the competitions show extreme satisfaction of development of practical engineering skills. Also, he argues that practical exercises are valued by the students and would also encourage them to be engaged in the theoretical aspects^{21, 23}.

Focusing on student engagement in engineering education is an influence of research in psychology and learning sciences. This is based on the idea of importance of student engagement advanced by a number of researchers including John Dewey, Astin and Light⁸. One of the aims of the DAD Project is also improving the student engagement. Another aim of the Project is to facilitate the participants' learning during the process of the design and construction. Understanding by Design (UbD) described by Froyed et al as an increasingly popular tool for educational planning that is a teaching method focused on a better understanding of students throughout a design process⁸.

4. Methodology

To appraise the potential benefits of the DAD Project, as an example of employment of full-scale physical models in civil engineering education, a 'mixed method' has been utilised. To elaborate, mixed methods are defined as the third methodological approach following the quantitative and the qualitative methods. In a mixed method, data collection or analysis may be done quantitatively and/or qualitatively in a single research²⁴.

The following sources are used in this research:

- A questionnaire survey (Appendix 1) administered to the students at the end of the Project. A few questions aim to determine the age, gender, mode of study (full-time or distance learner) and whether the participants have any prior experience of being involved in construction projects, particularly, construction of lattice spatial structures. Additionally, the participants were asked to choose a number (0-10, where 0 indicates disagreement and 10 indicates full agreement) for some statements about the Project (quantitative method). Finally, the participants were able to provide comments about different aspects of the Project such as usefulness, favourite parts, etc (qualitative method).
- Students' report after the project as a part of their assignment. The report provides an overview of the project and clarify the challenges experienced, namely, what went well, what can be improved and a summary of lessons learnt from the Project.
- Videos of the group meetings, as well as the construction sessions (assembly and dismantling the structure). The performance of the students during the construction session can be further investigated by analysing the videos.

Moreover, the Author who initiated and has been directing the Project, as an experienced architect/engineer in practice, observed the performance of the students throughout the Project. Incidentally, such 'participant observation' is claimed by Kawulich as a 'data collection method' ²⁵.

The collected data from two groups of nineteen MSc students participated in the Project in the academic year 2015-16 will be discussed in the next section. Also, pictures of the two structures assembled by the participants are shown in Figure 6. Moreover, the participants have been asked to give consent to disseminate the findings from the feedback provided and an attempt was made to maintain the anonymity of the participants whose feedback is being used in the research.

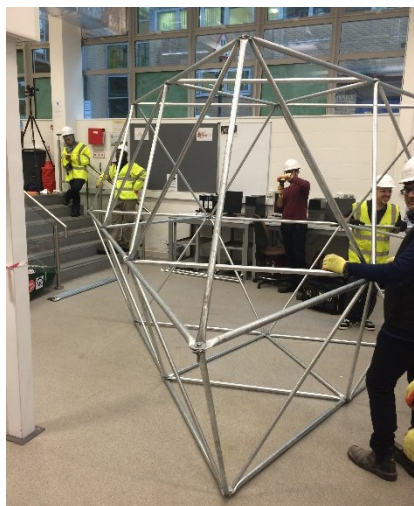


Figure 6: Structures assembled by two groups of MSc students in the academic year 2015-16. The present paper is based on the data collected from these two groups. Left figure: A 4.5 m high triangular based pyramid. Right figure: A fully triangulated minimal structure/sculpture.

5. Concluding Remarks

It was optional for the students to complete the questionnaire survey and over 65% of them (25 students out of 38) have participated in the research. The gender of the participants, as well as their modes of study are given in Figure 7. The variations of the gender and the mode of study of the research participants were quiet similar to those of the all participants of the Project, therefore, the outcome of the research can be reasonably generalised to the whole group. Additionally, the collected data show that most of the research participants were in their twenties, while two of them were over forty years old, Figure 7.

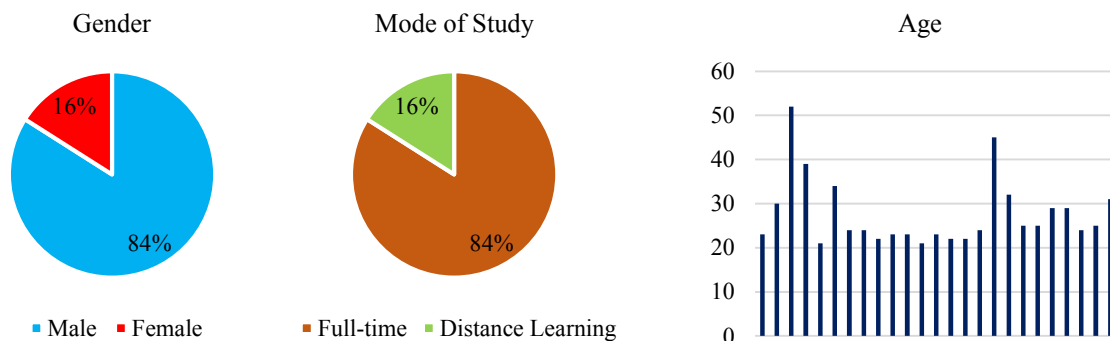


Figure 7: Gender, mode of study and age of the research participants

Regarding the construction experience prior to the DAD Project, over 40% of the participants (11 out of 25) had no such experience, while the rest of them were involved in different construction projects for a period as short as 2 months to much longer up to 8 years. Such variation of the participants is a potential value for the groups to be able to combine both, experience and energy/enthusiasm.

Three statements in the questionnaire were addressed the enjoyment, engagement and the development of communication skills of the participants and the average numbers given to the statements were 9.2, 8.9 and 8.1 (out of 10), respectively. The numbers given to the mentioned statements, as well as the observation of the Author during the Project, verify the high level of teamwork in an enjoyable active environment. Such environment in engineering education would increase the level of understanding of the participants, as well as the retention rate¹⁷. Incidentally, having background information about the participants facilitates more in depth data analysis. For instance, one of the participants gave 5/10 to the statement about the improvement of the communication skills. This would be a reasonable number, considering his experience for 5 years in the industry. Moreover, the following comments provide examples of the participants' feeling about the teamwork in the DAD Project:

- 'It was a good experience and I enjoyed working as a member of the team.'
- 'I got chance to be engaged more with my fellow colleagues.'
- 'The DAD Project combined a useful learning process with fun activity. It was also a good way of developing teamwork.'

There were two other statements in the questionnaire addressing the idea that working with a full-scale physical model is useful in engineering education and helps the students to get a deeper understanding about the construction. In particular, preparing an appropriate risk assessment, as well as the general health and safety considerations during the construction was a challenge. The average number to both these statement were 9.1 and 9, subsequently, and the observation validates the appreciation of the participants working with a full-scale physical model. Also, the benefits of such a model were mentioned in some individual reports and the following comments are examples of the participants' satisfaction in this regards:

- 'It could be more interesting having the possibility to build several structures during the module.'
- 'My favorite part was build and dismantle. It showed the whole project coming together with a practical result.'

Another set of three statements in the questionnaire were focused on the improvement of the practical considerations in design. These include the planning for the construction (assembly strategy), detailed design (size and direction of bolts) and the application of theory in practice. Here again, the average number given to these statements were above 8. Also, the observation of the group meetings show a reasonable trial and error process during the Project to improve the design and construction. Incidentally, the 4.5 m pyramidal structure (Figure 6 left) was constructed in 34 minutes with no lifting equipment. Considering the condition of the construction venue (small space comparing to the dimensions of the structure), this achievement was due to a great team effort in planning/practicing the assembly and optimising the assembly strategy during the construction. Moreover, practical considerations such as the length/direction of bolts, importance of appropriate assembly/dismantling strategy and communication between the construction team were addressed in a number of reports.

The final statement aimed to assess the usefulness of organising similar hands-on activities in engineering education and whether the participants are happy to be involved in such activities. The average number given to this statement was 9.3, the highest number to a statement in the questionnaire. This number, together with different lessons learnt in the Project (as mentioned in the reports) and the positive comments in the questionnaire encourage the Author for further development of using full-scale physical models in engineering education. Examples of the comments are:

- 'The project was extremely beneficial for those taking the module and gave a great appreciation of many aspects involved in the design and construction of lattice structures. It would be great to do a similar exercise on a membrane structure.'
- 'The DAD Project initiative is commendable and in my opinion should be sustained and strengthened. It offers graduates of the department the advantage of hands-on experience with space structures, which is not common in other institutions.'
- 'It was so useful to do a DAD Project to understand more about space structures. It was great experience working as a team to accomplish the design model.'

Finally, the Author would like to address the following challenges regarding the organisation of using full-scale physical models in civil engineering education:

- There are potential risks in working with such models, however, having industrial experience would help the instructor being familiar with those risks and being able to control them. Also, presence of additional supervisor(s) during the construction session will make the risks manageable.
- Managerial support for the organisation of such hands-on activities is crucial. Although the costs of running these activities are, usually, much less than what is expected, it would be a potential challenge to convince the head of the departments. For instance, in the case of the DAD Project, the ‘teaching kit’ costs less than £2.00 per participants, considering the kit being a prefabricated durable steel structure which has been used around 30 times since 2014.
- Considering the great value and high retention rate of peer-learning in education, it would be beneficial for the distance learners to get involved in the practical activities. However, this makes the team building slower and complicates the whole organisation.

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Appendix 1

Appraisal of the Educational Benefits of the DAD Project

The DAD Project (Design, Assemble and Dismantle) is designed for the students in the Department of Civil and Environmental Engineering of the University of Surrey to focus on the 'Practical Considerations' in designing 'Spatial Structures'.

As a participant of the DAD Project (part of the 'Space Structures' Module – ENGM043), you are kindly invited to take part in the appraisal of the project. This is a voluntary activity and by participating in the appraisal, you are giving consent to disseminate the findings from the feedback provided. The anonymity and confidentiality of the participants whose feedback is being used in the appraisal is maintained at all times.

First we would like to ask a few questions about you:

How old are you? _____

What is your gender? Female Male

What is your mode of study (FT, PT, DL)*? _____

What programme are you doing (e.g MSc in Structural Eng)? _____

Have you been involved in construction of any structure? If yes, please specify the construction type, your role and the duration of your involvement (e.g site manager in a concrete bridge construction for 6 months).

* FT=Full Time, PT=Part Time & DL=Distance Learning

For the next several questions, please choose a number from 0-10 and write it in the box next to each statement to indicate how much you agree with that statement.

0	1	2	3	4	5	6	7	8	9	10
Not at all									Completely	

Statement	Score
I enjoyed participating in the hands-on activity as a part of the module.	
I felt engaged and a part of the team in the Project.	
My communication skills improved during the DAD Project.	
It was useful to work with full scale physical models in the DAD Project.	
Working with full scale model helped me to get a deeper understanding about construction.	
Participating in the Project, I now feel confident in the design, assembly and planning strategy for a similar lattice structure.	
The Project made me aware of practical details (e.g size/direction of bolts) in the design of prefabricated lattice structures.	
The practical activity helped me to have a better understanding of the theoretical aspects of design.	
It is useful to participate in similar hands-on projects on structural systems (e.g membrane structures).	

Any comment about the DAD Project (e.g usefulness, organisation, favourite part, etc):

If you are interested in getting information about the outcome of the study, please provide your email address: _____

Thank you for your participation.