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Innovative spatial timber structures: workshops with physical modeling explorations from small to full scale

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Abstract

Architects and Engineers are educated and work within two separate cultures yet they are both concerned with conceptual structural design. The collaboration between the professions is especially important when designing buildings where the structure to a great degree forms the spaces, as in the cases of form generating structures such as gridshells, reciprocal frames, space trusses etc . This paper describes several specialist research based workshops developed at KA over the last two years that use physical modelling of 1:1 innovative timber load-bearing structures such as gridshells and reciprocal frames.

Keywords: physical modelling, conceptual design, morphology, gridshells, tensegrities, reciprocal frames

1 Introduction

The Engineering and the Architectural profession have become separate in the last 100-150 years. The time before the Industrial Revolution was characterised by the *Master builder* as the main creator of any large scale building structures. The art of designing and constructing was based on explorations with physical models and building of prototypes. To a great extent the knowledge, skills and technical understanding were tested by trial and error. However, the Industrial Revolution brought great advances in the fields of technology and material sciences. As a result it was no longer possible to have a one overall profession dealing with design and construction. This was the beginning of real progress in the field of the technical and material sciences. It was a time when the real separation into two distinct and separate professions – Architecture and Engineering started.

2 Architectural versus Engineering training

The two professions: Architecture and Structural Engineering are taught and work within two separate cultures. This is fully appropriate when they address different aspects of a design project. However both architects and engineers are concerned with conceptual structural design. Thus it is important that they are able to collaborate and together that they are able to develop design proposals that are imaginative, creative, efficient and practical. The need of collaboration is especially important when designing buildings where the structure to a great degree forms the spaces, as in the cases of form generating structures such as gridshells, reciprocal frames, space trusses etc.

In that sense it is worth mentioning the successful collaborations of architects and engineers who have been able to achieve a real synthesis in their building designs.

The Savills Garden Gridshell, Windsor Great Park (2006)

Figure 1a and b: The gridshell roof at The Savills Garden Gridshell

The collaboration between Glenn Howells Architects, Buro Happold Structural Engineers and Green Oak Carpentry has produced the delightful roof structure at the Royal Landscape. The project houses a visitor centre, shop, services and café, forming a gateway entry into the landscape garden. Measuring 90m long by 25m wide, making it the biggest roof of this kind in the UK. The roof form consists of three domes, and is of a sinusoidal shape.

The concept of the visitor centre was based on the concept of a leaf lying gently on the landscape. The design team consisted of Buro Happold Structural Engineers and Green Oak Carpentry who had previous experience of working together and who had built up a working relationship whilst working on the Weald and Downland Jerwood timber gridshell (2002) with Edward Cullinan Architects.

The building rests within a green-field setting of the Royal Landscape within Windsor Great Park. The larch and oak timber used in the construction of the gridshell roof is derived from commercially managed forestry grown on-site within the grounds.

The reiterative process of design was consolidated from the team's expertise and experience on previous timber construction.

"……many people talk about collaboration but on this one (Savill's Gridshell), one of the rules was that we did not regard ourselves as the decision maker. The architect was not at the top of the tree. It was very even between the craftsperson, the engineer and the architect, " said the architect Glenn Howells. This respecting collaborative relationship is very much valued in the creation of building with such an crafted output with a strong conceptual structural design.

The Eden Project, St. Austell, Cornwall, UK (2000)

Fig 2 a and b The Eden Project ETFE Roof (construction and finished)

This working relationship and mutual understanding between the architects and engineers is apparent in the highly engineered Eden Project in St. Austell, Cornwall. The friendship and working relationship between the architect Nicholas Grimshaw and the structural engineer, Tony Hunt, can be traced back to many preceding projects. The results of their working relationship included projects can be seen in projects such as the innovative roof at Waterloo EuroStar Train Terminal in London.

The Eden project consists of a series of 8 interlinked geodesic domes/ biomes made by stretching ETFE across lightweight steel to form pentagonal/ hexagonal triple-layer

0.2mm thick foil ETFE cushions each measuring a maximum of 11m across and 70m2 in area. The lightness and ultra-violet light translucency required by plants and the long lifespan of 20 years, coupled by the ease of maintenance due to its lightness made ETFE the preferred choice of cladding material when compared to glass.

The success of the project which attracted 2 million visitors in the first year of opening in March 2001 (www.grimshaw-architects.com) and the conceptual design development is a testament to the successful collaboration of the architect and structural engineers.

Apart from teams that create a seemless resolution between architecture and engineering, there are many other architect/ structural engineers that straddle the true definitions of the 2 professions - single individuals who bridge this separation. The thinking and rationalisation of the individuals can be seen in the structural experimentation of lightweight structures by Frei Otto, the thin Gaussian vaults of churches and silos of Eladio Dieste in Uruguay, the thin concrete shells of Heinz Isler in Switzerland, the paper gridshell structures of Shigeru Ban in Japan and Antoni Gaudi's hanging chain models in the exploration of forms and the organic structural expressions for the Sagrada de Familia in Barcelona.

The reverse is true and widely accepted - when the collaboration of the architect and engineer has not been well established, the resulting design solutions are often not as well-integrated when the structural integrity is diluted.

During an interview with David Kirkland, project director of the Eden Project at Grimshaw's, he comments, "……the architect describes the structure from an aesthetic angle, then asks the engineer to make it work. That approach has produced some of the worst failings of high-tech architecture over the last few decades."

The ability of architects not only to think spatially, but also to create, design and analyse structurally, is a useful attribute to produce strong, powerful conceptual results. This is partly made possible and enhanced by the process of making and physical experimentation.

2.1 The Royal Danish Academy of Fine Arts (KA) tradition

Founded in 1754, The School of Architecture at the Royal Danish Academy of Fine Arts was originally named 'The Royal Danish Painting, Sculpture and Building Academy of Copenhagen', and was offered as a gift to King Frederik V on the occasion of his 31st birthday.

The academy was built as an addition to the painting and drawing academy founded by King Christian VI and King Frederik VI in 1738 and 1748 respectively, and was inspired by the first European, royal academy of fine arts, which was founded in Paris in 1648. 1771 was a very important year in the history of the Academy. This was the year when the Academy's name was changed to 'The Painting, Sculpture and Building Academy'. And that very same year, the Struenses Reglement of 21 June 1771 was implemented, which meant that the schools were obligated to not only educate artists, but also offer tradesmen an education. Thus, craftsmanship and the study of fine arts were unified.

The connection to the crafts is still one of the distinct qualities that the education at KA still offers today. Both the obligatory courses and the specialist courses are very much "hands-on" and incorporate the "art of making" into the way of learning.

2.1.1 Undergraduate courses

The teaching of load-bearing structures is offered as part of the obligatory courses in Architectural Technology as well as in the form of Specialist courses. The obligatory courses are offered across the whole year level typically to about 200 students at a time. The subject of Load-bearing Structures is taught in TEK 1 (first year) and TEK 2 (second year) with a strong emphasis on the understanding of materials, their use to create load-bearing structures as well as their implication on architecture. The courses are thought as a combination of lectures, seminars and workshops where students experiment with small scale physical models.

2.1.2 Specialist courses

Innovative new courses have been offered but a special initiative by the first author has been to develop innovative courses to expand the basic understanding of structures, to inspire and also to offer learning by making based on the research of the authors of the paper. Several such courses have been offered during the last two years[1]. They include: Structural Morphology which had been established by Assoc. Prof Ture Wester; Advanced Structures and Organic Structures. New courses that will run in 2010-2011 include Conceptual Structural Design, Advanced Conceptual Structural Design and Applied Advanced Conceptual Structural Design.

All the above courses have in common that they are research based and are a combination of hands-on workshops which are supported by seminars and lectures. The experimentation with small to large physical modelling is a very important characteristic of the courses.

2.2 Organic Structures course

Due to the limited space this paper describes in detail the "Organic Structures" specialist course that was run for the first time during 2009/2010 at KA. It was aimed at Y3 students and the main topic of study was Nature inspired load-bearing structures and their application in Architecture. Special emphasis in the 1:1 "hands-on" modelling workshops were put on Gridshells and Reciprocal Frames. The course was initiated and organised by the first author of the paper, supported by the second author as well as Prof Tony Hunt, visiting Velux Professor at KA, founder of Anthony Hunt Associates (now

[1] Since August 2008 when the first Author of this paper joined KA

SKM AHA), Tom Hay, Associate Director Buro Happold Copenhagen and Consultant to KA, and Biagio de Carlo, Architect from Italy.

2.2.1. Reciprocal Frames

Reciprocal Frame Structures (RF) are a form of a three-dimensional grillage structure. In their simplest configuration they are formed by placing beams in a closed circuit in which each beam is supported by the preceding beam at the inner end, and by an external wall or ring beam on the outer end. In their more complex configurations gridshell-like structures with a double curvature can be formed. Although RFs have been used in many countries throughout history and are known under different names: Serlio-type ceiling; Reciprocal frames, Svastica structures, Nexorades, Lever-arch structures etc., they are not widely known and used in bildings. The most beautiful contemporary examples have been built in Japan. The work of architects Kazuhiro Ishii and Yasufumi Kijima as well as structural engineer Yoichi Kan, shows the potential of RFs for creating imaginative architectural and structural forms.

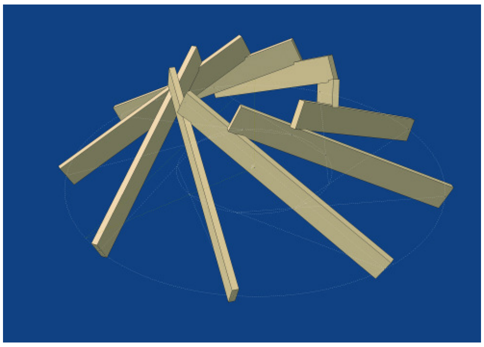

Figure 3a and 3b: Reciprocal Frame CAD model, The Auditorium building in Seiwa

2.2.2. Grishells

Gridshells are a three-dimensional structural system in which short members are combined to form a load-bearing grid structure. Due to the achieved shell action the members in the grid work mainly in compression which makes the system structurally more efficient. In addition the three-dimensional forms of the structure create a distinct architectural aesthetic and a possibility for creating a new language of expression.

Gridshells have not been used widely in architecture, yet they have so much to offer. If constructed out of timber they offer a great opportunity for material saving. This is due to the fact that the clear span grids are formed by using short and small section pieces of timber joined together to form long flexible laths, which are assembled into a three-dimensional system of mutually supporting load-bearing structure. At a time when sustainable approaches in design are becoming increasingly important, the opportunity to save material by using an efficient structural system is essential. In addition, gridshells offer the opportunity of creating distinct three-dimensional architectural forms. This three-dimensionality of gridshells as a structural system has an architectural/spatial implication. The structural/technical and the architectural/aesthetic aspects are inseparable in the gridshell design process.

Examples of timber gridshell buildings include: The Mannheim Multihalle, 1975, by Carlfried Mutschler, Frei Otto and Ove Arup & Partners (Engineers); Roof canopies, Expo 2000, Hanover, by Thomas Herzog and Bois Consult Natterer (Engineers); The Weald and Downland Jerwood Gridshell, near Chichester, 2002, by Edward Cullinan Architects and Buro Happold (Engineers); The Savill Building, Windsor (2008) by Glenn Howells Architects and Buro Happold (Engineers)

2.2.3 The Organic Structures Student Workshop 8th – 13th March 2010 , Royal Danish Academy of Fine Arts, Copenhagen, Denmark

The workshop commenced with presentations by workshop leaders and teachers on organic structures. This included tensegrities, geodesics, gridshells and reciprocal frame construction and related structural principles. The presentations gave an overview of the different types of structural systems and are aimed to get students interested and understand better the applications of such structural configurations with a view of constructing either a reciprocal frame or a gridshell structure at the end of the week-long workshop.

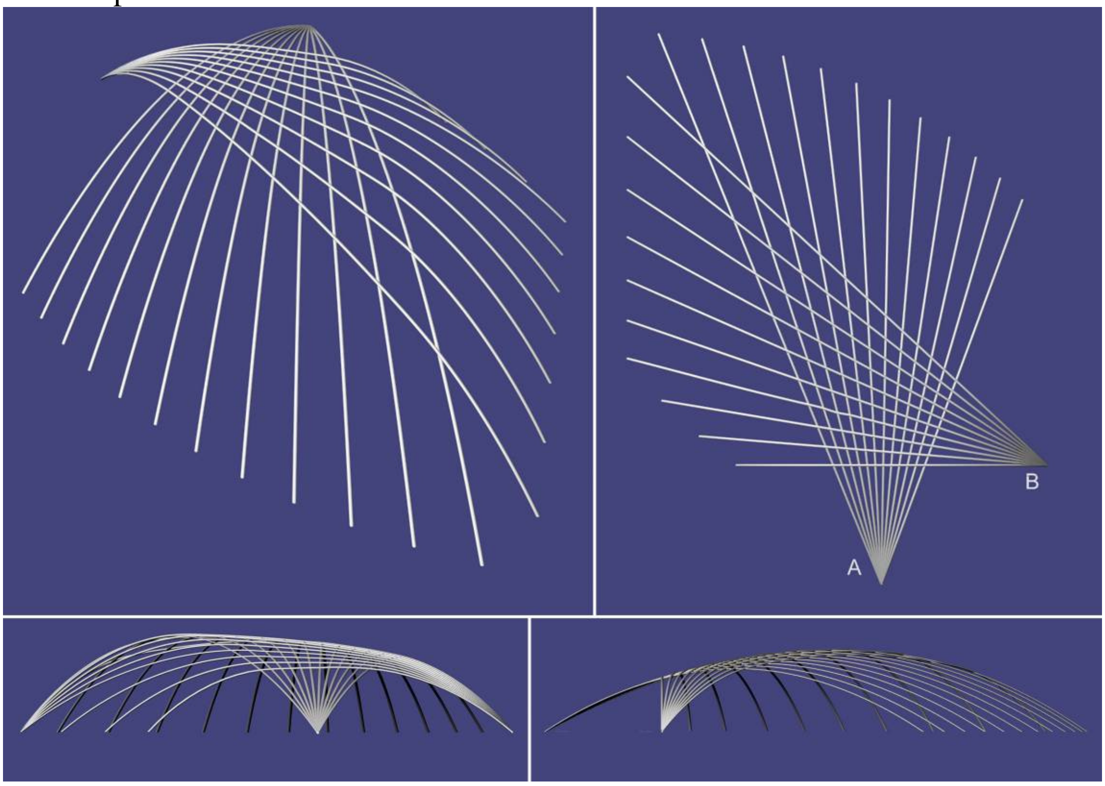

Figure 4: The gridshell design

On Day 2, the students were given a list of topics related to the presentation topics of the day before. The students were required to carry out research in small groups to prepare a group presentation the following day. Before the students dispersed to carry out their research, they were provided with small timber members (model-making timber of various lengths) to make and test their new knowledge, ideas, structural principles and exercise their creativity in application. All results of this enquiry and testing of new knowledge were presented the day after.

The Day 3 presentation was immensely lively, interactive and student-led. The different student groups produced numerous interesting models under an array of headings for the presentation.

One group produced an interesting gridshell model on foam board. Inspired by flying machines invented by Leonardo Da Vinci, the gridshell is conceived poetically as wings protecting and enveloping a space underneath .

This scheme was further developed into a larger scale model, this time under more consultation and design input from the teaching staff. For the gridshell to maintain structural integrity, the structural elements had to be increased in numbers from 5 to 10 on one wing and 4 to 12 on the other wing to create a denser "weave" of structural members.

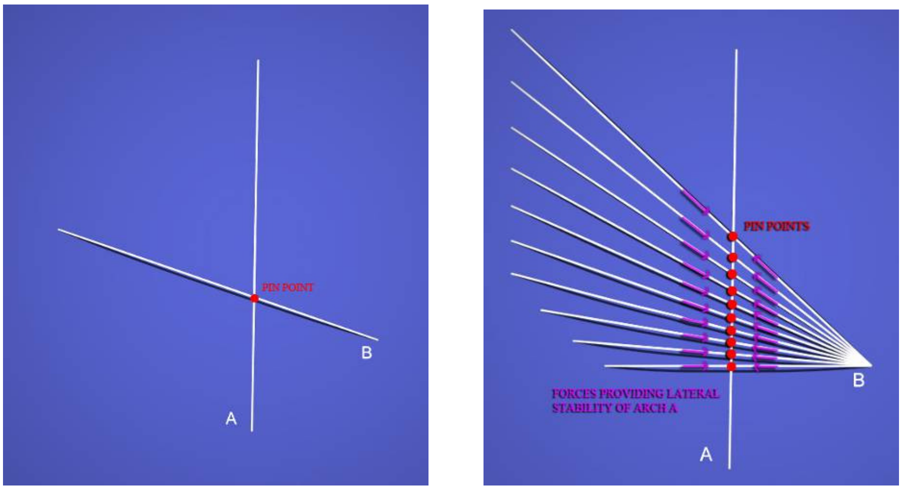

Figure 5a and b: CAD structural diagram

Next, the structural members are numbered systematically. The entire model was appropriately scaled up. Each structural member was correspondingly scaled up in length.

To construct the gridshell, each structural member was made-up by joining 10mm diameter bamboo canes together using nylon cable ties. Each structural member was made-up and labelled individually. Before being joined up, the 2 metre long bamboo canes are rigid. However, when they are connected together, these longer constructed elements achieved a considerable increased bending and flexibility.

Subsequently, when all the bamboo structural members of various lengths were made, they were brought to "site" and assembled. The locations of these members were transferred from the scaled model as grid co-ordinates onto the grassed area.

Figure 6: The construction was under way

The design has 2 springing points where each "wing" is collected together and from which the structural members arched out. A hollow metal profile piece was positioned into the ground at each location that enabled the respective structural members to be placed.

As this was a temporary structure, the opposite ends/ terminating ends of the structural members were inserted directly into the grassed earth to a depth of 100mm

With the help of the students, each structural member of the first "wing" was held up individually. Subsequently, with the structural elements erected into position subsequently, the intersections of the elements between the 2 "wings" are loosely fixed by 2 diagonal cable-tie fixings. The lateral stability of the gridshell is strengthened as more structural members were introduced to complete the gridshell. Whilst the structural members are finding their final position, the diagonal node fixing cable ties are tightened to fix the node positions which gave the gridshell the "relaxed" form.

Figure 7a and b: The completed gridshell

The gridshell structure was left in situ for 3 months and has generated much interest from fellow students and visitors.

The reciprocal frame workshop occurred simultaneous to the gridshell construction exercise following the same programme format. Experimentation using short length models were made and the students saw the principles and possibilities of each reciprocal frame unit being either convex or concave.

Following further consultation with the tutors, a mobius loop strip structure was conceived and was decided as the design to be built.

Square section pine timber pieces of (sectional dimension 25 mm by 25mm and 1metre long) were cut to length. 3 holes of diameter 5mm were drilled at a distance of 33 cm from each end to enable the members to be attached together.

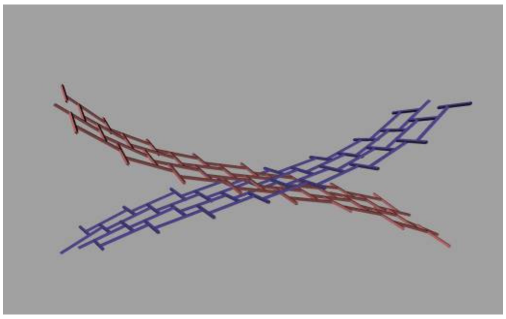

Figure 8a and b: The RF design and the RF segment

Figure 9a and b: The single module, the first RF "shells"

Single units consisting of 4 timber members held together are constructed as modules. They were further linked together to form 2 shells measuring approx 2m in diameter.

These two "shells" were offered up towards each other in an attempt to link them together as in the smaller scaled mock-up. However, due to the limited amount of materials that was available, the shape and size of the structural model had to be modified. The 2 components had to be held together by some improvisation in the form of raffia string tied from each "shell" as the entire loop could not be completed, which would otherwise support the loop.

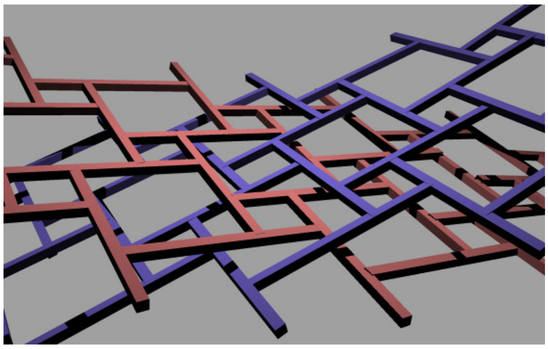

Figure 10 and b: The RF shell – detail of Physical and, CAD model

Figure 11a and b: The complete reciprocal frame structure

2.5 Discussion, Conclusions and Acknowledgements

The two design and building exercises were successful in serving as educational vehicles to illustrate the importance of structural design and consideration in architecture. However, differences can be observed between the two.

Compared with the reciprocal frame activity, the gridshell construction involved more planning. As a result additional stabilisation was not necessary as the structural principle was more defined and structural behaviour more predictable. The reciprocal frame structure, on the other hand exposed the students to a reactive, organic and an *ad hoc* system of design that required quick thinking, ingenuity and creative responses to problems that occurred during the building process. In both activities, the students took on a design lead, developed their organisation and communication skills and displayed the systematic breaking down of tasks. Due to the limited building material available, the reciprocal frame structure turned out to be more "open-ended" and suggestive as a form.

Repetition, patterning and structural principles were apparent and fundamental in the teaching and learning of both structural systems. Material used for the two exercises aptly demonstrated the different qualities of timber. The reciprocal frame relied on the rigidity of short timber members to create a webbed structure whilst the gridshell required the inherent flexibility offered by longer timber members to enclose a space. Visually, the structural systems imparted a different sense of aesthetics. The gridshell formed a visually pleasing, curving form with a regularity in the spacing of the structural elements. As it was made from thinner tubular bamboo, the gridshell structure tended to be more "invisible" compared to the reciprocal frame structure. Conversely, the reciprocal frame is more visually discernible due to the angular and larger sectional timber members. As the structure did not rely on the bending ability of the material, this allowed shorter but larger timber sections to be used.

The students exuded confidence, enthusiasm and importantly, professionalism. They worked effectively as a team. Upon completion of the RF structure, the students generously helped the other team to complete their gridshell structure. Grateful gratitude is extended to the students at the KA who participated in the workshop. The workshop also depicted the blurred boundaries between architecture and engineering, imposing a bearing on how structural engineers and architects are taught in the modern day.

The workshop also illustrated how materiality and their implied structural principles can affect the spatial experience. It also showed how by having a strong and interesting structural concept from the project outset can enrich and have an implication on the aesthetics of the space it encloses. The workshop gave an opportunity to architecture students to explore with full scale models and learn about complex innovative structures. The workshop gave an insight into the structural concepts of gridshells and complex reciprocal frames.

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