Structural Prototypes from Plants

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The inventiveness and economy in the engineering of nature's structures serve as design strategy in optimising minimal resources for maximum effect. This is evident when all organisms compete for available energy and limited resources in order to grow, procreate and enhance survival. Related to the harnessing of limited resources for the survival of the organism is the way it structures itself in order to grow, assimilate and process energy to adapt to its physical environment.

The technological outcome of borrowing ideas from nature is termed biomimetics.[1] It was an aesthetic as much as it was a practical pursuit in the 19th Century.[2] Whereas Binet's Paris World Exposition Entrance Gate was inspired on a visual basis by Ernst Hackel's drawings of *radiolarian* corals, mechanical analogues were derived from wood boring pipe worms for tunnelling shields by Marc Brunel.[3] Engineer C Culmann related the force lines of bone *trabeculae* he saw in anatomist's Hermann Meyer's cross-section studies of bone tissue, as the structure of his construction crane. D'Arcy Thompson in his 1917 mathematical analysis of biological growth, explained form as a diagram of forces that were acting on it or which have acted on it. He theorised that even when biological parts or wholes were not shaped directly by physical forces, they assumed optimal forms of ideal geometry as solutions to problems of morphology.[4] Biomimetic interest lies in the process by which useful ideas are abstracted from the living world because the underlying basis of reducing wastage in the deployment of construction material is common to biologists, engineers and architects in the search for form.

This article documents an important application of biomimetic thinking in a studio experiment which attempts to relate structural learning in architectural design. Related to the physical and mathematical logic of designing structures are the implicit design values of economy, minimizing the complexity of the problem (and thus the design), stability, strength, and safety factor of the building structure to be designed. However, the epistemic learning of theoretical aspects in building structures does not enable architecture students to apply it readily to architectural design. The architectural design process generates an entirely different set of questions concerning structure and these are essentially configurational in nature and related to the creation of form and space.

In a studio project, plant structures were studied as a basis for structural development where plant anatomy was used as a reference for studying structural configuration in achieving strength through form. In particular, structural lessons in how movement, flexibility and the resisting load are achieved with the distribution of both rigid and flexible plant tissue, serve as a means for prototyping architectural structures.

PROJECT AND PROCESS DESCRIPTION

Second-year undergraduate students from the Department of Architecture, National University of Singapore completed the projects documented in this article in a seven-week project in November 2002. The works of D'Arcy Thompson and Frei Otto were used as references for nature's strategies in achieving strength through tissue form.[5] Robert Le Ricolais' experimental research workshop at the University of Pennsylvania provided a basis for analogical design approaches in the development of structural prototypes.[6] All the authors explored the idea of using minimum material in strengthening form and the patterning of structural members into highly effective load bearing configurations.

In the first phase, students attempted to understand transpiration, photosynthesis and reproduction and researched plant biology in respect of their classifica-

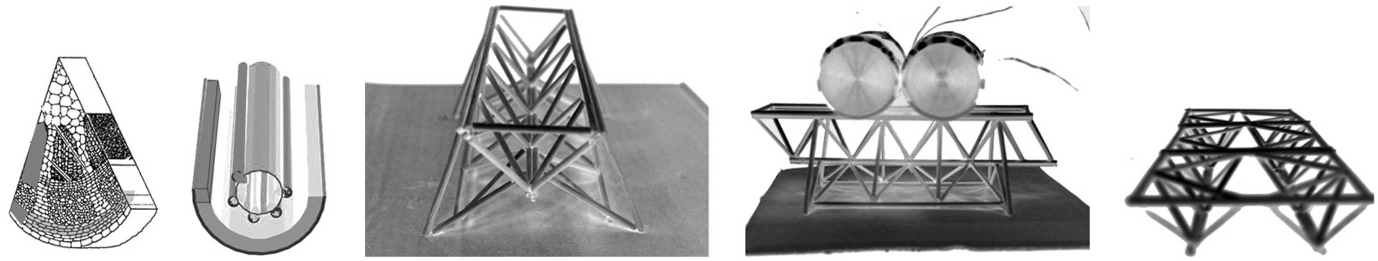

Fig. 1. Analogue translation of the longitudinal section

tion, general, special types, structural strategies for food production and conveying water, accommodating movement, growth and reproduction.[7] Students sought structural patterns in the overall configuration of the plant and in its element parts, which form an overall strategy in achieving strength through shape. Biological studies covered an interesting scope of plant life: leaf flutter for transpiration served as a model for studying movement and leaf growth, and developed as a pattern strategy to minimize self shading in a tree to maximize photosynthesis. Leaf cell patterns were also studied as a transformable surface. Most significantly, the growth of rigid and soft tissue to enable both flexibility and rigidity in plant stems, branches and vines served as useful design strategies in configuring long span and vertical structures. These studies were translated into initial models representing form and structure.

In the second phase, structural models were developed from initial models in the first phase, and were tested to determine their behaviour under loading conditions. Models were developed in relation to the way they deformed and modifications made to strengthen them in ways observed in plant growth and anatomy, and re-tested for improved strength. Studies in other cases focused on joint and support design which amplified movement specific to spatial and structural configurations with the potential of being incorporated into real sites and programmes.

The fully developed and refined structural models (prototypes) were evaluated on the main criteria of inventiveness in form-making and structural efficiency. Lightweight solutions to form that were best able to maximize rigidity and resist buckling under loadings were considered to be the most successful. The students' intuitive and theoretical understanding of the structural form was also carefully assessed. Other criteria were also considered as important as structural efficacy. For example, the degree to which structural action in the prototype maintained its reference to the biological strategy of the originating plant was important in relating process to design product. Similarly, the extent to which its normal configuration advantaged architectural space whilst increasing the stability and strength of the prototypes was of equal significance. The structural quality of the prototype was also an aesthetic that was evaluated for its ability to define architectural space.

THE STUDENT'S PROTOTYPES

Students selected monocotyledonous and dicotyledonous plants for study. Their exploration fell into two categories: the first explored folding structures and the second, vertical and long span structures.

Vertical and Long Span Structures

Collenchyma Bridge

Cells of a dicotyledonous stem are arranged in a fixed radial pattern. Its stem tissue act in both compression and tension elements when the plant is subjected to wind load and loads imposed by rain or animals. Upon loading, the *collenchyma* cells resist bending with its 'honey-comb' like structure, maintaining the shape of the stem. The *sclerenchyma* cells allow flexibility in the movement of the more rigid vascular bundles by forming a layer of elastic tissue on the outer edge of the vascular bundle. As both the *collenchyma* and the vascular bundles are compression elements in the stem, these were translated into longitudinal trussed beams tied intermittently along their length. The last model was of one vascular bundle. The ability to twist and bend without buckling or crushing when subjected to loading is a translation of how the *sclerenchyma* works in protecting the vascular bundle when the stem moves, as illustrated in Figure 1.

References were also made to Ricolais' study of long span structures which seek to attain maximum strength with minimum weight. Ricolais uses tetrahedral configurations and triaxial networks of hexagons, triangles or tessellation of triangles and hexagons to attain strong but extremely lightweight bridges. The tetrahedral element reduces buckling length of grid members in resisting compression and form an inner ''core'' of compression elements interacting with an outer edge of tension elements. Similar to Ricolais' bridges, the modular units were configured primarily for compression: and interconnected longitudinally by a central compression spine with tension elements in the periphery. The difference was that more usable space was attempted in the configuration of this structure derived from the vascular bundle in the following ways. Each modular unit represented one 'honeycomb' or the *collenchyma* cell. This module was repeatedly linearly to form a bridge. When the compression elements were confined to the mid-section, slender tension members at the periphery of the structure freed the view from the interior spaces of the bridge. Linearity was used as a strategy to follow the form of the stem as closely as possible. It also opened more possibilities for the use of space (Figure 2). Ricolais' bridge in contrast, uses parabolic forms, limiting the use of the space to only the mid-section).

The *collenchyma* bridge spanned between 2 supports with a span/depth ratio of approximately 10:1. The bridge structure consisted of 2 parts put together — the result of individual studies. The bridge maintained a light structure that could withstand load and provide space. Depending on how load was applied, roles were interchanged between upper and lower sections. This is typical of a stem/ branch. Triangulation was used as a strategy in connecting all structural members to form the entire bridge ''beam''. The members were closely strutted to reduce individual buckling lengths. The 'band' of spaces above the mid-section might be framed with lighter supports resting on the mid-section, spanning the entire distance between bridge supports. The 'band' of spaces below the mid-section might be framed with even more slender tension elements, hung from the mid-section. With a span to depth ratio of 10:1, the *collenchyma* bridge was able to take up to 30 times its own weight, whereas the tower was able to take up to 40 times its own weight.

The bridge structure was also tested as an asymmetrical tower by turning it on one end. The vascular bundle prototype was very stiff and rigid as a tower and could take more load than as a bridge. In a load test of 1kg-5kg, it was observed that the tower had a natural tendency to lean towards the section with more members (more weight), bipod legs were added to counteract the toppling tendency, defining a possible architectural entrance to the tower structure. Upon increasing the load to 6kg, the tower now leaned towards the opposite direction and another set of bipod legs were necessary to stabilize the tower with a near symmetrical base. The tower could withstand 8kg of load with minimal deformation without torsion. The structural form of the vascular bundle prototype here was stronger as a column than as a beam. As a tower, the aspect ratio of H/B was 10:1. The configuration was able to resist bending as a tower within this aspect ratio more efficiently than as a beam simply supported. Vertically, the strutting pattern created a trussed tube tower with a central ''core'' frame of thicker modules.

PROTOTYPE BRIDGE BASED ON XYLEM VESSELS

The xylem vessels of dicotyledonous plant stem consists of compression and tension members. It helps to maintain the upright form of the plant through the orderly arrangement of its xylem tissues and has a chief characteristic of being stiff yet flexible. In dicotyledonous plants, it is able to grow and resist compression through the development of the different xylem vessels: reticulate, pitted, annular and spiral. These vessels are lignified to resist collapse under large tension forces set up by water pressure differences caused by transpiration. The spiral form was chosen as it is able to effectively resist both compression and tension.

A prototype bridge was developed around the idea of a spring, which resists both tension and compression. The prototype was a form of the dicotyledonous stem while being strengthened in the horizontal axis. It followed the dicotyledonous xylem arrangement of locating xylem vessel bundles (which are strong in tension and compression) near the periphery. This could be seen in the arrangement of vascular bundle in a dicotyledonous vine stem of the *aristolochia*. To configure a tensile bridge supported at either ends, attempts were made to reduce its deadweight. To achieve this, the number of structural members were kept to a minimum. The design of the central core consisted of two main members which were made of stiff springs capable of tension and compression. The placement of the cables and rods linking between bridge sections was located closer towards the core to take advantage of the greater strength of the central reinforcement. The arrangement of the support cables and their proximity towards each other and the ''central core'' secured the overall rigidity of the bridge section (Figure 3).

Spatially, the bridge could be traversed at several levels. A variety of uninterrupted circulation paths were formed analogous to the movement of water in the continuous dicotyledonous xylem vessels. The idea of the connection between the stem to the leaves were developed as peripheral spaces for viewing out of the bridge.

BUTTRESSED FAN MODULE

Plant structures have a primary function of supporting the entire organism to enable photosynthesis, transpiration and obtaining soil nutrients. As part of the food making process, sunlight is essential for photosynthesis and optimum humidity and temperatures maximise evaporation during transpiration. Consequently, tropical rainforest trees try to grow high enough to obtain enough sunlight from the sky whilst creating a microclimate beneath their canopies. In order to support vertical growth, trees develop strong trunks and roots to resist lateral forces. In order to fork and spread their branches as wide as possible to create a large crown, wide-spreading roots near the ground surface are also necessary to intercept as much rainwater as possible.

Buttress roots have a wide-spreading, tapering growth pattern, and are able to resist wind and lateral load through planar, triangulated cross-sections. Prop roots may be sent down from branches, as seen in the *Banyan* fig. These aerial roots help to absorb moisture from the

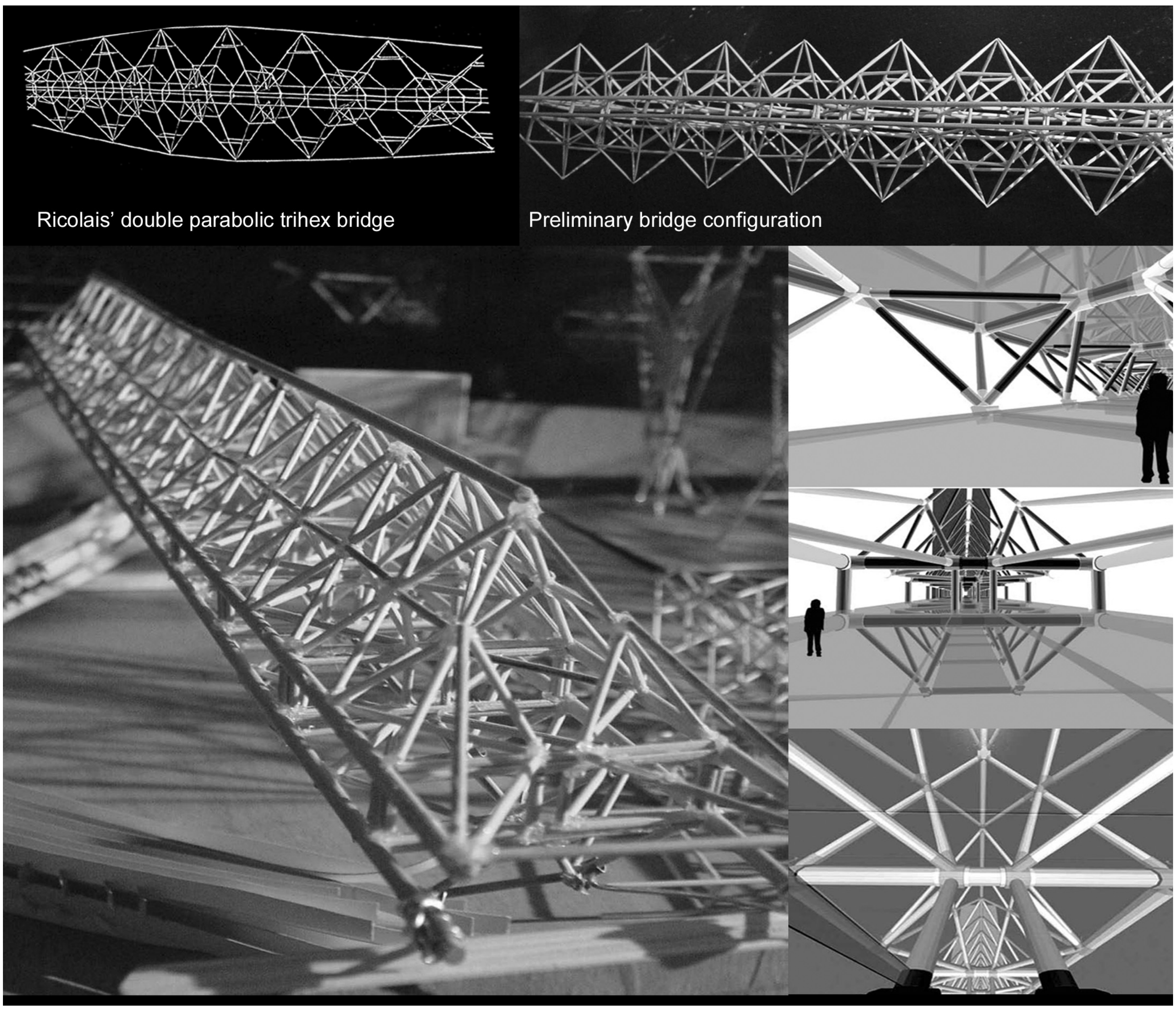

Fig. 2. Collenchyma cell *bridge prototype*

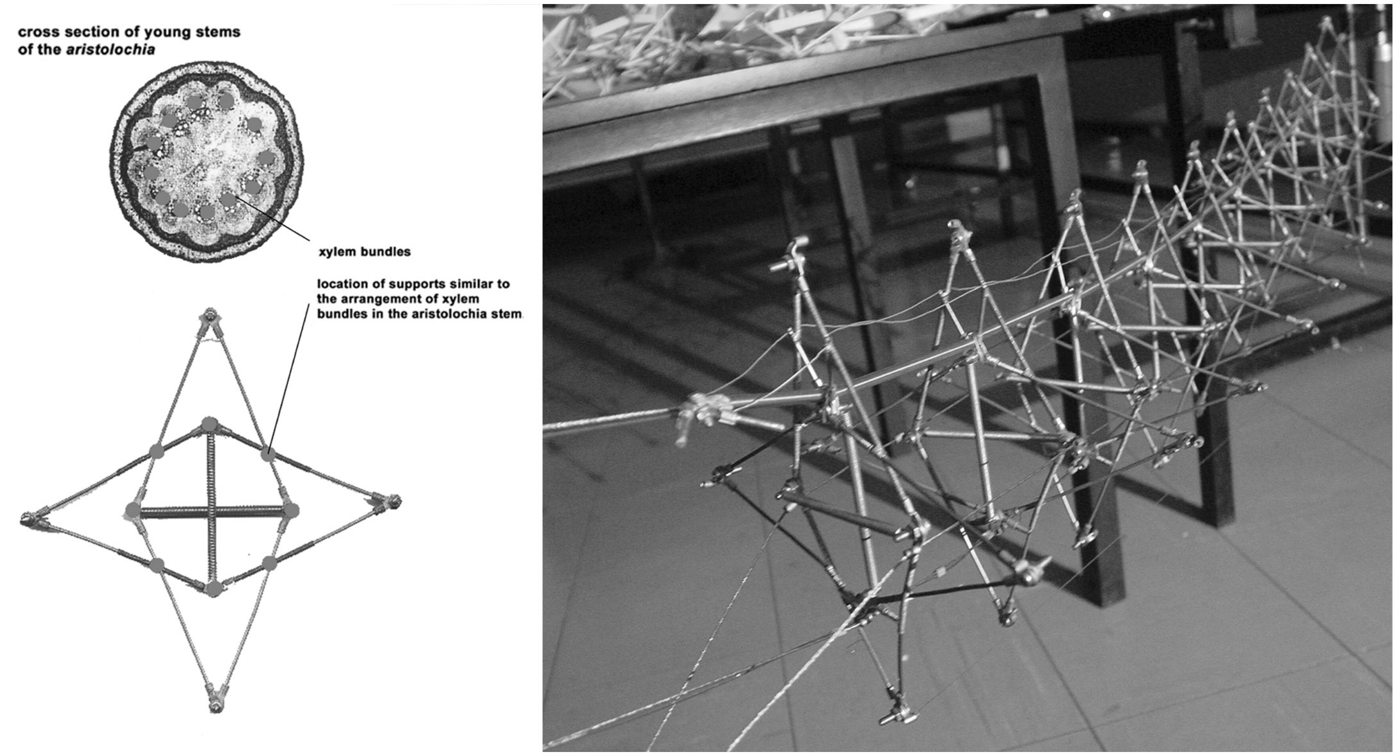

Fig. 3. Xylem vessel *bridge prototype*

air. When they reach the ground, the roots thicken and stiffen, acting as both tension and compression members, increasing the stability of the plant. The lower portion of the palm stem is strengthened by circumferential tissue growth forming a structural ring beam in effect. This strategy is also apparent in the *Strangling* fig *(Ficus prolixa)*. The inter-weaving and binding action around its host eventually forms a self-supporting compression member so that when the 'host' tree eventually dies, the *Strangling* fig is still able to stand by itself.

The buttress idea was explored in developing a structural module for a space with a height of 30m. In attaining height in the structure, the challenge was to shape support elements to resist buckling without incurring physical girth. Following the strategy of buttress roots in tall trees, the base of the column was widened and configured as a tripod whilst the midsection was shaped in three 'buttress elements' meeting in the central axis of the column. The stems of the *Madagascar* palm leaves are arranged as buttresses acting towards the centre of the plan in a radial pattern. In the prototype, the transverse buttresses fanned outward at the upper portion to become a canopy, forming structural roof cantilevers (Figure 4).

Load tests were carried out to identify weak parts of the structure. In increasing the load-bearing strength of the structure, five modifications were necessary throughout load testing. The strutting of the structural members was intended to create patterns sympathetic to the overall form and shape of the entire module. The individual structural modules were then combined in a series of patterns to study their effect on defining space with the clear spans achieved. Configurations 3 and 4 create the widest distances between vertical supports but secondary roof forms would be necessary to span the gaps between the module roofs (Figure 5).

Folding Structures
A roof structure based on the fluttering movement of a *Buddhi* leaf petiole

The *Buddhi* plant is non-flowering. Its leaves are held horizontally by long petioles that branch from its stem and each leaf has 5-9 pairs of principle lateral veins spreading out from the mid-rib vein. The petiole often forms a curved spine, thickening at its base which measures 8-10cm in length. The leaf has two parts: the blade and the petiole (leaf stalk). The petiole is critical in enabling photosynthesis and respiration as it supports the leaf blade in a way which orientates it towards the sun. It also connects the leaf blade to the stem. One of the characteristics of the *Buddhi* leaf is its long petiole that cantilevers the leaf considerably from the stem. This enables the leaf to flutter easily. Leaves flutter to maximise their exposure to sunlight which is required for photosynthesis and also to prevent the

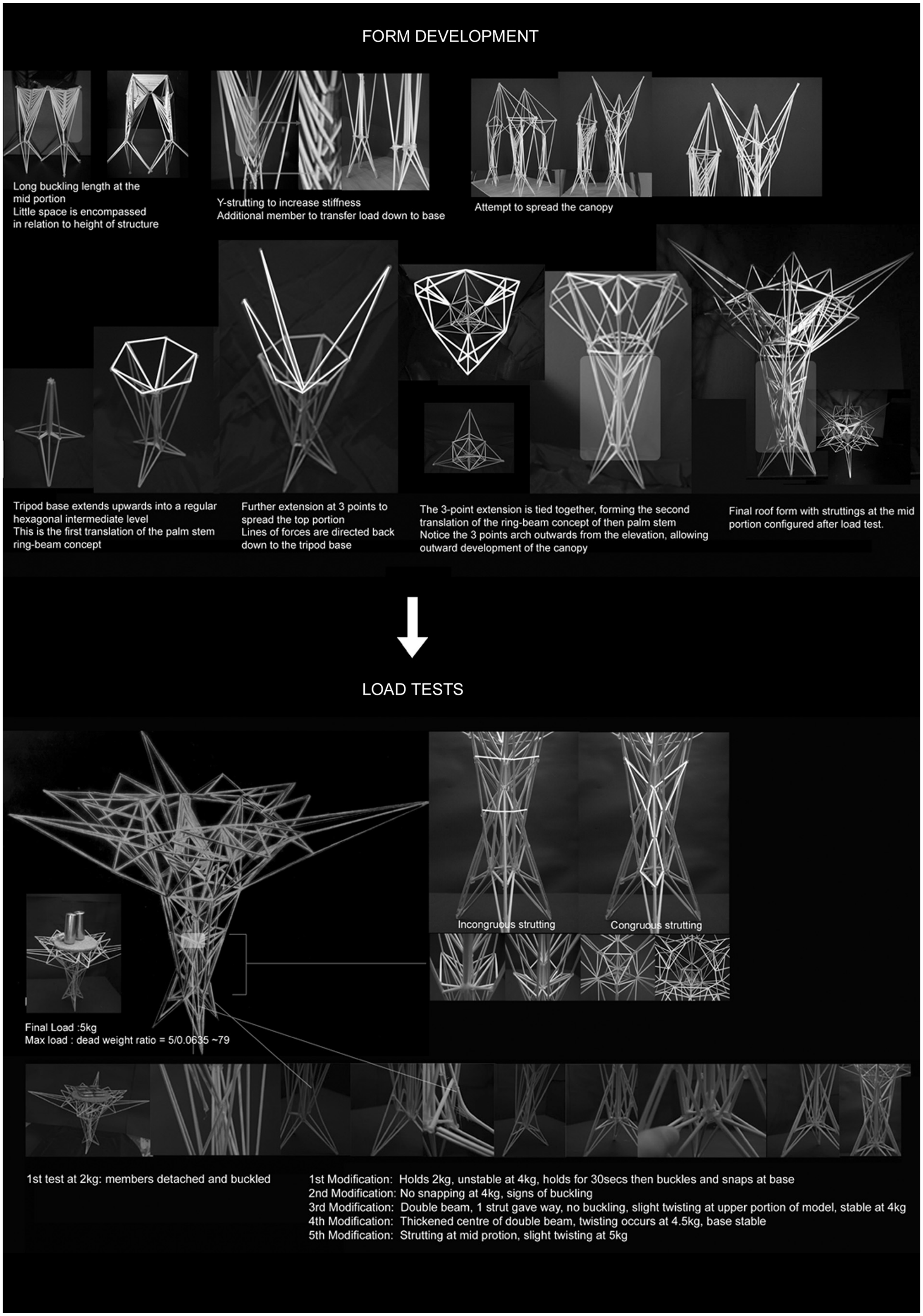

Fig. 4. Buttressed fan roof module derivational process

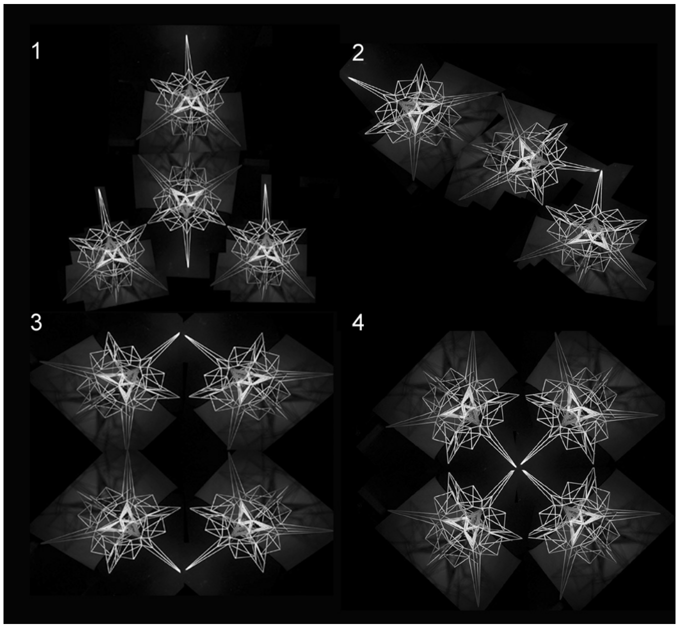

Fig. 5. Four plan configurations

plant from overheating. In some cases, fluttering also protects the plant from small insects and pests that may be harmful to the plant. In developing a structural analogue to enable fluttering, a ''mainframe'' was conceived as the biological stem which supported movable arms representing leaf petioles. Each individual arm was hinged along its length and rotated in one plane. The arms rotated in positions different from one another but when viewed collectively, the surface formed an undulating roof/ ceiling element (Figure 6).

FOLDING CANOPY BASED ON THE FOLDING PATTERN OF A HORNBEAM LEAF

The *hornbeam* tree grows in temperature zones. There are different variations of the species found in Europe and North America. The leaf is folded in the bud scales during the winter and is folded like a series of parallelograms. This results in a system that allows the leaf to be ''pushed out'' from a single driving point. The folding

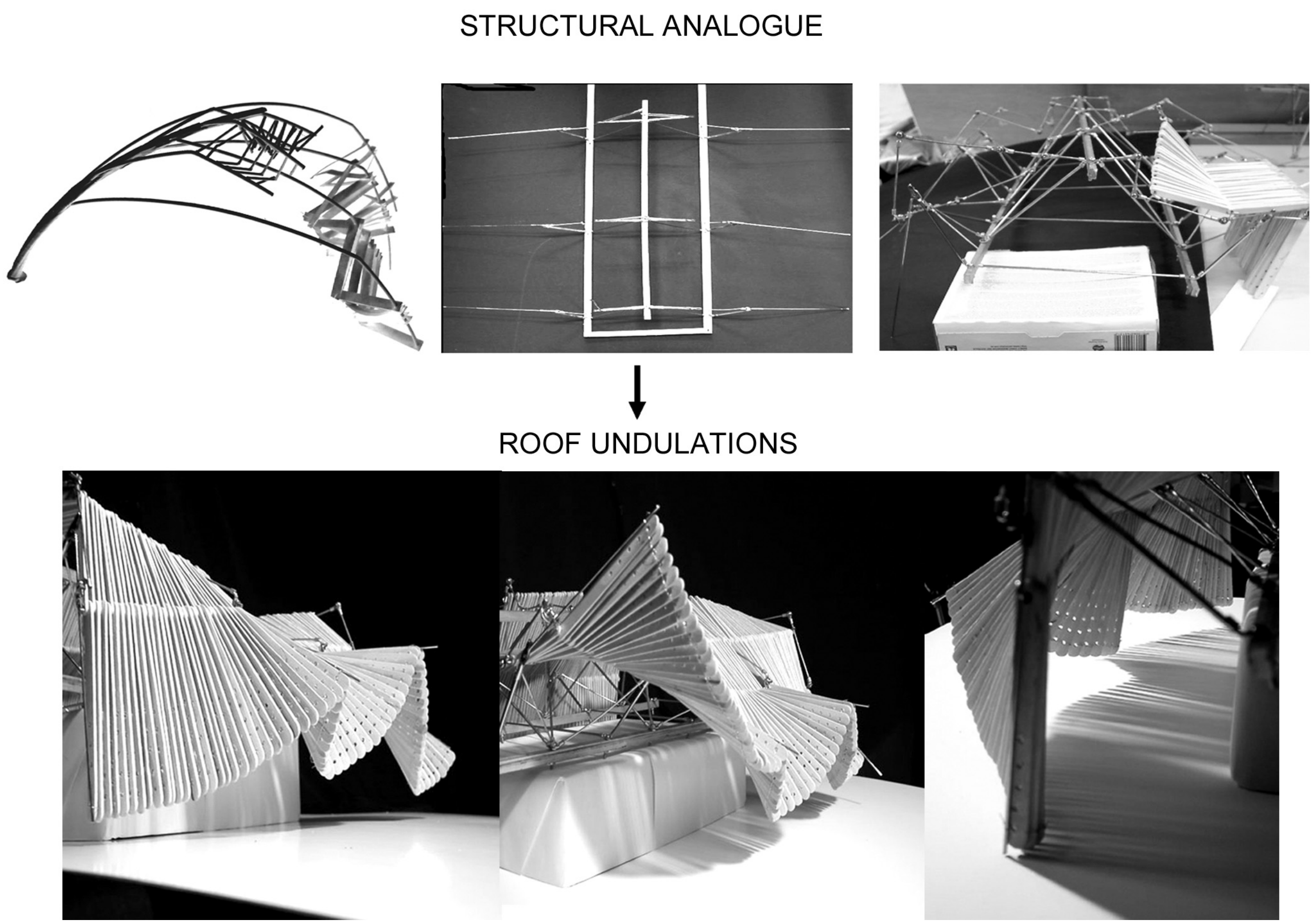

Fig. 6. Roof structure based on fluttering movement of a Buddhi leaf petiole

pattern can be likened to a corrugated sheet, the folded profile enhances the rigidity of the lamina. The initial models were modelled closely to the pattern of the leaf itself. It had an angled corrugation that allowed it to open and fold up. This angled corrugation also enhanced the stiffness of the model. Another initial model had a different size of panel, though still a parallelogram. As the model opened out, the corrugation got flatter and less pronounced. This means the canopy would get less stiff and tend to bend over. The *hornbeam* leaf overcomes this by growing the central leaf vein straight. Later models were based on variations of parallelograms.

The unfolding pattern as illustrated in Figure 7 was studied when individual ''leaves'' of varying proportions were joined side by side. This combined configuration was more efficient as the entire canopy could be made to unfold by applying a force at one point. When the shape of individual panels varied whilst maintaining their fold angles, openings were possible in the surface of the canopy as it folded. This could be used as skylights or ''windows'' in exterior surfaces. The final configuration had two different sizes of panel. All parallelograms had similar interior angles. The result was a configuration that allowed light and air through openings that could vary in size. Studies on the canopy showed that in stages of unfolding in elevation, the canopy grew longer and also flatter as it unfolded, whereas in plan, it covered a greater area as it unfolded. As it was necessary to move the canopy on tracks which were supported on beams, this study enabled the trajectory of the panel vertices as the canopy unfolded. Beams would be shaped according to the trajectory to enable rollers on tracks to move the canopy panels.

The middle of the canopy was designated as the driving point by which the roof was activated. This point moved only up and down. A driving mechanism such as a hydraulic piston could be used to activate the canopy from this point. Images of the canopy were taken in varying stages of opening and overlaid onto each other. This allowed the locus of the movement of the points of contact to be traced. The locus therefore traced the path of the tracks on which the canopy moved. The canopy panels were connected via hinge pins. The pins converged to another upright pin with a roller at the end. This roller would run along a C-channel track. The entire canopy rested on a series of bipod shaped columns to counter the lateral forces of the unfolding roof panels (Figure 7).

THE PEDAGOGICAL VALUE OF PLANT BIOMIMESIS

J.F.V. Vincent's biomimetic map of folding cellular plant structures attempts to chart the transfer of a biological idea into its structural application. Six biological aspects were identified as a basis for biomimesis, and correlated to the student projects in respect of folding structures, folding pattern, cellular growth, growth control, shape control and sensing (Figure 8). In the folding canopy inspired by the *hornbeam* leaf, Vincent observes that unlike the radial actuation of the umbrella and its derivatives, a cover based on the leaf could be deployed and supported from a single extending strut.[8] In a radial leaf, experimentation shows that it can be actuated from a single fold. With the same *hornbeam* leaf, the student project however demonstrated the potential of asymmetrical folds actuated from a single point to cover a substantial area with simple supporting mechanisms. The student had created a surface which could unfold in two axes with openings perpendicular to its surface and configured a structural mechanism capable of transforming space through movement (Figure 9).

Whereas the *hornbeam* leaf analogue was directly related to its leaf pattern and mechanism, the *Buddhi* leaf abstraction was different but with equal potential as a prototype. The *Buddhi* leaf study translated the leaf flutter into an undulating surface activated by winged arms. Here, the winged arms were a mechanical translation of petiole action and not a biomechanical replica. Vincent believes that in biomimetics, ''the further down one moves from the natural origin the more general and therefore, the more powerful the concept will be.'' The learning of structures in architecture through the biomimetic approach in the development of prototypes allows students to explore the relationship between force, form, and idea in generative modes of thinking crucial to design thinking (Figure 8, right diagram).

In analysing engineering patents, Altshuller identifies levels of innovation which he listed below:

— A single improvement to technical system requiring knowledge available within that system

— An improvement that includes the resolution of a technical contradiction requiring knowledge from a related area

— An improvement that includes the resolution of a contradiction at the level of physics requiring knowledge from other industries

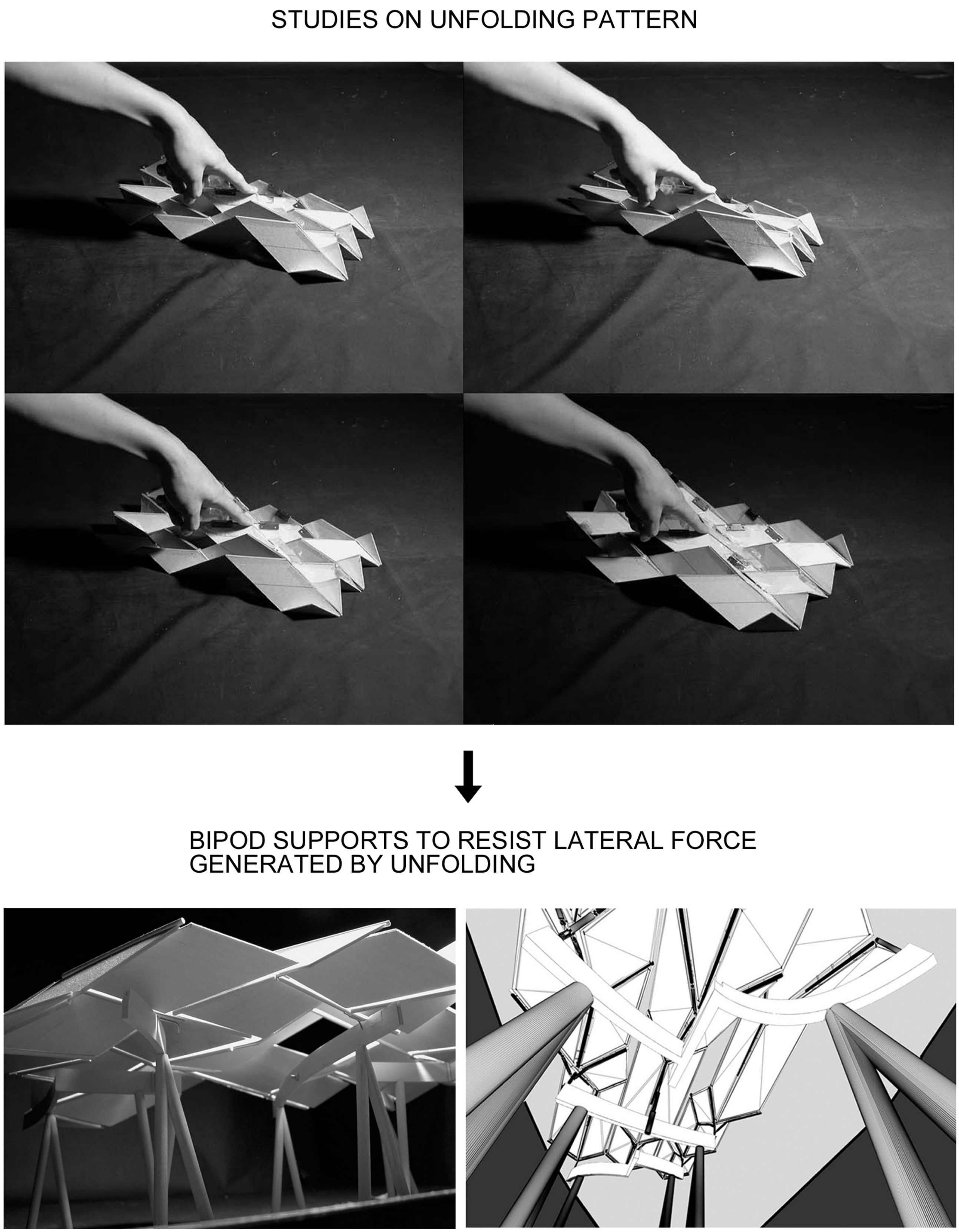

Fig. 7. Hornbeam *leaf unfolding roof*

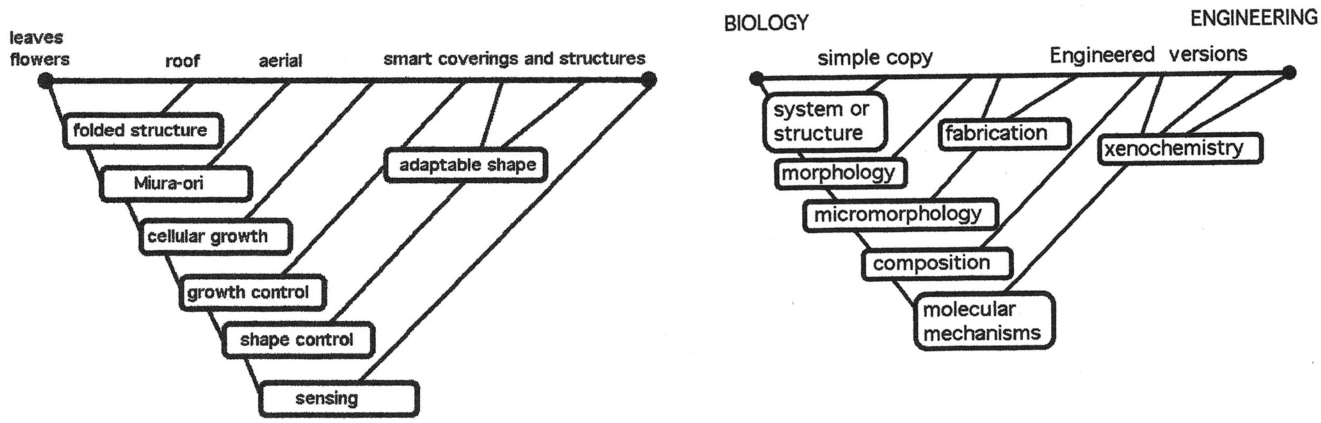

Fig. 8. Biomimetic map of folding cellular plant structures (left) and its illustration on the idea that the more abstract a concept is, the more adaptable it is within another discipline

— A new technology which involves a "breakthrough" solution requiring knowledge from different fields of science

— Discovery of a new phenomenon

Altshuller believes that the analogical transfer of ideas from biology into architectural structures can be made at a variety of levels, depending on the remoteness of the technical problem from its biological model. If the remoteness is extreme, then a more basic analysis of the biological system is necessary in order to generate a useful paradigm.[9] The biological basis of the studio projects is useful at the conceptual level of generating a rich variety of potential structural solutions in architecture, whilst allowing students to explore different levels of innovation in the design process.

CRITICAL OBSERVATIONS ON PEDAGOGY

The studio project was an excellent vehicle in bridging structural theory with form making and in the development of an intuitive understanding of structural action by testing structural models and observing their deformation and behaviour under varying load conditions. The improvement of the load bearing capacities of the

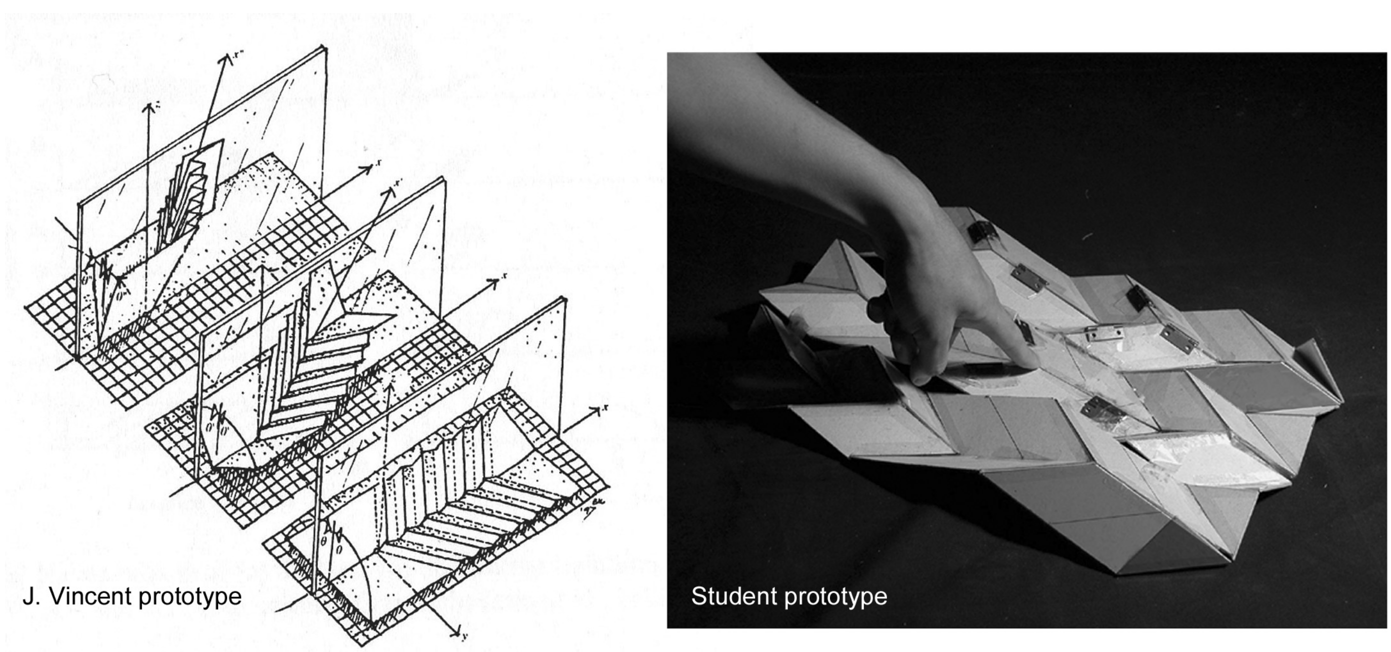

Fig. 9. Increased expansion of roof coverage

test models by carefully directed reconfiguration enabled the visual and intuitive understanding of force in relation to the deformation and strengthening of form. In this respect, the accuracy of the observations depended to a very large degree on how well the models were made.

The studio was not without certain difficulties, in particular, those associated with translation and modelling. The use of timber, metal and cardboard as analogous modelling materials for moveable and rigid structures was problematic as they depended on accurate jointing for forces to be transferred from one member to another, or for forces applied to one member to effect the movement of other members. The winged joints of the *hornbeam* leaf canopy had to be accurately aligned in order to unfold without jamming. The *Buddhi* leaf undulating roof required opposite pairs of its segmented arms to be co-planar in order to effect a continuous undulating surface. The connection of hardwood sections as compression and tension elements in the *collenchyma* bridge and tower prototype required precision and consistency without which structural efficacy would be compromised. The xylem vessel bridge was perhaps the most difficult to fabricate, requiring the connection of stainless steel cables with tubular sections acting in tension and compression respectively. Perhaps, the most significant challenge for the students was in the translation of the biological model into an abstract analogue capable of being developed into a structural prototype. Despite its complexity, the studio process integrated technical considerations in the conceptual stages of the design process and in the generating of strategic form-space-structure relationships fundamental to architectural learning.

REFERENCES

[1] Julian F.V. Vincent, ''Stealing Ideas from Nature'', *Deployable Structures* (ed. S. Pelligrino) (Springer, Vienna)

[2] Philip Ball, ''Life's Lesson in Design'', *Nature 409* (London, 2001*)*: p. 413-416

[3] E. Krausse, *Die Rezeption von Evolutionstheorien im 19. Jahrhundert* (ed. E. M. Engels) (Frankfurt, 1995); Tom F. Peters, *Building the Nineteenth Century* (MIT Press, 1996)

[4] D'Arcy Thompson, *On Growth and Form* (Great Britain, Cambridge University Press, 1961)

[5] Frei Otto, *Frei Otto: Structures* (London, Longman, 1972)

[6] Peter McCleary, ''Robert Le Ricolais' Search for the Indestructible Idea'', *Lotus International 99* (Milan, 2000) p.101-131

[7] F. Halle, R.A.A. Oldeman, P. B. Tomlinson, *Tropical trees and forests: an architectural analysis* (New York, Springer-Verlag, 1978); Capon Brian, *Plant survival: adapting to a hostile world* (Portland, Timber Press 1994)

[8] Julian F.V. Vincent, ''Deployable Structures in Nature'', *Deployable Structures* (ed. S. Pelligrino) (Springer, Vienna)

[9] G. Altshuller, *Creativity as an Exact Science* (Gordon & Breach, New York, 1988); G. Altshuller, *And Suddenly the Inventor Appeared* (Technical Innovation Center, Inc., Massachusetts, 2001)

CREDITS

Collenchyma prototype bridge, Lee Mei Yan, Sandra

Xylem Vessel prototype bridge, Ngoh Meng Yian

Buttressed Fan roof module, Leung Ying Wah, Eva

Buddhi Leaf roof structure, Wong Lee Yung

Hornbeam Leaf unfolding roof, Tham Wai Hon

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