On Shells and Skins

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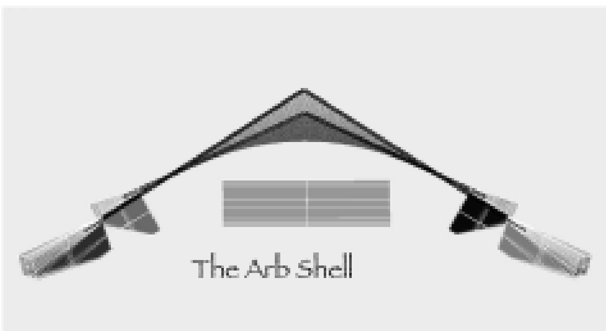


A discussion on shell forms with reference to a built prototype hyperbolic paraboloid studio project for a band shell using transfer technologies and hybrid geometries with composite materials.

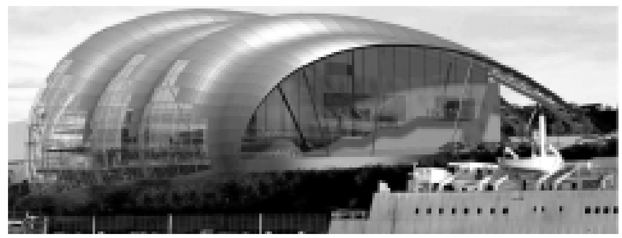
BACKGROUND

Shell structures once enjoyed their place in history as one of the most efficient and elegant of structures ever developed and saw a meteoric rise in popularity originated by the likes of Gaudi, Candella and Eisler, as depicted in Fig 1.

Fig 1.

Tony Robbin (1) remarks: "The appeal of shells is that they are strong......" and contemporary structures of similar stature are the roof canopy of the Gateshead Music Center and the British Museum Great Court Roof in Britain, (3). Examples of these structures are shown in Fig's 2 and 3, both elegantly formed in architecturally exposed structural steel rather that concrete.

Fig 2



It is worth looking closer at a new set of relationships that define shells. A shell is more than a general surface that describes 3 dimensional space as a continuum. The skin of a shell has rigidity, therefore it is more than a simple poly-surface graphic, it is a surface that possesses intelligence based on material and geometric properties, which could include texture, transparency and climatic performance.

In this paper I will primarily be discussing attributes of shells and skins in relation to their material and geometric properties, using a case study example of a recently completed project to illustrate some of these principles. In support of this, the manufactured surface can depend on the choices of

Fig 3

materials, their micro composition, their micro geometry within the skin and the resulting derived surfaces that produce the final skin. One such process is described in this paper, which employs patterned and standard panel surfaces at the skin micro structure scale, twisted to derive larger complex surfaces at the macro structure scale. Nurbs modeling allows such surfaces to be developed without relying on the need to describe surface geometries only with flat surface facets. The philosophical and practical advantages of this approach are demonstrated, using these principles. It is suggested here, that most surfaces can both be described and manufactured in this way, leading to increased potentiality of integrated skin (microstructure assemblies) and surface (macrostructure resulting form) geometries.

INTRODUCTION TO THE CASE STUDY PROJECT

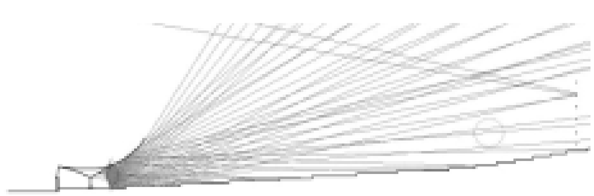
During the winter semester of 2004 a group of graduate students and faculty, joined forces with graduate landscape architectural students to design and build an amphitheater in an arboretum park setting.

This interdisciplinary graduate studio was concerned to develop a dialogue between the natural landscape and a built artifact, an object that would hover between earth and sky. The project became a band shell that would host live performances and attract artists to perform in the park. The enclosure covers approximately 35 feet, with a clear span of 50 feet to the foundations, above a stage 15 by 25 feet. The amphitheatre is part of the natural landscape and can accommodate 300 + people.

EXPLORATIONS OF SHELL

The initial trials of form for the bandshell recognized the need to provide a surface that would be hard enough to reflect sound and convex in form to avoid focusing towards the audience. Studies of the shells acoustic performance were carried out, see Fig 4.

Fig 4.



Ideally it would also reflect sound between the performers on the stage. The form also had to be dynamic and perhaps provide some organic reference point to its natural surroundings. The students were inspired by the image of a falling leaf, hovering above the landscape. One form that seemed to come naturally was the anticlastic shape of a hyperbolic paraboloid, arrived at from a variety of possibilities. A few examples of alternative forms studied are shown in Figs, 5, 6, 7, 8.

Fig 5

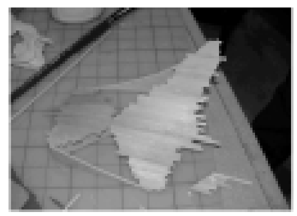


Fig 6

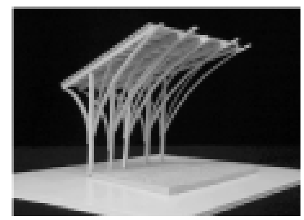


Fig 7

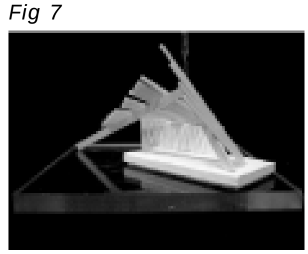
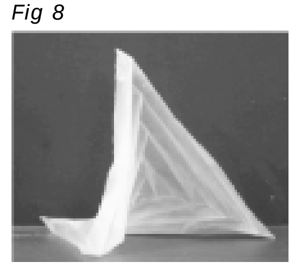


Fig 8



The model in Fig 8, began to describe what the chosen solution became, a model formed out of paper, that describes an overall hyperbolic form, as a consequence of origami folding technique. Curiously Fig 8, aptly exemplifies the principle described earlier, whereby macrostructure (shell) is derived from microstructure (skin).

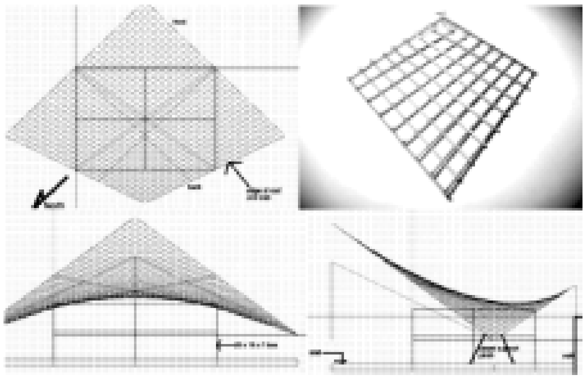
A number of key advantages emerged out of the hyperbolic paraboloid form and they included:

- convex form for acoustical reflection to the audience, which at the same time provides
- concave form to reflect sound between the players, owing to the natural synclastic form
- structurally stiff form that maximizes slenderness
- a form that is organic yet geometrically define, a positive resonance with nature.

A number of small scale physical and CAD models were experimented with, including a dramatic off center cantilever shell as depicted in Fig 9.

Various ideas for the supporting structure were explored, varying from vertical columns to raking and tapering solid walls. The final solution extended

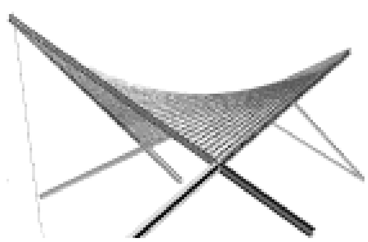
Fig 9.



the natural line of the hypar outer edge from the support apex to become a pair of raking supports that accentuate the back tilt of the shell, adding a further dynamic, by visually making the front and back of the overall structure unequal, albeit the form being derived from a doubly symmetric plan form. One can think of the constituent parts resembling the form and function of the elemental components of a deckchair as depicted in Fig's 10 and 11.

Fig 10

Fig 11



The dynamic nature of the form was further accentuated by placing the raking columns on sloping concrete buttresses in the ground, reminiscent of arch bridge construction, clearly articulating the force line from the structure to the foundations. The out of balance forces resulting from imposed snow and wind loads are understood from the need to provide a 3rd vertical support located at the rear of the stage.

EXPLORATION INTO SKIN

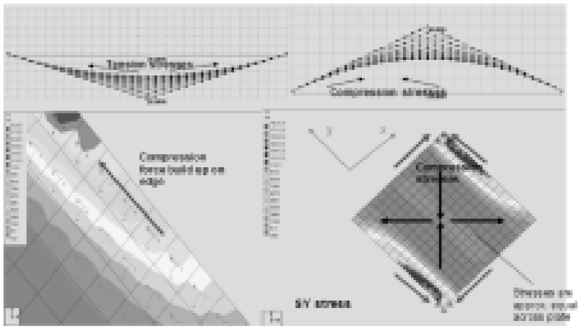
A shell structure, as it name implies, is constructed out of a thickness, which is very much smaller than its overall surface area dimension. This thickness needs to possess both axial and bending stiffness. In the case of a 'pure' shell, of funicular form, the thickness is only required to carry axial tension and compression. This is why many of the concrete shell structures built in the 60's were able to be made so thin. However this demand on a pure funicular form stress regime places severe restrictions on the overall shell shape and application/function, which can be derived for a dominant loading condition such as the self weight of the structure or a symmetrical imposed loading, say from snow or wind. This is of course unrealistic to assume, since most dominant loads are asymmetric, causing bending through the shell thickness. Therefore, rather than trying to force a particular loading pattern related form, it is more effective to accept that bending forces will exist and attempt to approximate an efficient form under maximum symmetrical loads and then cater for of the out of balance conditions by exploiting the bending stiffness of the shell.

What this argument leads to is an appreciation of the opportunities of shell as "bending surface". This behavior was extensively demonstrated in a paper (3), where the primary structural shells on several projects were shown to behave efficiently in a hybrid axial and bending stress state. Here the author refers to " ...an alternative emphasis .....relates more to the materials of construction ......using a structural form that works principally in compression, which however performs as a hybrid structure, as a shell in compression with some significant bending actions, combining innovative construction techniques that require an understanding of the structural mechanism at all stages of construction as well as the nature of the material both during construction and its performance in the final structure."

This is precisely the approach adopted for the Arboretum band shell. A number of alternative types and methods of assembling materials that would provide both axial and bending stiffness were considered. The shell from was initially analyzed as a continuous thin shell, in an attempt to identify the critical stiffness and strength requirements.

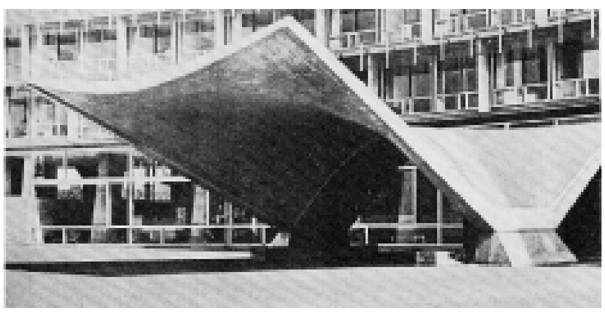
As expected, even though the structure was raised in the air and was supported at 3 points, a classical axial stress distribution for a hyperbolic surface was observed in the shell skin, see Fig 12, whereby the stresses flow towards the free edges of the surface and progressively accumulate at the center support. This form related effect is also illustrated in past hypar surface structures as illustrated in the UNESCO build-

Fig 12



ing in Paris (2), designed by Nervi and shown in Fig 13. where the actual surface thickness was varied according the stress levels.

Fig 13



However, since we were beginning to consider some kind of laminated skin of constant thickness, we had to consider how the classical stress regime would be contained within a constant thickness shell. Another desire was to make the shell as thin as possible, so that it began to resemble a stressed skin fabric structure, albeit that the overall desire was to have a wood surface, resembling the underside of a boat hull. This was consistent with forming a complex surface out of thin warped and connected strips, as one observes in canoe building technology using Cedar strips as shown in Fig 14 and 15.

Fig 14

Fig 15

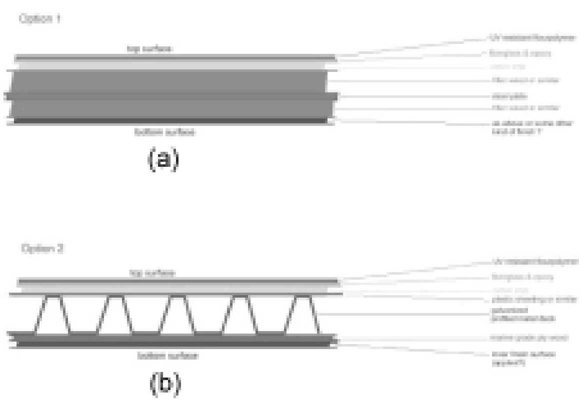
Canoe technology was studied at length and appeared to be an appropriate technology to adapt to this situation. The strength of the canoe depends on the wood strip skin form stiffness, for a given thickness of a standard Cedar strip. This is further enhanced by layering the outer surface with a fiberglass and resin finish, which also provides a durable and finished waterproof surface, that the outside of a boat demands. We began to see a resonance between this technology and the formation of the upper exposed surface of the band shell.

It was at about this stage that the idea of a laminated shell was conceived, using an outer wood strip surface attached to a structural core. What the early stress analysis trials demonstrated, was that wood alone was not stiff enough to construct a thin shell, therefore the idea of constructing a hybrid of wood with a strong material was explored. A few options that included steel plate were studied and finally the idea of using a corrugated steel sheet as the inner core connected to outer laminated ply wood sheets appeared to resolve most of the issues discussed above, as shown in Fig 16 (b).

Although it was easy to conceive that laminated plywood sheets could be twisted into hyperbolic shape with reference to canoe building technologies, where the wood strips could be made narrow enough to from a complex surface, it was less clear how a warped surface could be developed out of steel sheet without the need for tessellation of flat surfaces to create a curved plane (as is done to mesh complex surface forms, the accuracy of which depends on the mesh size). However, the author has in the past on a number of building project slab and roof constructions, used a technique that warps a 4 sided corrugated steel sheet by ‘springing’ the sheet on one corner to achieve a warped surface. This is made possible, since a hyperbolic paraboloid surface is essentially constructed out of a series of straight lines, where in this instance the straight lines are formed by the stiff longitudinal ribs of the corrugation (3 to 4 inches deep).

In the perpendicular direction to the ribs, the sheet is relatively flexible since by comparison, the structural depth is only the sheet thickness, (20 gauge typically). Therefore, for this scale of project with sheet lengths of 20 feet, it was predicted that it would be relatively easy to twist the corrugated profile by up to 6 inches, allowing the surface to be formed by hand, without the need for any spe-

Fig 16



cial equipment required for forming or bending the sheets. The elegance of this solution is that the entire sandwich of wood/steel plate/wood can easily be laid up by 2 people, resulting in a connected composite stiffness of the hybrid laminate that is far greater than the sum of the individual components. In order to gain confidence both in this construction technique and its final strength, various composite sandwiches were made into typical flat panels and load tested as shown in Fig 17 and 18.

Fig 17

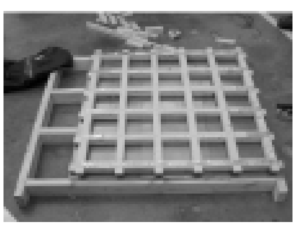


Fig 18

In addition, once the composite panel type, was confirmed to be the most efficient from a strength and stiffness to weight ratio perspective, the warped form was also trialed on a test jig to get an appreciation of the connection and manufacturing issues that would need to be addressed as shown in Fig 19.

The initial trial stress analysis procedures also tested the shell behavior, with the decking running in one direction, using anisotropic material properties. This demonstrated that a uniaxial stiffness would not be adequate to both provide sufficient overall stiffness of the shell, nor was the shell able to gather the accumulated forces on the edges.

Fig 19

Therefore, it was necessary to provide equal stiffness in the two orthogonal directions. But the problem was that this could not easily be achieved using any cellular form, because it is always complicated and difficult to achieve a 2 way system owing to the number of continuous/fixed joints that would be required in say a 2 way egg-crate panel comprised of vertical stiffeners. This complication is solved by layering 2 corrugated sheets, with the ribs running orthogonally to each other to achieve two-way stiffness. The question was how to connect the sheets to ensure adequate shear strength between the 2 layers and to what extent the layered sandwich would act compositely with the outer wood strip layers through the combined depth of the panel. This effect was studied analytically using finite element stress analysis, Fig 20 and 21, and then verified by testing actual panels, Fig 18.

Fig 20

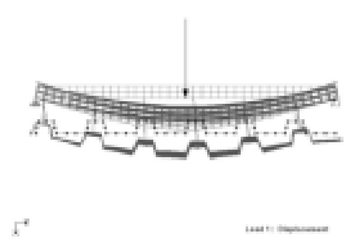
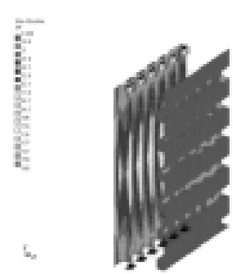


Fig 21



The overall stiffness of the composite plywood and steel deck sandwich was approximately twice that of a single corrugated steel sheet, whereas the ultimate strength was approximately 50% greater than a single sheet. This was very encouraging since stiffness was the governing design criteria and it also demonstrated the advantage gained in strength and stiffness by using the composite arrangement of materials in this way. This was not the result of an initial intuitive solution, but rather an incremental voyage of discovery, facilitated by stress analysis techniques, referenced transfer technology and a process of research into materials and combined forms.

The entire composite skin was framed along the perimeter with a structural member that gathered the edge stresses and then also extended out in the manner described earlier to form the elevated support member for the shell as a whole. The edge members were made out of a 5 inch deep C shape steel profile, which was connected to the composite sandwich, by using the corrugated deck as the connecting medium, as shown in Fig 22 and 23.

Fig 22

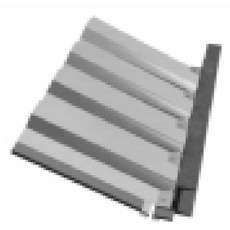
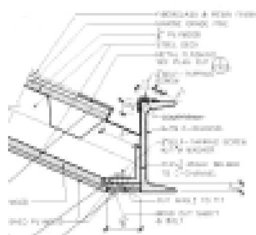


Fig 23



The decking was 1.5 inches deep 20 gauge steel and each sheet of laminated plywood was 0.5 inches thick marine grade Okume, layered with an outer skin of fiberglass fabric laid up with polyester resin and a gel coat finish.

STRUCTURAL ANALYSIS

Following the initial explorations into materials, layering and shell forming, we had to figure out the actual size and shapes of the corrugated sheets and the laminated wood panels. A full structural analysis was carried out, using properties of the actual corrugated profiles and material properties. It was not appropriate to approximate shell behavior from a complex layering of micro geometry and various materials. Therefore an analysis model was set up that modeled each sheet corrugation as a set of finite element layers with a varying uni axial and bending stiffness in each of the orthogonal directions. The modeling of the uni axial properties was further complicated by the continuously changing axis of warp for each element, requiring a model that approximates non planar members through varying 'beta angle' magnitudes. Some of the analysis detail is illustrated in Fig 24 and the stress pattern on the overall structure is shown for a typical snow load case in Fig 25.

Fig 24

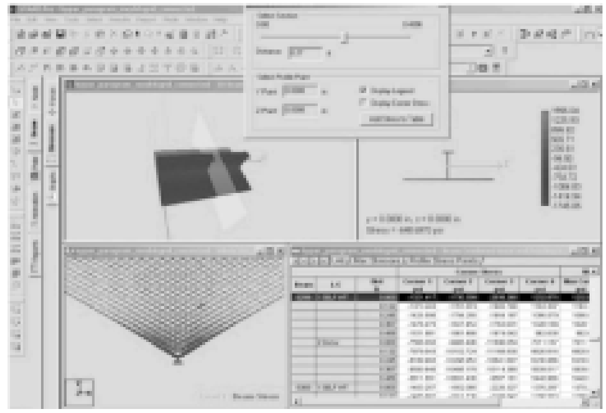


Fig 25

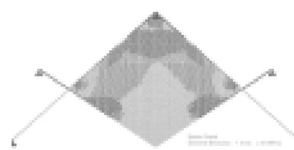
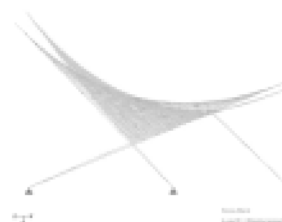


Fig 26



The orthogonal layering was approximated as a single plane of members, the properties of which were parametrically modified based on the initial panel studies and the results of the load testing behavior. The key to modeling the composite layering was to represent an accurate combination of both axial and bending stiffness for the complex composite arrangements to resemble shell behavior, such that when flexure begins to dominate and is superimposed on axial effects, the overall behavior is accounted for in the analysis. This is because the section properties rely largely on the state of stress at any given stage of loading pattern and as such can vary significantly under different loading arrangements. A number of load cases had to be considered. These included full and partial, symmetrical and asymmetrical loading patterns resulting from a combination of snow and wind loading. The effects of maximum tip deflection (as one would predict for an aircraft wing) to avoid wind flutter, lateral side sway and foundation spread was integrated into the overall analysis and the prediction of overall deformation compared well with field measurements. The overall behavior of the shell, its elevated supports and foundations were combined in terms of stiffness, strength and stability of the entire model, details of which are illustrated in this paper, and a typical deflected shape for one of the load cases is shown in Fig 26.

FABRICATION AND INSTALLATION

The final fabrication took place in 2 steps. Initially, the main jig was erected on a flat plane in the workshop to set out the main temporary lumber supports, see Fig 27 and erect the first pass of

Fig 27

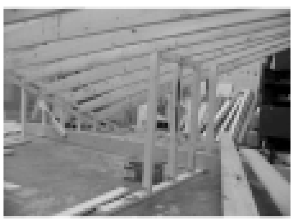


Fig 28

metal decking to ensure a tight fit up, see Fig 28. This was the first time that the entire surface was erected. The detailing issues and resolution thereof, owing to the distortion of a flat sheet of constant width subject to end warp was also verified. The lack of fit was accommodated in the sheet overlap which in turn was tied together by the orthogonal corrugated steel sheet. A perfect fit was never expected and since the metal deck is clad with ply wood, the lack of fit was not visible, however it is structurally sound. This exercise was carried out at the same time as the framing steel was manufactured, see Fig 29 and 30.

Fig 29

Fig 30

Following this, the jig was disassembled and erected on site to the required tilt on an elevated base jig. See Fig 31 and 32.

The steel framing was erected by crane and attached to the ends of the corrugated steel decking with Tec screws, the connection of which had to be tested in the laboratory for shear strength, since this is the point where significant stress accumulation occurs. Once the entire frame was erected and connections made, the assembly became a very rigid shell with the double layer of metal corrugated decking only. The ends of the steel frame

Fig 31

Fig 32

were left elevated above the ground and the foundation buttresses were constructed around the base plates. This was a strategic decision to build the shell from the top down, since it eliminated the need for absolute accuracy of fit up between the foundation and the base plate and avoiding locking in secondary stress due to lack of fit. Once the foundations were set, the jig was removed entirely, such that the shell comprised of the double layer metal only, which was adequate for this temporary condition. It also allowed the ply wood sheets to be laid on both the top and bottom surfaces unhindered.

The ply had to be cut to a particular pattern that would fit the hyperbolic parabololid surface geometry. This was determined from nurbs modeling of the constructed surface, cut into panels and developed into flat planes. This procedure was checked using stressed fabric patterning software and the results compared well to within fractions of an inch, as shown in Fig 33.

The panels were cut out of 4' wide sheets and therefore had to be efficiently nested to minimize wastage. In fact the ply strip width was decided from

Fig 33

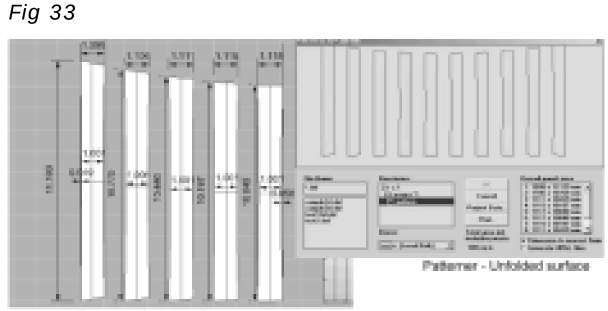


Fig 34

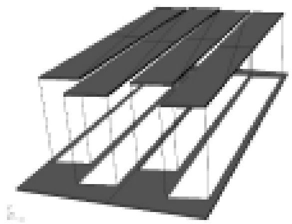
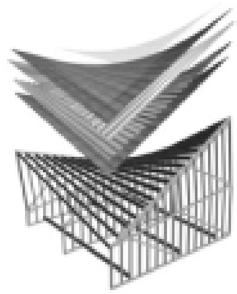


Fig 35



the available sheet size and then the patterning and nesting exercise was carried out to optimize on sheet usage. The sheets were digitally cut from from a CAD file using a CNC router that both cut and stamp marked each sheet to the precise pattern, as shown in Fig 34. The sheets were then fixed down onto the corrugated metal deck in the exact patterning order as draw, and warped to follow the hypar surface profile. The entire shell/skin composite is shown in Fig35. The installation methodology minimized field work to simple fixing of panels, avoided large scale prefabrication (which was initially one of the possibilities considered but then later abandoned) and resulted in a very rigid shell construction as a consequence of the laminated and twisted skin configuration. The one essential feature of this design for shell and skin is that a stiff yet thin shell was constructed out of flexible sheets that could easily be transported, manipulated and twisted into the surface form through simple connections. The one area that posed the most significant installation problem was finding good weather to lay up the fiberglass and resin coating. The project was continually plagued by rain, varying temperatures and high winds, making scheduling difficult, since the polyester resin had to be applied in dry conditions at a specified temperature range to allow the matrix to set. Essentially the surface application needs to be carried out within a complete enclosure to keep out the weather and temperature controlled as necessary.

THE PRODUCT

The completed project was celebrated this summer (4), (5) with an inaugural concert in the park and the acoustics of the enclosure performed remarkably well. A number of important lessons were learnt by both faculty and students, since the scale of the project was perhaps bigger than the original perception of what it would entail. In conclusion, a number of pioneering aspects were developed, incorporating digital technology that facilitated the development of a highly efficient structural form, derived from the micro structure of the skin that holds the form together. The author is currently conducting further research into similar applications, developing skin derivative shell forms, using a variety of core microstructures together with recycled materials or materials that can easily be recycled. The first of these projects will incorporate the use of cardboard that will be stiffened through the skin and layered into a hybrid, using a combination of different materials to form a surface that will provide adequate durability for the entire shell form. The purpose here is to devise a method to enclose space with materials that possess a high stiffness to weight ratio and which in themselves are extremely light and contribute towards sustainability principles for the built environment.

Studio collaboration: working session with students and faculty around the test jig.

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