

Cloud Arch

Application of an EPS composite to create an ultra-lightweight long-span sustainable structure

Shinya Okuda¹, Saurabh Bhagra²

National University of Singapore, Singapore

¹akiso@nus.edu.sg, ²saurabhbhagra@yahoo.com

Abstract. Expanded Polystyrene foam (EPS) is a chemically inert and 100% recyclable material that is lightweight and has a good compression strength per weight ratio; however, its current construction use is mostly limited to insulation or landfill. The key concept of this paper is to develop an EPS composite to create an ultra-lightweight long-span sustainable roofing structure by integrating the minimum necessary structural tension layer with a certified fire protection system. The authors present this concept in the following four steps, 1) EPS composite structural specimen test, 2) structural optimisation of the reversed displacement model, 3) discretisation with developable surfaces and 4) CNC hotwire rapid prototyping and assembly in scaled prototypes. The Cloud Arch is an economical, material-efficient, thermally insulated, quickly assembled ultra-lightweight construction that eliminates the need for formworks for long-span structures. It can be applied to many types of column-free spaces, such as in factories, gymnasiums, markets and cafeterias.

Keywords. Lightweight; prototyping; composite; digital fabrication; performance.

INTRODUCTION

Expanded Polystyrene foam (EPS) is a chemically inert and 100% recyclable material often used as insulation and sub-grade infill in construction industries worldwide. Despite its lightweight characteristics (it comprises over 90% air), it has a good compression strength per weight ratio (close to that of concrete); however, its current structural use is mostly limited to landfill for landscaping works. EPS foam components can be rapidly customised from standardised EPS foam blocks by using manual/computer numerically controlled (CNC) hotwire machines. Nevertheless, straight hotwires restrict its producible geometries. Moreover, EPS foam can be fire-retardant with

additives that do not spread fire but it is not possible to be fireproof, as it may melt under excessive heat.

In order to utilise EPS foam as a permanent construction material, two commercially viable methods are currently available: the structural insulated panel (SIP) and Dryvit systems (Figure 1) [1]. The SIP system aims to sandwich rigid polymer foam between two layers of structural boards, such as oriented strand boards, whereas the Dryvit system comprises polymer-based cementitious coatings on EPS foam with glass fibre mesh reinforcement. Both methods have been applied in the US construction industry since the 1970s. While SIP can be used for

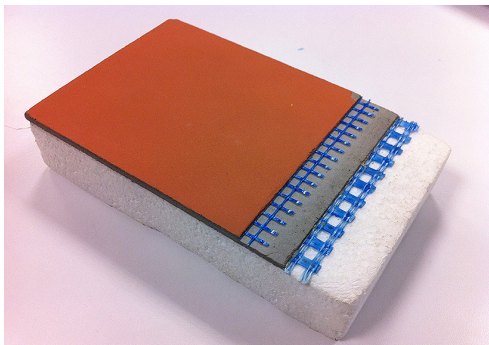
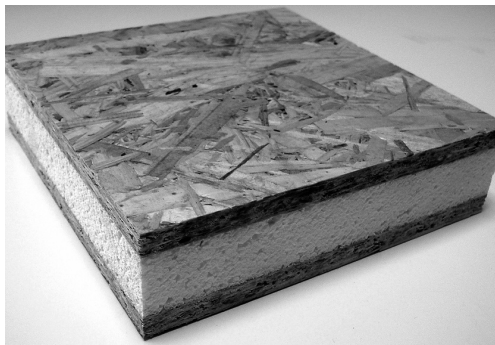


Figure 1

Left: SIP was among the early methods to apply an EPS composite as a prefabricated construction material; however, oriented strand board layers are hardly curved unless they are fully CNC milled out. Right: The Dryvit system is cementitious-coated with a glass fibre mesh top on the EPS foam, which is a fire-rated construction system. By utilising glass fibre meshes or any alternative materials as structural tension layers, the EPS composite can provide ultra-lightweight long-span roofing structures.

structures, it is rarely applied for long-span arch/shell, as the rigidity of the structural boards limit its application to rectilinear forms only. A prototype of doubly curved Wood-Foam Sandwich Shells has previously been explored with full CNC milling processes (Bechthold, 2004). By contrast, the *Dryvit* system's fire protection layer has very high traceability to structural movement and its EPS foam core can be customised relatively easily; however, it has not yet been used for structural purposes.

CLOUD ARCH

A structurally optimised arch is purely in compression, which is suitable to experiment with EPS foam, whereas a long-span arch often requires a relatively high rise compared with the functionally required ceiling height in architecture. If we lower the rise of the arch, it is no longer purely in compression; rather, it has various tension forces at the bottom/concave side of arch. Finite element (FE) structural analysis methods can thus effectively visualise regions that are in tension and compression. Similarly, the same principles and simulation methods can be applied to thin shell structures.

The key concept of this paper is that we utilise a glass fibre mesh, which forms a part of the fire protection layer, and other alternative materials as the structural tension layer in order for the EPS composite to be used as a long-span roofing structure. The density of the fibre mesh can be adjusted according to the structural requirements indicated by the FE

analysis. The result is a low-cost, recyclable, quickly assembled, material-efficient, thermally insulated, innovative and ultra-lightweight fire-resistant composite roofing system.

The authors present this key concept in the following four steps: 1) EPS composite structural specimen test, 2) structural optimisation of the reversed displacement model, 3) discretisation with developable surfaces and 4) CNC hotwire rapid prototyping and assembly in scaled prototypes.

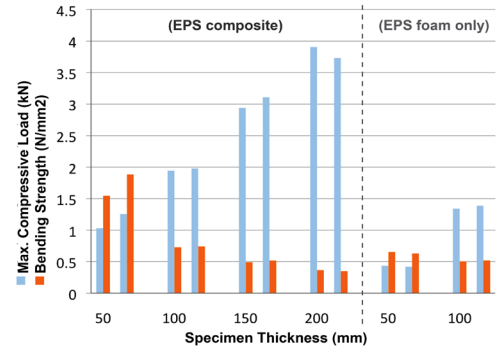
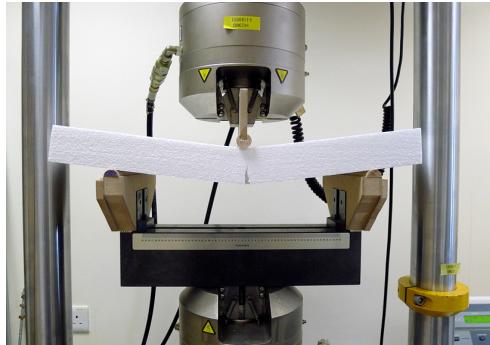
Structural Specimen Test

In order to understand the structural effect of adding a glass fibre mesh and cementitious coating to EPS foam, three-point bending structural specimen tests are carried out with both pure EPS foam and an EPS foam composite. The foam is coated with a single layer of glass fibre mesh and a 2 mm thick cement mixture on its top and bottom sides. A servo-hydraulic controlled fatigue system, *Instron 8516*, is then used for the testing. All specimens are identically shaped in plan views (500 × 200 mm), but in four thicknesses, namely 50, 100, 150 and 200 mm, in order to understand the structural effect of the 2 mm coating layer for these different EPS foam core thicknesses (Figure 2 left).

The test results are shown in the summary graph (Figure 2 right) along with the maximum compressive load before its failure and the bending strength of the four specimens. Bending strength describes the ability of the material to resist deformation un-

Figure 2

Left: EPS composite: three-point bending structural specimen tests (Instron 8516).
Right: The specimen test results in the four thicknesses (50, 100, 150 and 200 mm).



der load. The graph shows that the EPS foam composite has much greater bending strength and can withstand higher compressive load compared with the pure EPS foam of the same thickness (50 and 100 mm specimens). In particular, for the 50 mm thick EPS foam composite, the maximum compressive load and bending strength is nearly 2.5 times higher than that for the pure EPS foam of the same thickness. Therefore, the coating of the EPS foam composite provides it with more structural strength and rigidity. This result also suggests that the EPS foam composite can be thinner overall compared with a pure EPS foam in arch/shell form. Please note that we could not ascertain a test result for the pure EPS foam of 150 and 200 mm thickness, as the three-point fixture on the testing machine penetrated the specimen before it reached structural failure.

Overall, as the thickness of the specimen increases, the difference in the maximum compressive load and bending strength between the EPS foam composite and pure EPS foam becomes less obvious. This is because the proportion of the coating layer on the foam composite decreases, while the thickness of the specimen increases; thus, the structural effect of the coating becomes less apparent.

Further experiments and studies can be carried out to analyse the structural strength of the EPS foam composite, especially with different tension materials and different densities. The *Dryvit* cementitious coating has very high traceability owing to its structural movement. If we were to replace the

glass fibre mesh with other types of structural tension materials, such as carbon fibre mesh, bending strength may increase; however, its traceability to deformation would be unknown. Therefore, the next step is to find the best balance between a higher bending strength and the traceability of the tension layers to structural movement.

Structural Optimisation of the Reversed Displacement Model

Among the various types of composites, our EPS composite seems to be similar to laminated composite structures. Laminated composites have been analysed to show that the failure mode is usually the delamination of the layers and that the mechanical properties of a composite depend upon the geometry and aspect ratio of the fibre mesh. Further, woven fibre composites are considered to be non-directional, which is different to unidirectional long fibre composites. As tensile stress is usually transferred through the matrix of fibres in a composite, we could effectively complement regions of higher tensile stress with denser fibre meshes. During deformation by bending, one surface is extended in tension, while the opposite surface is compressed (Shanks, 2010).

For our experiment, the glass fibre meshes are non-directional and delamination is not observed due to the high traceability to its structural movement during the structural specimen tests. When the specimen approaches its maximum bending

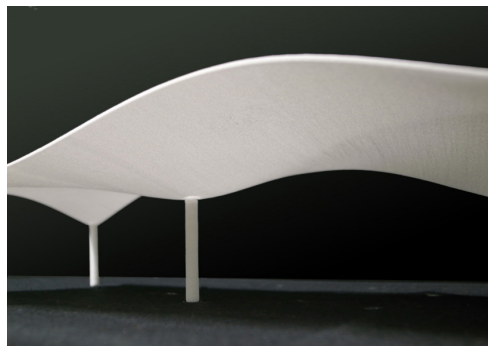
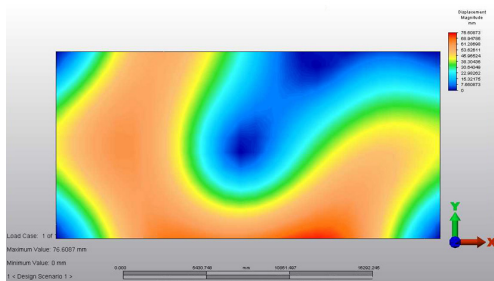


Figure 3
Left: Sample image of a structural displacement contour diagram of a flat plate that is supported by six randomly positioned columns. Right: The 3D printed reversed displacement model at 1:100 scale (EOS Formiga P100), which demonstrates the possibility of the EPS composite being used as an ultra-lightweight long-span sustainable structure.

stress, the glass fibre mesh and cementitious coating layer suddenly crack together with the EPS foam cores almost without any advance sign of structural failure. However, the *Dryvit* system behaves as if it were a totally integrated part of the EPS foam. Considering these structural behaviours, we rationalise the EPS composite as an equivalent non-composite material for the modelling technique in our preliminary FE structural analysis.

The first author proposed a reversed displacement model for the quick approximation of performance-based freeform structures in early design stages (Figure 3 left). The moderately magnified displaced 3D geometries were re-imported into the FE simulation software in reversed form, which effectively reduces the stress concentration of its hanging model-like structures (Okuda and Chua, 2011). In our previous experiment, we used polymer-based laser sintering 3D printing (Figure 3 right) to fabricate its doubly curved form, which usually requires fully customised formworks in actual concrete constructions for instance.

Developable Surface Panelization Strategy

Structurally optimised long spans tend to be non-uniform curved surfaces, such as catenary arches or doubly curved thin shell forms. These structures usually require fully customised formworks as in the cases of bricks or concrete shells. In this paper, we fabricate and assemble the long span structure in a cost- and time-effective manner without us-

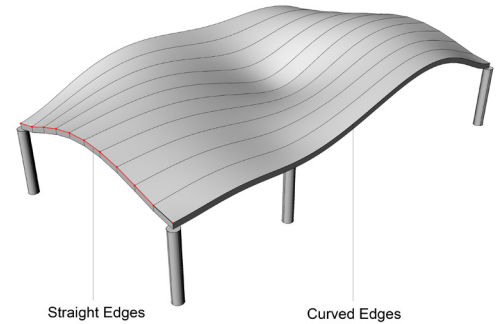
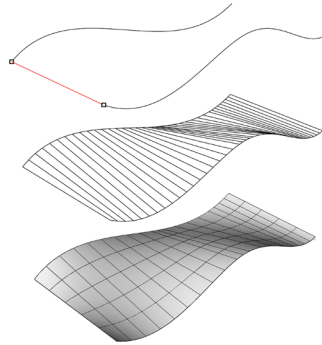
ing formworks. One of the key strategies is how to panelise doubly curved surfaces into a series of ruled surfaces that can be fabricated by using CNC hotwire cutting.

Flöry and Pottmann (2010) developed an algorithm to approximate a doubly curved surface into a series of ruled surfaces while ensuring maximum surface continuities. This method has the advantage of achieving smoothly connected surfaces by utilising a number of ruled surfaces, while reducing its construction cost compared with fully doubly curved forms. This method seems to be suitable for constructing freeform architecture. In this method, the discretisation pattern may need to be in the form of a Zick Zack layout in order to maintain smooth surface continuities; thus, each panelised component's footprint is different. The geometric calculations for the panel generation are rather complex, for which *Evolute GmbH* [2], a geometry expert company, provided software and consultation for the approximation of the freeform surfaces. *Zaha Hadid architects* have also made use of this strategy for hotwire-cut EPS foam mould productions.

By contrast, our challenge here is not freeform or smooth surface continuity, but rather producing structurally efficient forms in a cost-effective manner. The CNC hotwire-cut EPS foam for the Cloud Arch project is not meant as a façade or as moulds for structures, but rather for the structure itself. Our challenge is how to cut a shell-like shape with thicknesses and join them together structurally. We in-

Figure 4

Left: The CNC hotwire cutting process defines the developable surface geometry. Right: The discretisation of structurally optimised doubly curved geometries (12 × 24 m) into a series of ruled surface strips.

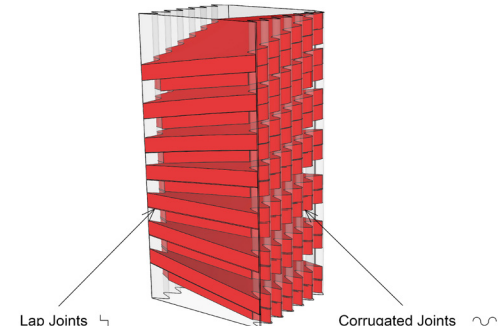
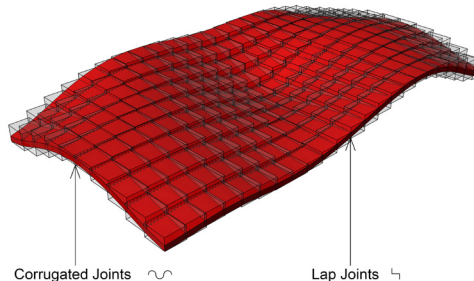


investigate a radical panelisation strategy for doubly curved forms, which uniquely fits with the Cloud Arch project.

Firstly, doubly curved surfaces are discretised into a series of ruled surface strips, each of which is defined by straight lines that sweep along two rail curves or loft curves with straight sections. All curved lines are parallel in plan view with an equal distance of 1.2 m. These ruled strips are considered to be equivalent to a CNC hotwire cut with independent axis control (Figure 4). We make the straight segments as short as possible from a reasonable production point of view so that the continuity of the straight edges becomes close to the original smooth curve. The result is quasi-doubly curved surfaces that are optimised from both a structural and a fabrication efficiency point of view.

Figure 5

Left: The developable surface strips are further articulated into 1.2 × 1.5 m sized components, which are placed within bounding boxes. Right: As the component dimensions in plan view are identical, all components are effectively stacked into larger blocks for both material- and time-efficient CNC hotwire cutting. The curved boundary edges are cut vertically with corrugation at first and then each component is cut out with lap joints horizontally.



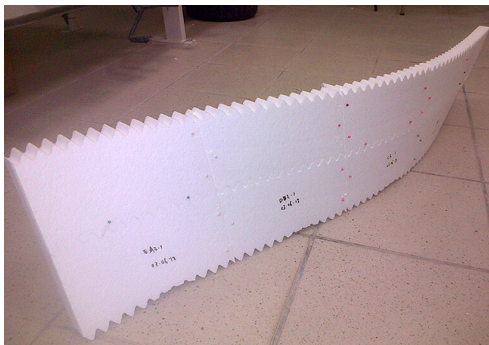
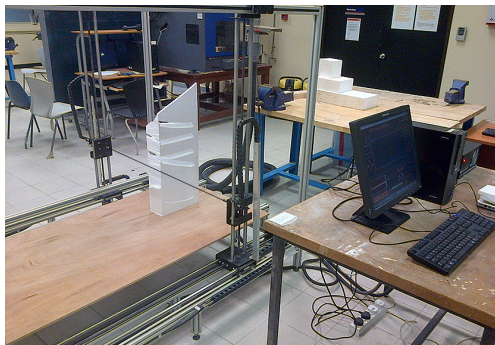


Figure 6
Left: CNC hotwire cutting process for the 1:10 scaled prototypes (CNC Multitool, CUT 2300S), which can cut singly curved components rapidly. Right: 12 m span at 1:10 scale partial EPS composite shell for assembly testing with corrugation joint problems.

CNC Hotwire Rapid Prototyping and Assembly

The proposed panelisation strategies are tested with a scaled prototype at a 1:10 scale.

Firstly, EPS foam blocks are placed horizontally on the CNC hotwire machine in order to cut the corrugated profiles. Secondly, the blocks with the corrugated profiles are erected vertically and then a series of stacked components are cut out including lap joint profiles (Figure 6 left). As the CNC hotwire machine provides independent axis controls at both ends of the hotwire, each component can have unique ruled surfaces as profiles. These components are assembled in strip form with lap joints first and then aligned to the next strip with corrugated joints. The result is smoothly connected quasi-doubly curved surfaces (Figure 6 right). Compared with CNC milling processes, these stacked CNC hotwire

cutting strategies reduce the amount of wastage by half and provide a processing speed that is more than 10 times faster.

Both lap and corrugated joints are then covered with the glass fibre mesh and cementitious coatings to ensure the structural continuity of the quasi-doubly curved surfaces (Figure 7 left). The quasi-doubly curved surfaces are structurally optimised, so that the assembled 1:10 prototypes are effectively supported by the three column positions successfully, which may look like a cloud (Figure 7 right).

One of the pioneers of large-scale doubly curved composite structures was the glass fibre-reinforced plastic sandwich roofing of the Rabin Center in Tel Aviv (Eekhout, 2007). However, the key goal of the Cloud Arch project is ultimate material efficiency not simply fluid 3D forms. A large-scale structural prototype in a catenary arch, which is

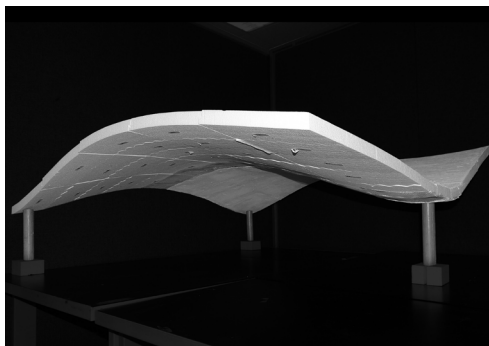


Figure 7
Left: Glass fibre mesh and cementitious coating application process. Right: 12 x 12 m span Cloud Arch prototype at 1:10 scale (before coating).

Figure 8
4 m span, 1:5 scale EPS
composite arch prototype. The
EPS foam has a Dryvit coating
applied to the top and bottom
sides. It is exceptionally light
as a construction material and
can easily be carried by two
people. It is also structurally
stable with a person standing
on top.



one of the simplest structurally optimised forms, is also fabricated and tested with loading under gravity in order to prove the concept. The prototype size spans about 4 m, which is at least equivalent to a 20 m span at 1:5 scale. A *Dryvit* coating is applied to the top and bottom sides of the EPS foam core; the top coating is only necessary for fire and weather protection not for structural purposes. The prototype proves that it is rigid enough to support one person standing over the 4 m span, which is equivalent to a minimum point design live load for a full-scale roof. Despite its large size, only two people are needed to carry the prototype as over 90% of the EPS foam core is air, which results in a new type of ultra-light-weight structure (Figure 8).

CONCLUSION

The structural optimisation using FE analysis points out the regions with high stress in tension, which can be reinforced effectively with an additional layer of glass fibre mesh. Subsequently, the meshes can be selectively reduced from regions with minimal tensile stress values from a structural point of view, although all surfaces are covered with a minimum amount of mesh for fire protection reasons.

According to the structural simulation of the EPS composite structure, the core material (EPS foam) thickness/section at the bottom part of the arch needs to be very thick due to the very low density of the material. For the bottom part of the arch, it may be reasonable to alternate with higher density

materials, such as concrete, for reasonably thinner sections and high resistance to the horizontal thrust. The composite FE structural simulation method can be explored further, which may open up the possibility to control the distribution of tension layers more accurately.

The *Dryvit* system is flexible due to the use of a polymer-based cementitious coating and glass fibre mesh. This coating eventually traces the movement of the EPS foam to which it is attached, which is a great advantage for the EPS composite structure, as its structural behaviour is rather dynamic not static like concrete.

The rationalised panelisation strategy is proposed for the EPS composite structure and tested with scaled prototypes to prove the concept. It works successfully at a 1:10 scale fabrication test in both a cost- and a time-efficient manner to produce a quasi-doubly curved optimised structure. Our current assumption is that lap and corrugated joints with glass fibre meshes and cementitious coatings may tightly integrate all components structurally. In order to prove this aspect, further studies and joint testing need to be carried out. Tension layers with other materials, such as carbon fibre meshes, may significantly increase the bending strength of the EPS composite; however, this needs to be in balance with traceability to the core materials.

Overall, the Cloud Arch project has high potential to be realised as a cost- and time-efficient sustainable structural system for long-span roofing, which can provide material-efficient, ultra-light-weight, thermally insulated, economical, sustainable and quick construction systems as well as reduced scaffolding and formworks. This could be applied to many types of column-free spaces, such as factories, gymnasiums, markets and cafeterias.

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