Design of a Folded Roof for the V&A Museum in London

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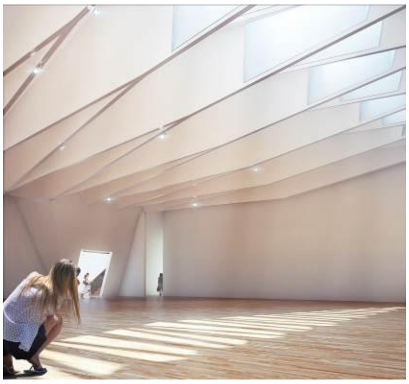
Lee Franck, born 1984, received her MSc in Civil Engineering from the Ecole Polytechnique Fédérale de Lausanne. For the past 3 years, she has worked in a multi-disciplinary building engineering group and has recently joined Arup's civil structures and bridges team in London.

Summary

This paper describes the design of a folded roof for a new 1500m^2 gallery for the Victoria and Albert Museum (V&A) in London. It includes the description and development throughout the design stages of a unique roof system. It focuses on the optimisation of the geometrical shape of the roof both for structural efficiency and the highest architectural quality. Parametrical modelling has been used both by the architects and engineers as a tool for option exploration and effective communication and collaboration. Automated design software was used to investigate a large number of structural configurations which have also benefited from early Contractor advice to evaluate their fabrication and construction implications.

Keywords: Folded structures; complex geometry; optimisation; parametrical design; 3d-printing.

1. Introduction



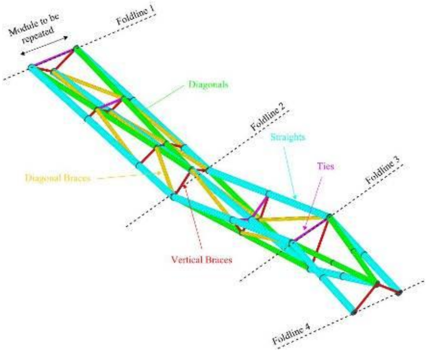
Arup and Amanda Levete Architects (AL_A) teamed up for the design of a new gallery set below a new external public courtyard which was to house installations and events. The concept for the gallery roof results out of the integration of both structural and architectural aspirations – making use of an innovative and efficient structural system and continuing the V&A's tradition of ornate ceilings. The efficiency of folded structures has been proven by nature as can been seen in shells or palm sheets. The structural depth inherent in the folds allows the roof to span the 35m column-free space and the adaptability of its three-dimensional shape enables it to wrap around a mezzanine and the changing level of the external courtyard.

2. Geometry

The integration of the services requirements of the high-specification gallery was most easily achieved with a folded truss structure which could be prefabricated off-site to minimise works on a very constrained site. The folded roof gives support to both the courtyard and mezzanine floors. The internal wall of the mezzanine floor allows the introduction of a truss running perpendicular to the folded structure hence reducing the roof span. The folded roof pattern is a linear folded plate surface formed of triangular folds. In this geometry the maximum structural depth only occurs at foldlines which therefore have to be placed strategically to obtain an efficient structural system. Each crease line of the folded plate pattern is created by chord elements which either run parallel or diagonally on plan. The trusses are braced and tied at foldlines and intermediate bracelines restraining the chords and preventing the module from unfolding sideways. Diagonal bracing on each face help transfer shear loads between chords.

https://doi.org/10.2749/222137813808627370

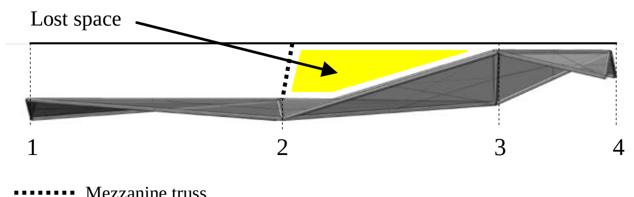
3. Optimisation



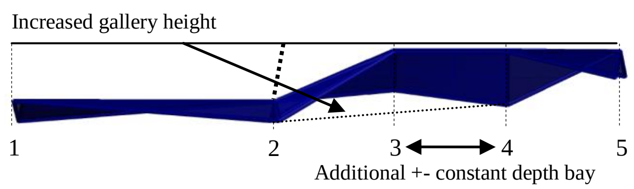
The folded roof geometry can be defined by a set of parameters such as the number of foldlines, their location and associated depth, the width of the module and the number and position of bracelines. All these parameters have been explored and optimised throughout the design process making use of the parametrical modelling tool Grasshopper. For each option the elements were sized iteratively by an Excel script which allowed the designers to compare different options rapidly and objectively. To avoid any redrawing and limiting the risk of error, the sized geometry was exported from the analysis programme directly into Revit to produce a final set of structural drawings.

Initially a 4-fold geometry was adopted, with a foldline located at mid-span to create maximum depth at maximum moment location. The width of the module was set at 2.84m for maximum efficiency of the roof and courtyard structure and the right visual balance between sharpness and flatness. The optimum number of bracelines was investigated both for minimum roof weight and fabrication/erection cost. This study benefitted from specialist subcontractor advice and resulted in a lighter, less complex roof structure. For each geometry, open versus closed sections were compared and evaluated as per their weight and unit fabrication cost.

To regain the lost space between roof and courtyard structure, the optimum number of foldlines was reiterated. A 5-foldline geometry with a constant depth bay in the middle third of the span was adopted matching the shape of the bending moment diagram at its best. A modular construction was made possible by adopting channel sections for the top structure which could be connected back to back to the adjacent module. At the same time the shallow folded plate structure under the mezzanine was replaced by variable depth deep beams which are not only lighter, but also simplify construction.



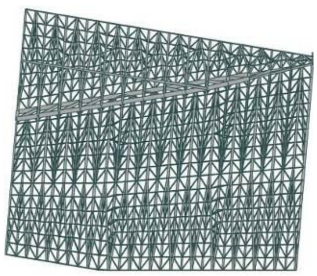
Stage D



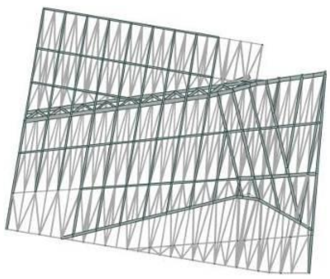
Stage E

4. Conclusion

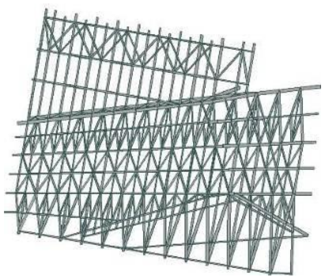
Throughout the design stages, every effort was made to create the most efficient folded plate roof structure which can respond to the high loading criteria of the courtyard. Intense optimisation was used, eventually reducing the roof weight to almost half its initial value. At the same time the number of structural elements and connections were reduced leading to a less complex structure with reduced fabrication and assembly costs. Each iteration having as well an impact on the aesthetic of the ceiling, close collaboration between the engineers and architects was key to achieving an efficient structure of the highest architectural quality. With design complete at the time of writing, works on site are due to commence in summer 2013 with completion in 2015.



Stage C
306 kg/m^2



Stage D
241 kg/m^2



Stage E
166 kg/m^2