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A practical grid generation procedure for the design of free-form structures

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ABSTRACT

Computer aided design software enables the rapid conceptual creation of a curved surface geometry, whereas it is neither a convenient nor an obvious task for engineers to create a discrete grid structure on a complex surface that meets architectural and aesthetic requirements. This emphasizes the importance of grid generating tools and methods in the initial design stage. This paper presents an efficient design tool for the synthesis of free-form grid structures based on the "guide line" method, employing a fast and straightforward approach which achieves grids with rods of balanced length and fluent lines. The process starts with defining a limited number of curves (named the "guide lines") on the surface, which are then used to determine the directions of the 'rods' of the grid. Two variations of this concept are introduced in this paper: the 'Guide Line Scaling Method' (GSM) and the 'Two Guide Lines with Two End Vertices Method' (2G2VM). Case studies are provided which illustrate the successful execution of these procedures. The results show that the free-form grid structures generated with the proposed methods feature a regular shape and fluent lines, thereby satisfying aesthetic requirements. These two methods have been programmed into the software ZD-Mesher, enabling rapid grid generation for structural design purposes.

1. Introduction

New techniques in computer aided design, such as parametric modelling and scripting, have enabled a new level of sophistication in design. Among other developments, this has facilitated the increased inclusion of 3D free-form surfaces in structures, marrying the expression of architectural creativity with the application of cutting-edge technology. Complex free-form structures are one of the most visually striking trends in contemporary architecture. A number of structures with attractive designs and eye-catching shapes have recently been erected, as shown in Fig. 1(a)–(d). While they are constructed with sometimes vastly different materials, they all exemplify the emergence of free-form grid structures.

If a curved surface with a suitable form is chosen and well-positioned supports are added, an efficient flow of the forces within the structure can be obtained [3], where a single layer grid-shell structure consisting of a lattice of rods can be used to transmit the external loads down to the foundations mainly by means of axial forces within the members. This structural form often brings benefits in the form of reductions in material usage, enhanced aesthetics, better structural performance, ease of fabrication and an increase in unobstructed service space. However, it is not always obvious how to create an efficient grid structure on a given surface. For example, Fig. 2 illustrates the roof structure of Daishan Sports Stadium in China by Ding and Wang [4]. The curved free-form surface shown in Fig. 2(a) was determined by the architect in the early conceptual design stage, but subsequently the structural analysis required an arrangement of nodes and elements on the curved surface. In this particular case, this was achieved manually with tedious iteration, with the result being shown in Fig. 2(b). Fig. 2(c) shows the resulting structure in an architectural rendering with the skeleton in Fig. 2(b) covered by roof panels. Given the increasing popularity of free-form grid structures, a practical grid generation tool which can quickly and efficiently generate a structural grid on a given free-form surface is necessary in order to assist structural designers, particularly in the early design stage.

Earlier studies on free-form grid structures have mainly concentrated on the structural design aspects [1,5], form-finding methodologies [2,6], connections [7] and optimization techniques [8–10].

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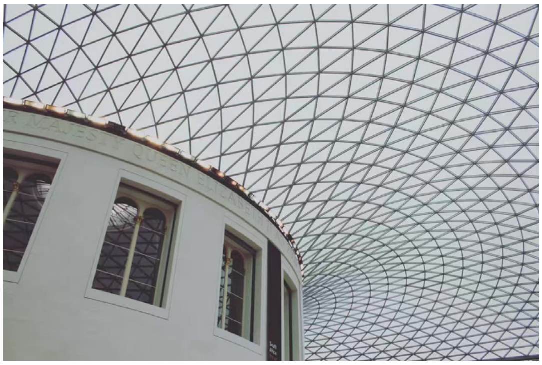
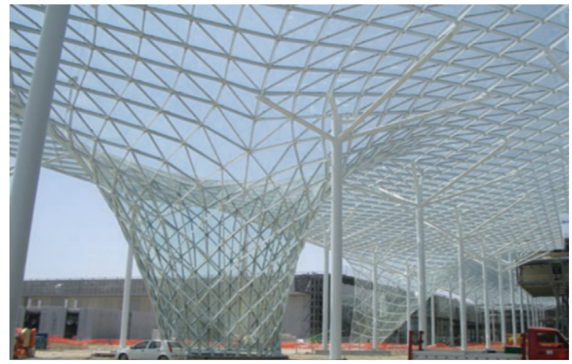


(a) British Museum Great Court (London, UK)



(b) Vela-roof in Milan Trade Fair (Milan, Italy)[1]

(c) Shenzhen Sports Center stadium (Shenzhen, China)

(d) Toledo timber grid shell (Naples, Italy)[2]

Fig. 1. Examples of free-form grid structures.

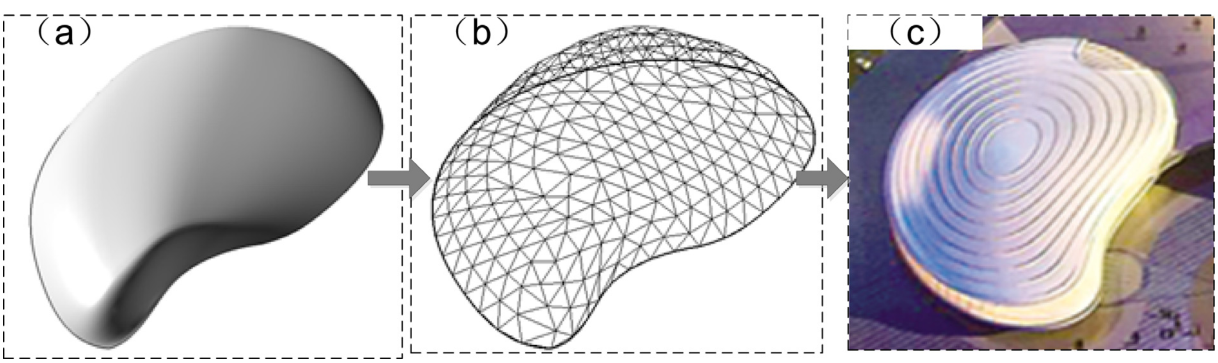


Fig. 2. Creation of a free-form single layer grid structure (Daishan Sports Stadium, Daishan City, China) [4].

However, previous research on grid generating methodologies is rather limited. Park et al. [11] and Shepherd and Pearson [12] demonstrated that topology optimization methods can be used to create an efficient structural grid on a predefined surface, with both studies presenting a layout optimization algorithm for both single and double layer shells in the conceptual design stage. Wu et al. [13] conducted theoretical and experimental research on grid generation for a cable supported dome using topology optimization techniques. However, a drawback of all these topology optimization studies [11–13] is that the resulting topology is rather coarse and cannot directly be used in design (i.e. some refinement is required).

Research has also been conducted at the University of Cambridge [14] with the aim of generating practical and efficient grids over free-form surfaces, while considering the mechanical performance under multiple load cases. In this process a discrete grid structure consisting of repeating quadrilateral or triangular cells was first specified. A homogenization process was then used to represent this lattice of rods by anisotropic continuum shell elements for the purpose of structural analysis. The rod orientations were then optimized using a Genetic Algorithm.

In other research by Su et al. [15], the main stress trajectories on the surface under loading were used in a grid generation tool. A modified 'advancing front' mesh technique was thereby used. While this method is geared towards an efficient structural performance of the grid, an iterative process and FE analysis are needed in the grid generation procedure, requiring significant computational time. Another drawback of this method is that it may lead to a non-uniform grid with distorted unit cells, as show in the generated grid for Sun Valleys at the Shanghai EXPO in Fig. 3.

In practice, rather than optimizing structural performance, it is sometimes more important to generate a grid on a curved surface

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