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Quadrilateral panelization of freeform surface structures

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ABSTRACT

Freeform surfaces need to be discretized into manageable sized panels so that the surface can be fabricated in smaller pieces that are then assembled on site. This discretization process comprises numerous challenges; including not only the aesthetic and spatial concerns, but also the structural and constructional needs. The mesh generated has to fit to the surface, without distorting the form; meanwhile the panels have to preserve their planarity in order to prevent any brittle failure due to warping. This study proposes a unique approach to quadrilateral discretization by incorporating the form, material capacities and fabrication challenges in order to obtain a structure that can be realized and constructed.

In this paper, quadrilateral discretization of freeform surfaces is studied with the focus of material properties. The possibility of utilizing quadrilateral meshes with limited non-planarity is explored. The capacity of materials against warping is calculated, by structural experiments and simulations to obtain the limiting values that are integrated into design as tolerance of panels to non-planarity. Consequently, the amount of non-planarity becomes a parameter that needs to be considered during the generation of the quadrilateral mesh in order to generate an optimum surface discretization.

1. Introduction

Freeform surface structures can be distinguished from other types of structures by their unique, amorphous shapes, smooth continuous lines, and complex geometries [1]. In contrast to traditional structural design of horizontal beams and vertical columns, freeform surface structures do not have a separate structural system; instead the surface is designed to function as the main structural system. Therefore, the integration of the structural system with the amorphous form causes complexities, not only in the design process, but also in the realization and construction of the structure. These problems of design and fabrication of freeform surfaces have always been an important issue from the early examples of freeform surfaces in 1920s till today's more contemporary examples.

Heinz Isler (1926–2009), a pioneering name on lightweight concrete shells, used physical models to generate efficient forms; shells that carried the required load with the minimum possible material [2]. As concrete could be poured into the desired form; Isler's shells could be fabricated and constructed. However, the challenge was to obtain formworks with the complex geometry. Moreover, his method was feasible to construct in concrete but did not work with other materials.

Due to these limitations, discrete systems had been considered, which provided the application of other materials than concrete. A common application has been the grid shell, where the surface is made up of discrete structural members, mostly orthogonal to each other, with panels fitting in between them. Grid shells have been considered in the design of freeform surfaces in order to overcome the fabrication problems [3]. These discrete surfaces have not only offered advantages for fabrication and construction, but have also provided spacious designs due to the use of transparent materials for the panels [3–5]. The main structural framing is usually selected to be steel, whereas glass has been preferred for the panels because of both its strength and transparency. Because of the brittle property of glass, panels have mostly been used as planar sheets. In some rare cases, glass was utilized as bent or curved sheet; i.e. spherical dome of the swimming arena in Neckarsulm (Fig. 1a), where the glass sheets were manufactured with curvature [6] or in the case of the German Historical Museum roof, where the glass plates were manufactured flat and then bent and warped during the assembly to obtain the continuous smooth roof system required [7] (Fig. 1b).

Grid shells have mostly been applied to surfaces with regular geometries (translational, rotational, etc.). However, when the form is organic, not generated by simple geometric rules (not a derivative of a translational, rotational surfaces), the panelization (discretization) process becomes a challenge. The panels obtained by the discretization have problems either with size, form or structural strength. Different patterns (triangulations, quadrilaterals, or hexagons) of discretization have been applied on freeform surfaces, resulting in meshes with different advantages and limitations.

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Fig. 1. (a) Swimming Arena in Neckarsulm [7]. (b) German Historical Museum [7].

Triangulations have been the most common pattern in order to discretize freeform surfaces not only because of their stable geometry, but also aesthetically satisfying organization and the way they generate planar surfaces [8]. However, automation of the construction process is difficult due to the non-standardization of the nodes in triangulation. Each node needs to be custom-designed as six members per node causing a complex joint assembly.

To prevent the problems encountered with triangulation, quadrilateral panels are considered where 4 members join at one node in contrast to 6 members in triangulation. With less number of members connecting at each node, design and construction of these joints become less complicated. In addition, quadrilateral meshes generate a less dense network of members that provides a more spacious feeling underneath. However, the major problem for quadrilateral discretization is that not every quadrilateral panel is planar. Therefore, unless all the panels are fully planar, there is the problem of sudden fracture of brittle materials, such as glass that is commonly used for discrete surface panelization. That is why quadrilateral discretization focuses on the planarity of panels while generating the mesh.

Various methods for the generation of planar quadrilateral meshes have been studied. Some propose triangulation on a surface as the initial step where they can be re-meshed to generate quadrilaterals with planar faces [9–11]. Other studies use methods and algorithms that generate quadrilaterals on the surface directly [9,12,13]. Alliez et al. [9] had a geometric approach to this problem where they proposed an algorithm based on lines of principal curvatures,[1] which intersect each other at right angles and generate approximately planar panels by the intersection points of these curvature lines [8]. Their study projects a great potential for the freeform surfaces to be mapped with these principal curvatures and obtaining planar quadrilateral panels. However, when the method is analysed considering its practical applications, it is observed that panels generated by the principal curvature lines do not have constant or similar mesh size, especially when they are applied on freeform surfaces, which have dramatic changes of surface curvature, resulting a non-homogeneous mesh distribution (Fig. 2a) [14]. These uneven mesh sizes cause problems at the fabrication process. Panels that are close to umbilic points[2] or high curvature points are so small that they can neither be materialized nor physically constructed (Fig. 2b). At the points where principal curvatures do not solve the singularities, non-quadrilateral panels need to be used in order to obtain the continuity of the generated mesh.

Another method to generate quadrilateral meshing on freeform surfaces has been an optimization algorithm, Evolute Pro [15], that has constraints, such as planarity, surface closeness, fairness of curvature, etc. where many of these constraints can be applied simultaneously with the appropriate weights assigned to them. Panels are generated either as triangulated or quadrilateral. The advantage of this tool is its ability to optimize a homogeneously distributed quadrilateral mesh on the surfaces considering both the planarity of the panels and their best fit to the original surface. However, the size and/or number of the generated panels are determined automatically. Therefore, the designer does not have full control over the final mesh design. Moreover, with the increase of complexity of the surface, the absolute planarity is not achieved completely for all panels.

These aforementioned studies demonstrate that obtaining freeform surface discretization with planar quadrilaterals has various challenges; either problems to obtain absolute planarity of the panels, or to control the distribution of panels (both size and number) through these surfaces. This study focuses on the planarity issue of these panels and questions the limits of planarity in order to help the meshing process. In recent works, panels have been designed with the obligation of being planar and some precision is accepted for the planarity measurements with no consideration of the material properties [16–18]. However, the tolerance of each material to non-planarity is different and this tolerance can be used in the design process to obtain an optimized design.

2. The methodology

This study demonstrates the utilization of non-planar quadrilateral panels for the discretization of free form surfaces. The first step is to determine the tolerance of materials for non-planarity by structural analyses. These analyses are conducted through the steps of choosing a designated material, building the appropriate set-up, and to conduct the experiments. Then, a parametric relationship is derived between the panel sizes and the deformation limits, in order to calculate the limiting condition for any panel size. Finally, the generated quadrilateral mesh is analysed, and the curvature occurring at the panels is compared with the limits of the selected material. If the selected material is not capable of resisting to that curvature, then either the material can be changed or the surface can be re-discretized.

This study particularly aims to demonstrate the complete methodology more than to conduct a structural analysis study. The focus is, therefore, more on the process and the idea of utilizing non-planarity into design than the detailed study of structural analyses. Results obtained in this study are case-specific to demonstrate the application of the methodology that can be used in further studies as a foundation. For this study, analyses are conducted with one selected material and the experiment set-up is built for this case in the lab.

2.1. The material

In this study, glass is selected as the designated material experiment material; because glass has been a common material for freeform

[1] Principal Curvature Lines: At any specific point on a surface, infinite number of plains that are normal to the surface at that point can be drawn, corresponding to a specific normal curve that is a part of a circle that defines the surface curvature at that point. Among these infinite sections and curvature lines, there occur a unique set of minimum and maximum curvature lines at each point that are called as principal curvature lines. They are represented by k_1 and k_2 respectively where $k = 1/\text{radius}$.

[2] Umbilic Point (Umbilics): Points on a surface where there are no unique maximum or minimum, but infinite principal curvature lines. The surface is either flat or spherical at that point.