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Design optimization and additive manufacturing of nodes in gridshell structures

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ABSTRACT

In this paper, two new design approaches are proposed to design structural nodes of complex shapes for gridshell structures, seeking improved structural performance and design efficiency by using the transitional section method and the bi-directional evolutionary structural optimization (BESO) method, respectively. Detailed design methodologies are introduced and compared with two types of conventionally designed structural nodes in real use, i.e., Seele node and Sun Valley node. Finite element analyses are conducted to evaluate the stress distribution, maximum stress and mean compliance of different structural nodes. The results show that, although the BESO node has the highest stiffness and the lowest structural volume, it seems to have a higher maximum stress level. Multiple load cases are considered in the analysis and design optimization processes. Moreover, the application of Laplacian smoothing in structural node design effectively reduces the stress concentration. Prototypes of the newly designed structural nodes are fabricated by additive manufacturing, which enables the rapid and precise manufacturing of customized structural nodes optimized for specific loading and boundary conditions.

1. Introduction

Gridshells, also called lattice shells or reticulated shells, are lightweight spatial structures. Their organic shape and column-free space, free-form surface and maximum transparency provide unlimited design freedom for architects and structural engineers [1]. Regardless of different form definition methods in the design, either by using funicular modelling as Frei Otto suggested [2] or arbitrary double curved free-form shape according to application needs, these innovative spatial structures derive their strength from having double curvature forms [3].

Geometric non-linearity in gridshell structures may bring global instability, which is strongly influenced by both the geometric parameters and the joint rigidity [4–8]. It has already been reported that, much like continuous shells, grid shells could collapse in buckling mechanism which is sensitive to imperfections and stiffness of structural members and nodes [9–13]. Many structural node configurations have been developed to connect members of gridshell structures [14–16]. However, most of them have limitations in moment capacity, stiffness and manufacturability which would affect the curvature of the gridshell surface [14], global stability of gridshell [9–13] and cost of manufacturing.

It is a great challenge to generate a significantly large number of three dimensional (3D) customized structural nodes of complex shapes by conventional design and manufacturing methods, which usually involve cutting individual parts and welding them together. It has been reported that structural nodes are one of the most costly parts in constructing 3D structures [14,17]. The large amount of welds and the stress concentration in sharp edges and connections of conventionally manufactured structural nodes increase the risk of fatigue failure under repeated loads. Therefore, structural nodes that combine design flexibility and manufacturability sometimes become favourable, such as those with smooth transitions and flexible forms by casting [18–20]. Laplacian smoothing, a mesh optimization algorithm [21], is an effective design tool to smooth the FE mesh geometry. In Laplacian smoothing, nodes of the mesh are iteratively moved to the geometric centre by weighting the contribution of each neighbouring node in an averaging function [21–23]. Unfortunately, these smoothed structural nodes with transitional features cannot be precisely fabricated by using conventional manufacturing technologies. However, newly developed additive manufacturing (AM) technology [24–27] can easily and conveniently achieve it with significantly high efficiency and accuracy, which could fabricate structures, or structural components such as structural nodes, of complex geometries.

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In this paper, two different types of approaches are proposed to design structural nodes for gridshell structures, aiming to find general ways for designing complex structural nodes of better mechanical performance, which could be fabricated by additive manufacturing. The first approach is the transitional section design, which connects a simple node centre to the members by transitional volumes. The second approach is the bi-directional evolutionary structural optimization (BESO), which seeks to achieve the best performance of the entire structural node whilst satisfy various constraints [28]. Triangular pattern is the most common pattern used in gridshell structures and the six-way node is the dominant case in this pattern. Therefore, a typical six-way arbitrary structural node from a free-form gridshell structure made of rectangular steel tubes is extensively studied by using different design methods. Laplacian smoothing algorithm is used to obtain the final topologies by both design approaches to minimize the stress concentration in sharp edges. Conventionally designed structural nodes of similar shapes and sizes used in Sun Valley project of the Expo 2010 Shanghai (Sun Valley node) and Westfield Shopping Centre in London by Seele company (Seele node) are compared and their mechanical performance is assessed by finite element modelling. The volumes, structural mean compliances and maximum von Mises stresses of the newly designed structural nodes and the Sun Valley and Seele nodes are further investigated. Prototypes of the newly designed transitional node and the BESO node are precisely fabricated by additive manufacturing.

2. Designing structural nodes for gridshell structures

2.1. Transitional section design

Structural nodes are usually subjected to complicated spatial loads, which makes them difficult to be designed and manufactured, especially when a large number of design parameters are involved. To simplify the design procedure, transitional design approach is firstly applied in this paper. The key idea of this approach is based on two successive stages. In the first stage, the centre part of the structural node is designed based on a series of processes of projections and rotations of all the members so that the members and the nodes are on the same plane. In the second stage, the members and the centre part are connected by using transitional volumes based on the parameters of the projection and rotation operations. As shown in Fig. 1, the transitional volume contains curved transitional side surfaces and two flat ends of

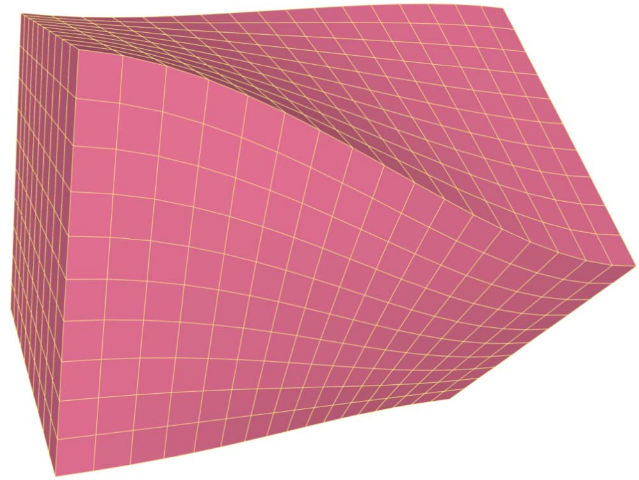

Fig. 1. An illustration of a transitional volume connecting two rectangular end sections of different sizes in a twisted angle.

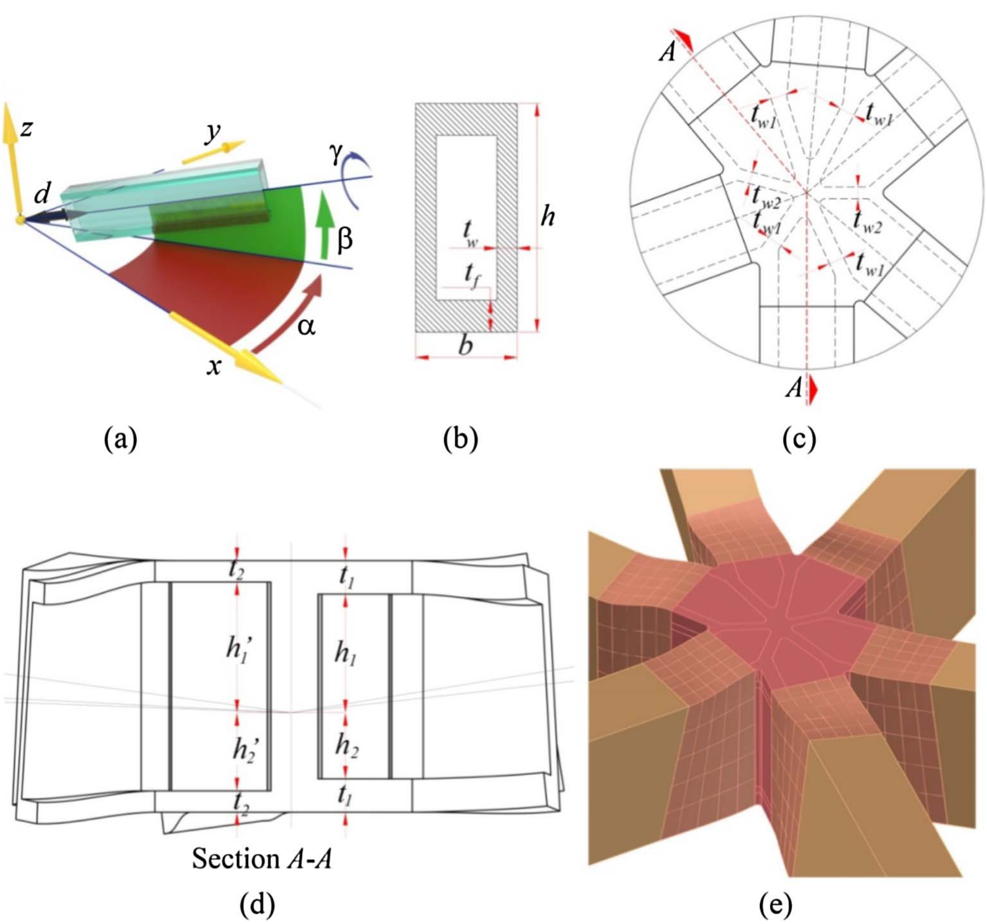

Fig. 2. (a) The spatial position of a member determined by three rotation angles in Cartesian coordinate; (b) cross-section of the steel rectangular tube member; (c) top view of the structural node and its internal structure; (d) view on A-A section of the structural node showing the internal structure of the centre part and the transitional volume of the structural node; (e) a designed structural node connecting to six rectangular tube members by transitional section design approach.