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Synthesis and Optimisation of Free-Form Grid Structures

by

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Abstract

Computer-aided design software allows architects and designers to create shapes which are limited only by their imagination. Creating an efficient grid structure to support a given free-form surface is a major challenge. Laying a lattice of rods on the surface, to form a grid-shell, is a popular scheme. However, it is not obvious how to best position rods on a surface, due to multiple competing criteria, e.g. buckling, deflection, alternative load-cases, aesthetics, constructibility etc.. This thesis presents a set of novel techniques for synthesis and optimisation of grid structures, created from repeating unit cells, on a given surface. Three new approaches are developed using research from aerospace composites, computer graphics and multi-objective optimisation.

The first approach takes principal stress vectors from a continuum shell analysis and automatically creates a grid geometry on the surface that is aligned with these directions.

The second new approach uses periodic boundary conditions to find the homogenised stiffness of a variable geometry unit cell. A complete grid shell structure can thus be represented using an equivalent stiffness continuum shell model; changing entries in the homogenised material stiffness matrices is analogous to altering the direction of the rods in the grid structure. Rod orientations can then be optimised for structural performance using a multi-objective genetic algorithm, without having to regenerate any geometry.

The third design approach uses surface parameterisation techniques from computer graphics to rapidly and robustly create a complete lattice of rods on any given free-form surface, using just a small number of variables to define the rod directions. A multi-objective genetic algorithm is then used to optimise multi-disciplinary criteria, e.g. buckling, deflection and panel flatness. The final outcome is a set of diverse Pareto-optimal designs, between which the designer/architect has freedom to choose.

The design approaches are successfully demonstrated using a range of case studies. For instance, multi-objective optimisation using the third design approach for a doubly-curved roof gave 33% higher buckling load and 55% lower deflection than a conventional equal mesh net grid layout. The Panopticon sculpture case study demonstrates synthesis and optimisation of grid designs on a highly curved surface with holes. Optimal rod orientations for a non-topological surface are considered in the Rest Zone case study. The Elephant House Roof case study considers user-guided grid synthesis, as well as optimisation of numerous practical project requirements, including individual member stresses and mass of steel.