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P. Winslow and Professor S. Pellegrino, (Cambridge University Engineering Department), and Dr S. B. Sharma, Buro Happold, look at some new design tools

Free form grid structures

The advent of uninhibited free-form 3D modelling software has allowed architects and designers to create almost any shape imaginable. In order to physically realise these computer models as a building or sculpture, a cumbersome internal armature can be used along with non-load bearing panels to create the required external surface e.g. Gehry's Guggenheim Museum, Bilbao. Use of grid structure, consisting of a lattice of rods such as the British Museum Great Court roof, (see Fig 1) may be more desirable giving the potential for reductions in material usage and increased internal space. However, it is not always obvious how to create an efficient grid structure on a given architectural surface form – a problem often encountered by the industrial partner, Buro Happold.

Design of grid structures is often still carried out in a similar manner to the early work of Frei Otto; a grid topology/geometry is chosen and then this is followed by surface form-finding. The process for the Mannheim Gridshell was carried out by manually creating a grid of chains at 1:100 scale and then hanging it from a support system to find the inverted surface shape[1]. Although more recent projects may have conducted this procedure numerically rather than physically, the design process is still broadly similar; the connectivity and length of rods in the grid remain largely unaltered throughout i.e. 'fixed grid, form-found surface'.

The corollary of this is 'fixed surface, form-found grid', which has been studied little to-date in structural engineering. Existing techniques focus on simple geometrical rules and algorithms to map a grid onto the surface, such as the very popular uniformly spaced 'diagrid'. Optimisation and rationalisation rarely consider significant adjustment to the grid shape and topology; they are often limited to sizing of rods within the lattice.

Aims of the research

This research, carried out in conjunction with the Buro Happold SMART team, therefore aims to:

- 1. Develop methodologies for mapping a grid of rods onto any given surface using results from simple structural analyses.
- 2. Investigate and create schemes for grid optimisation.

This will enable efficient and elegant grid

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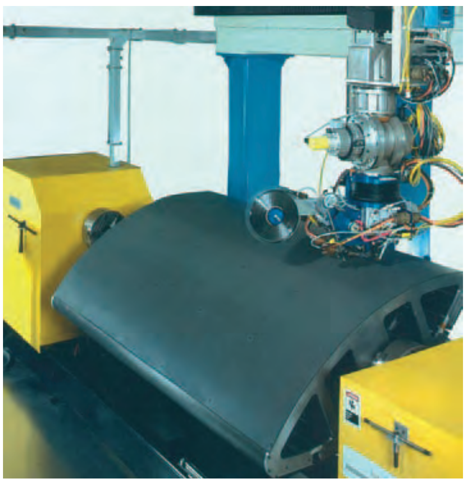

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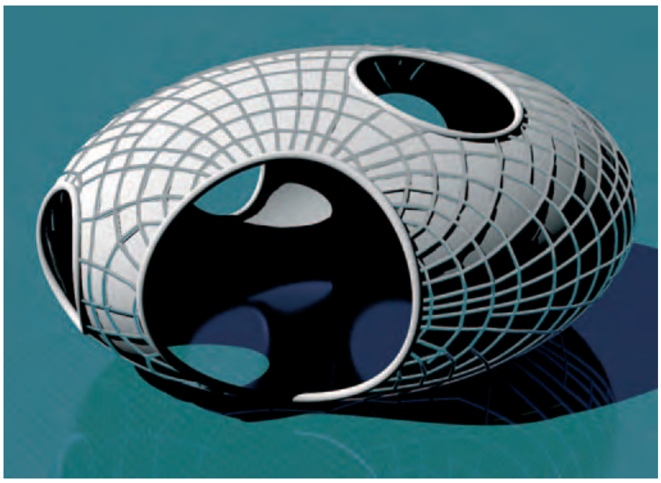

Fig 1. Great Court Roof, British Museum, London UK *(credit: Andrew Dunn)* / Fig 2. Variable angle fibre placement machine *(credit: Automated Dynamics)* / Fig 3. Principal stress grid, on Panopticon surface, UK

structures to be synthesised on any desired complex surface.

Aerospace composites research is being applied and developed to help tackle these aims in a novel way. This is facilitated by the analogy which can be drawn between rods in a grid structure and fibres in a reinforced polymer composite: both lie on a chosen surface such as a roof or an aircraft fuselage.

The orientation of rods/fibres can be varied so as to change the stiffness distribution within the surface (Fig 2).

The rod/fibre direction in one region of the chosen surface could be very different to the directions elsewhere, thus the structure can be tailored to meet a chosen set of objectives e.g. minimise mass, maximise stiffness, maximise buckling load etc., as described by Gurdal[2].

Principal stress mapping

The first aim of the research, to develop methodologies, has been approached by considering a simple optimality criterion, based on the analogy with composites research undertaken by Pederson[3].

Hypothesis

Aligning rods along principal stress trajectories will give a two-way grid with low in-plane bending, hence it is structurally efficient.

Basic procedure

Figure 4 shows the sequence of basic procedures There are a number of other difficulties which must be overcome and refinements which have been made (including in-plane *vs* out-of-plane bending, points of biaxial stress and use of stress magnitude data in addition to directional information). The end result is a tool which can produce a grid on any complex or unusual surface, see Fig 3. These grids have an organic form in which rods 'mimic' the flow of forces and their structural performance can be significantly better than conventional mapping schemes (when measured by maximum deflection).

Grid optimisation

Principal stress grids have a strong rationale if there is a single dominant load case for which low deflection is required (and provided the designer is happy with the constraint that rods must always be perpendicular). However, in real projects there are many competing load cases and multiple objectives, so a more robust approach is desirable. At the present time two-way grids are being considered (i.e. quadrilateral mesh).

Grid optimisation algorithm

Figure 5 shows the sequence of actions. The optimisation process has been coded in C++, linking in with ANSYS finite element package. To date it has successfully carried out for test cases, using open source multi-objective evolutionary algorithms[4]

Tests to validate the above process are currently underway and it is envisaged that very soon it will be possible to input any desired surface and create a set of efficient grid-based structural schemes.

Applications

These structural engineering design tools are being developed in collaboration with Buro Happold, with the aim of applying them during the initial design stages of real projects in the near future. When the designer wants to realise a given surface (with complex geometry) then these tools will be used to rapidly create feasible and efficient structural schemes.

Perhaps one reason why structural optimisation has not been more widely adopted is the tendency to push for a single 'best' design; something that is often not commensurate with architectural projects that have many competing (and often non-quantifiable) requirements. Therefore a key focus for these tools is to create a near-optimal envelope of solutions, thus providing design freedom. se

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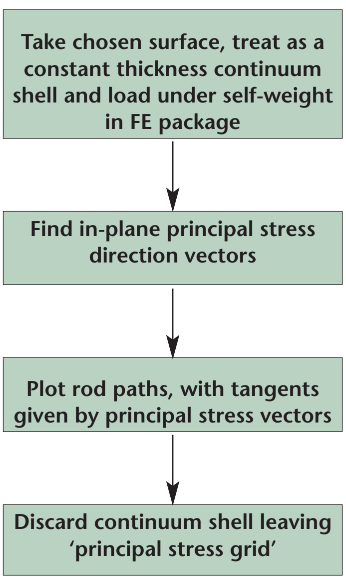

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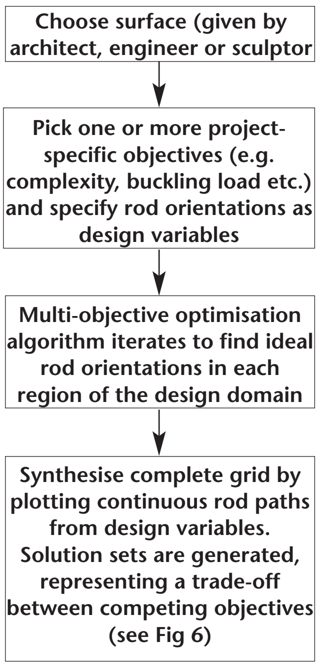

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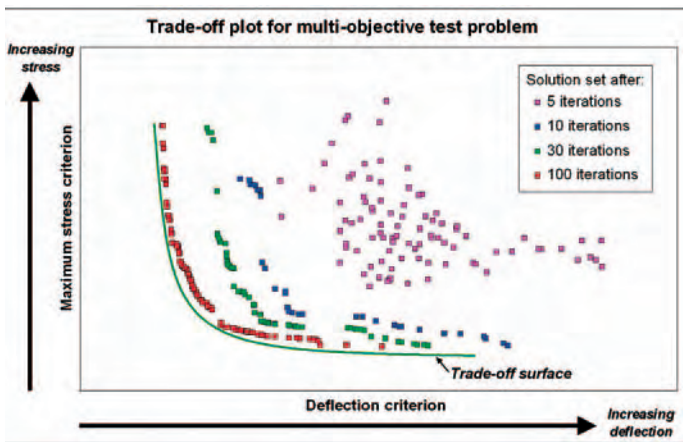

Fig 4. Basic procedure / Fig 5. Grid optimisation algorithm / Fig 6. Trade-off plots