NON-LINEAR MATERIAL MODELS FOR COATED WOVEN FABRICS

CONTEXT

Development of Membrane Structures by Ove Arup & Partners

Arup's early opportunities to design tensile surface structures coincided with Frei Otto's phase of work, from 1975 onwards – the Hanging roofs at Mecca, the Bundesgartenschau at Mannheim, City in the Arctic, Berlin Olympic Stadium and Government Buildings in Riyadh. This period was concurrent with the presence of gifted engineers such as Peter Rice and Alistair Day; the latter being the originator of the Dynamic Relaxation (DR) algorithm, a mathematical technique that could reproduce the behaviour of non-linear/large displacement structures. This technique became Arup's primary intellectual tool for calculating the shape of these structures and analysing and predicting their behaviour.

A major constraint on the production of large-scale surface structures at that time was the accurate definition of their spatial geometry. This was necessary for analysis and justification purposes as well as for detailed drawings and cutting patterns for construction. In these respects physical models were labour intensive and prone to measurement errors.

The break through for Arup came in using our own software, based upon DR, to reproduce the shapes of a variety of domes and vaults that Otto had been developing with inverted hanging chain models following a method similar to Gaudi. One of these structures was to be 90m span and errors in measuring the physical model were shown to have very significant effects. Rather than start from an approximation to the final form by taking measurements from models, the imaginative step was to see that a precise statement of the net's topology (i.e. which element is joined to which and the lengths of each) would be sufficient input data for DR to compute the large displacements involved with all the elements starting from within the same plane as the support points. In doing this we were exactly replicating the physical behaviour of the net model as it falls and takes up its shape. Similarly a soap film forms itself naturally into a figure of equilibrium produced by surface tension. Again, crucially, it was seen that DR could actually move a set of "finite elements" into the same figure of equilibrium between the same points of support.

Thus started a process of developing our software to be able to replicate what we perceived as the essential material and structural phenomena associated with prestressed membranes and cable networks. Naturally it has gone through several cycles of development and it is used for design visualisation, analysis, patterning and drawing production.

A further important development has been the inclusion of beam elements into the program giving us the capacity to produce structures with slender ribs. This followed from the perception that the buckling of slender compression elements can be inhibited by appropriate arrangements of tensile bracing elements. For instance, the arch ribs within the roof framework at Bari have fans of bracing rods that increase their "in-plane" buckling capacity allowing quite slender members to be used. Similarly the cable nets forming the surface of the Youde Aviary in Central Hong Kong brace a series of arches up to 60m in span both in-plane and out of plane. Creating these analysis "tools" has been part of our engineering effort in enabling us to design these structures and maintain Arup's leading international position.

"Design" in one sense is the process of developing a concept into an effective and elegant three-dimensional configuration of elements, however this concept must from the beginning embody a means of being prestressable. This truth runs all the way through the design process until it finally informs the working details of boundary connections. The full scope of engineering design however is quite broad even after establishing the basic concept. Analysis is required to establish the size of all supporting members and all the rotational movements that need to be provided at connections, both during the structure's working life. This also extends to the construction phase, since prestressing sometimes can be achieved by whole body movements of parts of the supporting structure (e.g. masts, arches etc). The design engineer therefore uses intuition throughout the development of the design to ensure constructability.

Whilst Contractors and Consulting Engineers such as ourselves, are distinct commercial entities we both share a common culture of being "constructors". This is in the sense that we have created similar "intellectual tools" that are directed towards broadly similar goals. Determining how a structure is actually to be built is ultimately the contractor's responsibility. This involves him conceiving a sequence of assembly and the step by step means of achieving the specified prestress distribution through out the whole structure. Such a sequence needs to be proved in advance of construction and for many tent structures it may be self evident that a satisfactory outcome is achievable.

However, on large and unusual structures - ones that might include flexible beams that interact with the membrane - the sequence needs to be verified, and possibly developed, in advance by numerical modelling. This is in addition to the extensive numerical work required to establish the structural form and demonstrate the design.

We have made installation analyses directly for contractors, with examples including the Schlumberger building (Cambridge, UK) and the Grande Arche (Paris). The way this work is done is by disassembling the computer model of the whole structure, including the membrane at prestress, in a series of steps that are the reverse of the intended construction process. On the Schlumberger project it was important to know what the worst cumulative effect of tolerances in cable fabrication, position of the mast tops and variation in membrane stiffness could be on the membrane prestress field. For the Grande Arche, although there are a number of possible ways of stressing the cable network, it was important to find one with the least number of jacking points closest to the ground and to know the forces and displacements that would be required.

Our recent work very much involves the integration of membrane roofs into large building projects. It is wholly aligned with national and international sustainability issues and demonstrates very much an advanced multi-disciplinary solution. The Amenity Building at the Inland Revenue Centre (Nottingham UK) is one such example with other large flagship projects including the Saga Headquarters building (Sandgate, UK) and the Dynamic Earth Project (William Younger Centre, Edinburgh, UK). All three cover up to 2000m^2 each and are based on taking a low energy approach to the climate control within the building envelope. In summer cross ventilation is generated opening a system of vents using an automatic controls acting in response to ambient air temperatures and wind speed and direction. During winter, warming of the occupied zone is achieved through the use of underfloor heating and wall mounted electric radiant heaters. The saving in lighting costs achieved by the membrane translucency very much offsets the electrical energy used for heating through the year.

Membrane structures are very much a maturing technology bringing some special qualities to contemporary architecture and with it high profile engineering projects (see Annex – *Selected Projects: Lightweight Structures 1995-2001*) that contribute significantly to Arup's international visibility. Arup has been at the forefront of this development over the past thirty years with an established international reputation as a world leader. It is the aim of this proposed project that this position is maintained, reinforced and diversified with increased commercial success.

Fabric Structure Engineering – Industry Perspective

Fabric structures (and other smooth and faceted lightweight structural continua) fulfil the requirements of changes in modern working practice, social behaviour and commercial needs. A fabric structure enables the internal environment to be modified rather than controlled and occupancy to be part-time or full-time. Construction (and subsequent repair and refurbishment) speeds are fast while unit costs are extremely competitive (frequently the minimum) with good durability and low maintenance (a feature enhanced by the introduction of self-cleaning PTFE coated glass fabrics). Architecturally dramatic forms are intrinsically achievable, often leading to award winning completed projects that are high profile and readily recognised by the general public. Over the last decade, the number of fabric and lightweight skeletal structures has increased significantly, with both types often leading refurbishment and regeneration projects. For example, fabric roofs have been erected at *Butlins*' Skegness, Minehead and Bognor Regis resorts, where the objective was to roof over the central open spaces as part of a revitalisation programme. In choosing this form of structure, problems associated with load transfer onto and around existing buildings of uncertain performance, budget constraints and closure limitations, were overcome, leading to architecturally striking skyline.

Fabric structures (including tents, prestressed and air supported, sails and inflatables) resist applied loads by a combination of curvature and tension (prestress). A flat fabric panel cannot resist a pressure, however much tension there is in it, until deflection of the panel gives it curvature. The lateral stiffness produced by the tension in a structure is referred to as geometric stiffness. The analysis of a fabric structure is, therefore, strongly non-linear. Curvature is introduced through the cutting pattern, support configurations and partly by the applied loads (e.g. wind and snow). It is a combination of the surface geometry, prestress and loading that determines the design and performance of a fabric structure. The appropriate determination of wind loads for design forms the basis of this proposal.

Compared with standard construction practice, it is an unusual feature of the industry surrounding the 'supply' of fabric structures, that at all stages complex analytical concepts are applied and solutions to problems sought which tend to be almost unique to each contract. This is reflected in the list of external contributors to the project that includes consulting engineers and contractors. This field of structural engineering is supported by very little published guidance.

In the 4th February 1999 issue of *New Civil Engineer* a special feature appeared under the title "Creative tension – wiring into tented structures". The main article, written in the context of the Millennium Dome construction, opened with the following - **"Are giant tents domed? Tensile fabric structures are among the most spectacular of the 20th century – and the most controversial"**. This statement was made with reference to the collapse of the new fabric roof over Montreal's Olympic Stadium in early 1999 (*NCE* 28th January 1999). The actual cause of the failure was identified as design based and not arising from accidental damage. This event, which is not unique, serves as a timely example of the need for further research in the design of fabric structures.

PROJECT OUTLINE (aim, benefits to the Arup Partnership and BG6, strategic fit, integration to existing programme, methodology, tasks)

Aim

The overall aim of the research programme is to ensure and to diversify Arup's position at the forefront of high profile and internationally visible fabric structures engineering through the enhancement of current analytical and numerical tools for analysis and design, and development for and application to other industries.

Objective

The objective of this project (as a component of the total programme) is to develop a non-linear analytical model for coated woven fabrics and fabric systems.

Other objectives identified to fulfil the aim are related to associated current projects (e.g. the Royal Society Project *Collimate – Collaborative Solutions for Membrane Structures*, £45k, 2000-2002, BG6, University of Newcastle; TENSINet – EC funded European Network Programme, £24k, 2001-2003, BG6) and projects to start or planned (e.g. BRE Foundation Award *A Generic Element Approach for the Prediction of Wind Loading on Fabric Structures with Applications to Faceted Continua*, £58k, 10/2001-10/2004, BG6, University of Newcastle).

SCIENTIFIC METHODOLOGY

Coated woven fabrics are complex composite non-linear materials mainly comprising two components, yarn and coating, that act together in a manner characterised by (Schock 1986):

- The crimp interchange – the interaction of the two yarns or fibre directions under uniaxial and biaxial stresses. The ratio of the warp and weft stresses determines the equilibrium position of the yarns, and therefore, significantly influences the stress-strain behaviour of the material.
- The load-extension behaviour of the yarn.
- The coating, with the kinematic crimp interchange restrained by the coating (and other factors – e.g. internal friction). The load extension characteristic of the coating will usually be highly non-linear and time dependent.
- The bedding-down of the warp yarn onto the weft yarn. This effect is due to the initial slack between the individual fibres of the yarns, requiring a lateral pressure to be applied for contact reactions to be established between the warp and weft yarns. The coating material having partially penetrated the yarns usually restrains the bedding-down.

Two fundamental approaches may be adopted in the determination of the required non-linear fabric behaviour:

- Analytical models based on physical test data.
- Analytical models based on numerical model representations of the component parts and non-linear rules describing their inter-dependency.

In both cases the target outcome is effectively the same: a predicted relationship between the stress and strain in the fabric in each warp and weft directions as a function of the corresponding prestress ratio for use in an existing computational tool (GSA-Fablon).

Analytical models based on physical test data are characterised by a level of certainty inferred by mean and standard deviation information and other statistical metrics (e.g. ‘T’ test). The tests themselves are tangible, with results established on the complete coated woven fabric. Interactions between constituents are captured exactly, therefore. Creep (Day, 1986), fatigue (Ansell, 1985; Ansell et al, 1983), damage (Perkins 1996), weathering and standard static tests can be conducted to provide a full range of performance and behavioural measures including inherent variability in the parent material.

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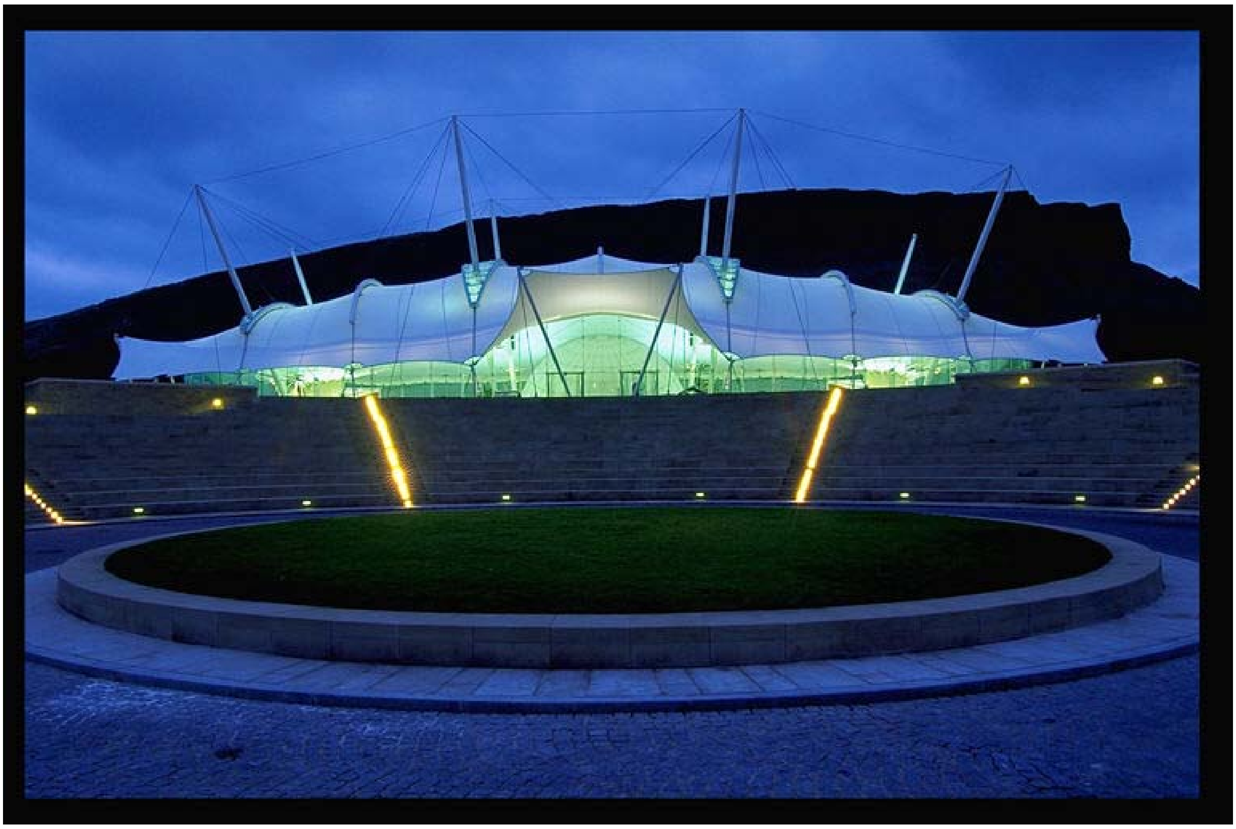

Fig.1 William Younger Building (Dynamic Earth Project)
Edinburgh, UK.

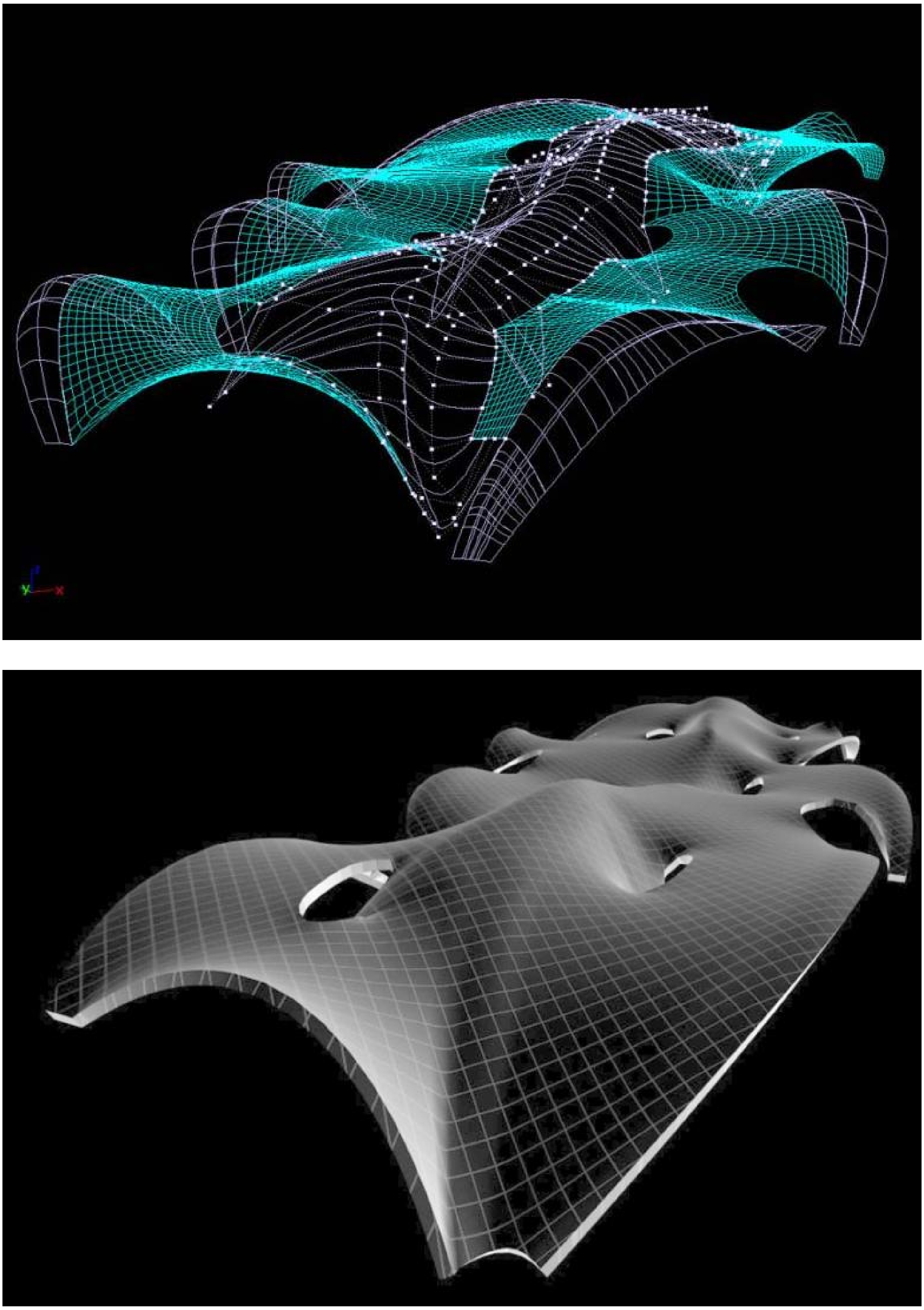

Fig. 2 Numerical representation of a 25 000m^2 canopy (grid-shell) roof
Chavasse Park, Liverpool, UK.

Fig. 3 Goodwood Racecourse, Goodwood, UK.