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Autor: Dalland, Todd / Gill, Colin

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Design of the New Concert Pavilion, Pier 6, Baltimore, USA

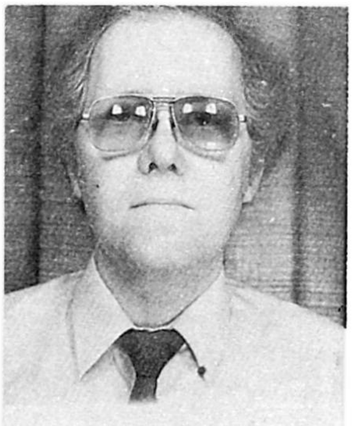
Projet d'un espace de concerts à Baltimore, USA

CED-Entwurf eines Pavillon-Membrandaches in Baltimore USA

Todd DALLAND
Principal
FTL Associates
New York, NY, USA

Todd Dalland graduated from Cornell University with a Bachelor of Architecture. He began his career in tensile structures in 1971 and founded FTL Associates in 1977. He is a founding Executive Committee Member of the Architectural Fabric Structures Institute, 1984 Chairman of the International Symposium on Fabric Architecture, and a founding director of Surface Forms Research Group.

Colin GILL
Princ. Engineer
Buro Happold
Bath, UK



Colin Gill, born 1952, graduated in Civil Engineering from Southampton University in 1973 and obtained his MSc in Concrete Structures at Imperial College, London, in 1980. After initially specialising in highways structure design, he has for the past eighteen months been Principal Engineer with Engineering Consultants Buro Happlod, responsible for lightweight structures.

SUMMARY
This paper describes the mode of operation of the TENSYL form-finding load analysis and cutting pattern generation suite of programs from the user's standpoint. It is illustrated by reference to the new Baltimore Pier 6 concert pavillion in which these techniques were successfully used.

RÉSUMÉ
L'auteur décrit le mode de fonctionnement du progiciel TENSYL, et ses fonctions de recherche de formes d'analyse des charges et de génération de patrons de coupe, du point de vue de l'utilisateur. Les exemples font référence au nouveau pavillion de concerts Baltimore Pier 6, dans lequel ces techniques ont été utilisées avec succès.

ZUSAMMENFASSUNG
Der Beitrag beschreibt aus der Sicht des Anwenders, wie das Programmsystem TENSYL für Membrantragwerke zur Formfindung in der statischen Berechnung und zur Generierung der Schnittmuster eingesetzt wird. Illustriert ist die Vorgehensweise am neuen Konzertpavillon "Pier 6" in Baltimore.

Surface-stressed tension structures are necessarily built with totally prefabricated elements of complex geometry. Within the current state of the art it would be impossible to process this geometry without computer techniques. Buro Happold use TENSYL, an integrated program suite which handles shape generation, load analysis and fabrication information for cable and fabric structures. The hardware for this program is a Hewlett Packard 9000/350 workstation with SRX graphics processor and a high resolution 19" colour monitor. The computer uses the UNIX operating system and TENSYL is written in C programming language. The SRX graphics processor gives very fast processing of 3D surface modeled images with a simultaneous display of over 16 million different colours. This program suite replaces the old TENSYL, which ran on an HP 9845 desktop computer.

This paper is illustrated by reference to the design of the new concert pavilion in Baltimore's inner harbour, which replaces the previous fabric pavilion built in 1980 by the same design team. The new pavilion covers approximately 3,000 seats with an additional outdoor seating area to accommodate 1,000 people. Dressing rooms and public toilets are housed in attractive permanent structures directly behind the stage. As an expanded and improved facility, it keeps pace with the rapid eastward development of the inner harbour and maintains a public-spirited covered building for music and recreation on Pier 6. The new building sits centrally on the pier with a water's edge promenade along each side. The entrance to the site confronts the city with a strong, bright facade and gates. The access to the theatre leads through an outdoor lobby and small water-front village of soft-coloured buildings via the water's edge promenade into the theatre and grassy hill beyond.

The new building reflects the changes in design philosophy of the design team. The dialogue between the hard and soft buildings has been developed and the structural form of the hard and soft buildings are integrated. The high-tech structural details have been modified and refined to become decorative elements around the perimeter.

USER INTERFACE

In TENSYL there is a graphical image of the numerical model on the monitor at all stages of the program. Simultaneously a menu of commands is displayed on the right hand side of the screen. These commands may themselves perform a function directly or provide access to a further menu of commands. Figure 1 shows the *Home* menu. Most of the options on this menu take the user into specific command menus.

Both the menus and the graphics model are driven by the user using a two button mouse. The mouse moves an on-screen cursor. The right hand button switches the cursor between model and menu interaction modes while the left hand button initiates the desired action. Direct keyboard entry of data is kept to a minimum. When necessary a prompt and editing display zone is activated below the graphics display area.

THE DESIGN PROCEDURE

To set up a numerical model for a membrane structure it is first necessary to define the membrane system points by keying in the co-ordinates. The system points are mast tops and fixed points on the boundary. Boundary lines and ridge lines connecting these points are then defined using the mouse on the *Topology* menu. The membrane surface is divided into fields by ridge lines. Each field must be surrounded by a closed boundary of cable or rigid elements.

The mesh generator is used to subdivide each field into a rectangular mesh. Using the mouse the mesh is sketched onto a screen display of the field's boundaries. The mesh lines run from boundary

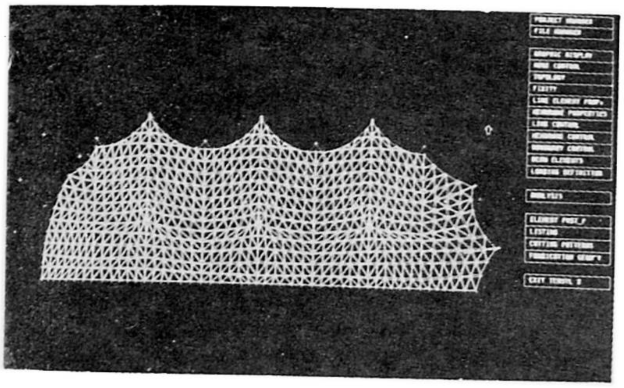


Figure 1 - TENSYL Home menu

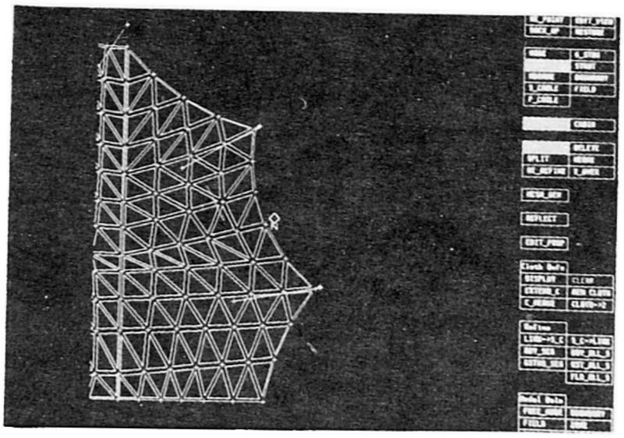


Figure 2 - Topology menu: adding link to boundary cable

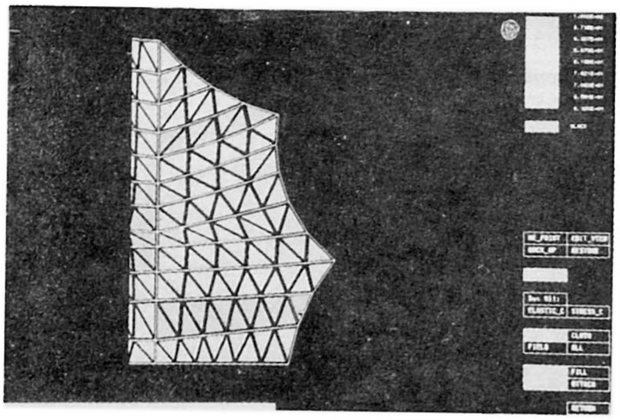


Figure 3 - Membrane stresses display

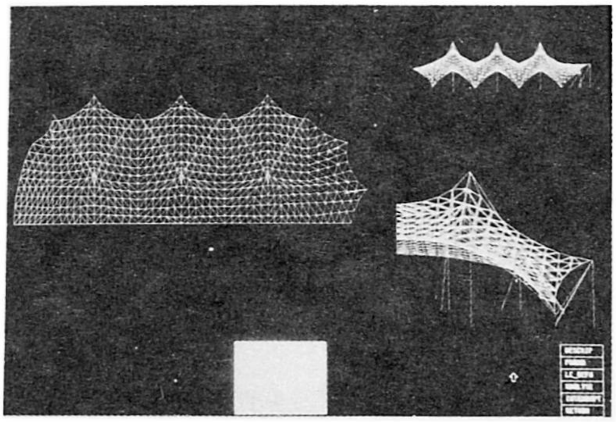


Figure 4 - Graphic display during analysis

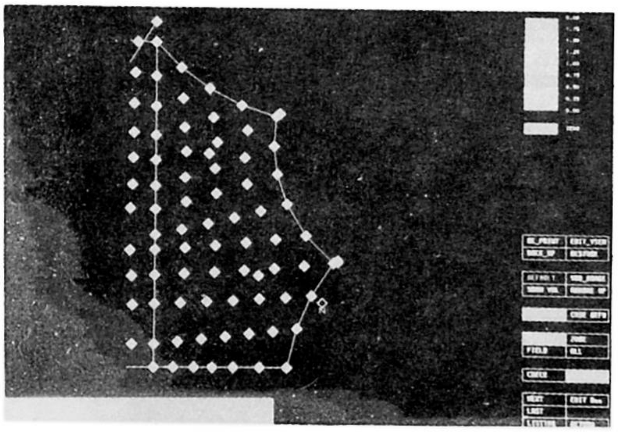


Figure 5 - Loading coefficient nodal display

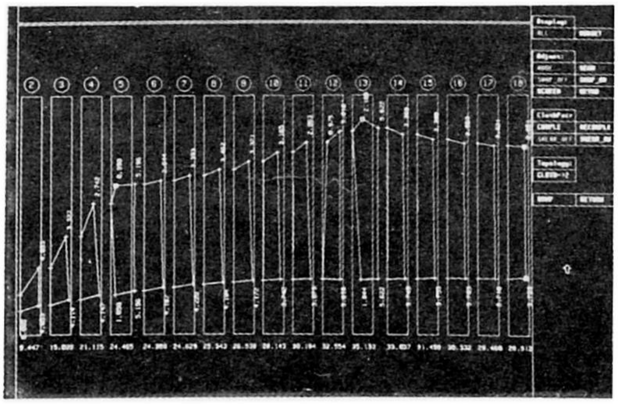


Figure 6 - Cutting pattern field display

to boundary in roughly orthogonal directions. The lines can be added in any order and adjusted using *Delete* and *Command* options. When complete the mesh can be solved to generate the spatial co-ordinates of the node points at the crossovers.

Once solved, membrane and geodesic line elements are then automatically generated within the rectangular topology. The geodesic lines *Gstrings* are potentially seam lines on the surface and serve to order the triangular membrane elements. Having exited the mesh generator, then individual elements of any type may subsequently be added, deleted or edited directly on the screen using the *Topology* menu. (Figure 2)

Node restraint conditions can be activated graphically using the *Fixity* menu with direct attachment or detachment of a selected combination of translational fixities. There are no limits to the number of restraints, as these are held within a node's internal data structure. Likewise element elastic properties and specified stress levels are attached and assigned on screen using the *Line Element Properties* or *Membrane Properties* menus. Elements are filled with varying colours to illustrate magnitudes of stress. (Figure 3)

For form generation specified stress membrane elements will be used with boundary elements being assigned mostly elastic properties. It is usual to assign a few links with specified tensions to adjust boundary shape or the equilibrium at a certain node but care must be taken to keep the model in control.

Form generation and load analysis use the same analytic section of the program. The solution procedure is 'dynamic relaxation' in which each node is moved towards its equilibrium position by the out-of-balance forces on it in accordance with Newton's laws of motion. [Ref 1] The graphic display during analysis shows both plan and elevations of the problem, which are updated at interim solution points as the analysis proceeds. (Figure 4) The node with the current maximum out-of-balance residual force is flagged, to aid the detection of physical instabilities. Analysis control parameters and load case numbers are assigned via on-screen edit boxes.

For load analysis the structure is fully elasticated. In this operation the specified stress elements are replaced by elastic elements; the slack length of the element being adjusted so that at the prestress geometry each element has the same stress as before.

Individual nodal loading coefficients are assigned interactively on a separate command page. Up to five sets of coefficients may be held at any one time. These coefficients are multiplied by wind or gravity loading factors when defining a particular load case (Figure 5). Combined cases are permissible, together with the application of an internal pressure which might represent the inflation of an air-supported structure or an internal wind pressure.

The post processing module gives a colour display of element stresses, and facilitates the rapid assimilation of a large amount of data. Hard copy listings of all results and co-ordinates may be output via a laser printer, which can also be used for graphics dumps of the screen image.

The fabrication geometry module provides for the generation of membrane cutting patterns (Figures 6 and 7) and associated component geometry, such as masthead and membrane plate angles. Adjustment of boundary node positions for cloth width optimisation is assisted by an on-screen display of all the unfolded cloths associated with a particular field.

STRUCTURE VISUALISATION

An advanced structure visualisation module has been included in TENSYL to aid the interpretation of complex surfaces and their relationship to adjacent solid elements. Coupled with the high form computation, this creates a powerful interactive facility for architectural interpretation at preliminary design stages, as well as providing high quality images for presentation to the client. This module of TENSYL makes full use of the SRX graphics coprocessors attached to the workstation. These provide hardware implementation of hidden surface removal, smooth surface shading, multiple light sources and full surface texture and specular reflection modelling (Figure 8).

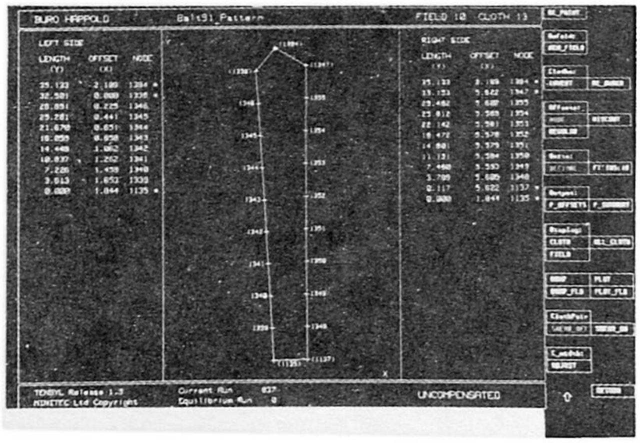


Figure 7 - Cutting pattern cloth display

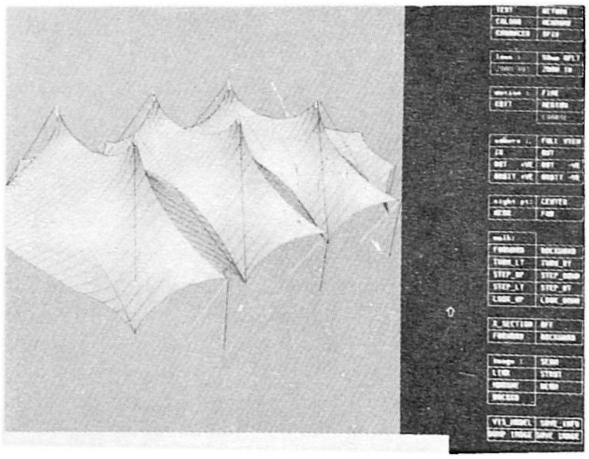


Figure 8 - Surface visualisation of membrane structure

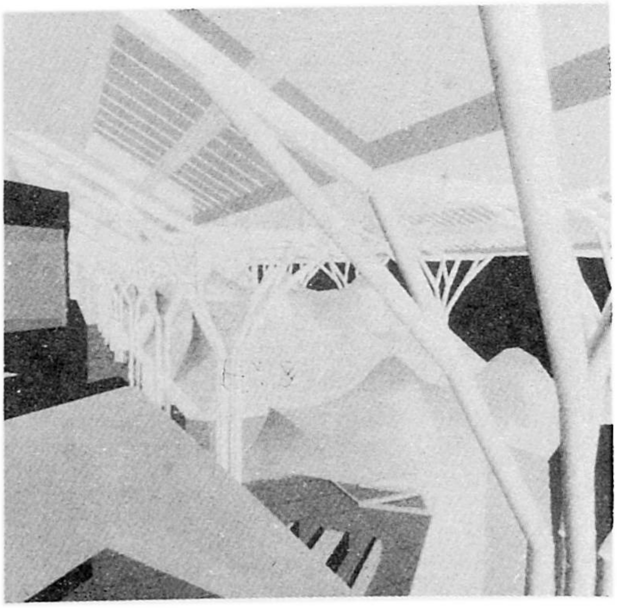
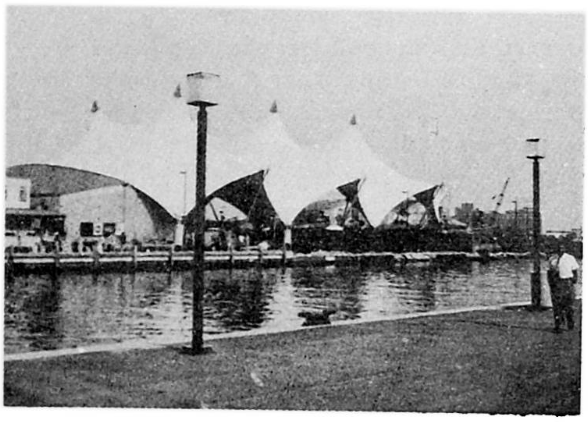


Figure 9 - Interior of shopping mall



gure 10 - External view of Baltimore Pavilion

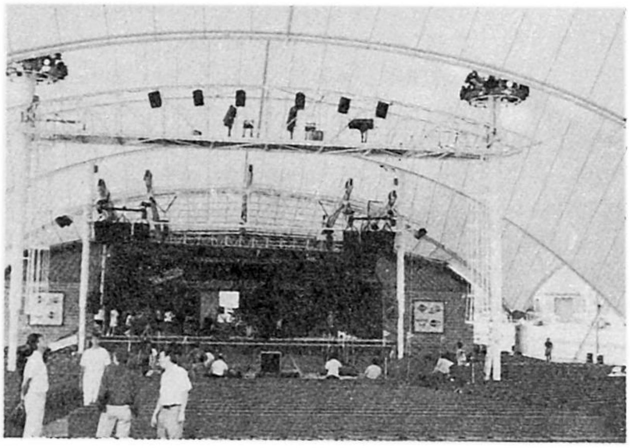


Figure 11 - Interior view of Baltimore Pavilion

In addition the surface representation of complex elements is assisted by the support of non-uniform rational spline surfaces.

The analytic model has been supplemented by the addition of further modelling primitives. These include general brick elements, walls, floors, and straight or radiused tubes or rectangular sections (Figure 9). Individual textures and colours may be assigned to these additional elements, which may also be displayed in outline form as wire frame models.

Varying degrees of transparency may be assigned to the membrane. There are a number of lighting options including ambience, parallel and point light sources which can all be assigned different colours, intensity and location. The model can be viewed from any point with a view ranging from wide angle to telephoto. Rapid changes of viewpoint allow walk through effects.

APPLICATION TO BALTIMORE PAVILION

The potential benefits of the fully interactive CAD system in the new TENSYL program were realised on the Baltimore project. From an engineering user's standpoint the system is easy to learn and popular in use, mainly because of the elimination of tedious manual manipulation of large data files. Early projects indicate a minimum five-fold improvement in total time taken for numerical model assembly and application. The analytic section of TENSYL now computes about sixty times faster than the old version. When coupled with the high quality visualisation capability, this speed of form generation and adjustment made it practical for the architect to work directly alongside the engineer at the preliminary design stage. This joint interactive involvement benefitted the project, and has particular relevance with the increasing use of tensile elements integrated into a total building.

As part of the structural design on Baltimore it was required to maintain the ridge and valley cables on lines secure across the access and to get repetition of fabric patterns where possible. This was achieved by form finding a typical centre field then reflecting it and elasticating it where identical fields were required. The end fields which were different were then form found on to the already elasticated part. It was found that the stresses in the elasticated parts changed from the originally specified stresses but not sufficiently to cause any over stressed or slack elements. The completed project is shown in Figures 10 and 11.

FUTURE DEVELOPMENTS

The areas where there is room for further extension of the numerical processing procedures are in the use of automatic cutting pattern machines and the development of shop drawings for the various supporting hardware and connection plates. At the moment the patterns are output as system line geometry. If automated pattern cutting is introduced, the seam margins and other edge detail corrections need to be added into the patterns. The supporting steelwork details, particularly the corner plates where boundary cables are connected back to the masts are developed by hand from geometrical information taken from the cutting pattern module. We are presently working on data transfer to an AUTOCAD draughting program in which a library of details can be set up. This will help to reduce the risk of errors at this interface and speed up the production of shop drawings.

ACKNOWLEDGEMENTS

The photographs of the completed project provided by fabric contractor Clyde Canvas Ltd are gratefully acknowledged.