Projects and Construction
Abstract. The paper describes the organisation and use of CAD software for lightweight tensile structures which has been developed particularly for large groups of students without prior experience of such systems and software. The structural systems covered by the software include prestressed membranes, air-supported and pneumatic structures, geodesic and uniform mesh cable networks, grid shells and spline stressed or batten membranes. The application of the software in the support of design project teaching is illustrated with relation to a single project with diverse planning and conceptual aspects. The project, entitled “Bath Rugby” was undertaken by students following a final year undergraduate option module on lightweight structures. The project had a real client and a stadium ground with difficult site constraints - particularly with restricted site lines from surrounding properties to the historic centre of Bath, and the need to clear large areas of seating to clear the ground in summer for use by a cricket festival. This required the provision of various demountable or retractable stadium canopy structures in conjunction with folding or retracting seating throughout much of the site in order to provide for a stadium with up to 14000 capacity. The total design project time was 8 days. The above work is essentially related to the teaching of lightweight structures and appropriate structural mechanics theory - mainly for specialist option courses within undergraduate degree schemes in Civil/Structural Engineering. Unfortunately there are only a handful of such courses (or course modules) in Europe and the paper is intended to help develop appropriate material for a greater range of such courses. A future objective of the TensiNet grouping might be to provide support for this through its website.
1  HISTORICAL DEVELOPMENT OF THE SOFTWARE

The software was originally developed by the author for use by the Architectural and Engineering design company for lightweight structures, IPL at Radolfzell in Germany. The intention at that time (1992) was to provide a package which could simultaneously handle a large number of tensile membrane structures on a low power Unix system. It was also essential that the various projects and associated data files could be remotely and easily checked. This is also the requirement needed when teaching through design project work large numbers of students simultaneously - the tutor(s) must be able to access and correct, with the help of on screen error traces, the separate individual data files for each student/project. Over the years, with the use of the software for both complex real projects by expert users and the simultaneous use by large numbers of students with no experience, the software package has developed into a robust and easily learned system which is capable of handling the most complex projects; although of course the latter do not usually occur with student use.

2  ANALYTICAL BASIS OF THE SOFTWARE

The analytical and numerical basis of the software is the method of Dynamic Relaxation (DR). A major advantage of the method, particularly in a teaching context, is its simplicity - it can be taught / explained solely from the basis of Newton’s laws of motion, without extensive knowledge of structural mechanics or matrix methods, or indeed much mathematics. It is therefore very suitable for University student groups of architects and engineers working on interdisciplinary design projects - who should, in the context of specialist option courses, need to understand the theoretical basis of a CAD package, not simply just its use.

The physical (and numerical) basis of the method is to trace step-by-step for small time increments the motion of a structural assembly from the time when it is initially loaded or stressed until the time when, due to artificial or imposed damping, it comes to rest in static equilibrium. In form finding the process may be started from some arbitrary and inaccurate specification of geometry (apart from boundary constraints), with the motion caused by imposing a stress or force specification in some or all of the structure components. For load analyses, which must start from a correct initial or prestress equilibrium state, the motion is commenced by sudden application of the loading.

In its original form DR was applied with viscous damping of nodal movements proportional to the product of nodal velocities and mass components; most rapid convergence being obtained by critically damping the lowest mode of vibration \([1,2]\). However, to cope with very large locally unbalanced forces (and their associated high frequency modes), due for example to grossly deformed elastic members during initial stages of form-finding from a very inaccurate starting geometry, additional controls were sometimes necessary to achieve convergence. An alternative “kinetic damping” procedure was found to be entirely stable and rapidly convergent when dealing with these large disturbances \([3,4]\). In this procedure the undamped motion of the structure is traced and when a local peak in the total kinetic energy of the system is detected, all velocity components are set to zero. The process is then restarted from the current geometry and repeated through further (generally decreasing) peaks until the energy of all modes of vibration has been dissipated and static equilibrium is achieved. A detailed explanation and full review of the DR method is given in reference \([5]\).
2.1 STRUCTURE IDEALISATION

The temporal idealisation of DR is a central difference integration of the equations of motion at each node of the structure in each of the co-ordinate directions. The spatial idealisation can be regarded as a finite element mesh for cable and membrane components, but using only "simplex" elements - ie line elements for cables and triangular elements for modelling membranes; for beam and arch supporting components the idealisation reverts to a finite difference modelling with a sequence of nodes along a system line (curved or straight "spline"). The reason for using these simplex and spline elements is that it allows the structural system to be analysed using only translational degrees of freedom and greatly simplifies, with improved accuracy, the modelling of on/off slackening in cables or membranes and snap-through buckling of arches or masts. An essential aspect of the modelling of prestressed membrane surfaces is the definition of the fabric weave directions to which must be referenced the prestress (in warp and weft) for form finding and the fabric stress/strain properties during load analyses. Additionally, for reasons of economy in fabrication patterning (and the avoidance of shearing wrinkles) the warp direction of the fabric (and panel seam lines) should always follow geodesic paths over the doubly curved membrane surface - (a geodesic is, by one definition, the path that a flat tape of material will follow over a curved surface without shearing). To comply with all of these conditions the modelling of a fabric membrane surface, by whatever means (net or finite elements), should contain a set of geodesic or warp lines over the surface with the spacing between them being dependent on the required modelling accuracy - normally with much closer spacing than typical fabrication panel widths. The warp prestress for form finding will always be parallel to these directions (and the form finding process will itself be modifying the directions). Similarly the weft prestress will be normal to the warp directions. For a surface to be modelled by triangular elements, one side of each element will thus always be parallel to or contain a warp line (Fig. 1). A description of how this is implemented in form finding, and the modelling of warp and weft stress/strain relations for load analysis, is given in reference [5].

Fig. 1 Warp line segments follow geodesics on the surface, triangle bases follow warp direction
3 SOFTWARE ORGANIZATION

Two linked programs are used for the CAD package: one for form finding and one for load analysis. A single data file is used as input (for the form finding) which specifies initial system point geometry, system lines (topologically) such as scallop cables or truss chords, additional links (or groups) such as masts, tie-backs (and truss bracing), membrane fields with fabric warp direction controls, and membrane and cable link prestress values. In addition to form control values for prestress and fictitious elastic properties, the data file contains real (estimated) values for stress/strain properties of the various structural components. These latter are not used in form finding but are carried forward for the load analysis stage after the form finding process. The form of the structure can be displayed (and controlled) interactively at any stage either as a wire-line model or shaded surface model. The output from the form finding stage is a prestress weightless state file containing the equilibrium geometry, stress state and elastic properties of all elements. Note that the form finding is always carried out for an assumed weightless state; dead load conditions are assessed subsequently as a particular load case.

The load analysis stage uses the prestress output file for geometrical, stress and elastic properties, but otherwise all load conditions for self weights, snow and wind loadings, and other aspects such as settlements or checks for failed regions or components are input interactively. The prestress state can also be factored at the start of the load analysis - thus a prestress factoring of 2 will not alter the initial geometry but merely double all stresses and link forces (and, for pneumatics, any internal pressures carried forward from the form file). During load analyses membrane (and form) can be displayed interactively with colour stress contouring for either warp or weft stresses (or contouring for ponding).

3.1 DATA STRUCTURE

Tensile membrane structures can generally be described in terms of one or a set of membrane fields bounded by ridge and scallop cables, fixed system lines, cone rings, arches or truss chords. Within any membrane field the warp fibre directions (governing the orientation of fabric properties and prestress directions) are defined by warp control lines. The membrane area bounded by any two adjacent warp control lines or a field edge system line (such as ridge cable, truss chord or scallop) is termed a panel. These panels are not physically the fabric roll panels between seam lines which would be fabricated to form the real membrane surface, but normally are much larger areas convenient for simplifying data for numerical analysis.
The panels are, however, divided into triangular regions along their length and each such region is sub-divided into a much finer set of triangular facet elements. The division of fields into panels, regions and subdivision into individual elements is illustrated in Fig. 2.

The sub-division density is controlled by a single parameter in the data file. With a subdivision of 1 each region has a single element, and with a subdivision of 10 each region contains 100 elements. In Fig. 2 the field is bounded by only scallop cables. More generally, one or more edge system lines might be (eg) a space truss chord with discrete node spacings governed by the truss system. Cable scallops joining the truss would need to match with these nodes (as in reality), but for membranes continuously connected along the truss chord the membrane nodes (governed by the sub-division density) need not match with the truss nodes - the program automatically accounts for any mis-match of nodes by reassigning residual forces and geometry to comply with a continuous connection. The same process, in which parasitic system lines allow a mismatch of nodes between one region and an adjoining structure or region, also allows for selective mesh refinement in areas of higher stress gradients/concentrations.

4 DESIGN PROJECT TEACHING (CAD)

It will be apparent from the foregoing that for each structure only a single data file is set; initially from a sketch (or simple model) of the structural scheme, and any subsequent adjustments, either interactive during form finding or by editing following the form run, must be made to this data file. The main reason for this approach, rather than the more obvious one of an interactive pre-processor for setting the data file, is simply to avoid chaos during the tutoring of numerous students (with different structures) in a single studio group. Put simply, the process forces each student to read the manual and try out the associated tutorial examples before preparing a data file for their own structure - it imposes the process of thinking before doing. However, it is clear that an on-screen tutoring system and linked data preparation could be more efficient.

The subsequent stages of the design process (at least at student level) are relatively easy since the load analysis stage is wholly interactive with coloured stress plot outputs, together with member forces and moments, and deformations of significant points. Following this the detail design work for steel components applies previous knowledge, and cable components such as scallops and stressing out systems are taken to a workable conceptual level drawing mainly from precedent studies of built projects. The latter can for example be drawn from the TensiNet website.

5 "BATH RUGBY" PROJECT

This project was used at Bath University for the final year engineers' individual design project in March 2003 - concentrating mainly on the roof structure systems; and it will be used again as the basis for a more extensive interdisciplinary project for groups of architects and engineers in the autumn term of 2003. Bath Rugby ground and club-house are situated at the west end of the “Rec” - which is a green area of land held in Trust for all to
use for recreational purposes. In order to fulfil the terms of the Trust the East spectator seating area is a temporary stand which is erected and dismantled at the beginning and end of each rugby season (Sept - May). This allows the whole of the Rec to be opened up for other events (eg - a cricket festival). The existing stadium capacity of only 8200 needs to be substantially increased, both by extending the East Stand and by replacing the ageing and low grade West Stand, Club House and standing area on the North side. Whilst this could achieve a stadium for 12500 - 14000 spectators, it may only be possible from the viewpoints of public acceptance and financial viability provided the following aspects are taken fully into account:

- The entire scheme, which probably must be phased, should provide a really substantial improvement on the visual appearance and amenity (particularly shelter) of the existing facilities.
- Height restrictions on the stands are important - the views from the east side of the Rec towards the Abbey and from the west/Grand Parade over Pulteney Weir to the stadium ground (and beyond to the east side of the Rec) cannot be impaired.
- The possibility of providing a demountable canopy type covering/weather protection over the upper tiers of the East stand should be considered - for example by employing transparent or foil type canopies, very flat coated fabric canopy, or truly retractable canopies.
- The walk along the river is very popular. The back of the existing West stand does nothing to enhance this amenity; a new scheme should do so - for example by the provision of sitting out and cafe areas.
- The Club-house building and North stands are old, tired and inefficient. They house offices, changing facilities, a bar area and a supporters club. A new building must give substantial benefits - visually, thermally, acoustically and financially.
- The main corner entrance areas at the north and south ends should be improved - visually and functionally (allowing also for more adjacent seating and/or standing).

Fig. 3  Sketch views of the stadium: Top - looking north, bottom - looking south west.
The above formed the background to the initial design brief. The project had two phases: a group phase of two weeks to consider the overall development, followed by individual structural design work for a further 4 weeks.

5.1 SOME INDIVIDUAL PROJECT EXAMPLES

A small sample of the variety of individual schemes is given in the following illustrations:

**Corner Membranes**

The first deals with the development of the corner areas to provide covered seating and standing in the winter rugby season - a permanent network suspended from the main lighting towers (without imposing bending on the towers) is employed to support a seasonally deployed membrane covering below. The membrane has to be taken down in the summer in order to comply with the freeing of site lines imposed by planning restrictions.
**Deployable Mast Wands**
The west stand can employ an upper stage of seating provided there is no permanent roof covering to restrict the views from “Grand Parade” to the east side of the recreation ground. Flexible fibreglass deployable wands with retractable membrane covers to be used only on match days are proposed - Figures 8 & 9 below show two of the final (A1) presentation boards.

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Fig. 8  Fibreglass splines in unstressed (vertical) & stressed states (lower).

Fig. 9  Presentation for membrane deployment system.
West Stand Inverting Membrane

Again to comply with height restrictions for any canopy coverings other than masts, one scheme for the west stand employed inverting membranes - although the principal reason for employing them in the elevated state (upper sketch Fig. 10 or Fig. 11b) was to clear the view for hospitality boxes at the back of the stand.
CONCLUSIONS

The foregoing are just a few of the individual design solutions produced - the total number was 24 and others involved schemes such as deployable umbrella systems, folding upper stands, transparent foil systems and tilting canopies; all of these being governed by the strict planning constraints on site lines when the stadium is not in use. The type of project is ideal because it involves a group master planning phase (in 6 groups of 4) with a real client involved fully in the brief, followed by the individual work in a competitive situation relating to design ideas and their development but with collaboration in relation to the use of CAD software and precedent studies.

As regards the further development of the software, an on-screen manual and tutoring system is to be implemented together with extended graphics facilities. It is intended that the complete system will become available from the TensiNet website as public domain software for teaching purposes. The whole website should then provide a very useful facility for the extension of courses in lightweight structures at University level.
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REFERENCES


