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Technical/Economic Evaluation of Cables for Long-Span Structures

Réflexion technico-économique sur les câbles de structures de grande portée

Technisch-ökonomische Betrachtung von Seilen für weitgespannte Tragwerke

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SUMMARY

Large 'tents' and 'airhouses', which have achieved the status of permanent structures, require ropes or cables to support loads. Collaboration between materials scientists and engineers is essential for advance. Compatibility with cladding membranes and other factors leads to a list of engineering requirements. Modern ropes exist in a large number of materials, particularly high-performance fibres, and constructions, whose quasi-static and long-term properties must be selected to meet the needs.

RÉSUMÉ

Les câbles ou faisceaux de câble sont indispensables au transfert des charges des "tentes" et des "bulles" de construction permanente. Les progrès dépendent d'une étroite collaboration entre ingénieurs et spécialistes de la science des matériaux. Les exigences techniques requises découlent de la compatibilité des câbles avec les membranes de couverture, tout comme d'autres facteurs. Les câbles modernes sont réalisés dans une grande variété de matériaux, surtout les fibres ultra performantes. Le type de câble doit être choisi en fonction des propriétés quasi statiques et de longue durée requises.

ZUSAMMENFASSUNG

'Zelte' und Traglufthallen, die den Rang permanenter Bauten erreicht haben, benötigen Seile oder Drahtbündel zum Lastabtrag. Ein Fortschritt kann nur in enger Zusammenarbeit von Materialwissenschaftlern und Ingenieuren erzielt werden. Die Verträglichkeit mit Verkleidungsmembranen und anderen Faktoren ergeben eine Liste entwurfstechnischer Anforderungen. Moderne Seile gibt es in vielen unterschiedlichen Werkstoffen - insbesondere hochleistungsfähigen Fasern- und Aufbauarten, deren quasi-statische und Langzeit-Eigenschaften den Bedürfnissen entsprechend ausgewählt werden müssen.

1. INTRODUCTION

Since civilisation began, man's built environment has been defined more by the materials available than by his imagination. Where there was nothing but ice, man developed the igloo; where there was mud, man produced bricks; where there were fibres and skins, man developed the "tent". In tents, the interior volume is enclosed by a membrane, usually a textile fabric, whose tension carries its own weight and any applied loads (due to snow, wind, etc). The membrane is held up in the air, supported by rigid elements in compression or, less efficiently, bending, or, in the more recent development of "airhouses", by air pressure.

In the 20th century, polymer engineering led to high strength fibres, weather resistant plastic coatings, and high strength films with life-time performances well in excess of earlier natural products. This has allowed tension structures to develop rapidly in recent years [1], achieving permanent structure status in several countries, including the USA. However, the materials are not yet perfect, and nor are they necessarily being used in the most effective way. Engineers have found design and manufacturing techniques which allow currently available materials to be used safely and reasonably economically. But, as materials science advances, the structural engineer must also move and influence it into directions where there is a perceived need or exploitable opportunity. Collaboration is vital. In this paper, we concentrate on the role of ropes and cables, though this cannot be separated from the developments in membranes.

In principle, in simple tents, such as the classical bell-tent and modern frame tents, and in airhouses, ropes are not needed, except perhaps as guy-lines to hold out walls or to give added stability: the membrane itself fills all the mechanical needs. In other forms of tent, masts have to be stayed by lines. However, in large structures, there is a need to gather the surface tensions in the membrane into linear elements, such as cables, ropes, and webbings, before transferring the tensions to the supporting medium. This requirement has been intensified by the introduction of new light-weight films, which have no fabric reinforcement. To control strain, they can only be used in conjunction with linear elements of stiffer materials acting in tension, compression or bending.

A total structure will consist of a number of fields bounded by the linear elements (cables, beams etc). Each field may be composed of a number of fabric panels sewn or welded together.

In addition to their principal structural functions, linear tension elements have many other roles in places of assembly and long-span structures. These range from demanding purposes, such as the support of movable equipment, to minor applications, such as cords used to pull curtains.

2. REQUIREMENTS FOR LINEAR STRUCTURAL ELEMENTS

The scale of structures using stressed membrane skins to carry the load is limited by the strength of available membranes. To control deflections in a tension structure the membranes must be prestressed. This can be achieved with flat fabric fields, but greater stiffness can be gained by introducing anticlastic curvature (saddle shapes) into the surface to produce immediate geometric stiffness under applied loads. For large structures, the size of a membrane field is usually limited by the strength of the fabric and the degree of curvature built in. To achieve sufficiently high curvatures, and so limit stresses, the surface of a large structure must be broken down into fields each with their own anticlastic curvature, separated by linear tension elements (cables, ropes or belts), which collect load from adjacent fields.

Alternatively, the fabric must be supported by an independent network of cables, which carries the load out of the cladding membrane directly. Elements used as linear restraints at the junctions of membrane fields (scallops, ridges and valleys) are more dependent on compatibility with the membrane performance than complete load carrying networks.

The prime criteria for selection are: (1) Facility to transfer load from membrane to element, allowing for parallel and perpendicular force components; (2) If not free to slide, element strain compatible with membrane strain; (3) Elements flexible enough to follow curves in three dimensions; (4) Elements with sufficient in-line stiffness to ensure load transfer; (5) Consistent, predictable in-line stiffness, unchanging with time, preferably linear; (6) Durability to exposure conditions; (7) Easy termination and economical transfer of tension to other components; (8) Cost, including site handling, compatible with total structural cost; (9) Required strength; (10) Easy transportation; (11) For networks, easy linking at crossing nodes.

In order to understand the nature of the forces on and deformation of typical linear elements in a tension structure, we consider two examples.

(1) A typical structure, spanning 40m and 60m long, consists of two central fields and two end fields. Maximum fabric stresses in the central fields (due to applied loads) will be about 25kN/m, creating boundary cable tension of 200kN and ridge cable tension of 500kN. A common difficulty arises at the field boundaries due to the anisotropy of the material. The highest stress levels occur in the warp or weft yarns, which are oriented in the direction of principal curvatures. Since the yarns are rarely orthogonal to the edges of fields there are both perpendicular *and* tangential forces on the linear elements at the boundary. Usually the tangential forces are transferred to the linear elements through sewn-on edge belts or bolted metal edge clamps, thus transforming the shear forces into rope tensions. The normal forces are directly carried by sideways pressures on the cables or ropes, with the residual force balanced by components of tension in a rope following a curved path. Smooth transfer of these forces is difficult to achieve, especially where fabric, belt and cable each have their own nonlinear elasticity, and where connections are imperfect. This situation would be simplified if one element were suitable for carrying all the load from the fabric regardless of weave orientation.

(2) In a typical airhouse, the connection between fabric and ground perimeter demonstrates the problems created by incompatible straining. The fabric strains under in-plane longitudinal stresses, but the ground will not strain. This results in shear distortion of the membrane towards the ground. An airhouse spanning more than 40m will require cable restraint to limit in-plane fabric stresses, and define distinct areas of membrane to transfer load into the network. The form which they take up must be predicted, so that the fabric can be patterned to match it. Hence predictability of strain is a very important feature. Compatibility of strain becomes an issue when the restraining cables are not free to move across the membrane surfaces. This effect will occur where two-directional cable nets are used to "lock-in" to the deformed membrane surface.

Design loads may be over 500kN for cables in large roofs, but actual loads are highly variable. Usually the prestress levels will be only 10 to 20% of the ultimate design load, which is predicted to occur only once in the building's lifetime. However, the frequency and magnitude of load vary with the patterns of wind and snow forces. Wind loads, having a significant dynamic component, will create short term peaks of stress measured in seconds, whilst snow loads may have durations of several days. Whether wind or snow is the critical load case will clearly depend on the location of the structure. In addition to the dominant in-line tension, any curvature leads to tensile and compressive bending strains and other forces: these are greater at detail points such as eyelets.

For membranes where tear propagation is the dominant failure mode, design stresses must be sufficiently limited to ensure that relatively small tears remain stable. Factors of safety between 8 and 6 on tensile strength are commonplace. For linear elements, factors of between 2 and 3, on ultimate breaking strength, are normally acceptable when used as an integral part of a permanent structure, whilst a factor of 5 would be used for stand-alone lifting equipment where the chance of overload is greater and the handling might cause damage.

In building, construction at least cost is a vital consideration. Investment decisions normally underemphasise "least lifetime cost" in favour of "least initial cost". Membranes currently used are PVC coated polyesters with lifespans of 10 to 15 years and PTFE or silicone coated glass fibre with lifespans of 25 to 35 years. The additional linear elements must have at least a comparable lifespan. If a replacement membrane is planned, longer-life elements might be appropriate, but there is a strong possibility that new materials with better characteristics and different properties will become available, and so make complete replacement more logical. Where the membrane merely clads a cable network, and if strain compatibility is not important (as with a polymer panel cladding on a cable net), independent replacement of the cladding is highly feasible. Therefore there may be sound economic justification for selecting ropes or cables that outlive the membrane.

3. MODERN FIBRE ROPES

From ancient times until 150 years ago, ropes were made from natural fibres; then steel wire ropes displaced fibre ropes from serious uses in structural engineering. The situation changed again 50 years ago with the invention of two generations of strong man-made fibres, the first (nylon, polyester etc) more extensible, and the second (carbon, aramid etc) with high modulus. Since these were continuous filaments, high twist was not essential, and ropemakers have developed a range of new constructions. The choice is enormous: it is estimated that, for any given purpose, 500,000 combinations could be considered. Architects need specialist advice from experts who know the field and have facilities for computing performance. In this paper, we can only give some general information, more related to the main structural need formulated above than to the ancillary uses also mentioned in the introduction.

Table 1 lists materials currently available for ropes, with rough indications of strength and stiffness relative to weight and price; more detailed plots have been given elsewhere [2]. Except for low cost for minor uses, which favours polypropylene, and ancillary uses needing high extensibility and energy absorption, which favour nylon, the choice is between polyester, at lower cost, or the high-modulus high-tenacity (HM-HT) fibres at lower weight. The brittle (in bending) fibres, carbon and glass, are only suitable for use when bonded by a matrix as solid pultruded rods. Such rods may also be used with other fibres, in order to reduce the problems of axial compression.

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natural fibres with limited performance
hemp, sisal, cotton etc [1/0.1/2/2]

man-made fibres adequate for common uses
regular melt-spun polyethylene, polypropylene [2/0.2/5/1]

intermediate performance fibres
polyamide (nylons) [3/0.5/4/1]; polyester [3/1/4/2]
glass [5/1.5/10/10]

advanced [HM-HT] fibres from liquid crystals
aramid (®Kevlar and others); LCAP (®Vectran); PBO [7/4/1/1]

other high modulus, high strength (HM-HT) fibres
high-modulus polyethylene (HMPE) (®Spectra, ®Dyneema) [10/7/1/1.5];
carbon [8/10/0.4/2]

steel wire [1/1.5/1/5]

Table 1 Materials with approximate ratings for:
[strength÷wt/stiffness÷wt/strength÷price/stiffness÷price]

Ropes and cables may be categorised in five broad groups. *Twisted* constructions comprise the familiar three and four strand ropes. High twist was necessary to hold short fibres together, but the tensile efficiency is low and torque balance is poor. Ease of splicing on site leads to their use as guy lines for tents and marquees. *Plaited* and *braided* constructions, interwoven from equal numbers of clockwise or counterclockwise strands, may be either solid (e.g. 8-strand) or circular. Single circular braids have hollow centres. Double braids are made with a second single braid over an inner braid. *Stranded (wire rope)* constructions are similar to twisted constructions, but have lower twist to improve tensile performance. The strands (or wires) are arranged in concentric rings, and may be designed to minimise torque generation. They should be used when the application requires the rope to be worked over sheaves (pulleys) at high loads. Whereas jacketing is merely desirable in some other constructions to provide wear and light resistance, it is essential in stranded rope to hold the construction together. *Parallel* constructions comprise parallel yarns, strands or sub-ropes held together by an external cover, which may be extruded polymer or a braided jacket. They have high tensile efficiency, but should not be worked over sheaves at high loads. Some types need special terminations. *Pultrusions*, which have excellent strength and fatigue resistance, but are costly to make and difficult to terminate, comprise an assembly of fibres in a rigid or flexible resin. Other linear elements include flat woven or braided webbings, which may be easier to join to membranes or to use as slings. Round slings, consisting of parallel yarns in a textile casing, offer much higher specific strength for lifting applications. Since many variants of the above types, including blended forms, are possible, it is easy to see why the choice is so large. Furthermore, terminations may cause as many problems as the ropes themselves; the available types are variants of grips, splices, resin sockets, and barrel-and-spike.

Computer programs have been developed to predict the load-elongation and torque-twist properties of ropes [3]. These can be used to design ropes with properties which match the membrane properties, and meet the other requirements specified above. By way of example, Table 2 gives properties of a few candidate ropes for the strength requirement of 500kN.

FIBRE	ROPE-TYPE	WEIGHT kg/100m	STIFFNESS kN/1% extn	PRICE £/100m	NOTES
manila	three-strand	500	40	600	GRADE 1
steel	galvanised	300	360	700	6x36IWRC
	plastic coated	"	"	1000	stranded
	stainless	"	"	2500	
poly-propylene	8-strand X-plait	200	20	500	worked & rested
polyester	double braid	220	30	1500	ditto
nylon	double braid	150	15	1200	ditto
polyester	parallel strand	150	40	1000	ditto
carbon	pultrusion	70	600	10,000	1x6 helical
aramid	parallel yarn	50	180	2500	w'rkd & r'std Kevlar 29
HMPE	stranded	40	80	1600	stiffness 0.1Hz

Table 2 Rope properties at 500kN strength (approximate values only), excluding terminations.

In addition to the quasi-static properties, long-term performance is vital. Failure often occurs at terminations. Of the six "fatigue" mechanisms identified in ropes [4], the following are likely to be of most importance in building structures. Creep rupture, determined by "average peak load", is a major weakness of HMPE, and, to a lesser extent, nylon, and is always the default mechanism in the absence of others. Internal abrasion is most serious in nylon. Axial compression fatigue is a potential killer in HM-HT ropes, and, to a much lesser extent in polyester and nylon. Even when the ropes themselves are always under positive tension, axial compression can occur (and has caused embarrassing failures in marine uses), especially with low minimum loads, due to twisting of ropes that are not torque-balanced, differential response of components, or bending. Computer programs have been developed to model these fatigue responses [5] (and hysteresis heating), though the theory is less certain than for the quasi-static behaviour and input data are not always available.

4. THE COMPETITIVE POSITION

At present engineers are generally selecting steel ropes and strands wherever high strength, high stiffness and durability is needed. Steel dominates the field for structural rigging, "cable" nets and boundary scallops. However, steel is not ideal for the following reasons: steel ropes have a nonlinear stress-strain relation at low (working) stresses; it is difficult to transfer forces tangentially into a steel cable; steel cables cannot be sewn or welded onto coated fabrics and require special, costly additional clamps; steel ropes can damage and chafe the fabrics used; normal oils present in cables can harm fabric coatings; for transport, steel cables need to be removed from the fabric panel to allow it to be packaged small and to avoid damage; steel cables and their terminations must have corrosion protection unless stainless steel is used. Against this, steel cables have a cost advantage over any man-made fibres that might be able to perform better. Advanced fibres, such as Kevlar, offer potential advantages of high and reliable stiffness and light weight. They are attractive to the structural engineer for these reasons, but their use can rarely be justified. Their most notable use is as stiffeners to sails for racing yachts, where relatively small improvements in performance and control win the race. In building structures, properties are rarely that critical and price dominates. However, with current advances in the technology, the cost advantage of steel may not continue to be the case for long, especially when the indirect cost savings as well as the direct cost are taken into account.

The clearest advantage of the most recently developed fibre ropes over steel cables is low weight-to-strength ratio. This can be useful for mobile structures to give ease of handling, but becomes especially relevant for extremely large air-supported structures covering many hectares. For a structure spanning 500 meters, the weight of restraining steel cables is likely to be between 8 and 15kg/m^2. With normal inflation pressure of 20 to 30 g/m^2, such a weight is very significant; therefore operating pressures would have to be increased. However, recent research shows that the sensitivity of such structures to aerodynamic instability, as well as buffeting from the wind, depends on the net over-pressure. Using an aramid rope of the same strength, the weight of the restraining cables would reduce to between 2 and 4kg/m^2. In addition to the stability advantage, the saving in inflation equipment, easing of access route pressurisation problems, and reduction in required strength of cladding membrane needed to withstand the pressure could be sufficient to pay for the additional capital cost of the cables. Design studies would be needed to determine the long-term durability of such ropes, particularly in terms of the need to avoid axial compression fatigue.

The above example is based on a technical solution in terms of rope strength; but there is also a strong case for considering an intermediate solution using polyester ropes. The weight would be greater, thus reducing some of the benefits, but the rope cost would be lower and current indications are that polyester is more rugged in use. Rope experts have more confidence in its resistance to fatigue. Another consideration is the axial stiffness of the rope, which needs to be considered in relation to compatibility with membrane properties.

5. CONCLUSION

It has taken some forty years to develop mebrane materials which can adequately carry loads and which have a decent life. Simultaneously, it has been necessary to develop analytical tools for engineers who design with these materials. Now that both are available, architects world-wide are designing tents. In large structures, the membranes are bordered and prestressed by linear tension elements, which not only gather high forces but act as tear stoppers. These elements have their own problems and, again, the role of new materials must be addressed. As well as the intrinsic properties of ropes, cables and webbings, questions of connections, including clamps and terminations, come up.

Force is not the principal issue. It is more important to consider compatibility - of strain and other aspects of physical behaviour, performance in fire, lifetime, and so on. Above all, economy is a major factor: a 10% increase in load-carrying capacity means little, but a 10% reduction in cost is a revolution. This paper encourages architects and engineers to address the problems of linear tension elements with an open mind, taking account of the availability of new materials and structures and the many complex and interacting features of performance and cost. Since the next major building type, once the visual conservatism and reluctance to think of buildings as machines is overcome, is the airhouse, which is the most economic climate moderator one can think of, the opportunities for new linear tension elements will be even more important.

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