An introduction to cable roof structures

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Preface

During the sixties and early seventies it was thought by many that the architectural and economic potential of cable roof structures would lead to an increasing demand for these types of buildings. Consequently a great deal of work was carried out world wide to study the behaviour of different types of structural systems. The interest in cable structures also stimulated an increasing interest in the use and development of numerical methods for solving large systems of nonlinear equations, made possible by the emergence of the high-speed electronic computer.

The early expectations for the demand of cable roofs have, however, so far not been realised, and to date the total number of cable roofs in existence is a relatively modest one. There may be several reasons for this. The need for larger clear spans has been less than expected. Architects and engineers are not in general familiar with their design and have tended to consider them only for the less usual structures such as sports stadia, ice rinks and exhibition halls. Their industrial potential and their use in earthquake areas have never been properly exploited. The cost of tension anchors where these have been required has been relatively high and is thought to be partly due to lack of constructional expertise and lack of research.

This book is written to encourage the use of cable roof designs and show that a large variety of practical structural forms can be simply and cheaply constructed by the use of such common and well-known materials as prestressing strand and metal decking, timber or concrete. The book is not intended as an exhaustive study of the architectural, structural and technological aspects of cable roofs but, rather, as the title implies, as an introduction to these types of structures. It is, however, hoped that it contains sufficient information to enable interested engineers in possession of a small computer to carry out their own designs without any outside assistance.

Those who are particularly interested in the architectural aspects of lightweight structures should consult the work of Professor Frei Otto, University of Stuttgart, whose endeavours in this field span several decades. For those whose interest is more in the analytical field the work of Dr H. Møllmann and Dr H. Irvine is recommended, together with one of the many books on numerical mathematical methods. (See refs. [3.1], [4.15] and [4.19].)

In writing the chapter on wind and earthquake loading the main object has been to present the reader with methods for generating wind and earthquake histories that may be used in conjunction with the nonlinear theory given in chapter 5. The generated histories are strictly only applicable to linear structures, but can also be used for nonlinear structures if the approach suggested is adopted. More research, however, is required in order to develop theories for generating histories which are immediately suitable for nonlinear structures.

When writing the chapters on cable beams and grids it was originally intended to include a number of nondimensional graphs for the purpose of design. It ver, soon became clear, however, that the number of graphs required was so large as to be impracticable. In their place a number of tables with nondimensional values of forces and displacements for structures the writer has analysed have been inserted, and it is hoped that these will help the reader to obtain some feeling for the influence of the variation in design parameters on the structural characteristics of cable roofs.

In writing the book the author has been helped and encouraged by many people. He is in particular, grateful to M. J. Tawse of British Ropes Ltd. for writing the chapter dealing with the manufacture and properties of cables, to Dr, ing. P. Spinelli and Mr D. Kay for supplying the original drafts on wind and earthquake loading respectively, and to Mr R. Dixon for contributing to the chapter on design considerations. The writer also wishes to thank Mr J. Armishaw for helping him to update a paper on tension anchors, which the author had previously written together with Mr N. Vadgama, the contents of which now constitute the chapter on tension anchors.

The author also wishes to express his gratitude to Dr P. Regan, Professor P. Krishna and Professor H. Tottenham for their many useful suggestions and for checking the manuscript, to Dr S. Moosavinejad and Dr H. Tabar-Heydar for their help with the computer analysis, to Mr D. Mutlow for preparing most of the illustrations and to his wife Mrs R. Buchholdt for preparing the tables, graphs and diagrams and for typing the manuscript.

Finally the writer would like to express his gratitude to the Science and Engineering Research Council and the firm, White Young and Partners, who both have supported the work on cable roofs for a number of years, and to those of his colleagues who have facilitated the author's research and the writing of this book by undertaking a larger share of the undergraduate teaching than they otherwise would have had to do.

H. A. Buchholdt
1984

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1 Structural systems

Introduction

The development of the high-tensile steel cable has made it possible for man to transmit large axial forces in tension at a relatively low cost. The ever-increasing spans and elegance of the modern suspension and cable stayed bridges are the most obvious examples of the economical way in which large loads can be supported by the use of members in tension.

The use of steel cables in the design of long span roofs has only relatively recently begun to interest architects and engineers. It is probably true to say that the cable roof structure which first fired their imagination was the building of the North Carolina State Fair Arena at Raleigh, USA. The arena was completed in 1953. The main structure of this building consists of a cable net supported between two intersecting concrete arches, each inclined at approximately 21° to the horizontal, fig. 1.1. Stiffness of the roof was achieved through curvature and pretensioning of the cables. A diagram showing the way in which the tensile forces in the cables are balanced by the compressive forces in the arches is shown in fig. 1.2. Since the completion of the Raleigh Arena different roof structures using steel cables have been studied, developed and built in various parts of the world.

Cable roofs have a wide field of application and have been used to cover such differing buildings as stadia and sports halls, swimming pools and water reservoirs, concert halls and theatres, cooling towers, hangars, warehouses and factories. Experience has shown that cable roof structures have considerable architectural, structural and economical potential. Their use has often resulted in attractive buildings, with structures that are stable and efficient since a large proportion of the main load-carrying members are in tension.

The use of cable roof structures has in the past mainly been considered for buildings which require large column-free areas. One reason for this is undoubtedly the general belief that they are only an economical proposition when used to bridge large spans. There is, however, a considerable amount of evidence which indicates that cable structures also can be competitive alternatives for smaller span structures. With the continuing rise in the cost of steel, the use of cables is steadily becoming a more attractive economic alternative to conventional forms of structures such as portal and space frames.

Tension roofs can be divided into categories based upon whether the roof cladding is supported by:

(a) simply suspended cables;
(b) pretensioned cable beams;
(c) pretensioned cable nets;
(d) pretensioned cable grids.

The total structure may be either self-balancing or non-self-balancing. A self-balancing building is one in which the structure supporting the cables has a geometry which permits the forces in the cables to be balanced internally. A non-self-balancing building is one in which the geometry of the building supporting the roof structure is unable to resist the cable forces without the aid of ground anchors.

Fig. 1.1. Diagram of the North Carolina State Fair Arena at Raleigh, USA.

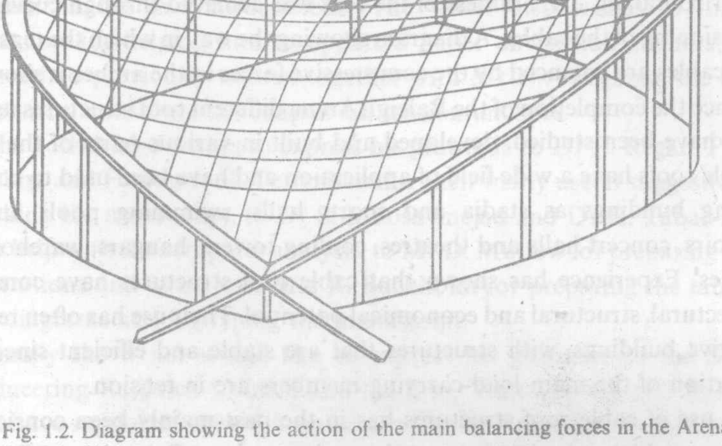
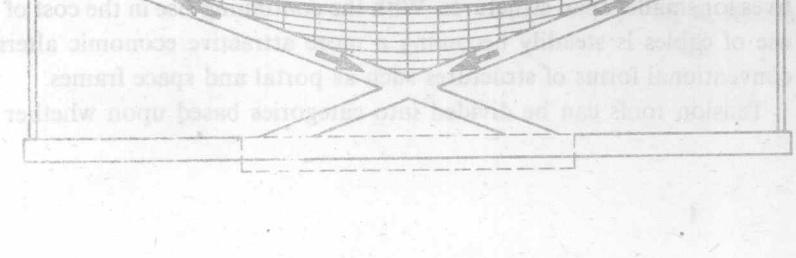


Fig. 1.2. Diagram showing the action of the main balancing forces in the Arena at Raleigh, USA.



Simply suspended cable structures

The cladding of roofs which are rectangular or trapezoidal in plan can be supported by a series of simply suspended cables hanging in vertical planes (fig. 1.3). In roofs which are circular or elliptical in plan the cables are suspended radially and attached at the perimeter of the roof to a compression ring and at the centre to a tension ring (fig. 1.4). For roofs which, in plan, are ellipsoids or of similar shapes, a combination of the above two geometrical patterns of suspension may be used. This is achieved by constructing the tension ring in two halves and connecting these with two horizontal cables, as shown in fig. 1.5. The result is an elongated form of tension ring which permits cables to be suspended in

Fig. 1.3. Simply suspended cable roof with the cables suspended in parallel planes.

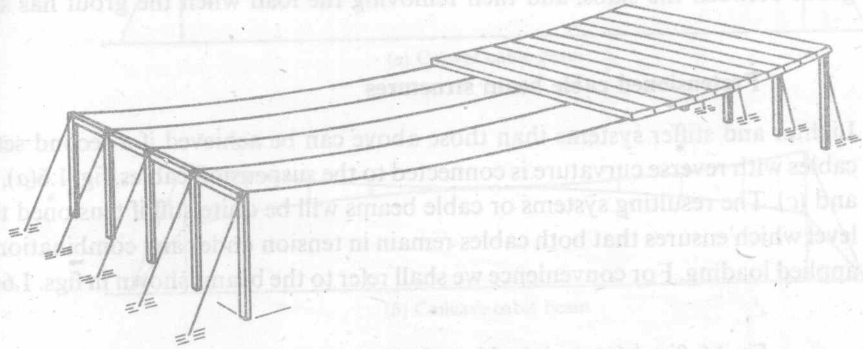
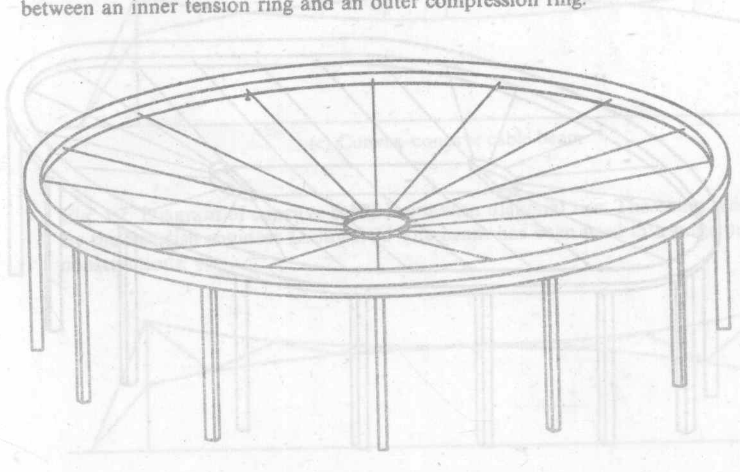


Fig. 1.4. Simply suspended cable roof with the cables suspended in radial planes between an inner tension ring and an outer compression ring.



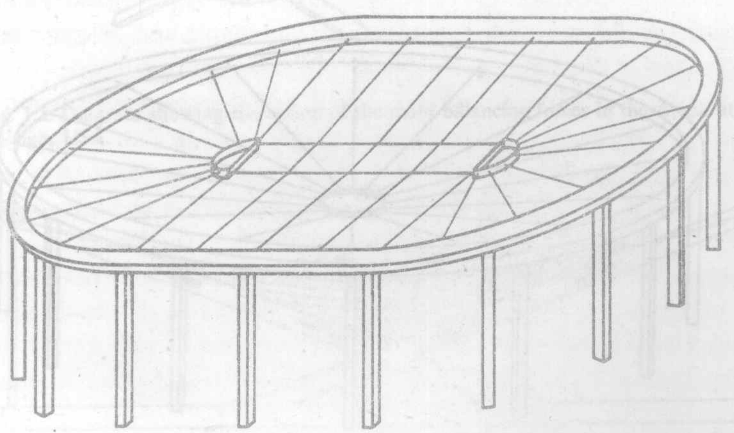
parallel planes in the central area of a roof and in radial planes at either end.

For basket-shaped roofs as described above, drainage must be provided centrally. Systems of this type have no stiffness. To reduce the movements which will be caused by any form of applied loading the roof cladding must either be very heavy or act as a shell. Obviously, for simply suspended cable roofs, concrete is the most suitable roofing material. The concrete may be placed either as prefabricated slabs or *in situ*. Both methods are used. If the concrete is placed *in situ*, plywood or insulating panels clamped underneath the cables may be used as shuttering. In either case it is advisable to apply a certain amount of pretension to the cables in order to stiffen the structure during construction and to prevent cracks forming in the finished roof. In the case of circular structures, this can and has been done by jacking the central tension ring downwards and releasing it after the concrete has set. When prefabricated slabs are used, prevention of cracking can also be achieved by placing an overload on the roof before inserting grout between the slabs, and then removing the load when the grout has set.

Pretensioned cable beam structures

Lighter and stiffer systems than those above can be achieved if a second set of cables with reverse curvature is connected to the suspension cables, fig. 1.6(*a*), (*b*) and (*c*). The resulting systems or cable beams will be quite stiff if tensioned to a level which ensures that both cables remain in tension under any combination of applied loading. For convenience we shall refer to the beams shown in figs. 1.6(*a*),

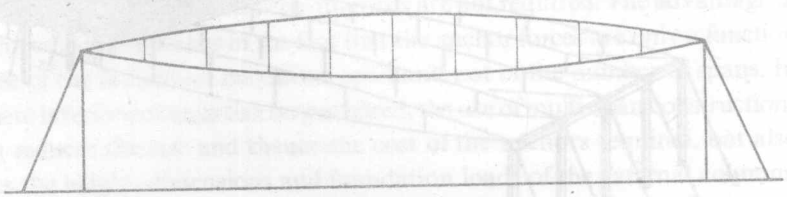
Fig. 1.5. Simply suspended cable roof with the central cables suspended in parallel planes and the cables at either end suspended between an inner split tension ring and an outer curved beam.



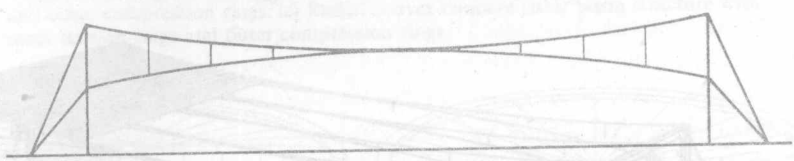
(*b*) and (*c*) and 1.7 as convex, concave and convex–concave beams respectively. In the first of these beams, the connecting members are in compression, in the second in tension and in the third the two outer members are in tension and the remainder in compression.

Fig. 1.8 shows a cable truss which was developed by the Swedish engineer, David Jawerth. Here the ties are inclined and connected in such a way that they, together with the suspension and pretensioning cables, form a system of

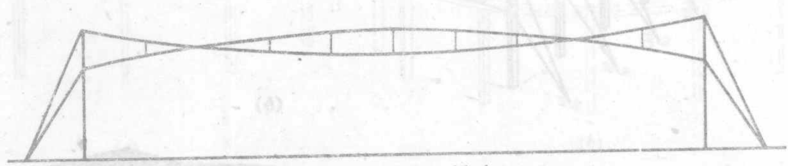
Fig. 1.6. Pretensioned cable beams.



(*a*) Convex cable beam

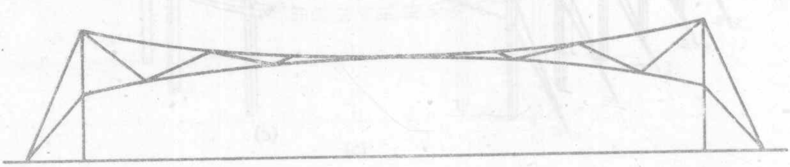


(*b*) Concave cable beam



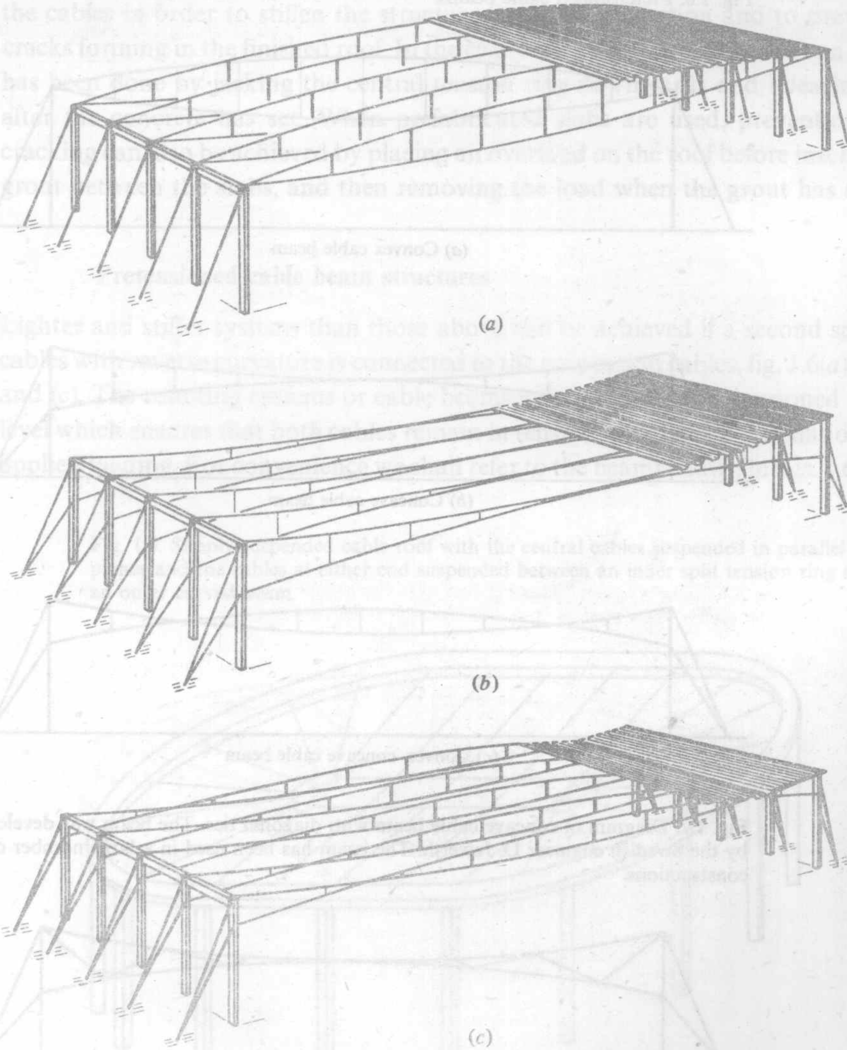
(*c*) Convex–concave cable beam

Fig. 1.7. Diagram of concave cable beam with diagonal ties. The beam was developed by the Swedish engineer D. Jawerth. The beam has been used in a large number of constructions.



pretensioned triangles. Thus, after having been pretensioned, this truss is a structure, as opposed to the beams shown in fig. 1.6 which are structural mechanisms. The level of pretension is usually such that the ties remain in tension when subjected to dead load only. The application of increasing live load,

Fig. 1.8. (*a*) Convex cable beam structure with corrugated metal roof decking.
(*b*) Concave cable beam structure with corrugated metal roof decking.
(*c*) Convex–concave cable beam structure with corrugated metal roof decking.



however, will cause some of the diagonals to go slack until only half of them remain in tension. The truss changes to a structural mechanism at the stage when one or more of the ties go slack. The Jawerth Truss has been successfully used in a large number of buildings with spans ranging from approximately 15–100 m.

For roofs which are rectangular, trapezoidal, circular or elliptical in plan, cable beams may be arranged in geometrical patterns similar to those described for simply suspended cable structures. Examples of such arrangements are shown in fig. 1.9(*a*), (*b*) and (*c*).

Multi-span cable beam constructions such as those shown in fig. 1.10(*a*), (*b*) and (*c*) can be used with advantage where either a number of large spans can be interconnected or where column-free interiors are not required. The advantage of multi-span constructions lies in the fact that the anchor forces are only a function of the size of the individual maximum span and not of the number of spans. In cases where interior columns can be permitted, the use of multi-span constructions not only reduces the size and thence the cost of the anchors required, but also decreases the height, dimensions and foundation loads of the external columns.

Fig. 1.9. (*a*) Radial convex cable beam structure with inner tension rings and an outer compression ring. (*b*) Radial concave cable beam structure with inner tension rings and outer compression rings. (*c*) Radial convex-concave cable beam structure with inner tension rings and outer compression rings.