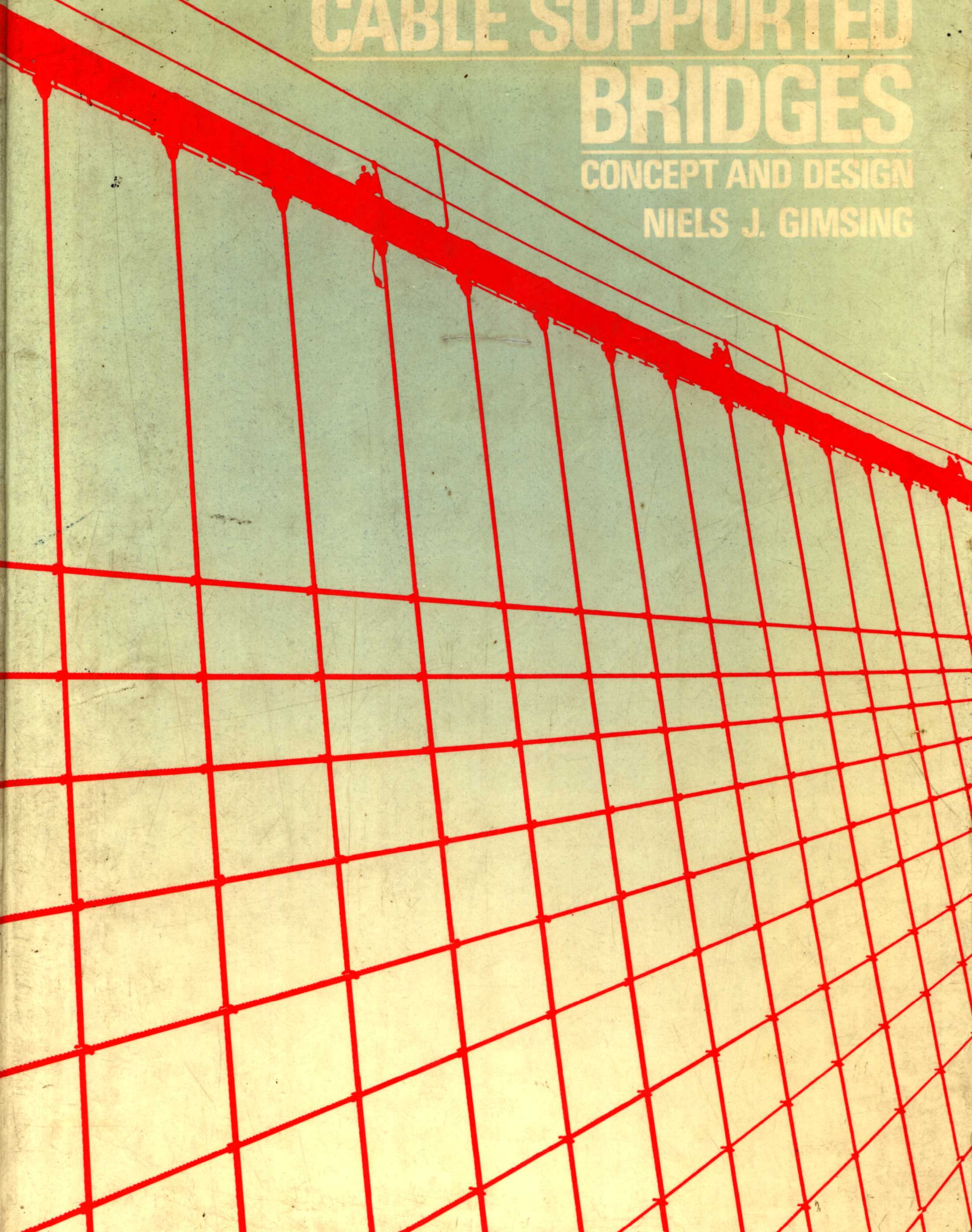
CABLE SUPPORTED BRIDGES

CONCEPT AND DESIGN

NIELS J. GIMSING



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Preface

In the design process of cable supported bridges analytical problems have played a dominant role for a long period. Thus, much effort has been aimed at developing new methods of calculation and consequently the majority of the scientific publications in this field has concentrated on these analytical aspects.

However, during the last two decades the vast developments within electronic computers have changed the situation significantly, so that the day is within sight when the detailed analysis of cable supported bridges can be made by general structural programs prepared to deal with any three-dimensional structure under static and dynamic loading.

A detailed description of the analytical methods that were previously used specifically for the analysis of cable supported bridges would therefore be doomed to become superfluous within a short span of years.

Because of this, in the present work, I have chosen to concentrate on a synthesis of cable supported bridges. This is also motivated by the fact that the elimination of analytical limits due to the introduction of electronic computers has increased the importance of a synthesis in the design process for cable supported bridges.

In times past, when the amount of numerical work that could be carried out was limited by the capacity of the slide rule and mechanical calculators, the analysis required a profound comprehension of the structural behaviour as the necessary simplifications would only lead to an acceptable result if they were based on a clear distinction between important and unimportant actions in the load-carrying system. With this followed an adequate background for selecting between structural systems with different levels of efficiency.

Today the almost unlimited capacity of electronic computers means that very complicated structural systems can be analysed without any deeper understanding of their behaviour or efficiency.

This, combined with the fact that the computer will not on its own suggest favourable modifications to a less efficient structural system, might lead to the acceptance of unfavourable systems.

In the design process the most important decisions are generally made in the early phase where the synthesis dominates over the analysis. However, in this phase the synthesis must be supplemented by simple analytical methods to quantify the different structural forms.

The simple analytical methods required in the preliminary design phase are not the approximate methods that were applied before the electronic computer took over, but much simpler (and less accurate) methods. Thus, only a few loading conditions and only the main action of the load-carrying system need be considered.

The simple analytical methods included in the present publication are suited for giving a realistic input for the first computer run and to establish an early quantity estimate. Furthermore, the methods might be used in a preliminary comparison between different structural systems, as the relative values generally are more accurate than the absolute values.

Also, some simple analytical methods are included mainly to illustrate the behaviour of structural elements and the variation of quantities rather than to form a part of an actual design process.

The manuscript of the present book was prepared in the period from the spring of 1980 to the summer of 1982.

The major part of the text was completed during a sabbatical semester spent at the University of California, Berkeley in the spring of 1981, whereas the remaining text as well as all drawings and photographs were prepared at the Department of Structural Engineering, Technical University of Denmark.

In the process of completing the manuscript assistance was received from many members of the staff at the Department of Structural Engineering, among which the following should be especially mentioned for their good work and enthusiasm: Mrs Susanne Kjærgaard Nielsen (typewriting), Mrs Esther Martens (drawing), Miss Annemette Tranders (drawing), Mr Benny Leisten (drawing and copying), and Mr Christian Bramsen (photographic work). Outside the Department Mrs Karen Gimsing rendered an appreciable effort in reading the proofs of the manuscript.

Finally, the author wants to express his gratitude to the governing body of the Department of Structural Engineering at the Technical University of Denmark for its sympathetic attitude towards the task of writing the present book — an undertaking that inevitably influenced the time available for other activities at the department.

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Technical University of Denmark
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The remaining 128 photographs were all taken by the author during the period 1959–82.

Contents

Introduction

In the family of bridge systems the cable supported bridges are distinguished by their ability to overcome large spans. Actually, cable supported bridges are competitive for spans in the range from 250 m to 1500 m (and beyond), thus covering approximately 5/6 of the present span range.

For the vast majority of all cable supported bridges the structural system can be divided into four main components as indicated in Figure 1:

(1) the stiffening girder (or truss) with the bridge deck;
(2) the cable system supporting the stiffening girder;
(3) the towers (or pylons) supporting the cable system;
(4) the anchor blocks (or anchor piers) supporting the cable system vertically or horizontally.

The different types of cable supported bridges are distinctively characterized by the configuration of the cable system.

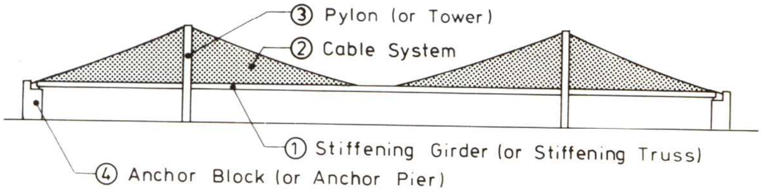

Figure 1 Main components of a cable supported bridge

The suspension system (Figure 2) comprises a parabolic main cable and vertical or slightly inclined hanger cables connecting the stiffening girder to the main cable.

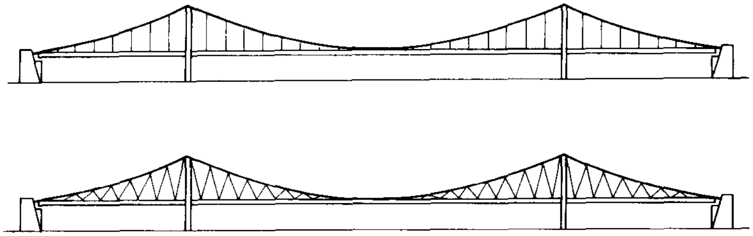

Figure 2 Suspension bridge systems: top, vertical hangers; bottom, inclined hangers

The cable stayed system (Figure 3) contains straight cables connecting the stiffening girder to the pylons. In the fan system all stay cables radiate from the pylon top, whereas parallel stay cables are used in the harp system.

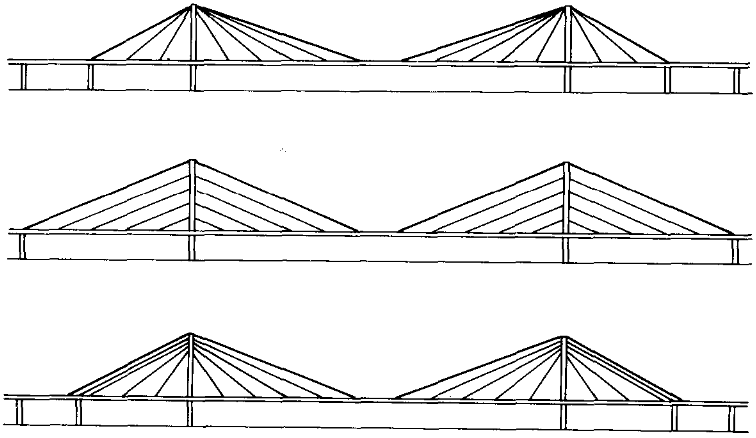

Figure 3 Cable stayed bridge systems: top, pure fan system; centre, harp system; bottom, modified fan system

Besides the two basic cable stayed systems (the fan system and the harp system) intermediate systems can also be found. Thus, in the modified fan system the cable anchor points at the pylon top are spread sufficiently to separate each cable anchorage.

Combined systems containing both the suspension system and the cable stayed system (Figure 4) have been applied in cable supported bridges built in the 19th century, such as the Brooklyn Bridge having its main cable and vertical hangers supplemented by stay cables in the fan configuration.

Figure 4 Combined suspension and cable stayed system

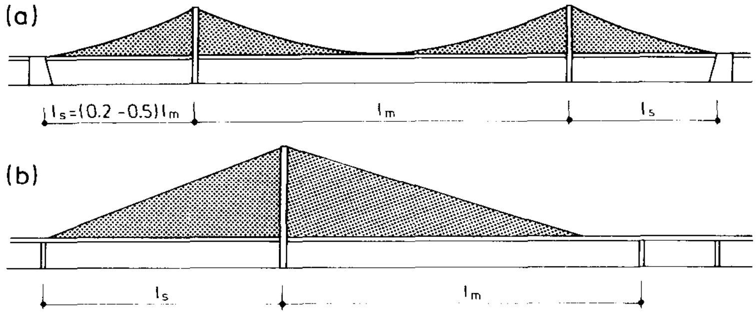

Figure 5 Three-span and two-span cable supported bridges

The most common type of cable supported bridge is the three-span bridge with a large main span flanked by two smaller side spans (Figure 5(a)). However, within cable stayed bridges an asymmetrical two-span arrangement with a large main span and a somewhat smaller side span (Figure 5 (b)) has also been used in a number of cases.

Multi-span cable supported bridges with several main spans of equal size (Figure 6) have so far only been built in a few cases.

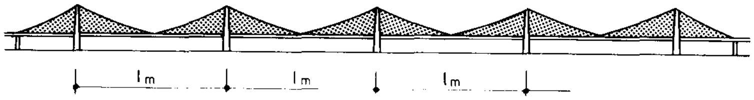

Figure 6 Multi-span cable supported bridge

For cable stayed bridges the trend has been to move from systems with relatively few heavy stay cables to multi-cable systems with a large number of stay cables supporting the stiffening girder more continuously (Figure 7).

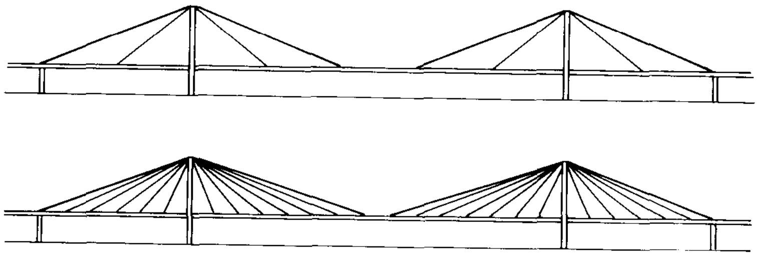

Figure 7 Cable stayed bridge with fan systems: top, system with few, concentrated stays; bottom, multi-cable system

In the multi-cable system each stay cable consists of a single prefabricated strand (mono-strand cable), whereas the stay cables of bridges with few, and therefore larger stays, have to be composed of several prefabricated strands (multi-strand cable). This will complicate the design of the anchorages at the stiffening girder as a flaring is needed to allow an individual anchoring of each strand (Figure 8).

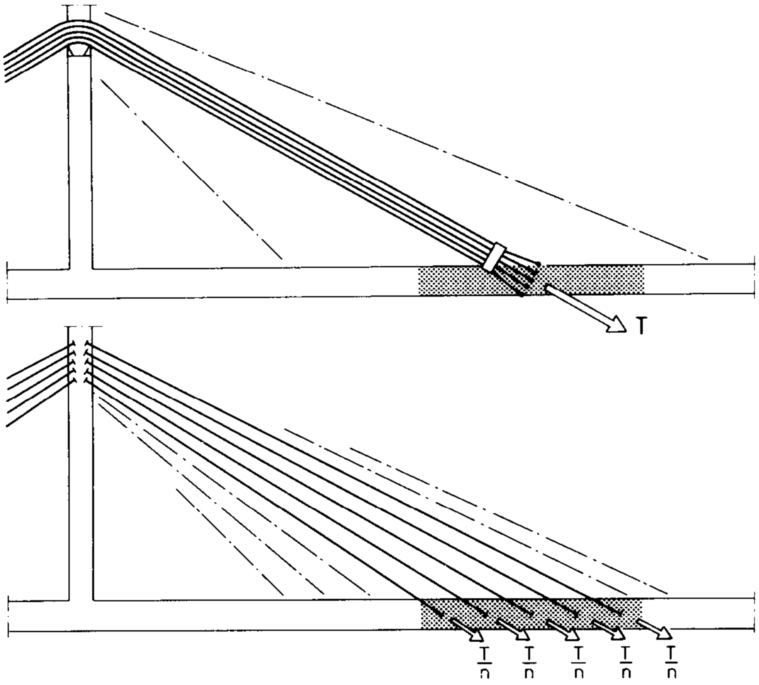

Figure 8 Comparison between a system with fcw, multi-strand stay cables and a multi-cable system with mono-strand stay cables

Also, the use of heavy, concentrated stay cables will require a local strengthening of the stiffening girder to allow the transmission of the large forces from the stays to the girder.

Moreover, because the multi-cable system will allow for easier and more efficient erection and also permit the replacement of stay cables damaged by corrosion or fatigue, it seems reasonable to assume that multi-cable systems will be preferred in the cable stayed bridges of the future.

Besides the configuration of the cables, cable supported bridges can also be characterized by the way the cable system is anchored at the ends.

In the earth anchored systems both the vertical and the horizontal component of the cable force is transferred to the anchor block (Figure 9 (a)).

In the self-anchored system the horizontal component of the cable force is transferred to the stiffening girder, whereas the vertical component is taken by the anchor pier (Figure 9 (b)).

In principle both earth anchoring and self-anchoring can be applied in suspension bridges as well as in cable stayed bridges. However, in actual practice earth anchoring is primarily used for suspension bridges an self-anchoring for cable stayed bridges.

In the transverse direction of the bridge a number of different solutions for the arrangement of the cable systems can be found.

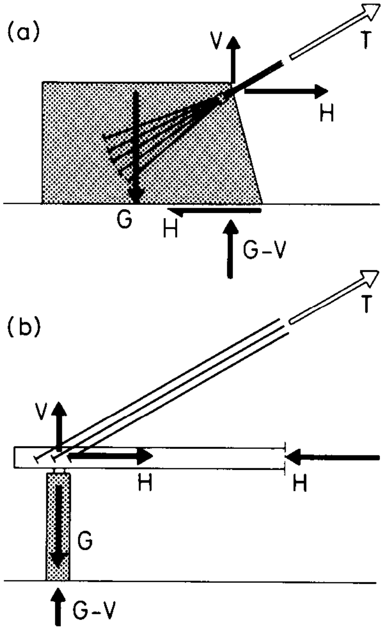

Figure 9 Connection between side span cable and anchor pier in an earth anchored system and in a self-anchored system

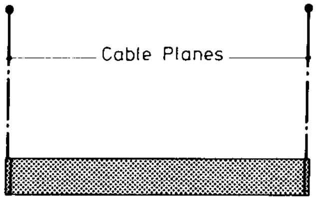

Figure 10 System with two vertical cable planes positioned outside the bridge deck

The arrangement used within suspension bridges comprises two vertical cable planes supporting the stiffening girder along the edges (Figure 10). With this arrangement, which is also found in many cable stayed bridges, the stiffening girder is supported by the cable systems vertically as well as torsionally.

In cases where the bridge deck is divided into three separate traffic areas, e.g. a central railway or tramway area flanked by roadway areas on either side, the two vertical cable planes might be placed between the central area and the outer areas (Figure 11 (a)). This arrangement is especially attractive if the central area is subjected to a heavy loading that would introduce a considerable bending in the floor beams, had the cable planes been placed at the edges of the bridge deck. On the other hand the displacement of the cable planes from the edges towards the centre of the bridge deck drastically reduces the torsional support offered by the cable systems.

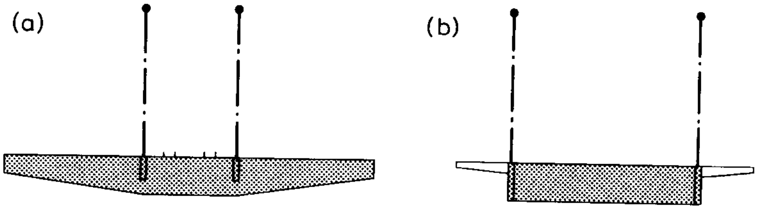

Figure 11 System with two vertical cable planes positioned between three separate traffic lanes

A more moderate displacement of the cable planes from the edges of the bridge deck is found in bridges with cantilevered lanes for pedestrians and bicycles (Figure 11 (b)).

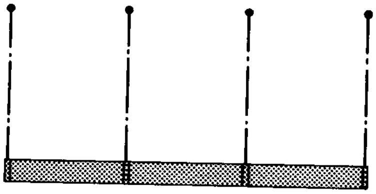

Figure 12 System with four vertical cable planes positioned outside and between three separate traffic areas

The application of more than two vertical cable planes (Figure 12) can be seen in some large suspension bridges from the end of the previous century and from the beginning of this century. In bridges with a large width of the bridge deck more than two cable planes might very well be considered also today, as the material required to carry the load transversally will be reduced significantly.

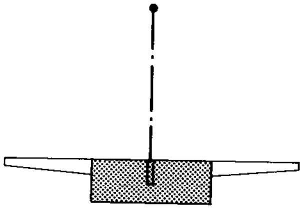

Figure 13 System with one central cable plane

Only one vertical cable plane (Figure 13) can be seen in a number of cable stayed bridges. With this arrangement the stiffening girder is only supported vertically by the cable system, and torsional moments must therefore be transmitted through the stiffening girder. This requires the application of a box girder with a considerable torsional rigidity.

Inclined cable planes (Figure 14) attached at the edges of the bridge deck and converging at the top are found within cable stayed bridges having pylons of A-shape. With this arrangement, the girder is supported both vertically and torsionally by the cable system.

As a general remark it should be emphasized that the highest efficiency of the cable supporting is achieved by application of multi-cable systems giving both vertical and torsional support. Consequently, a true cable supported bridge should contain two (or more) cable planes attached at (or near to) the edges of the stiffening girder.

In cable supported bridges carrying vehicular traffic the cable systems are generally arranged primarily to transfer vertical loading as this dominates. However, in bridges carrying pipelines, cable systems giving vertical as well as horizontal support have been used (Figure 15). Similar systems comprising outward leaning cable planes or supplementary horizontal cable planes have also been proposed for bridges carrying vehicular traffic but so far none of these proposals has reached the construction stage [81.2].

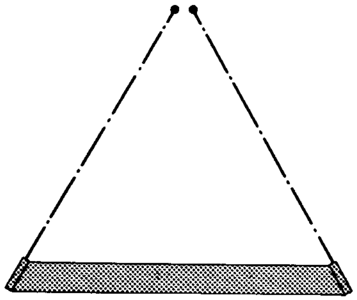

Figure 14 System with two inclined cable planes

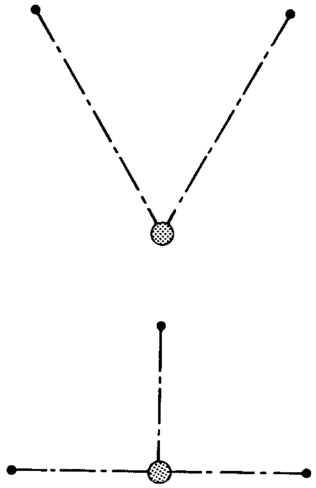

Figure 15 Pipe line bridges with two inclined cable planes or three cable planes to give efficient support vertically as well as horizontally

1

Evolution of cable supported bridges

The principle of carrying loads by suspending a rope, a chain or a cable across an obstacle has been utilized since ancient times, but for the modern bridge building technique, the early examples of suspension bridges are of limited interest, although most impressive structures can be found among the early predecessors of the cable supported bridges of today.

The ancestor of the modern suspension bridge is justifiably accepted to be the Brooklyn Bridge across the East River in New York (Figure 1.1). Opened to traffic in 1883, this bridge has a centre span of almost 500 m (486 m) and side spans of 286 m, giving a total cable supported length of 1058 m.

Figure 1.1 Brooklyn Bridge across the East River in New York

The Brooklyn Bridge — or as it was called at the time of construction: The East River Bridge — was the chief work of the unusually gifted bridge designer John A. Roebling, who was born in Germany but emigrated to the United States of America at the age of 25. Before the start of the East River Bridge construction, Roebling had already designed several impressive cable supported bridges, among these the railway carrying Niagara Suspension Bridge with a main span of 250 m, and the Cincinnati and Covington Suspension Bridge over the Ohio River with a main span of 322 m — prior to the East River Bridge the longest bridge span in the world.

During the period when Roebling worked as a bridge designer in the United States, a fatal bridge disaster took place when the suspension bridge across the Ohio River at Wheeling was destroyed by the wind in 1854. This accident made a strong impression on Roebling and inspired him to take several measures to increase the stiffness of suspension bridges beyond what is obtained by the cable itself. In his bridges, following the Wheeling disaster, he therefore introduced stiffening trusses with a considerable bending stiffness and stays to supplement the pure suspension system.

This understanding of the aerodynamic problem is clearly indicated in his own description of the East River Bridge concept: 'But my system of construction differs radically from that formerly practiced, and I have planned the East River Bridge with a special view to fully meet the destructive forces of a severe gale. It is the same reason that, in my calculation of the requisite supporting strength, so large a proportion has been assigned to the stays in place of cables.'

This description proves that Roebling knew very well that a cable stayed system is stiffer than the suspension system, and the fact that the stays of the Brooklyn Bridge carry a considerable part of the load can clearly be seen when observing the curve of the main cable having a smaller curvature in the regions where the stays carry a considerable part of the permanent load than in the central region where all load is carried by the main cable.

The efficiency of the cable stayed system in the Brooklyn Bridge (Figure 1.2) is clearly demonstrated by the following remarks by Roebling: 'The supporting power of the stays alone will be 15000 tons; ample to hold up the floor. If the cables were removed, the bridge would sink in the center but would not fall.'

John Roebling had started his engineering career in a period when bridge designing was still more of an art requiring intuition and outlook, than a science. This made it necessary for him to acquire a profound understanding of the structural behaviour of cable supported bridges. Having developed this feeling for the behaviour, he was able to design structures of great complexity, as he could combine his intuitive understanding with simple calculations giving adequate dimensions of all structural elements.

In the case of the Brooklyn Bridge, the system adopted is one of high indeterminateness as every stay is potentially redundant. A