Under-slung Cable Structures-A Feasible Alternative?

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Abstract

This paper examines the behaviour and feasibility of under-slung cable structures. Consideration is given to their structural behaviour, their dynamics, their cost-effectiveness and the practicality of adopting such structures. The parameters that govern the behaviour and response of these structures are investigated and structural arrangements and details are proposed, which it is suggested would make the construction of such structures feasible. The aim of the paper is to generate discussion of this novel form of construction and to identify opportunities for the exploitation and development of such a concept.

This paper discusses how underslung structures, when combined with a radical trussed stiffening girder, can provide an innovative but more sympathetic structure, which is stiff, stable and economically viable for both medium and long-span structures. It is shown that when there is a need to minimise the number or limit the location of the foundations required, such structures provide a means of adopting relatively large spans, while restricting the height of the cable supports and hence minimising the impact of the structure.

The paper concludes by summarising the benefits that can be obtained from such structures both during construction and in use, and seeks to identify the opportunities and challenges that must still be met to facilitate the exploitation and development of such a concept.

Introduction

Suspension type bridges have been established from the early stages of primitive man, far before the first records of modern girder bridges ever existed. Towers were generally built between trees, the cables consisted of hemp ropes, and typically the footway consisted of transverse timber boards and suspended by more or less vertical rope hangers. Such structures were common practice in early communities as it was a relatively straightforward form of construction without a need for any real understanding of their mode of behaviour. The so-called "Western Civilizations", only became interested in suspension bridges after the introduction of wrought iron, firstly in China in the form of chains. In the UK in particular, these were firstly forged on a large scale for use as anchor chains for ships, and bridges using such chains were often built near the early shipyards. However, most of these early types suffered oscillations in high winds and some collapsed as a result [1].

The economic utilization of materials for construction demands that, as far as it is possible, the predominating stresses in any structure should be those for which the material is best suited. In particular, the great strength and reliability of materials like steel and high-tech composites in tension and the uncertainties and inefficiency involved in the design of massive compression members dictates that the form that should be adopted for long span bridges, for economic designs, should generally be one that exploits these tensile properties. Indeed, this argument explains why cable structures dominate bridge design to such extent at all span levels - short to super span (>1200m) – and the extent of their application is such that nowadays, they can be used in virtually any situation. By nature, they are aesthetically stunning structures, renowned for their sensitivity to excitation and deformations, but extremely safe structures incorporating a high degree of redundancy. They are particularly flexible, cost efficient in terms of their weight/cost ratio and sustainable given their ease of maintenance, replacement of components and consequential longevity.

More recently, further structural developments have been achieved with regards to suspension and cable-stayed bridges with short to moderate spans.[2&3] These developments have incorporated the use of either concrete or steel as the main load bearing members, and the success of these projects has been assured by the use of simple but ingenious geometrical arrangements.

Concrete self-anchored suspension bridges have been introduced in China, with the construction of the Golden Bay Bridge, Lan Qi Bridge and Wan Xin Bridge. As described by Zhang et al[2] these projects, apart from being aesthetically pleasing, have resulted in significant savings in their construction costs. In particular, it is estimated that for the Lan Qi Bridge, the self-anchored suspension system resulted into a saving of nearly US$ 4.17 million when compared with a gravity-anchored solution. These designs incorporate a closed loop cable system with local anchorages in the girders, thus making them fully pre-stressed structures for any loading condition.

Under-slung cable arrangements have not been widely used and examples are few and far between. Ruiz-Teran and Aparicio[3] report that only twenty such cable-stayed structures have been built in the past thirty years, although they do acknowledge that a number of this type of design have been proposed but not built. It is suggested that the reasons for this are that there is a lack of understanding of their structural behaviour, a scarcity of studies of these structural forms and a reluctance of public authorities to accept such highly unconventional structures.

The aim of this paper is to generate discussion of these novel forms of construction and to identify opportunities for the exploitation and development of such concepts. The paper discusses how underslung structures, when combined with a radical trussed stiffening girder, can provide an innovative but more sympathetic structure, which is stiff, stable and economically viable for both medium and long-span structures. It will be shown that when there is a need to minimise the number or limit the location of the foundations required, such structures provide a means of adopting relatively large spans, while restricting the height of the cable supports and hence minimising the impact of the structure.

The generic arrangement that is considered can be summarised as a deck, supported by vertical compression struts below the deck, which are themselves supported by the cables. Various layouts may be adopted according to the requirements of specific sites and Ruiz-Teran and Aparicio[3] describe a range of single and multi-span structures that are both externally and internally anchored.

Structural behaviour

For the purposes of this paper, a generic arrangement is discussed (Figure 1) that co uld be adapted to suit a range of situations by appropriate modification of the stiffening girder and the suspension system. The particular design that is presented was developed in response to an undergraduate design competition[4] for an 8m wide (an unusually narrow structure), 150m span structure that was required to carry an imposed loading of the order of 20 kN/m ^{2}.

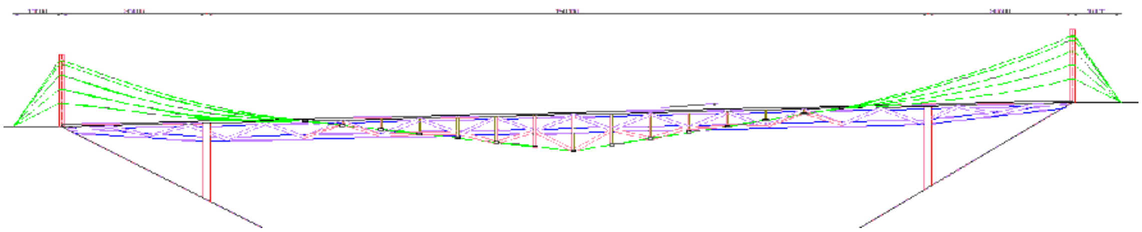

Figure 1: General Arrangement

Stiffening girder

Truss arrangements are excellent for dealing with high moments and shear forces and in addition they provide outstanding torsional stiffness (Figure 2). Because an under -slung arrangement is adopted, the compression chord will also carry and distribute local bending moments due to flexure between the nodes of the truss[1]. Treating the truss as one single beam, a simple static analysis can be performed. For the arrangement shown in Figure 1 in which the stiffening girder is supported at the piers this results in the maximum moments in the stiffening girder occurring over the piers and being of a hogging nature. As a result, the chords of the stiffening girder have to be designed for both ten sion and compression, a condition for which the type of truss proposed is again ideal because of its balanced configuration.

For the design proposed here it was suggested that rectangular hollow sections should be used for the top chords in order to increase the surface area through which the composite action with the deck can be achieved. Hollow sections are aesthetically pleasing but it is recognised that their use will increase the cost and complexity of the fabrication process. As such, it will probably be more economic to use open sections and, although this will require careful consideration of local buckling effects, the relatively short bay lengths that are possible with the proposed arrangement should relatively easily facilitate this change.

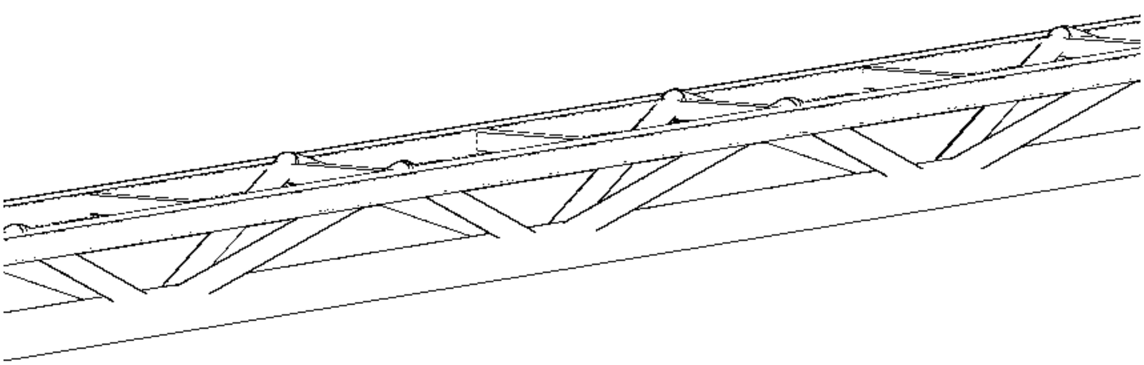

Figure 2: 3-D Model of the proposed truss system

For the bottom chord, a single member may be used. This layout will result in cost savings due the reduction in structural steelwork that is required. Additionally, this arrangement will improve both the aerodynamic behaviour of the structure and its aesthetics. Again, in the particular example presented here, circular hollow sections were proposed because of their small surface area, excellent torsional stiffness and high tensile and compressive capacity.

The induced axial forces in the truss are inversely dependent to the depth of the truss, although a balance needs to be struck between ensuring that it has sufficient stiffness to distribute the load as evenly as possible to the main suspension system th at supports it, while not making it so stiff that it acts as a beam between the rigid supports at the fixed piers. To achieve this relatively shallow depths are preferable, as they will also reduce the impact of the structure on the surrounding environmen t, be less susceptible to adverse wind loading, and be easier to transport and assemble. For individual, large -scale projects the optimum depth will need to be determined. This will be a function of the axial forces, the amount of structural steelwork required to accommodate them and the resulting stiffness of the composite girder.

With regards to the elevational, inclined diagonals (Figure 1), it was proposed that they should also be circular hollow sections to reduce air drag and to enable them to with stand the large tensile and compressive axial forces that are induced in them, particularly near the fixed supports where the shear forces are large. To triangulate the structure in three dimensions these members were also inclined in cross -section (Figures 2 &3). This enhances the torsional stability of the structure and thus improves its sway resistance.

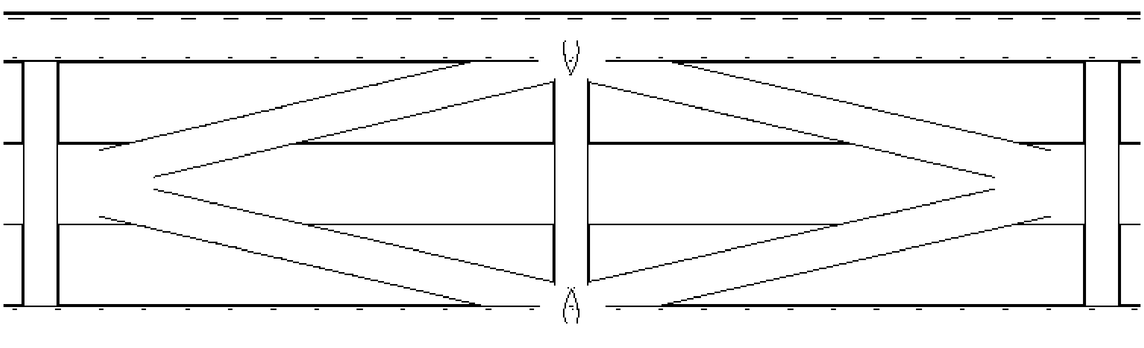

Figure 3: Top view of the truss arrangement, showing inclined diagonal members

Stability cross-bracing for the top chords can take one of two forms . They can be independent of the deck slab and used solely to provide restraint to the compression chords and therefore relatively slender, or they can also be part of the composite truss -deck system. If the latter approach is adopted the cross -members will also carry local moments. It is likely that such an approach is more appropriate when larger deck widths are required, therefore necessitating a thicker slab, although in this case fatigue of the cross -member / chord member connections due to torsional load effects may be a significant design criterion.

Cable system

The analysis of the proposed system is similar to that applicable to traditional suspension bridges; therefore the required sag of the cables determines the height of the pylons. For under-slung arrangements, the critical sag is the dip of the cable under the deck as it is over this length that the cables are loaded. Arguably, the optimum cable dip lies somewhere between 1.5 and 2.0 times the depth of the truss. However, what needs to be ensured is that the cables make best use of their excellent tensile resistance and hence cost effectiveness and that to do this they should be designed to carry the full imposed load and a significant proportion of the self-weight of the whole system.

Vertical struts are used to transfer the loads to the cables, and these struts are connected as shown in Figure 4. The main concern with this detail is the local bending that is likely to be induced in the struts because of the differential movement that will occur between their ends due to the difference in stiffness between the cables and the stiffening girder. This effect needs to be investigated in more detail.

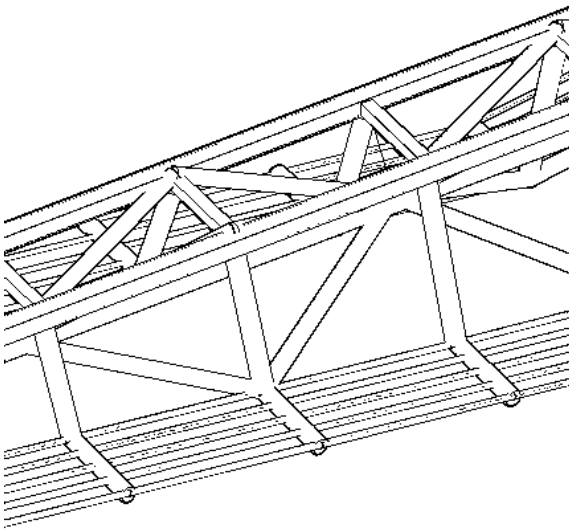

Figure 4: 3-D view of the whole structural system, emphasizing the cable connections

To provide transverse restraint to the cables additional diagonal members are added locally to enhance the transverse stiffness of the structure. These are again diagonal elements as shown in Figures 4 & 5. In order not to over-complicate the structure and to minimize the amount of additional steelwork required, it is proposed that these bracing members should be placed at every second position. The studies made to date suggest that such an arrangement is sufficient and indeed contributes to ensuring a uniform distribution of load between the stiffening girder and the cables.

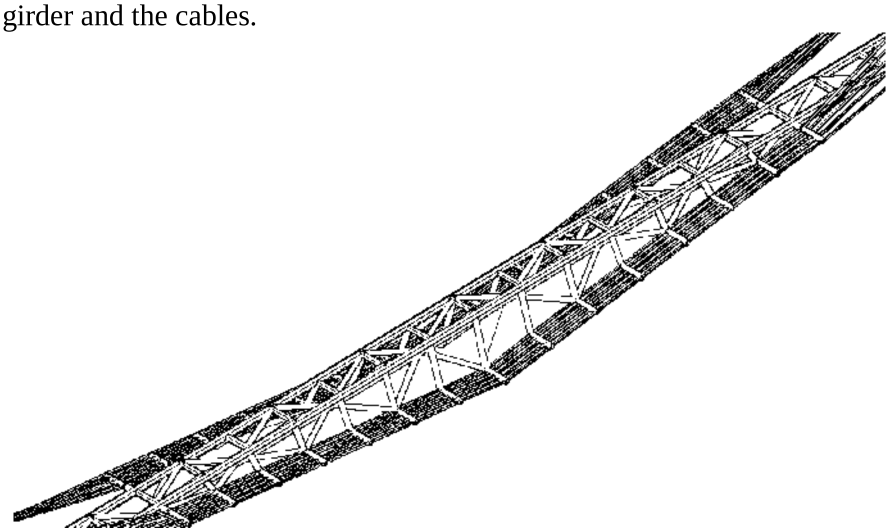

Figure 5: Isometric view of the structural arrangement

Pylons

The main purpose of the pylons is to accommodate the displacements and the vertical forces generated by the cables. Traditionally, the pylon's height has been dictated by the sag of the main cables. However, in this particular case, the critical sag is the one below the bridge deck and as a result the pylon's height is in theory of no great significance. Nevertheless, the lower this height the greater the resultant horizontal force in the cable and the less efficient the design. Also the greater these forces the larger the anchor block that is required, although if short pylons are required to minimise the visual impact then this design does facilitate this option.

Dynamic Response

The importance and significance of the dynamic response of suspended structures has been appreciated for many years. However, the detailed analysis of such effects is complex and very dependent on structure specific details. To date, time has not permitted such an analysis of the proposed design but the effects that need to be considered and the conceptual approach that has been adopted in order to limit the response of the structure to these effects are outlined here.

The flow of air over the slender deck of any bridge structure (Figure 6) produces vertical bending and torsional oscillations of the deck. The response of the deck to these oscillations can take the following forms:-

Vortex shedding response

The periodic shedding of vortices from the upper and lower surfaces of the deck causes alternating aerodynamic forces to be applied to the structure. The response will decrease when structural damping is increased but will increase when the intensity of the turbulent flow is increased.[1]

These vortices create turbulences and consequently vibrations. The distance of the vortices from the structure is speed dependant thus the worst-case scenario is when the airflow is perpendicular to the cross-section. These vortices can also move both vertically and horizontally, thus exacerbating the vibrations, but it is believed that the cross section that has been adopted will limit these effects.

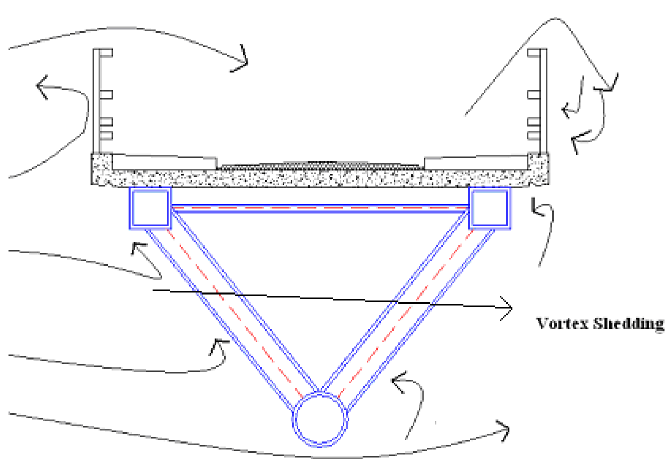

Figure 6: Airflows around the proposed structure

Turbulent or buffeting response

Wind loading also varies due to the continuous fluctuation of the direction and velocity of the wind. If the energy of the turbulance generated by these fluctuations is sufficient then the resulting forced oscillations can in turn be sufficient to affect the serviceability of this type of structure. Such events are not uncommon and even the long-span Akashi Kaikyo Bridge has been closed six times because of such serviceability concerns. Further work will be required to address this issue for the proposed design.

Flutter response

Near what is defined as the critical wind speed for the cross-section, the vibrational response of the structure is amplified. This response can either be vertical or torsional, however for traditional deck arrangements, torsional instability is normally dominant.[4] Flutter occurs when the torsional and bending frequencies of the structure coincide. To prevent this structural damping of at least one of the frequencies may be required to ensure that this does not occur.

For the proposed design, the truss has excellent flexural and torsional stiffness and therefore should not be susceptible to this effect, provided that these stiffnesses are sufficiently different. Additionally, for moderate wind speeds the presence of such a complex configuration and the shear size of the elements will partially divert the flow of the air away from the deck resulting in reduced aerodynamic pressures on it. The scattered airflow will eventually produce turbulences and vortices but these will now favour stability, as they will reduce the fluttering effect.

Forms and Methods of Construction

In the form of cable structure proposed in this paper the aim has been to enhance the axial capacity while limiting the required flexural capacity, under both permanent and variable loading. The axial response is a function of the tension in the main cables and the compression capacity of the pylons, struts and deck. The flexural response is related to the flexural stiffness of the deck structure. In the proposed design, increasing the tensions in the cable can enhance the axial response and as a result the flexural response can be reduced, resulting in a more slender and hence less expensive structure. However, by adopting a truss for the main girder it is possible to balance these two responses and in the current design the truss has been deliberately sized to ensure that it can largely carry the permanent loads in flexure to aid both the proposed construction technique and the three span configuration that was required for this location.

In theory, using arrangements similar to the ones shown in figures 7 & 8 it is possible to compensate for 100% of the permanent loading, so that bending in the deck is limited to the local effects between the points of support provided by the cable system[3]. In this case the vertical struts will act as virtual pylons and the effective clear span can be radically reduced, offering great savings both in terms of materials and costs.

For externally anchored designs such as that proposed in this paper, the disadvantage of this approach is that they require significant anchor blocks to accommodate the large tensile forces in the main cables. In the case of the competition for which this design was developed, this was not a problem as the ground conditions were such that the cables could be socketed directly into competent rock. However, where this is not the case self-anchored solutions[2] should provide an appropriate alternative and using one or other of these approaches, such designs are applicable in theory to both single span and multi-span bridges.

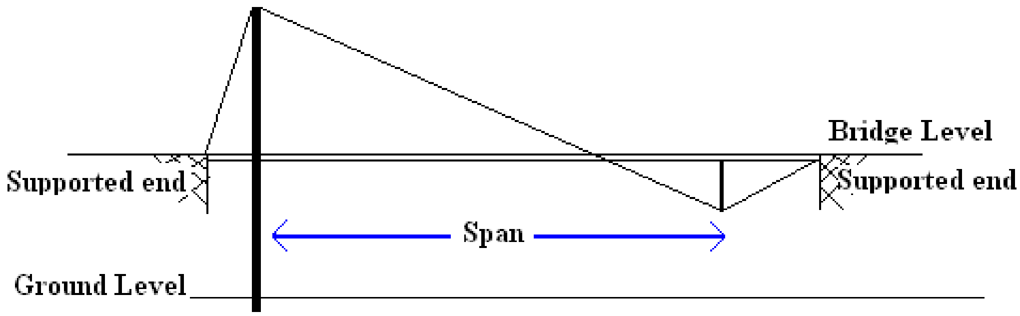

Figure 7: Idealised unsymmetrical mono -under-slung arrangement

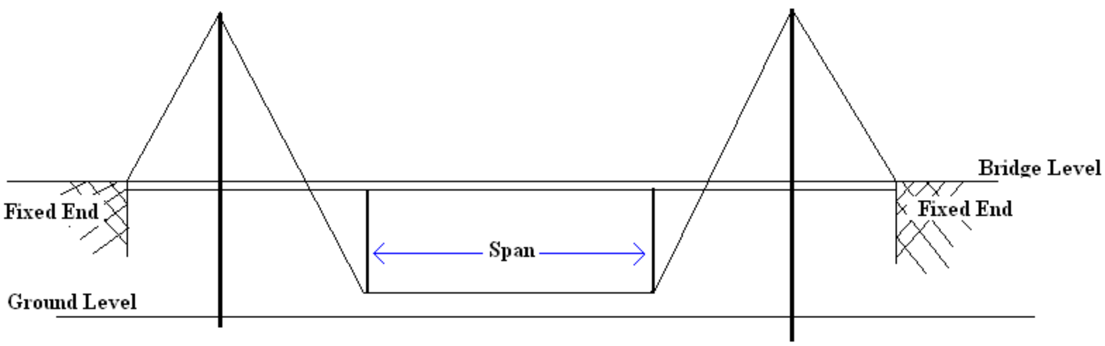

Figure 8: Idealised symmetrical under -slung arrangement

In the competition design the cable system that was proposed comprised ten preformed, spiral strands. Readily manufactured, they can be loosely attached to the deck either prior to erection if the latter is launched into position, or immediately after erection if it is lifted into position. Once in position, these cables can then be stressed in a predetermined sequence to ensure an even distribution of load both between each of the cables and between the deck and the cables. Preformed spiral strand is typically designed with a fa ctor of safety in excess of 2.0 because of the high local fatigue effects generated within the strand as individual wires move and flex over one another due to the helical, spring like structure of the strand. Despite this, because of the high tensile str ength of the drawn wire from which they are constructed, such strands are extremely efficient and are nowadays the favoured form of cable for both cable-stayed and suspension bridges.

Of course, in the form of structure proposed here, as in a trampoline, the greater the load in the cable the greater the stiffness of the structure. Indeed, such systems can be so efficient that, under live loading, fatigue of the connections between the cables and the deck can be a significant issue. Again further work is required to both quantify this effect in relation to the balance that is struck between the axial stiffness of the cables and the flexural stiffness of the deck and the detailed design of the cable clamps to accommodate this fatigue.

The construction of this type of design could be achieved in a number of ways. The main components of the truss are relatively lightweight and, as such, the elements could be assembled on site or could be prefabricated into larger parts and then transported to site for erection. This, in turn, could then be achieved either by cantilevering the sections from the supports using temporary stays or by launching the structure from one or both sides of the crossing, again either staying the cantilevers with temporary supports or relying on the inherent flexural stiffness of the deck if the cantilever is not too great. Launching sequences are ideal where site constraints are of crucial importance, such as bridges over deep gorges, where the availability of intermediate supports is limited or in cases where intermediate pylons cannot be used because of unstable ground conditions. In the competition design the truss was deliberately chosen and proportioned to enable it to carry its self-weight in flexure so that it could be launched without the need for any special temporary works other than a launch nose. This made the truss heavier than it needed to be for the final condition but did enable the specific site constraints to be satisfied and the final tension that was required in the cables to be reduced.

Conclusions

In response to an undergraduate design competition a novel, under-slung cable structure was proposed. This paper has considered the parameters that govern the behaviour and response of such a structure and structural arrangements and details have been proposed which it is suggested would make the construction of such a structure feasible.

The paper has discussed how underslung structures, when combined with a radical, trussed stiffening girder, can provide an efficient and innovative but more sympathetic structure, which is stiff, stable and economically viable for both medium and long-span structures. It has been shown that when there is a need to minimise the number or limit the location of the foundations required, such structures provide a means of adopting relatively large spans by using 'virtual' supports, while restricting the height of the cable pylons and hence minimising the impact of the structure.

The paper has addressed the benefits that can be obtained from such structures both during construction and in use, and has identified a number of opportunities and challenges that must still be met to facilitate the exploitation and development of such a concept. These include the need for a detailed consideration of the wind, vibrational and fatigue response of what will be an inherently flexible structure and a closer look at the design of details such as the cable clamps, saddles and connections, which will be subject to significant static and fatigue load effects.

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