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Static Issues in Long-Span Suspension Bridge Design

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Summary

A terrific increase of the maximum span length of a suspension bridge has occurred in the last years. First the 1624 *m* Great Belt East Bridge in Denmark, and then the 2000 *m* Akashi Kaikyo Bridge in Japan, were completed. A 3300 *m* span has been proposed to cross the Messina Strait. The feasibility of longer spans is related to the implementation of new high-strength light-weight materials. As a matter of fact, as spans become longer, cables become heavier. Therefore a high percentage of the cable stress is related to its own self-weight. Furthermore the stiffening contribution of the deck on the structural behaviour becomes negligible. In this paper the main aspects of the very long-span suspension bridge behaviour under static loads are discussed.

1. Analysis of the Structural Behaviour

The terrific increase of the bridge span requires the basic concepts of the structural behaviour to be revised, also under static loads. The preliminary design can be carried out by referring to the unstiffened cable, ignoring the contribution of the girder stiffness. Suppose that the geometrical shape is fixed and so is the parameter $k = f/\ell * \cos\alpha_m$, f being the height, ℓ the span and α_m the maximum value of the slope angle α, with respect to the horizontal. The self-weight of the cable can be supposed to be uniformly distributed and equal to $w_c = \gamma_c * A_c * L_c / \ell = \gamma * A_c$, A_c being the cable cross-sectional area, γ_c the cable weight per unit volume and L_c the cable length. The structure is also subject to a uniform permanent load w_p. So the total dead load is:

$$w = w_p + \gamma A_c$$

As usual, two kinds of travelling loads are considered: a slight vehicular load p_1 uniformly distributed on the main span and a uniform railway load p_2 coming to the main span, whose maximum length is $c_2\ell$ ($c_2<1$). The maximum value H_{max} of the horizontal component of the cable tension occurs when p_2 is placed symmetrically around mid-span. With reference to this load condition, by equalling the maximum stress in the cable with the allowable one, the limit value of the span, i.e. the span at which the cable will just support itself, can be deduced

$$\ell_{lim} = 8k \cdot (\sigma/\gamma)/(1+\beta)$$

where $\beta = [w_p + p_1 + p_2 * (1-(1-c_2)^2)]/\gamma A_c$ is the ratio between the permanent-plus-live load and the self-weight of the cable. The limit span increases linearly with σ/γ and with k, while the influence of β is more significant. In Fig. 1 the diagram of ℓ_{lim} versus σ/γ is plotted for different values of β and k=1. For a fixed ℓ, the previous equation allow to find out the cross sectional area A_c of the cable

$$A_c = \left(w_p + p_1 + p_2\left(1-\left(1-c_2\right)^2\right)\right) \Big/ \left(8k\,\sigma/\ell - \gamma\right)$$

and therefore it is very useful in the preliminary design.
A numerical investigation was carried out. The main span was supposed to be simply supported at the pylons. The following realistic values of the loads were assumed: w_p = 250 *kN/m*, p_1 = 20 *kN/m*, p_2 = 300 *kN/m* with c_2 = 750 *m*. The cable material was characterised by the allowable stress σ = 850 *MPa*, the weight per unit volume γ_c = 0.078 *MN/m*^{3}, and the Young's modulus E_c=180000 *MPa*. Values of ℓ ranging from 1000 *m* to 3500 *m* were considered, keeping k = 0.1. The cable cross-section was designed by using the previous relation. Then the analysis of the stiffened cable was carried out for different values of the girder bending stiffness. The tension H and then the equilibrium configuration of the suspension bridge were found by using an

iteration procedure, that leads to the same results, i.e. with the same approximation, of the deflection theory (Nicolosi et al. 1998).
In Fig. 2 the diagrams of the maximum vertical displacement v versus ℓ, for different values of the girder bending stiffness EI [$MN \cdot m^2$], are plotted. In the case of $EI = 0$ the displacement v increases up to its maximum value at $\ell = 2800$ *m*, this span value being related to the length of load p_2 (750 *m*). For $\ell > 2800$ *m* the vertical displacement v decreases. This maximum is reached for higher values of the span when the girder stiffness gets higher. The curves tend to be closer to each other when the span increases, i.e., the vertical displacement is independent of the girder stiffness when ℓ becomes very high. This behaviour is due to the increase of w_c. In fact, when the span gets higher w_c gets higher too, and a large percentage of the cable capacity is required to carry its own self-weight. Stresses in the cable due to live load are very low and so are the displacements. As obvious, for usual spans a noticeable reduction of the displacement is obtained if the girder bending stiffness is high. The maximum displacement occurs always at 0.27 ℓ. The corresponding horizontal tension H, obtained with the same load condition is also plotted in Fig. 2 (dashed line). It is only slightly lower than the maximum value of the horizontal component of the cable tension (continuous line), which occurs when p_2 is placed symmetrically around mid-span. The girder stiffness has no significant influence on the maximum tension. Therefore the values of the diagram are relative to the unstiffened cable ($EI = 0$).

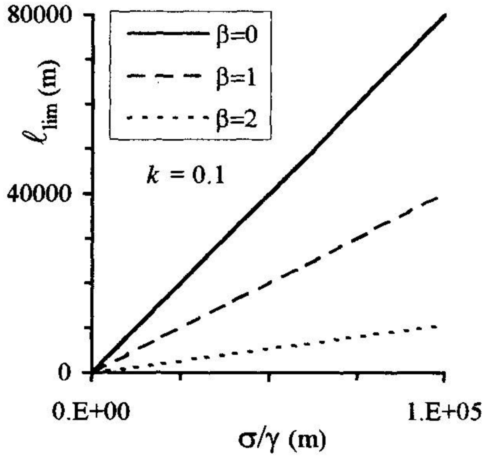

Fig. 1 Limit span versus σ/γ

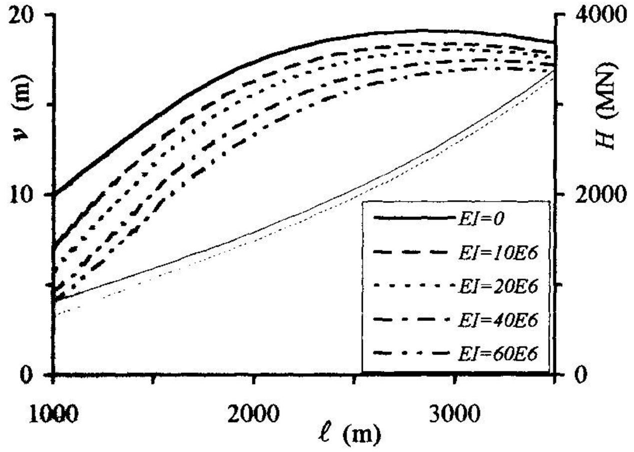

Fig. 2 Maximum displacement and horizontal tension versus ℓ

2. Conclusions

In very long-span suspension bridges the contribution of the stiffening girder is negligible and the structure behaves like an unstiffened cable. The limit span of a suspension bridge is obviously related to the material characteristics. The numerical results shown in this paper are relative to steel cables, but they can be easily generalised to other materials. Materials, characterised by low values of σ/γ_c, represent the future of the long-span structures, but they are too expensive at the present time. In particular, carbon fibre composite cables seem to be very good because of their high strength and their very low unit weight, but may have a lower Young's modulus. The aerodynamic behaviour of light cables is also to be investigated. Use of new structural types is advisable in order to span longer distances in the future.

References

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