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The Design Approach for a New Composite Space Frame Bridge System

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Summary
This paper describes the design approach to SPACES, a new bridge system comprising a tubular steel space frame, participating roadway slab, and an enclosure shell in advanced composite material. The system, which is suitable for girder bridges over 40m in span and long span cable-supported bridges, affords steel weight savings of up to 50%, and significant benefits in life-cycle costs . Bridge configuration criteria, structural behaviour, simplified methods of analysis , and design criteria for key elements are presented.

1. The bridge system

The SPACES bridge system combines an optimised steel space frame, a concrete roadway slab acting compositely with the space frame, and a corrosion-free enclosure shell in advanced composite material which permanently protects the steelwork against corrosion (Fig. 1). The system is designed to provide competitive solutions on a life-cycle cost/benefit basis to a broad spectrum of bridging needs for highways, railways, and footways, ranging from girder bridges and viaducts over 50 m in span to long span cable-supported and overhead arch bridges. The system and its advantages for the owner and end-user have been described in Ref. 1, 2.

The space frame is normally configured as a double-layer rectangular grid connected by diagonal braces arranged on a tetrahedral pattern (Fig 2). It is an all-welded structure fabricated from tubular steel members connected either directly to each other or to cast steel nodes. The space frame acting compositely with the roadway slab is an efficient structural form which affords material and fabrication savings over conventional forms of steel bridge construction such as plate girders, stiffened box girders, and trusses formed from fabricated sections, for spans greater than 50 m.

The enclosure shell is formed from interlocking modular FRP components having the strength and stiffness to constitute a permanent structural platform for inspection and maintenance (Ref. 3). It is attached to the underside of the steel space frame by a system of hangers. It may be shaped to achieve particular architectural or aerodynamic objectives, and may be conformed to a variety of bridge alignments. Depending on the specific requirements of the application it can be made to participate structurally with the rest of the structure to increase its torsional rigidity.

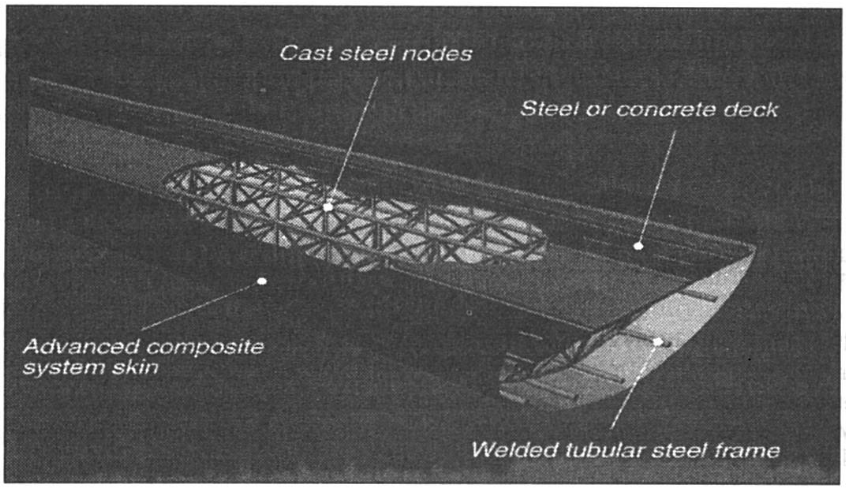

Figure 1 SPACES System Technology

2. Bridge configuration

The objective sought in the geometric configuration of the space frame is to achieve maximum regularity and repetition of standard modules along with well-conditioned node geometry, within the overall functional and aesthetic criteria informing the design of the bridge. The space frame grid and the enclosure can be readily configured for bridges skewed or curved in plan. The direction vector of the space frame diagonals (Lx, Ly, Lz) is selected to minimise the node and member density, thereby improving fabrication economy; and render the angles between members suitable from the point of view of node geometry and ease of fabrication. The relationship of tube diameters is selected to avoid intersection of brace footprints at nodes, maximise node strength, and facilitate automated cutting and welding. The deck span/depth ratio is chosen to optimise the weight of steel.

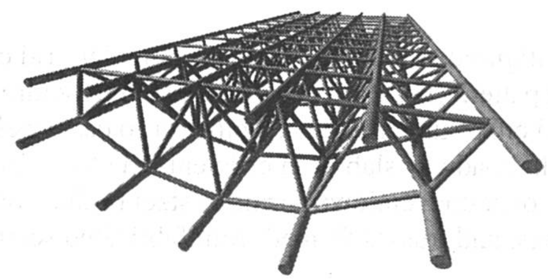

Figure 2 Space frame configuration

In girder bridges, the longitudinal chords are normally the primary members and may therefore run continuously through nodes with the other members branching off . In cable-supported bridges where there is more significant biaxial bending, chord sizes are sometimes varied across a section in order to achieve a clear separation between diameters of intersecting longitudinal and transverse chords, so as to maximise joint strength and fatigue resistance.

Cast steel nodes are used where dictated by joint strength or fatigue endurance requirements, typically at points of high transverse load such as at bearings and in hogging moment regions of continuous viaducts. Diagonals are welded directly onto primary chord members or onto node stubs. The cost of cast nodes is a function of the external volume of the nodes. Therefore one aims to minimise the diameter of the principal chords by adopting the minimum permissible diameter/thickness ratio in the most heavily loaded member.

3. Structural performance

A naked rectangular grid space frame as used for roofs possesses considerable longitudinal and transverse stiffness due to the bi-directional array of chords but has negligible torsional stiffness. Moreover, if not properly restrained externally, it can have a low global buckling strength due to lack of in-plane stiffness of the compression grid. However when the top grid is combined with a participating concrete slab, the structure acquires considerable torsional stiffness and global buckling strength. The high torsional stiffness results in negligible torsional rotation of the deck under eccentric lane loading, leading to a uniform distribution of stress between longitudinal chords, the torsional moment being absorbed primarily by forces in the brace members. The combination of high transverse and torsional stiffness gives the deck an excellent ability to distribute concentrated loads from vehicle axles and abnormal vehicles, thereby reducing fatigue stresses and other local effects. It also renders the deck particularly suitable for cable-supported bridges, where biaxial bending is more significant than in girder bridges and torsional stiffness may be required for adequate aeroelastic stability. The triangulation in the transverse plane ensures that the cross-section is relatively free from distortion.

As a result of the slab acting as a stiff shear plate in its own plane and the tetrahedral arrangement of braces, all the nodes are effectively restrained laterally. Hence the global critical buckling mode is limited to local buckling of members between nodes. Given the relatively low slenderness ratio of the tubular members, they can mobilise a high proportion of their yield strength in compression. This is in contrast to traditional thin-walled steel bridge structural forms based on steel plate and stiffeners, in which as the depth of the structure increases, the plates become progressively weaker in buckling, and the stiffeners, which do not make very efficient use of material, become increasingly heavier, with a significant penalty in material usage. As a result, it has been found that in the 100 m span range, the weight of steel in SPACES decks approaches 50% of that in a conventional steel box girder structure.

Tubular members have the advantage of optimum compressive capacity in relation to weight, of being available in a much wider range of weights than rolled steel sections, and of enabling three-dimensional joints to be readily formed without the need for complex fabrications involving stiffeners and corrosion traps. The lower slenderness of tubular brace members compared to equivalent stiffened plates also results in higher local natural vibration frequencies. As result there is less noise emission in dynamically loaded structures such as high speed railway viaducts.

4. Modelling and analysis

Due to the resistance of the cross-section to distortion, the structure may be analysed accurately enough for preliminary design purposes as an equivalent beam for global effects and an equivalent orthotropic plate for local effects of concentrated loads. The stiffness properties of the beam and plate can be readily determined by imposing the displacement field for the deformation mode associated with the stiffness property of interest, applying the virtual work or minimum strain energy method to determine any unknown modal parameters (e.g. in the case of the torsional mode, co-ordinates of shear centre and nodal values of warping functions), and using equilibrium to obtain the stiffness value. The properties of interest for the beam model are the flexural and shear stiffnesses EI, and GA_s and the torsional and warping stiffesses GK and EI_w, while for the orthotropic plate model the parameters are flexural stiffness D_{xx}, D_{yy}, D_{xy}, D_{33}, and shear stiffnesses S_x, S_y.

Critical loading patterns and magnitudes are determined from beam influence lines and plate and orthotropic plate influence surfaces which are readily obtained. Once the stress resultants in the equivalent continuous structure have been calculated by the usual methods of structural analysis (with a significantly reduced number of degrees of freedom), the stress resultants in the space frame members and the concrete slab may be derived on the basis of the modal distribution of member forces determined during the calculation of the modal stiffness parameters . Thus an apparently complex structure, having a large number of degrees of freedom, can be analysed by simple methods which can be carried out manually or implemented on a spreadsheet, yielding results typically within 5% of a more accurate analysis.

For detailed design, the structure is analysed by the finite element method. The space frame members are modelled as three-dimensional beams and the slab by shell elements at the appropriate eccentricity from the top grid members. When used compositely the enclosure is modelled by anisotropic shell elements. Joint elements may be used to represent the shear connectors if required. By virtue of the regularity and repetitiveness of the structural configuration, finite element models can be generated automatically with simple macros. The advantage of finite element modelling is that colour-coded stress resultant contour plots may be produced for specific families of elements (e.g. chords or braces), which can be also read as tube size distribution maps (Fig. 3). The ease with which tube sizes can be varied to suit the load envelope pattern is another reason for the structural efficiency of the composite space frame. The finite element modelling takes into account the stage-by-stage incremental build-up of the structure, with the concrete slab being typically applied in various stages after the erection of the space frame.

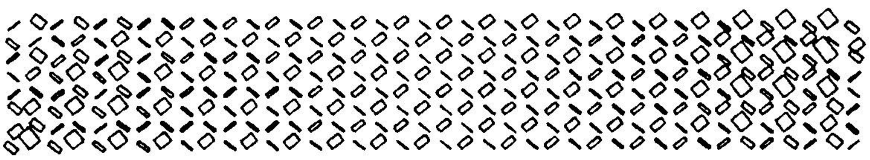

Figure 3 Typical brace maximum axial load 'contour' plot

Structural elements are designed for strength considering factored extreme load effects and ultimate strength, and for fatigue and durability under actual load spectra. Nodes are designed for strength and fatigue using when applicable parametric strength equations given in such references as [Ref 4 - 7], modified for multiplanar joints [Ref 5]. Otherwise nodes are analysed by finite element analysis, assuming the Von Mises yield criterion in the strength analysis and the hot spot stress criterion as defined in BS 7608:1993 in the fatigue analysis.

5. Contribution of enclosure shell

The primary purpose of the enclosure is to provide long-term corrosion protection to the tubular space frame and access for inspection and maintenance. In terms of material, it is typically equivalent to a 10 mm thick plate weighing 20 kg/m^2 and the elastic properties of the e-glass/polyester composite material are in the order of E_x= 20 GPa, E_y= 8 GPa, ν_{xy}= 0.18, G_{xy}= 4.0 GPa. The shell is not normally required to act compositely with the space frame, but can be made to do so if advantageous for the application. When not acting compositely, the fixings and joints are designed to accommodate relative movements between the steel and the composite. If connected so as to act compositely, the enclosure has little impact on the longitudinal stiffness of the lower grid because of its low longitudinal modulus and area. However in applications in which the lower grid is not triangulated, and therefore does not possess significant shear stiffness, the enclosure shell can make a significant contribution to the global torsional stiffness of the deck, increasing it by up to 50%.

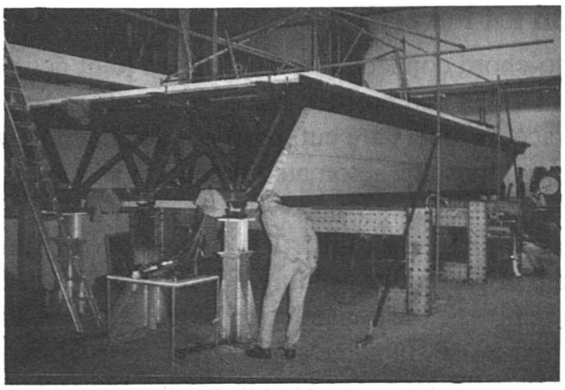

Figure 4 Cambridge half scale model of SPACES deck

Tests were carried out at the University of Cambridge [Ref ...] on a half scale model of a composite space frame deck (Fig. 4), which demonstrated that in that instance the shell increased the torsional stiffness by about 50% (Fig. 5). Clearly in larger bridges the enhancement would be less, and in general when it is necessary to increase the shear stiffness of the lower grid it is sometimes more economic to do so by adding in-plane bracing. The difference between the experimental and predicted response with the participating shell is due to the slack in the connections.

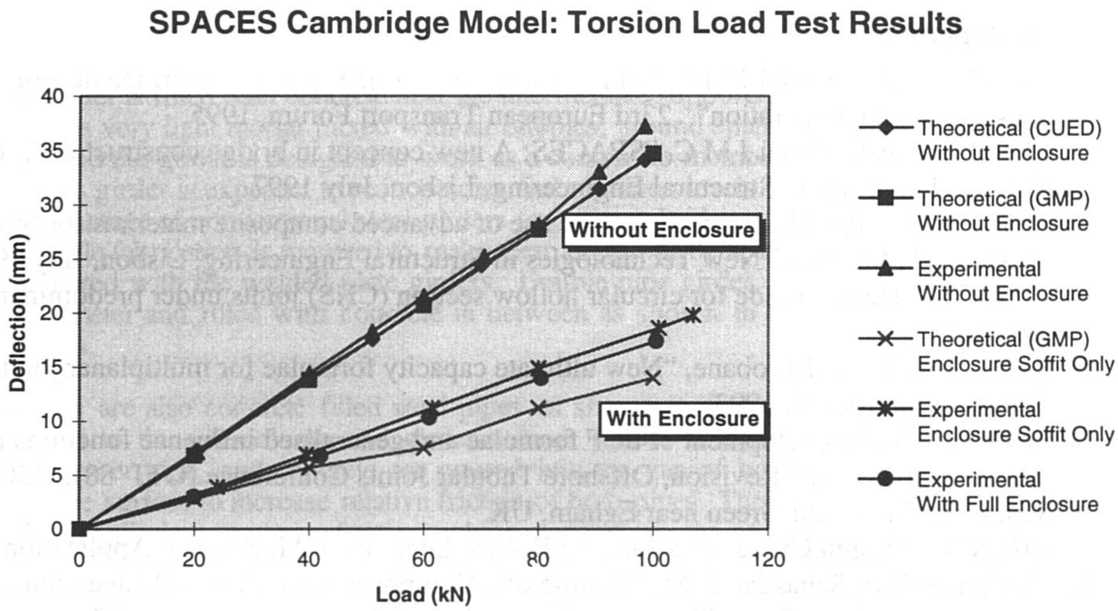

Figure 5 Comparison of experimental and theoretical results with and without participation of FRP shell

6. Design for fabrication and erection

In the case of welded brace-to-chord connections, the detailed joint geometric data needed to define continuously variable member end profiles and edge bevel angles is calculated by computer programme. The brace members are cut, profiled, and bevelled by automatic milling machines. Welding is carried out by semi-automated processes where convenient.

The space frame is erected in complete span units. The rigidity of the frame makes it possible to achieve good fit-up to facilitate in-place butt welding. Since SPACES decks are usually continuous over intermediate supports, the construction of the concrete slab is sequenced to minimise permanent tension in the slab. In some applications post-tensioning cables are used within the space frame to prestress the slab. The slab is always connected to the longitudinal chords by shear connectors and may also be connected to the transverse chords in the case of larger grid sizes to increase 2-way spanning action. Slab panels are typically cast on permanent formwork, which can be propped off the space frame lower grid. When there is a sufficient gap between the slab and the transverse chords, the slab can be cast on a travelling form.

7. Conclusions

A steel space frame acting compositely with a roadway slab is a more efficient structural form than a plate or box girder structure for longer spans. The provision of an enclosure ensures that the space frame members which on account of their spatial orientation could be difficult to maintain are protected from corrosion. The space frame's regular modularity enables rapid design and fabrication. The design approach has been validated by a half-scale model test .

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