Multicell box girder bridge with prestressing in webs and top/bottom slab modelled as 3D shell structure

SHELL SHOCK

A new approach for designing reinforced and prestressed 3D shells is outlined by **Georg Pircher** and **Jürgen Bellmann**

The design of up to 40 reinforcement layers within a single shell cross-section in accordance with different code-checking procedures is one of the new capabilities in the latest version of Sofistik's specialist bridge software.

This latest release does not just offer a way of checking forces, stresses and displacements in 3D structural systems that also contain shell elements; it also enables a check of serviceability and ultimate limit state where, for a given general reinforcement layout – such as concrete cover and inner lever arm, rectangular or skew orientation within the shells as well as a minimum reinforcement –

Layer design with (smeared) prestressing tendons, decompression check.

the necessary reinforcement results from the design code-checking procedure.

During software development, special attention was paid to improving the design process for prestressed shell elements, which includes pre- and post-tensioning as well as bonded and non-bonded tendons.

While numerous code-checking and design methods were already available in the software for reinforced and prestressed shells, modern technologies and ongoing research led to a new design method that improves the quality of the design results. The design of up to 40 reinforcement layers in one shell cross-section is now possible.

Some theoretical background is important to fully understand the details of the new features. For the uniaxial reinforcement design of rectangular beam sections, a simple procedure is usually employed in which the full use of the compression zone defines an inner lever arm, and thus the forces in the reinforcement layers. Here, the orientation of the reinforcement matches the direction of the internal forces that are in line with the beam orientation.

For shell elements, however, the orientation of internal forces does not usually match the direction of the reinforcement bars. The orientation of principal forces and stresses show an angle different to the reinforcement bar direction, and there is an additional in-plane shear force which cannot be compensated by the rectangular reinforcement. Only by applying and considering a stiffening concrete compression strut can the reinforcement also carry skew tensile forces *(see red arrow on illustration opposite)*. Consequently, a simple uniaxial design is not sufficient on its own to define the orientation of the reinforcement.
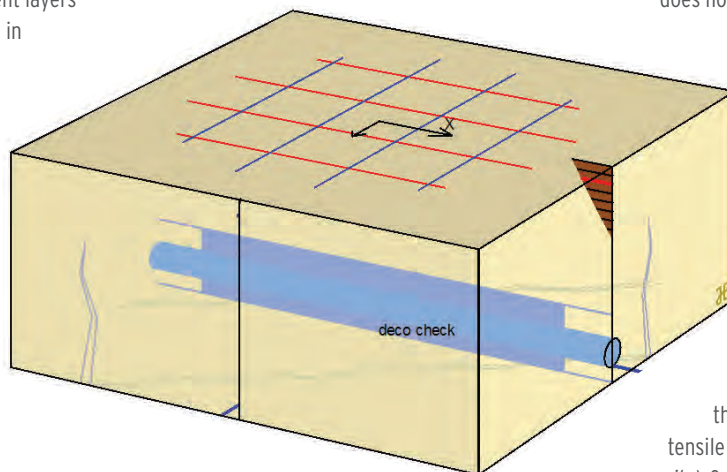
Several methods for generating appropriate design results are available; some have been implemented in Sofistik in the past and are still in use.

Typical procedures in previous versions of the software include; the Baumann procedure; the uniaxial design with moments in two reinforcement directions; the Capra Maury procedure; and the Sandwich model, as per EN-1992-2 annex LL.

The Baumann approach has been part of Sofistik since 1985 and is similar to the Sandwich model from the EN. In both, the inner lever arm is first established, allowing the in-plane shell forces to be separated into a top and bottom layer at the position of the reinforcement meshes, for which an individual design is performed. The resulting concrete compression force is considered mathematically correct.

At this point, some finite-element programs increase the internal forces in the x- and y- directions, being the direction of the bars in the reinforcement mesh, by taking the in-plane forces and the shear forces which are under consideration. These increased internal forces in the direction of the reinforcement bars are now used for a uniaxial design, without considering the interaction of these forces with the transverse stresses. This procedure is known internationally as the Wood Armer method.

Under the Capra Maury method, which was developed in France, designs in several directions between 0° and 90° are performed using 5° or 10° steps. The internal forces and corresponding reinforcement quantities derive from a transformation that takes the ratio between current angle and sectional cut under consideration. As before, there is no interaction between forces and stresses acting transversally to the design direction.

As already mentioned, the Sandwich model as per EN-1992-2 is similar to the Baumann method. Here, an interaction between the in-plane-shear forces and the bending is added.

The newly-developed Sofistik layer design is based on the precise 3D state-of-plane strain and can therefore properly integrate all known effects. The 3D state-of-plane strain consists of three linear expansions and three flexures which are balanced iteratively with the six external forces until equilibrium is achieved.

The non-linear stress-strain diagrams of concrete and steel are taken into consideration in this process, but no concrete stresses are considered at the area of the reinforcement steel cross-section. For biaxial compressed concrete the Poisson's ratio is considered, but not for biaxial tension where the concrete then only acts uniaxially and parallel to the crack direction. Any further crack-opening occurs without the influence of Poisson's ratio.

As this method incorporates all components – both strains and flexures – the limitations of the Baumann method do not apply. In the case of the compression strut that runs at 45° to the main reinforcement direction, we now get the actual stiffening concrete force.

Having used the ultimate-limit-state design to establish the amount of reinforcement required, the procedure for the serviceability check is relatively easy. The six balanced forces in equilibrium give six strain parameters for which a method based on the Crisfield iteration is used.

For the ultimate limit state, the method is more complex because at the beginning of the process there is no reinforcement information and the concrete fails under external load, giving huge strains.

In this case Sofistik uses an approach in which additional reinforcement is taken into account together with a limit for the maximum strains.

For additional reinforcement, a steel strain of 25 per thousand is usually ideal. If there are problems in the compression zone of the concrete, the steel strains are reduced, and we also use compression reinforcement to reach equilibrium. The state II design is carried out in the traditional way by using the lever arm from the bending design.

This layer approach also allows consideration of both bonded and non-bonded

Shell element under skew moment strain showing the resulting diagonal compression strut

prestressing tendons, where the decompression check can be performed precisely and realistically.

In summary, this consistent iteration of the complete tensile strain for the layer design provides good and realistic results for the reinforcement design, mainly for ultimate limit state.

For the serviceability limit state and when comparing it to the Capra Maury method and other uniaxial methods, the interaction of all force components results in more realistic stresses.

In addition, the new software enables up to a maximum of 40 designs of reinforcement layers per shell, which is a common requirement for projects in northern Europe

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