Analysis and Design of Box Girder Bridges

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Abstract— In this paper, various design principles are discussed relevant to design of a cast-in situ post tensioned box Girder superstructure. The objectives were to understand its structural behaviour and various methods are been presented which are being used by engineers to analyse and design standard box girder with sufficient accuracy so as to be adopted as standard procedure allowed all over the world.
Keywords: Box Girder Bridges

I. Introduction

In recent years, single or multicellular prestressed concrete box Girder Bridge have been proposed and widely used as economic aesthetic solution for the over crossings, under crossings, grade separation structures and viaducts found in modern highway/railway system. The very large Torsional rigidity of the box girder‘s closed cellular section provides structures beneath is more aesthetically pleasing than open-web type system. In this paper basics of analysis and design of prestressed box girder is being outlined, giving the reader a brief outlook into the structural behaviour of the box girders and broad steps required to analyse and design the box girders.

The box girder superstructure could be a part of a variety of structural systems, however here only the standard case of a box girder directly supported with bearings over piers/abutments is considered having small width to span ratios and prestressed only longitudinally.

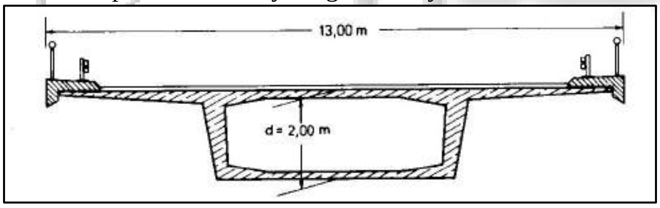


Fig. 1:

A. General:

The box girder represents a special form of a folded plate structure. The loads are always carried three dimensionally. The analysis of sectional forces to which the structure is subjected can be handled with the aid of the following:-

- Analogy of beam on elastic foundation
- Folded plate theory with the use of series expansions
- Finite strip method
- Finite element method

As the last three produce voluminous amount of data and therefore are greatly susceptible to error in the evaluation of the results, hence below described procedure is adopted which is simpler and produce sufficiently accurate results in lesser amount of time.

B. Simplified Structural Analysis:-

With this approach, the box girder loaded symmetrically in the transverse direction can be analysed longitudinally as a beam and transversally as a frame independent of each other. This is valid if the slenderness ratio span/depth > 4 & span > 1.5 x width and if the disturbance zone at the introduction of the applied forces are separately handled.

The particular problematic nature of the simple analysis approach to the behaviour of a box girder under load arises with unsymmetrical loading in the transverse direction. In this case the longitudinal and transverse stresses are connected with each other, a connection which shall be designated in what follows here as the folded p1ate action. This connection is taken account of through the formulation of the condition of compatibility between the separately analysed longitudinal and transverse directions.

Warp resisting supports and diaphragms or discontinuous eccentric loading produce warping torsion along with St. Venant torsion. The additional stresses due to warping torsion die away rapidly or are small in comparison with other stresses, and therefore can be neglected.

The analysis procedure suggested here is so selected that the results are increasingly refined the further one proceeds. If desired, one can break off the analysis without considering the folded plate action. One can also include that action sufficiently accurately for a critical loading case and extend the results to the other loading cases by means of a uniform factor.

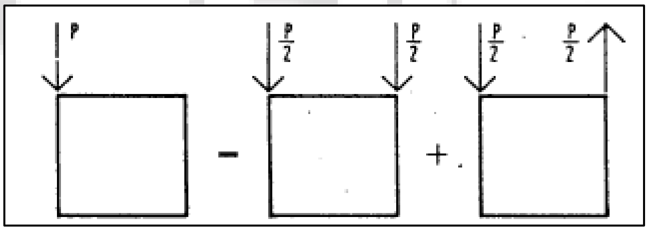


Fig. 2:

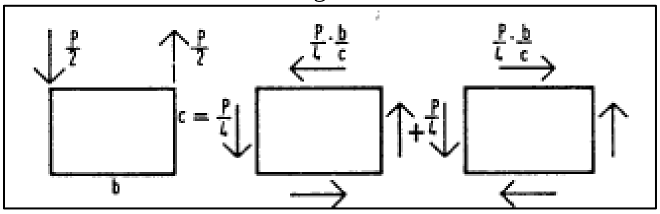


Fig. 3:

II. Analysis procedure

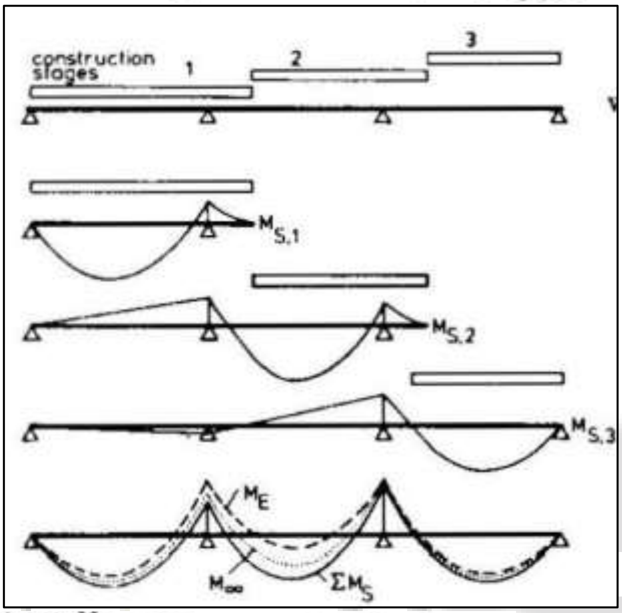
A. Longitudinal Analysis

First the box girder is analysed in the 1ongitudinal direction as a beam, i.e. with the assumption of a rigid cross-section. All transverse loadings are integrated together to form point loads or line loads. With these loads the longitudinal bending moments and shears are determined, and the accompanying or least favourable torsional moments of the entire cross-section are determined with the eccentricities, of the load resultant.

The sectional forces of the beam (bending moments, shears, normal forces and torsion) due to external loads and imposed deformations can be obtained with known methods of the theory of structures.

Sectional forces due to external loads are only altered by creep if components acting together within the structure contain concrete of varying ages or varying composition. This is indeed the case for segmental construction. For a sufficiently exact calculation of the final time-dependent moments, the following equation can be used:

$$M_\infty = \Sigma M_{S,i} + (M_E - \Sigma M_{S,i}) \cdot \frac{\varphi_\infty}{1+\rho\varphi_\infty}$$



where $M_{S,1,2,3}$ ... moments at the time of stripping of the falsework of the different segments, i.e. moments due to self-weight plus prestress

M_E ... moments assuming that the entire bridge is constructed at the same point in time

φ_∞ ... creep factor at time ∞

ρ ... relaxation factor taken

As long as individual construction segments are not prestressed very early or to extremely high values of prestress, the changes in the sectional forces due to prestress as a result of shrinkage and creep can be calculated with sufficient accuracy as a uniform reduction in prestress up to time t:

$$\Delta P_{c+s+r} = A_p \Delta\sigma_{p,c+s+r} = A_p \frac{\varepsilon_{cs}E_p + 0.8\Delta\sigma_{pr} + \frac{E_p}{E_{cm}}\phi(t,t_0)\sigma_{c,QP}}{1+\frac{E_p}{E_{cm}}\frac{A_p}{A_c}\left(1+\frac{A_c}{I_c}z_{cp}^2\right)(1+0.8\phi(t,t_0))}$$

Where symbols have their usual meanings.

Reference could be made to IRC-112 2011 for detailed explanations. After calculating prestressing losses, the final cable forces are calculated including 100-year losses (or more if required) and stresses are computed assuming uncracked sections and stresses are compared with permissible ones to arrive at final prestress layout.

Transverse Analysis

The box girder is analysed in the transverse direction with the actual load distribution. For the practical analysis, the clearest method is first to analyse all flange sections as if they were rigidly fixed at their junctures with the webs and then to redistribute the total moments acting at these junctures according to the frame's stiffness

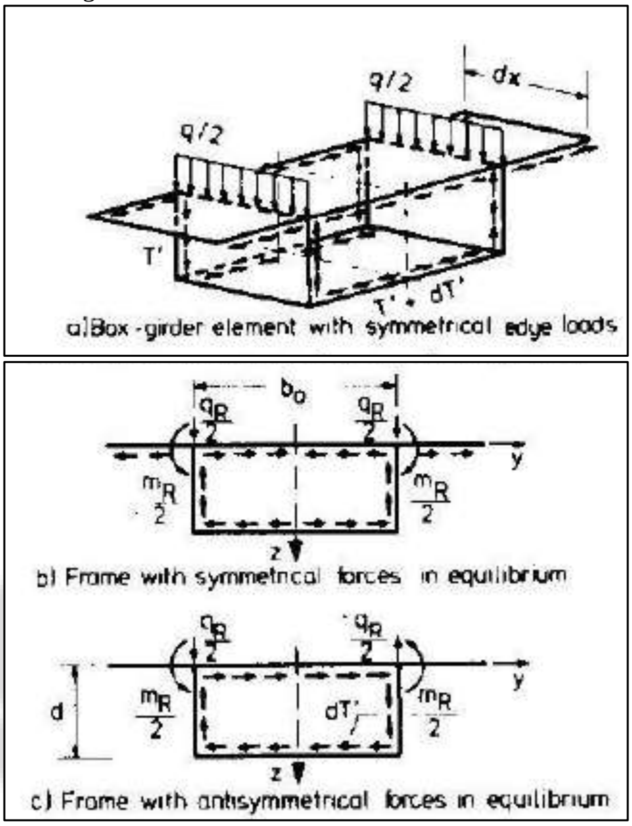


Fig. 5:

For box girder bridge transverse analysis, the segment is modelled transversely to represent box girder segment. The modelling was carried out by standard structural analysis software. One-meter length of the box girder is modelled by using beam element. The model is subjected to load effect from dead load including weight of concrete, parapet and wearing course. For maximum load effect from traffic load, the box segment is subjected to IRC Class 70R wheeled loading.

The sections are then checked for ULS and SLS combinations, which would then be used to arrive at design bending moments and shear forces in the transverse direction and from which reinforcement would then be calculated. For wide box girders transverse prestressing could also be used with segmental construction instead of untensioned reinforcement.

III. ANALYSIS FOR DISTORTION

The box girder section will transmit the twisting effect of eccentric loads essentially by means of shear flow round the perimeter of the section. A single load acting vertically over one of the webs could be replaced by symmetric and anti-symmetric pair of loads. The anti-symmetric component produces twisting and also differential bending. If the torsional rigidity of the box section is low the majority of the load will be carried by differential bending producing warping and transverse distortion. The torsional component of the loading can be considered in terms of pure torsion and distortion.

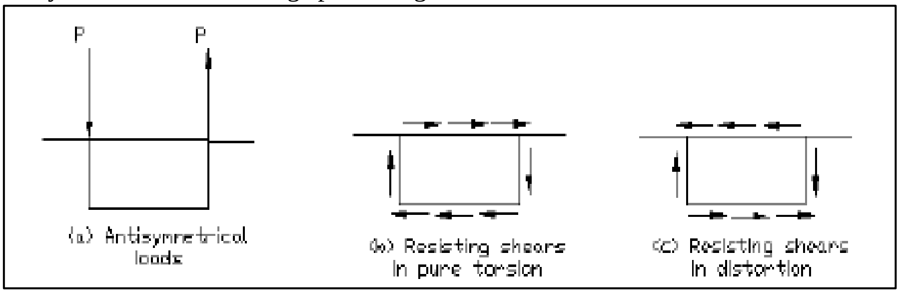


Fig. 6:

In a box section walls can develop transverse frame action and thus complete behaviour is combination of simple beam and the portal frame. Thus the physical behaviour of the structure is that of a beam on elastic foundation, the elastic foundation being the transverse frame action. In 'rigid body rotation' or 'pure torsion' effects, the section merely twists or rotates causing St. Venant shear stresses and associated warping stresses which can be evaluated by the elemental theory of torsion as applied to closed sections of thin walled members. It may be emphasized that due to very high stiffness in 'pure torsion', the box girder will twist very little, and that the webs will remain almost vertical in their original unloaded position. Also, the associated longitudinal stresses due to warping restraint when present are negligible as compared to those induced by the longitudinal flexure and hence could be ignored.

The theoretical behaviour of a thin-walled box section subject to pure torsion is well known.

For a single cell box, the torque is resisted by a shear flow which acts around the walls of the box. This shear flow (force/unit length) is constant around the box and is given by q = T/2A, where T is the torque and A is the area enclosed by the box. The shear flow produces shear stresses and strains in the walls and gives rise to a

However, pure torsion of a thin walled section will also produce a warping of the cross-section, Of course, for a simple uniform box section subject to pure torsion, warping is unrestrained and does not give rise to any secondary stresses. But if, for example, a box is supported and torsionally restrained at both ends and then subjected to applied torque in the middle, warping is fully restrained in the middle by virtue of symmetry and torsional warping stresses are generated. Similar restraint occurs in continuous box sections which are torsionally restrained at intermediate supports.

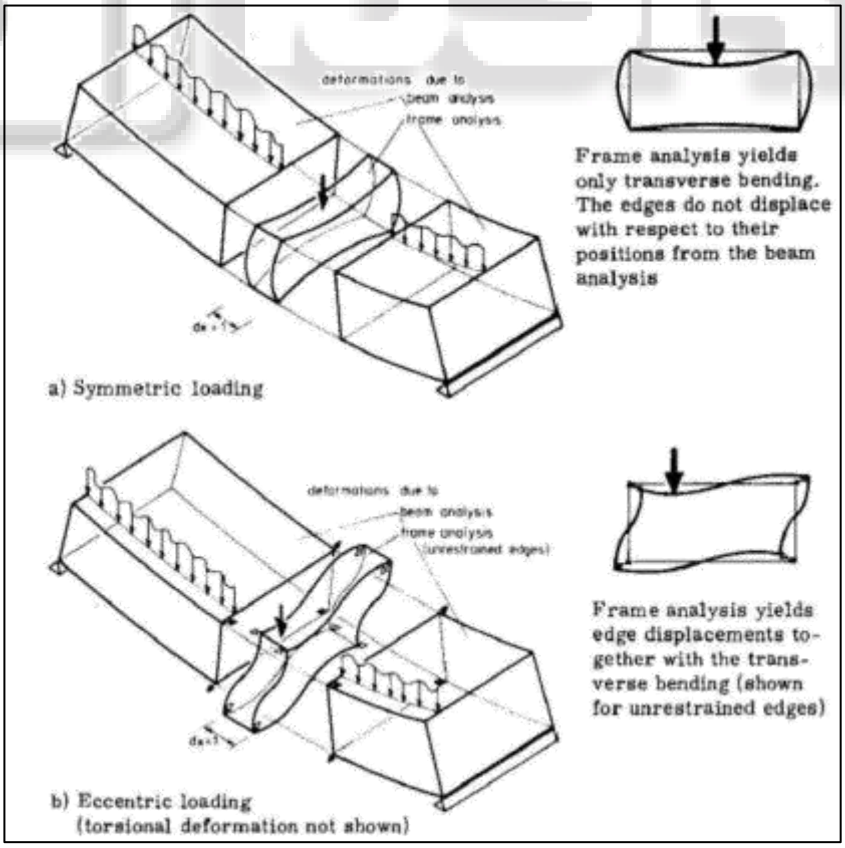


Fig. 7:

This restraint of warping gives rise to longitudinal warping stresses and associated shear stresses in the same manner as bending effects in each wall of the box. The shear stresses effectively modify slightly the uniformity of the shear stress calculated by pure torsion theory, usually reducing the stress near corners and increasing it in mid-panel. Because maximum combined effects usually occur at the corners, it is conservative to ignore the warping shear stresses and use the simple uniform distribution. The longitudinal effects are, on the other hand greatest at the corners. They need to be taken into account when considering the occurrence of yield stresses in service and the stress If torsional loading is applied, there are forces acting on the plate of elements, which tend to deform the cross section. The movements of the plate elements of the cross section cause distortion stresses in transverse direction and warping stresses in longitudinal direct

When torsion is applied directly around the perimeter of a box section, by forces exactly equal to the shear flow in each of the sides of the box, there is no tendency for the cross section to change its shape. Torsion can be applied in this manner if, at the position where the force couple is applied, a diaphragm or stiff frame is provided to ensure that the section remains square and that torque is in fact fed into the box walls as a shear flow around the perimeter. Provision of such diaphragms or frames is practical, and indeed necessary, at supports and at positions where heavy point loads are introduced. But such restraint can only be provided at discrete positions.

When the load is distributed along the beam, or when point loads can occur anywhere along the beam such as concentrated axle loads from vehicles, the distortional effects must be carried by other means. The distortional forces shown are tending to increase the length ofone diagonal and shorten the other. This tendency is resisted in two ways, range under fatigue loading. But since the longitudinal stresses do not actually participate in the carrying of the torsion, the occurrence of yield at the corners and the consequent relief of some or all of these warping stresses would not reduce the torsional resistance.

In general the distortional behavior depends on interaction between the two sorts of bending. The behavior has been demonstrated to be analogous to that of a beam on an elastic foundation (BEF), and this analogy is frequently used to evaluate the distortional effects.

If the only resistance to transverse distortional bending is provided by out-of-plane bending of the flange plates there were no intermediate restraints to distortion, the distortional deflections in most situations would be significant and would affect the global behavior. For this reason it is usual to provide intermediate cross-frames or diaphragms; consideration of distortional displacements and stresses can then be limited to the lengths between cross-frames.

The distortion of section is not same throughout the span. It may be completely nil or non-existent at points where diaphragms are provided, simply because distortion at such points is physically not possible. The warping stresses produced by distortion are different from those induced by the restraint to warping in pure torsion which is encountered in elementary theory of torsion. The compatibility of displacements must be satisfied along the longitudinal edges of the plate forming the box, which implies that these plates must bend individually in their own plane, thus inducing longitudinal warping displacements.

Any restraint to this displacement causes stresses. These stresses are called longitudinal warping stresses and are in addition to longitudinal bending stresses. A general loading on a box girder such as for a single cell box, has components, which bend twice and deform the cross section. Using the principles of super position, the effects of each section could be analyzed independently and results superimposed.

Distortional stresses also occur under flexural component, due to poisson effect and the beam reductance of the flange in multi cellular box, the symmetrical component also gives rise to distortion stresses and it is significant percentage of total stresses. With increase in number of cells, the proportion of transverse distortional stresses also increase. However for a single cell box the procedure of considering only the distortional component of loading for evaluation of distortional stresses in adequate for practical purposes.

The concrete boxes in general have sufficient distortional stiffness to limit the warping stresses to small fraction of the bending stresses, without internal diaphragms. But for steel boxes either internal diaphragms or stiffer transverse frames are necessary to prevent buckling of flanges as well as of webs and in most cases, these will be sufficient to limit the deformation of the cross section.

Sloping of the webs of box girder increase distortional stiffness and hence transverse load distribution is improved. If section is fully triangulated, the transverse distortional bending stresses are eliminated. This form could be particularly advantageous for multicell steel boxes. Therefore, distortion of box girder depends on arrangement of load transversely, shape of the box girder, number of cells and their arrangement, type of bridge such as concrete or steel, distortional stiffness provided by internal diaphragms and transverse bracings provided to check buckling of webs and flanges.

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