Effect of initial distortions on the carrying capacity of welded I-girders

Effect of Initial Distortions on the Carrying Capacity of Welded I-Girders

L'influence des déformations initiales sur la résistance à la ruine des poutres en I soudées

Der Einfluss anfänglicher Verformungen auf die Traglast geschweisster I-Träger

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The welded I-girders are in common use in all the areas of structural steel construction. The theoretical assumptions of the current technique for both analysis and design of such girders suppose any idealized cross section with absolutely regular geometrical contours.

In practice, however, there are always existing some distortions in the theoretical geometry of a girder and their causes are very different.

In the first place such a cause may lie in welding stresses of the metal as a result of high local heating due to welding and plastic compressive deformations arising in the weld sone.

In the fight against unfavourable effects of deformations due to welding there are provided both constructive and industrial measures. One of industrial measures is the straightening of an article after welding, i.e. its plastic straining by thermal or mechanical action. The straightening process has also to be used for structures with local distortions due to imperfections in relled plates or shock in the course of transportation and erection.

The straightening process itself, either mechanical or thermal, leads inevitably to the initiation of residual stresses and changes in mechanical properties of the metal.

The amount of straightening depends in large part on the specified tolerance on the steel members.

Local distortions in the web of girders are the least studied type of total and local residual deformatione.

The importance of problem to throw light on the actual behaviour of a girder with initial web distortions is governed by the practical need to define the tolerances on the fabrication of plate girders to avoid a great deal of work in straightening rolled plates and articles at the shop.

The allowable value of initial web buckling is principally defined by its effect extent on the carrying capacity with respect the local stability of a girder, i.e. with respect to such limit state in which a structure loses its capability to resist external effects or receives residual deformations which do not permit any possibility of further service.

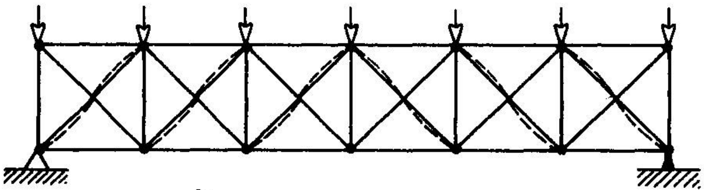
To assess the effect of initial distortions in the web of welded I - girders and define the values of corrections for critical stresses of ideally plane plates, it is used an analysis procedure proposed by Dr. B.M. Broude (1) and based on the linear bending theory of plates and non-linear bending theory of low-curvature shells.

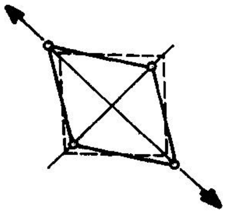
There are two modes of buckling to be distinguished, namely : the first mode which is possible only in case of ideal geometrical, physical and static conditions and the second mode, in such systems where under some conditions such load redistribution is possible that its resultant will be well above the critical load resultant.

The second-mode buckling occurs in all cases in which there are existing initial deviations from the exact geometrical shape or some eccentricities in the application of forces.

From the second-mode critical state definition itself as a reached maximum load condition it follows that a post-critical stage does not take place, i.e. the critical load is a limit quantity. Loss of web carrying capacity is the upper boundary of a limit state considered as a service stopping condition.

The behaviour of a thin-walled plate I-girder under load may be reproduced as that of a truss with flexible diagonals between posts-stiffeners.





The diagonals in compression are buckled under load and only diagonals in tension are working.

Under these conditions the significance of chords and stiffeners is particularly increased.

The limit state with respect to strength in the thin-walled I-girders occurs when the stress in the most stressed diagonals in tension becomes equal to the yield point.

Given initial distortions, the thin web of a girder, incapable of bending resistance, will again function only in tension. In addition to that the web bands in tension shall at first become straight (to compensate initial buckling).

As the plate thickness increases, the diagonals in compression will resist the straightening of diagonals in tension. In this case the additional tensile stresses (membrane stresses) will start to develop in the diagonals in tension. The plate will function in the same manner as a low-curvature shell and some initial buckling will cause no additional deformations of a girder.
As the thickness of a increases, a difference between the values of critical loads with respect to web local stability and those of ultimate carrying capacity with respect to strength of web diagonals in tension will decrease.

The initial distortions may be divided into two modes which are as follows :

(a) The plate is bent over a cylindrical surface and subjected to compression along the generatrix; in this case the buckling mode remains the same as in the ideal plane plate.

(b) The plate has an initial distortion with either full or partial invariability of a contour; in addition to that a growth of deflections takes place from the very beginning of loading up to the critical state development.

Just the second mode of initial distortions is of the most interest when considering the behaviour of plate I-girders.

The restraining conditions of plate edges in the plane of its contour are of great importance for estimating the critical load. If the edges of a rectangular plate may be freely deformed under loading conditions, the initial distortion reduces always the critical load as compared to the case of a plane plate.

If the loaded edges of a plate can move only in the translation motion form when remaining rectilinear, the critical load may be either increased or decreased in terms of the design plate depth-to-thickness ratio and initial deflection rise.

To study the first case the linear bending theory of plates may be used. In the second case the middle plane extensibility shall be considered. To accomplish this the mathematical means of the non-linear bending theory of low-curvature shells shall be applied. This is particularly essential for the relatively thin plates or in case of large initial deflection rises.

If a critical plate stress σ_o is not over the proportional limit and the ratio of an initial deflection rise f_o to a plate thickness : is not over 0,3 ($\frac{f_o}{\tau} \leq 0,3$), the linear bending theory of plates shall be used. In the case where these conditions are exceeded the non-linear bending theory of low-curvature shells shall be applied.

This criterion is also applicable to other states of stress (pure bending, load on the upper edge of a web).

The ratio $\frac{\sigma}{\sigma_o \sigma_o}$ where σ is the maximum normal stress and σ_o is the critical stress, is used as a figure of a state of stress.

As the initial deflection rise increases, the $\frac{\sigma}{\sigma_o}$ value for a given plate depth-to-thickness ratio at first decreases and next increases.

The ratio $\frac{\sigma}{\sigma_o}$ in thin plates may exceed the unity.

Since the crane girder operation conditions do not permit to consider the web edge to which a load is applied as nondeformable, the initial web distortion effect shall be defined by the methods of the linear bending theory of plates.

The girders carrying the nodal or static load may be permitted to have considerably greater web deformations as compared to those of crane girders and here the effect of initial distortions shall be considered in accordance with the second case conditions by using the non-linear bending theory of low-curvature shells.

The studies carried out in conformity with the above mentioned statements permit to formulate the following recommendations :

(a) The initial distortion effect on the stability of a web may be taken into account by the use of a special coefficient w which is introduced into the plate stability equation together with the simultaneous action of a moment as well as lateral and compressive forces :

$$\sqrt{\left(\frac{\sigma}{\sigma_o} + \frac{\rho}{\rho_o}\right)^2 + \left(\frac{\tau}{\tau_o}\right)^2 + \frac{1}{6} \cdot \frac{\tau}{\tau_o} \cdot \frac{\sigma}{\sigma_o}} \leq m_o w$$

where

σ, τ, ρ – normal, tangential and local compressive stress, respectively;

σ_o, τ_o, ρ_o – critical normal, tangential and local compressive stress, respectively;

m_o – rated coefficient of work conditions;

w – coefficient of critical stress reduction for account of initial distortions of a plate.

(b) The average w = 0,9 is permitted to be accepted for crane girders and similar structures, the top chord of which is subjected to a direct effect of movable load.

(c) w = 1 is permitted to be accepted for girders where the load is applied only at the location points of transverse stiffeners.

The above mentioned principles of theoretical definition of the initial web distortion effect were used as a basis of an analysis technique for designing a steel-reinforced concrete superstructure with welded plate girders of I-section (3).

A girder portion between transverse stiffeners was treated as a flexible rectangular plate having an initial distortion and rigid external contour.

For the maximum approximation of a design scheme to the actual structure it was imperative to introduce trigonometrical as well as hyperbolic - and - trigonometrical infinite series into the stress function along with biharmonic polynomial terms.

In accordance with the requirements of variational methods a made of both initial and additional distortions was prescribed in the form of trigonometrical functions of two variables.

The analysis of behaviour of a girder at the two stages was carried out according to a single procedure, but with appropriate variations in the geometrical properties of a section, actual forces and initial distortion amount. The distortion amount for the second stage was determined as a sum of initial and additional distortions at the first stage (prior to the introduction of a slab into work in conjunction with girders).

At the first stage of loading in a girder (prior to the introduction of the reinforced concrete slab into work) a web portion is under eccentric compression conditions, while at the second stage the web is subjected to eccentric tension when loading the gipder.

The analysis has shown that the local stability in the studie panel at the first stage of girder work may be provided only with due regard for fixing the web in the chords. An initial web distortion is a cause of development of additional stresses in a structure and particularly in the cross sections of a girder.

If the average stresses for a panel in the chords are known, it is possible to estimate the reducing correction coefficients for the design values of both cross section area and moment of inertia of a girder for a given initial distortion of its web and given load. As the initial distortion increases, these coefficients decrease.

The initial distortion effect is more essential to the axial deformability of girders.

The available technique provides for a possibility to take into account the deformed web effect on the state of stress and deformations in a girder with vertical stiffeners. For analysis goals one must know the actual forces, size of a structure and initial distortion outline in the panel.

The carried out studies have shown that the Standard allowed initial distortions of the web of welded bridge girders are not dangerous for the carrying capacity of a structure.

An experimental study of the initial web buckling effect on the carrying capacity with respect to both local stability and strength in the welded bridge I-girders made of low alloy steel "15XCHD" and provided with transverse stiffeners was carried out at the All-Union Research Institute of Transport Construction (2).

The experimental girders having overall sizes corresponding to actual values were loaded by successive steps, at first by 10- ton steps and next a step intensity was decreased to 3 to 5 tons up to the maximum load.

It is important to note, however, that in this case the experimental load was applied through the stiffeners and this was not in full accord with conventional work conditions of girders.

A comparison of obtained experimental critical load values for girders with different deflection rises has shown that these loads for girders with larger distortions were no lower, but even higher than those for girders with lesser distortions. These data allowed to draw a conclusion that the existence of initial web distortions up to 0,024 times the web depth did not reduce a critical load with respect to local stability.

An examination of variations in web buckling rise values at the centre of tested girder portions in terms of load increments has shown that some existence of initial distortions does not increase the web buckling intensity and even somewhat decreases it.

It was also found that initial distortions do not worsen the state of stress in both web chords of a girder.

On the basis of these studies and also generalization of statistical data on deflection rise values in initial web distortions of fabricated girders, the current Standards for fabrication of bridge superstructure plate girders accept the allowable buckling rise as equal to 0,006 times the web depth, i.e. twice the tolerance accepted in the earlier Standards.

The experimental studies of the behaviour under load in case of welded I-section crane girders with initial web distortions have shown a somewhat other picture (4).

Unlike the bridge plate girders where live load forces are transferred to the girders through a rigid reinforced concrete slab of roadway or ballast bed and a unit pressure transferred to the girder is relatively small, the crane girders are subjected to the direct effect of a concentrated movable dynamic load which is transferred through crane rails. Any eventual eccentricities of crane load application, caused by imperfections in the position of rails and lateral effects of crane wheels, have also a significant influence upon the state of stress in girders.

In addition to that there are arised bending-and-torsional deformations which result in both yielding and loss of carrying capacity of a girder.

The experimental studies of crane girders have shown that the existence of initial distortions above a certain value increases deformations, predestines a point of failure and, hence, reduces the service ability of girders. The decisive buckling has initiated just at the panels with a deformed web.

The theoretical analyses performed by the method put forward by Dr. B.M. Broude (1) have defined the allowable deflection rise value of initial distortions in a welded I-section crane girder as equal to 0,003 times the web depth. This tolerance was accepted in the current Structural Standards.

Present-day in our country no comprehensive data are available on all the aspects of behaviour of a girder with initial distortions under complicated loading conditions.

The experimental studies of girders under dynamic load action will give rather important corrections to our conceptions of the behaviour of girders with initial distortions.

Such studies of the 11.0 m - span welded I-girder 1.5m high with vertical stiffeners are being carried out at present.

The experimental girder is subjected to the pulsating load with the constant amplitude of vibrations.

Resistance wire-strain gauges are placed at the points of the most probable initiation of fatigue cracks due to "breathing" of the web, at the bottom portions of panels near stiffeners.

It is proposed to subject the girder to the effect of pulsating load with 2-million cycles.

The experimental data on the normal stress maximum-to-minimum ratios $(\frac{\sigma\ max}{\sigma\ min})$ will permit to evaluate the effect of initial web distortion on the carrying capacity of a girder with respect to its endurance.

To summarize the above mentioned statements the conclusions to be drawn are as follows :

(a) A rated value of the allowable deflection rise of initial web distortions in crane girders is confirmed by both theoretical and experimental studies;

(b) It would be sound practice to check this characteristic for the girders of bridge superstructures by means of testing under non-nodal (non only above the stiffeners) load application conditions;

(c) Experimental studies of the behaviour of girders under dynamic loads will permit to evaluate the effect of initial web distortions on the carrying capacity of a girder with respect to its endurance and substantially complement our conception of the behaviour of girders with initial distortions under diverse conditions of both loading and state of stress.

SUMMARY

The methods of the linear bending theory of plates and non-linear bending theory of low-curvature shells, accepted as the basis of analysis, permitted to prove the rated values of allowable deflection rises of initial distortions in welded I-girders. Experimental studies under static load have confirmed these data for crane girders and defined those more exactly for plate girders of bridge superstructures.

Nowadays, an experimental study of the behaviour of I-girders with initial distortions is being carried out under dynamic load conditions.