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Buckling of Curved Webs in Steel Box Girders

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Abstract

Today, bridge girders with curved flanges and webs are becoming more common in order to increase the aesthetic value and to improve the quality of the structure. Despite the use of these new shapes, not much research has been done in this field. The aim of the present research is to find the influence of the web curvature on the buckling resistance. Therefore, numerical models are created, which have curvature radii of 1500, 5, 3, 5/3, 1, 0.7 and 0.55 times the web height. GMNIA is performed with these models, the first mode shape being used as geometric imperfection. Amplitudes of 0.1 times to 3 times the web thickness are used. The results are analyzed on multiple levels. The imperfection sensitivity towards curved webs is visible by the deformation pattern, the buckling load, and the load-deformation curve of a web. These last curves also give an indication of the behaviour in the post buckling region.

Keywords: Curved webs, FEA modelling, imperfection sensitivity, panel buckling

1 Introduction

Designers have become keen on using curved shapes in bridge designs. Curves are used in the longitudinal direction and webs and flanges of girders are given curved shapes. A rail bridge in Zemst [1] and a cyclist bridge in Bruges (Figure 1) [2] are recent examples in Belgium, where curved webs are used.

These shapes are used in order to increase the aesthetic value and to improve the overall quality of the structure. However, when using these curves, there are no standards or codes available to design the panels. In addition, not much research is available in this field, especially not regarding the use in bridge design.

A main concern is the way these curved panels transform the shear forces between the flanges, and whether the elastic buckling capacity of the curved webs remains sufficient.

Figure 1. Cyclist bridge in Bruges

Previous research [3] stated that the failure load of a beam with two curved webs, increases for an increasing radius of the curvature. The failure load values were chosen as the maximum load the beam can support. Although it is not clear

whether this includes the post buckling capacity of a panel.

To understand the behaviour of curved panels, it is important to distinguish between the elastic buckling and the post buckling state of the panel. Previous research [4] has shown that beams with curved panels are more likely to behave as a shell. This would implicate that the elastic and post buckling behaviour of the curved panels are much more sensitive to imperfections. A nonlinear analysis is performed to find these differences.

2 Geometrically and Materially Nonlinear Analysis with Imperfections (GMNIA)

2.1 Model characteristics and properties

A GMNIA is performed on closed steel sections with varying web curvatures. Radii of 1500, 5, 3, 5/3, 1, 0.7 and 0.55 times the web height are used. The web height for these models is 1m, and the web thickness is 10 mm. This makes the web slenderness b/t equal to 100. The panels between the diaphragms are 1m wide, which makes the aspect ratio 1. The diaphragms are steel panels of 25 mm thick, which cover the full box opening. The total beam length is 4 m.

Figure 2. Numerical model

The use of a completely closed section implies that the boundary conditions of a single curved panel are not perfectly simply supported. This generates more realistic results for bridge design applications, but makes the thickness of the flange more important. For these models, the thickness is chosen as three times the web thickness, thus 30 mm.

The material is chosen as a S355 steel, which is used for all parts of the box. The nonlinearity of this material is provided by the stress-strain diagram, illustrated in Figure 3.

Figure 3. Stress-Strain diagram S355

The GMNIA is performed in the FEA software package Siemens NX, using the Nastran solver [5]. For the mesh, 2D elements CQUAD4 are used, with an overall size of 10 mm for the webs, and 20 mm for the stiffeners and the flanges. These two latest elements have a rougher mesh, because their behaviour is of less importance for this study.

2D elements are chosen, since Eurocode 3 [6] suggests to use the middle plane of a shell to load the plate and to evaluate the buckling behaviour. The imperfections are placed on the model through these 2D elements, by altering the element nodes in the desired shape.

2.2 Model test setup

At one side of the beam, the entire end cross-section is clamped. At the location of the second internal stiffener, a downwards force is placed. This creates the same model setup as in previous experimental research [4]. Because of symmetry only one half of the model is simulated, with clamped boundary conditions.

Because of this setup, the internal force lines in Figure 4 are applicable. The beam is clamped at the left side, as in the numerical model. Due to the downwards force, the model is loaded by a constant shear force, equal to the applied load. The bending moment at the middle support is twice the length of a field, multiplied with the applied force. Because one field is a meter wide, the bending moment is the applied force

multiplied by two. This focus on the appearance of bending moments notwithstanding, the shear forces are the dominant factor for web buckling.

Figure 4. Internal force lines

3 Geometric imperfections

In order to perform a GMNIA, geometric imperfections are introduced. Since curved webs in bridges are not that common, there is no data available of realistic imperfection amplitudes and shapes. The part about shell structures in Eurocode 3 [6], suggests to use the modes of a linear elastic bifurcation analysis (LBA), unless any other unfavourable shape can be determined. The aim of this research is to compare the beam behaviour with different web curvatures. Therefore, it is chosen to use the first mode of the LBA, neglecting the other possible imperfection shapes in this first phase.

Another uncertain imperfection parameter is the amplitude. Again, Eurocode 3 [6] gives some suggestions, based on the wave length of the panels. If these rules are applied on these models, the amplitudes are different for each radius of curvature and have rather high values for the flat webs. The values of the amplitude varies between 5.5 mm and 27.2 mm. The different amplitudes make it difficult to compare results. Thus, the same amplitudes as suggested in previous research about curved panels [7] are used. These values vary between $0.1t$ and $3t$, with t as the thickness of the plate. These boundaries do cover the amplitudes suggested by the Eurocode as well.

Figure 5 shows the first buckling modes for all different models. The figures are ordered in a way that the model with the flattest webs is placed first, and each increment of curvature radius is placed next to it.

In the flattest web model, the well-known diagonal tension line develops as a buckling pattern, and is symmetrical for both sides of the cross section. With increasing web curvature, more and smaller bulges start to develop, parallel to the diagonal main bulge. In addition, the larger bulge starts to shift towards the lower side of the web.

Figure 5. First mode of LBA for all models

Research on the same topic [8] used the non-dimensional curvature parameter Z (equation (1)), which is proposed by S. B. Batdorf et al [9], to order the buckling patterns of the webs. The curvature parameter Z is a function of b as the smallest axial or circumferential dimension of the panel, r as the radius of curvature, t as the thickness of the web and μ as the Poisson's ratio of the material.

$$Z = \frac{b^2}{r \cdot t} \cdot \sqrt{1 - \mu^2} \quad (1)$$

In recent research [8] three different buckling patterns are distinguished, which results in stable and unstable behaviour of the panels. The panels with a Z value lower than 30 (one bulge) or higher

than 145 (three bulges) should have a stable behaviour, due to the symmetric buckling pattern. Panels with a value in between these boundaries have an unstable behaviour (and two bulges in the buckling mode). Table 1 gives the Z values for the models used in this research. These Z values correspond to the stable and unstable buckling shapes that can be distinguished from Figure 5 and the proposed boundaries for these regions. These different behaviours should also be visible in the GMNIA.

Table 1. Z-values of used models

b/r	0	0.2	0.33	0.6	1	1.43	1.82
Z	0	19	32	57	95	136	173

The obtained buckling shapes are implemented in the numerical model by shifting the mesh nodes of the webs, in order that the pattern becomes the imperfection shape. The amplitudes are varying between 1 mm and 30 mm, which is three times the web thickness.

4 Numerical results

The results, obtained from the GMNIA for the different models, give information on multiple levels. First, the deformations of the web are investigated and compared with the shape of the initial imperfection. Subsequently, the elastic buckling load of the different beam setups are evaluated, together with the influence of the imperfection amplitude. Finally, the load deformation curves of the buckled web are generated and give information about the initial stiffness and the post buckling behaviour.

4.1 Web deformation

The web deformation determines the behaviour and the sensitivity to imperfections of the panels. The imperfections induce an initial deformation, which influences the buckling pattern. This is visible in Figure 6, wherein the models with the flattest (above) and the most curved webs (down) are presented, with at the left side a small (0.1t) and at the right side a large imperfection amplitude (2.5t).

The figure clearly shows that the initial imperfection not only affects the buckling load,

but also the deformation pattern of the web. When a small imperfection is introduced on the web, the buckling pattern is comparable in shape with the one obtained from the LBA. However, when large imperfection amplitudes are used, the pattern fundamentally differs from the initial imperfection. The deformed parts have larger amplitudes and different shapes than the models with a small amplitude. For the flattest webs, the buckling pattern has a deeper, but smaller tension line, and the occurrence of two small bulges at the corners is more prominent. When the webs have larger curvature, the deformation pattern has less, but deeper bulges than the initial imperfection.

Due to the higher imperfection amplitudes, the buckling shape is initiated at the most deflected nodes, which creates larger bulges. There, the boundaries of the web have almost no deformations, so the larger translations have to be neutralized towards these edges. Hence, the webs have different buckling patterns, because the deeper bulges create shifts of the neutral zones and pop out some smaller bulges or create new bulges. This happens for the most curved web, where one bulge disappears when the imperfection amplitude increases, while for the flattest web, two new smaller bulges are created.

Figure 6. Web deformation of flattest web and most curved web with imperfection amplitude 1 mm (left) and 25 mm (right)

4.2 Elastic buckling load

In FEA modelling, it is not clear which load exactly is the elastic buckling load. In this paper, the ultimate load step of the simulation is used. Another possibility would be to use the principle of the Southwell plot on the linear elastic part of the load displacement curve, however due to the different build-up of the displacements for flat webs and curved webs, these results are less reliable.

Figure 7 shows the elastic buckling load as a function of the curvature. The curvature is expressed by the parameter b/r , which is the height of the web divided by the radius of curvature of that web. This results in almost zero for the flattest web and a value a bit smaller than two for the most curved panel. The values of the buckling load are results for the whole beam and not for one single panel.

These curves show some remarkable results. All previous research ([3][4][7][8]) stated that curved webs, whatever the applied imperfection amplitude, have a larger elastic buckling load. However, this is only the case for the models with no initial imperfection or with a very small imperfection ($A = 1 \text{ mm}$). When this amplitude increases, the curved panels become more imperfection sensitive, and the elastic buckling load decreases.

The imperfection sensitivity can also be expressed in percentages as follows. An imperfection amplitude of 30 mm decreases the buckling load of the flattest webs by approximately 10 %, while in the most curved web, this value is close to 30 %. Since curving the webs has only a benefit of about 8 % for the maximum load when no imperfections are applied, it is logical the curve decreases for higher imperfection amplitudes.

The difference between these results, and earlier results can be explained as follows. First of all, the boundary conditions of the model are different. In previous research, the edge conditions are simply supported or perfectly straight flanges. In other words, the boundary conditions are perfect for these models. However, due to the appearance of the bending stresses, the flanges also have some deformations in the LBA. These deformations are

implemented as initial geometric imperfections, and results in the boundary conditions of the web no longer being perfect. This deformation of the flanges do especially occur for larger imperfection amplitudes and for the most curved webs.

A second reason is the difference in web slenderness. As suggested in [4], this parameter of the panel can have a huge influence on the web behaviour. For all the models of previous research, this slenderness is different, which makes comparison of actual buckling loads quite difficult.

An odd results in Figure 7 is found for the model with a curvature ratio b/r equalling 0.33. The elastic buckling load has a higher drop for even a small imperfection than the other models. A clear explanation for this phenomenon is not available, but the web with this curvature ratio lies on the boundary of flat and shell-like web behaviour. The Z value of this model is 32, which is on the boundary between stable and unstable buckling modes. It seems that this model is influenced by both categories. It is obvious that the web is sensitive to imperfections, since the smallest imperfection results in a lower bearing capacity. However, this should also be the case for the beams with a higher curvature ratio. A reason for this remarkable difference is possibly the occurrence of stabilizing forces in curved panels. These forces results in a perfectly curved panel being harder to deform and having a higher buckling load in perfect conditions. Since the panel with a curvature ratio b/r equalling 0.33 is still quite flat, it seems that these stabilizing forces do not have a big influence.

4.3 Post buckling behaviour

Although the web has buckled, it can still resist additional loads, defined by the post buckling capacity of the beam. This behaviour is obtained with the use of the arc-length method. The arc-length method is a very efficient method for solving non-linear systems of equations when the problem under consideration exhibits one or more critical points [10].

Figure 8 shows the load deformation curves of the node with largest displacement of the buckled web. The graphs compare models with different

web curvatures having identical imperfection amplitude (the same curvature ratio b/r as in Figure 7 is used for each model). The models with imperfection amplitudes of 1 mm and 25 mm are

shown. The graphs not only illustrate the post buckling behaviour but also gives an indication about the initial stiffness of the webs.

Figure 7. Elastic buckling load per imperfection amplitude

The deformation pattern is similar for all web curvatures. All different buckling modes first show a linear elastic behaviour. The load increases in large steps and the displacements remain small until the webs loose stability and buckling is starting. This buckling load, as earlier explained, is taken as the maximum load in the curve. After this point, the web behaves in the post buckling region and continues deforming, with a decreasing load.

The elastic part of the graph of the models with an imperfection amplitude of 1 mm is almost straight. This indicates that the panels are stiff in the prebuckling phase. Only a small variation in the elastic area is distinguished between these models. If the load reaches higher values, the flatter webs show larger deformation and are more flexible. However, the ability to develop larger deformations, implies larger post buckling capacity. These results confirm the existence of two different web categories, being the flat webs and the shell-like webs, as suggested in [4].

The graph at the right side of Figure 8 illustrates the models with an imperfection amplitude of 25 mm. The initial stiffness of all webs is clearly

affected by these imperfections. The linear elastic part of the graph shows larger deformations for smaller loads. The flatter webs are less affected by the imperfections, as expected. The shell-like webs are more imperfection sensitive and hence have a smaller initial stiffness. However, the decrease of stiffness has no linear correlation with the increase in web curvature. For example, the models with a curvature ratio $b/r = 1$ and $b/r = 1.82$ have a larger initial stiffness than the other curved models. For most curved web, this can be due to the stable imperfection pattern, however this is not the case for other values of curvature and unstable imperfection modes. It is also remarkable that models with a smaller initial stiffness are still able to have a larger maximum load, which can indicate that there is a difference between the maximum load and the elastic buckling load.

Once the maximum load is reached, there is not much difference between the models when it comes to the post buckling behaviour. For small imperfection amplitudes, the difference in web displacement between flat webs and curved webs

is clear. However, when the imperfections increase, this difference is flattened out. The increased imperfections thus influence both the elastic and the plastic behaviour of the webs.

Figure 8. Load deformation curve of all models with imperfection amplitude 1mm (left) and 25mm (right)

5 Discussion and further research

A large range of possible radii of curvature is being considered. It seems that the behaviour of the web depends on the curvature parameter Z . This should mean that models with different radii and thicknesses, but with the same Z -values, should have the identical behaviour and buckling pattern.

Apart from the web characteristics, the thickness of the flanges is a second uncertainty. The boundary condition of the web depends on the stiffness of the flanges and the bending stresses. For the most curved webs, the flange has larger deformations, and thus the flange thickness has increasing influence on the web behaviour.

Finally, the interpretation of the elastic buckling load is an issue. The drop for the model with curvature ratio $b/r = 0.33$ with a small imperfection is due to a drop of the maximum load the web panel can resist. However, the elastic stiffness of this web is higher than the flatter webs, which indicates that the drop not directly means that this curvature has bad results.

6 Conclusions

Using the mode shape as initial imperfection does affect the buckling behaviour of curved webs on

multiple levels. An increase in imperfection amplitude may fundamentally modify the web buckling pattern.

In addition, the maximum load increases for an increasing curvature ratio, for perfect webs. However, when increasing the imperfection amplitude, the maximum load decreases and is higher for more curved panels. This results in a decrease of the maximum load.

The initial stiffness of the webs has been investigated as well. For small imperfection amplitudes, the elastic stiffness is larger when the webs have a larger curvature. With increasing amplitude, this correlation does not exist anymore.

For small imperfections, the flatter webs have larger post buckling capacities. With increasing imperfection amplitudes, the difference in post buckling behaviour is flattening out and all models do deform quite similar.

The overall conclusion is that curved panels are indeed imperfection sensitive and should be constructed with great care. When the use of this type of panel is carefully built, the increased aesthetic value can also result in an increased structural value.

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