Stability and node-detailing of tubular steel arch bridges

Ph. Van Bogaert
Ghent University, Civil Engineering Department, Ghent, Belgium

ABSTRACT: Steel tubular arches are highly valued because of their aesthetic value. However, as trust force is an essential element of arch behaviour, during erection the development of this force from dead load should be fully assured. In addition top concrete deck slabs can contribute to the arch stability, especially if the slab is connected to the abutments, thus constituting an integral bridge. The most important design issue is concerned with the fatigue resistance of welded nodes. This resistance can consistently be improved by adding internal diaphragms in the main arch tube. This is demonstrated by the hot spot stress method and careful assessment of the stress concentrations. Adding diaphragms inside the main arch tubes seems to reduce stress concentrations effectively, thus increasing the arch fatigue resistance.

1 INTRODUCTION

1.1 Steel tubular arch bridges

Steel tubular arch bridges arch rarely built, because they are considered to be costly and need particular care during erection. In general, this type of structure is appreciated for its high aesthetic value. Circular tubes can constitute fine truss structures and show delicate transitions of light and shaded areas. Especially nodes, connecting the truss bars can be totally smooth and express the consistency of force flow.

However, as pure and simple these structures may seem, the nodes are difficult to build and comprise various types of stress concentration, seriously lowering the fatigue strength of tubular arch bridge of which they are part. This has been a main reason why in many of these bridges the nodes are made from cast steel. Casting of nodes mainly mitigates the stress concentrations caused by welding, leaving only those due by geometric disturbance and stress flow changes. In addition cast steel nodes show large fillet rounding, further decreasing stress concentrations.

A second characteristic of steel arches in general is concerned with the achievement of trust force after erection. Obviously, trust forces are the main characteristic of arch bridges. They are due to all types of loading, including the dead weight of the structure. It is imperative that after erection the dead weight also contributes to the total trust force. This may require special erection procedures.

1.2 Integral bridge behaviour

Since arch bridges are either hinged or clamped at their springs, horizontal deformations are prevented. If the arch is below the bridge deck, displacements of the latter may be free or also prevented. Free displacements result in horizontal shift between the deck and the arch and increasing bending moments in the vertical struts or the truss system connecting the deck to the arch. However, if the upper bridge deck is also connected to the abutments, preventing horizontal displacement, the bending of the connecting system becomes less heavy. Obviously, this requires the bridge to act as an integral system, introducing higher earth pressures on the abutments.

2 BRIDGE DECK SLAB BEHAVIOUR

2.1 Slab action

The principle of preventing horizontal displacements of the upper concrete slab on a steel tubular arch bridge was successfully applied in the case of the Merxemstreet bridge (Van Bogaert 2006), shown in fig. 1. This double track railway bridge, carrying the high-speed railway line from Brussels to Amsterdam, consists of a single steel tube of 914 mm diameter and spanning 27.4 m. The bridge deck slab has 0.4 m concrete thickness and is fixed to the abutments by concrete hinges.

Figure 1 : Merxemstreet Tubular Arch Bridge.

Obviously, the concrete slab can act as a compression member, while the main steel tube would loose its primary function as compressed arch. However, the analysis has shown that this is not entirely true, the effect being limited to the central part of the arch. This can be seen in the plot of the main tube normal force above if no constraint of horizontal displacements is applied and below for restraining these displacements.

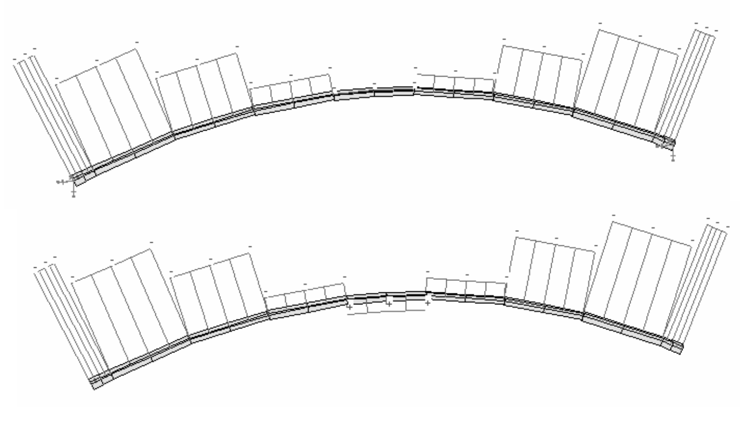

Figure 2 : Local arch tension due to integral bridge behaviour.

2.2 Arch stability

Evidently, the concrete slab also contributes to the arch stability, especially if it is connected to the abutments. The elastic critical arch compression force is a relevant quantity to assess the arch stability. In the case of the bridge of fig 1, the critical compression force increases by 57%, although this has no tremendous effect on the arch slenderness, since it decreases from 0.69 to 0.55. Taking into account the χ-factor, the effect of integral bridge behaviour is limited to a reduction of compression stresses by 11%.

3 ARCH ERECTION AND TRUST FORCE

3.1 Arch springs

Since thrust force is essential to develop arch behaviour, the arch springs need either to be hinged or to be clamped. Steel hinges are complicated to build, especially for tubular arches. Hence, clamping of tubular arch springs is mostly preferred. Fig.3 displays one spring of the arch of the Merxemstreet bridge. The main tube ends with a heavy base plate and additional stiffeners, because of the high local bending moments. The base plate is connected to the abutment by prestressing bars.

Figure 3 : Arch sping clamped by prestressing bars.

If the effect of bending moments does not exceed the compression stresses caused by the trust force and vertical reaction, the arrangement of fig 3 is sufficient to resist shear force perpendicular to the arch axis and torsion.

3.2 Introduction of trust force during erection

After erection of the arch, the trust force due to dead weight should be active entirely and the dead weight should behave as a distributed load. In view of this, the use of erection supports should not be advised.

In the case of the Merxemstreet bridge of fig.1, the steel structure was prefabricated entirely at the workshop and could be placed as a single element. During erection, the structure was supported near the centre of the arch, introduced shortening of the total length by 14mm, thus allowing it to fit between the concrete abutments. As the arch is lowered gradually, the local reactions of the temporary central supports disappear, and the dead load becomes distributed. However, this did not accommodate with the prestressing bar heads as shown in fig 3. Hence, these bars were installed after lowering of the arch tube.

Obviously, this type of erection procedure is not applicable for large arch bridges, as the main tube must be assembled on the building site. The use of erection supports then can no longer be avoided. This is the case for the double steel tubular arch of the Woluwelane bridge, near Brussels, shown in fig. 4 and carrying 3 tracks at various levels.

Figure 4 : Woluwelane Bridge.

Since the subjacent road has several shoulders, allowing the location of erection towers, the building procedure includes assembling of the main tubes, struts and crossbeams in four parts, welded together above the existing roads. After this, the main tubes are supported by concentrated reactions at the towers. The idea is then to install a two-way jacking system to further compress the arches and lowering them, in order to pass above the prestressing bars of the arch springs. The two-way jacking system first heaves the main tubes from the vertical supports and further compresses the structure. This assures the effect of the dead load to be distributed, complying to the aforementioned requirement.

4 NODE DETAILING

4.1 Fatigue resistance of welded nodes

Welded tubular nodes contain various stress concentrations, both by the welding process itself as by geometric discontinuities. Obviously, this situation reduces the fatigue strength in a decisive manner. In addition, the stresses reach high peak values near to the weld toe of the joints. In tubular bridges, the struts, connected to the main tube also introduce local bending of the arch tube, according to the ratio of tube diameters. Romeijn (1997) has detected large stress concentration in multiplanar tubular joints and has established stress concentration factors (SCF's) for various types of nodes. This research contributed extensively to the recommendations for lattice girder node joints of Eurocode 1993-1-9. According to the latter, the fatigue resistance class varies from 90 to 45 MPa for K-joints and from 71 to 56 MPa in case of overlap joints. All these fatigue details correspond to S-N-curves of m = 5 exponent.

Extensive numerical and experimental research by Schumacher et al (2003), has shown that stress concentration factor in main tubes vary from 1 to 1.5 and for truss bars between 1.5 and 2.5. These results contrast to the former opinion that the SCF mostly equals 2. This research proposes the use of normal S-N-curves with the classical branches of m = 3 and 5 and fatigue detail class of 80 MPa. This proposal results from the conclusions that, although stress concentration factors are lower than expected previously, the actual fatigue resistance also proves to be lower.

The results of experiments and numerical simulations all indicate that the fatigue resistance of welded nodes depends on a variety of parameters, such as the ratio of the thickness of the tubes, the ratio of tube diameter to thickness, the gap between connected diagonal bars on the main tube and the type of welding. Hence, at the present state, assessment of the fatigue resistance of welded nodes should be based on the geometric hot spot stress method as developed by Niemi and Marquis (2003) and mentioned in Annex B of EN 1993-1-9. The latter specifies the detail categories caused by the welding itself, without further influence of stress concentrations caused by geometric discontinuities.

4.2 Effect of additional diaphragms in the main tube

The nodes of Merxemstreet bridge have overlapping diagonal members as can be seen in fig 5. The ratio of arch tube and en diagonal struts thickness of 50/36 almost equals 1.4. Hence, the design of the nodes was based on fatigue class 71 MPa, without any further consideration.

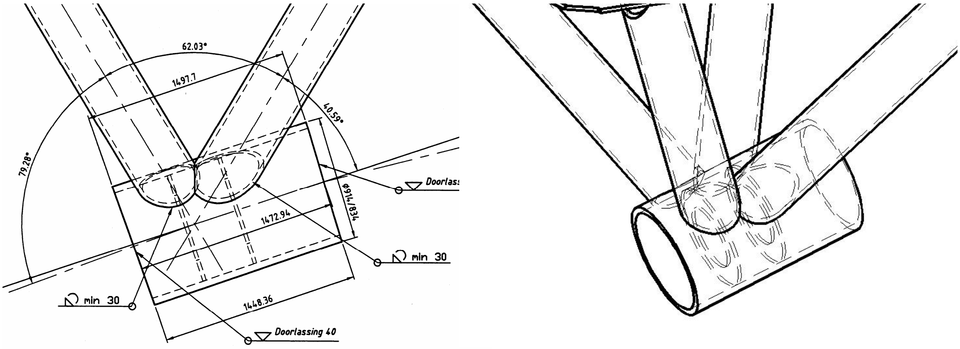

Figure 5 : Nodes of Merxemstreet Bridge.

However, the normal force from the diagonal struts might cause additional circumferential stresses in the main tube and eventually flattening of the latter. This may be prevented by adding internal diaphragm stiffening to the main tube.

In the case of the Woluwelane Bridge, each node contains no more than 3 connected tubes. Obviously, the bending moments will be much larger in this structure, since the lack of truss effect. As a consequence, stiffening of the nodes seemed imperative, although not evident. In addition the stiffening could be used for lowering of the SCF. Fig. 6 shows the results of SCF's for various cases.

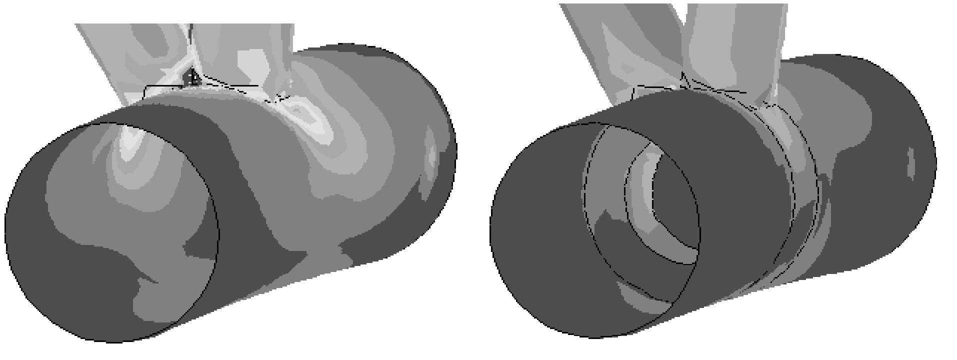

Figure 6 : FE-modelling of first 2 stiffening cases of nodes.

In the left part of fig. 6 the vonmises stresses are shown in the most critical node of the Woluwelane Bridge, whereas in the right part an identical model has been completed by adding two circular diaphragms, located at the centre line of the diagonal members. The scale of stresses is identical for both models. Obviously, the location of the largest stress concentrations remains identical and corresponds to the overlap spot of the welding of the vertical tubes to the main arch tube. Obviously, the location of the diaphragms may be improved. This has been done in the FE-model of fig. 7, by adopting higher spacing between both diaphragms.

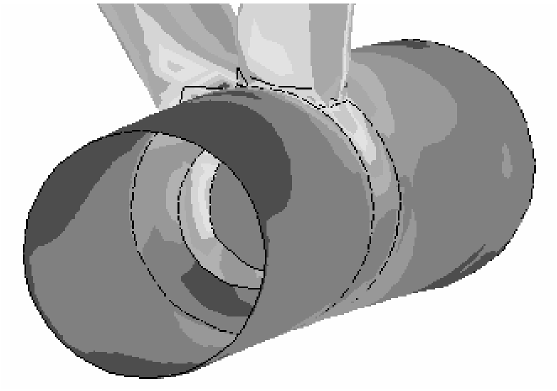

Figure 6 : FE-modelling of first 2 stiffening cases of nodes.

Although the last model still shows stress concentrations at the node welds, their magnitude become comparable to the current stresses in the built-up secondary tubes. Table 1 shows the SCF for these 3 alternatives.

Table 1 : SCF for alternative diaphragms

Alternative	Without diaphragm	Diaphragms at centre line	Increased spacing
SCF	7.21	2.34	1.09

The values of SCF's of table 1 demonstrate that the use of diaphragms may considerably lower stress concentrations and consequently improve the fatigue resistance. Obviously, diaphragm stiffening can only be installed if the main tube is sufficiently large to allow working inside.

Regarding the use of the hotspot stress method for this particular case, Annex B of EN 1993-1-9 does not provide an adequate category for the penetration welds of the nodes. However, most categories result in 100 MPa fatigue class. Hence, if the stress concentration factors approach 1.1 the assessment of the nominal fatigue resistance must exceed 80 MPa. This coincides with the results of Schumacher et al 2003.

4.3 Fatigue resistance improvement measures

Hammer or needle peening is generally accepted as an effective way of improving fatigue resistance. Unfortunately it is not commonly known nor applied by steel construction manufacturers. Haagensen and Maddox (2001) provide with practical rules for post-welding treatments, in particular needle peening. However, grinding of steel parts is a very effective way of disposing of irregularities and notches.

Grinding of welds allows to satisfy ground flush smoothing conditions as mentioned in EN 1993-1-9. The application to welding of perpendicular connections is possible if carried out with sufficient care. As for needle peening, grinding must be inspected afterwards and result in flat, smooth surface conditions.

In the case of the Merxemstreet Bridge, all node welds were grinded. This can be seen in fig. 7, a detailed picture of the grinding result. This figure demonstrates that the individual welds can still be noticed, the surface condition being completely smooth. Peening may result in deeper effect on the weld notch effects, but will not result in better surface conditions. As the welds toe is at a rather large distance from the secondary tube nearest surface, it may be believed that the grinding solution may be equivalent to peening.

Figure 7 : Grinded node welds.

4.4 Node detailing

As a consequence of the results mentioned in paragraph 4.2, the nodes of the Woluwelane bridge have been designed with double diaphragm stiffening. After closer analysis, bending stresses seem to occur in the diaphragm edges as well. Because of this, additional stiffening of the diaphragms themselves was provided. This can be seen in fig 8, showing views of the node stiffening.

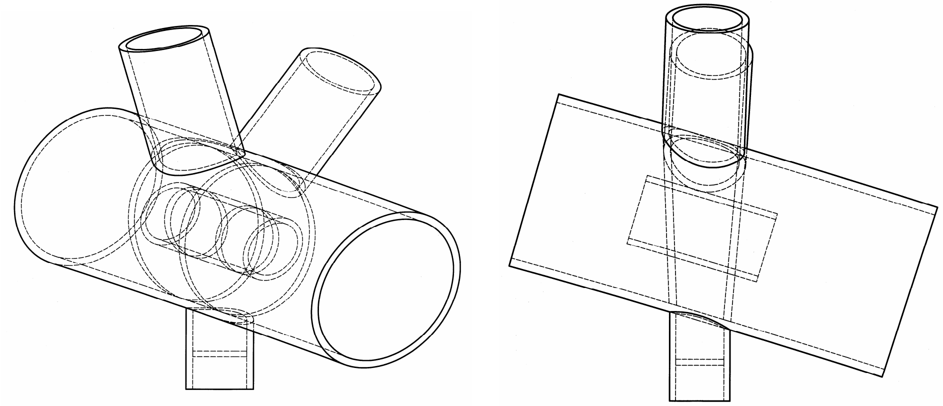

Figure 8 : Detailing of nodes of Woluwelane Bridge.

It may be noticed from fig. 8 that the diaphragms are not perpendicular to the main tube, but continue in the direction of the vertical secondary tubes. This improves the direct transmission of forces, although it may disturb the effects mentioned in 4.2. The angle made by the vertical members with the main tube axis may cause additional bending of the diaphragms, which in their turn are stiffened by a short tubular member, as shown in fig. 8.

The solution of fig. 8 does not correspond necessarily to the best of all options. Variation of the angles between diaphragm stiffeners and the various tubes may be considered, as well as further increasing the distance between these stiffeners to completely correspond to the aximum stress peak at the weld toe. This may be explored in further research, which the writer would like to start.

5 CONCLUSIONS

It was implied that integral bridge behaviour may contribute to arch stability by increasing the critical arch compression force, without disturbing fundamentally the arch behaviour.

In addition, erection procedures must ensure the structure dead load to act as distributed load and introduce trust force effectively in a controlled manner.

The main issue with tubular steel arch bridges is the fatigue resistance of the nodes. If welded nodes are used, adding internal diaphragm stiffeners in the arch main tube at adequately chosen locations, mar reduce the stress concentrations effectively, thus contributing to increasing the fatigue resistance of tubular arches with welded nodes.

REFERENCES

Haagensen, P.J. and Maddox, S.J.. 2001 IIW *Recommendations on Post Weld Improvement of Steel and Aluminium Structures*. IIW Commission XIII, XIII-1818-0

Niemi, E. and Marquis, G. 2003. *Structural Hot Spot Stress Method for Fatigue Analysis of Welded Components*. International Conference on Metal Structures, Miscolc, Hungary, April 3-5, ISBN: 90 77017 75 5 pp 39-44

Romeijn, A. Karamanos, SA. and Wardenier, J. Effects of joint flexibility on the fatigue design of welded tubular lattice stuctures. *Proc. of the Seventh Int. Offshore and Polar Engineering Conference***.** Vol. 4, pp. 90-97. 1997

Schumacher, A., Sturm, S., Walbridge, S., Nussbaumer, A. and Hirt, M. 2003. *Fatigue Design of Bridges with Welded Circular Hollow Sections*. Report Nr 489E ICOM – EPFLausanne Dec 2003

Van Bogaert, Ph. 2006. 'Design and Construction of the Merxem Bridge – A Single Tubular Arch'. *Proc. 6th Int. Symposium Steel Bridges*.CAOK-CVUT-European Convention for Structural Steelwork ECCS. May 31- June 2 Prague 2006. Ed Studnicka, J. ISBN 80-239-7168-9. pp 56-65