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LOCAL EFFECTS OF TRUSS NODE FORCES ON SHEAR CONNECTION IN COMPOSITE TRUSS BEAMS

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Design of composite steel and concrete truss girders is discussed, with an emphasis on longitudinal connection of the steel truss and a concrete slab. While a strongly non-uniform distribution of longitudinal shear due to localized force transfer in truss nodes occurs in elastic stages of early loadings, the plastic redistribution follows up to collapse. The former is of primary interest in the design of bridges, class 3 and 4 cross sections, non-ductile shear connection, and serviceability limit states in general. This research clears up the distribution in elastic phases and the process of plastic redistribution by using data of real bridge structures. Wide parametric studies provide insight into important parameters influencing the distribution, such as rigidities of shear connection, rigidities of steel chord and concrete slab, concentration of shear connectors above truss nodes, influence of temperature effects, shrinkage and creep. Design according to Eurocode 4 is discussed together with common procedures used by designers, referring to rather improper/conservative solutions. The necessity of densification of shear connectors above truss nodes is discussed in detail and suggestions for an iteration analysis for reasonable connection design is proposed.

Keywords: Composite trusses, Concentration of connectors, Eurocode 4, Longitudinal shear, Shear distribution, Shear rigidity.

1 INTRODUCTION

Composite steel and concrete trusses are commonly used both in buildings (as primary or secondary beams) and in bridges. In the 1990s, comprehensive research by Skidmore staff (1992) resulted in design recommendations showing a wide range of relevant design aspects. Accordingly, the plastic design can be performed as for a common plate girder including the design of a steel-concrete shear connection, provided that the shear connectors are ductile. The elastic design, however, is necessary for class 3 and 4 cross sections (classified acc. to Eurocode 4), rigid shear connectors due to their limited deformation capacity and generally in bridges. As a result, the highly non-uniform distribution of longitudinal shear in a composite truss girder caused by transmitting the shear to concrete slab in truss nodes needs to be taken into account. Local effects of the concentrated longitudinal force introduced into concrete slab due to prestressing were investigated by Johnson and Ivanov (2001) and introduced into Eurocode for design of composite bridges (Johnson 1997). The Eurocode (*cf*. EN 1994-2 or ENV 1994-2 in more detail) proposes formulas for the local effect of concentrated longitudinal force, acting either in the concrete slab or steel truss, and distribution of the longitudinal shear force into shear flow between steel section and concrete slab. The approach is also suitable for dealing with truss node forces.

The detailed experimental and theoretical analysis of composite truss behavior both in plastic and elastic region was presented by Machacek and Cudejko (2009, 2011), comprising vast parametric studies on longitudinal shear, including the effect of concentration of shear connectors above truss nodes. The numerical model employed *ANSYS* software, proved to correspond excellently with experimental results and serves subsequently as a benchmark. Among others a railway bridge with span of 63 m was investigated (Figure 1) in which the shear connection was modeled with headed stud connectors Ø 19 mm, having characteristic shear strength 91.4 kN, located uniformly in 4 parallel rows with longitudinal spacing of 400 mm.

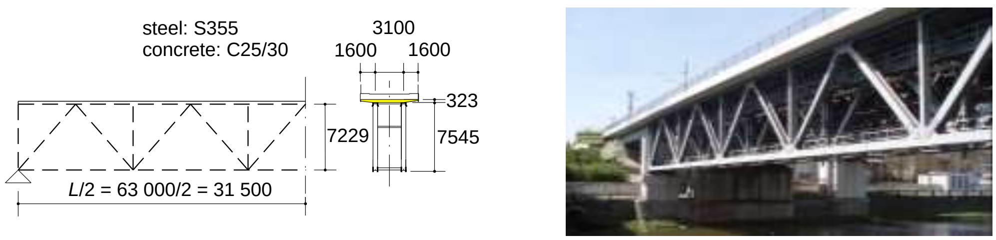

Figure 1. Bridge geometry and photo.

After commencing plasticity in the bottom chord of the truss (at approx. loading q = 270 kN/m, Figure 2) and following plastification of shear connectors (at approx. 82 kN per connector), a rapid plastic shear flow redistribution yields into truss collapse at q = 325 kN/m. For full geometrical and material data see Machacek and Cudejko (2011).

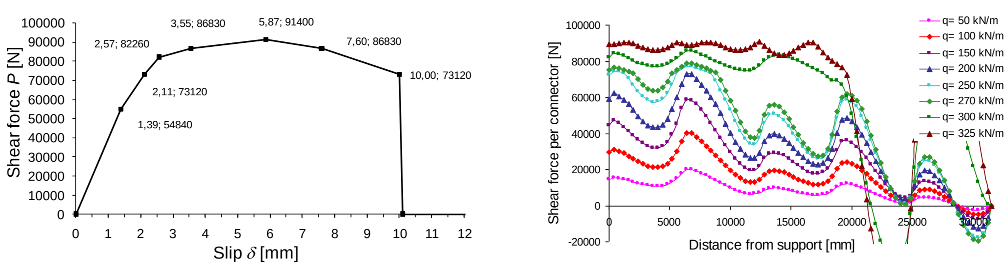

Figure 2. Load-slip diagram of one stud (Oehlers and Coughlan 1986) and shear forces for increasing uniform loading per one truss up to collapse.

Recently new studies embracing various parameters concerning steel truss chord, concrete slab, and shear connection in composite truss bridges were published by Bouchair *et al.* (2012) and Bujnak *et al.* (2013).

In this paper, the distribution of the shear flow along concrete-steel interface of composite truss bridge girders was analysed using simplified 2D elastic analysis and common “frame” software. The results were compared with 3D materially non-linear analysis and Eurocode proposals for design level of bridge loading. The following parametrical study cleared up influence of various entry data, including temperature effects, creep and shrinkage. Finally, practical recommendations were suggested.

2 SIMPLIFIED NUMERICAL MODEL

The 3D MNA (materially non-linear analysis) using *ANSYS* software and shear connectors modeled as non-linear springs is demanding; therefore the simplified 2D LA (linear elastic analysis) using common "frame" software (*SCIA Engineer*) was suggested for analysis in elastic region. The shear connectors were modelled as cantilevers sticking out from a member representing a steel truss chord, and pin connected at mid-plane to a concrete slab represented by a concrete strut (neglecting slab tension zone as recommended conservatively by Eurocode 4 for shear connection analysis) (see Figure 3). Stiffness of the cantilevers corresponds to a linear part of load-slip relationship of relevant shear connector (e.g., as shown in Figure 2 up to 55 kN). In the case of the bridge in Figure 1, the 4 parallel studs giving the same behavior were modelled as circular bars of length 305 mm with diameter of 109.64 mm. A comparison of 3D MNA and 2D LA results of longitudinal shear flow, under loading of 200 kN/m (approx. design bridge loading), together with Eurocode 4 approach, is shown in Figure 3. The 2D LA reasonably and conservatively imitates the 3D MNA, justifying its use for parametric studies of longitudinal shear in elastic phase. The Eurocode approach and other "analytical" solutions used by designers seem conservative/improper.

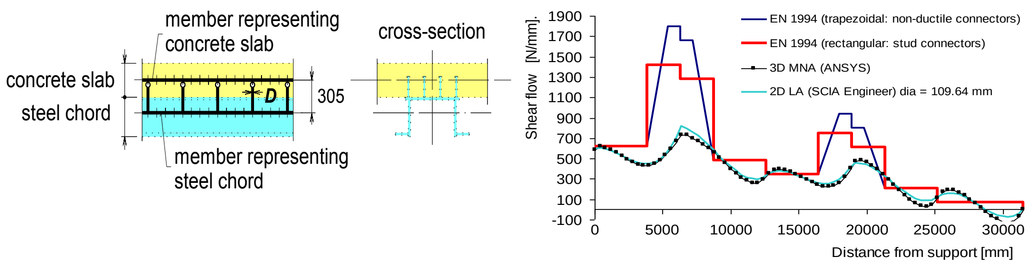

Figure 3. 2D model of shear connection and comparison of 3D MA (ANSYS), 2D LA (SCIA) and Eurocode 4-2 distribution under uniform loading 200 kN/m (approx. design loading).

3 DISTRIBUTION OF ELASTIC LONGITUDINAL SHEAR

All studies below concern a railway bridge with span of 35.2 m according to Figure 4, under EN 1991-2 classified design loading using LM71 model, with appropriate coefficients in a position giving maximal longitudinal shear. Unpropped bridge construction was considered, without supplemental dead loading (amounting ≈ 54 % of the total); for loading of one truss girder (see Figure 5). First welded studs of 19/150 mm with regular spacing of 200 mm and various number placed in parallel (1, 5, 10) were considered with load-slip relationships (Oehlers and Coughlan 1986) (Figure 5).

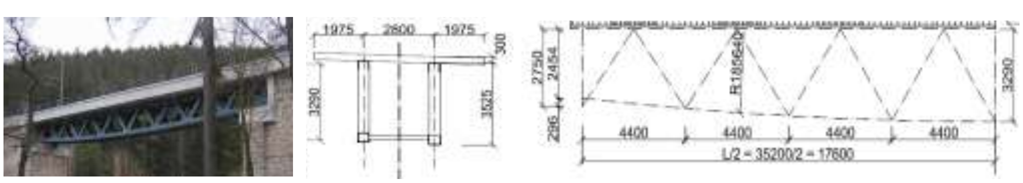

Figure 4. Photo and geometry of the bridge under investigation.

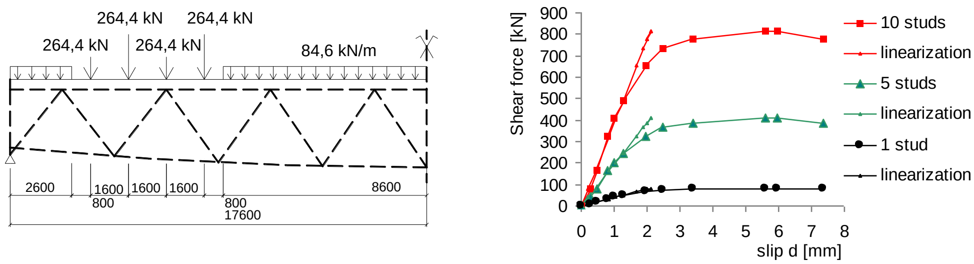

Figure 5. Traffic loading considered in the study and load-slip relationships for shear studs 19/150 mm with characteristic/design strength per one stud P = 81.6/65.3 kN.

The relationships were linearized and resulted according to Chapter 2 into cylindrical cantilevers with length of 280 mm and appropriate diameters (72, 108, 128 mm). Due to the differing number of studs, instead of shear force per connector the shear flow is monitored to show the influence (Figure 6). Results point to significant increase of shear peaks above truss nodes due to increasing shear connection stiffness.

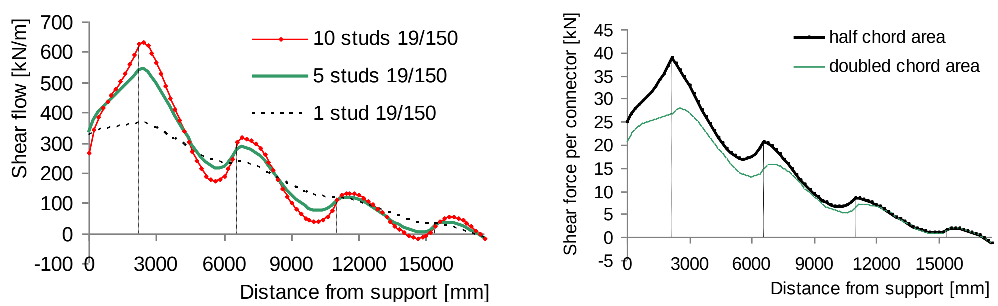

Figure 6. Effect of shear connection rigidity on shear flow (L); effect of steel chord area (R).

Influence of both area and second moment of area of the steel truss chord in case of 5 parallel studs was also investigated. Influence of the chord area is presented in Figure 6, were the area from initial value (33,500 mm^2) is half or doubled (16,750 mm^2 or 67,000 mm^2, respectively) while the chord second moment of area remains the same (4.9 x 10^8 mm^4). On the other hand, changing steel chord second moment of area and keeping the same chord area has negligible influence on shear force per connector.

With a greater amount of concrete mass connected to the steel truss, the shear flow increases and shear peaks above truss nodes become less noticeable. The study (not presented) confirms the great influence of concrete mass on shear force values. On the other hand, an aspect ratio of the slabs (width/depth) proved not to be substantial.

Temperature effects were investigated according to simplified method of EN 1991-1-5 for a constant temperature difference between concrete and steel parts only. The design temperature difference in the studied bridge at load combinations amounts to ± 9ºC (Figure 7). Obviously the result roughly corresponds to the *Eurocode 4* assumption of triangular distribution of longitudinal shear force due to temperature effects along the effective shear lag width for global analysis (b_{eff} = (0.55+0.2) x 35.2/4 = 6.6 m, while available 3.375 m), with no peaks of the shear distribution above truss nodes.

Creep effects on shear forces were studied for uniform supplemental dead loading 94.05 kN/m. Modules of hardened concrete after 28 days, 2 months and 100 years were considered. The reduction of shear per one stud is shown in Figure 7 (right), together with total creep differential influence after 100 years. Shrinkage effect corresponds to temperature effect concerning cooling of concrete slab however reduced by creep.

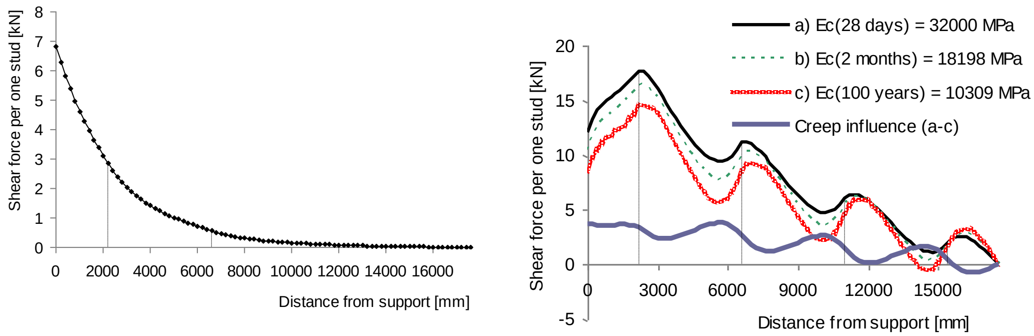

Figure 7. Effect of temperature difference of ± 9° C (left). Effect of creep (right). All effects for 5 welded studs 19/150 in 200 mm spacing.

4 DENSIFICATION OF SHEAR CONNECTORS ABOVE TRUSS NODES

A concentration of shear connectors above truss nodes in the regions of the longitudinal shear peaks is common in design practice. The optimal design requires an iteration process (Figure 8) for the bridge above. Consider the first distribution with 3 parallel studs 19/150 mm at uniform spacing of 200 mm under loading (Figure 5). First iteration of densification corresponds to the ratio of maximum to average shear force per stud along the truss in the first and second node regions, and leads to approx. 7.3 and 4.1 parallel studs (proposed within quarter distances between the nodes) at 200 mm spacing respectively. Second iteration corresponds to the same rearrangement using average shear force per stud along the truss from the first iteration, and leads to approx. 15.5 and 6.0 parallel studs at the first two nodes. Due to the increase of the shear flow above the nodes, the third iteration needs to be performed, leading to approx. 27.5 studs and 9.5 parallel studs at the first and second node, respectively (all at 200 mm spacing).

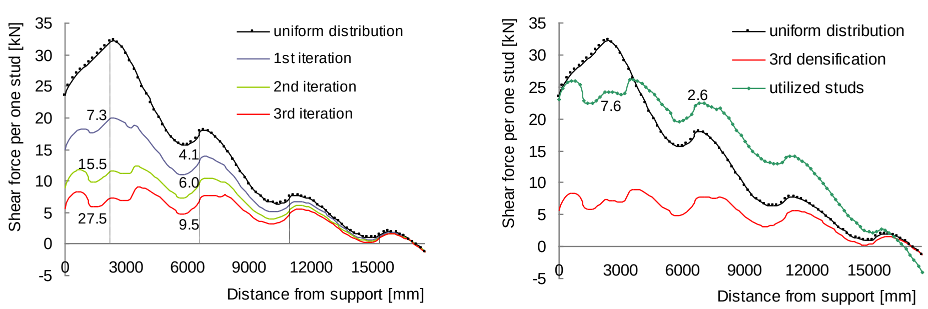

Figure 8. Optimal densification of studs (left); distribution to utilize capacity of studs (right).

With the densification process, the shear forces per connector decrease. A linear magnification of the distribution according to Figure 8 may result in an appropriate utilization of the shear stud capacity (here with respect to supplemental dead loading ≈ 0.54x48.9 = 26.4 kN along substantial truss length. Resulting distribution with 7.6 and 2.6 parallel studs above the first and second node (in 200 mm spacing) corresponds to maximum shear force in the studs 26.2 kN. All stud spacing in real design must respect Standard limit values and other effects (temperature, shrinkage).

5 CONCLUSIONS

The results of proposed 2D LA simplified model concerning elastic distribution of longitudinal shear in shear connection proved to be sufficient for both parametric studies and real bridge design. Eurocode 4 approach and usual "analytical" solutions seem to be enormously conservative. The studies resulted into following conclusions:

- Stiffness of shear connection determines the peaks of the longitudinal shear distribution: the higher the stiffness (either uniformly distributed or more concentrated above truss nodes), the higher the peaks in the distribution.
- The greater the area of steel truss chord, the lesser the shear distribution peaks (i.e., the area of gusset plates in node region is also important), while the distribution seems to be little affected by the steel chord second moment of area.
- The greater concrete slab dimensions, the greater values of longitudinal shear.
- Concentration of shear connectors above truss nodes requires an iteration procedure concerning both intensity and extent of the densification.
- Creep, temperature and shrinkage modified by creep are similar as in common plated composite steel and concrete bridges.

Acknowledgment

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