Design of Shear Connection between Steel Truss and Concrete Slab

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Abstract

Composite steel and concrete trusses used in floor and bridge structures are analyzed with respect to shear connection between a steel truss and a concrete slab. Elastic and elastic-plastic behaviour of the shear connection is studied in detail. On the basis of experimental investigation the suitable 3D and 2D analyses are presented and influence of principal parameters are studied in wide scope. While some plastic redistribution of the longitudinal shear is admissible in some cases for floors of buildings, the elastic distribution is essential for design of bridges. Distinctive peaks of the shear flow above truss nodes within elastic behaviour are numerically studied in various real bridge configurations and compared with approximate approach given in Eurocode 4. Influence of shear connectors densification above truss nodes is discussed in details. Finally some recommendations for practical design are presented.

Keywords: composite structures; composite truss; Eurocode 4; longitudinal shear; numerical analysis; shear distribution.

1. Introduction

Composite steel and concrete trusses are commonly used both in buildings and bridges for decades [1]. In the ninetieth the comprehensive research [2] resulted in design recommendations showing wide range of relevant design aspects. Concerning design of shear connection, the common plastic redistribution as in standard plate girders was suggested, provided the shear connectors are sufficiently ductile.

Such redistribution, of course, cannot be considered for an elastic behaviour of shear connection, where highly non-uniform distribution of longitudinal shear is caused by transmitting forces predominantly from truss nodes to concrete slab. Plausible explanation of distribution of the longitudinal shear between steel truss and concrete slab under concentrated longitudinal force were investigated only much later [3]. However, instead of impact of a force arising in steel truss nodes the one of a concentrated force introduced into concrete slab of a composite continuous girder due to prestressing was investigated. Results of the parametric study were introduced into Eurocode 4 [4] pointing out to possible use in design of shear connection of composite trusses.

The analysis of a composite truss behaviour both in elastic and plastic region was presented by the first author (Machacek et al. 2000; in more detail [5], comprising parametric study of floor trusses having various load-slip diagrams and investigation of densification effect of shear connectors above truss nodes. Other studies were concentrated on shear connection of composite steel and concrete bridges [5-6].

Recently an important study embracing various shear connector parameters in composite truss bridges was published [7]. Similarly other recent studies are relevant to following investigations [8-14].

Composite truss bridges are becoming required structure – e.g. in the Czech Republic only, twelve such bridges with spans between 21 and 63 m were completed during last decade (e.g. Fig. 1, Fig. 2), similarly in other countries [15].

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Current study covers principal aspects concerning distribution of the longitudinal shear both in plastic and elastic region with respect to common design. Particular attention is paid to primary parameters influencing the peaks of longitudinal shear above truss nodes in elastic region which are decisive for design of bridges (both in serviceability limit states and ultimate limit states, incl. fatigue) and always necessary for Class 3 and 4 cross sections or rigid shear connectors with respect to their limited deformation capacity, see Eurocode 4 [4].

2. Floor trusses

First, the behaviour of common floor trusses was investigated experimentally [5], testing two identical truss girders of 6 m span and using perforated shear connectors providing “full” shear connection, see Fig. 3.

Test results of both trusses together with common analytical calculation (as for plated beams) of elastic ($F_{el}$) and plastic ($F_{pl}$) capacity taking into account real geometrical and material characteristics and full composite action according to Eurocode (EN 1994-1-1) are presented in Fig. 4.

Therefore, the tests justified common simple calculations for floor composite trusses. More precise numerical 3D analysis using ANSYS software package clarified the entire process of longitudinal shear distribution along an interface between steel and concrete parts of composite trusses. Truss geometry was taken according to Fig. 5, for details see [5].

Bottom chord and web bars were modelled by beam elements with appropriate cross section (BEAM24) and upper chord was composed of shell elements (SHELL43). Special 3D reinforced concrete elements (SOLID65) were used for the concrete slab. Shear connection was modelled by non-linear springs located uniformly in distance 100 mm along span and
placed between the steel chord and the concrete slab. Two-node spring element COMBIN39 was employed which makes possible any nonlinear relation between force and extension to model correctly shear forces in direction of girder axis. No uplift effects were considered in the analysis.

Typical results of extensive parametric study are presented only.

For full shear connection (i.e. capacity of shear connection is higher than truss flexural strength) the shear forces in shear connection (placed by 100 mm) are shown for one half of the truss in Fig. 6. The curves show values for load steps $q$ increasing up to the numerical collapse value (given by maximal value in the caption). Horizontal axis gives the distance from support (truss nodes are in distances 2400, 4800 and 6000 mm).

While distinctive peaks of the shear in low loadings (elastic region) are evident a later redistribution is obvious. This is even more pronounced in partial shear connection (i.e. where shear connection decides about resistance of the composite truss), see Fig. 7.

A question arises about influence of densification of shear connection capacity/rigidity above truss nodes, where the shear is predominantly transmitted, see Fig. 8.

Taking into account the above results, such a concentration has sense mainly to eliminate the peaks of the shear above truss nodes in the elastic region of behaviour. Such measures are required especially in bridges, before redistribution takes place.

Vast parametric studies resulted into two interesting knowledge. First concerns concentration of shear connection rigidity above truss nodes. More shear connectors transmit higher shear values; on the other hand however, the greater shear rigidity attracts more shearing above the node – similarly as known e.g. from distribution of moments in continuous girder with haunches. This effect for the same truss is illustrated in Fig. 9 for the elastic resistance loading 38.2 kN/m. Triple densification of shear connectors within quarter of node distance – marked in thick line, is presented only.
3. Bridge trusses

More attention was applied to the longitudinal shear in the elastic region of behaviour (corresponding to lower loading, before plastic redistribution of shear takes place). Elastic distribution is usually required in design of bridges for design loading (EN 1994-2 tolerate 10% plastic redistribution in given segment).

Instead of 3D ANSYS analysis, much simpler 2D common frame elastic analysis proved to give sufficiently good results. SCIA Engineer software was used, modelling shear connection as short cantilevers between the steel truss and the concrete slab. Only the first linear parts of the stress-strain relationships for both steel and concrete (Young’s modulus $E$, $E_{cm}$) were used in this analysis. Welded headed studs as the most common shear connectors were employed with relevant load-slip diagrams, see e.g. Fig. 10 for ø19 mm studs with ultimate strength of $f_u = 450$ MPa [16].

While broad spectrum of the diagram linearizations were studied, again use of the first linear part proved to be sufficient for design loading of bridge structures. The 2D model was compared with 3D ANSYS solution for the railway bridge in accordance with Fig. 11. The circular cantilevers representing the studs according to Fig. 10 needed the diameter ø109.64 mm, length 305 mm and were sticking out from steel flange axis and pin connected at midplane of concrete slab represented by a concrete strut (neglecting slab tension zone as required by Eurocode 4 [4]), see Figure 12.
The comparison of the longitudinal shear distribution for simplified frame 2D SCIA and 3D ANSYS analysis is presented in Fig. 13. The loading of the bridge (for one truss) in the study was taken as uniform $q = 200$ kN/m, which is slightly above the design bridge loading. The simplified analysis reasonably imitates the ANSYS results, while conservativeness (higher values in shear peaks) of simplified elastic solution is obvious.

![Fig. 13. Comparison of both analyses and Eurocode 4 approach](image)

Eurocode 4 [4] distribution of the shear flow for loading 200 kN/m in the peaks is also shown for both non-ductile shear connectors (inclined, trapezoidal distribution) and ductile ones (rectangular distribution) in Figure 13. According to EN 1994-2 approach (cl. 6.6.2.3) the effective width available ($b_{eff} = 3.15 \text{ m} < L/4 = 15.75 \text{ m}$) and relevant value $e_d = 1500 + 2 \times 148.5 = 1797 \text{ mm}$ give the maximum shear flow due to nodal local force $V_{L,Ed}$ acting at the respective node using trapezoidal shear distribution (in case of non-ductile shear connectors) as

$$v_{L,Ed,max} = V_{L,Ed} \left( e_d + b_{eff} / 2 \right)$$  \(1\)

or using rectangular distribution (ductile headed studs) as

$$v_{L,Ed,max} = V_{L,Ed} \left( e_d + b_{eff} \right)$$  \(2\)

The longitudinal concentrated local nodal force $V_{L,Ed}$ due to difference of upper truss chord nodal forces $\Delta N = (N_{right} - N_{left})$ results from equilibrium condition of the composite truss cross section transmitting axial force $\Delta N$ and moment $\Delta Ne$ as

$$V_{L,Ed} = \Delta N - \Delta Ne \frac{A_d}{I_d / z_d} = \Delta N \left[ \frac{A_{rc}}{A_i} - e(A_i / A_{rc} / e) \right]$$  \(3\)

where $A_i$ and $I_i$ are the transformed area and second moment of area, respectively, of the uncracked composite section in “steel units”; $A_d$ and $A_{rc}$ are the cross-sectional areas of the truss flanges and concrete slab, respectively, in “steel units”; $e$ is the distance from centroid of the area $A_i$ to the line of the force $\Delta N$ (positive downwards); and $z_d$ the distance from centroid of the area $A_i$ to the centroid of the area $A_{rc}$, positive when downwards.

It follows from more detailed study that Eurocode approach is always conservative and the more conservative the less rigid the shear connectors are. Agreement of FEM and Eurocode approach is always better at lower loading (thanks to similar initial stiffness of the shear connection).

In bridges, with the elastic design of shear connection, the concentration of shear connectors above truss nodes to cover shear peaks is common. Geometry of densification [17] of the bridge shown in Fig. 11 is given in Fig. 14. Parametric study with various shear connector arrangement resulted into optimal arrangement to be within a quarter of node distance ($d/D = 0.25$).

![Fig. 14. Densification of shear connectors above truss nodes](image)
An example with the quadruple densification of connectors within quarter of node distance is shown in Fig. 15.

Fig. 15. Influence of quadruple densification of shear connectors within quarter of node distance under uniform loading of 200 kN/m.

The results lead to similar conclusions as presented above for floor trusses (Fig. 9). Instead of a quarter about half loading of the concentrated connectors only was achieved as shown in Fig. 15, because the total shear transmitted in the densified area nearly doubled.

Optimal concentration of shear connectors above truss nodes is related to stiffness of upper truss steel chord and possibly gusset plates. Results of the parametric study concerning this stiffness for a bridge without gusset plates (Fig. 16) are illustrated in Fig. 17.

Fig. 16. Road bridge without gusset plates and photo of a modified bridge with stiff support blocks

The span of the truss is 21 m and steel members are from flats only [mm]: upper flange 250x20, diagonals 250x40, bottom flange 300x40, the full shear connection is arranged through headed studs Ø19 mm ($f_u = 340$ MPa) located in 3 parallel rows in distance of 200 mm.

Fig. 17. Influence of upper steel chord thickness

The elastic distribution of shear forces under loading of 75 kN/m depends strongly on upper steel chord thickness $t$ [mm]. The thinner chord flange the higher node shear peaks must be expected. A great deformation of very thin chord eliminates the transfer of the shear force, which is then transmitted by the connectors directly at the nodes only.

Similar results were received from the elastic analysis of the railway composite bridge shown in Fig. 18.

Fig. 18. Railway bridge with span of $L = 35.2$ m

The influence of steel chord stiffness was investigated using elastic 2D analysis for design bridge loading LM71 in central position (acc. to Eurocode 1, see Fig. 19). Shear connection in these studies was modelled for 5 parallel studs with $\varnothing 19$ mm ($f_u = 360$ MPa) in longitudinal spacing of 200 mm.
The actual stiffness (second moment of area) of the upper steel chord was lowered to half and doubled as shown in Fig. 20. Again, the less stiff upper steel chord leads to higher shear peaks above truss nodes.

On the other side, wider or thicker concrete slab leads to greater shear flow, however with less pronounced shear peaks due to greater concrete slab stiffness. The influence of rearranging concrete slab thickness is presented in Fig. 21.

Other parametrical studies of this bridge on longitudinal shear elastic distribution concerned influence of creep, shrinkage and temperature effects. For example, lowering temperature of the concrete slab with respect to steel truss by $9^\circ$ C as required in this case by Eurocode 1 resulted in shear forces shown in Fig. 22. Such distribution correspond well with Eurocode 4 assumption of triangular distribution of longitudinal shear force due to temperature effects along the effective shear lag width for global analysis ($b_{eff} = (0.55+0.2) \cdot 35.2/4 = 6.6$ m, while available $3.375$ m), with no peaks of the shear distribution above truss nodes.
Conclusions

The paper deals with the longitudinal shear in shear connection of both floor and bridge composite steel and concrete trusses. Numerical elastic simplified 2D analysis and 3D elastic-plastic analysis up to shear connection collapse are proposed, described in some details and experimentally verified.

Longitudinal shear in floor composite trusses may be analyzed plastically provided the Eurocode 4 [4] conditions are met (i.e. Class 1 and 2 cross sections, shear connectors are ductile). In results the full redistribution of longitudinal shear may be supposed in simple design in spite this is not achieved for full shear connection, see Fig. 6.

In composite truss bridges the longitudinal shear is to be analyzed elastically. 2D simplified frame design for analysis of pure longitudinal shear proved to give liable results. Eurocode 4 approach describing distribution of longitudinal shear in shear connection due to local effects is very conservative.

Investigation of the longitudinal shear flow distribution in the elastic region of its behaviour pointed to importance of stiffness both steel truss chord and concrete slab. The less stiff chord flange the higher node shear peaks above truss nodes must be expected. Wider or thicker concrete slab leads to greater shear flow, however with less pronounced shear peaks due to greater concrete slab stiffness.

Common concentration of shear connectors above truss nodes has to be designed with caution. More shear connectors transmit higher shear values but greater shear rigidity attracts more shearing above the node, thus suppressing the concentration effectiveness.

Suitable extent of shear connectors densification above truss nodes requires optimization process (taking into account stiffness ratio of steel chord, concrete slab and shear connection) but appropriate densification within quarter of node distance seems to be optimal for majority of trusses.

Effects of temperature and shrinkage modified by creep are similar as in common plated composite steel and concrete bridges and may be considered according to Eurocode 4.

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