Strengthening of a Composite I-girder Bridge by Trusses Introducing Box-Action

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Abstract. The increased amount of traffic and the increasingly heavier loads on the road network push the existing infrastructure to its design limit. Bridges, which are an important part of the road network, need to be adopted to the new traffic demands regarding both the load capacity and the fatigue limit state, FLS. Steel-concrete composite bridges, with twin steel I-girders, is a common bridge type in the Nordic countries. These bridges are often designed using beam models, assuming that the concrete deck is a statically determinate structure supported on the two steel girders in the transversal direction. This assumption implies that the most loaded girder can sometimes be subjected to even more than 100% of an eccentric load, e.g., the traffic loads in the design codes. If the girders are strengthened to be able to share the eccentric loads more equally, it would have a significant impact on the load capacity, especially for the fatigue limit state. By introducing horizontal trusses between the bottom flanges of the girders, making the cross-section act more like a box-girder, the torsional stiffness will increase so that the girders will share the eccentric loads more equally. The bracing system of the trusses can be designed in different shapes, each of them with pros and cons for the existing bridge structure. In this paper, the effects from different shapes of the bracing are evaluated of a single span I-girder composite bridge. The increased torsional stiffness and the change of the internal shear flow will increase the load capacity of the steel girders.

Keywords: bridge; steel-concrete composite; I-girder; case study; horizontal trusses; torsional stiffness; strengthening; composite bridges

1. Introduction

In the Nordic countries, a common bridge type is the twin steel I-girder bridge with a composite concrete deck slab. The cross-section of these bridges is not as torsional stiff as a corresponding box-girder, which has a closed cross-section. By installing a horizontal truss between the bottom flanges, a semi-box cross-section can be achieved. This cross-section will gain some of the benefits from a closed cross-section, as in a composite steel-concrete box-girder, with an increased torsional stiffness, see Fig. 1.

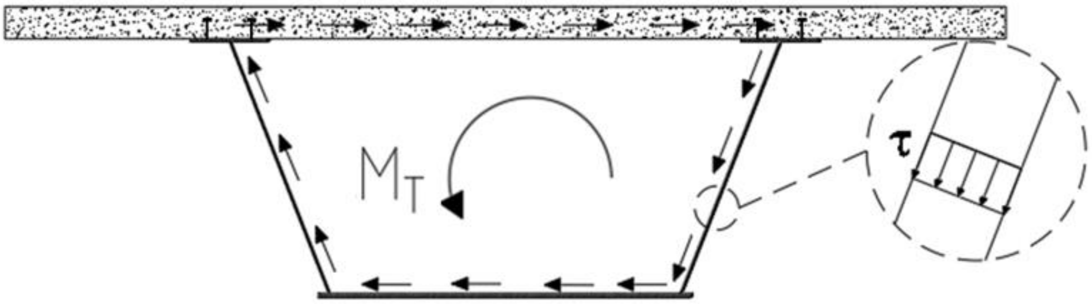

Fig. 1 Shear flow for a closed cross-section in a steel-concrete composite box-girder.

The impact on the load distribution, from eccentric traffic loads, between the two I-girders have earlier been studied by Vestman et al. (2018) and Ivanov et al. (2020). The result in these studies indicate that the implementation of a horizontal truss between the bottom flanges increases the load distribution between the girders, which lowers the bending stresses in the most loaded girder. The decreasing of the bending stresses from traffic loads, will in terms of bending moment- and shear capacity, be increased for the steel girders.

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On the other hand, for this type of bridges the load effects from the dead loads are quite large. This means that the decreased stresses from the eccentric traffic loads will not have the same impact on the ultimate limit state, ULS, as the impact on the stresses in the fatigue limit state, FLS. Other studies about the use of horizontal bracing system in steel girder bridges shows the benefits of different truss shapes. In both Fan and Helwig (1999) and Rageh et. al. (2012) the effects of horizontal trusses between the upper flanges in box-girders during construction and casting, are shown. In both studies, the results indicate, that the shape of the bracing system in many cases is not the most important factor. The same conclusions were drawn in the studies by Vestman et al. (2018) and Ivanv et al. (2020). It can however have an impact on other effects than just the load distribution of eccentric loads for the global bending. This needs to be considered in the design if horizontal trusses are used, e.g., if the new load distribution will increase the normal forces in the cross-frame members.

This study includes further numerical investigations regarding the use of post-installed bracing systems between the lower flanges in twin I-girder composite bridges. In this study the authors considered additional shapes of the trusses, compared to earlier studies. Also, the impact on existing structural parts as shear studs, support- and internal cross-frames are investigated. The Yxlö Bridge in Sweden was chosen as a case study since the bridge has been used in another study regarding post-installation of shear connectors. The composite behavior between the concrete slab and the steel girders is essential for the horizontal trusses to be able to form a semi-box girder with some of the benefits of a closed cross-section. In Tjernberg (2022) the effects from post installed shear connectors were theoretically investigated for the Yxlö Bridge. The results showed a substantial increase of the load capacity of the steel girders, by creating composite action with post-installed shear connectors.

2. The Yxlö Bridge

The Yxlö Bridge in Sweden is a simply supported bridge in one span of 31 meters over the Yxlö channel south of Stockholm, see Fig. 2. The bridge was built in 1961 and consist of two steel I-girders with a concrete deck on top of the girders. The bridge has two traffic lanes, one in each direction, and a free width just over 7 meters. The bridge is designed as a non-composite bridge which means that shear connectors was not designed to transfer a shear flow between the concrete and the top flange of the girders. Only a small number of steel-stirrups were used to prevent separation of the girders and the deck. This type of bridges, where the concrete is not designed to be in composite action with the steel girders was common up to the 1980's in Sweden.

Fig. 2 The Yxlö Bridge (The Swedish Transport Administration, n.d.)

The detailed geometry of the bridge and its cross sections are presented in Fig. 3, Fig. 4 and Table 1. The cross-section used in the FE-analyse is an equivalent cross-section where the concrete deck is horizontal instead of the with the 5 % superelevation as the real bridge section has. This has only a minor impact on the result, and it is neglectable for the purpose of showing the effects of different truss-shapes. In Fig. 3 the two girders are denoted as girder 1 and 2. The bridge has cross bracings over the supports and two internal cross bracings located 9,8 meters from the supports.

The concrete deck slab has a thickness of 233 mm between the girders and decreases to around 150 mm at the edge beams. The concrete quality of the slab is K35 (~C35/45) with a characteristic compressive strength, f_{ck}, of 35,5 MPa and a modulus of elasticity, E_{cm}, of 34 GPa.

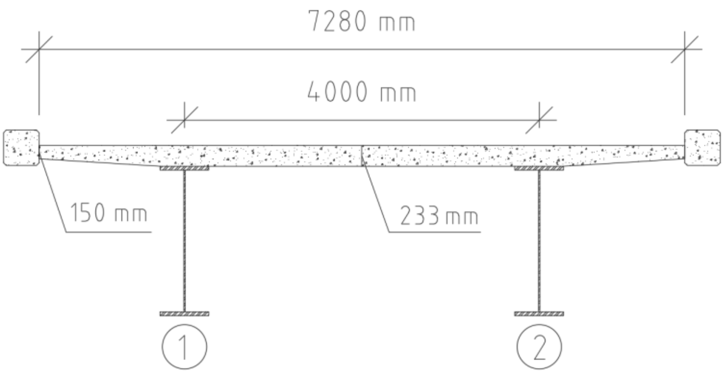

Fig. 3 The equivalent cross-section of the bridge used in the analysis

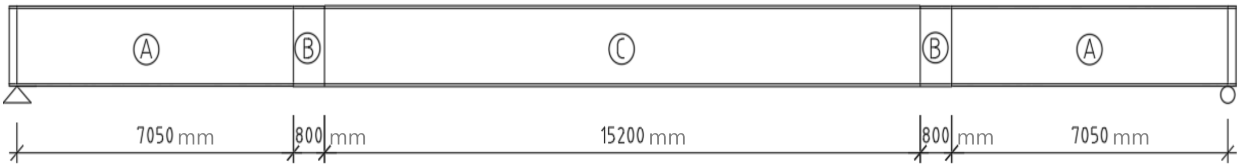

Fig. 4 Elevation of the steel girders

Table 1. Steel girder cross-section properties

Steel sections		A	B	C
Top flange	Width [mm]	550	550	550
	Thickness [mm]	40	40	55
Web	Height [mm]	1600	1600	1600
	Thickness [mm]	15	15	15
Bottom flange	Width [mm]	550	550	550
	Thickness [mm]	40	55	55

Note: The Youngs modulus of the steel, E_s, is assumed to be 210 GPa.

3. Finite Element Model of the Yxlö Bridge

In this study the FE-models are based on shell elements for the steel girders and the concrete slab, and beam elements for the cross bracings and horizontal trusses, see Fig. 5.

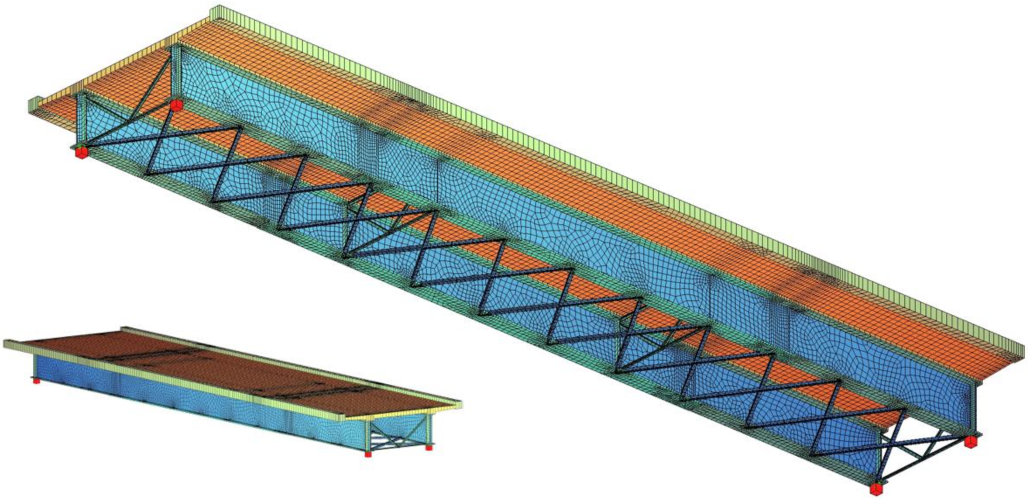

Fig. 5 FE-model showing the horizontal truss with the shape: X-truss

The steel-concrete interface is modelled with rigid connection elements to capture the theoretical behavior of a composite section, see Fig. 6. The commercial FE-software SOFiSTiK was used for the analysis. No consideration regarding the influence of the substructure has been taken since it has no significant impact on the results from vertical loads on a simply supported structure. The superstructure is thus modelled with nodal supports at the position of the bearings. The arrangement of the bearing system is with one fixed-, one unidirectional- and the other two as multidirectional bearings. This for the system to be determinate.

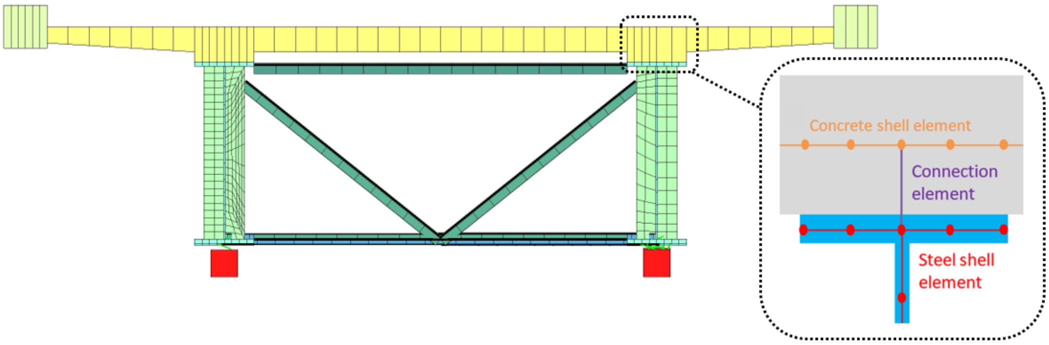

Fig. 6 Bridge cross section with a schematic illustration of the steel-concrete interface

The horizontal trusses were modelled with five different shapes and one additional alternative where only horizontal struts between the flanges were used. A squared hollow section, SHS, with the dimensions 100x100x4 mm was used for the horizontal trusses in all models. All six shapes are presented in Fig. 7 along with the original design of the cross-bracing without horizontal trusses. The different models are denoted follows, counted from top left in the figure: No truss (original), Horizontal, K-truss, X-truss, D-truss + horizontal, D-truss and Z-truss.

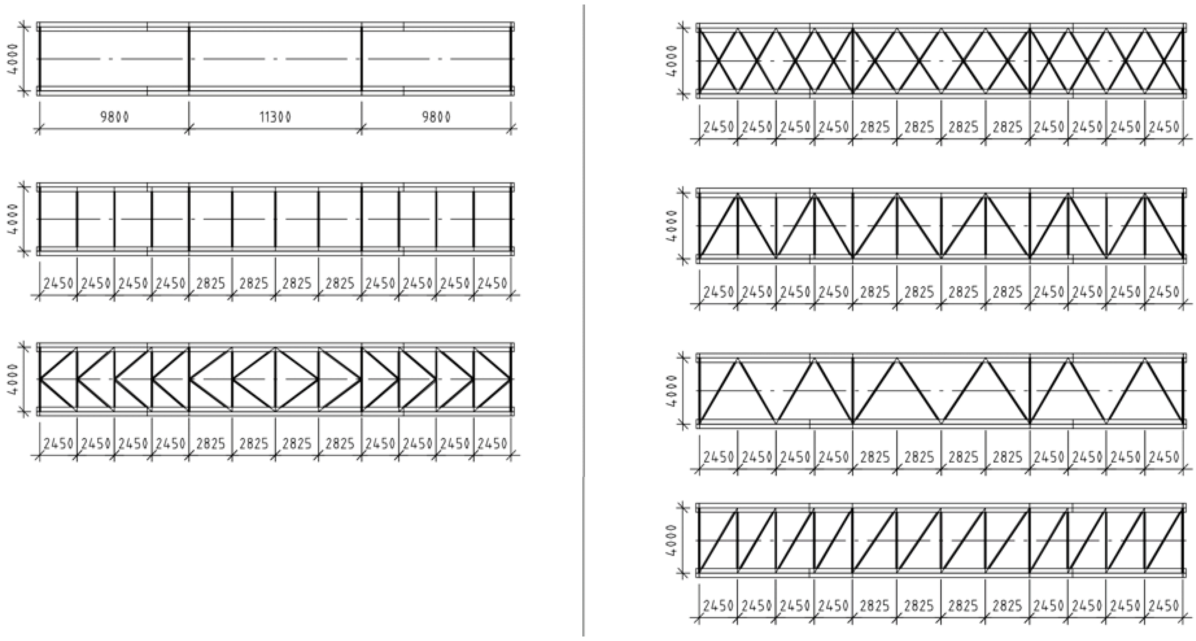

Fig. 7 Layout and shapes of the original design and the six different bracing systems

Two load cases were used in this study: one load case with an eccentrically located load and one load case with the load placed symmetrically at the middle of the deck. The two load cases will be called centric and eccentric. The analyzed load is the Fatigue Load Model 3, FLM3 from the Eurocode, EN 1991-2 (2005). The axle loads for FLM3 are 120 kN. The eccentricity from the center line of the bridge to the center of the axles for load cases and their longitudinal position is shown in Fig. 8.

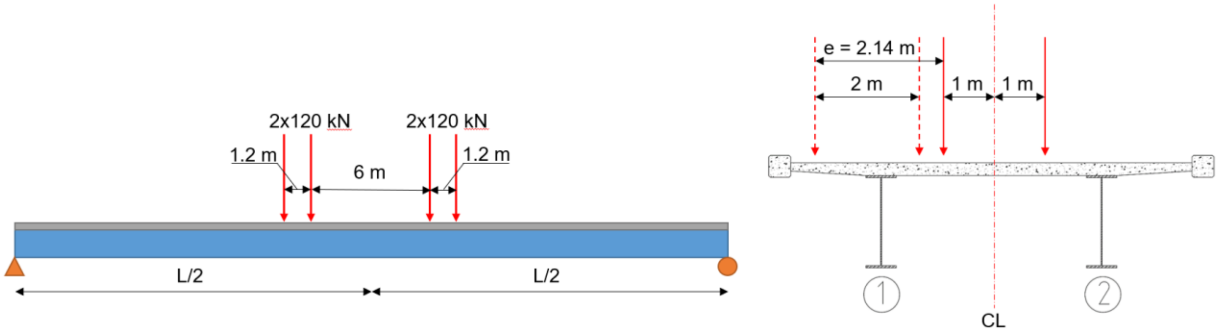

Fig. 8 Load position for the two load cases

4. Results

The deflections and the membrane stresses (σ_m) and the lateral bending stresses(σ_b) from the two load cases and the seven models are presented in Table 2 and Table 3. The deflection is taken at the middle of girder 1 and 2 and the stresses are taken in the middle of the bottom flanges at the same location of the girders. In Table 2 the results for both vertical-, δ_v, and transversal-, δ_t, deflection is presented for both girders. The sum of the vertical deflection of the two girders, $\delta_{1,v} + \delta_{2,v}$ is also presented. In Table 3 the corresponding values for eccentric load case, as for centric load case in Table 2, are presented

Table 2. Deflection at mid sections for load case: centric

Type	$\delta_{1,v}$ [mm]	$\delta_{1,t}$ [mm]	$\delta_{2,v}$ [mm]	$\delta_{2,t}$ [mm]	$\delta_{1,v}+\delta_{2,v}$ [mm]
No truss	7,0	0,1	7,0	0,1	14,0
Horizontals	7,0	0,0	7,0	0,0	14,0
K-truss	7,0	0,0	7,0	0,0	14,0
X-truss	7,0	0,1	7,0	-0,1	14,0
D-truss + horizontals	7,0	0,0	7,0	0,0	14,0
D-truss	7,0	0,1	7,0	0,1	14,0
Z-truss	7,0	0,0	7,0	0,0	13,9

Table 3. Deflection and stress at mid sections for load case: eccentric

Type	$\delta_{1,v}$ [mm]	$\delta_{1,t}$ [mm]	$\delta_{2,v}$ [mm]	$\delta_{2,t}$ [mm]	$\delta_{1,v}+\delta_{2,v}$ [mm]	$\sigma_{1,m}$ [MPa]	$\sigma_{1,m+b}$ [MPa]	$\sigma_{2,m}$ [MPa]	$\sigma_{2,m+b}$ [MPa]	$\sigma_{1,m}+\sigma_{2,m}$ [MPa]
No truss	12,8	6,1	1,2	6,1	14,0	37,0	40,0	3,4	6,3	40,3
Horizontals	12,8	6,1	1,2	6,1	14,0	37,3	40,6	3,4	6,3	40,7
K-truss	10,4	2,3	3,7	2,3	14,0	29,5	29,6	10,6	10,6	40,0
X-truss	9,9	1,4	4,1	1,2	14,1	28,7	29,4	11,8	12,6	40,5
D-truss + horizontals	10,8	2,6	3,3	2,5	14,1	30,8	32,2	10,5	12,0	41,3
D-truss	10,8	2,6	3,3	2,5	14,0	31,0	31,4	9,4	11,4	40,4
Z-truss	11,1	3,1	2,9	3,1	14,0	32,1	32,3	8,4	8,8	40,5

The normal forces in the members of the cross bracing located x= 9,8 meters from the support are presented in Table 4. In Fig. 9 the cross bracing is illustrated with the index of each bar member and the arrows indicates the positive direction of the normal force in each member.

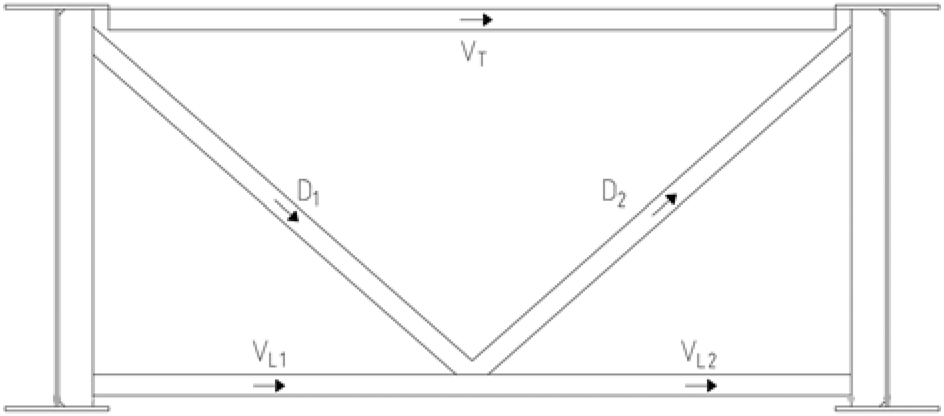

Fig. 9 Internal cross-frame with numbered bar-member

Table 4 Normal forces in the internal cross-frame at x = 9,8 m for the load case: eccentric

Type	D_1 [kN]	D_2 [kN]	$V_{L,1}$ [kN]	$V_{L,2}$ [kN]	V_T [kN]
No truss	-2	2	2	-2	-5
Horizontals	-2	2	2	-2	-5
K-truss	-42	42	37	-39	-5
X-truss	-48	48	31	-43	-5
D-truss + horizontals	-35	35	15	-40	-6
D-truss	-36	36	15	-40	-6
Z-truss	-28	28	-7	-51	-6

The shear flow from the eccentric load at the steel concrete interface of girder 1 is presented in Fig. 10 for each of the seven models. Also presented in the figure is the longitudinal load position of the axles. To clarify the difference between the model cases a segment, at x-coordinate 29-30 meters, of the shear flow diagram in Fig. 10 is shown in Fig. 11.

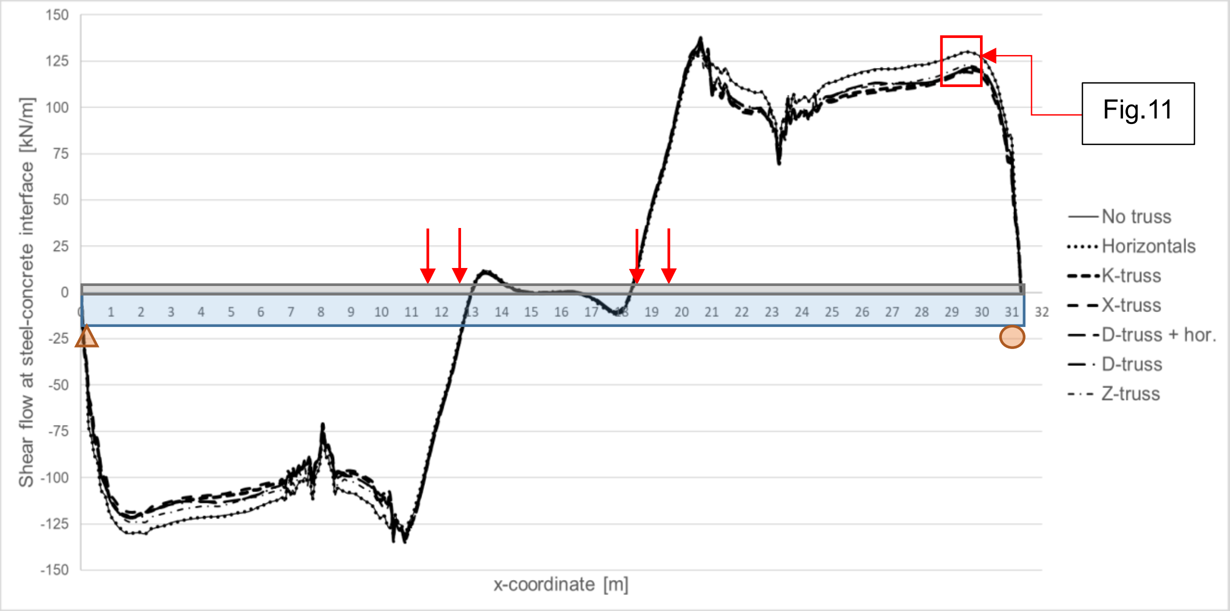

Fig. 10 Shear flow at steel-concrete interface along girder 1 for the eccentric load case

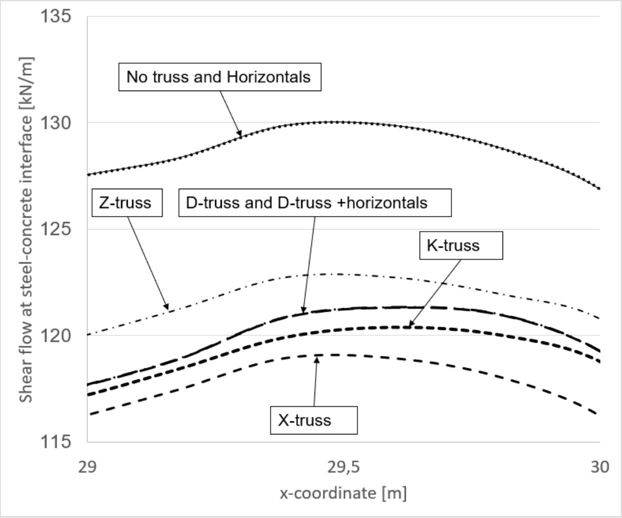

Fig. 11 Detail view of Fig. 10

5. Analysis

As the results from the centric load case show, the bridge models behave symmetrical. The deflections presented in Table 3 indicates that no truss shape, with SHS 100x100x4 mm, has significantly increased the total bending stiffness of the cross section. The X-truss would by its shape give some increase of the stiffness. In this case however, the lack of additional web stiffeners at the location of the truss-flange connection is limiting the contribution from the truss to the global stiffness of the cross-section. The total amount of deflection for the two girders is by that identical for all the cases.

The stresses in Table 3 indicates that the shapes of the trusses have some impact on the load distribution between the girders. The difference in the stress level, at the analyzed section, is however small between the truss-shapes. As for the deflections the sum of the stresses in girder 1 and 2 is almost identical between the analyzed models. If the load effects are represented by the proportion of deflection or stress in girder 1 compared to the sum of the deflections or stress in girder 1 and 2, the following table can be used to evaluate the impact from the different trusses.

Table 5 Comparison of the load effect distribution

Type	$\delta_{1,v} / (\delta_{1,v}+\delta_{2,v})$ [-]	$\sigma_{1,m} / (\sigma_{1,m}+\sigma_{2,m})$ [-}
No truss	0,91	0,92
Horizontals	0,91	0,92
K-truss	0,74	0,74
X-truss	0,71	0,71
D-truss + horizontals	0,77	0,75
D-truss	0,77	0,77
Z-truss	0,79	0,79

From the resulting normal forces in the cross-bracing it can be noticed that the implementation of a horizontal truss, except for the case with only horizontals, will change the shear flow and thus also the member forces in the existing structure. The load used in this analysis is used in design for fatigue verifications. Nevertheless, the increase of the normal forces in the cross-bracings, from 2 kN up to almost 50 kN for this load model, indicates that a verification of the existing structural elements is essential when implementing box-action in a twin I-girder composite bridge.

The impact on the shear force distribution can be evaluated from the resulting shear flow diagram, Fig. 10, which shows the shear flow at the steel-concrete interface. The detailed view in Fig. 11 indicate that the maximum decrease of the shear force, or the best distribution of the load between the girders, is with the horizontal x-truss. The shear flow between the steel and the concrete is decreased from 130 kN/m to 118 kN/m, a difference of 9%, which can be compared to the 22% difference when deflections or stresses are compared, see Table 5. This is expected, since even for a closed box girder with eccentric loading (where the deflections of both the left and right web are almost the same) the webs will have substantially different shear forces. This is since the webs will get an additional contribution of the total torsional moment from eccentric loading acting on the cross section.

6. Conclusions

The main purpose of the study has been to further analyze the impact of a horizontal bracing system on the existing structure. The bracing system consists of trusses between the bottom flanges and has theoretically been investigated on an existing I-girder composite bridge. By implementing horizontal trusses, the overall behavior of the structure will be changed to a box-action behavior instead of the twin girder system. The result from this study has confirmed a more equal load distribution between the girders. In addition to these results the reduction of shear force and additional normal forces in the internal cross bracings have been analyzed. The concept is however dependent on composite action between the steel girders and the concrete deck, which could also be obtained for existing bridges by e.g., the use of post-installed coiled sporing pins, see also Hällmark (2018) and Tjernberg (2022).

Based on the result from this study, regarding adding horizontal trusses on an existing twin I-girder composite bridge, the following conclusions can be drawn:

- Any shape of the studied horizontal trusses is approximately equally efficient in distributing an eccentric load between the girders, except the shape with only horizontal members.
- Both with and without trusses the ratios of deflections and stresses between the girders for eccentric loading in the two girders are similar.
- The impact from the horizontal truss on the shear force distribution is more limited than the impact on the bending stresses, due to the nature of the shear force distribution for a box-section.
- Additional checks are needed for internal members, like the cross bracings between the girders, when a horizontal truss is added. In this case an increase of around 45 kN (25 MPa).
- In contribution to post-installed shear connectors the horizontal truss could increase the load capacity or at least increase the fatigue limit for existing I-girder bridges with a composite concrete deck.

Acknowledgments

The research presented in this paper was financially supported by: the Development Fund of the Swedish Construction Industry (SBUF), the Swedish Transportation Administration (BBT), the Ramboll Foundation and the Finnish Transportation Infrastructure Agency (Väylävirosta).

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