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Transversal Shear Force in the Shear Connection of Twin-Girder Composite Bridges – Open vs. Semi-Closed Bridge Cross-Sections

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ABSTRACT

Steel-concrete composite bridges are commonly designed with full composite action between the steel girders and the concrete deck to enhance structural efficiency and durability. This composite action is achieved through shear connectors, which transfer shear forces and ensure that both materials act as a single unit. While full composite action is preferred, partial composite action may be sufficient in certain cases, depending on interlocking effects between steel and concrete. One strategy to improve the performance of composite bridges is the implementation of horizontal trusses between the lower flanges of the steel girders, which enhance load distribution and lateral stability.

Although previous research has investigated the effects of horizontal trusses on global load distribution, their influence on shear force distribution, particularly at shear connectors, remains largely unexplored. Studies on monorail track beams indicate that transverse shear forces significantly affect shear connectors, reducing their capacity and altering failure mechanisms. A similar effect may occur in composite bridges with twin girders and horizontal trusses.

This paper presents a case study of a single-span steel-concrete bridge in Sweden, examining the impact of a torsional rigid structure with a semi-closed cross-section on local shear flow distribution. The study also investigates how shear connector rigidity affects force distribution along the steel-concrete interface.

Key words: bridge, case study, composite action, horizontal truss, shear connectors, shear distribution, steel-concrete, strengthening, torsional stability.

1. INTRODUCTION

Steel-concrete bridges can be designed either with or without full composite action between the steel girders and the concrete deck. The option with full composite action is the most commonly used approach when designing new steel-concrete bridges, as it maximizes structural efficiency and durability. In composite bridges, the steel and concrete components work together as a single structural unit, significantly improving the bridge's stiffness and load-bearing capacity. This composite action is achieved through shear connectors, which are typically welded studs or other mechanical fasteners placed along the interface between the steel girders and the concrete deck. These connectors transfer shear forces, preventing slip and ensuring that both materials act in unison under loading, ultimately enhancing the bridge's overall performance and service lifetime. In contrast, in non-composite bridges, no interlocking between the steel and concrete elements is assumed. Leading to lower stiffness and reduced structural efficiency. However, studies and experimental tests have shown that unintended interlocking effects caused by friction or other mechanical interactions between steel and concrete may be sufficient to provide partial composite action under certain load levels [1]. The degree of composite action in a bridge significantly influences its structural behaviour, particularly in terms of bending resistance, deflections, and fatigue resistance [2]. While full composite action is generally preferred in new bridge designs, the potential benefits of partial composite action in certain situations require further investigation to optimize design efficiency and material usage.

Steel-concrete composite bridges are widely used in modern infrastructure due to their structural efficiency, durability, and cost-effectiveness. A critical aspect of their design is ensuring adequate bending capacity, stiffness, and stability under various loading conditions. One structural strategy to enhance the performance of such bridges is the implementation of horizontal trusses between the lower flanges of the steel girders [3].

These horizontal trusses typically consist of diagonal and horizontal members that connect the lower flanges, or lower part of the web, of the longitudinal steel girders. They are usually made of steel profiles or tubular elements and function by creating an integrated structural system that reduces deformations and enhances lateral stability [4]. The trusses also contribute to a more uniform load distribution between the girders and help mitigate torsional effects that may arise from asymmetric loading, such as uneven traffic loads and wind pressure [5]. The positive impact of horizontal trusses on the global load distribution between the longitudinal steel girders has been studied in previous research [6]. However, current research on the impact of horizontal trusses on shear force distribution remains limited. While the influence of horizontal trusses on longitudinal shear flow distribution has been observed, studies focusing on local effects, particularly on shear connectors, are scarce.

A related study on monorail track beams [7] highlighted that the effects of transverse shear forces on shear connectors remain largely unexplored, necessitating further research. The study examined the shear performance of stud connectors subjected to bidirectional shear forces through modified pushout tests and finite element analyses (FEA). The results demonstrated that transverse shear forces significantly reduced the shear capacity and stiffness of the studs. Additionally, transverse shear altered the failure modes at the stud root and increased the damage range in the surrounding concrete. Numerical simulations were validated against experimental data, confirming key aspects of load-slip behaviour and failure mechanisms. Based on these findings, a strength reduction factor was proposed to account for the presence of transverse shear forces, providing valuable insights for refining design guidelines for monorail track beams.

For steel-concrete composite bridges with a twin-girder system where a horizontal truss is implemented between the lower flanges, a similar effect could potentially occur at the transverse cross frames connecting the two girders. At these locations, torsional moments induced by eccentric loading would be redistributed between the girders, leading to a transverse shear flow that acts in addition to the longitudinal shear flow on the shear connectors. This combined shear force could influence the performance and fatigue life of the connectors, necessitating further studies to understand its impact on bridge serviceability and design optimization.

In this paper, a case study of a single-span steel-concrete bridge in Sweden is conducted to analyse the impact on the local shear flow distribution at the intersections where the transverse cross frames are located. The study examines the local effects of implementing a more torsional rigid structure with a horizontal truss, semi-closed cross section, and investigates how the modelling principles of shear connector rigidity influence the force distribution along the steel-concrete interface.

2. THE YXLÖ BRIDGE

The Yxlö Bridge, located south of Stockholm, Sweden, is a simply supported structure with a span of 31 meters across the Yxlö channel, see Figure 1. Built in 1961, it consists of two steel I-girders supporting a concrete deck. The bridge accommodates two traffic lanes, one in each direction, with a total width slightly exceeding 7 meters. Unlike steel-concrete composite bridges, the Yxlö Bridge was not designed with shear connectors to transfer shear forces between the concrete deck and the steel girders' top flange. Instead, a few steel stirrups were incorporated into the design to prevent separation between the girders and the deck. This design, where the concrete and steel components do not work together in composite action, was common in Sweden up until the 1980s.

Figure 1. The Yxlö Bridge (The Swedish Transport Administration, n.d.).

2.1 General

The detailed geometry of the bridge and its cross-sections are shown in Figure 2, Figure 3, and Table 1. For the FEA, an equivalent cross-section was used, where the concrete deck is modelled as horizontal, rather than having the 5% superelevation present in the actual bridge section. This simplification is considered to have only a minor impact on the results and is considered negligible for the purpose of analysing the shear flow changes when lateral bracing is introduced between the bottom flanges of the steel girders. The bridge includes vertical cross bracings over the supports, as well as two internal cross bracings positioned 9.8 meters from the supports.

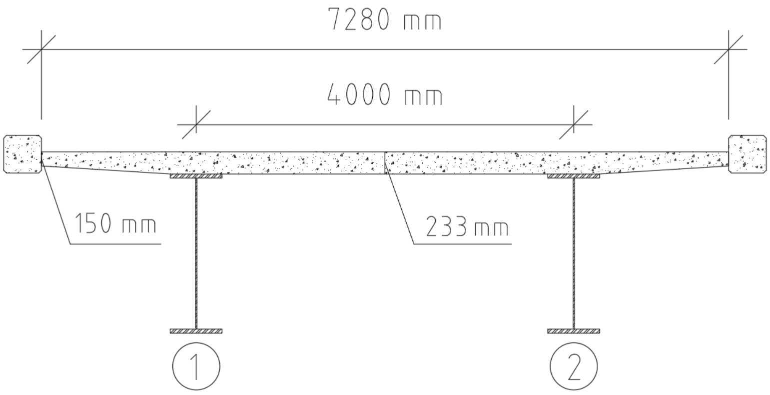

Figure 2 – The equivalent cross-section of the bridge used in the analysis.

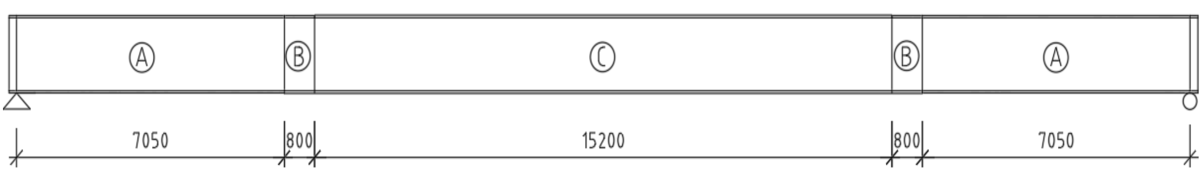

Figure 3 – Elevation of the steel girder.

Table 1 – Cross section dimensions.

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

3. FEM

Two numerical 3D Finite element models (FEM) of the Yxlö Bridge superstructure were created in InfoCAD software. Both models are identical, except that one includes horizontal bracing between the bottom flanges of the steel girders, while the other one does not. An "X"-bracing type was chosen for the additional horizontal bracing, as it provides higher torsional stiffness to the superstructure compared to other bracing types, according to [8]. The geometry was designed to incorporate the existing vertical bracing elements, see Figure 3.

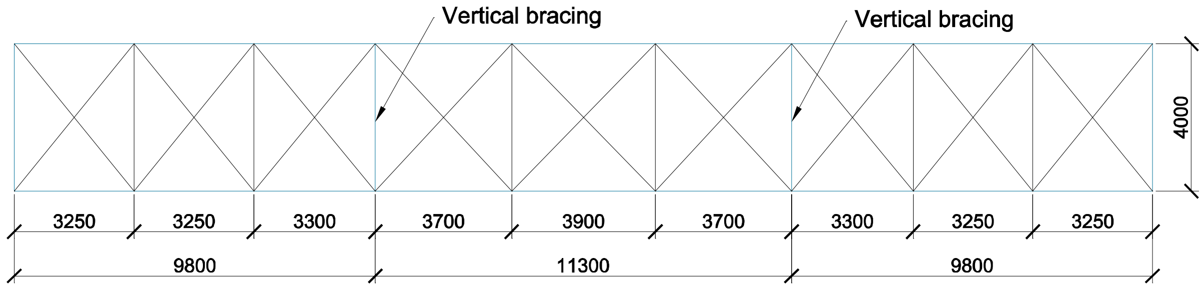

Figure 3 – Horizontal bracing configuration.

The FE model(s) consists of a total of 6274 elements, including 5444 four-node shell elements and 830 two-node beam elements. All elements have six degrees of freedom per node. A mesh size of approximately 25×25 cm is used.

The boundary conditions in the FE models represent the actual bridge bearings. One steel beam is supported by a fixed-point support and a linearly movable support allowing longitudinal movement. The other steel beam is supported by two point supports that are movable in all directions except the vertical (z) direction. All supports allow free rotation. The concrete deck, webs of the steel girders, and vertical stiffeners are modelled using shell elements, while the vertical bracings, horizontal bracing, flanges of the steel girders, and the two edge concrete beams are modelled using beam elements.

The material properties, and cross-sections are adopted according to the original bridge design, as described in Section 2. All elements of the vertical and horizontal bracings utilize square hollow steel sections (SHS) with dimensions of 100 × 100 × 4 mm. The modelled bridge is shown in Figure 4.

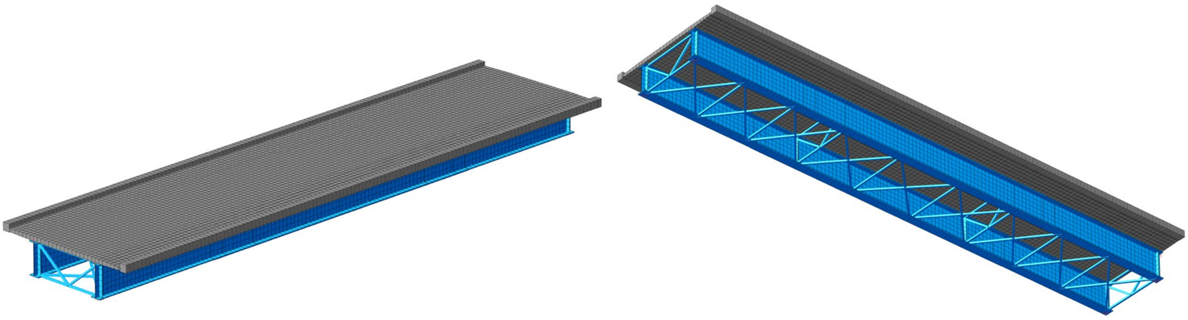

Figure 4 – General views of the FE model with horizontal bracing.

Both FE models differ from the original design of the Yxlö Bridge by incorporating a shear connection between the concrete deck and the steel beams. Originally designed without shear connectors, the steel beam cross-sections are larger and stiffer than those typically used in conventional steel-concrete composite bridges. This inherently results in a reduced longitudinal shear flow, which should be kept in mind when interpreting the results.

The connection is modelled using linear spring elements placed at 250 mm intervals, see Figure 5. Each spring element has six degrees of freedom, with the three rotational degrees left free. The shear stiffness is identical in both horizontal directions, while the vertical stiffness is set one order of magnitude higher.

In this study, the horizontal shear stiffness is treated as a variable parameter. However, its variation range is based on the stiffness of a single shear stud connector with a diameter of 19 mm or 22 mm.

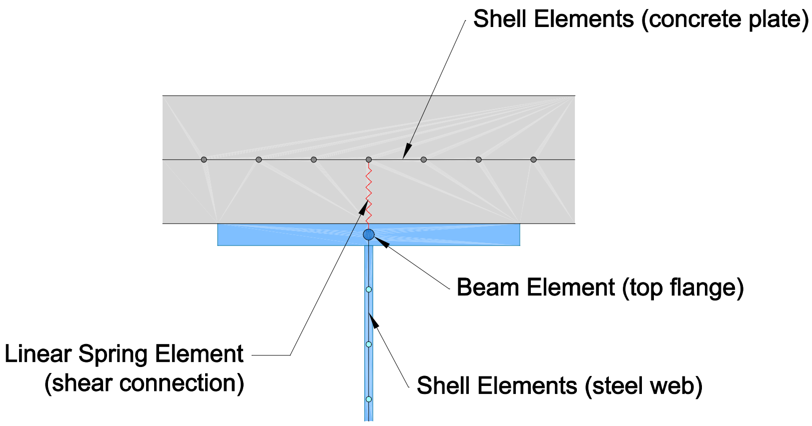

Figure 5 – Representation of the connection into the FE models.

To account for the flexibility effect of the connection under serviceability conditions, the effective stiffness of a shear stud connector embedded in a solid concrete slab is calculated according to [9]. The obtained values for concrete class C35/45 embedment are approximately 190 kN/mm and 220 kN/mm for the two stud diameters, respectively. To define the range of shear stiffness variation, a mean value of 200 kN/mm is selected, with a factor of 5 applied. Consequently, the stiffness range is set between 40 kN/mm and 1000 kN/mm.

In addition to the shear stiffness of a single stud connector, another crucial factor in estimating the shear stiffness of the connection in the FE models is the distribution of shear studs along the length of the steel girders. Since the original bridge design does not include such connections, the adopted distribution is presented in Figure 6.

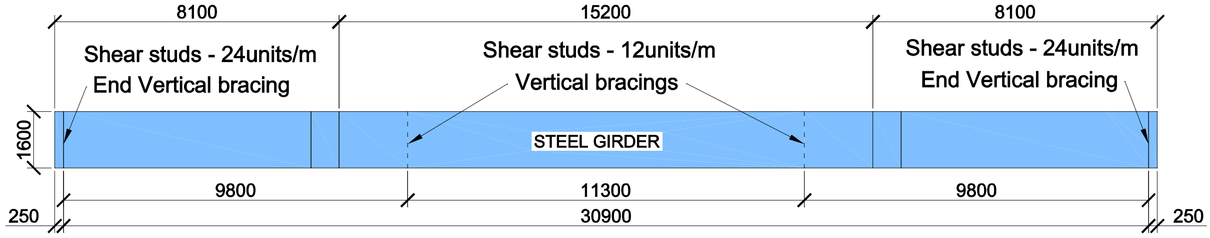

Figure 6 – Shear studs' distribution and vertical bracings arrangement.

Only one load case is considered in this study: a traffic load applied eccentrically to the bridge axis. Permanent loads are not included in the analysis, as they do not contribute to the torsional moment acting on the bridge superstructure due to the bridge's straight alignment and symmetric positioning.

The applied load follows the Fatigue Load Model 3 (FLM3) from the Eurocode 1, Part 2 [10], with axle loads of 120 kN. The specific eccentricity and longitudinal position of the load case used in this study are shown in Figure 7.

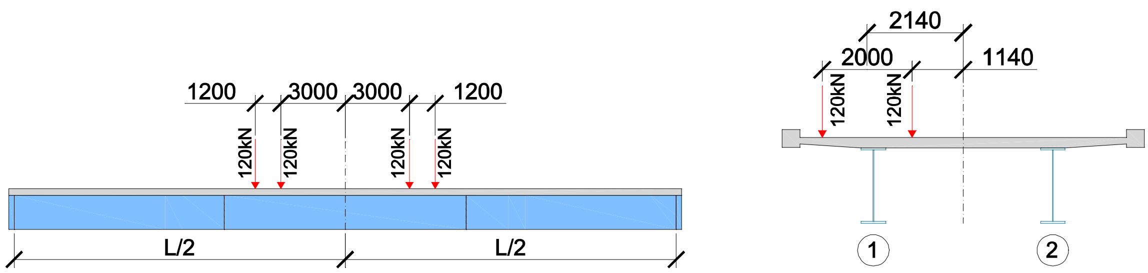

Figure 7 – Load position of the applied load, FLM3

4. RESULTS FROM FE ANALYSIS

The longitudinal shear forces obtained from the spring elements of the shear connection are presented in Figure 8. The results are calculated using a horizontal shear stiffness of 200 kN/mm for the connectors. The applied load corresponds to FLM3, positioned at the mid-span of the bridge but eccentrically to the bridge axis, as illustrated in Figure 6.

The results are provided for both bridge configurations: the open cross-section (without bracing) and the semi-closed cross-section (with bracing).

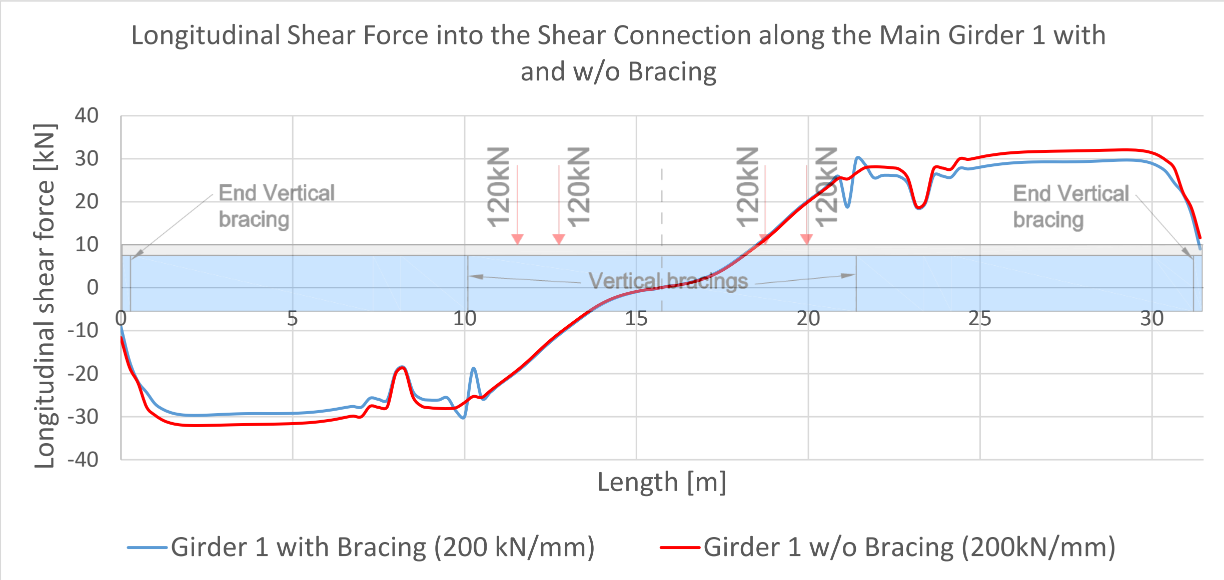

Figure 8 – Longitudinal shear force into the spring elements along Girder 1

In Figure 9, the results for the transverse shear forces in the spring elements representing the shear connection are presented. These results are obtained from the same load case applied to the FE model of the bridge with additional horizontal bracing (semi-closed cross section) and different horizontal shear stiffness values.

For comparison, the results for a shear stiffness of 200 kN/mm in the open bridge cross section (without bracing) are also included in the figure, represented by a dashed line.

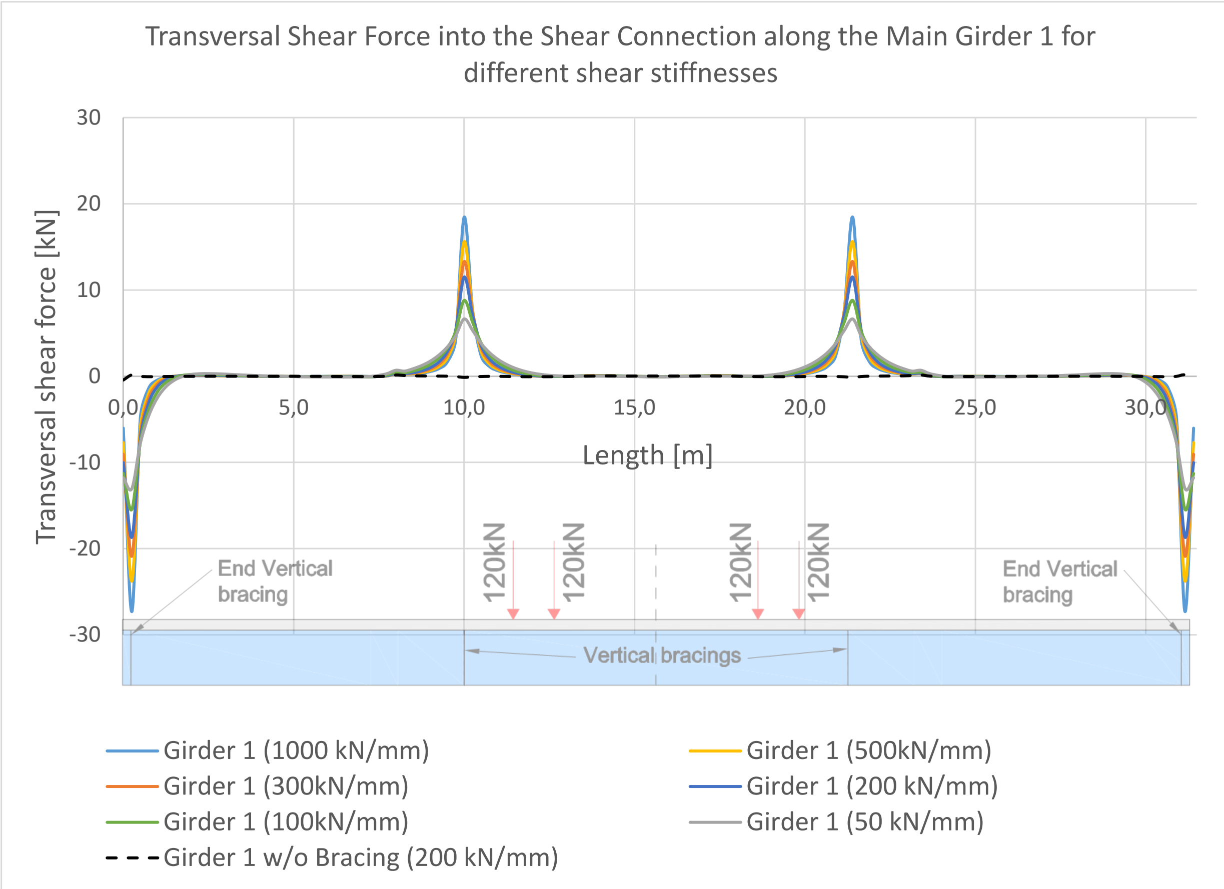

Figure 9 – Transversal shear force into the spring elements along Girder 1

In Figure 9, it is evident that the transverse shear force in the semi-closed bridge cross section increases with the shear stiffness of the connectors. To further investigate this relationship, the transverse shear force at the location of the intermediate vertical bracing is plotted against the horizontal shear stiffness, as shown in Figure 10.

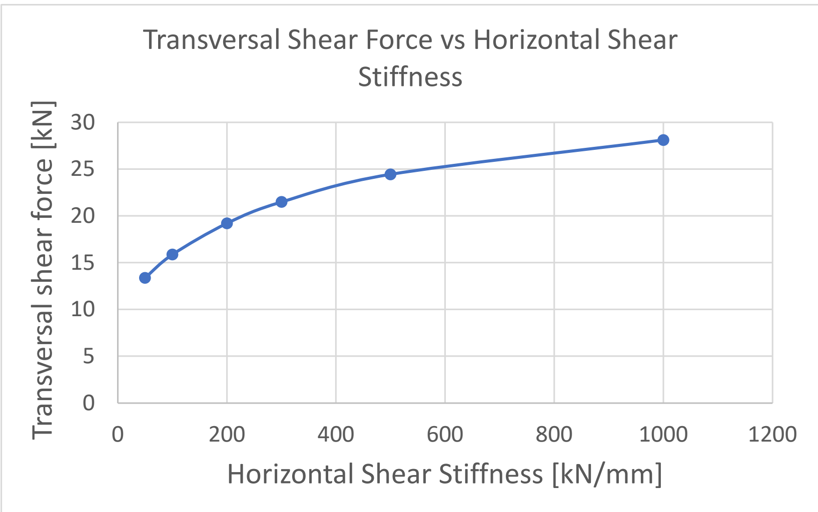

Figure 10 – Transversal shear force vs horizontal shear stiffness

Comparison between the transversal and longitudinal shear force at the location of the intermediate vertical bracing for different values of the shear stiffness is presented in Figure 11.

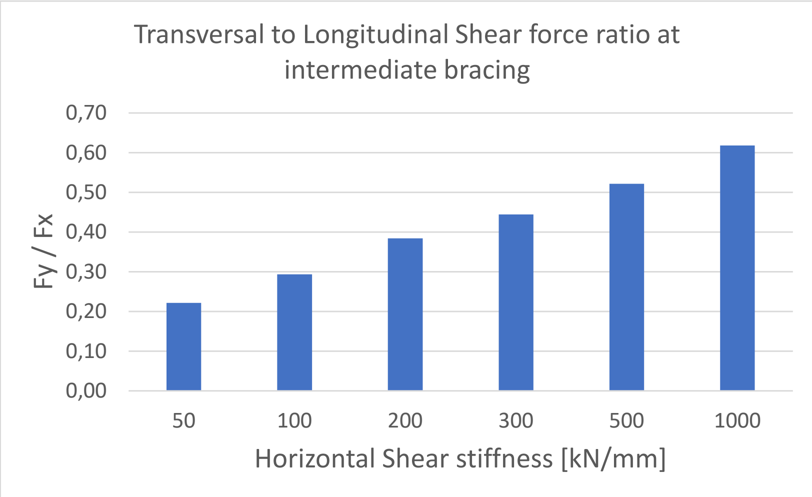

Figure 11 – Transversal to Longitudinal shear force ratio.

5. ANALYSIS OF THE RESULTS

With the addition of truss bracing at the level of the lower flanges in a steel-concrete composite girder bridge, the torsional stiffness of the cross-section is increased. This results in a distinctly different structural behaviour compared to the conventional open bridge cross-section when torsional moments are applied. Torsional moments in the bridge superstructure can arise from both vertical and horizontal loadings. For example, vertical loading could include permanent loads in a non-straight alignment, eccentrically applied vertical traffic loads, vertical eccentric components of other variable actions, as well as accidental actions. Horizontal variable loads, such as wind, can also induce torsion in the bridge cross-section. When considering horizontal loads, it is important to note that the transformation of the bridge cross-section also changes the vertical position of the shear centre.

This investigation focuses specifically on the changes in the loading exerted on the shear connection due to the transformation of the bridge cross-section.

From Figure 8, it can be observed that the longitudinal shear force in Girder 1 (the loaded girder) decreases in the semi-closed cross-section. This is due to the improved distribution of the eccentric loading between the two steel girders. A larger portion of the vertical eccentric load is transferred from Girder 1 to Girder 2 in the semi-closed cross-section compared to the open cross-section. While this leads to a slight increase in the longitudinal shear force in Girder 2, the values remain significantly lower than those in Girder 1. Therefore, the transformation of the cross-section has a generally positive effect on the longitudinal shear force exerted on the shear connection.

Another important consideration when transforming the bridge cross-section from open to semi-closed, aside from the addition of the horizontal bracing, is preventing distortion of the structure using enough vertical cross bracings. The intermediate vertical bracings are the locations where the torque is introduced into the semi-closed cross-section, as shown in Figure 12.

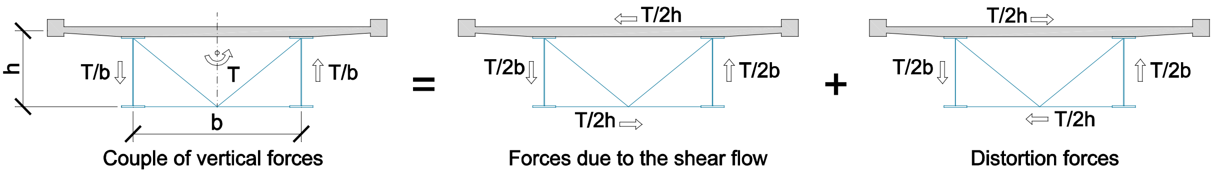

Figure 12 – Decomposition of the torque from the torsional moment.

From Figure 9. there is a considerable transversal shear force at the locations of the vertical cross bracings for the model with additional horizontal bracing. It is mainly coming from preventing distortion of the cross section due to the applied torque, see Figure 13.

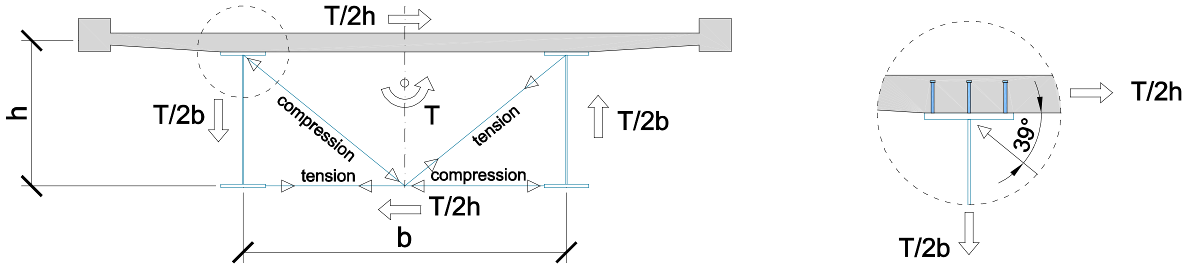

Figure 13 – Transversal force into the upper node from preventing distortion.

In Figure 14, the results at the intermediate cross bracing location are presented. The normal force in the diagonal of the vertical bracing is 51kN and its angle to the horizontal is 39°. Thus, the horizontal projection of the diagonal compression force equals to 51cos(39°)=39,6kN. This force is distributed as transversal shear force over 10-11 spring elements (see right side in Figure 14), meaning the distribution width is approximately 2.5 m. These results are based on a horizontal shear stiffness of 200 kN/mm. As the stiffness of the shear connection increases, the distribution width decreases, which leads to an increase in the maximum transverse shear force.

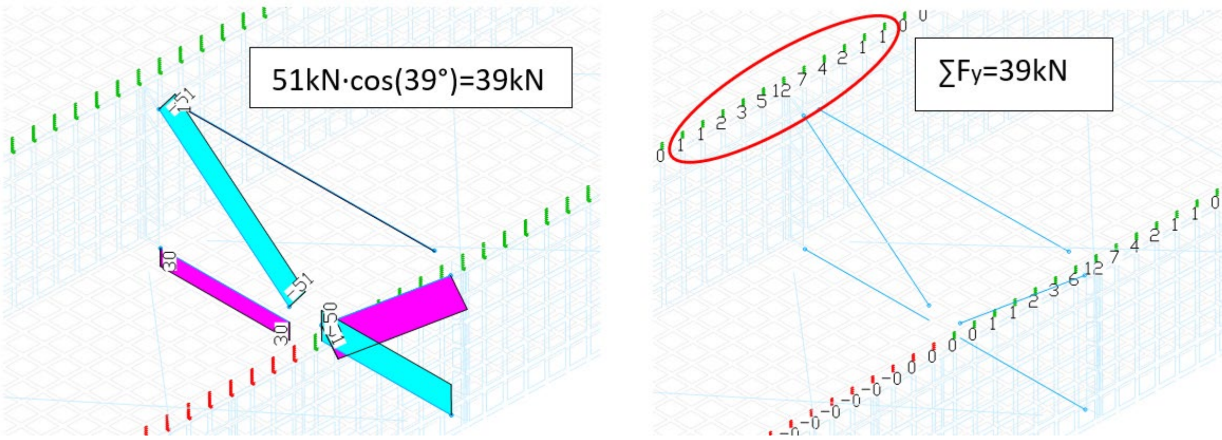

Figure 14 – Normal forces in the vertical bracing elements (left) and transversal shear forces in the spring elements (right).

This effect can also be observed by zooming in on the results presented in Figure 9 at the vertical bracing location, as shown in Figure 15. The increase in maximum transverse shear force is not proportional to the increase in horizontal shear stiffness. Beyond a certain point, the graph presented in Figure 10 begins to level off.

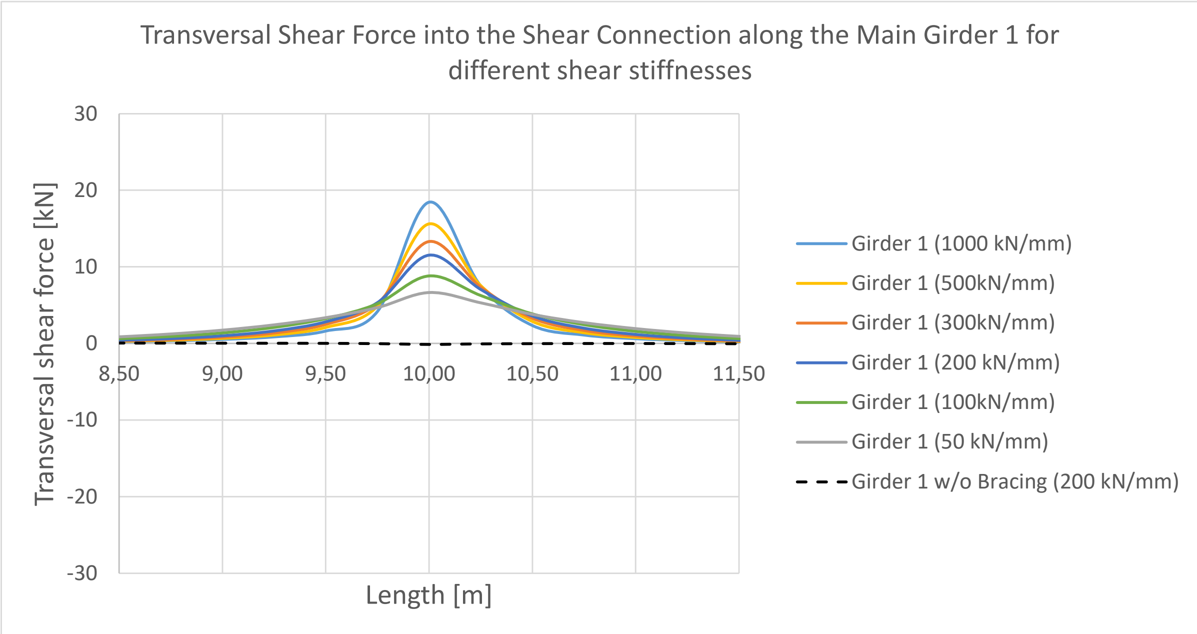

Figure 15 – Transversal shear force into the spring elements close to intermediate bracing.

Due to the transverse shear force, the shear stud connectors at the location of the vertical cross bracings are subjected to additional loading, as shown in Figure 16. The transverse loading, for a shear stiffness in the range of 200-300 kN/mm, is approximately 40-45% of the longitudinal shear force. This results in a resultant force that is about 10% higher than the longitudinal shear force.

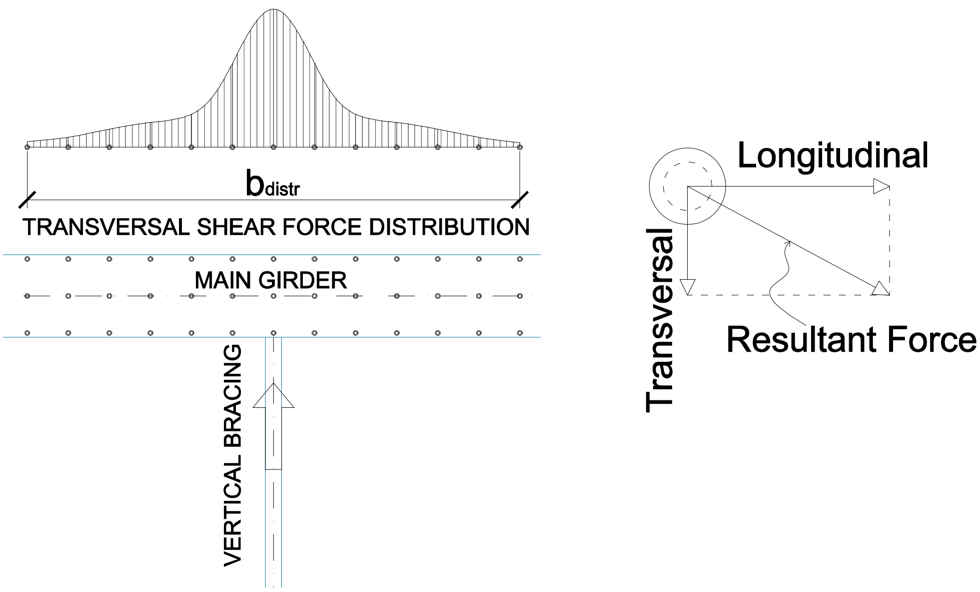

Figure 16 – Loading of the shear studs at the vertical bracing location.

6. SUMMARY AND CONCLUSIONS

Based on the analysis presented, the following conclusions can be drawn regarding the loading applied on the shear stud connection due to the transformation of the bridge cross-section:

- The longitudinal shear force is reduced in the semi-closed cross-section due to improved transverse load distribution between the two main girders under eccentric loading. This enhanced distribution reduces the demand on individual shear studs, potentially improving their fatigue performance and overall structural efficiency.

- Eccentric loads induce transverse shear forces in the shear connection of semi-closed girder bridges. These forces primarily occur at the locations of the vertical cross-bracings, including both intermediate and end bracings. The presence of these forces highlights the importance of considering bidirectional shear effects in the design of shear connectors.

- The magnitude of the transverse shear forces increases disproportionately with an increase in the horizontal shear stiffness of the connection. This phenomenon is mainly attributed to the reduction in the effective length over which the transverse shear force is distributed. A stiffer connection leads to a more localized shear transfer, potentially increasing stress concentrations at the position of the vertical cross-bracings.

- The transverse shear force at the location of the intermediate bracings is found to be between 30% and 60% of the longitudinal shear force for a given loading scenario for the case with a horizontal truss. The exact percentage depends on the shear stiffness of the connection, suggesting that variations in connector rigidity can significantly influence the shear force distribution along the steel-concrete interface.

- At the location of the end vertical bracings, the transverse shear force is approximately 50% higher than that at the intermediate bracings, regardless of the shear stiffness of the connection. This indicates that the end bracings are subjected to higher shear forces, which should be carefully considered when designing the shear stud connections in these regions to prevent potential overloading or fatigue-related issues.

These findings highlight the need for a comprehensive understanding of shear force distribution in steel-concrete composite bridges with semi-closed cross-sections. Further research and refined modelling techniques are necessary to optimize shear connector design, ensuring both adequate load transfer and long-term structural performance.

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