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Shear Force in Bolted Connection Due to Traffic and Temperature Loads in Hybrid Steel-FRP Bridges

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Abstract. As many bridges are reaching the end of their service life, researchers are searching for new solutions to extend the lifespan of those bridges. Fibre reinforce polymers (FRP) could be possible a solution for bridges with deck problems. Lightweight FRP decks can be installed quickly via bolted connectors on steel substructure. In general, shear force in the connector is not taken into account during the design of FRP decks because slip behaviour and interaction with steel substructure is unknown. This research connects to research at TU Delft on non-slip shear connectors for FRP decks. Aim of this paper is to quantify shear forces in bolted connectors due to traffic and temperature loads. The direction of webs, fibres in panel facings and the expansion coefficient of resin has been investigated to determine the influence of the FRP deck on the shear force in the connectors. To investigate the results of traffic loading and temperature loading on real bridges, a database of bridges in the Netherlands has been used. Results from the analyses offer an indication of the influence of the laminates on the shear force in the connectors and show shear force ranges that can occur in existing bridges.

Keywords: FRP · Connectors · Shear force · Traffic load · Temperature load

1 Introduction

Many bridges in the Netherlands are reaching the end of their lifespan. Figure 1 shows the number of bridges and viaducts that have been built in the last 100 years. An overall trendline is indicated in blue. Since most bridges in the Netherlands have a theoretical lifespan of 100 years, the identified trend can be imposed on the next century. From this it is clear to see that a large number of bridges and viaducts will need replacement or renovation in about 30 years. At this moment the bridges that need renovation or replacement are most of the time renovated, thereby extending their lifetime by 30 years. As a result, bridges that need replacement and renovation in 30 years is only growing. Rijkswaterstaat, being the practical executor of public works in the Netherlands, has limit capacity to replace and renovate bridges. This raises the question regarding how to prevent that bridges need to be closed due to not meeting requirements.

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Fibre reinforced polymers (FRP) can be a solution to help solve this bridge renovation problem. Conventional decks can be replaced by FRP decks to extend bridge lifetime. FRP is a widely used material in many application. However, the material is not (yet) used as often in civil engineering, despite FRP's has a high strength-to-weight ratio. The high strength-to-weight ratio reduces the self-weight of the deck compared to conventional decks and thus reduces the load on the substructure and foundation. Lighter decks prevent reinforcement of foundations and substructures and allow for heavier traffic to be accommodated. Furthermore, FRP decks can be prefabricated in a controlled environment and transportation is simplified due to light weight decks. Prefabricated deck also reduces traffic hinderance. Additional benefits include better durability and corrosion resistance than steel and concrete (Davalos et al. 2010, Reising et al. 2004).

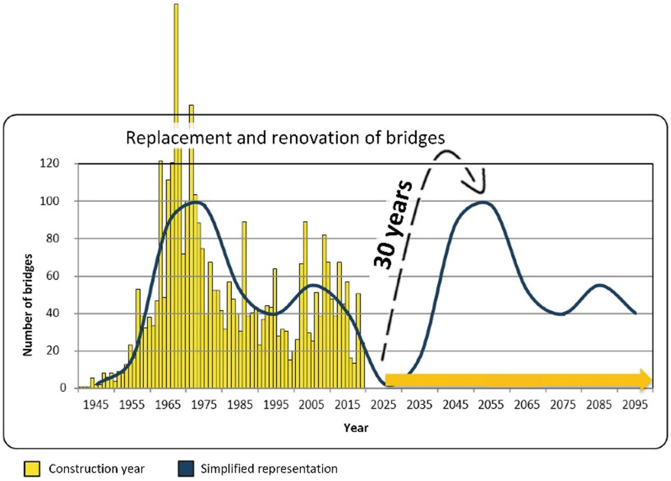


Fig. 1. Trend of requirement on replacement and renovation of bridges in the Netherlands.

Extensive research has been conducted on FRP decks in form of sandwich panels, pultruded decks and panels with integrated webs. To connect the FRP decks to the substructure, different type of connectors are being investigated. Subsequently different types of connectors result in different level of interaction between the steel and FRP structural members, referred to as hybrid interaction. Park et al. (2006) investigated the level of hybrid interaction that can be achieved with bolted connectors. Davalos et al. (2012) also investigated the level of hybrid interaction but for shear connectors. Besides bolted and shear connectors hybrid interaction may also be achieved via bonded connections (Keller and Gürtler 2005).

The aim of this paper is to investigate the shear force in non-slip bolted connectors due to hybrid interaction. The shear force due to traffic and temperature loading in bolted connectors is determined. The idea is to subsequently gain knowledge into the influence of FRP decks on the shear forces in connectors. A SOFiSTiK model is used to calculate the shear forces in the connectors. Database of 56 girder and arch bridges in the Netherlands is used to obtain envelope of extreme forces in connectors.

2 Scope of Analysed Bridges and Model Definition

SOFiSTiK finite element software is used to create models of bridges. Two type of bridges have been investigated in the research: girder and arch bridges. The layout of girder and arch bridges and definition of parameters used can be seen in Figs. 2 and 3, respectively. The longitudinal direction of the bridge is the x-direction and the transverse direction is the y-direction. For laminates the amount of fibres in each direction must be defined, namely in the 0°, ±45° and 90° directions, as indicated in Fig. 2. Two types of supports are used in the model. Both bridge types are simply supported.

The bridges consist of two components: steel substructure and FRP deck. The substructure, which consists of the longitudinal (main or secondary) girders and cross girders for the girder bridges, and also includes arches and hangers in arch bridges, is modelled with two-noded beam elements. Four-noded shell elements are used to model the FRP sandwich deck on a laminate level. The FRP deck is implemented in the model as a single piece. The bolted connectors are modelled with spring elements. These spring elements are used to couple the beam elements to the shell elements. A transverse stiffness of 100 kN/mm is used to simulate the shear properties of non-slip connectors, as obtained experimentally in several non-slip connectors by Csillag and Pavlović (2018).

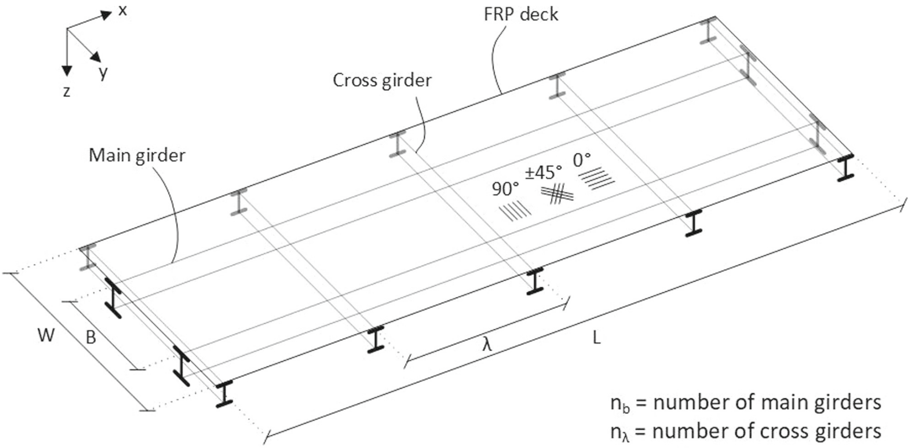


Fig. 2. Parameters used for the girder bridges

In the FRP deck several types of laminates have been used for facings, consisting of multiple plies orientated in different directions, as shown in Table 1. Ply properties are kept constant and are based on E-glass unidirectional (UD) plies (fibres volume fraction 50%). The properties of the laminate depend on the percentage of fibres in each direction. For the facings, three variations have been implemented. In general the major fibre direction, as well as web orientation is in the direction of load transfer. In turn, the load transfer depends on the dimensions of the substructure. Cross girders spaced closely to each other will mostly result in load transfer from the deck to the cross girders, while large distances between cross girders will result in load transfer from the deck to

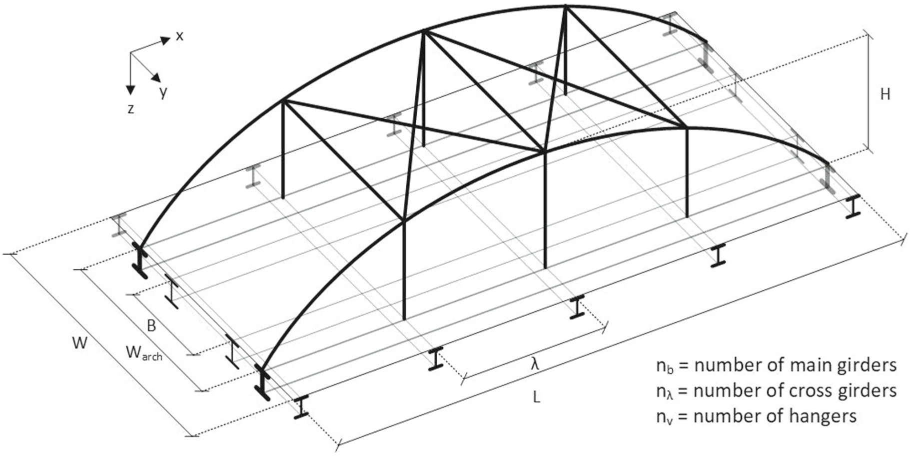


Fig. 3. Parameters used for the arch bridges

the longitudinal girders. The laminate for the facings is adapted to the dimensions of the substructure. For the webs one type of laminate (focused on shear load transfer) has been used. A linear finite element analysis is preformed to determine the shear forces in the connectors.

Table 1. Properties of the laminates

	t [mm]	0° [%]	±45° [%]	90° [%]
Laminate 1 (facing)	20	62.5	12.5	12.5
Laminate 2 (facing)	20	12.5	12.5	62.5
Laminate 3 (facing)	20	25	12.5	50
Laminate 4 (web)	10	12.5	37.5	12.5

3 Hybrid Interaction in a Generic Girder Bridge

To understand hybrid interaction at different load levels, first a reference case is investigated wherein only three parameters are changed. The direction of the webs, the laminate of the FRP deck facing and the expansion coefficient of the resin are varied, resulting in 18 generic cases. By applying traffic and temperature load, the influence of these properties on the shear force in the connectors is determined. The direction of the webs already influences results, as the connectors are located in different positions. For practical reasons the bolted connectors must be located between the webs. In the case of longitudinal and transverse webs, this implies that connectors are placed on the cross girders and longitudinal girders, respectively, see Figs. 4 and 5.

The dimensions of the generic cases are fixed, namely a simply supported bridge with a width of 7.2 m and a length of 14.4 m. The dimensions of the FRP deck are also fixed and can be seen in Fig. 5. The distance between the bolted connectors is 0.48 m. A bolt is located 100 mm from the centre of the girders at each side.

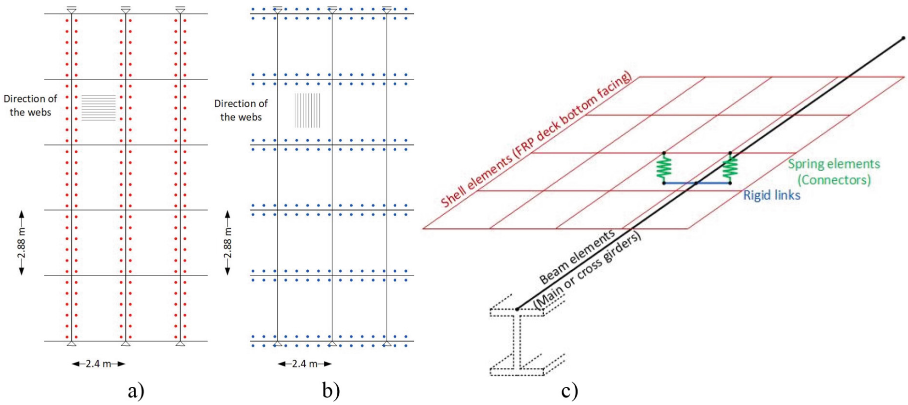


Fig. 4. The bolted connector layout of the generic bridge, a) Transverse webs (Web_{90}), b) Longitudinal webs (Web_0), c) Detail of pair of rigid and spring elements that connect steel beam to FRP deck in model

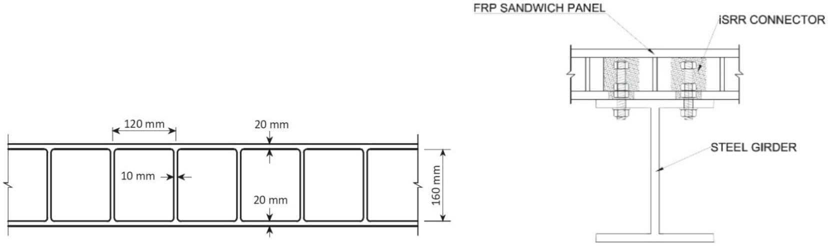


Fig. 5. The dimensions of the FRP deck and layout of the connection to steel girder.

3.1 Traffic Load

Traffic load model 1 is applied according to Eurocode 1991-2 (2003b). As seen in Fig. 6, axle loads are applied per lane. The axle load applied is dependent on the lane as can be seen in Fig. 6. For each connector the most severe combination of axle loads on each lane is determined. Only 6 generic cases need to be investigated as the expansion coefficient, which can be modified without changing other properties, has no influence for traffic load. The connector with the highest shear force is selected and shown for each of the generic cases in Table 2. Connector shear force in longitudinal direction (PX) being higher than the shear force in transverse direction, only the one to the PX is shown.

Laminate 1 has most fibres in the longitudinal direction, increasing the hybrid interaction. This results in higher shear forces compared to the other laminates. Webs parallel

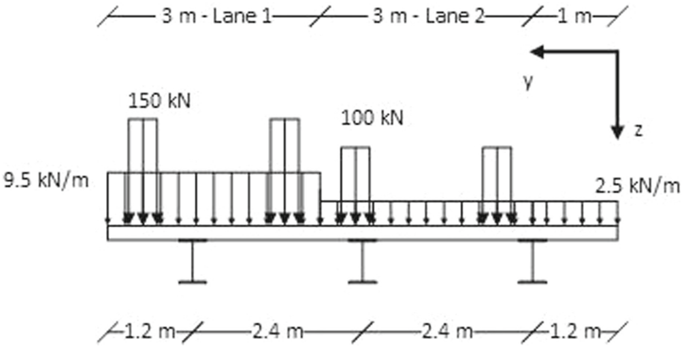


Fig. 6. Cross section of the generic bridge with loads

Table 2. The shear force in connections due to traffic load

	PX laminate 1 [kN]	PX laminate 2 [kN]	PX laminate 3 [kN]
Web_0	50.6	50.0	50.1
Web90	87.3	69.6	73.9

to the main girders (web_0) will increase the cross sectional area and so the hybrid interaction. Webs perpendicular to the main girders (web_{90}) cannot be completely accounted for the cross sectional area and therefore have less hybrid interaction. Despite this, it was found that the case wherein webs are parallel to the main girders, lower shear forces in the connectors were observed. This discrepancy is attributed to the connector layout and bending of the cross girder. Traffic load results in lateral bending of the cross girders reducing the hybrid interaction between the connected cross girders and deck. Moreover, the largest shear forces are located close to the supports. Connectors on the cross girders result in a more equal distribution of the forces over the connectors.

3.2 Temperature Load

Uniform temperature load will be the governing temperature load as this creates the largest displacements between top and bottom of the connectors and consequently leads to the largest shear forces in the connectors. Due hybrid interaction between the FRP panel and the girders, the magnitude of largest force in the connector will depend on the orientation of the fibres in facings and whether the panel is connected to the longitudinal or the cross girders. A uniform temperature load of +38°C has been applied to the generic bridge (Eurocode 1991-1-5, 2003a). Different types of resins can be used which results in different coefficient of thermal expansion (CTE) for a UD ply. The range of CTE as mentioned in the CUR 96 (2017) has been used and are listed in Table 3. Depending on the CTE of the plies and the percentage of fibres in each direction, different CTE for the laminates are obtained. The CTE of the laminates have been calculated by classical laminate theory for the x and y direction, as shown in Table 4.

Table 3. The coefficient of thermal expansion of the UD ply

	$\alpha_r = 50\ [\cdot 10^{-6}\ K^{-1}]$	$\alpha_r = 85\ [\cdot 10^{-6}\ K^{-1}]$	$\alpha_r = 120\ [\cdot 10^{-6}\ K^{-1}]$
α_1	7.2	8.9	10.5
α_2	23.2	37.0	50.8

Table 4. The coefficient of thermal expansion of the laminates

Resin	$\alpha_r = 50\ [\cdot 10^{-6}\ K^{-1}]$		$\alpha_r = 85\ [\cdot 10^{-6}\ K^{-1}]$		$\alpha_r = 120\ [\cdot 10^{-6}\ K^{-1}]$	
Laminate	$\alpha_x\ [\cdot 10^{-6}\ K^{-1}]$	$\alpha_y\ [\cdot 10^{-6}\ K^{-1}]$	$\alpha_x\ [\cdot 10^{-6}\ K^{-1}]$	$\alpha_y\ [\cdot 10^{-6}\ K^{-1}]$	$\alpha_x\ [\cdot 10^{-6}\ K^{-1}]$	$\alpha_y\ [\cdot 10^{-6}\ K^{-1}]$
1 (facing)	8.6	16.1	11.3	24.5	14.0	32.9
2 (facing)	16.1	8.6	24.5	11.3	32.9	14.0
3 (facing)	13.4	9.9	19.8	13.7	26.2	17.3
4 (web)	11.5	11.5	16.4	16.4	21.2	21.2

For all 18 generic cases, the shear force in the connectors has been calculated and depicted in Fig. 7. Distinction has been made between the shear force in longitudinal direction of the bridge (PX) and the shear force in transverse direction of the bridge (PY). Each marker represents a generic case that has been investigated. The various laminate types used are indicated by means of different marker types, whereas the colour represents the direction of the webs. For each colour and shape combination three dots are presented representing the different expansion coefficients of the resin.

The anisotropic material behaviour of FRP results in different CTE in the longitudinal and transverse direction, subsequently yielding different shear forces in these directions. A wide range of shear forces is found in the connectors with values varying from 3.4 kN to 63.3 kN. In general, the closer the CTE of the facings is to the expansion coefficient of steel, the lower the shear forces in the connectors. Therefore laminate 1 results with lowest connector forces since is CTE is closest to that of steel. However, since the analysed laminates all have one dominate fibre direction, the other direction has a notably different CTE than steel. This results in higher connector forces in one direction as opposed to another. In general it would be best practice to design the FRP panel by taking into account both directions with regards to fibre orientation as well as considering the means by which the panel is connected (i.e. to longitudinal or cross girders), in order to minimize the connectors forces in both directions. Figure 7 indicates that the case with laminate 3 and a $50 \cdot 10^{-6}\ K^{-1}$ CTE of the resin is optimal in the case of the generic bridge.

The direction of the web also influences shear forces in the connectors. When the webs are directed in the transverse direction, higher shear forces in the connectors in x-direction are obtained compared to webs placed in the longitudinal direction. This difference can be explained with respect to the bolt layout. In the case of longitudinal webs, the bolts are located on the cross girders. This allows the deck to extend between the cross girders reducing the shear forces in the connectors. For transverse webs the bolts are located on the longitudinal girders which limits the extension of the deck in the

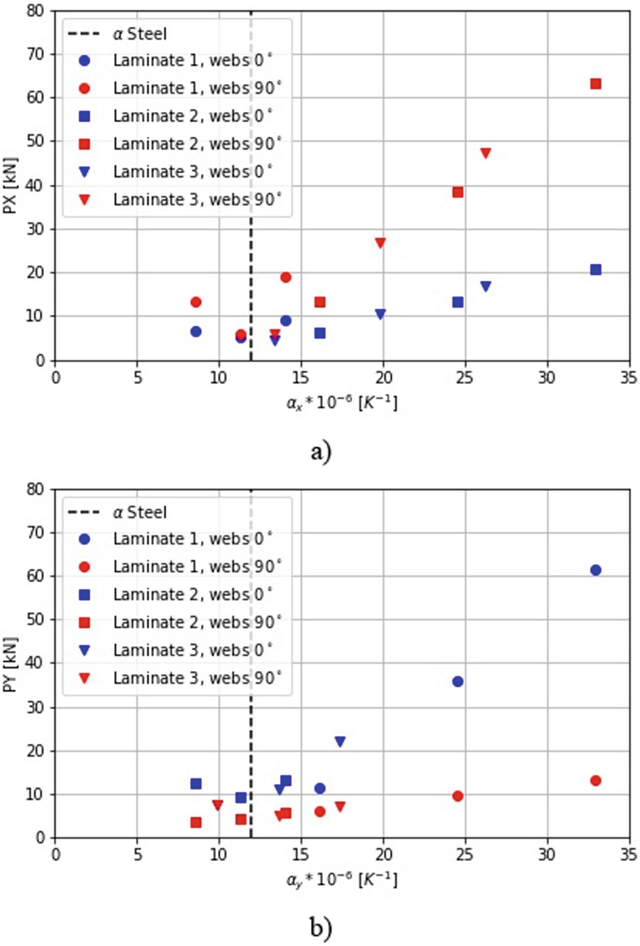


Fig. 7. Shear force in connections due to temperature load, a) in x-direction, b) in y-direction

longitudinal direction and results in higher shear forces in the connectors. For the shear forces in y-direction the results are reversed.

The CTE of the resin and the percentage of fibres in each direction determines the CTE of the laminate and together they influence the shear force in the connectors. The volume fraction is kept constant in these cases but this parameter could be changed to adjust the CTE of the laminate and stiffness properties. Upon the inclusion of temperature effects, a large variation in connector shear forces are obtained. This highlights the importance of including temperature loading during designing. It is possible to adjust the laminate in such a way that the shear forces in the connectors due to temperature loading are relative low.

Following the notion of webs and most fibres in the directions of the load transfer, bridges with many cross girders will have most of the fibres and webs orientated in the longitudinal direction and will therefore use laminate 1. This means that the shear forces in the longitudinal direction will be small but in the transverse direction significant shear forces can occur. Bridges with nearly no cross girders will have most of the fibres and the webs orientated in the transverse direction and therefore will use laminate 2. This will, depending on the type of resin, result in high forces in the connectors in the longitudinal direction, whereas in transverse direction the forces are relative low.

Placing the webs and most fibres in the direction of the load transfer using the dimensions of the generic bridge results in webs in the transverse direction. Laminate 2 or 3 would be used as the distance between the cross girders is longer than the distance between the main girders. In terms of shear forces in the connectors due to traffic load this would not be the ideal configuration as webs in the other direction result in lower forces. Similarly, this configuration is not optimal with respects to temperature loading. The ideal configuration for the lowest possible shear forces in the connectors is to use longitudinal webs and laminate 1.

4 Results on Hybrid Interaction in Highway Bridges in the Netherlands

To investigate the use of FRP decks with bolted connections in reality a database containing bridges owned and maintained by Rijkswaterstaat is used. Girder and arch bridges are included, whereas orthotropic decks are excluded. Removing the deck of orthotropic bridges results in removing the top flange, as it is required to connect the deck to the girders. In total 29 girder bridges and 27 arch bridges are included in the research. A quick survey, based on expert judgement by Rijkswaterstaat, showed that respectively 13 and 16 girder and arch bridges may suffer from possible deck problems. The dimensions of the bridges are diverse, from four-lane highway bridges with spans over 200 m to one-lane bridges with spans of 30 m. The ranges of dimensions of the bridges can be seen in Table 5. The FRP panels used as refurbishment solution have the same dimensions as the panels for the generic girder bridge. Each bridge has one of the three facing laminate as shown in Table 4. Which one is chosen is based on the distances between longitudinal girders and distances between cross girders. The layout of the bolts is the same as in the generic case, so placement on the longitudinal or cross girders depends on the facing laminate. The distances between bolts is 0.48 m. Figure 8 shows an example of an arch bridge generated by the model.

Maximum shear forces in the connectors due to traffic and temperature loads are determined for each of the bridges included in the aforementioned database. The applied load is the same as for the generic case. For the temperature load the expansion coefficient of the average resin is used: $85 \cdot 10^{-6}$ K^{-1} for each case. The webs are for laminate 1 directed in the longitudinal direction and for laminate 2 and 3 in the transverse direction as those are the shortest distances between girders. The results can be seen in Fig. 9 where the shear force is plotted against the span of the bridge.

The maximum shear force in the girder bridges varies from 10 to 110 kN due to traffic load and from 5 to 60 kN due to temperature load. Bridges with laminate 2 as facings, which are bridges with a relative large distance between cross girders, perform better under traffic loading but worse under temperature load compared to bridges with other laminates.

Table 5. The range of the dimensions of the bridges.

	Girder bridge	Arch bridge
Bridge length	13–530 m	60–300 m
Main span (L)	13–77 m	40–170 m
Width (W)	4.5–22.5 m	4.5–23 m
Number of longitudinal girders (n_b)	2–8	2–10
Number of cross girders (n_λ)	2–58	11–67
Distance between longitudinal girders (B)	1.28–9.85 m	0.9–5 m
Distance between cross girders (λ)	1.74–11.26 m	2.14–19.8 m

In most cases, arch bridges have larger spans than the girder bridges. In general this does not results in larger shear forces in connectors compared to girder bridges. This can be explained because the hangers function as intermediate supports. The arch bridges behave as bridges with multiple smaller spans. The maximum shear force in arch bridges varies from 10 to 60 kN due to traffic loading and from 5 to 50 kN due to temperature loading. There is not a facing laminate on the arch bridges that performs best for traffic load, mainly because the number of lanes varies. Bridges with laminate 1 have lowest shear forces due to temperature loading.

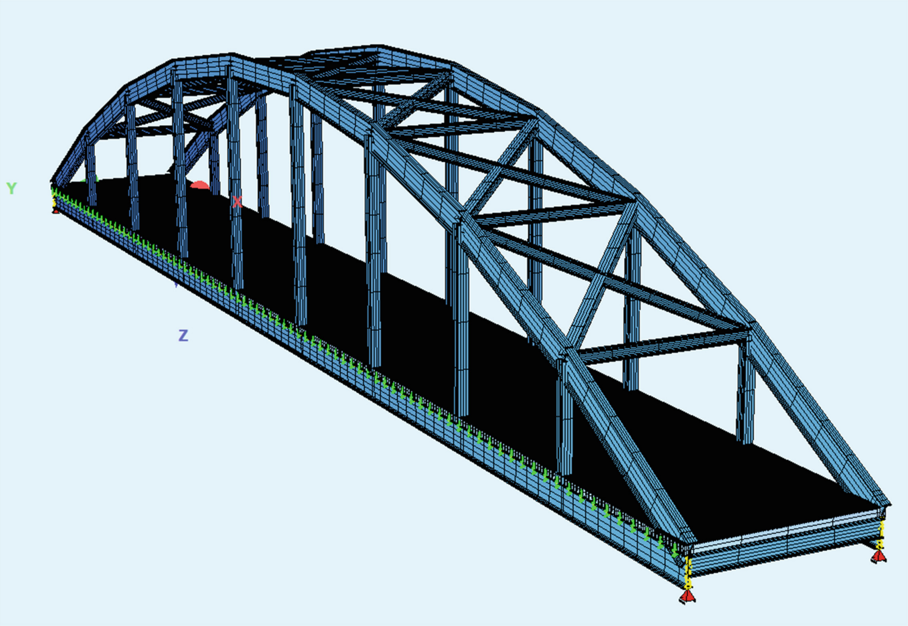
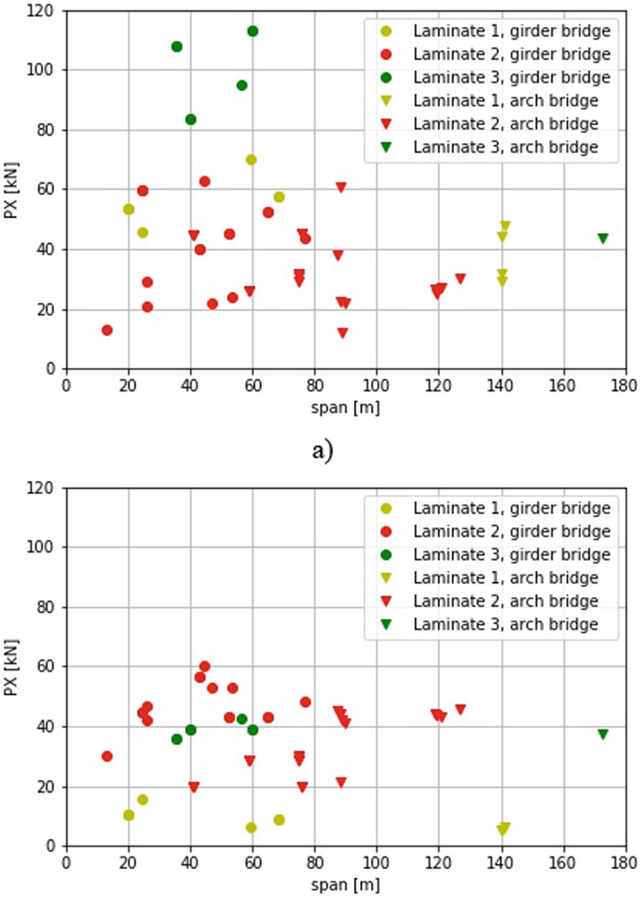


Fig. 8. Arch bridge model generated by parametric script in SOFISTiK



a)

b)

Fig. 9. Shear force in connections a) due to traffic loads, b) due to temperature loads

The regular design practice would be to place the FRP deck in the direction of the local shortest span, i.e. over the cross or longitudinal girders. The results presented here show that this is only one of the aspects to be considered when designing a bridge where hybrid interaction between the deck and the steel superstructure is engaged. Figure 7 shows that "wrong" orientation of the panel and fibre reinforcement in the facings, as well as incompatible CTE of the panel influenced by resin can results in high forces in the connectors, which are not feasible.

In this research the layout of the bolts is kept the same for each bridge and results from only the most heavily loaded connectors are used. Those connectors are close to the supports. Bolted connectors in the middle of the bridge are loaded less. Optimisation of the layout is possible to reduce the number of connectors. In situations where shear forces in the connectors are higher than feasible, extra connectors can be placed on the locations where required.

5 Conclusion

The shear force in the connectors has been investigated for hybrid steel-FRP bridges. A parametric SOFiSTiK model has been used to determine the shear forces in non-slip connectors in 56 bridges in the Netherlands where hybrid interaction would be engaged in renovation projects. The following conclusions and recommendations are drawn:

- The magnitude of maximum shear forces in the connectors in girder bridges due to traffic load are in most cases up to 70 kN. However, the analysed cases considered FRP deck layouts optimised for of for transferring traffic loads, which in some cases gives high shear forces in connectors, up to 120 kN. More optimum results in terms of desired laminate composition, web direction and support layout can be achieved if the design is optimised for low shear forces in the connectors.
- Temperature load must be taken into account. Incorrect orientation of the laminate in the facings can result in signification shear forces in the connectors up to 60 kN, due to design values of temperature loads on bridge decks according to EN1991-1-5.

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