UPGRADING OF AN EXISTING CONCRETE-STEEL BRIDGE USING FIBRE REINFORCED POLYMER DECK- A FEASIBILITY STUDY

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Abstract

This paper examines the structural efficiency of fibre reinforced polymer (FRP) decks for replacing traditional concrete decks intended for bridge upgrading. The investigation, which is performed by means of finite element analysis, is demonstrated on an existing non-composite concrete-steel bridge. The bridge had an inadequate structural capacity to bear the current traffic loads. Two alternative solutions are considered: replacing the old deteriorated concrete deck with a mechanically connected FRP (i.e. without composite action) and a solution where the deck acts compositely with the underlying steel girders. Different connection techniques between the girders and FRP deck are examined for both solutions. The finite element analysis is used to assess the overall structural behaviour of the bridge as well as the interfacial stresses between the FRP deck and the steel girders under different loading conditions. The results show that a significant stress reduction can be obtained by replacing the concrete deck with the lightweight FRP deck. This reduction is more pronounced if the deck is designed to work compositely with the existing steel girders.

Keywords: bridge, bridge deck, composite action, connections, fibre reinforced polymer, FRP deck

1. Introduction and Objectives

Nowadays, numerous road bridges are posted as structurally deficient or functionally obsolete due to deteriorated structural components or low load carrying capacity. In general, the main load-carrying members of these bridges are in good condition while the bridge deck is deteriorated. This applies to concrete decks in steel-concrete bridges, as well as to steel bridges with orthotropic steel decks, where fatigue cracking of the steel deck is often a major problem. What concerns steel-concrete bridges, the current practice when rehabilitating these bridge decks is to demolish the old deteriorated concrete deck and replace it by a new concrete deck which might be either precast or cast in place. This ascends the problem of construction time and traffic delay, especially in urban areas, where a crucial request for the rehabilitation of bridges is fast erection in order to minimize traffic disruption. Another demand is to limit the environmental impact at the construction site. In that respect, one potential solution which has evolved during the last decade is the use of fibre reinforced polymer (FRP) composite bridge decks. These decks offer superior properties such as high strength and stiffness-to-weight-ratio, high fatigue and corrosion resistance and enhanced durability. FRP decks can be prefabricated offering several advantages such as reduction in installation and labour costs, improvement in quality control, and reduction in traffic shutdown which on congested highways may represent 30 to 50 % of total bridge construction costs. In addition, due to less delay in traffic the environmental and economic impact (for instance, the amount in wasted fuel, noise and pollution) will be less. Fast construction results also in decreased inconvenience of the user as well as user cost (fuel cost, value of time). These qualities make FRP a well-suited material to be used in bridge decks for rehabilitation of existing bridges while maintaining the original steel or concrete girders.

Upgrading of an existing bridge by replacing the concrete deck with an FRP deck is demonstrated in this study. The objectives of this feasibility study are: i) to study the efficacy of FRP decks in upgrading existing concrete-steel bridges; ii) to study the performance of different structural solutions with the FRP deck working non-compositely and compositely with the steel girders through different connection techniques; iii) to investigate the interfacial stresses between the FRP deck and steel girders for the design of connections under different loading conditions. To achieve these objectives a detailed finite element analysis is carried out on a case-study bridge located in northern Sweden.

2. Description of the bridge

The bridge considered in this study was built in 1948 in the north of Sweden over a small watercourse called Rokån [1]. The bridge is simply supported spanning 12 meters. It had a free width of 6 meters and carried two lanes of traffic. The bridge consisted of reinforced concrete deck of depth 265 mm placed on two steel girders having a spacing of 3.8 meters (see Figure 2.1). Steel girders have a yielding stress of 255 MPa. The girders were not designed to act compositely with the concrete deck. Due to increased traffic loads over the years the load carrying capacity of the girders was not sufficient. Another problem was the deterioration of the concrete deck and the bridge deck needed to be widened by one meter. To overcome these problems the bridge was in need of rehabilitation where one of the requirements was fast construction in order to minimize the inconveniencies for road-users which leads to savings in both terms of time and cost. One potential solution for the rehabilitation of this bridge which is considered in this paper is replacing the concrete deck with an FRP deck.

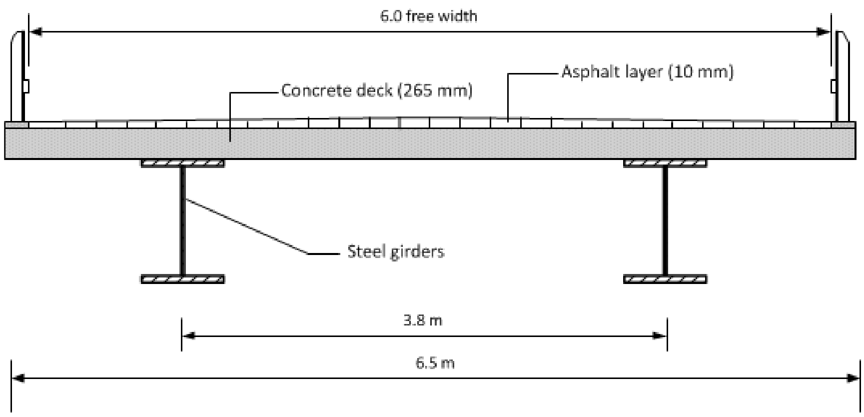


Figure 2.1. Cross-section of Rokån bridge

3. Bridge deck replacement with FRP deck

3.1 FRP bridge deck system

The commercially available FRP deck considered in this study is the ASSET deck manufactured by Fiberline Inc. The ASSET deck is 225 mm deep and is formed by assembling 299 mm long interlocking components to form any length of the deck necessary. Figure 3.1 shows the geometry of one deck component.

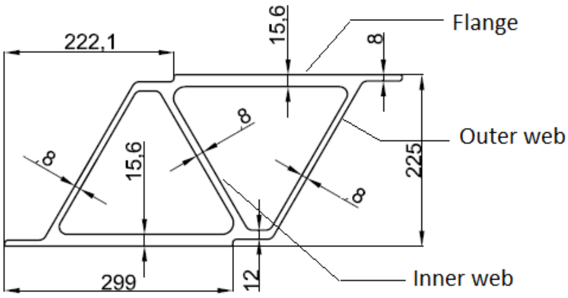


Figure 3.1. Configuration and dimensions of the ASSET deck component.

The self-weight of the deck is 0.925 kN/m^2. The manufacturer's reported material properties are given in Table 3.1.

Table 3.1. Reported material properties of FRP bridge deck (ASSET)

[MPa]	E_x	E_y	G_{xy}	f_{xu}	f_{yu}
Flange plates	23000	18000	2600	300	220
Outer webs	17300	22700	3150	180	255
Inner webs	16500	25600	2000	213	225

*X: pultrusion direction, Y: transverse direction

3.2 Deck replacement scenario

The deck replacement scenario considered is one in which existing RC deck will be replaced with an FRP deck. The FRP deck is oriented to span transversely between the longitudinal bridge girders. To assess the deck replacement scenario, two cases are studied:

1. FRP deck acting non-compositely with the supporting girders
2. FRP deck acting compositely with the supporting girders

In the first case bolted connections are used to connect the deck to the existing girders. In the second case two connection concepts of attaining composite action are considered, one in which the deck is adhesive bonded to the steel girders and one where shear stud connections are used along with concrete over a portion of the deck. In Figure 3.2, the three connection concepts are illustrated.

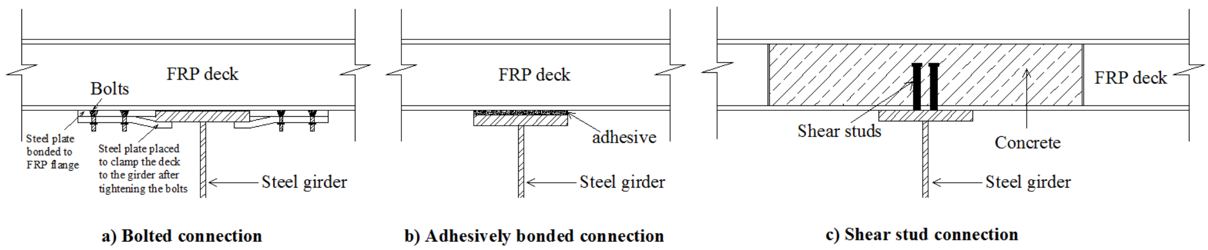


Figure 3.2. Concepts of FRP deck – steel girder connections: a) bolted connection b) adhesively bonded connection c) shear stud connection

Usually the bolted connections in FRP-steel bridge applications have been done by tightening bolts between the steel girder flange and bottom flange of FRP deck. In this study a combination of adhesive bonding and bolts is proposed in order to avoid drilling holes in the

FRP deck which might cause stress concentrations and rupture of the FRP plates. In addition, the proposed connection facilitates a fast and flexible installation process. Up to now the application of shear studs has been discrete where the decks are pre-fabricated with pockets to receive steel shear studs. Shear studs are welded to the steel girders and then usually non-shrink grout is poured to fill the joint. In this analysis, the concept of having shear stud connection with continuous concrete along the span of the bridge is studied. The width of the concrete is taken as one meter. In this condition, concrete will contribute – in addition to facilitating the connection between the deck and the girders - as a compression flange resulting in enhancement of the structural performance of the hybrid girder.

4. Numerical modelling

4.1 Loading conditions

Traffic loads according to the European Code EC1 were considered in the analysis of the bridge [2]. Vertical and horizontal loads corresponding to load model 1 in EC1 were used. In addition, horizontal forces acting on the surface of the deck such as braking or acceleration forces and lateral forces were considered. For the ultimate limit state these loads are increased by a load factor of 1.35.

4.2 Finite element model

A finite element model was created in the software ABAQUS (ver. 6.8.2) in order to simulate the structural behaviour of the composite FRP-steel bridge. The FRP deck and the steel girders are modelled by means of 3-D deformable shell elements (element type S4), since the structure is mainly dominated by flexure behaviour. The orthotropic material properties of the ASSET deck presented in Table 3.1 were used. The deck to girder connection adopted in this bridge model is created using hard contact surface to surface connection. The girders were modelled as simply supported and the boundary conditions were assigned at the end of the bottom flanges. The entire bridge model is illustrated in Figure 4.1.

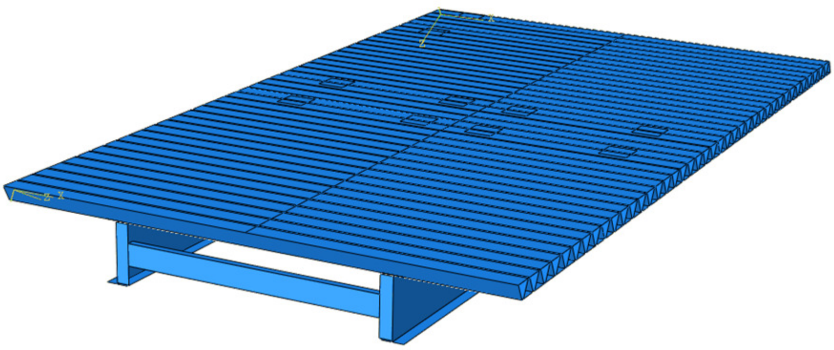


Figure 4.1. Finite element model of the bridge

5. Results

5.1 Superstructure stresses

One output of interest was to compare the stress reduction in the steel girders when the concrete deck is replaced by an FRP deck for the different scenarios. In order to obtain the maximum stresses on the girders both lanes are load in the middle span. The maximum tensile stresses in the steel girders are presented in Table 5.1 for the different scenarios studied alternatives.

Table 5.1. Comparison of superstructure stresses for different cases

Bridge	Maximum tension Stress	Reduction
	σ [MPa]	[%]
Non-composite RC bridge – existing bridge	304.67	-
Non-composite FRP bridge	268.33	11.9
Composite FRP bridge with bonding	239	21.5
Composite FRP bridge with shear studs	215	29.4

A significant stress reduction of about 12% could be obtained by replacing the concrete deck with the lightweight FRP deck. This confirms the benefit of light-weight FRP decks which allows for increase in traffic loads. However, for this particular case study, the maximum stress in steel girders exceeds the design yield stress of the stress material which necessitates- if this solution is to be considered for the bridge – a strengthening of the steel girders. In the case of composite action this reduction increases to 21.5 % and 29.4 % for adhesively bonded and shear stud connections respectively. In the case of adhesively bonded FRP deck, the effective width of the FRP deck participating in the load-carrying capacity of the girder was estimated to 63% of the deck width (half of the span between the girders plus the overhang). The level of assistance of FRP flanges to the composite girder is calculated based on the upward shift of the neutral axis by back-calculating the effective FRP flange width using standard transformed section properties. The maximum reduction is achieved in the case of composite FRP-steel bridge with shear stud connections due to the contribution of the concrete that acts as a compressive flange in the hybrid girder, which increases the efficiency of the composite action. For both alternatives with compositely acting FRP deck, the maximum stresses in the steel girders are less than the design yield stress of the girder steel material which makes it possible to keep the original steel girders.

5.2 Behaviour of the FRP deck

Another objective of the study was to investigate the behaviour of the FRP deck under different loading conditions. The analysis clearly shows that the ASSET deck exhibits truss-type behaviour while transferring the forces to the underlying steel girders. This 'truss-action' is generated by the triangular configuration of the deck. One of the webs carries tension and the other compression forces. The components of these forces will create force couples in the flanges which will result in local bending and high shear forces between the intersections of diagonals (see Figure 5.1). The moments in the intersections are higher because the moment is a function of the length of the force couple. Thus, peak moments and shear forces result in the intersection between the web and the flange. As noted in Figure 5.1, the locations of intersection between flanges and webs are critical for the bearing capacity of the deck and are the potential locations of the initiation of failure.

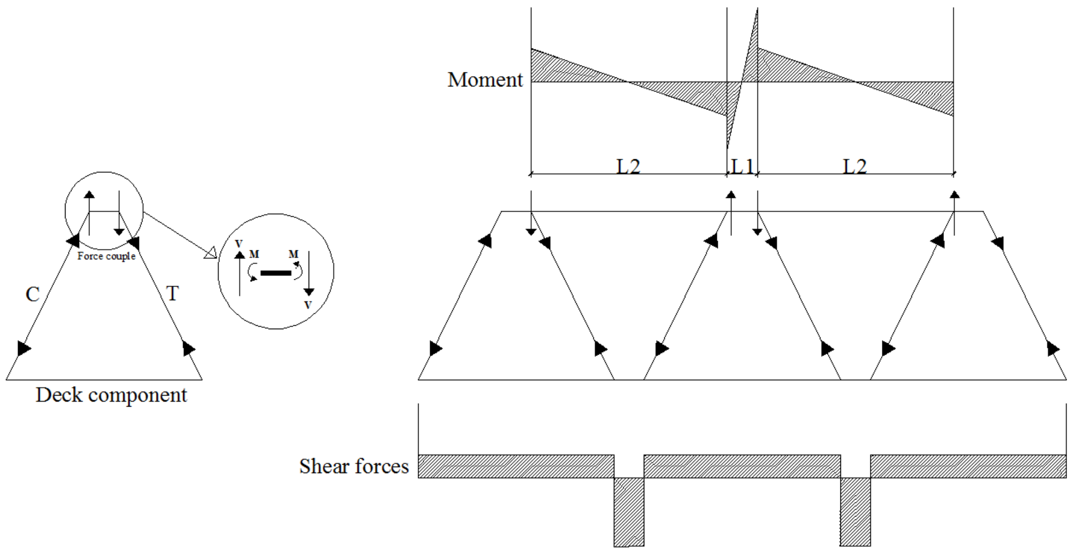


Figure 5.1. Illustration of transfer of the forces in one component of the deck and moment and shear force distribution in the flanges of the ASSET deck

5.3 Interfacial stresses

In the design of connections, peeling and shear stresses acting on the surface between FRP deck and steel girders are essential. The most critical forces for the design are the tensile forces resulting from uplift of the deck due to transverse bending of the deck. Maximum uplift of the deck results when vertical loading is applied in one lane of the bridge. Maximum shear stresses between the girder and the deck are attained when the braking and lateral forces are applied. A schematic of how these forces are applied on the bridge is depicted in Figure 5.2.

The maximum values of the interfacial stresses were attained when the forces are applied in the end of the bridge and not in the middle. The results of peeling and longitudinal shear stresses are depicted in Figure 5.3. Resulting transverse shear stresses were quite small thus they were neglected.

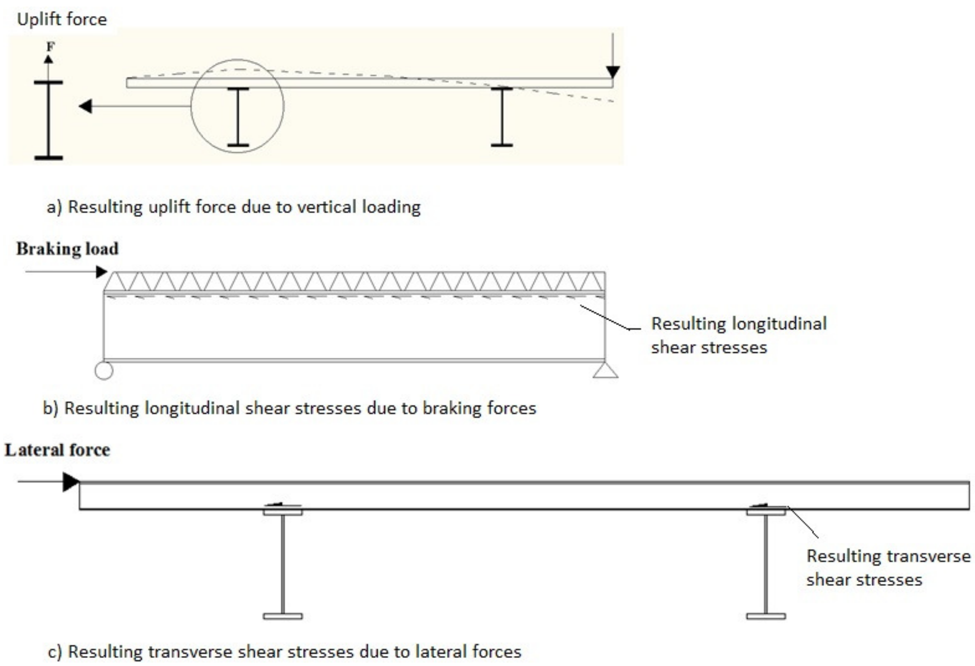
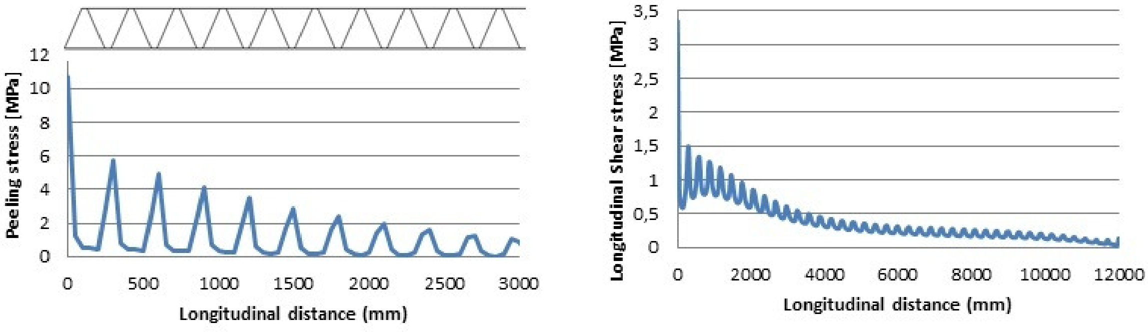


Figure 5.2. Schematic of resulting interfacial forces on different loading conditions



a) Peeling stresses

b) Longitudinal shear stresses

Figure 5.3. Interfacial stresses between FRP deck and steel girders

As noted in Figure 5.3, the peak stresses are obtained under the webs. This non-uniform distribution of interfacial stresses is generated by the cellular configuration of the deck and the forces are transmitted through the webs resulting in concentrated forces as described in the previous section. The maximum peeling stress was found to be 11 MPa and shear stresses 3.5 MPa. These values combined together were compared with the results of through-thickness tensile-shear interaction strength of adhesive bonded connection developed by Keller et. al. [3].

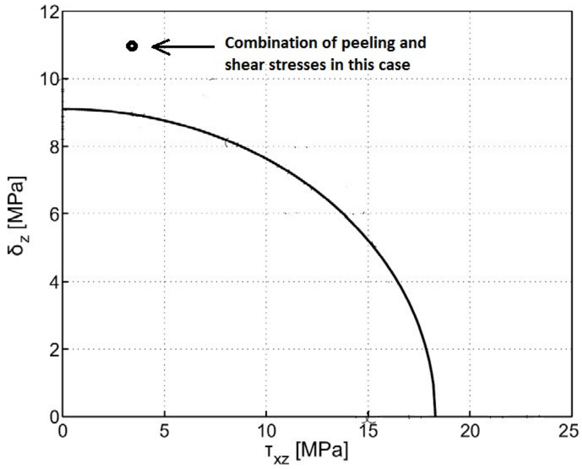


Figure 5.4. Combined through-thickness shear and tensile FRP strength [3]

As observed in Figure 5.4, the peeling stresses exceed the pure through-thickness tensile strength of the FRP material, while the shear stresses are well below the pure shear strength. Thus, the critical stresses in the joint are peeling stresses. It is worth mentioning here that rather conservative assumptions in the analysis. In the finite element model shell elements were used for the deck and therefore the thickness of the flanges and webs is not taken into account. A more reasonable model, with solid elements for example, will result in a more even peak stresses with maximum values well below those predicted by the current model. Nevertheless, it is clear from the results that the truss-like configuration of the deck results in high local stresses in the interface between the deck and the steel girders. These local stresses need to be accounted in the design of the studied concept.

For the alternative in which the composite action is achieved through welded shear studs and concrete, the problem with interfacial stresses becomes less pronounced. The design of this alternative presumes Φ 22 mm shear studs with a c/c distance of 350 mm. As mentioned before, the efficiency of this solution is increased by having the concrete block working as a compression flange, thus reducing the live load stresses even more.

Conclusions

A feasibility study was conducted on upgrading an existing steel-concrete bridge by replacing the concrete deck with a lighter FRP deck. This study was performed by means of finite element analysis, where different solutions for the connection between the new deck and the existing steel girders are considered. The following conclusions can be presented:

- A stress reduction of about 12% could be obtained by replacing the concrete deck with the lightweight FRP deck. Higher stress reductions in the superstructure are obtained when the deck acts compositely with the underlying girders. In this particular case study the deck has to be designed with composite action in order to facilitate a utilization of the existing steel girders.
- Two alternative solutions to obtain composite action between the new FRP deck and the existing steel girders are considered; adhesive bonding and shear studs with concrete strip. The stress reduction in the steel girders under live loads was ca. 22% and 30 % respectively.
- In case of adhesively bonded decks, accurate estimation of the interfacial stresses in the interface between the deck and the steel girders is very essential. Shear stud connections have adequate capacity to bear the loads generated by the composite action. However, further study has to be done to develop the proposed connections considering factors such as prefabrication, installation and local effects in the design.

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6. References

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