IMPORTANCE OF INTERFACE LAYER ON BEHAVIOUR AND DURABILITY OF ORTHOTROPIC STEEL DECKS

Sofia Teixeira de Freitas*, Henk Kolstein** and Frans Bijlaard***

*Ph.D. candidate, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands, Phone: +31-152782287, S.TeixeiraDeFreitas@tudelft.nl; **Senior Researcher / Lecturer, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands, Phone: +31-152784005, M.H.Kolstein@tudelft.nl; *** Professor of Steel Structures, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands, Phone: +31-152784581, F.S.K.Bijlaard@tudelft.nl

Abstract

Deck plates of orthotropic steel bridges experienced early and threaten fatigue cracks at the heavy vehicle lane. Previous research developed a new stiffer surface layer for renovations of the fixed bridges based on reinforced high performance concrete. The study presented in this paper focuses on a possible renovation system for movable bridges in which a second steel plate is added to the existing bridge deck. The properties and durability of the interface layer between the two steel plates strongly influence the response and efficiency of the structure. The study focuses on two solutions, thin epoxy layer namely Bonded Steel Plates and thick polyurethane layer namely Sandwich Steel Plates. Structural calculations were carried out based on analytical solutions using Classical Laminate Plate Theory and First order shear Deformation plate Theory. The different parameters of the renovations structures were varied and the results for the two solutions are compared. Based on the weight restrictions and geometrical properties of the existence deck plate, one can choose the most efficient interface layer from the material available, i.e., the lightweight structure solution that provides the increase of stiffness required for the renovation.

Introduction

Recently, orthotropic steel bridges experienced some early fatigue failures of several welded connections in the steel deck plate. The most threaten cracks initiates at the welded connection between the trough web and the deck plate. These fatigue cracks are located at the crossbeam and grow through the thickness of the steel deck plate. They are caused by the cyclic loading of the axles of heavy vehicles in the heavy vehicle lane (Jong 2006) (Kolstein 2007). It became clear that new renovation techniques to stiffer the deck structure were needed and that the current design methods for surfacing were to optimists and lead to lifespan smaller than predicted.

A previous research program was carried out at Delft University of Technology where (Medani 2006) developed a new design concept for the commonly used asphalt surface layer and (Jong 2006) achieved an effective solution for renovation of fixed bridges. This renovation system consists of replacing the usual mastic asphalt wearing course by a layer of 50mm reinforcement high performance concrete. This renovation system started to be applied in several fixed bridges in The Netherlands.

For movable bridges, no efficient solution was yet achieved due to the weight limits required for the renovation system. Some possible solutions are proposed but all need further research (Jong 2006).

One of the proposed solutions is also based on a concrete renovation layer, but for the movable bridges, the usual epoxy surfacing is replaced at the heavy loaded lines by a thin layer of Reinforced Ultra High Performance Concrete (UHPC) of 20mm to 30mm (Schrieks 2006) (Boeters 2007). Further study is needed to conclude about the efficiency of this solution.

The other proposed solution is to add a second steel plate to the old bridge deck. The existing wearing course is removed and, after adding the new steel plate by application of the interface layer, a new surface is applied at the top of the new steel plate as a wearing course.

For the interface layer between the existing deck plate and the new steel plate, different solutions can be selected: (i) Bonding with a thin adhesive layer the new steel plate or (ii) applying a sandwich system where the adhesive layer behaves as the core and the existing deck plate and the new steel plate as the faces. The usual low density of the core materials can make the sandwich system a light weight solution although the increase on the total height. In this paper, the bonding system refers to the first option and the sandwich system to the second option.

On the bonding system, previous research was carried out using epoxy with 2mm thickness and 5 mm thickness for the new steel plate (Jong 2006). Small and full scale tests were performed both in static and fatigue load using. For the full scale fatigue test, delamination occurred at the adhesive layer. New application methods of the adhesive layer can be a solution for this problem (Jong 2006) but need further research.

Concerning the sandwich system, (Overduin 1999)studied a renovation structure composed by a second steel plate of 10mm thickness connected with the existing deck by a synthetic layer of 30mm (EC-deck system). Results concluded that the core material used for the system studied was too weak (core properties: E_{EC}=32MPa and G_{EC}=10MPa).

A more promising solution is the sandwich plate system (SPS) in which the sandwich of two steel plates is separated by a solid polymer (polyurethane) core. The material properties of the core are much higher than for the previous system (core properties: E_{SPS}=750MPa and G_{SPS}= 285MPa) (Sedlacek 2007) (Vicent 2004). A pilot application of SPS to strengthen an orthotropic bridge deck was carried out on the Schönwasserpark Bridge (Feldmann 2007) in Germany.

The study presented in this paper focuses on bonding and sandwich systems for possible renovation techniques of movable bridges. The properties and durability of the interface layer between the existing deck plate and the new steel plate strongly influence the response and efficiency of the structure. Two solutions for this interface layer are studied, one with thin epoxy layer namely Bonded Steel Plates (BSP) and another with thick polyurethane layer namely Sandwich Steel Plates (SPS).

Structural calculations were carried out based on analytical solutions using Laminated Plate Theories. The different parameters of the renovations structures were varied and the results for the two solutions are compared.

Material Properties

The materials used for the bonding and sandwich renovation systems are steel, for the existing deck plate and new plate, and polymer adhesives for the interface layer. Both materials are isotropic.

The properties of the steel used for the faces of the rehabilitation structure were:

$$\left.\begin{array}{ll}\text{Young's modulus} & E_f = 210GPa \\ \text{Poisson ratio} & \nu_f = 0.3\end{array}\right\rangle \text{Shear modulus } G = 81GPa \quad \text{Density } \rho_f = 7850\, kg/m^3$$

The subscript *f* will be used for the properties of the faces.
The selection of the adhesive was based on the following main requirements:

- → Good adhesion resistance to steel
- → Cure at room temperature (practical application of the system)
- → Mechanical properties (structural adhesive)

Two types of structural adhesives were selected: epoxy for the bonding system and polyurethane for sandwich system. Both adhesives are polymer based materials. Epoxies are the best known and most widely used structural adhesives. The two-component epoxies are cured at room temperature. The polyurethanes adhesives are flexible, contrary to epoxies adhesives. The cure process can either be made at room temperature or at high temperatures.

The polymers are considered to be isotropic materials and their behaviour depends on the temperature, the strain rate and the pressure installed at the service state.
After a market prospective on the adhesive materials available, four epoxies and four polyurethanes were selected and used for the current study. A complete list of the mechanical properties is not available on market information, so only the Young's modulus E_a, Shear modulus G_a, Poisson ratio υ_a and density ρ_a are presented. To obtain values for the mechanical properties as tensile, compression and shear strength, material tests have to be performed.

Table 1 lists the available mechanical properties at room temperature of the adhesives used (subscript *a* will be used for the properties of the adhesive layer).

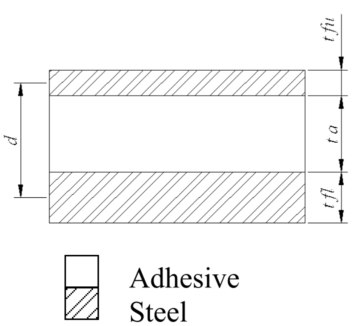
Table 1. List of adhesives.

Renovation System	*n*	G_a [MPa]	E_a [MPa]	υ_a [-]	ρ_a [kg/m^3]
Bonded Steel Plates	**EP1**	350	1560	0.41	1150
	EP 2	483	1920	0.41	
	EP3	550	2100		
	EP4	930	1000		
Sandwich Steel Plates	**PU1**	0.5	2.9		
	PU2	40	840		
	PU3	80	1580		
	PU4	285	874	0.5	

Renovation Structures

The renovations system presented in this paper consist in adding a new steel plate to the existing bridge deck in order to reduce the stresses on the deck and enlarge the lifespan of the orthotropic bridge. Two solutions are studied for the interface layer between the two steel plates. The Bonded Steel Plates (BSP) consists of a thin epoxy interface layer (maximum 3mm thickness) working as an adhesive between the two steel faces. The Sandwich Steel Plates (SSP) consists of a thick polyurethane (PU) layer working both as an adhesive and a core between the two steel faces.

The typical cross section of the renovation system listed before is then defined by the three layers. The following figure lists the symbols and definitions used – Figure 1.



t_{fl} – thickness of the lower face (existing steel deck plate)

t_a – thickness of the adhesive layer

t_{fu} – thickness of the upper face (new steel plate)

$d = \frac{t_{fl}}{2} + t_a + \frac{t_{fu}}{2}$ – distance between face's centroids

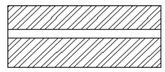
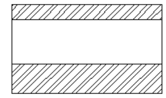
$h = t_{fl} + t_a + t_{fu}$ – total height

$W_e = t_a \cdot \rho_a + t_{fu} \cdot \rho_f$ – weight of the renovation system

Figure 1. Renovation system's cross section (list of symbols).

The geometrical and mechanical properties are resumed at Table 2 and some limits on the application of each system are defined.

Table 2. Description of BSP and SSP renovations systems.

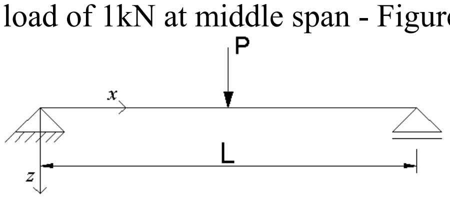
Renovations System		**BSP**	**SSP**
Cross section			
Faces (f)	Thickness t_{fu} and t_{fl}	t_{fu}: Minimum thickness of 5mm. t_{fl}: 10mm or 12mm thickness.	
	Material E_f and G_f	Steel	
Adhesive (a)	Thickness t_a	Thickness restriction due to height limits of the practical application	Maximum 3mm due to epoxy limited thickness application
	Material E_a and G_a	Epoxies: EP1, EP2, EP3 and EP4	PU: PU1, PU2, PU3 and PU4
Weight - W_e		40 to 70kg/m^2	

The steel deck plate of most of orthotropic bridges is 10 or 12mm thickness. The weight limits for the renovation systems were chosen based on previous researches in movable bridges where the range of values were in this limits (Schrieks 2006) (Boeters 2007).

Generally, sandwich systems have high flexural stiffness-to-weight ratio compared to bonding systems and monocoque systems (one single plate with double thickness). As a result, sandwich systems are expected to lead to lower transversal deflections and lower stress values. Thus, for a general given set of mechanical loads sandwich systems usually results in a lower structural weight than to other configurations (Vinson 1999).

Analysis

An analytical study was carried out in order to analyse the behaviour of the two types of rehabilitation structures: Bonded Steel Plates (BSP) and Sandwich Steel Plates (SSP).
The model analysed was a beam simply supported with 1m span, loaded with a point load of 1kN at middle span - Figure 2.



$P -$ point load located at middle span; $P = 1kN$

$L -$ beam's span; $L = 1m$

Figure 2. Simply supported beam with point unit load at middle span.

The cross section of the beam is defined on Figure 1, with a unit width (b=1m). The flexural rigidity of the cross section D is defined by equation (1.1)and the first moment of area B by equation(1.2).

$$D = \int \left(E \cdot z^2 \right) dz \qquad (1.1) \qquad\qquad B = \int \left(E \cdot z \right) dz \qquad (1.2)$$

The normal stresses and shear stresses on the cross section were calculated by equation (1.3) and (1.4), respectively

$$\sigma_x^j = \frac{M_x}{D} \cdot z \cdot E_j \qquad (1.3) \qquad\qquad \tau_{xz} = \frac{T_x}{D} \cdot B \qquad (1.4)$$

where M_x and T_x are the moment and transverse force, respectively, of the cross section x and j each layer that composed the cross section (Figure 1).

The analytical calculations for the displacements were solved with equivalent single layer theories. The classical laminate plate theory (CLPT) and the first-order shear deformation plate theory (FSDT) were applied to the renovations structures. For the Bonded Steel Plates (BSP) with thin layer of epoxy adhesive, the CLPT is used. For the Sandwich Steel Plates (SSP) with a thick layer of polyurethane adhesive, the FSDT is used. When applied to beams, this theory is also known as the Timoshenko beam theory (Zenkert 1997). These theories assume full composite connections between the layers and only the linear elastic behaviour of each material is considered (Reddy 2004).

The deformation calculated using the CLPT is due entirely to bending. The shear deformation is neglected as it adds marginally to the total deformation ($\gamma_{xz} = 0$). The First-order Shear Deformation plate Theory (FSDT) takes into account the shear deformation assuming the transverse shear strain to be constant along the thickness $\left(\gamma_{xz} \neq 0 \wedge \gamma_{xz} \amalg z\right)$ (Reddy 2004).

For both renovation systems BSP and SSP, the adhesive material has much lower shear stiffness than the steel. However, the adhesive thickness, on the Bonded Steel Plates, is small when compared to the steel plates and its shear deformation can be neglected using CLPT.

On the contrary, the adhesive thickness of the Sandwich Steel Plates is much greater than the plates, acting both as bonding layer and a core layer in the sandwich system. The transverse shear deformation is important and must be taken into account for the total deformation using FSDT.

For the model used and considering the equilibrium equations of the structure, constitutive equations of each material and strain-displacements relations of each theory, the displacements for bending and shear, at middle span of the beam, are given by equation (1.5) and (1.6), respectively.

$$w_b\left(L/2\right) = \frac{P \cdot L^3}{48 \cdot D} \qquad (1.5) \qquad\qquad w_s\left(L/2\right) = \frac{P \cdot L}{4 \cdot S} \qquad (1.6)$$

Where S is the shear stiffness of the beam and is defined on (Silva 1996). The stiffness K for each solution is defined for the middle span deformation.

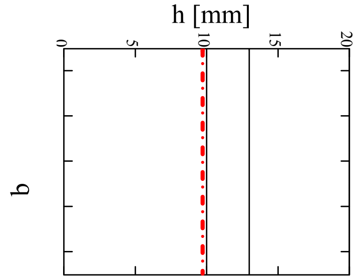
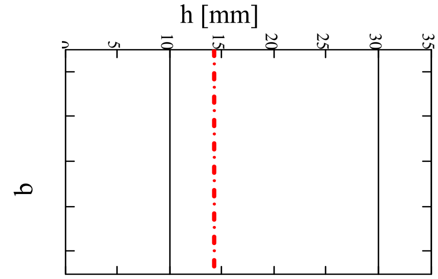
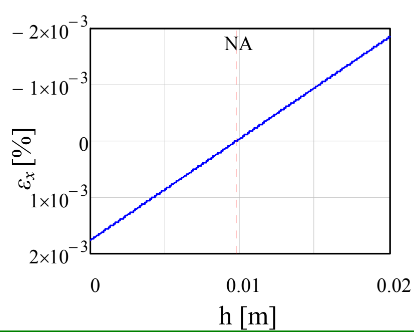
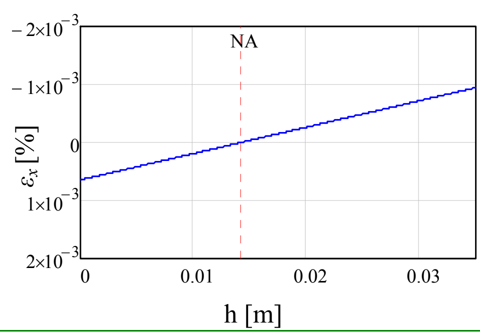
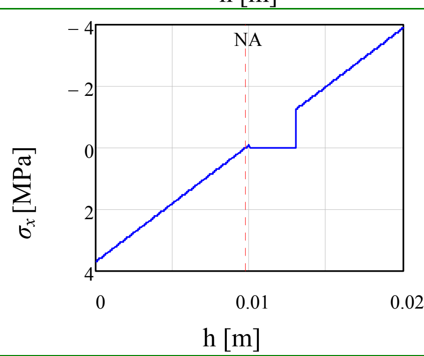
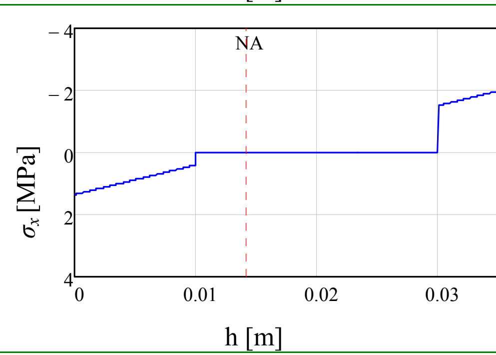
At Table 3 the deformation and stiffness for both solutions are listed.

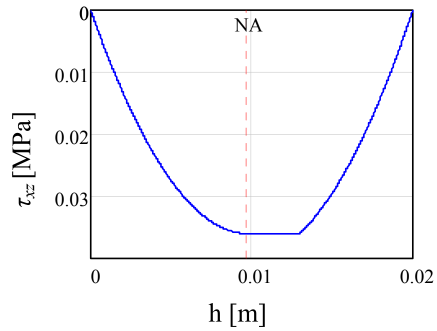
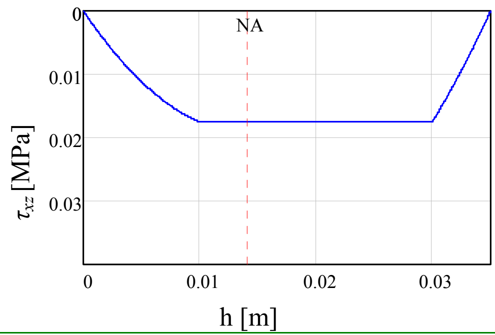
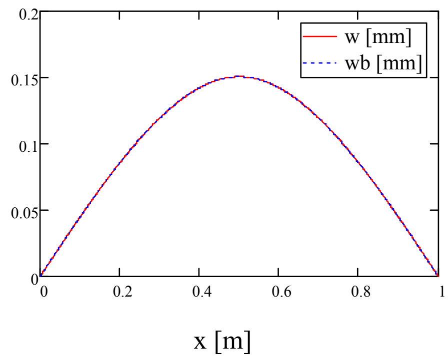
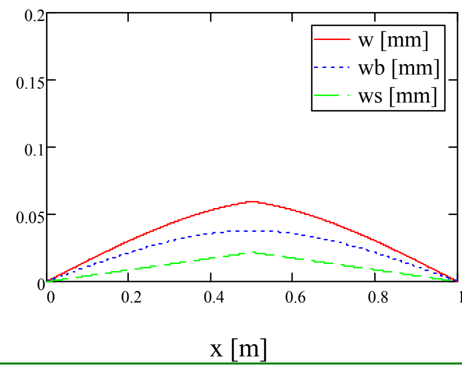
Table 3. Theories, deformations and stiffness for SSP and BSP.

Solutions	Theory	Deformation	Stiffness, K
BSP	Classical laminated plate theory	$w_{BSP} = w_b$	$K_{BSP} = \dfrac{P}{w_{BSP}(L/2)}$
SSP	First order shear plate theory	$w_{SSP} = w_b + w_s$	$K_{SSP} = \dfrac{P}{w_{SSP}(L/2)}$

One example of the normal and shear stress distribution for the middle span cross section is presented at Table 4 for both solutions as well as the deflection along the span. The examples are with an extra weight of approximately 60kg/m^2.

Table 4. Example of BSP and SSP: stresses, deformation and stiffness.

	Bonded Steel Plates	Sandwich Steel Plates
Properties	$t_{fu} = 7mm \quad t_a = 3mm \quad t_{fl} = 10mm$ $f - Steel \quad a - Epoxy\ EP3$	$t_{fu} = 5mm \quad t_a = 20mm \quad t_{fl} = 10mm$ $f - Steel \quad a - Polyurethane\ PU3$
Cross Section		
Strain ε_x *x=L/2*		
Normal stress σ_x *x=L/2*		

Shear stress τ_{xz} *x=L/2*		
Deformation ***w***		
Stiffness *K* *x=L/2*	$K = 6.5 \times 10^3\, kN/m$	$K = 17 \times 10^3\, kN/m$

From the strain diagram ε_x, it is show that this analysis is based on a full composite connection between all the layers (one unique neutral axis) and only the elastic behaviour of the materials is taken into account.
With the same weight and just increasing the total thickness 15mm, the strain and stresses decrease when changing from BSP to SSP (around 50%). The displacements also decrease and the stiffness increase in almost 3 times factor.

Parametric study

Calculations of the stiffness and displacements values for both renovations systems BSP and SSP, using previous equations, were performed varying the weight, thickness and adhesive properties. The aim was to understand the differences of the two solutions rather than its result values as they can be a rough approximation of the reality. Only after validation, both by numerical calculations and experimental test, these results can be evaluated.

Parameters and Functions. The geometrical parameters of the systems were varied: t_{fu}, t_a and t_{fl}. The weight W_e of the renovation system is also a parameter of the solutions as it can vary from bridge to bridge. The mechanical properties of the adhesive layer of each system were also varied between the ranges presented on Table 1.

For the parametric study no restrictions were made for the thickness, neither of the polyurethane layer nor the upper face layer, in order to understand the total behaviour of the system. When applied to the reality, theses limits should be present and taken into account – see Table 2 .No restrictions were imposed to the height of the renovation structure.

The weight W_e, the thickness of the adhesive t_a and the thickness of the upper face t_{fu} are related by the following equation (1.7).

$$W_e = t_a \cdot \rho_a + t_{fu} \cdot \rho_f \tag{1.7}$$

Hence, only two of these three parameters are independent. Due to their importance on the optimization of the structure, the weight and the adhesive thickness were chosen for independent parameters and the upper face thickness is defined as their function. Hence, the thickness of the upper face (new steel plate) is given by the following equation(1.8).

$$t_{fu} = \frac{W_e - \rho_a \cdot t_a}{\rho_f} \tag{1.8}$$

These values are varied at the stiffness function of each system (see Table 3) that now can be written as:

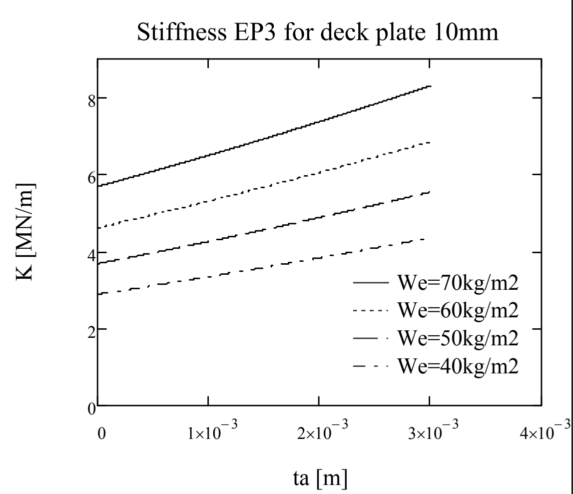
$$K = K\left(t_{fl}, t_a, W_e, n\right) \tag{1.9}$$

The aim is to find the optimum parameter values that maximize the stiffness function.

Results. For the following graphs, the stiffness functions from equation (1.9) for each system are plotted as function of one parameter which is varied continuously and the other parameters are either fixed or discretely varied.

Graphs of Figure 3 present the influence of the thickness of adhesive layer t_a, extra weight W_e and upper face layer t_{fu} (equation(1.8)) to the stiffness K of the systems BSP and SSP - equation (1.9).

BSP



SSP

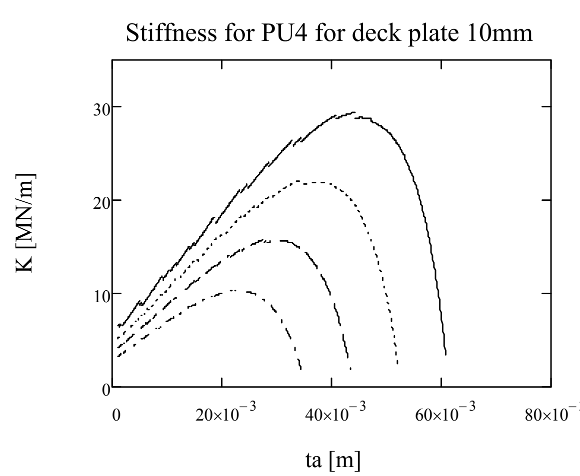


Figure 3. BSP and SSP stiffness as function of adhesive thickness t_a of EP3 and PU4 and 10mm thickness for the existing deck plate.

From the graph of BSP in Figure 3, we can observe that increasing the epoxy thickness slightly increases the stiffness of the system, K_{BSP} and higher extra weight shifts the stiffness function. This smooth variation of the stiffness is due to the restrict variation of the thickness of the Epoxy adhesive.

From the graph of SSP in Figure 3, we can observe a maximum value for the stiffness function K_{SSP} that corresponds to an optimum adhesive thickness, $t_{a.op}$.

$$K_{\max} = K\left(t_{fl}, t_{a.op}, W_c, n\right) \qquad (1.10)$$

Lower values of t_a increase the stiffness but higher values decrease the stiffness. The increase of extra weight shifts the stiffness function up.

From the $t_{a.op}$ taken from the graph for a given W_e, the optimum upper face thickness $t_{fu.op}$ can be determined by equation(1.8). Hence, a SSP system can be defined to maximize the stiffness choosing the appropriate thickness ($t_{a.op};t_{fu.op}$) for a giving adhesive property, deck plate and extra weight allowed.

The reason for the maximum value is related to the two components that compose the total deformation of SSP – see Table 3. Increasing the adhesive thickness (i) increase of the flexural rigidity D (increase of distance d – see Figure 1) and decreases the bending deformation w_b – equation(1.5) but (ii) decreases the shear stiffness S and increases the shear deformation w_s – equation(1.6). As the total deformation for the SSP system is the sum of the bending and shear deformation (Table 3), the optimum thickness combination ($t_{a.op};t_{fu.op}$) is when the increase of flexural rigidity starts not to compensate the increase of shear deformation of the system.

Table 5 table illustrates two examples of the optimum structures revealed from the graphs with W_e=70kg/m^2. On the SSP, the optimum thickness of the upper face is lower than the limit and when applied to reality this should be taken into account.

Table 5. Geometries of the optimum renovation systems for a maximum extra weight of 70kg/m^2 for existing bridge deck of 10mm.

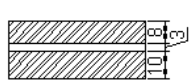
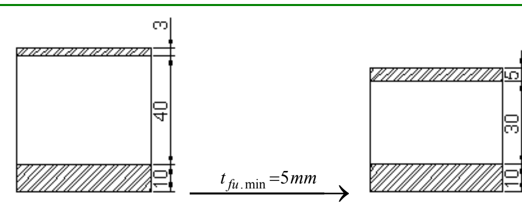
BSP	SSP
	

Figure 4 shows the same graphs but now the thickness of the deck plate is discretely varied (10mm; 12mm) and the extra weight is set to 70kg/m^2. Thus, the influence of the deck plate thickness on the stiffness is presented.

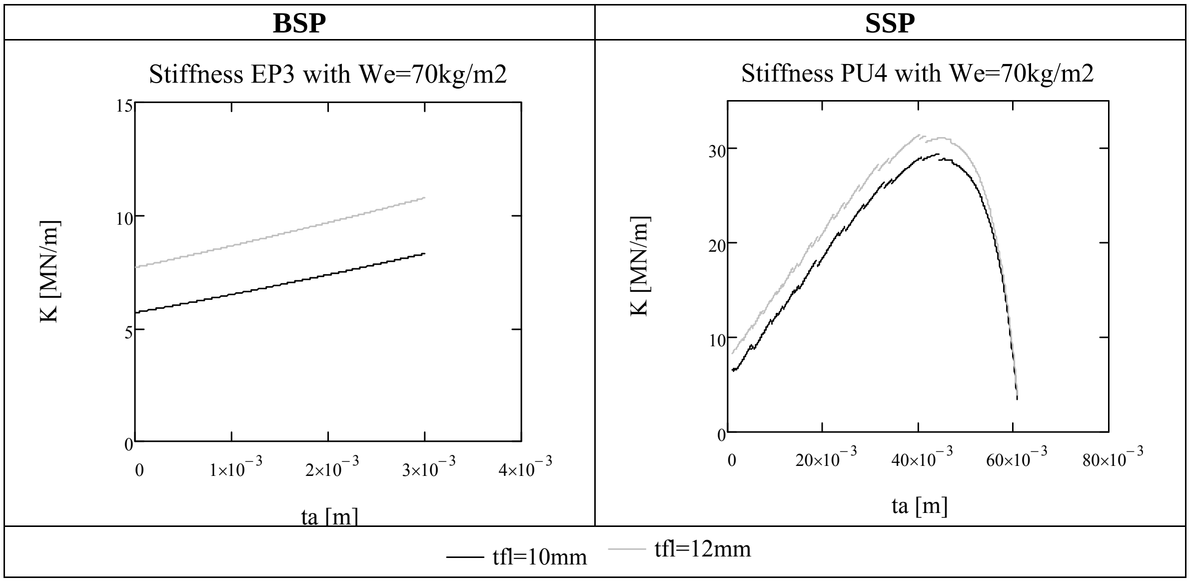


Figure 4. BSP and SSP stiffness as function of adhesive thickness t_a of EP3 and PU4 and 70kg/m^2 of extra weight.

As expected, a deck plate with 12mm thickness will have higher stiffness when the same solution is applied for a 10mm thickness deck plate.

In order to understand the influence of the extra weight on the stiffness of both systems, Figure 5 presents two graphs where the function ξ and K_{max} are plotted against the extra weight, W_e. The function ξ is defined by equation (1.11) and shows the increase of K_{BSP} and K_{SSP} from the minimum value up to the optimum solution.

$$\xi = \frac{K_{\max} - K_{\min}}{K_{\min}} \tag{1.11}$$

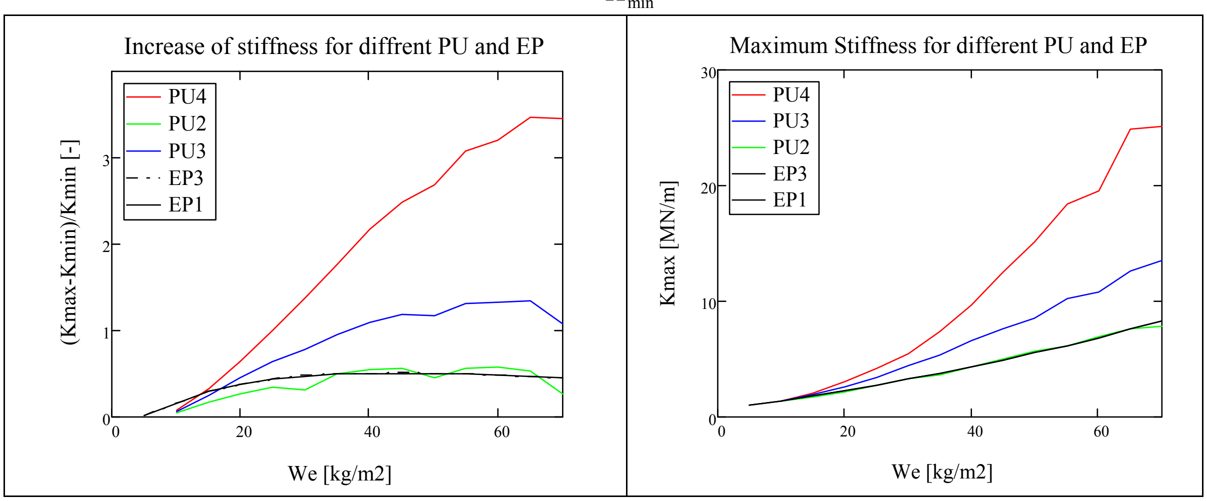


Figure 5. Increase of stiffness ξ and maximum stiffness K_{max} as function of extra weight W_e with 10mm thickness deck plate (EP – BSP and PU – SSP).

We can observe that the influence of the parameter W_e is much higher on the SSP system (polyurethane adhesives) than on BSP (epoxy adhesive). This difference is caused by the fact that as the epoxy layer has a small thickness limit, the increase of extra weight on BSP is implemented on the thickness of the upper face. However this is not the case on the SSP, where this is shared between the adhesive thickness and upper face thickness ($t_{a.op}$;$t_{fu.op}$) allowing to achieve a higher K_{max}. This advantage of the SSP system vanishes when the polyurethane adhesive is very weak (small value of G_a – PU2 and PU1) and the shear deformation doesn't compensate the rising of flexural rigidity. From right hand graph on Figure 5, we can also take the minimum extra weight necessary for a required stiffness and compare both system BSP and SSP.
Now that the influence of the layers thickness and weight parameter was studied, the missing parameter is the property of the adhesive that consists on its Young's modulus E_a and Shear modulus G_a.

On Figure 6, for different adhesives, the stiffness of each system, K_{BSP} and K_{SSP}, is plotted as function of the adhesive thickness. The extra weight parameter, W_e is fixed to 70kg/m^2 and also the thickness of the existing deck plate (lower face) is set to 10mm.

Graphs of Figure 6 present the influence of the adhesive properties (E_a,G_a) to the stiffness of each system BSP and SSP.

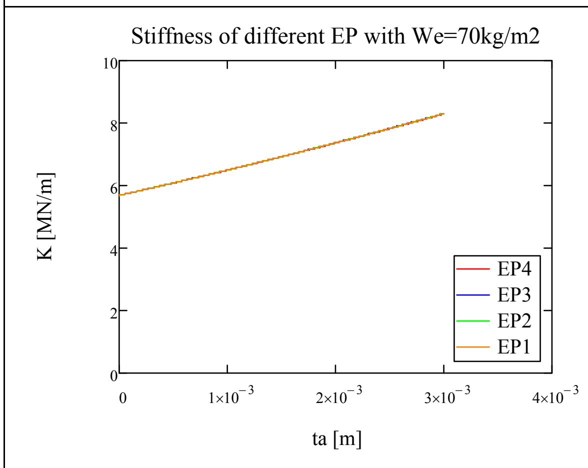
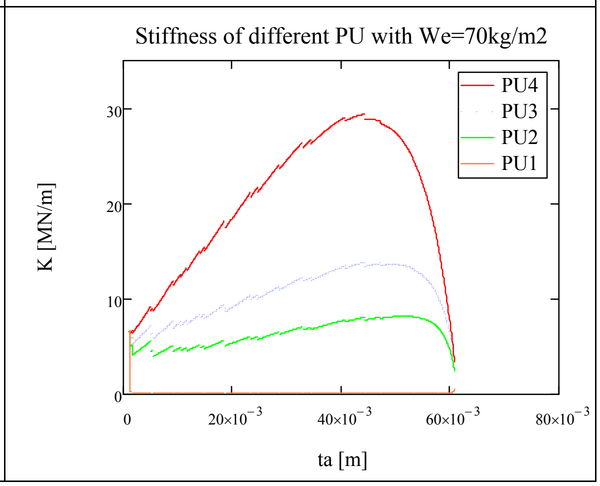
BSP	**SSP**
	

Figure 6. BSP and SSP stiffness as function of adhesive thickness t_a and 10mm thickness of deck plate and 70kg/m^2 of extra weight.

From the graph of K_{BSP} in Figure 6, we can observe that the adhesive properties don't affect the stiffness of BSP system. This is true when considering only the elastic behaviour of the materials and as long as the bonding layer assures the full composite connection. Hence, on these calculations the BSP system behaves as one single steel plate where the thickness is the sum of the lower and upper face and the adhesive has only the function to guarantee a perfect connection between these two layers. Considering this, as the stiffness of the BSP is only function of the bending deformation, only the Young's modulus is affecting this deformation when introduced in the flexural rigidity. As the Young's modulus of the epoxy is very small compared with the steel, the contribution of the adhesive in the total value of *D* is very small and so doesn't affect significantly its value.

Looking to the graph of K_{SSP}, also in Figure 6, a complete different behaviour can be observed. Stronger polyurethane adhesive leads to higher stiffness of the SSP. As the stiffness of the SSP is dependent also in the shear deformation of the system, higher Shear modulus, G_a, is traduced in less shear deformation and of course higher stiffness. For a very low shear modulus as PU1 (G_{PU1}=0.5MPa) the stiffness drastically decreases as soon as the thickness of the adhesive starts to grow. The shear deformation for this polyurethane is too high to compensate any solution of thickness.

Figure 7 shows the previous stiffness functions plotted in the same graph.

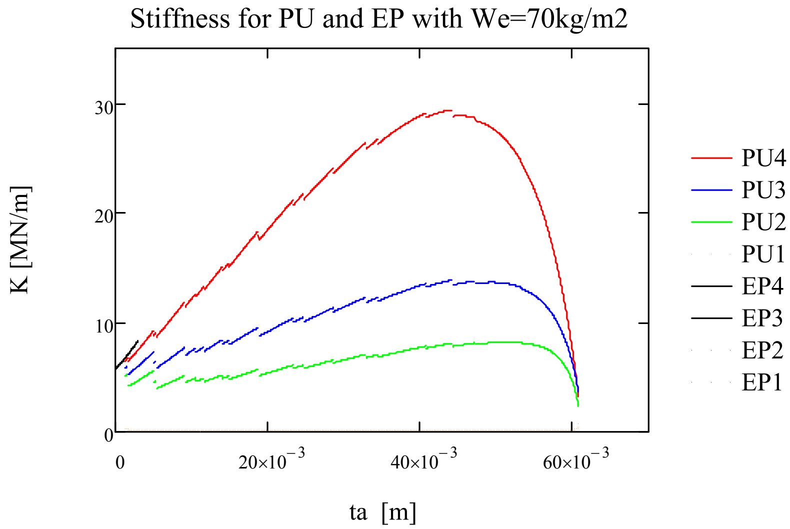


Figure 7. Stiffness as function of adhesive thickness t_a with 10mm thickness of deck plate and 70kg/m^2 of extra weight (EP – BSP and PU – SSP).

The Bonded Steel Plate system (EP – BSP) remains in the bottom left corner of the graph (black line) revealing its small range of options both in stiffness values and in thickness layers when compared with the Sandwich Steel Plate (PU – SSP) . It is also observed that a SSP is a better solution when it is available a polyurethane with high Shear modulus as PU4 (G_{PU4}=285MPa). This advantage decreases as the shear modulus of the polyurethane decreases till the point where the BSP is the best choice - PU2 and PU1 (G_{PU2}= 40MPa G_{PU1}=0.5MPa). Illustrations of the optimum geometries for each renovation system are presented in Table 5.

For establishing this minimum value of the shear modulus G_a of polyurethane adhesive from where the SSP is no longer the best solution, Figure 8 shows both the maximum stiffness of BSP and SSP as function of the shear modulus G_a and Young's modulus E_a.. The thickness of the system is set to the optimum combination of $(t_{a.op}, t_{fu.pt})$ for a fixed W_e equals to 70kg/m^2 and t_{fl} set to 10mm.

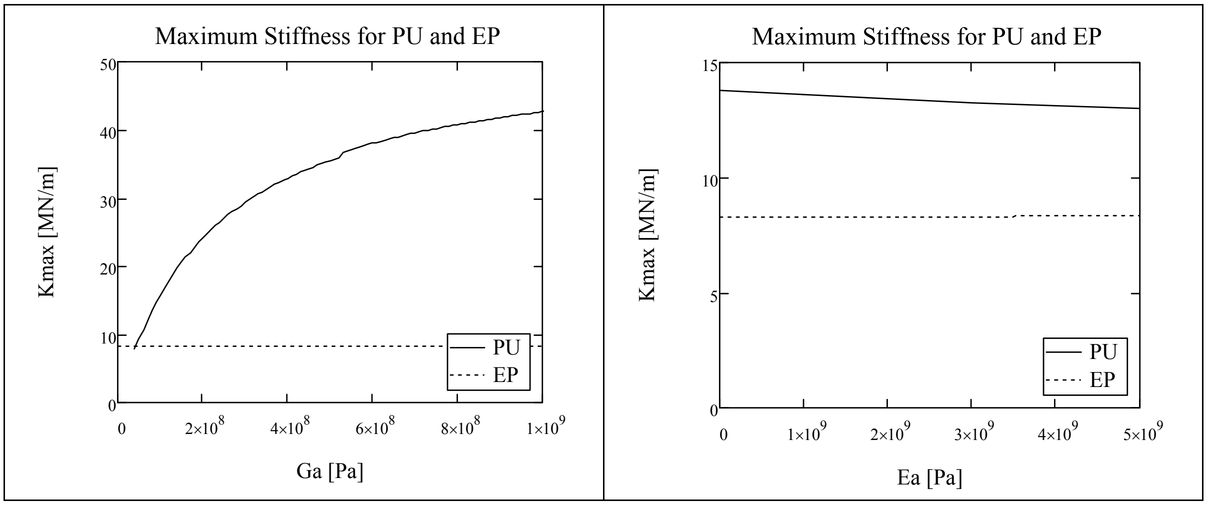


Figure 8. Maximum stiffness as function of adhesive properties with 10mm thickness deck plate and 70kg/m^2 extra weight (EP – BSP and PU – SSP).

On the left graph of Figure 8 this minimum of shear modulus is on the intersection between the function K_{maxBSP} and K_{maxSSP}. From this graph we can observe when one should choose a bonded steel plate or a sandwich structure concerning the range of available adhesives.

Thus, for a given steel deck plate with extra weight limit W_e and existing deck plate thickness t_{fl}, we can make requirement for the minimum mechanical properties of the polyurethane adhesive to apply in the SSP.

From the same graph, it can also be notice that for high values, the increase of shear modulus doesn't increase significantly the maximum stiffness of the system. The maximum stiffness K_{maxSPS} tends to a maximum limit that corresponds to the stiffness where the shear deformation is zero ($w_s \rightarrow 0$ when $G_a \rightarrow \infty$).

The right graph of Figure 8 plots stiffness K_{BSP} and K_{SPS} as functions of the adhesive Young's modulus, E_a. We can confirm that this property of the adhesive doesn't affect the behaviour of the system due to its small value when compared to steel (considering an elastic behaviour and full composite joint between layers).

Conclusions and Future Research

When opting for the Sandwich Steel Plates instead of Bonded Steel Plates with for the same weight restriction (60kg/m^2) and with height difference of only 15mm: (i) the normal stresses at the steel plate and shear stresses at the interface layer reduce approximately 50% and (ii) the stiffness rises three times.

An optimum combination of thickness at the Sandwich Steel Plates renovation system can reach high values of maximum stiffness provided by this system.

Increasing the weight limit for a renovation system is only advantage for the Sandwich Steel Plates. Using adhesive *PU4* (G_a=285MPa), 10kg/m^2 added to the weight limit, increases the stiffness in 50%.

For the Bonded Steel Plates, and as it was considered full connection between the layers and only the linear elastic behaviour, the mechanical properties of the adhesive don't affect the stiffness of the system. On the contrary, the stiffness of the Sandwich Steel Plates is affected by the shear modulus (G_a) of the adhesive but not by its Young's modulus (E_a). Higher values of polyurethane's shear modulus the leads to higher stiffness of the system.

Two limit values for this PU's shear modulus can be detected. A minimum limit value, $G_{a.min}$, required for choosing the SSP renovation system instead of BSP (for 40kg/m^2 is approximately 40MPa and for 70kg/m^2, 10MPa); and a maximum value, $G_{a.max}$, from which no improvement on the SSP's stiffness is achieved.

For future research, experiments (three point bending test) and Finite Element models will be carried out to validate the results presented.

In order to reach a practical application of the renovation systems to orthotropic movable bridges, full scale models with real geometry and real loads will be studied.

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