Case Studies in Structural Engineering 5 (2016) 18–26

Contents lists available at ScienceDirect

Case Studies in Structural Engineering

journal homepage: www.elsevier.com/locate/csse

An approach to the development of connections between fibre reinforced polymer bridge decks

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ARTICLE INFO

Article history:
Received 25 May 2015
Received in revised form 3 February 2016
Accepted 1 March 2016
Available online 4 March 2016

Keywords:
Bridge
Connection
Collaboration
Fibre reinforced polymer
FRP deck

ABSTRACT

The use of fibre reinforced polymer (FRP) bridge decks has attracted increasing interest as a competitive alternative to traditional decking solutions. Even though the use of FRP decks started in the early 1990s, the uptake of these decks has been slow in bridge construction and there remains a need for research in diverse technical areas to promote the widespread use of these decks. One such area is the detailing and design of deck panel level connections which enable rapid on-site assembly. The development of connections in FRP decks is a somewhat complex process, which should take account of not only the structural performance and durability of the joint but also the ease of application and the tolerances this necessitates. It should therefore be regarded as a process in which the bridge owner, the designer, the manufacturer and the contractor are all involved. This process has been applied in the development of a novel joint configuration for panel level connections presented in this paper. The collaboration between the bridge owner, designer, manufacturer and contractor led to the development of a connection concept, in which expectations originating from the views of all parties were included. In this way, a concept focusing on meeting the requirements of all bodies was designed.

1. Introduction

Fibre reinforced polymer (FRP) bridge decks are finding increased applications in rehabilitating existing structures or in the construction of new bridges due to the beneficial properties they offer, such as high stiffness- and strength-to-weight ratios, corrosion resistance and ease of manufacture into construction-friendly shapes [1–3]. The low weight, combined with the prefabrication of modular FRP decks, has led to bridges which can be more rapidly constructed, resulting in a better working environment and safety on site, a reduction in installation labour costs, improvements in quality control and durability, a reduction in periods of traffic disturbance and a reduced impact on road users and the surrounding community [4].

One challenge when it comes to FRP decks is the detailing and design of the joints between the prefabricated FRP deck panels. On the one hand, these joints need to be detailed to facilitate a rapid, secure installation process, which calls – among other things – for generous tolerances. On the other hand, a good fit between the prefabricated deck panels is required for stiff, safe and durable joints. The existing solutions for joining FRP decks on site have been mechanical connections in the form of shear keys or tongue and groove adhesively bonded connections [5–9], as shown in Fig. 1.

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http://dx.doi.org/10.1016/j.csse.2016.03.002

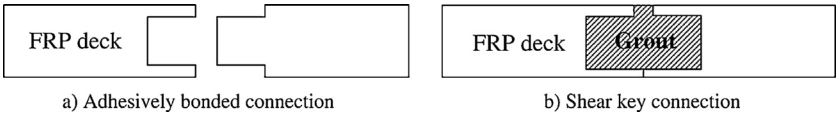

Fig. 1. Panel level connections between FRP deck panels: a) adhesively bonded connection, b) shear key connection.

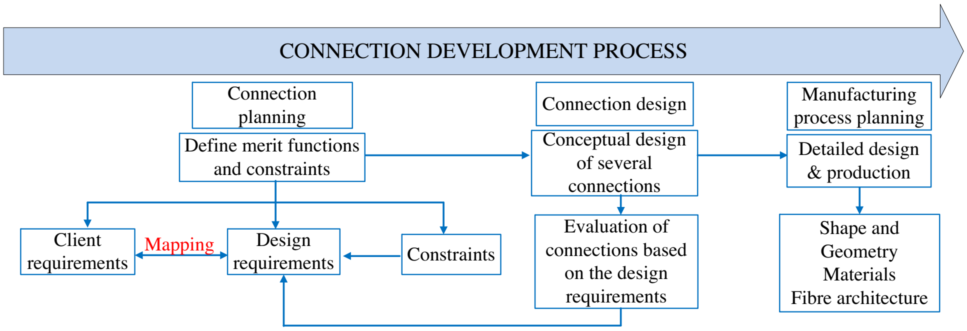

Fig. 2. The approach to the development of a connection.

Shear key connections have shown problems such as cracking and difficulty in transferring the load from one deck panel to the other in the existing constructed bridges [5,8–10]. The adhesive bonding technology is suitable for the off-site application of FRP deck panels, but it has to contend with the challenges of a long curing time and complicated application process that compromise the benefit of rapid on-site assembly [11,12]. The above-mentioned reasons call for a more convenient joining technique which is reliable and convenient for on-site assembly.

Motivated by this, an innovative panel level connection for FRP decks, which enables rapid and straightforward on-site assembly, was developed. The developed concept was the result of an interaction between the client, designer, contractor and manufacturer. The client in this paper is referred to as the bridge owner. A methodology, which is described in detail in this paper, was developed for the design of the connection, which included the aspects and demands of all the involved parties. The research presented in this paper was part of an EU-financed research project, “PANTURA” (see http://www.pantura-project.eu/).

2. Methodology

Recently, there has been an increasing emphasis on collaboration in the construction industry. This collaboration helps to deliver enhanced solutions, in which the input from different points of view is included. One successful example of effective collaboration is the ASSET project. The ASSET project was a four-year European project to develop an advanced composite bridge decking system as a solution to the disruptive and costly replacement of existing bridges and to enable the rapid installation of new bridges [13–15]. One key area of success in the project was the involvement of different partners, including research bodies, material suppliers, a contractor, a manufacturer, a designer and a local authority client, which is described in [16].

Due to the success that collaboration brings, it was employed in the design process of the connection concept presented in this study. The collaboration included a client (bridge owner), a designer, a manufacturer and a contractor. The approach to the connection development process, which consists of three main phases, is shown in Fig. 2. The phases are divided as connection planning, connection design and manufacturing process planning as seen in Fig. 2. The details of each phase are described in the following sections.

3. Connection planning

In the first phase, the merit functions and the constraints of the connection design were identified. The design of the connections should normally fulfil expectations originating from the customer (client requirements). The basic requirements for a bridge that are also regulated by codes and standards are:

- A life expectancy of approximately 50–100 years.
- Fulfil ULS/SLS requirements for all technical dimensions.
- Easy to maintain and repair.
- Affordable and environmentally sound.
- Comply with all basic regulations such as the Euro Code (EC).

These bridge requirements, originating from the client, form the basis when it comes to defining the merit functions and constraints for the design of the connections. The client requirements were defined as follows.

- *Support rapid bridge construction with no-skills labour.*
- *Affordable.*
- *Modular assembly.*
- *Maintenance free.*
- *Easy inspection.*
- *Quick repair and replacement in which no skills labour is required.*
- *Low environmental noise and vibration solution.*
- *Low energy and CO_2 solution considering the production, transport, assembly and construction of the full bridge.*
- *Safe considering health, welfare and environment.*

In addition to these requirements, the client identified design constraints such that no blacklisted materials were allowed in the design of the connection and the overall connection performance had to be secured. Additional constraints were also defined by the manufacturer, such as material, geometric shape, weight, machine capacity and cost.

The client requirements are functional, subjective requirements and they should be translated into design requirements that can be quantified and measured in order to design and evaluate the connections. Based on the client requirements and the constraints, design requirements were then defined by the designer.

While identifying the design requirements, the concept of 'design for manufacturing and assembly (DFMA)' [17,18] was also employed. The DFMA concept is used extensively in industries such as the automotive and aerospace industries, for example, to provide guidance to the design team in simplifying the product structure, reducing manufacturing and assembly costs and quantifying improvements. It is based on close communication between the design team and the manufacturing team, in order to take account of the manufacturing and assembly issues during the design process. The application of this method is relatively new and not well established in the construction industry, even though it has great potential, especially for the development of connections in bridges.

A wide range of strategies and criteria that are formulated successfully to implement DFMA can be found in [19]. They are intended to be used during the design phase as a catalyst to brainstorm ideas and distinguish beneficial practices from avoidable ones [20,21]. Some of these criteria were selected and applied as design requirements for the design of connections. In addition to these, other design parameters to fulfil client demands were identified. They are as follows.

- *Tolerances*: the connections should not be tolerance tight so that the production and assembly phases are quick and easy. If the assembly is easily done, the chance to damage the parts is less, resulting in fewer used resources and costs. Easy assembly also leads to a reduced amount of noise, vibrations and CO_2 produced by machinery and a safer environment for the workers who have to assemble. On the other hand, very high tolerances can make the assembly processes more difficult and make it necessary to undertake on-site surface finishing requirements.
- *Minimise on-site bonded connections*: on-site bonding includes health risks for workers and the adhesive needs time to develop full strength, a fact that offsets rapid construction. Moreover, the cost of on-site bonding is relatively high compared with other mechanical assembly methods due to the requirement of a controlled environment and the need of additional machinery such as hydraulic jacks. Dismantling of bonded connections is fairly impossible. It is therefore difficult to perform a quick repair and replacement in the event of damages. If the number of on-site bonded connections is reduced, less maintenance for such connections is needed.
- *Maximum repetition of the connection detail*: repeated connection details favour speed through workers learning, allows for industrialisation, modular assembly and reduced costs. The maximum repetition of a connection detail benefits their inspection as the same optimised process is followed.
- *Provide sealing*: for the connection to be durable in relation to environmental effects. Sealing enhances the durability of the connection leading to less required maintenance and costs.
- *Reduce number of parts in assembly*: reducing the number of parts enables a simplified design, as few fabrication steps are needed during manufacture, and rapid assembly. As the number of assembly parts decreases, the risk of committing errors during assembly is minimised, thereby permitting easier assembly and eventual disassembly processes. The need of maintenance and inspection is also decreased with reducing the number of parts.
- *Provide disassembly*: easy disassembly is required to enable rapid, easy replacements in the event of damage. If disassembly is possible, there is no need for demolition and the possibility for recycling is enhanced.
- *Mistake-proof connection*: mistake-proof products can be designed by allowing only one mode of assembly. If the connection can only be assembled in one way, the likelihood of making a mistake during assembly is greatly reduced. The advantages this brings are many such as rapid construction, easy modular assembly, less costs and increased safety for the workers and users.
- *Minimise movement and rotation*: designing the assembly parts to minimise movement, rotation or other non-value-adding manual effort is crucial in order to save time and cost and increase worker safety. One example of this can be assembling

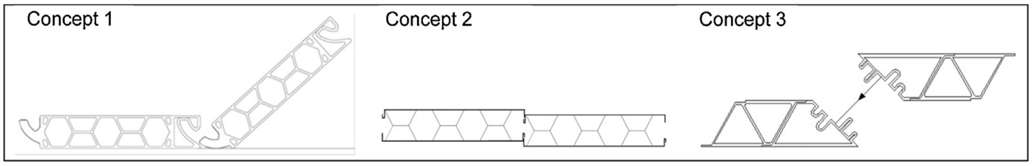

Fig. 3. Proposed panel level connection concepts for FRP bridge decks.

parts from one direction (unidirectional assembly) or taking advantage of gravity and keeping the largest mass on a low centre. By minimising movements and rotations, the risk of damaging the parts is reduced.

- *Avoid sharp edges*: parts with sharpedges can injure workers, as they require more careful handling. They can also damage product finishes and slow down the work pace.
- *Standardisation*: promotes repetition, economy in product design, development and fabrication, improved quality, less refined engineering analyses and no prototype testing. Moreover, if processes are standardised, handling and assembly operations can be more effective.
- *Avoid time-consuming fasteners*: Time-consuming fasteners delay the construction andrepair/replacement processes.

Once all the merit functions and constraints had been determined, the client requirements were translated and mapped to design requirements that could be quantified and measured in order to design and subsequently evaluate the design of the connections. The mapping of the client requirements to the design requirements helped to determine how and where the priorities should be assigned in the conceptual development of connections. The mapping was performed using a matrix (see Table 1), where the relationship between the client and the design requirements was determined by answering the question: 'What is the strength of the relationship between the client requirement and the design requirement?'. The relationship can be strong, medium or weak and carry a numerical value of 9, 4 or 1 respectively. If there is no relationship, no numerical value is assigned. To get a basic understanding of the considerations behind the relationship numerical values of 1, 4 or 9 of the design requirement to the client requirements, the reader can refer to the previous description of the design requirements. It is worth noting that Table 1 presents the final scoring that was a result of the collaboration of all the included bodies in the development of the connection.

The client requirements were also rated on a scale from 1 to 9 based on their importance (1: least important, 9 very important) by the client. This rating can be seen in the second column of the matrix in Table 1. Finally, the absolute importance of each design parameter is calculated by multiplying the cell value by the rate of the client importance and then add up the respective column. This determines the relative importance of each design requirement. Even though the scoring can be subjective, it gives a general idea of where the priorities in the design must be assigned. As a result of the translation in Table 1, two of the most important design parameters to be taken into consideration during design are to minimise on-site bonded connections and to take account of the design for standardisation.

The next step was to develop connection concepts and evaluate the developed connection concepts based on the design requirements and their importance using another matrix.

This approach to the design and evaluation of the connections was inspired and based on the idea of the quality function deployment tool. Quality function deployment is a systematic tool for designing a product in the planning phase in order to maximise customer satisfaction. It was first developed by Yoki Akao in Japan in 1966 and its efficiency was demonstrated at the Mitsubishi Heavy Industries Kobe Shipyard in 1972 [22]. It is used to guarantee design quality while the product is still in the design stage and to bring the voice of the customer into the product development process from conceptual design to manufacturing [23]. Additional information on the quality function deployment approach can be found in [24–26].

4. Connection design and evaluation

To develop feasible assembly techniques, a review of industrialised assembly methods and techniques in other sectors was made for potential knowledge transfer. The concept of interlocking connections found in the literature for use in the construction of FRP residential buildings [27,28] or footbridges [2] was found quite valuable. Interlocking connections carry the loads through geometric interference and surface friction between the connected parts.

Principally, the design requirements based on their importance, which is the outcome of the matrix presented in Table 2, were taken into consideration for the conceptual design of the connections. Several connection design concepts were developed and three of them, illustrated in Fig. 3, were pursued for further investigation. These connections were also analysed by using simplified finite element models to ensure that the proposed concepts can carry and transfer the loads from a mechanical point of view. According to these connection concepts, the connection modules are bonded to FRP deck panels off site and are then assembled on site.

Connection concept 1 allows the closing of the connection by self-weight, once the bar is introduced into the slot tilted at an angle between 30° and 42°. This concept is a mistake-proof concept, which means that the panels cannot be joined in any

Table 1
Translation of the client requirements to design requirements.

Client requirements	Rate of the client requirement	Design requirements										
		Tolerances	Minimise on-site bonded connections	Maximum repetition of the connection detail	Provide sealing	Reduce number of parts	Provide disassembly	Mistake-proof connection	Minimise movement and rotation	Avoid sharp edges	Standardisation	Avoid time-consuming fasteners
Rapid bridge construction	8	9	9	4		4		9	1	1	9	9
Affordable	8	4	9	9	4		1	4	1		9	4
Modular assembly	5			4			4	1			4	
Maintenance free	6		1		9	1			4			
Easy inspection	9			4		4	1				1	
Quick repair/replacement	9		9				9				1	4
Low environmental noise and vibration solution	5	4		1		1			1			
Low energy and CO2 solution	5	1	1	1			4				4	
Safe	9	1	9	1				4	4	9	4	
Absolute importance		138	317	179	86	79	138	145	81	89	238	140
Relative importance (%)		**8**	**19**	**11**	**5**	**5**	**8**	**9**	**5**	**5**	**15**	**9**

Table 2
Evaluation of the panel level connections based on the design requirements.

Design requirements	Relative importance (%)	Connection concept			
		Connection 1	Connection 2	Connection 3	Adhesively bonded connection
Tolerances	8	1	2	2	5
Minimise on-site bonded connections	19	4	1	4	1
Maximum repetition of any connection detail	11	5	5	5	5
Provide sealing	5	1	5	2	5
Reduce number of parts	5	4	4	4	4
Provide disassembly	8	5	1	5	1
Mistake-proof connection	9	5	4	5	3
Minimise movement and rotation	5	1	3	5	3
Avoid sharp edges	5	5	2	4	2
Standardisation	15	2	3	4	4
Avoid time-consuming fasteners	9	5	5	5	5
Total score		**3.6**	**2.9**	**4.1**	**3.2**

Tolerances: 1 = very low, 5 = high or irrelevant.
Minimise on-site bonded connections: 1 = too many, 5 = not at all.
Max. repetition of any connection detail: 1 = no or few repetitions, 5 = max. repetition.
Provide sealing: 1 = sealing needed, 5 = sealing not needed.
Reduce no. of parts: 1 = many parts, 5 = one part.
Provide disassembly: 1 = impossible, 5 = totally possible.
Mistake-proof connection: 1 = assembled different ways, 5 = one-way assembly.
Min. movement and rotation: 1 = much, 5 = none.
Avoid sharp edges: 1 = many, 5 = none.
Standardisation 1 = impossible, 5 = absolute.
Avoid time-consuming fasteners: 1 = many fasteners, 5 = none.

other way. The tolerances for this type of connection have to be very tight and precise to provide satisfactory performance. One concern of this connection concept is the opening of the bottom surfaces of the connection under service loads, which might create excessive movements of the deck and durability problems with time. Sealing is therefore considered important for this connection concept. Connection concept 2 is materialised by means of a snap-fit system, so that, once deck sections are placed, interaction between twin tongues and grooves fixes relative displacements along the length of the bridge. However, adhesive bonding was deemed vital for this type of connection. It was not possible to carry the traffic loads without adhesive according to the finite element analysis. In connection concept 3, the deck panels are assembled by sliding into one another at an angle of 45° and mechanical interaction between the tongues and grooves is ensured by geometric interference and friction. The features of this connection concept are that it is symmetric, the assembly is possible in only one way and the twin double tongue and groove system provides very good in-depth continuity. In order to avoid wear surface cracking due to possible movements of the deck elements during traffic loading, bonded FRP plates might be necessary on the top of the connection. The same idea applies also to the connection concept 1.

These developed connection concepts were subsequently evaluated according to the design requirements by means of a second matrix, as shown in Table 2. The design requirements and their relative importance resulting from the matrix presented in Table 1 are written down in the first two columns, see Table 2. Thereafter, the anticipated rate of fulfilling the design requirements of each developed connection was evaluated on a scale of 1–5. The scoring for each category is defined below the matrix in Table 2. This evaluation was done in collaboration with all the involved parties and the developed concepts were benchmarked with the typically used tongue-and-groove adhesively bonded connections for FRP decks, see Fig. 1(a). The total score for each connection is the sum of the product of the cell value related to the relative importance in Table 2.

The evaluation indicated that concept 3 in Fig. 3 fulfilled the design requirements most effectively, with a score of 4.1 out of 5. This led to the third step, which was the detailed design of the connection and the production. The detailed design of the connection was made using the finite element method and the design was further verified through experimental testing, which is described in detail in [12]. In the next Section, a brief overview of the performance of the proposed connection studied experimentally is given.

5. Experimental investigation

To verify the performance of the proposed connection, experimental work including manufacturing and testing a large-scale specimen of dimensions 3 × 3 m under static bending was carried out. The connection parts were manufactured using the infusion process because the manufacturer involved in this project had, for the time being, only the possibility of producing the connection parts with the infusion process. Otherwise, the pultrusion method could be a more efficient method for the mass production of this connection type. Production with pultrusion would provide regular, accurate geometries with minimum tolerances. The constituent materials of the connection modules were E-glass fibres and epoxy resin. Mats with chopped discontinuous fibres, which had a fibre volume content of 50%, were used for the production of the connection. This

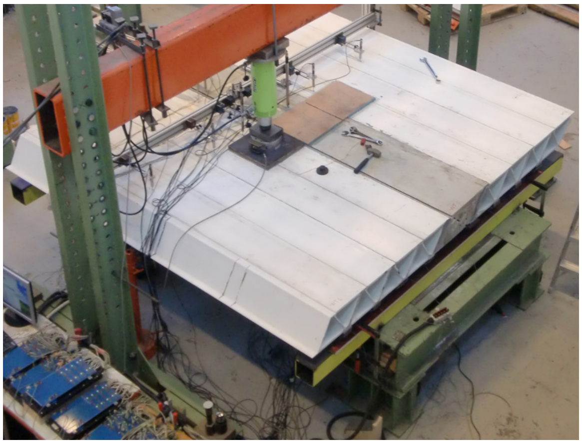

Fig. 4. Experimental set-up for testing the panel level connection concept.

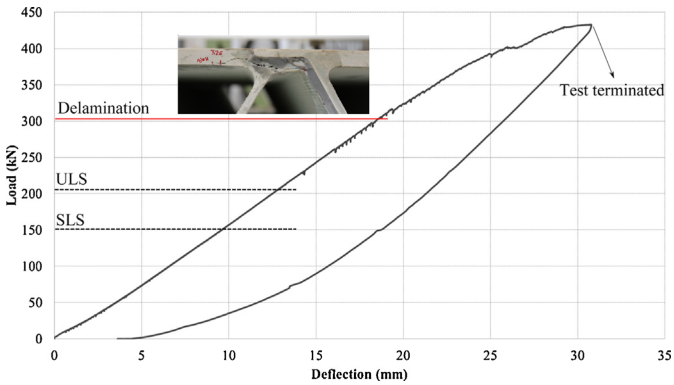

Fig. 5. Load-deflection behaviour of the test specimen.

provided a material with the same in-plane properties in the longitudinal and the transverse direction, which was validated by coupon tensile tests based on the ASTM Standard D3039/D3039M-14. The use of mats with chopped discontinuous fibres was a limitation from the manufacturer, which is further clarified in Mara et al. [12].

After manufacturing the connection modules were bonded to ASSET deck panels for testing. ASSET deck panels are pultruded fibre reinforced polymer bridge decks, a product of Fiberline Composites, Denmark (see http://fiberline.com/fbd600-asset-bridge-deck-product-data).

An overview of the test set-up is shown in the figure below. The specimen was simply supported on two steel beams on each side of the specimen in the longitudinal (pultrusion) direction, as seen in Fig. 4. The specimen was tested with concentrated loads, by means of a hydraulic jack, in different load positions. The load was applied on steel plates of dimensions 400 × 400 mm which represents a wheel load in Euro Code EN 1991–2 [29]. The specimen was instrumented with linear variable displacement transducers (LVDTs) to measure the deflections at different positions and stain gauges to measure the strains.

The measured load-mid-deflection behaviour of the specimen up to a load of 433 kN is shown in Fig. 5. The load is applied in the middle of the specimen as seen in Fig. 5.

The test was stopped at 433 kN due to the load limits of the hydraulic jack. It can be seen in Fig. 5 that the specimen is able to support considerably higher load than the ultimate limit state (ULS) load which is specified in the figure. The SLS load represents one wheel load (150 kN), according to the Euro Code EN 1991–2 [29] and the ULS load is 35% higher than the SLS load. The load-deflection curve displays pseudo-ductile behaviour. At a load of 315 kN, the first delamination failures in the flange-web intersections of the ASSET deck were observed and they progressed as the load increased. Additional information about the entire experimental study of this connection is described in Mara et al. [12]. The overall response of the proposed connection was promising according to the experimental test. In addition, the connection was effective with regard to rapid assembly, which translates a substantial reduction in the total on-site construction time. However, further tests are required to examine the behaviour of the connection in various static loading schedules as well as in fatigue loading and in different environmental effects.

6. Summary

A systematic approach to the development of an innovative connection between FRP deck panels is presented in this paper. This approach was based on close collaboration between the bridge owner, contractor, manufacturer and designer. Collaborative work was essential in the development of the connection, as it addressed different aspects of the product. Not only the primary functionality of the connection but also the productivity, buildability and serviceability were taken into account. In addition, a new way of thinking by introducing the 'design for manufacture and assembly' (DFMA) concept was embraced. The concept of DFMA helped in setting design requirements for the development of the connection. In this way, several innovative connection concepts focusing on meeting the requirements of all parties were proposed. Afterwards, the developed connections were evaluated by means of matrices which were developed specifically for the purpose of this work.

After evaluation, the winning connection concept was designed in detail and it was produced for experimental investigation. The advantages of the developed innovative panel level connection in this study are: a) it avoids the need to execute bonding operations on site; ii) it allows for more rapid installation; and iii) it makes the disassembly of bridge panels possible. After manufacturing, the connection was proven to be effective with regard to rapid assembly, which translates into a substantial reduction in total on-site construction time. The test demonstrated that the developed connection meets the stiffness and strength requirements. Slightly ductile behaviour was observed from the load-deflection curves.

The results of this study show that the proposed connection has good potential to be used for FRP decks. This, in turn, proves the efficiency of the followed approach for the development of the connection in this paper. Moreover, it supports the need for collaborative working to deliver innovative technology solutions. This methodology can also be used for developing other products than connections.

Acknowledgements

The research presented in this paper was part of an EU-financed research project, "PANTURA" (see http://www.pantura-project.eu/). The authors are grateful to the participants in the project (Trafikverket/Sweden, Mostostal Warszawa S.A./Poland and ACCIONA Infraestructuras S.A./Spain) for their collaboration and contributions.

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