MAINLINE

MAINtenance, renewal and Improvement of rail transport iNfrastructure to reduce Economic and environmental impacts

Collaborative project (Small or medium-scale focused research project)

Theme SST.2011.5.2-6.: Cost-effective improvement of rail transport infrastructure

Deliverable 3.2:
Bridges: Methods for replacement

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PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Abstract of the MAINLINE Project

Growth in demand for rail transportation across Europe is predicted to continue. Much of this growth will have to be accommodated on existing lines that contain old infrastructure. This demand will increase both the rate of deterioration of these elderly assets and the need for shorter line closures for maintenance or renewal interventions. The impact of these interventions must be minimized and will also need to take into account the need for lower economic and environmental impacts. New interventions will need to be developed along with additional tools to inform decision makers about the economic and environmental consequences of different intervention options being considered.
MAINLINE proposes to address all these issues through a series of linked work packages that will target at least €300m per year savings across Europe with a reduced environmental footprint in terms of embodied carbon and other environmental benefits. It will:

- Apply new technologies to extend the life of elderly infrastructure
- Improve degradation and structural models to develop more realistic life cycle cost and safety models
- Investigate new construction methods for the replacement of obsolete infrastructure
- Investigate monitoring techniques to complement or replace existing examination techniques
- Develop management tools to assess whole life environmental and economic impact.

The consortium includes leading railways, contractors, consultants and researchers from across Europe, including from both Eastern Europe and the emerging economies. Partners also bring experience on approaches used in other industry sectors which have relevance to the rail sector. Project benefits will come from keeping existing infrastructure in service through the application of technologies and interventions based on life cycle considerations. Although MAINLINE will focus on certain asset types, the management tools developed will be applicable across a broader asset base.

Partners in the MAINLINE Project

UIC, FR; Network Rail Infrastructure Limited, UK; COWI, DK; SKM, UK; University of Surrey, UK; TWI, UK; University of Minho, PT; Luleå tekniska universitet, SE; Deutsche Bahn, DE; MÁV Magyar Államvasutak Zrt, HU; Universitat Politècnica de Catalunya, ES; Graz University of Technology, AT; TCDD, TR; Damill AB, SE; COMSA EMTE, ES; Trafikverket, SE; SETRA, FR; ARTTIC, FR; Skanska a.s., CZ.

WP3 in the MAINLINE project

The main objectives for WP3 are to:

- investigate new construction methods and logistics for transport that minimize the time and cost required for the replacement of obsolete infrastructure. The focus here is on cost effective and environmentally sound methods that are easy to implement with low impact on the rail traffic and a short down time of the network.
- plan and optimize the construction processes on existing lines where replacement of existing infrastructure is an alternative. Here the systematic approach is extremely important. The results will help the infrastructure manager to decide for the most favourable measure from technical, environmental or cost demands.
- deliver input regarding data to the development of life cycle cost models and other decision support systems for infrastructure managers. This includes taking into account construction time and logistics, short- and long-term impact on the network, future maintenance.

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Glossary

Abbreviation/ acronym	**Description**
ACI	American Concrete Institute
BIM	Building Information Modelling
BREAMM	Environmental assessment method and rating system for buildings
BrIM	Bridge Information Modelling
CEEQUAL	Assessment and Awards Scheme for improving sustainability in civil engineering
CEN	European Committee for Standardization
DK	Deck
DoW	Description of Work
EC	European Commission
ES	End Support
ETR	Eisenbahntechnische Rundschau, journal for railway engineers
FRP	Fibre reinforced polymers
GFRP	Glass fibre reinforced polymer
HPC	High-performance concrete
HSC	High Strength Concrete
IM	Infrastructure manager
IS	Intermediate Support
LCA	Life Cycle Analysis / Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis / Assessment
LCAT	Life Cycle Assessment Tool
OHLE	Overhead Line Equipment
SB	Sustainable Bridges, EC FP6 Project
SPMT	Self-propelled modular transporter
UHPC	Ultra-high-performance concrete
UIC	International Union of Railways
WP	Work Package

1. Executive Summary

This report discusses development of existing bridge replacement methods presented in D3.1 “Benchmark of production and replacement of railway infrastructure” and also some suggestions on how to use novel or uncommon methods. While working on D3.1 it was found that many useful techniques exist throughout Europe but nevertheless not all of these are broadly known and used. All methods collected within the Benchmark in the D3.1 report are railway developed solutions best fitted to suit the individual networks of the partner railways. Further development of these railway technologies promises shorter down time of the network itself. The reader can find solutions for different types of replacement works. The focus here is on cost effective and environmentally sound methods that are easy to implement with low impact on the rail traffic and a short down time of the network. A main issue is to plan and optimize the construction processes on existing lines where replacement of existing infrastructure is an alternative. Here the systematic approach is extremely important and should always be connected to life cycle assessment. The results will help the infrastructure manager to decide the most favourable measures based on technical, social, environmental or cost demands.

The main focus in building within the railway environment is on the availability of track access. For all railway infrastructure managers this is a significant source of income. In addition, any period of track closure can affect the economics of the affected region. Consequently it is of great value to reduce any downtime period even though this may lead to somewhat increased investments in terms of labour, temporary solutions and machinery.

The main topics in this report can be categorized by:

- Development of large bridge replacement methods
- Improvement of small bridge replacement methods
- Improvement of logistics in terms of bridge replacement
- Improve use of prefabrication and production methods
- Use of advanced materials

The document serves as an important source of information for the development of the work in T3.4 which will produce a Handbook/Guideline for Infrastructure Managers all over Europe on how to propose, evaluate and select from the wide range of possible bridge replacement methods.

2. Acknowledgements

This report has been prepared within work package WP3 of the MAINLINE project by the following team with Deutsche Bahn AG as the WP-leader and Trafikverket as Task-leader:

- Deutsche Bahn AG (DB), Germany
- Trafikverket (TrV), Sweden
- Network Rail (NR), United Kingdom
- COWI A/S (COWI), Denmark
- Sinclair Knight Merz (SKM), United Kingdom
- Lulea tekniska universitet (LTU), Sweden
- Türkiye Cumhuriyeti Devlet Demiryollari Isletmesi (TCDD), Turkey
- COMSA (COMSA), Spain

3. Introduction

Bridges can be replaced in numerous ways and different countries in Europe tend to have a different set of most practised methods. Differences in bridge replacement methods can in some cases be motivated by regional requirements and by local aspects. However, it is also possible that some methods are preferred due to traditional or conservation reasons. By studying all existing methods in Europe and combining these, important improvements can be reached. Furthermore the Benchmark carried out in D3.1 identified some weaknesses in existing methods. There are further potential of improvements with small adjustments to well-known and often used replacement methods. Furthermore, it confirmed that some bridge replacement methods have not been extensively used for bridge replacement in railway infrastructure. The most promising possible improvements are:

- Reduce risks of quality and time
- Reduce costs
- Reduce track possession
- Improve sustainability, i.e. reduce material use and total emissions when replacements are necessary.
- Increase size of bridges to replace.

Suggestions to these possibilities will be studied and presented in this report. An important focus is on the improvement of logistics in terms of bridge replacement. Within the scheduling of the construction process many of the topics mentioned above can be significantly improved. Careful planning considering the particular location of the replacement activity and the appropriate railway line and surroundings are essential. This report will share railway knowledge from all over Europe to answer this challenge. Furthermore, improvement of small bridge replacement methods and development of large bridge replacement methods will be presented. In addition, advice on the use of advanced materials and better use of prefabrication and production methods are given. For a successful bridge replacement, methods need to be combined to minimize disruption and risks.

Deliverable D3.2 is a report on the activities of Task 3.2, which is described in the MAINLINE DoW as *“Development and improvement of new technologies for replacement “.* The D3.2 report is addressed to the asset maintenance engineers within the railways infrastructure owners or working for consultants and others involved in the planning and design of infrastructure renewal. Along with the “twin deliverable” D3.3 from Task 3.3 regarding replacement of switches and crossings this deliverable is intended to inform the work of Task 3.4 in producing a Guideline to replace railway infrastructure. This Handbook is the final output of work within WP3 and will feed into WP5, Task 5.5, which is to produce the MAINLINE Life Cycle Assessment Tool (LCAT).

Figure 3.1 shows schematically the general organisation of the project into work packages (WPs) and identifies the main interactions.

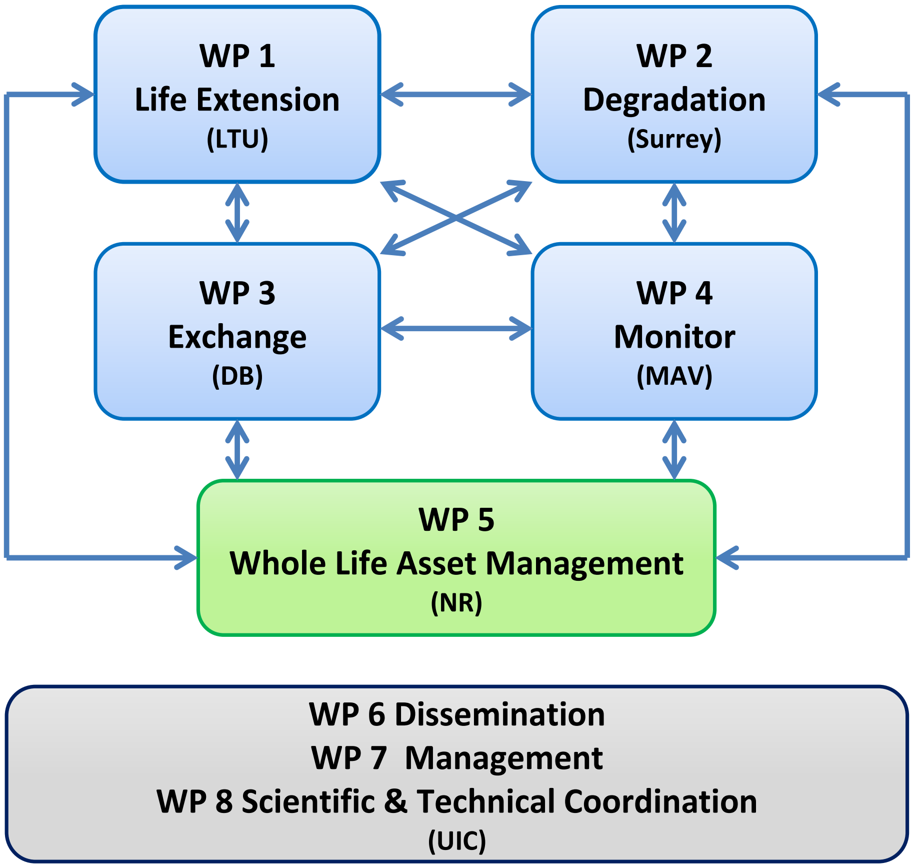

Figure 3-1 General organisation of the project

Part n°	WP3 Partners	Country
1	UNION INTERNATIONALE DES CHEMINS DE FER - UIC	FR
2	NETWORK RAIL INFRASTRUCTURE LTD	UK
3	COWI A/S	DK
8	LULEA TEKNISKA UNIVERSITET	SE
9	DEUTSCHE BAHN	DE
12	TECHNISCHE UNIVERSITAET GRAZ	AT
13	TÜRKIYE CUMHURIYETI DEVLET DEMIRYOLLARI ISLETMESI	TR
15	COMSA	ES
16	TRAFIKVERKET	SE
19	SKANSKA	CZ
20	SINCLAIR KNIGHT MERZ	UK

4. Logistics

4.1 General

Planning bridge replacement activities in the railway environment is a complex task. Different disciplines, building activities, track works and signalling etc., have to be coordinated. Furthermore, the rail traffic is temporarily interrupted or there is severe disruption. For a normal situation the available capacity is used to a quite high degree with limited tolerance for disruption. The significance of single connections strongly determines the possible interruptions needed for maintenance. Actual traffic needs to be considered in planning and certainly any future plans for the line concerned. Long-life assets like bridges need to meet a long-term strategy. In railway terms this means that any plans to increase speed, axle loading or successions of trains within the next 60- 80 years should be known when replacing a bridge. For example, known changes in line categories, becoming part of transnational corridors (either freight or passenger trains) must be considered. This is an important rule when deciding on design parameters (α-factors) and the necessary compliance with interoperability regulations and Technical Specifications of Interoperability (TSI). At a very early stage (~ 5 to 6 years prior to replacement activities) any activity influencing track availability should be declared.

Strategic considerations are made and handed over to be included in timetable planning. Here the track guiding of railways acts as a major concern. This long term construction planning can consequently result in both reduced traffic supply and longer journeys due to rerouting. Within this process the final track possession for the construction work is essentially determined by the consideration of real cost for track closure. Here different policies are followed across Europe. In some countries legal contracts between infrastructure manager (IM) and operator define the size of penalty or a negotiated length of traffic interruptions. Some contracts with operators include penalty payment from the infrastructure managers when track possession is not guaranteed. (Detailed information is available in WP5 deliverables and the WP5 LCA Tool for different asset types.) In some countries the cost for the track closure is evaluated in theory but no payment is paid physically. This background calculation serves to argue for the length of possible track closure on a line. Thereby the income, national importance of the link and other economic aspects are taken into account. Once the available track possession is determined the detailed planning process of the construction itself can be started. The implementation planning phase considers more details and looks closely on the construction process and situation. Here the surroundings and again train traffic plays an important role. Methods that fit in the time planning can be compared, evaluated and priced accordingly. Production phases are calculated in more detail: prefabrication and on-site methods are compared. A time planning with the permissible track possession is outlined.

Many so-called preparation activities before bridge replacement can be done in shorter track possessions before the main closure. This often affects the line for a longer period and manipulates the timetable. These short track possessions need good planning, too. Minor works take their time, machinery planning is necessary and safety back up is as important as for the major track possession. No improper workmanship can be accepted. Any works in track need a quality control to ensure that traffic can pass on.

4.2 Bridge information modelling in complex projects

Bridge Information Modelling (BrIM) has developed from Building Information Modelling (BIM) and is essentially the same process or tool. BIM comprises, ideally, a single digital model of a structure or system incorporating all relevant information to enable efficient design development, construction, and management of a building (or other structure). This is in contrast to the more traditional method of communicating information in construction which comprises separate two-dimensional drawings for each discipline solely providing sufficient information for construction (rather than maintenance and demolition/decommissioning, although in certain cases these may be included). A number of countries have developed guidance, standards and definitions for BIM or related to BIM, BS 1192 (2007), PAS 1192-2 (2013), BuildingSMART and NBIMS-US V2 – NIBS (2012). It can be seen from this that one of the main benefits in using BIM is better co-ordination between disciplines and stakeholders as interdependencies, conflicts and ambiguities can be more easily noticed during the design development process. One of the other potential benefits is the opportunity for information to be better controlled and managed over the lifetime of a structure, although this is yet to be proven in practice. However, it is considered that the use of BIM for asset management of structures may ultimately be the most important aspect, as one of the major challenges in maintenance of structures is retention and reliability of historic information. BIM has been used in the design and construction of complex buildings since the late 1980s (ref), although the full potential has only been realised more recently due to improvements in computer technology allowing visualisation, storage and transfer of large volumes of information or data. A good review of the history and status of BIM is provided in Eastman et al (2008).

BrIM is less developed than BIM, and has only been used in stand-alone bridge design and construction in a small number of cases, for example Shim et. al. (2011), and its use varies significantly between different countries. It has been used even less for ongoing management of bridges, although research has been undertaken on how information such as bridge condition can be incorporated into BrIM, Marzouk and Hisham, (2012). BrIM is most useful in the design, construction and management of complex bridges, whether this complexity comes from the structural material, form and details, or other aspects such as integration of multiple disciplines. For railway bridges, an example of this could be integration of permanent way, signalling and telecommunications, bridge and geotechnical engineering, mechanical and electrical engineering, architecture, when replacing multi-span railway viaducts. For railway bridge replacement in particular, visualisation of the entire construction process in detail can enable the most efficient method to be developed whilst minimising risks such as construction delays or geometric conflict.

The above discussion of BrIM suggests that it can be a very powerful tool but it should be noted that it is fundamentally reliant on good quality information. This is a challenge for railway bridge replacement and management which can often be characterised as a situation where information is limited or unreliable (e.g. incomplete record drawings, unknown historic changes) and instead engineering experience and judgement is used to provide replacement solutions that are adaptable, tolerant of minor deviations from record drawings, or have minimal reliance on the existing structure. Furthermore, the findings from the MAINLINE project show that the quality and quantity of information on old railway infrastructure in Europe, including bridges, is highly variable. In addition, in many cases the information that does exist is stored in independent forms (e.g. multiple separate spreadsheets) that would be difficult to collate into a single reliable source of information. Therefore, it is suggested that the main task that is required to enable the productive use of BrIM for railway bridge replacement, and management of railway infrastructure in general, is for IMs to collect and store reliable and extensive information on relevant existing infrastructure in a systematic way. This may not necessarily be required for all bridges and other infrastructure, but could be limited to complex or strategic bridges or a series of bridges of similar type where information could be stored in a single model. One of the very few significant examples of use of BrIM or digital modelling for informing management/maintenance of old bridge structures is the Baasis system used for Sydney Harbour Bridge (which carries a railway as well as highway and cycle/footways) and the Anzac Bridge (both in Australia). This system comprises an interactive 3D bridge model divided into numerous components, each of which can be linked to a database holding information about that component. The database information includes items such as condition ratings, past and planned maintenance, and structural assessment information. An example of the interactive 3D bridge model for Sydney Harbour Bridge is shown in Figure 4.1. The Baasis system was intentionally developed by the infrastructure manager as existing commercial BIM systems were found to be unsuitable for the purposes of ongoing management of large, complex existing bridge structures.

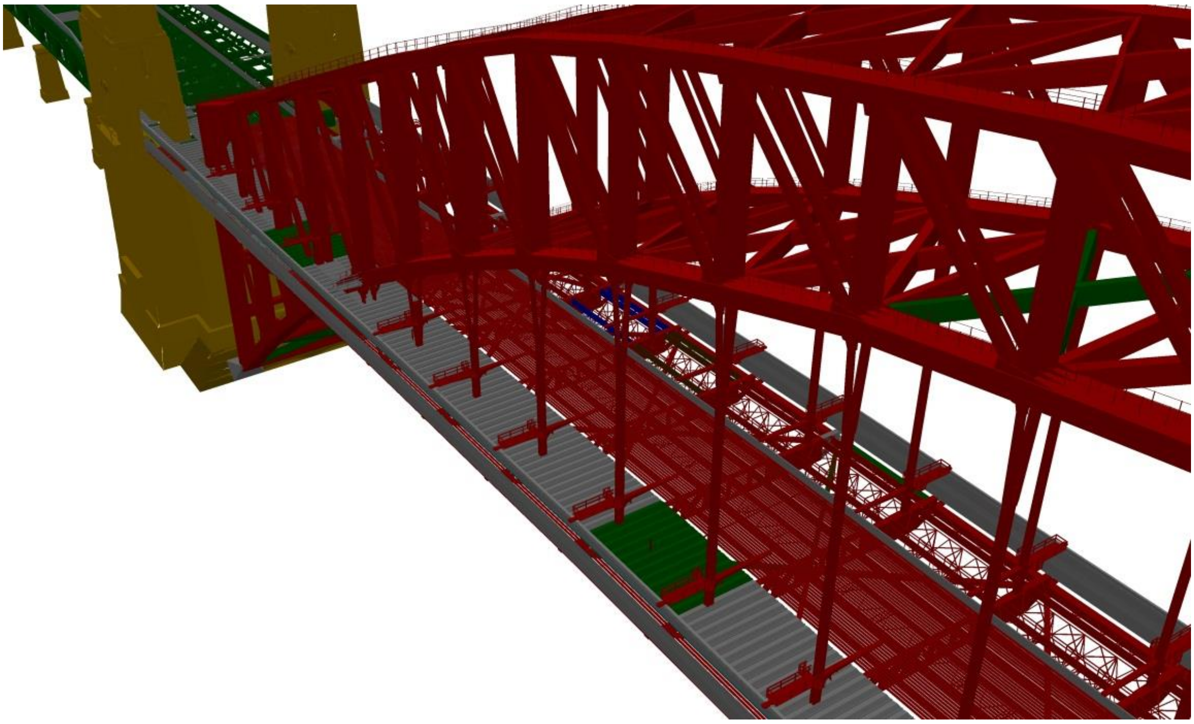

Figure 4.1: 3D model of Sydney Harbour Bridge
(courtesy of Roads and Maritime Services, Sydney, Australia)

When using BrIM during the planning period, construction period and over the full service life of a bridge, it is important to keep legal aspects in mind. The ownership and responsibility for the model must be agreed out for all stages and accessibility to information must also be granted and in some cases restricted. If the model is used during construction it will be a legal document between partners and all changes during the contract period must be well documented and traceable. With modern structural health monitoring, BrIM is an important system to keep data organized. However, availability of such data must be limited to the IM only so as to not reveal statistics on individual operators.

4.3 Preparation works with traffic

Some experiences from the replacement of road bridges are given by Meystre & Lebet (2006). They report 22 case studies of which 11 allowed full traffic during the replacement.

They conclude that rapid execution of the works is an important parameter that efficiently reduces the costs of traffic disruption. As track possessions should be minimized, it is essential to do preparation work beforehand. In the following text, the track possession is defined as the longer stop required for the actual replacement of the bridge. The preparation work will typically also need closure of track, however these closures are shorter and can often be made between trains. What is possible to do and when is very much dependent on local situations. For many bridges there are almost no limits on using the space below the bridge. For other bridges the time and space when the area below the bridge is accessible is limited. Finally, for some bridges the access is very limited also below the bridge. Nevertheless, all possible preparations should be made before track possessions. In the following a number of typical examples of preparation work are given.

4.3.1 Track

Cutting of rail can in most cases be made beforehand during a short closure of the track. Rails are cut and joined together with plates. When track possession starts, the rails can easily and quickly be decoupled without any need for special equipment. The procedure also facilitates the later installation of track once bridge has been replaced.

4.3.2 Bearings

For superstructure replacement, bearings can be time consuming to remove. Often hinge bearings are designed with some interlocking to stay in place during ordinary service and with typical corrosion the dismounting will be time consuming and should therefore be done beforehand. Often some cutting will be necessary. Also bridges without typical bearings can be difficult to release from supports. Mortar used for waterproofing or surface levelling attaches the superstructure to the supports and can cause trouble if not prepared before track possession. For superstructure replacement, the existing superstructure should be shown to be free to move before track possession.

4.3.3 Modification of supports

A typical bridge replacement is to change an old steel superstructure with direct fixed track to a superstructure allowing for ballasted track. This means that the supports must be altered to allow for ballast bed to continue over the bridge. To facilitate such work sleeper distance might need to be temporary increased. With temporarily increased sleeper distance as shown in Figure 4.2 supports can be altered for the ballast bed.

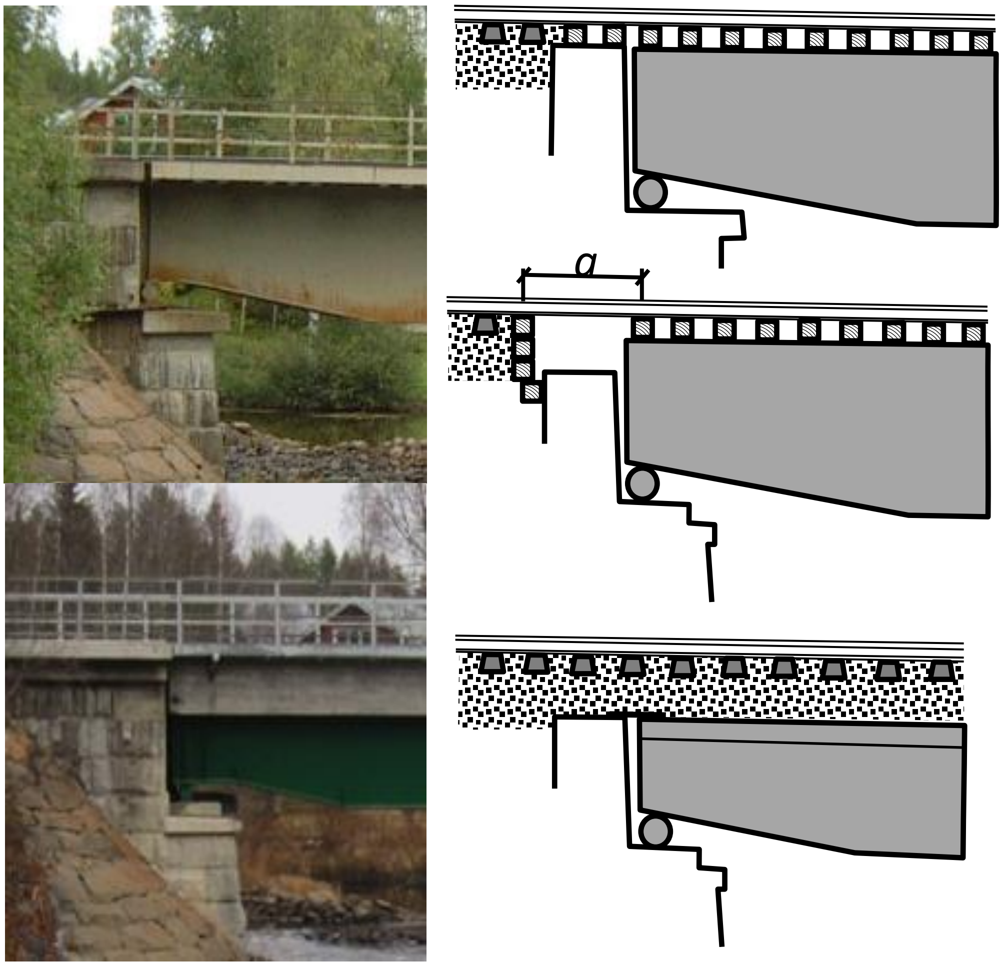

Figure 4.2: Different track lay ups and temporarily increased sleeper distance, a.

Obviously there are limitations on the increase in sleeper distance that can be allowed. In Table 4.1, suggestions for limits regarding temporarily increased sleeper distances are given for axle loads up to 250 kN.

Table 4.1: Temporary increased sleeper distance, a

Railtype	Maximum allowable speed [km/h]	With replacement [mm]	Without replacement [mm]
BV 50, 50 kg/m	30	800	750
	80	750	750*
UIC 60, 60 kg/m	30	1000	900
	80	900	900*

* Only applicable for 4-axle wagons with bogies

The distances are based on rails in good condition and cant deficiency limited to 50 mm, i.e. almost straight track. It is also required that rail supports and fastenings are stable not allowing for large torsion. Further, the figures in the table should only be seen as approximate and the allowable maximum sleeper distance should be evaluated in each case considering rail quality, rail type, track geometry, loads, extension, traffic, wagon type and other parameters.

In Figure 4.3, the temporary supporting wall holding existing ballasted track in place.

Figure 4.3: Temporary supporting wall made of soil anchored sleepers

The new superstructure is about to be lowered in place. Here also longitudinal supporting walls are used to allow the new structure to have longitudinal wings so transport along line is possible. The supporting wall can be made by timber sleepers piled and hold in place by rods anchored in embankment.

4.4 Short track possessions

4.4.1 General

Construction works influence the operational availability of railway lines. To ensure that replacement works and corresponding track closures can be included in timetables, detailed and advanced planning is necessary. Different railway networks and rail traffic situations have to be considered. In general, there is a planning process that starts approximately three years in advance. The different aspects to be considered will not be outlined in detail here. However, some key aspects should be considered already when planning for a bridge replacement. The individual importance of the line is difficult to determine. Regional trains on one hand and long distance trains including cargo trains on the other hand will influence the decision. The importance of commuter trains for the economy needs to be especially considered. Rerouting and redirecting passengers by bus are often impossible due to lack of capacity of streets and lines. Freight trains without rerouting possibilities must also be considered. To ensure a working society the planning of bridge replacement should be done in close cooperation with the planning process to find the optimal solution. With consideration to regional aspects such as rerouting possibilities, traffic intensity, available space, bridge complexity et cetera the current practice is that the typical time given for a bridge replacement differs between countries. As this report deals with bridge replacement methods, Table 4.2 shows the different track closures that are commonly available for a replacement of a bridge structure in different railways.

Table 4.2: Typical track possessions for bridge replacement works

Railway (country)	period	Remarks
Ceské Dráhy CD (CZ)	60 hours	Typically during weekends
Network Rail Infrastructure Limited (UK)	60 – 100 hours	Typically during Easter
Deutsche Bahn AG (DE)	60 hours	Typically during weekends
Danske Statsbaner DSB (DK)	56 hours	Typically during Easter
Administrator de Infraestructuras Ferroviarias ADIF (ES)	60 hours	Typically during weekends
Trafikverket (SE)	16-24 hours or 2x7 hours	Typically during weekends. Longer possession for bridge replacement carrier or two shorter with use of temporary bridge.
Türkiye Cumhuriyeti Devlet Demiryollari Isletmesi TCDD (TU)	2x7 hours	with use of temporary bridges and speed restriction

To ensure that the promised short track possession can be kept, the construction planning needs to be prepared for any expected hindrances. In the first place it is necessary to make sure that the equipment required for the construction work is ready for operation and one should think of a second set of machinery that is available at short notice. A detailed planning and a contact list of all responsible managers incl. personnel from operations are also recommended. Managers should be on standby state. To guarantee that they are ready to help if needed this should be a regional based person not responsible for too many construction sites at the same time.

4.4.2 Bridge replacement

When track possession starts the prepared rails are uncoupled and removed. With appropriate preparation work the replacement of the bridge should now be a straightforward procedure as described in MAINLINE Deliverable 3.1: Benchmark of production and replacement of railway infrastructure. The selection of best method will not be discussed here, however depending on selected method the track or ballast can be placed before or after and should be considered during planning. Also depending on selected method, removal of the old bridge from the site may be made during track possession or afterwards.

4.4.3 Placement of ballasted track

For situations when track is placed on the new bridge after replacement there are some options. One effective way is to place the track on the bridge on temporary propping and couple the track by joining plates. The props can be made of old parts of sleepers. On the propped track, wagons with ballast can go over the bridge. As ballast is unloaded the temporary props are removed continuously. When sufficient ballast has been placed on the bridge track is tamped and the track is ready to be reopened with speed restrictions. Another way of placing the track is to use a wheel loaded to place sufficient level of ballast so that sleepers and rails can be installed. With track in place, ballast is added, track is tamped and the line can be reopened with speed restrictions.

4.5 Completion work with traffic

The first trains may pass the bridge at walking speed. With additional tamping the maximum allowable speed can be increased to 40 km/h until a certain tonnage has passed. Typically 100 000 ton is needed to pass before normal speed can be allowed. Depending on traffic intensity, the speed restriction is needed for a couple of days up to a week in a typical case and also depending on local regulations. Depending on selected replacement method and available space it may be necessary to install walkways when the bridge is in place and the line is reopened. Walkways are then attached to the bridge at prepared locations with the final result as shown in Figure 4.4.

Figure 4.4: Walkways added after track possession

With continuously welded track, the track must be welded at the right temperature. It is also important to replace rails if sleeper distance has been temporarily increased. Sometimes, and dependent on regional codes, track must be replaced to avoid having welds too close to each other.

5. Efficient material use

Materials that have been developed during the last decades have not fully come to use in civil engineering in general and the railway industry specifically. Especially the use with railway loading is marginal in Europe. Nevertheless these materials are used across the world and are described here to complete this compilation of advanced techniques to replace railway bridges. Many IM own also footbridges and road bridges so their replacement activities do not only deal with railway loading and the resulting dynamic issues. Here the use of new materials can be cost and time efficient.

5.1 Fibre reinforced polymers

Fibre reinforced polymer composite (FRP) is a new construction material, gradually gaining acceptance from civil engineers. Bridge engineering is among the fields in civil engineering benefitting from introduction of FRP composite. Its advantages over traditional construction materials are its high tensile strength to weight ratio, ability to be moulded into various shapes, and potential resistance to environmental conditions, resulting in potential low maintenance cost. These properties make FRP composite a good alternative for innovative construction, see e.g. Keller (2003), Tuakata (2005), SEI (2010) and Potyrala & Casas (2011). Fibre reinforced polymer composites, developed primarily for the aerospace and defence industries, are a class of materials with great potential to use in civil infrastructure. The construction of the first all-composite bridge superstructure was in Miyun, China, in 1982. During the 30 years since, FRP has proved to be useful in a few areas of application: mostly in form of sheets and strips for strengthening existing bridge structures, and to some extent, as reinforcing bars substituting steel as concrete reinforcement, see e.g. Carolin (2003), SB Strengthening (2007), Blanksvärd (2011), and Sas (2011). Also, a number of constructions have built, in which FRP composites replaced traditional materials for structural elements (girders, bridge decks, stay cables). Among these constructions there is a relatively large amount of hybrid bridge structures, where only a part of the superstructure is made of FRP composites, and a much smaller amount of all-FRP composite bridge structures, with superstructures made exclusively of this material.

5.1.1 Definition and function

A fibre is a material made into a long filament. According to Potyrala & Casas (2011), a single fibre usually has a diameter up to 15 um. Bigger diameters generally increase the probability of surface defects. The aspect ratio of length and diameter can range from one thousand to infinity in continuous fibres. They usually occupy 30-70% of the volume of the composite and 50% of its weight. The main functions of fibres are to carry the load and provide stiffness, strength, thermal stability and other structural properties to the FRP. To perform these functions, the fibres in FRP composite must have high modulus of elasticity, high ultimate strength, low variation of strength among fibres, high stability of their strength during handling and high uniformity of diameter and surface dimension among fibres.

5.1.2 Properties

The type of fibres used as the reinforcement is the basis for classification of FRP composites. There are three types of fibre dominating civil engineering industry: glass, carbon and aramid fibres. Table 5.1 presents properties of various kinds of fibres and Table 5.2 presents values of modulus of elasticity and Poisson’s ratio for FRP composites.

The properties are also compared to other materials in Figure 5.1 and Figure 5.2, based on Carolin (2003) and Potyrala & Casas (2011).

Table 5.1: Properties of glass, aramid and carbon fibres, after Carolin (2003) and Potyrala & Casas (2011)

Typical properties	Fibres					
	Glass		Aramid		Carbon	
	E-Glass	S-Glass	Kevlar 29	Kevlar 49	HS (High Strength)	HM (High Modulus)
Density ρ [g/cm³]	2,60	2,50	1,44	1,44	1,80	1,90
Young's Modulus E [GPa]	72	87	100	124	230	370
Tensile strength R_m [MPa]	1700	2500	2300	2300	2500	1800
Extension [%]	2,4	2,9	2,8	1,8	1.1	0.5

Table 5.2: Typical values of the modulus of elasticity for unidirectional FRP composites, after Jara Mori (2008) and Potyrala & Casas (2011)

Composite (fibres/resin)	$E_{longitudinal}$	$E_{transverse}$	G	ν
	GPa	GPa	GPa	-
Carbon/Epoxy	181	10	7	0,30
Glass/Polyester	54	14	5,5	0,25
Aramid/Epoxy	76	5,5	2,3	0,34

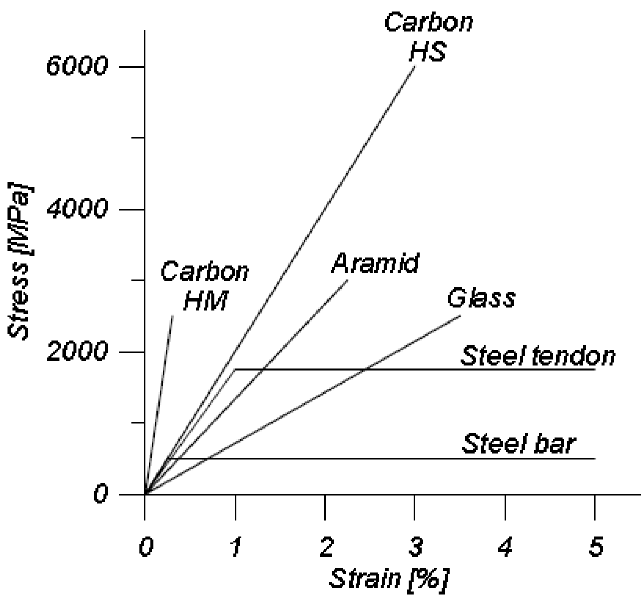

Figure 5.1: Properties of different fibres and typical reinforcing steel, from Carolin (2003)

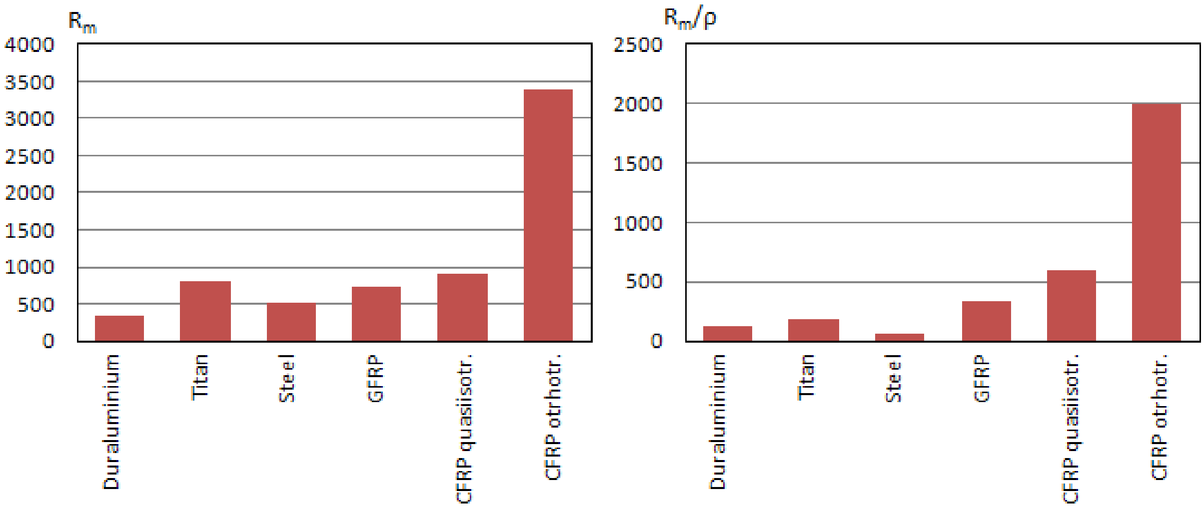

Figure 5.2 Tensile strength, R_m***, and density,*** ρ***, Potyrala & Casas (2011)***

5.1.3 Examples

FRP materials have found limited use. Denmark and UK are however using these materials both for building new structures and for strengthening existing structures. New structures are mainly footbridges, even though some rail and road bridges have been built. In Sweden and Spain FRPs are used for strengthening of existing structures. In Germany, Czech Republic and Turkey, FRPs are not significantly used for railway civil structures. In the railway sector, FRP has up to now mostly been used as footbridges crossing railway lines. One example is the St Austell Footbridge in UK, see Figure 5.3 and Figure 5.4. It is a glass fibre-reinforced polymer structure comprising pultruded and moulded elements installed on October 21st, 2007, see Shave et al (2010). The bridge is made up of three sections – two six metre side spans, each weighing two tons, and a central 14 metre span weighing only five tons.

Figure 5.3: Installing the central span of the footbridge at St. Austell, Pipex (2007)

Figure 5.4: Glass fibre-reinforced polymer bridge, Shave et al (2010)

The St Austell Footbridge, see Figure 5.4, is a light-weight glass fibre reinforced polymer (FRP) structure comprising pultruded and moulded elements, which crosses a railway line in St Austell, UK. When it was installed in October 2007, it was the first structure on the UK rail network to be entirely constructed from FRP materials. The bridge structure was designed to satisfy the aesthetic and environmental requirements of the client. Through rapid installation and the minimisation of any maintenance requirements, it has delivered economic, operational and sustainability benefits.

The Calder Viaduct in northwest England is Europe's first example of FRP being implemented to carry rail loading, i.e. LM71 with α equal to 1.1 according to BS EN 1991-2:2003 (2003), Canning and Speight (2009) and Canning (2012). The bridge comprises three spans with a total length of 50 m comprising a mix of cross girders and timber decking, see Figure 5.5 for an overall presentation of the bridge. The original bridge comprised three spans of half-through-type steel girders with timber decking and ballasted rail, constructed in 1922. Due to the coastal location of the viaduct, significant corrosion of the steelwork and deterioration of the timber decking had occurred. This type of timber railway decking on a metallic supporting superstructure is common throughout the UK. The structure was chosen for a pilot project for replacement of the timber decking with FRP composite materials. The chosen FRP decking solution comprised a standard pultruded glass fibre reinforced polymer (GFRP) deck with bonded and bolted GFRP top plate for ballast retention and wear resistance. Other types of FRP deck, such as bonded FRP pultruded sections and bespoke vacuum-cured FRP decks, were also considered. The choice of an FRP decking system was driven by a number of factors; ease of installation, adaptability, minimum depth/weight, compliance testing, durability/design life and cost. The installation method, design challenges such as achieving compliance for derailment loading, and procurement issues such as developing a generic specification to enable competition, were considered. By comparing the various FRP decking options available and their effect on ballast depth, together with proposals for repainting and strengthening the superstructure the most feasible solution was found. The FRP deck provided a highly durable system that complied with the current design standards.

Figure 5.5: Steel deck plates were replaced with FRP plates, Aspinalls (2014)

5.1.4 Outlook

FRP composites, thanks to their beneficial properties and various advantages over traditional materials, have great potential as a material used in bridge engineering. During the last 30 years, they have proved useful in a few areas: they are commonly used to strengthen existing bridge structures, see e.g. SB Strengthening (2007); they can replace steel as concrete reinforcement, and traditional materials for structural elements in hybrid and all-composite bridge structures. They exercise high specific strength and stiffness, a property particularly interesting from the point of view of designers, as it provides the possibility to consider new design concepts and also enables dead load savings, which is particularly important while retrofitting existing structures by replacing old bridge decks. Their good corrosion resistance, fatigue resistance, electromagnetic transparency and ability to withstand harsh environments make them a good alternative for traditional materials in particular cases, such as footbridges and bridge decks. Thanks to dimension stability and aesthetic appearance of FRP structural elements, they became popular as components of small-spanned footbridges in National Parks in USA (about 170 of 355 bridges listed in Potyrala & Casas (2011)) and recently in Moscow parks and train stations. Their light weight, enabling quick assembly without the use of heavy equipment, not only provide cost savings, but also make them preferable to traditional materials as a material for demountable or moveable constructions, and in cases where time-savings are crucial, in particular when minimal traffic interruption is allowed.

However, there are a number of uncertainties and disadvantages that prevent the use of FRP composites instead of traditional materials. Firstly, although many sources are very optimistic about the long-term durability of FRP materials and predict lower life-cycle costs for constructions made of them, it is not possible to fully justify the claims, because only a limited number of relevant projects have been built. High initial cost is also a big barrier. The second discouraging issue is the lack of design standards. Works on such standards are said to have been carried out for many years, but they are still not fully accepted. The problem seems to be the lack of knowledge on the material: since the properties of FRP composite depend on the quantity and orientation of fibre reinforcement, one cannot separate the design of the material and the design of the structure. As a result, usually the manufacturer has to design both the material and the construction. Finally, mechanical joints adapted from steel constructions are not appropriate for structural elements made of anisotropic FRP and the knowledge on adhesive connections is still limited. However, there is now a Eurocode under way.

FRP composites can be successfully used as structural elements in particular cases mentioned above, but they are still far from being accepted as a construction material equal to traditional materials. More projects involving FRP composites, especially those involving material-adapted concepts, are still needed to verify their long-term cost-saving and in-service durability.

5.2 High performance concrete

Concrete has been used since ancient times. Roman concrete was made with cement from volcanic ash and hydrated lime which was mixed with sand, gravel and water. The active substances in the cement are silica (Si) and calcium (Ca) which together with oxygen (O) form the binder, calcium silicates, 2á3(CaO)·(SiO_2). Modern concrete started to be used during the industrial revolution when cement clinker could be produced in kilns, Davies (1925). The strength of the concrete depends on the concentration of the cement glue. The concentration is characterized by the water/cement ratio. By using additives the ratio can be lowered and the strength increased. Nowadays concrete can be tailor-made with different properties for different applications. For bridges, properties such as strength and durability are quite important. When the compression strength exceeds about 80 MPa the material is usually called High Strength Concrete (HSC). High-performance concrete (HPC) is a relatively new term for concrete that conforms to a set of standards above those of the most common applications, but not limited to strength. While all high-strength concrete is also high-performance, not all high-performance concrete is high-strength. Some examples of such standards currently used in relation to HPC are:

- Ease of placement
- Compaction without segregation
- Early age strength
- Long-term mechanical properties
- Permeability
- Density
- Heat of hydration
- Toughness
- Volume stability
- Long life in severe environments

Ultra-high-performance concrete (UHPC) is a new type of concrete that is being developed by agencies concerned with infrastructure protection. UHPC is characterized by being a steel fibre-reinforced cement composite material with compressive strengths in excess of 150 MPa, up to and possibly exceeding 250 MPa. UHPC is also characterized by its constituent material make-up: typically fine-grained sand, silica fume, small steel fibres, and special blends of high-strength Portland cement. Note that there is no large aggregate. The current types in production (Ductal, Taktl, etc.) differ from normal concrete in compression by their strain hardening, followed by sudden brittle failure. Ongoing research into UHPC failure via tensile and shear failure is being conducted by multiple government agencies and universities around the world, see e.g. Schmidt & Fehling (2004).

5.2.1 Properties

High Strength/High Performance Concrete (HSC/HPC) is the object of extensive research, and its use in construction is increasing continuously. The high strength is obtained by reducing the water/cement ratio giving a higher strength of the cement glue. This is often done by adding a super plasticizer to increase the wetness of the concrete mix. It can also be achieved by increasing the activity of the cement paste by grinding, see e.g. Justnes et al (2007), Jonasson et al (2009) and Pike et al (2009).

The *fib* Bulletin 42 (2008) summarizes the available information on the material behaviour of HSC/HPC, and develops a set of code-type constitutive relations. Literature on experimental data and international guidelines, standards and recommendations are reviewed, and already-existing constitutive relations and models are evaluated. A design handbook and design examples for bridges were developed in a Swedish Research Project, see Elfgren & Apleberger (2000a, b). In the 1960s concretes with a compressive strength of up to 800 MPa were developed and produced under specific laboratory conditions. They were compacted under high pressure and thermally treated. In the early 1980s the idea was born to develop fine grained concretes with a very dense and homogeneous cement matrix preventing the development of microcracks within the structure when being loaded. Because of the restricted grain size of less than 1 mm and of the high packing density due to the use of different inert or reactive mineral additions they were called “Reactive Powder Concretes (RPC)”. Meanwhile there existed a wider range of formulations and the term “Ultra-High-Performance Concrete” or – in short – UHPC was established worldwide for concretes with a minimum compressive strength of 150 MP, see e.g. SETRA-AFGC (2002), Schmidt & Fehling (2004), FHWA (2013). Also the tensile strength may be quite high, in the range of 10 MPa, see Figure 5.6.

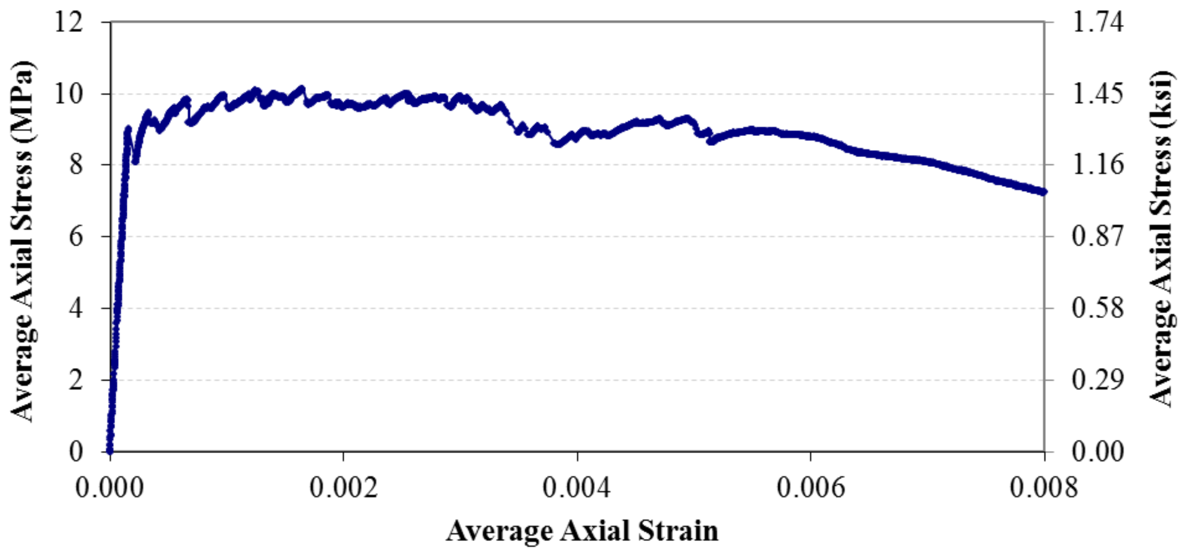

Figure 5.6: Tensile stress-strain response of UHPC with 2 percent volume of steel fibre reinforcement, FHWA (2013).

The fatigue properties are good; see e.g. Makita & Brühwiler (2013) and ML-D1.3 (2014)

5.2.2 Examples

The Japanese economy is very dependent on the railway system for transportation of materials and people. About 50 percent of the Japanese population uses the railways each day. Consequently, any interruption to traffic flow must be minimized. In addition, working space is very limited alongside the railway lines in urban areas. For improvements on the Chuo Line at the Tokyo station, new structures were built alongside the existing railroad bridge and then jacked laterally into place. The Japanese also have found it feasible to incorporate temporary girders into permanent girders, as depicted in Figure 5.7. A temporary bridge was first erected alongside an existing multi-arch viaduct using span lengths equal to those of the original viaduct. Train traffic was diverted to the temporary bridge (Figure 5.7 top) while the original viaduct was demolished. The depth of the temporary girder was then increased by adding girders below the temporary girders. Formwork was then added (Figure 5.7 middle) and the two girders were encased in concrete while the bridge was still in service (Figure 5.7 bottom). Finally, the new bridge was moved laterally to replace the previous viaduct. Intermediate piers were then removed so that the four original arches were replaced with a two-span bridge. This method reduced the period of railway service interruption, night-time work with closed tracks, site work, and total cost.

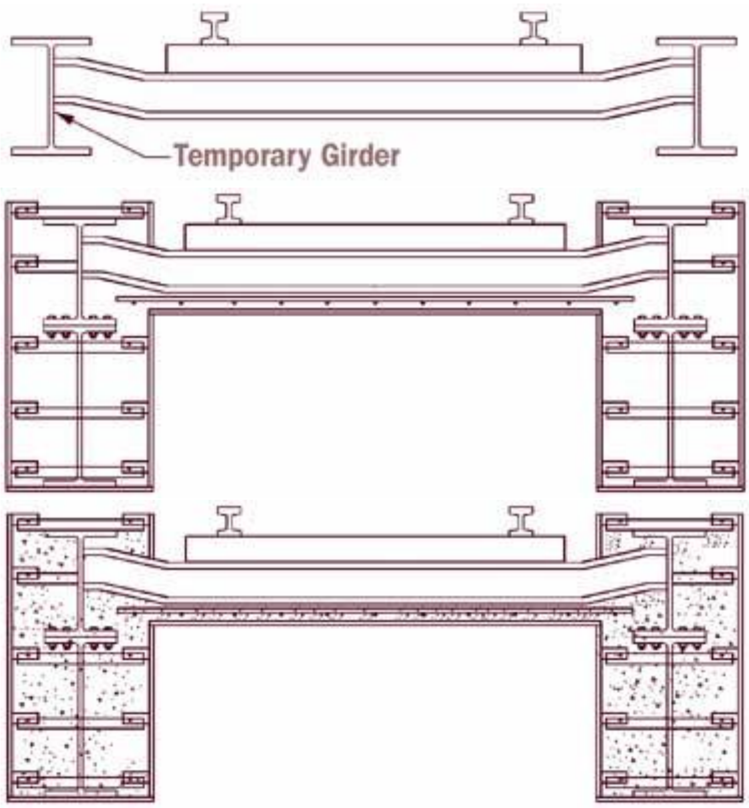

Figure 5.7: Use of temporary girders as part of the permanent structure, FHWA (2005)

On the new Joban Line near the Kita-Senju station, segmental precast girders were used to construct a bridge for a new railway line between two existing lines while keeping the lines in service. The sequence of construction is shown in Figure 5.8. After construction of the first two spans, the next girder was assembled on top of these spans (Figure 5.8a). A temporary steel erection girder was then placed in the next span (Figure 5.8b) and a suspension girder positioned above the span (Figure 5.8c). The concrete girder was moved across the span on the erection girder and hung from the suspension girder (Figure 5.8d). The erection girder was moved forward to the next span. The concrete girder was lowered into its final elevation (Figure 5.8e). The concrete girder was moved laterally to its final position and the sequence repeated for a second parallel concrete girder. The whole process was repeated on the next span.

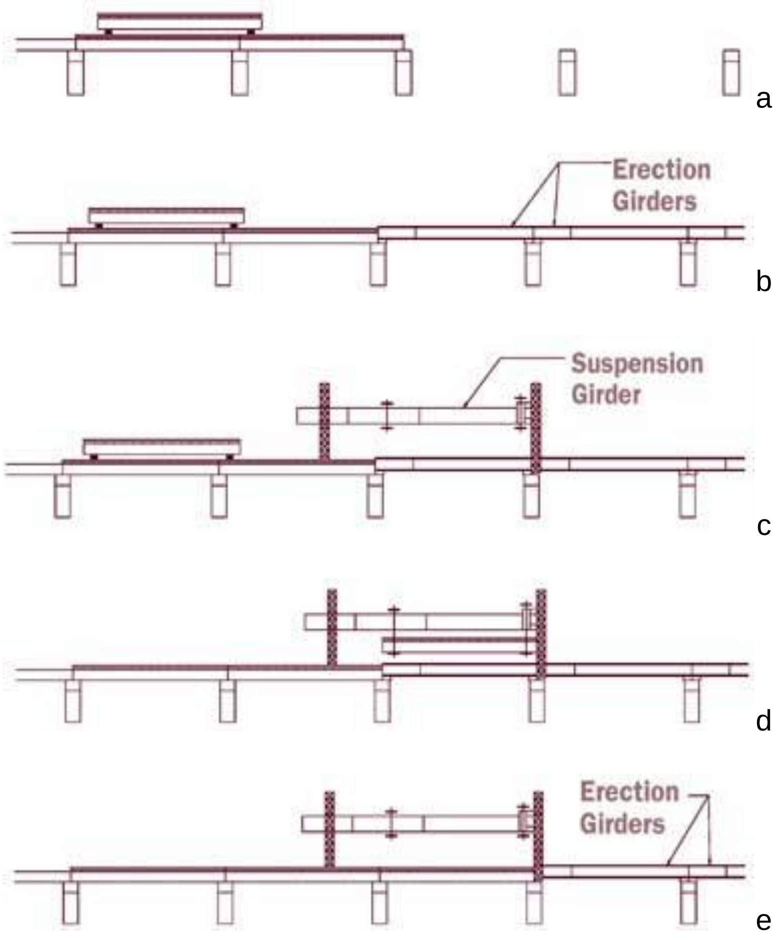

Figure 5.8 a-e: Construction on the new Joban Line, FHWA (2005).

5.2.3 Outlook

There are quite a few highway bridges being built with high performance and ultra-high performance concrete. So far not many railway bridges have been built but there is a great potential for this.

6. Production methods

6.1 Prefabricated bridges

Prefabrication, which can increase the rapidity of execution, is often an effective solution that for zero to medium increases in construction costs provides at least equivalent results in quality. The definition of prefabricated bridges is not obvious for railway bridges. Often when prefabrication is discussed, the underlying definition is that relatively small elements are produced in a stationary factory. In the railway environment, prefabrication also includes construction of a complete bridge at a temporary site just next to the final position. Such production can be controlled, does not normally have critical time restrictions and the bridge is prepared for transportation to its final position during a short track possession. Traditional prefabricated elements are however also possible to use in the railway environment as long as they allow for installation and desired quality at joints. In the following sections both types of prefabrication will be presented.

6.2 Standard bridges

All of the following standard bridges can be designed to load model LM71 with α=1.33 and can be prepared for speed conditions up to at least 200 km/h. It should be noted that all standard bridges need to be thoroughly considered and adjusted to fit the specific project and the given conditions.

6.2.1 Total bridge replacement- RC Frame

If the foundation structure is also to be moved to the permanent location, it requires certainty of good soil conditions. It should be noted that, even though the concrete abutments and piers are precast as a part of the total structure, it is still necessary to have some preparations before placing the structure. Typically 30 centimetres of compressed gravel and 5 centimetres loose gravel on top under normal soil conditions. If the foundation level is very deep or piling is required, additional time of track closure is needed, and the time advantage of this quick total bridge replacement is reduced.

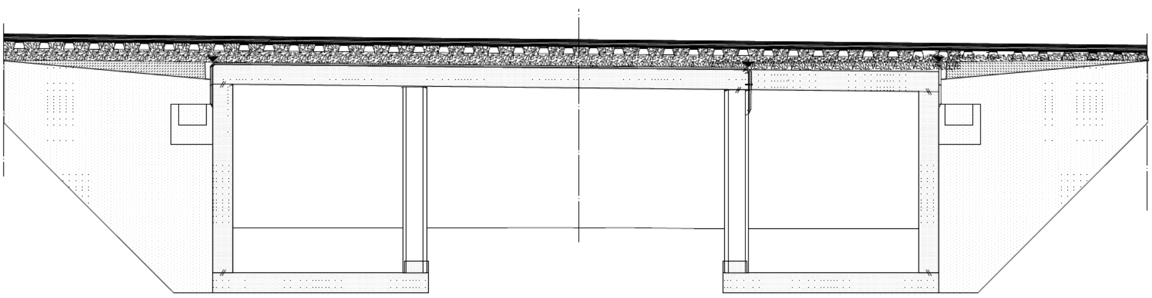

Figure 6.1: Longitudinal section of standard concrete bridge

This layout of the bridge facilitates two lane road traffic and a pedestrian/bicycle lane on each side. The pedestrian area is separated by concrete columns. The length of this standard bridge is approximately 25 meters and the weight around 1,000 tons. The edge beams are designed with integrated cable channels, so these can be placed outside the ballast layer. Furthermore, a small secondary railing is mounted next to the tracks to keep loose ballast stones from falling out between railings and hit road traffic underneath.

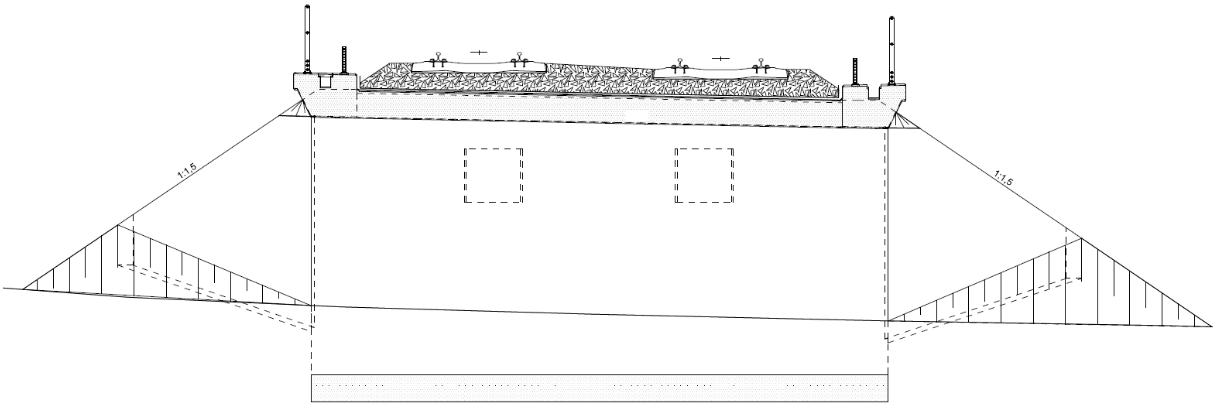

Figure 6.2 Cross section of standard concrete bridge

The method requires space close to the railway line in order to provide a reasonable construction site. It is noted that establishment of scaffolding, crane work, earthworks, concrete castings and general space for materials often requires significant space.

Details of design

As a part of the project the new structure was designed to be horizontal launched. Therefore cantilevers were cast on the rear of the abutment walls. These cantilevers were designed to the actual load model for launching. This temporary situation of launching caused different forces through the structure which caused supplementary reinforcement in parts of the structure.

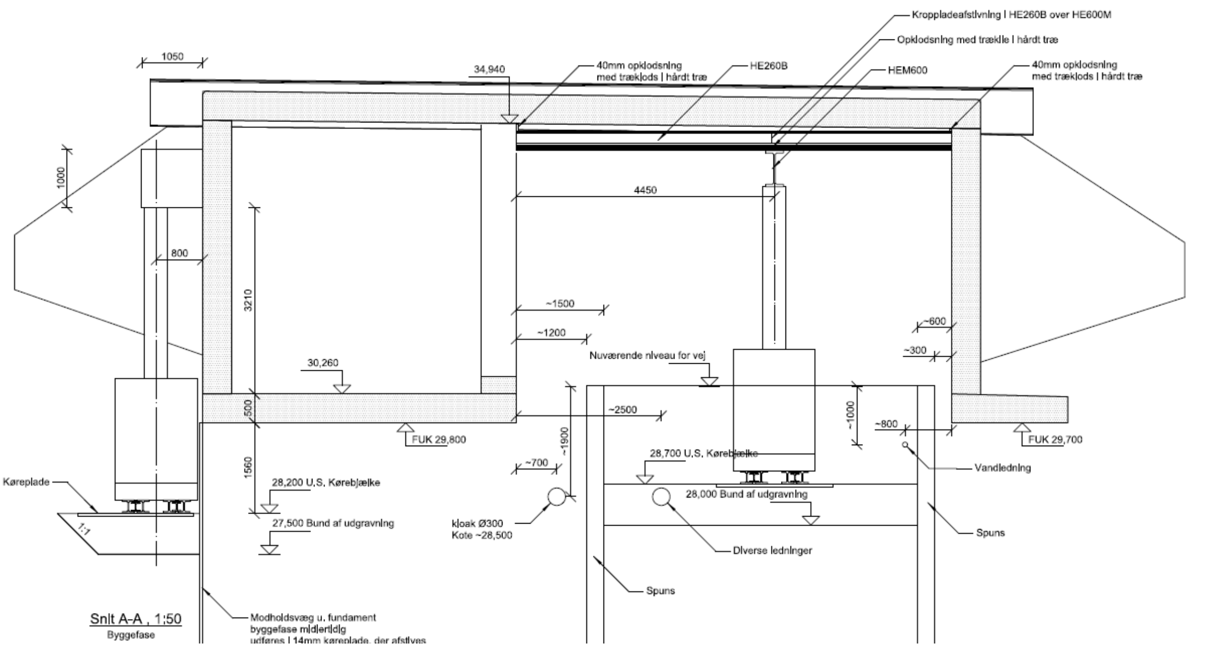

Figure 6.3: Cross section

The two cantilevers are shown in the picture below.

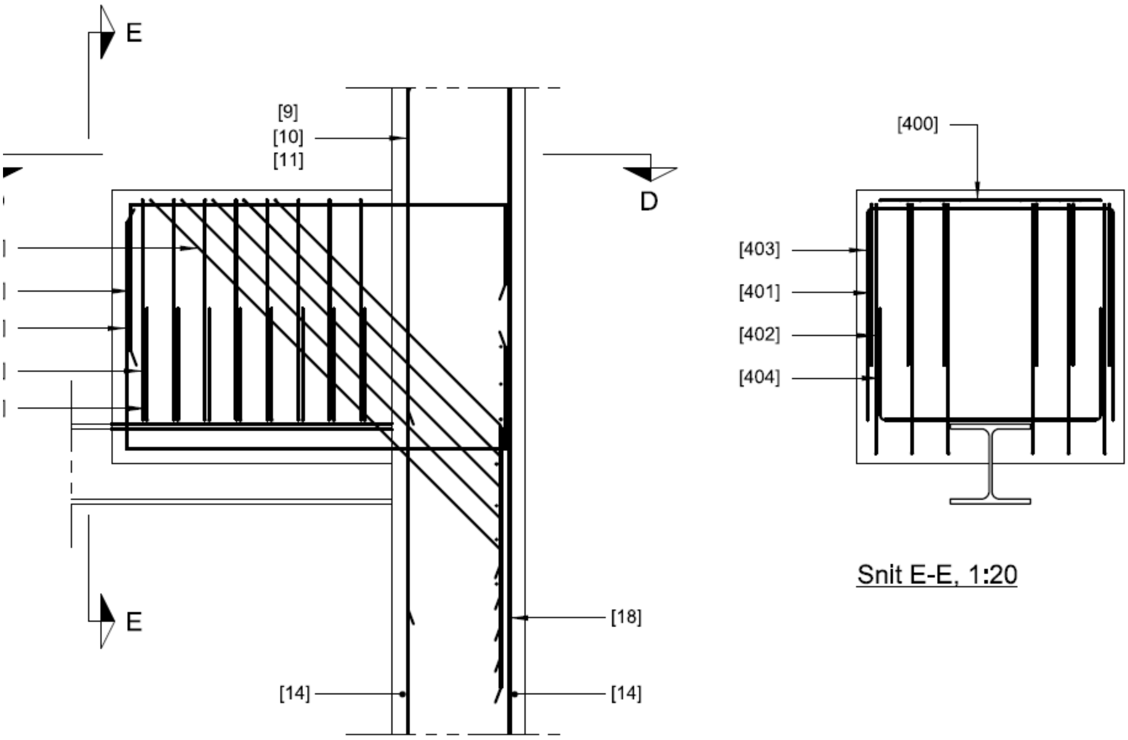

Figure 6.4: Cantilever beams for lifting

6.2.2 Total bridge replacement, Minor Bridge – RC frame

In situations where only a pedestrian tunnel is needed, very simple construction types can be used. Prefabricated concrete bottom and top elements can be used to establish or replace a tunnel under a rail line. The construction site is thereby reduced to a minimum, as well as the time period of rail line closure needed for execution. The establishment of the new tunnel can be executed in a weekend (approx. 48 hours). The elements can be placed by crane on compressed gravel. The method requires general good soil conditions.

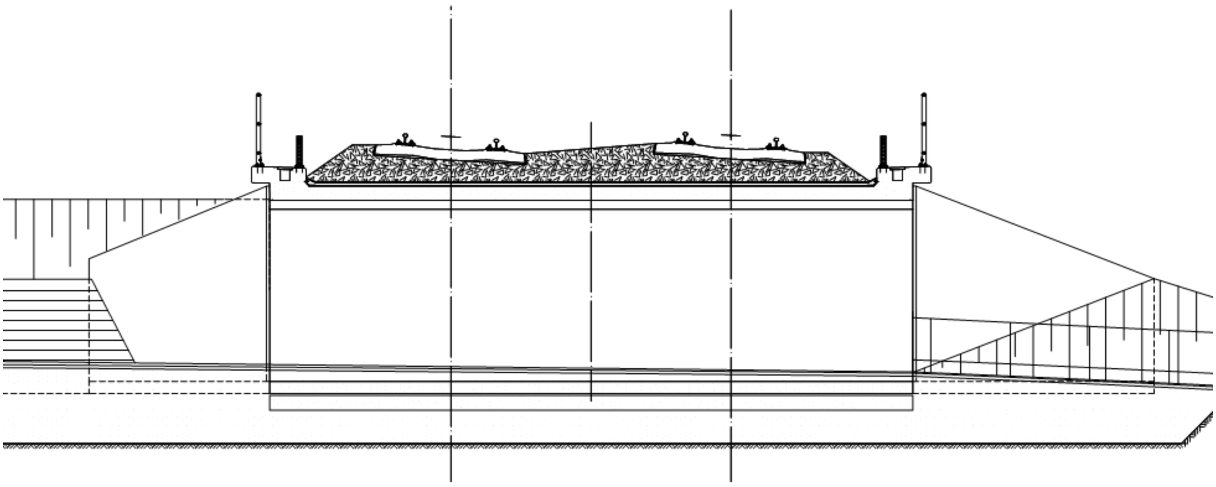

Figure 6.5: Cross section

All elements are prefabricated. It is therefore necessary to consider the design of edge beams, wing walls etc., so that elements can easily be assembled, and so the number of joints is limited. All joints need to be sealed by concrete casting or waterproofing.

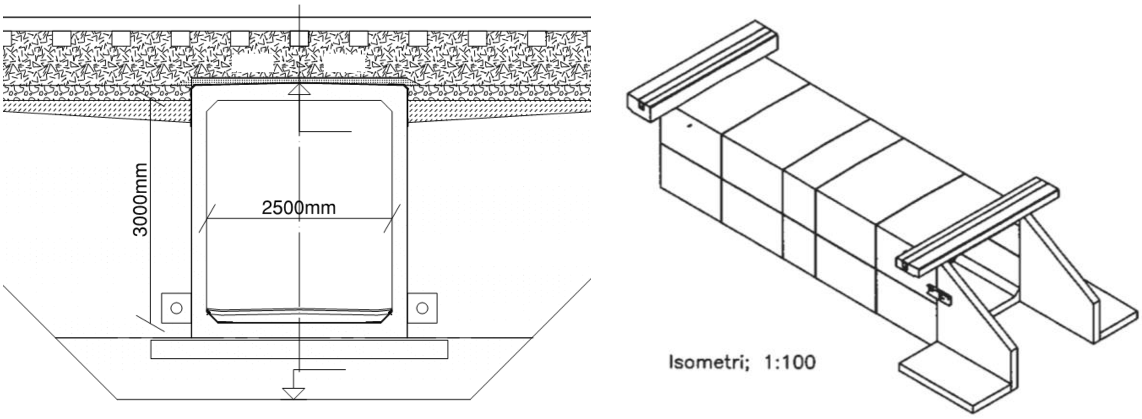

Figure 6.6: Longitudinal section and isometric view

This construction method is favourable for minor tunnels with limited span lengths and height, so that crane work can be executed with standard equipment. In Figure 6.7 assembly of prefabricated elements is shown

Figure 6.7: Assembly of prefabricated elements by crane

Assembly of elements is more time consuming compared to horizontal launching of a complete bridge. The method can still be competitive in areas where space is limited, longer track possessions are available for other reasons or if costs for bridge construction itself are critical.

Figure 6.8: Bridge in service whilst finalizing work is made

The asphalt, paving and general finishing works were done without interfering with rail line traffic.

6.2.3 Superstructure replacement – Concrete

In situations where a bridge construction needs to be replaced, but where the substructure can be saved, it is possible to reduce the period of disturbing rail line traffic. The substructure may need strengthening with additional concrete and reinforcement or small stage demolishing followed by subsequent reconstruction and/or strengthening. The preparations on the substructure may partly be executed while the old bridge is still functional. In situations with difficult soil conditions, it is still possible to maintain railway traffic, as long as any effect on the still functional bridge is addressed. The new superstructure can be constructed next to the rail tracks, and during a short rail line closure the superstructure is moved into place. In order to construct a new deck next to an operating rail line, it is necessary to have sufficient space to establish the construction site - the conditions have to be carefully analysed, when a replacement is planned to take place in cities or other densely built areas.

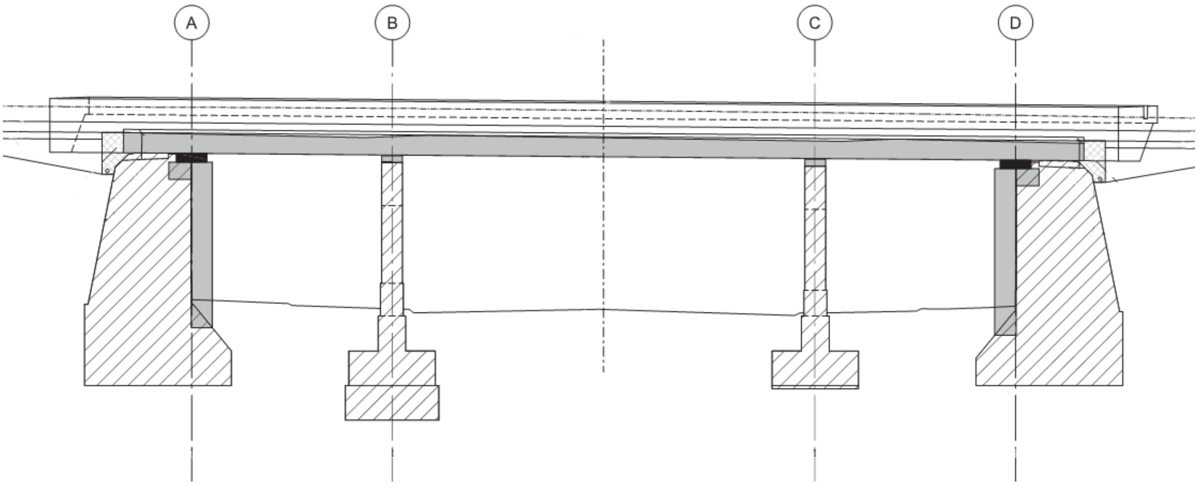

Figure 6.9: Longitudinal section with strengthened substructure

The length of the deck can be several hundred metres. The execution phase can be completed in a period of 1-3 days depending on the specific project. When replacing a superstructure it can be designed to allow for modern track. Figure 6.10 presents a superstructure with large main girders on both sides and a transversally carrying slab between in order to reduce the thickness of the slab and thereby increase the ballast layer which was not sufficient on the existing bridge.

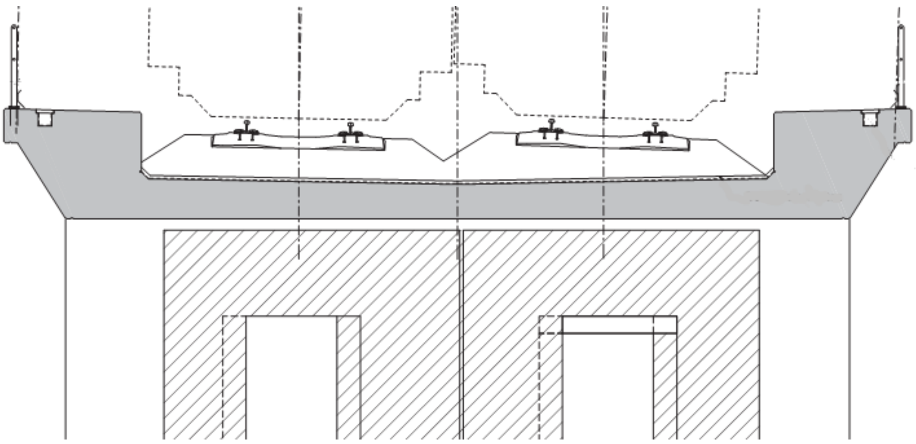

Figure 6.10 Cross section with strengthened and widened supports

In this specific case, the new deck was built 5 metres above ground level on scaffolding in order to maintain road traffic under the bridge during the construction period. To create sufficient space for the construction site, the neighbouring gardens were temporarily expropriated and lamp posts were removed.

Figure 6.11: Launching in progress

In the period of line closures the new superstructure including scaffolding was pulled on two support lines on a heavy temporary foundation. The deck was lowered on the substructure, and the earthworks and establishment of sleepers and tracks were finished. The line was opened for traffic, and the scaffolding was removed afterwards without interfering with track or road traffic.

The existing substructures needed to be improved in order to reuse them. The foundation slab was widened by establishing sheet piles as a part of the formworks. Thereby the deep foundations conditions did not require much spacing for earthworks and the undergoing road traffic could function without disruption. When the concrete casting was done the sheet piles were cut off as deep as possible.

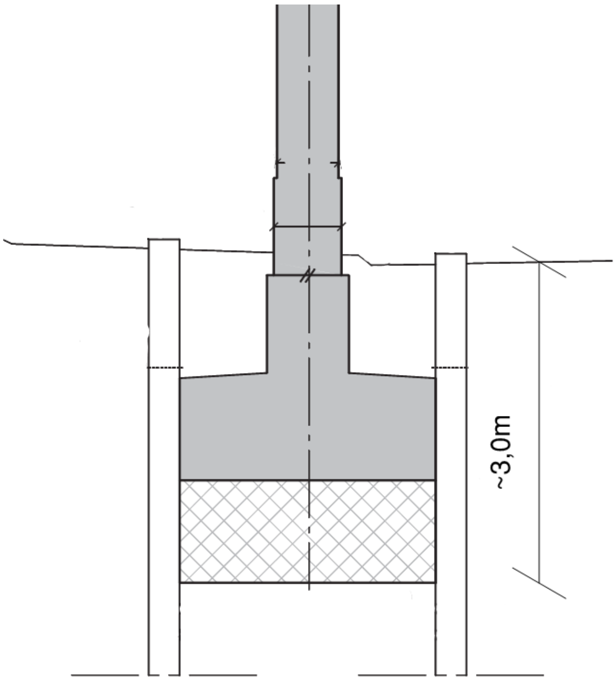

Figure 6.12 Widening of foundation

As a part of the preparation for the launching phase a layout of underground cables was made, see Figure 6.13. It was very difficult to establish foundation of the temporary scaffolding and the foundation for the launching system. However the overview of underground cables helped the contractor to evaluate the conditions and had a huge impact on the contractors bid.

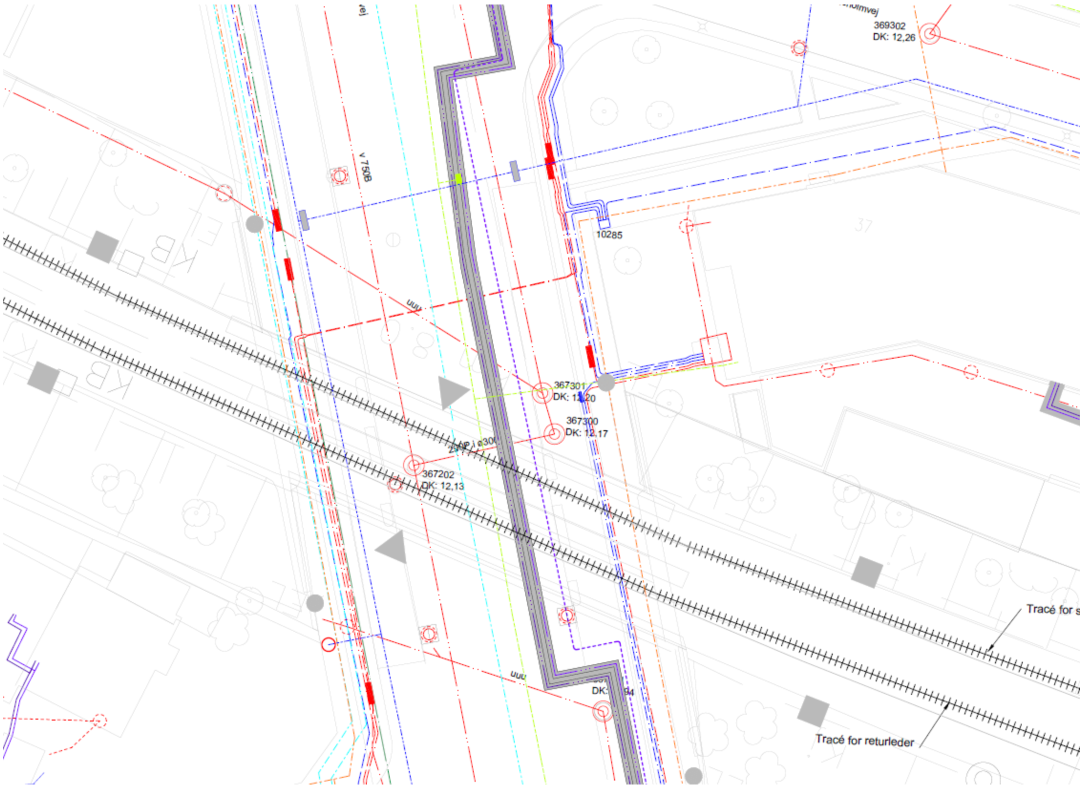

Figure 6.13: Layout of underground wires

6.2.4 Superstructure replacement – Steel

A steel superstructure may have some advantages to a heavier concrete solution. Instead of building the superstructure at the construction site next to the railway line, it is possible to carry out the complicated steelworks in a workshop under controlled conditions. When the welding is done and the coating is hardened, the finished structure is transported to the location shortly before track closure. The relatively light structure can be installed from either road or railway, depending on the most favourable position of the crane. This solution is ideal in situations where an adequate construction site is hard to establish, for instance in cities. Off course, it is still necessary to complete the works on the substructure on site. These reinforcement works can partly be executed without interrupting railway traffic and regardless of soil conditions. The design is possible with spans up to 20 metres, and the new construction can be established within a period of 1-2 days of railway line closure.

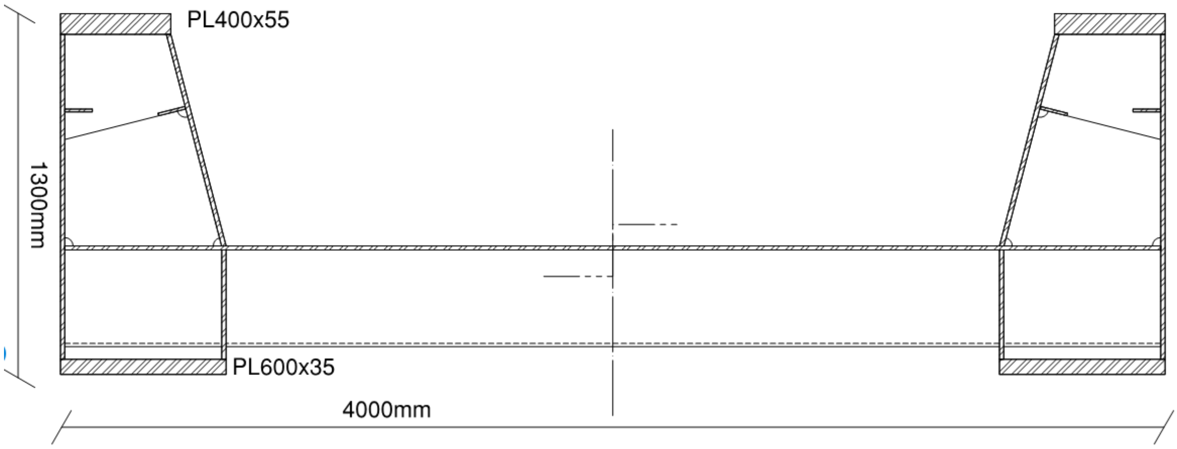

Figure 6.14: Cross section, loads are transferred from crossbeam to main girders

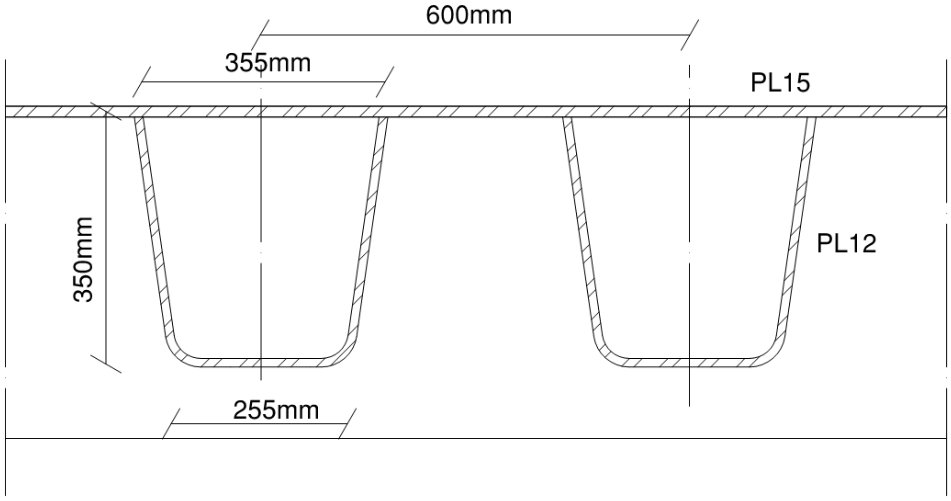

Figure 6.15: Cross section of deck plate

The launching methods are generally described in ML-D3.1. A steel superstructure is normally lighter than comparable concrete alternative. Therefor a steel superstructure will offer more alternatives when it comes to handling of the superstructure. In Figure 6.16 a multi wheeler with hydraulic jacks is used for transportation horizontally and vertically. A corresponding alternative of concrete could also be launched, however, it would need heavier equipment and possible longer duration.

Figure 6.16: Bridge launching with multi wheeler

6.2.5 Variations in the standard bridge

With respect to the bridge solutions above and previous solutions on standardized superstructures it is highly probable that it is possible to have a selection of bridges that could meet the demands for smaller bridges in all European countries. The practical differences between nationally determined parameters are small and cause almost negligible cost compared to benefits from an industrialized production. Some kind of adjustments before completing the standard bridge to a specific project should be expected. As a minimum, bridge specific drawings or bridge information models must be made for all projects stating which alternative of the standard bridge has been selected and also describing other parameters. A standard bridge will likely increase competition within the European market and also speed up replacement processes, especially in emergency situations.

6.3 Substructure construction

Sometimes substructures need to be replaced. There are several reasons why substructures might need replacement: deterioration, limiting of free opening or insufficient bearing capacity to mention a few. To construct new substructures in existing line without disturbing the traffic is a great challenge. One method possible to use when bedrock is not too deep is now presented. Without disturbing traffic except for shorter stops when establishing machinery, large diameter steel pipes are drilled from surface down to bedrock. Steel pipes with diameter of approximately 800 mm - 1000 mm are used. These will serve as columns and substructure for the new bridge. Typically four pipes are installed for a small bridge, one pipe close to each corner of the planned superstructure. The pipe can be drilled through old foundation slabs and depending on length, one pipe can be installed in approximately 10 hours. However, by placing the pipes outside the train profile, train traffic can run during installation. The following steps are illustrated in Figure 6.17. Once the steel pipes are installed the soil within the pipe is removed. A prefabricated reinforcement cage is lowered into the pipe. The pipe is filled with fresh concrete and the substructure is completed when concrete has hardened. The substructure has at this stage sufficient bearing capacity.

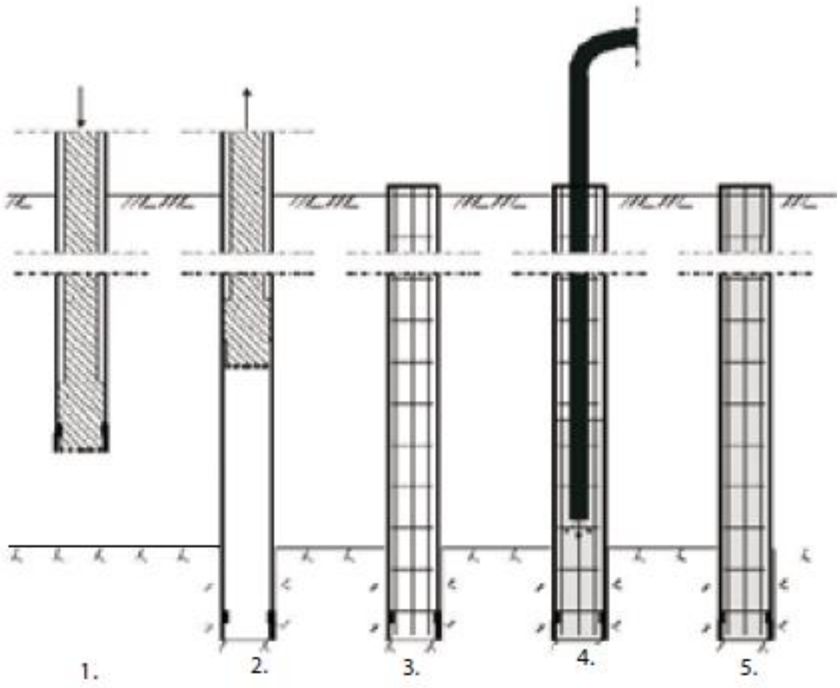

Figure 6.17: Installation of new substructure

In Figure 6.18 a completed railway bridge with steel pipe substructure is shown with a detail shown in Figure 6.19.

Figure 6.18 Bridge with steel pipe substructure

Figure 6.19: Detail of steel pipes

To ensure an aesthetic bridge, the steel pipes should however be covered by an outer layer of concrete to provide protection against corrosion and to allow a more proportional size compared to the planned superstructure, Ruukki (2009). There is also an alternative to use smaller pipes with a diameter of approximately 300 mm and place several close to each other. These pipes must typically be cast in concrete to ensure stability. One such example is shown in Figure 6.20 where steel pipes were used because of problems with high groundwater in combination with permafrost deeper down.

Figure 6.20: Steel pipe concrete composite supports

6.4 Replacement of decking systems

6.4.1 FRP Composites

Replacement FRP railway decking and railway bridges have only been used in a small number of instances around the world, excluding light duty elements such as access walkways.

Generally the replacement elements have comprised:

i) Replacement transoms supported on existing girders, Erp and Rogers (2008),
ii) Replacement decking supported on existing girders, Canning (2012),
iii) Replacement of entire bridges, Hillman (2012), Kim and Chandra (2012).

In total the number of structures globally that either have a FRP deck or FRP bridge supporting railway loading is very limited, although the advantages of FRP composites are particularly suitable for such applications. This is because replacement railway bridges and decking typically require the following characteristics:

i) Minimum weight to maximise capacity of existing retained girders and/or substructure,
ii) Minimum costly disruption to railway operations,
iii) Maximum fatigue capacity,
iv) Maximum durability (partially buried or hidden elements in a severe environment).

Review of Existing Applications

Farley Bridge, Hunter Valley, Australia

The use of hybrid transoms comprising steel reinforcement bars embedded and protected in FRP composite, has been trialled and described in Erp and Rogers (2008). The hybrid FRP/steel transoms are designed to be modular to allow a range of geometrical, strengthen and stiffness solutions. For the application in the Hunter Valley, the transoms spanned approximately 2m between supporting girders. The transoms are designed to provide a similar installation method to conventional hardwood transoms (although they are slightly heavier) together with better durability and structural performance. A recycled thermoplastic transom/sleeper has also been developed in the USA, Lynch and Nosker (2011). This product is generally less stiff and of similar strength to conventional hardwood transoms, but is generally accepted to have improved durability. The product has been under continuous trial on a heavy haul test track in the USA for over 10 years with no reported problems.

Fort Eustis, Virginia, USA, and Transportation Technology Centre, Colorado, USA

Only two applications exist of entire railway bridges manufactured from polymeric materials. The first is the HCB system which comprises a combination of FRP composite with concrete and steel, Hillman (2012), installed at the Transportation Technology Centre, Colorado, USA. The other application used the Struxure recycled thermoplastic system (with Ecotrax thermoplastic sleepers) described in Kim and Chandra (2012) and installed at Fort Eustis, Virginia, USA. The HCB system has been reported to enable much quicker installation, although the durability and lightweight benefits of FRP composites may be compromised by the inclusion of steel and concrete.

Development of New Applications

The review of existing applications has revealed a number of developments that could be made to enable cost-effective, durable replacement of existing elements on railway bridges. Replacement of railway deck elements would be particularly useful as these elements are exposed to the most severe environment and are partially buried/hidden. Examples of how this can be achieved, and any associated limitations, are now discussed. The following examples are based on two particular FRP products; ASSET (FBD600) produced by Fiberline, Denmark, and 36-inch DWB (Double Web Beam) produced by Strongwell, USA, shown in Figure 6.21. Both products have been previously used in heavy duty civil engineering applications.

Figure 6.21: ASSET profile FBD600, Fiberline(left) and 36-inch DWB, Strongwell(right)

Higher Capacity FRP Replacement Decking

A common bridge form in Europe is the half-through U-frame type comprising steel (or wrought iron) main girders with some form of cross-girders or decking between. Usually this decking comprises steel plate or timber decking on cross-girders, or a concrete deck with steel reinforcement or filler beams. The transverse span between main girders is typically approximately 3.5m (i.e. slightly larger than the kinematic envelope of a train) – the general arrangement is shown in Figure 6.22.

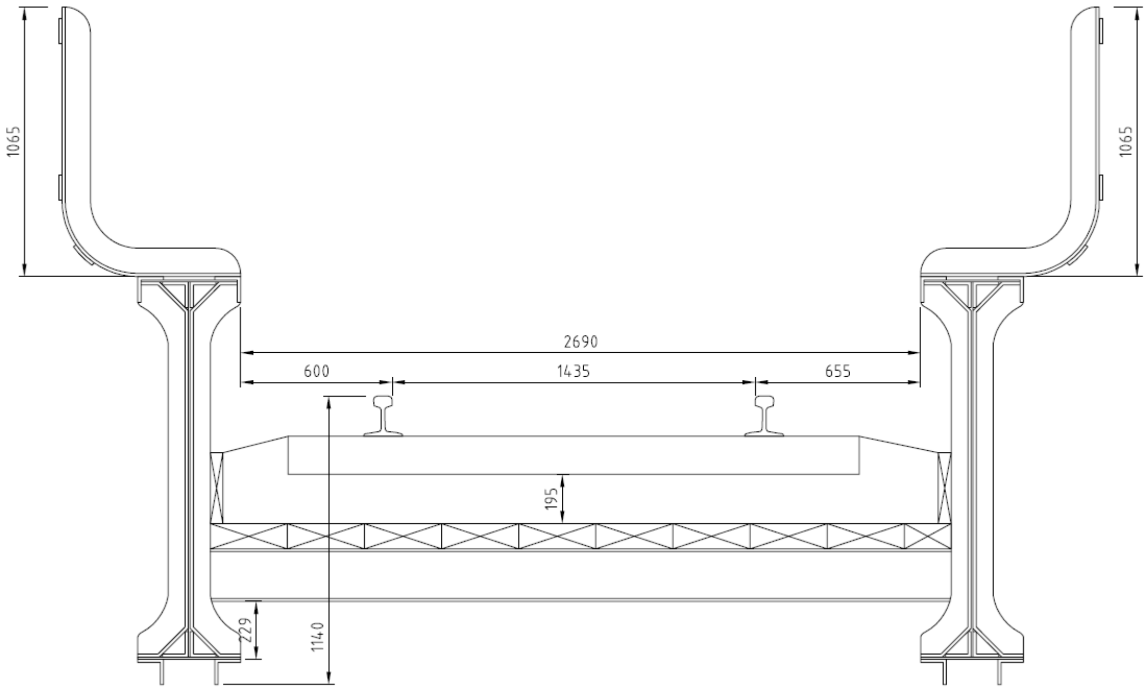

Figure 6.22: Typical U-frame type steel railway bridge for ballasted track

Where ballasted track exists, the decking is essentially inaccessible for maintenance/ inspection from one side (excluding disruptive railway possessions) and deterioration is more likely to occur to these elements. To overcome this, large prefabricated FRP deck components can be installed to act as the transverse part of the bridge U-frame. The weight of FRP deck for such an application would be 1.5-2.5 kN/m^2, and could comprise FRP deck systems such as DWB or 2-layer ASSET. This weight is only 25% or less of the weight of an equivalent filler deck to current design standards or the same weight as a historic steel cross-girder/timber deck (which does not typically meet current design standards). Alternatively, new steel U-frame cross-girders can be installed and the FRP deck installed to span between these. This is similar to existing installations for replacement FRP railway decking, however, the highlighted FRP deck systems would be sufficient to span up to 3.5m between cross-girders (rather than closer cross-girder spacing of approximately 1.2m or less, which is common on old railway bridges). A transverse deck span of approximately 3.5m is also common on medium span railway viaducts (e.g. 25m-50m spans) that traditionally comprise a concrete deck on concrete or steel box-girders or steel plate fabricated girders (see Figure 6.23 for an example). The weight of the concrete deck can comprise more than 50% of the entire weight of the complete bridge superstructure. It is clear in such circumstances that using an FRP deck could reduce the total weight of such a bridge by about 50% with significant cost benefits with respect to foundations, as well as the other benefits of quick installation of large lightweight prefabricated components and improved durability.

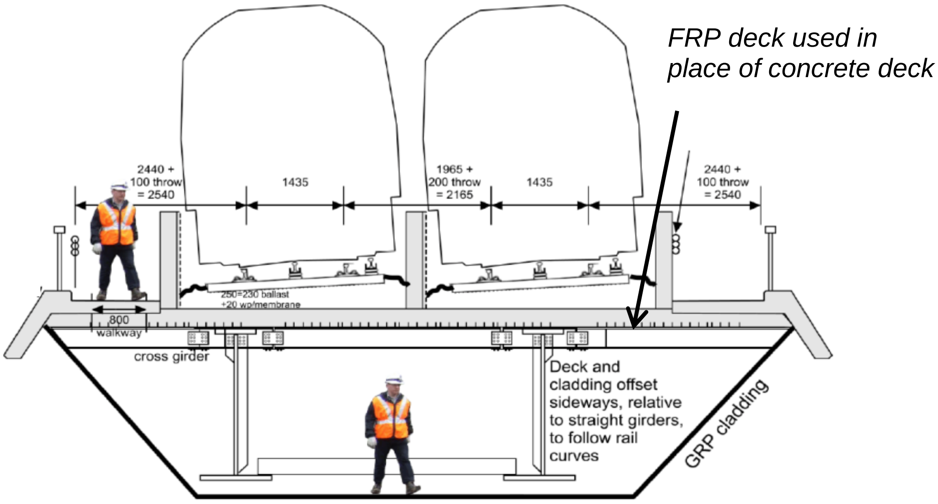

Figure 6.23: Medium span railway bridge comprising concrete deck on fabricated steel girders

FRP Railway Bridges

For railway bridges of up to approximately 50m span, it may be cost-effective and practical to use FRP decking, as described above, supported on FRP girders (an example using the DWB system is shown in Figure 6.24 but other FRP products would also be suitable). This raises the interesting possibility of manufacturing the majority of a railway bridge from a single modular component. The DWB railway deck would not necessarily be required to act compositely with the DWB girders, allowing a small number of bolted connections as well as full structural bonding, or a combination of the two. The main benefits of an FRP railway bridge would be improved durability and lightweight allowing easy/quick installation and smaller foundations.

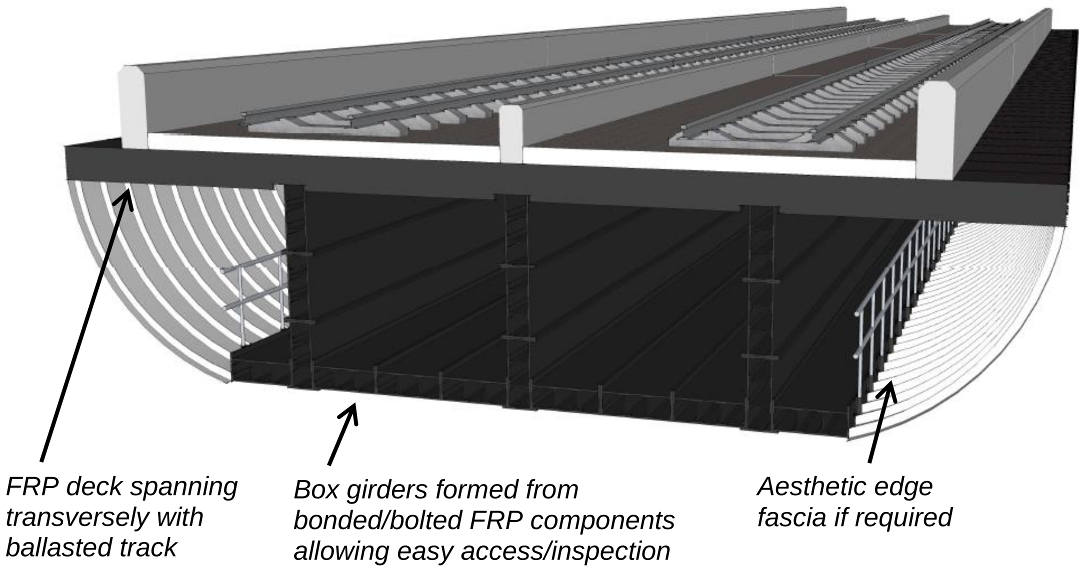

Figure 6.24: All-FRP modular railway bridge for up to 50 m spans

Limitations of FRP Composites for Railway Bridges

The primary limitation in extending the use of FRP composites for use in heavy duty railway bridge applications is the requirement for derailment protection or ‘robust kerbs’. There is currently no published evidence on the capability of FRP components to act as derailment protection. Although it is generally feasible to develop conceptual designs that theoretically provide derailment protection, it is assumed that infrastructure owners would require large-scale testing to prove adequacy for such a safety critical element. Conventional derailment protection typically comprises concrete upstands, steel girders, guard rails, or a combination thereof. The use of concrete upstands or guard rails attached to or embedded into an FRP deck would be generally feasible. Another limitation that is relevant for some railway bridges is fabricating a bridge with in-plan curvature. This is not easily possible if pultruded FRP sections are used, although it is achievable with moulded FRP components (geometric freedom being one of the main advantages of such components). However, the use of moulded FRP components also has disadvantages due to the increased labour and material testing required as part of the manufacture and fabrication. The merits of using pultruded FRP components or bespoke moulded FRP components would need to be considered by the designer on a project-specific basis. Currently, only three FRP decking systems used in Europe have been proven to provide derailment load capacity by large-scale testing (strengthened Duragrid panels for spans of up to 1.2m, ASSET or DWB decking for larger spans). These all comprise FRP components manufactured by pultrusion. ASSET and DWB FRP components have been considered above, but in principle any other FRP component with a proven similar capability could also be used in the railway bridge construction options discussed previously. Indeed, a number of similar FRP components and systems are available from North America, Australia, and South East Asia. The ASSET and DWB systems have only been considered due to the availability of information on those particular products and to highlight what can be achieved with currently available FRP components and products.

6.4.2 High performance Concrete

High performance concrete (HPC) has been used in civil engineering for many decades, although very few railway bridges have utilised this material. The primary aspects that are advantageous for railway decking are high strength (and hence more efficient material use, enabling a reducing weight and easier installation) and low permeability (and hence improved durability) and are discussed in detail in Section 5.2. It is noted that low permeability and improved durability can only be achieved with a well-designed concrete mix where early age cracking is limited and workability (and concrete quality) are considered appropriately, as well as the usual serviceability limits on cracking and site quality control. Historically this has been found to occasionally be an issue where high performance concrete has been used as discussed in Gjorv (2007).

Some of the earliest bridges using HPC were constructed in Japan in the 1970s, CEB Bulletin No. 222 (1994), and these appear to still be the only railway bridges where large-scale use of the material has occurred. The primary reasons for using HPC in this instance was to maximise durability and provide better acoustic performance than an equivalent steelwork structure. A review after 30 years of service of these structures confirmed they were performing adequately and as expected. Other bridge applications of HPC are provided in the Concrete Bridge Development Group Technical Guide No. 6, CBDG (2005) and Bickley and Mitchell (2001). Concrete technology has developed significantly since the 1970s and improved HPC products are available from a large number of suppliers. The main challenges in replacement of old railway bridge decking are:

i) Limited construction depth and ballast depth.

ii) Existing deck may not meet current derailment capacity requirements, but a replacement deck should meet such requirements.
iii) Limited durations available for deck replacement.
iv) Severe environment for new decking.

Conventional deck replacement types usually use heavy stiffened steelwork decking which requires significant maintenance, or heavy precast concrete decking which also often requires raising the track to provide adequate ballast depth, or a combination of the two comprising a steel/concrete filler deck. The use of HPC provides the potential to overcome the issues stated above. In particular, the use of HPC allows:

i) Construction depth reduced due to higher concrete compressive strength and lower concrete cover (although reduction in cover for HPC with low permeability is not generally yet recognised in European design codes). In some instances the construction depth compared to conventional decking can be reduced by around 25%, allowing ballast depth to be improved if required.
ii) A higher concrete compressive strength provides greater flexural and shear capacity for the same amount of material. Therefore, derailment capacity may be able to be provided with a lower construction depth.
iii) Lighter replacement deck units, which the use of HPC can provide, allow larger prefabricated units to be installed without requiring specialist or expensive lifting equipment or plant. This also reduces the amount and hence duration of site work.
iv) HPC provides better durability than conventional concrete types due to greater impermeability. HPC is also more durable and requires less maintenance than steelwork in the severe environment of railway decking in direct contact with wet ballast and various chemicals (noting that waterproofing systems invariably fail over a much shorter time period than structural components).

Although HPC decking will have a greater material cost than conventional concrete or steel decking, the majority of the cost in railway refurbishment schemes is associated with construction activity, duration, planning and management and disruption to the operational railway, rather than material cost. Although this is dependent on the particular details of any project, it is probable that in the majority of cases the use of HPC replacement decking would be no more expensive and more durable than conventional replacement decking. To enable the use of HPC in railway bridges to grow, the following work would be useful :

i) Further research leading to development of design guidance and standards that acknowledge the benefits of HPC in railway bridge applications.
ii) Initial field applications in low risk railway bridge applications that utilise the benefits of HPC.
iii) Monitoring and dissemination of railway bridge and similar applications where HPC has been used.

The comments made above regarding HPC will be even more relevant for ultra-high performance concrete (UHPC), although design guidance for such materials is less developed than for HPC. A useful review of UHPC in Europe is provided in Schmidt and Fehling (2005). The more rapid hardening provided by HPC can also be a benefit in railway bridge construction. When replacing a superstructure, parts of the substructure may need rebuilding. During replacement of a bridge in Denmark, see Figure 6.25, it was necessary to remove the top of each concrete column which carried the bridge superstructure. Approximately 40 centimetres were removed by high pressure water jetting, so that the existing reinforcement was preserved when the new bearing shelf was cast.

Figure 6.25: The superstructure being launched onto newly cast bearings shelves of HPC

To minimize the period of track closure the new superstructure had to be horizontally launched and mounted upon new neoprene bearings placed on the newly cast bearing shelf as early as possible. The strength of the concrete was therefore a time critical factor. A study of the necessary minimum strength was prepared, and it was calculated that strength of 5 MPa was sufficient to carry the bridge deck itself without ballast and any other live loads. A screening of several different concrete products with rapid strength development was done. Two products were chosen and a test was made at the construction site a month before the track closure. It was important to be sure of concrete performance in an environment close to zero degrees. A suitable high performance concrete was found, and the new superstructure could be mounted on the new concrete shelf less than 5 hours after casting.

7. Large bridge replacement

7.1 Multispan integral bridges

The overall aim of this study is to present a general method for full replacement of concrete multispan integral railway bridges, exemplified in Figure 7.1. This bridge is a common bridge type although not commonly replaced in an effective way.

Figure 7.1 Multispan integral bridge

The substructure is fixed to the superstructure. The type is divided into integral slab bridge and integral beam bridge where the latter one is used for longer spans. These types of bridges are today typically replaced during long track closures. Here one important prerequisite for the work is that 18 hours are available without railway traffic.

7.1.1 Preparations

With such short track possession a large amount of preparation work is needed. General preparation work and philosophies are presented in Section 4. Here bridge type specific preparations are given. Before the track closure the new bridge and the new columns have to be built. New substructure is constructed by installing large diameter steel piles as presented in Chapter 6.3. All work with new substructure is done under the existing bridge without any disturbance of traffic. The new superstructure will be built in the vicinity of its final position from where it typically will be horizontally launched. The new superstructure can be prepared with ballast before launching or ballast can be added later when the bridge is in place. To be able to launch the old bridge sideways there have to be temporary columns. This implies that temporary supports for both the old bridge and the new bridge are needed, i.e. temporary supports on both sides of the final bridge positions. These temporary supports do however only need to carry the load from the superstructure and not any traffic loads. The temporary supports can be made of crushed rock, timber grillage, concrete blocks, piles or other solutions depending on local conditions. The layout of the construction site depends heavily on local conditions and the space available. It is possible to launch the superstructure longitudinally to get it into position before the track possession. If the railway bridge is crossing a road a temporary structure can be used to protect the passing traffic beneath the bridge if the superstructure is built over the road. In Figure 7.2 the new superstructure on temporary columns is shown on the left side. In the middle the existing superstructure is shown and on the right side temporary supports.

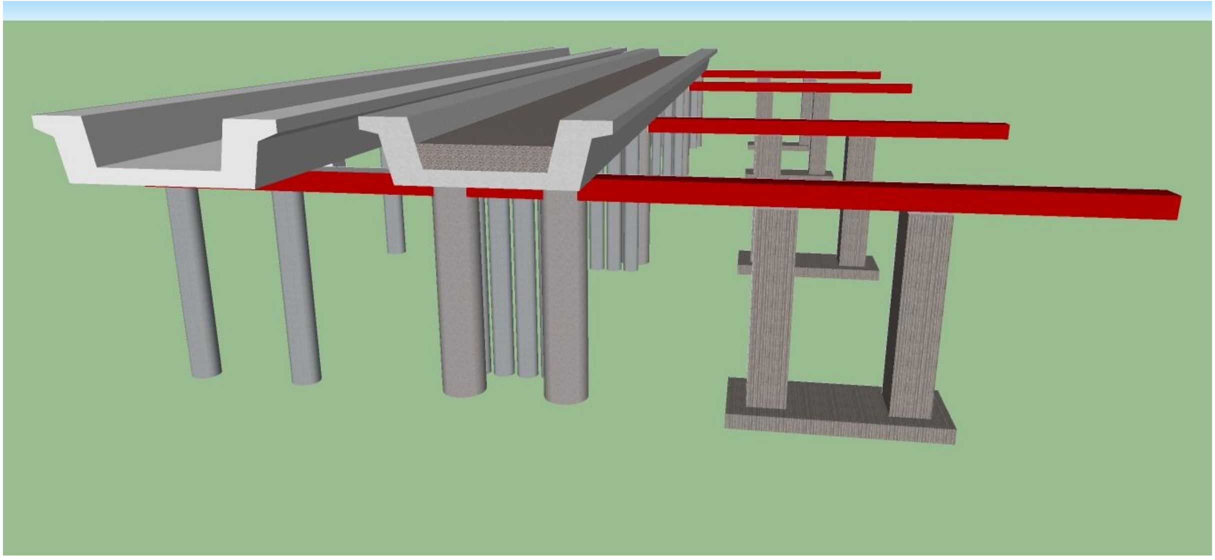

Figure 7.2: Superstructures ready for launching

Since existing columns are fixed to the superstructure, it is of upmost importance to cut the columns before the track possession starts. Depending on column design, it might be necessary to use some temporary coupling device before the columns are cut and the track possession starts. In Figure 7.3 cut columns are shown before start of launching.

Figure 7.3: Cut columns

Also the rail should be cut and only fixed by temporary devices before the train stop.

7.1.2 Short track possession

As all demolition works are made in previous steps, the work during track possession will be a simple shifting of superstructures. After removal of the already cut track, soil between the bridge wings must be excavated. The temporary anchorages that fix the columns to the substructure are released simultaneously with the excavation work.

First, the old superstructure is launched sideways and then the new superstructure is launched in place. Different launching methods are described in ML – D3.1 (2013).

When the new superstructure is placed in its final position the sub- and superstructure are connected. The top of the column is welded to prepared plates in the superstructure. The welding can be done simultaneously as the track is reinstated. Some attention must also be given to avoid lifting forces when placing ballast if that is not done beforehand. Two procedures for reinstalling ballasted track are given in Chapter 4. When welding is finished and the track is in place, tamping procedures can be undertaken and the track opened at reduced speed. Demolition of the old substructures is done after the bridge is in place and track is reopened.

7.2 Composite launching nose

The method below is developed for replacing longer bridges in areas that are difficult to access or where space is limited. The main idea is that the new bridge is connected with the old bridge to form one unit. The two bridges are launched together and then the old bridge can be transported away. The method is suitable to use for spans over 25 metres and when all work must be done from the track. This solution builds on the principal to use the old bridge superstructure as a type of launching beam during longitudinal launching. In this way the old superstructure is moved away from its position at the same time as the new superstructure is moved into its final position over the abutments. The launching procedure is undertaken just above and parallel to the track. This means the minimum of additional fill or space around the abutments is needed. In Figure 7.4 the first step in replacing the superstructure in this way is shown. The new superstructure, which is built elsewhere, is brought to the site on track-mounted trolleys. In the following figures the new superstructure is represented by a beam and the old superstructure by a truss.

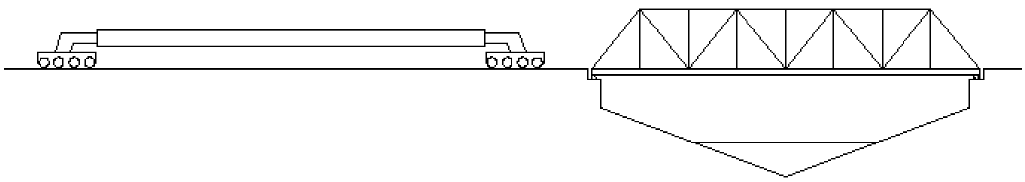

Figure 7.4 At beginning of replacement

Before the track possession and the physical replacement takes place, a lot of preparation work is needed. The rail must be cut, the old bridge must be detached from supports and will also probably need to be prepared for the connection device between the old and new structure. The old superstructure is lifted up to position above the track and connected to the new superstructure and the trolley as shown in Figure 7.5.

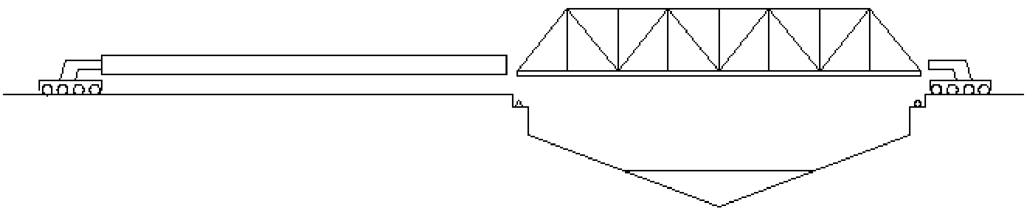

Figure 7.5 Old superstructure is lifted

The two superstructures are connected and launched horizontally to move the old superstructure away from the supports and to get the new superstructure in position, see Figure 7.6.

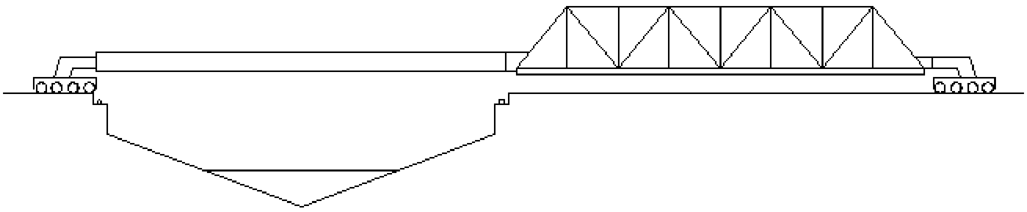

Figure 7.6: New bridge over supports

The two superstructures are decoupled and the new one is lowered into place, see Figure 7.7.

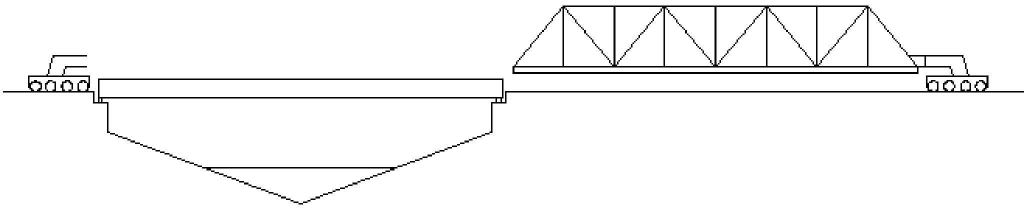

Figure 7.7: New bridge in place

When the new bridge is in place, the track is restored and the old bridge can be transported away. In the schematic sketches in Figure 7.4 - Figure 7.7 the span during launching is doubled which in reality is not an option. The new structure can be designed to carry such loads, however the launching will be very unstable and the connection device expensive so in reality additional supports must be used as illustrated in Figure 7.8.

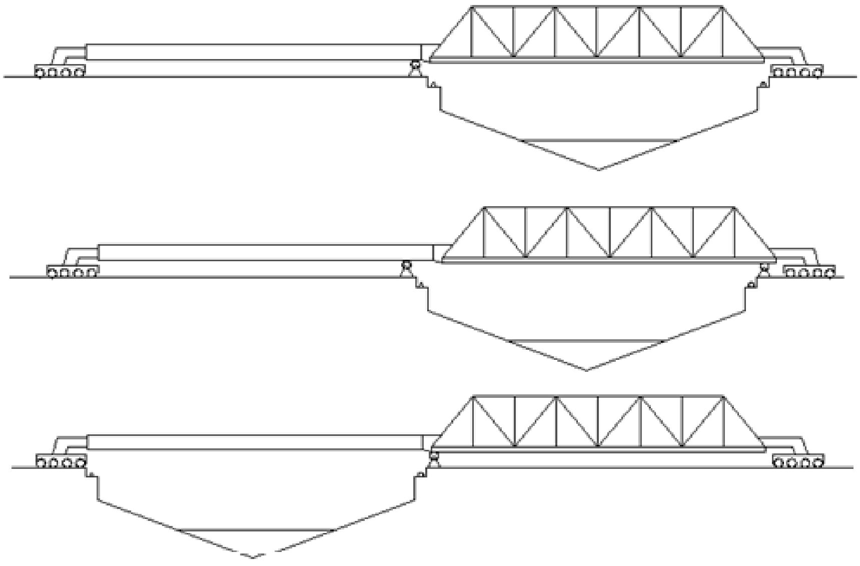

Figure 7.8 Supports during launching.

Figure 7.9 shows replacement of a road truss by connecting the two bridges for launching. The old bridge is on the left side almost on land and the new bridge on the right side almost in final position.

Figure 7.9 Replacement by using old bridge as launching nose

The connection between the old and new superstructures needs to be able to handle the moment and shear force during launching. The connection must be designed to fit both the old and new superstructure. The connection should be made by bolts for fast and safe coupling and decoupling. If the old structure is suitable for welding and if it is feasible the coupling in the old structure can be prepared before track possession. In the illustrations the two superstructures are placed next to each other. Depending on design and geometries it can also be possible to have an overlap between the two bridges. With an overlap of one third of the span length the coupling device will be stressed significantly less.

7.3 New bridge as crane beam

For longer bridges, i.e. around 30 metres and over, the new superstructure may sometimes be used as a crane beam to facilitate removal of the old superstructure. The new superstructure is constructed elsewhere. Preparation to the existing bridge is made according to Section 4.

When the track possession starts the new superstructure is placed on track next to the bridge as shown in Figure 7.10.

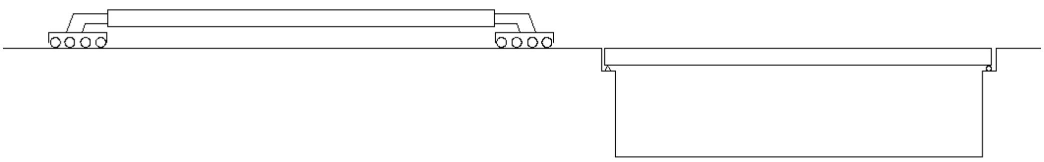

Figure 7.10: New superstructure next to the bridge

The new superstructure is positioned above the bridge and the old superstructure is connected by cables or bars, as shown in Figure 7.11.

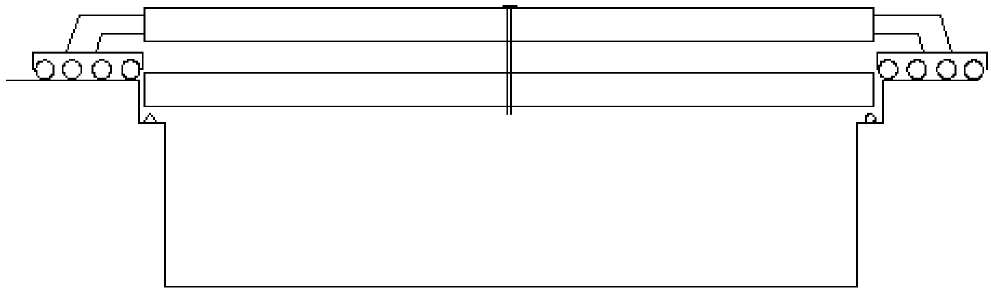

Figure 7.11: New superstructure acts like a crane beam.

The old superstructure is lifted from bearings and is rotated so it can be lowered between the supports, as shown in Figure 7.12.

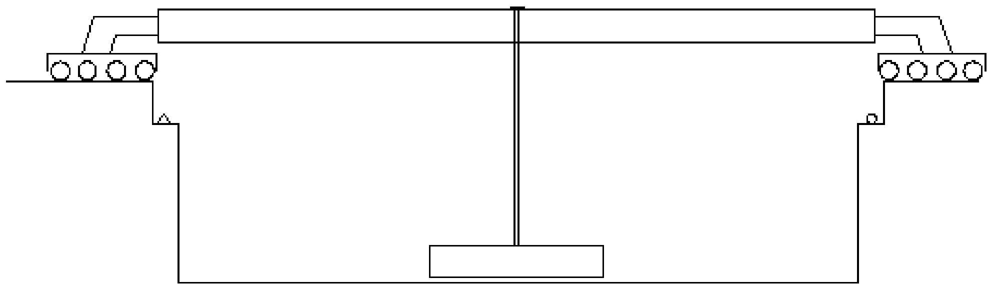

Figure 7.12: Old bridge rotated and lowered

Many different scenarios are possible in this situation. If there is a road under the bridge this must be temporarily closed. The old superstructure is transported away or demolished at site. If there is water underneath the bridge then a barge can be used to move the old superstructure away. The watercourse may not be big enough for a barge and then the superstructure can be manoeuvred to rest on the shore. The old superstructure can then be cut into smaller sections and taken away using a crane. The cutting and removal can also be done from ice if the climate and environment allows for that. Removal of the old bridge however normally takes place after the track is reopened. After the old superstructure has been lowered, the new one is lowered into place, as shown in Figure 7.13.

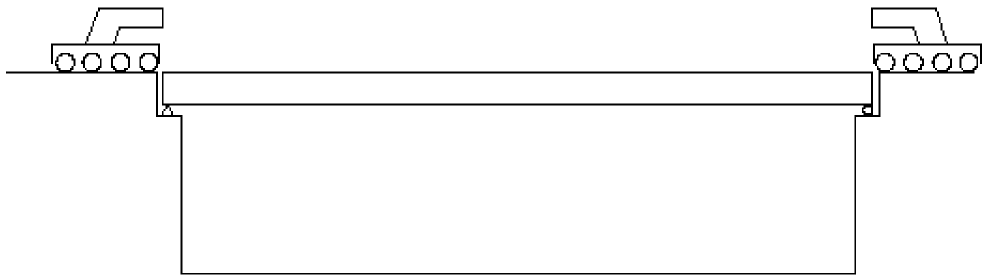

Figure 7.13: The new bridge in place.

This replacement method depends on the new superstructure being prepared for cables and cable forces. Holes for lifting are typically combined with holes for drainage. Depending on the design of the new superstructure, the lifting device must be made accordingly. Figure 7.14 shows how temporary beams transfer lifting forces to the new superstructure main girders to avoid damage of a concrete slab on a steel concrete composite bridge.

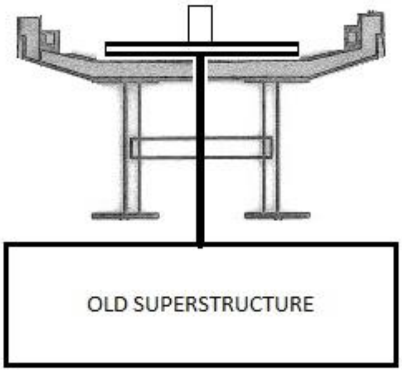

Figure 7.14: Example of lifting arrangement

The new superstructure must be designed to carry all loads during the replacement procedure and be sufficiently stable. As an alternative to lifting the whole old superstructure in the middle of the new superstructure it can be lifted in two points as shown in Figure 7.15.

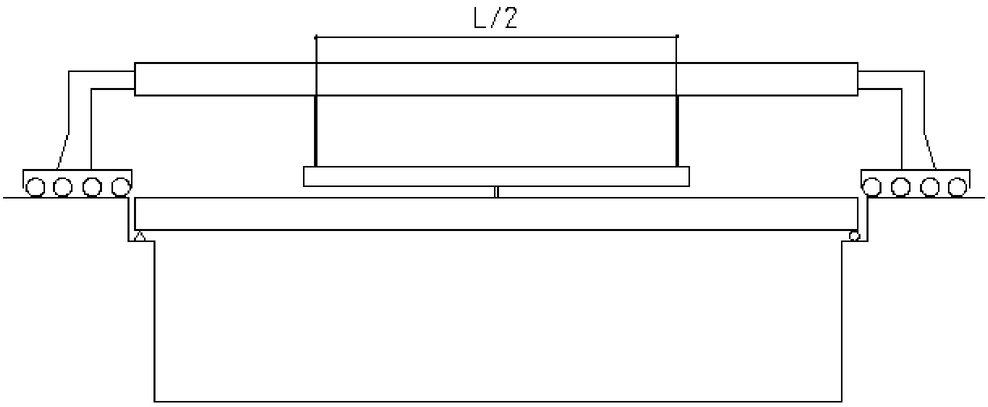

Figure 7.15: Distribution of lifting forces

A beam underneath the new superstructure divides the load into two lifting points with the length of half the span between. This arrangement will also reduce the forces needed in each jack, however, additional vertical space is needed.

8. Conclusion

The presented research in this deliverable answers questions related to a successful bridge replacement and closes some gaps in knowledge previously identified. Findings can be used to render more precisely the future work within the Work Package and the planned research areas to deliver a suitable “D3.4 Guideline for Replacement of obsolete Infrastructure”.

Improved methods and logistics for bridge replacement methods are introduced. The proposed ideas have been evaluated in real projects and are verified to work for both partial replacement and full replacement in various conditions. The more complicated a bridge replacement becomes the more difficult is the planning and logistics.

To have control of risks, this deliverable presents reliable methods that have potential of being seen as standard methods for bridge replacement. Experience with these techniques significantly lowers the risk during construction and allows European wide competition. This in consequence will positively influence another important concern when replacing railway infrastructure: cost. Competition and the ability finding suitable quality and professional skills in the construction industry grow when established techniques are used frequently. Both effects become more and more important in a growing European market.

The methods discussed in this report provide a valuable compilation for Eastern European railways showing various proven techniques that can be adopted for any network that significantly changes within a short time. Many methods shown in the report can be easily adopted (without any major material consumption or logistic challenge) from one country to another. Detailed information, recommendations and limitations on methods like the requirements on construction site and surroundings are to some extent provided. Moreover the experience from the consortium concerning the logistical planning while building within the railway environment has been compiled. An introduction for the use of bridge information modelling is given. This is a promising tool to plan infrastructure projects and especially of use for railways that can combine this with systems to use during asset management.

A number of solutions including so called advanced materials for construction industry are given. Unfortunately long term experience with FRP structures and high performance concrete in the railway environment is not available yet and therefore these materials should be studied further.

Small bridge replacements can be improved by applying presented logistic solutions. Risk, costs and total track possession can be reduced by detailed planning. Development of a small European standard bridge solution could increase efficiency in construction industry and facilitate planning. Therefore a case study for a short span bridge comparing different national annexes will be carried out within Task 3.4. Large bridge replacements can for suitable cases be made to a greater extent over Europe and more efficient by applying presented methods. Although a very important factor when discussing construction work within the railway sector, data on track possession cost or real down-time is sparse. Clarifications of track possession costs are needed. Ideally an easy to use model for a rough estimation considering particular network conditions should be proposed. This together with specifications of individual methods and an individual LCCA will be able to deliver input regarding data to the development of life cycle cost models and other decision support systems for infrastructure managers. The final WP3 Guideline will therefore offer a more detailed discussion on track possession cost.

9. References

Aspinalls (2014): Calder viaduct. Web page http://www.aspinall.co.uk/more_info.asp?current_id=140

Bickley, J.A., and Mitchell, D. (2001). A State-of-the-Art Review of High Performance Concrete Structures Built in Canada: 1990-2000. Cement Association of Canada, Ottawa, Ontario.

BS 1192:2007, 'Collaborative Production of Architectural, Engineering and Construction Information – Code of Practice', published by British Standards Institution, London, UK, 2007.

Blanksvärd, Thomas (2011): Strengthening of concrete structures by the use of mineral based composites: System and design models for flexure and shear. PhD thesis, Luleå University of Technology, 302 pp. ISBN: 978-91-86233-23-5. Available at http://pure.ltu.se/portal/files/2645294/Thomas_Blanksvard_DOC2009.pdf

Canning, Lee and Speight, N (2009): Briefing: FRP railway decking – Calder Viaduct. Proceedings of the ICE - Engineering and Computational Mechanics, Volume 162, Issue 3, 01 September 2009, pages 103 –106. DOI: 10.1680/eacm.2009.162.3.103

Canning, Lee and Luke, Sam (2012): Composites deliver lightness, strength and efficiencies. Sinclair Knight Merz Magazine, 2 pp. Available at http://www.google.se/url?sa=t&rct=j&q=&esrc=s&source=web&cd=4&ved=0CFIQFjAD&url=http%3A%2F%2Fwww.globalskm.com%2FInsights%2FAchieve-Articles%2FItems%2F2012%2FComposites-deliver-lightness%2C-strength-and-efficiencies.aspx%3Fpdf%3Dy&ei=l8b3UryNDcHOygPY3oHoDQ&usg=AFQjCNGttrRCmNNgd9WN8MtD5XO-Z7zG5w&sig2=2xe8YxMcQ7vyZb8Z_TNjeA

Canning, L. (2012). Developments in FRP Railway Bridge Applications. CICE 2012, Rome, Italy, 13-15 June 2012.

Carolin, Anders (2003): *Carbon Fibre Reinforced Polymers for Strengthening of Structural Members*. Doctoral Thesis 2003:18, Luleå University of Technology, June 2003. 190 pp. ISBN 91-89580-04-4. Available at http://pure.ltu.se/portal/files/151462/LTU-DT-0318-SE.pdf

CBDG (Concrete Bridge Development Group) (2011). Technical Guide No. 6 High Strength Concrete In Bridge Construction – A State-of-the-Art Report. Published by the Concrete Society, Camberley, Surrey, UK. ISBN 1 904482 155.

CEB Bulletin No. 222 (1994). Application of High Performance Concrete – Report of the Joint CEB-FIP Working Group. ISBN 978-2-88394-025-3.

Davis, A.C. (1925): A Hundred Years of Portland Cement 1824-1924. Concrete Publications Ltd, London, 282 pp.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2008) BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, John Wiley & Sons, Inc., New Jersey.

Elfgren, Lennart and Apleberger, Lennart, Editors (2000a): High performance concrete structures: Design handbook. Svensk byggtjänst, Stockholm, 127 pp. ISBN 91-7332-929-0

Elfgren, Lennart and Apleberger, Lennart, Editors (2000b): High performance concrete structures: Design examples & properties, Svensk byggtjänst, Stockholm, 157 pp. ISBN 91-7332-930-4

FHWA (2005): Prefabricated Bridge Elements and Systems in Japan and Europe. Prepared by the International Scanning Study Team, Federal Highway Administation,65 pp.

Available at http://international.fhwa.dot.gov/prefab_bridges/chapter_two_a.cfm http://international.fhwa.dot.gov/prefab_bridges/pl05003.pdf

FHWA (2013): Ultra-High Performance concrete: A State-of-the-Art Report for the Bridge Community. Publication No FHWA-HRT-13-060, 176 pp. Available at http://www.fhwa.dot.gov/publications/research/infrastructure/structures/hpc/13060/13060.pdf

fib Bull 42 (2008): Constitutive modelling of high strength / high performance concrete. fib Bulletin No 42. International Federation of Concrete, Lausanne, 130 pp, ISBN**:** 978-2-88394-082-6.

Gjorv, O.E. (2007). Norway - Concrete Construction Industry. Proceedings of Cement Based Materials and Civil Infrastructure (CBM-CI) International Workshop, Karachi, Pakistan.

Hillman, J. (2012). Hybrid Composite Beams – A New Colour. Proceedings of FRP Bridges 2012, 13-14 September 2012, London, UK.

Jara Mori G.A. (2008): *Estudio de la aplicabilidad de materiales compuestos al diseno de estructuras de contención de tierras y su interacción con el terreno, para su empleo en obras de infraestructura viaria - Tesis doctoral*, Universidad Politecnica de Madrid, E.T.S. de Ingenieros de Caminos, Canales y Puertos, Departamento de Ingenieria y Morfologia del Terreno, Madrid 2008. Cited from Potyrala and Casas (2011).

Jonasson, Jan-Erik; Emborg, Mats; Elfgren, Lennart and Wallin, Kjell (2009): How to build crack-free durable concrete structures: concrete hardening technology including modelling of shrinkage, creep and temperature of young concrete and its influence on durability and lifetime.

ISLECI 2009: The 4th International Symposium on Lifetime Engineering of Civil Infrastructure, Central South University of Forestry and Technology, Changsha, China, 6 pp. Available at http://pure.ltu.se/portal/sv/publications/how-to-build-crackfree-durable-concrete-structures(64c60fb0-e054-11de-bae5-000ea68e967b).html

Justnes, Harald; Dahl, Per Arne; Ronin, Vladimir; Jonasson, Jan-Erik and Elfgren, Lennart (2007): Microstructure and performance of energetically modified cement (EMC) with high filler content. Cement and concrete Composites, Vol 29, Issue 7, pp 533-541. http://dx.doi.org/10.1016/j.cemconcomp.2007.03.004

Keller, Thomas (2003): Use of Fibre Reinforced Polymers in Bridge Construction. *Volyme 7 of Structural Engineering Documents*, International Association for Bridge and Structural Engineering (IABSE), Lausanne, 2003, 131 pp, ISBN 3857481080, 9783857481086

Kim, J.S., and Chandra, V. (2012). World's First Thermoplastic Bridges Made of Recycled Plastics. 18th Congress of IABSE, Seoul, 2012. pp 1033-1040.

Lynch, J., and Nosker, T. (2011). The Development of Recycled Thermoplastic Composite Bridges, Proceedings of SPE-ANTEC 2011, 1-5 May 2011, Boston, MA, U.S.A.

Makita, Tohru and Brühwiler, Eugen (2013): Tensile fatigue behaviour of Ultra-High Performance Fibre Reinforced Concrete combined with steel rebars (R-UHPFRC). International Journal of Fatigue, 8pp, in press. Available at http://infoscience.epfl.ch/record/189779/files/2013_TM_EB_Tensile%20fatigue%20behaviour%20of%20R-UHPFRC.pdf?version=1

Marzouk, M., and Hisham, M. (2012) Bridge Information Modelling in Sustainable Bridge Management. ICSDC2011: Integrating Sustainability Practices in the Construction Industry. pp 457-466.

Meystre, Th & Lebet, Jean-Paul (2006): Remplacement de ponts sous traffic (Replacement of bridges under traffic. In French with an English summary). Office féderal des routes, Bern, 79 pp. Available at http://www.mobilityplatform.ch/de/shop/show-item/product/2758/page/4/search/zustandserfassung%20von%20br%C3%BCcken/

ML-D1.3(2014):New technologies to extend the life of elderly infrastructure. Report to be published by MAINLINE.

ML-D3.1(2013): Benchmark of production and replacement of railway infrastructure

Muncke, Martin; Freystein, Hartmut; Schollmeier, Peter (2005): Handbuch Entwerfen von Bahnanlagen

NIBS (National Institute of Building Sciences), 'National BIM Standard – United States Version 2', National Institute of Building Sciences buildingSMART alliance, 2012.

Oai, G. L. and Vue, X. G. (2003): The recent research and application of high performance concrete to railway bridge construction in China. 28th Conference on Our World of Concrete Structures, 28-29 August 2003, Singapore. 8 pp. Available at http://www.cipremier.com/e107_files/downloads/Papers/100/28/100028030.pdf

PAS 1192-2:2013, 'Specification For Information Management For The Capital/Delivery Phase Of Construction Projects Using Building Information Modelling', published by British Standards Institution, London, UK, 2013.

Pike, Clinton W.; Ronin, Vladimir and Elfgren, Lennart (2009): High volume Pozzolan concrete: three years of industrial experience in Texas with CemPozz. Concrete in focus, Volume 8, Issue 2, pp 22-27. Available at http://www.nrmca.org/news/connections/mar_apr_09.pdf

Pipex (2007): St. Austell Footbridge. Pipex Structural Composites, 5 pp. Avialable at http://www.ngcc.org.uk/LinkClick.aspx?fileticket=yV87tMfI-cQ%3D&tabid=84&mid=456

Potyrala, Pawel Bernard and Casas, Joan Ramón (2011): Use of Fibre Reinforced Polymer Composites in Bridge Construction. State of the Art in Hybrid and All-Composite Structures. Univessitat Politècnica de Catalunya, Barcelona, 93 pp. Available at http://upcommons.upc.edu/pfc/bitstream/2099.1/12353/1/Use%20of%20Fibre%20Reinforced%20Polymer%20Composites%20in%20Bridge%20Construction.%20State%20of%20the%20Art%20in%20Hybrid%20and%20All-Composite%20Structures..pdf

Sas, Gabriel (2011): FRP shear strengthening of reinforced concrete beams. PhD Thesis, Luleå University of Technology, 248 pp, ISBN 978-91-7439-239-5 Available at http://pure.ltu.se/portal/files/32725277/Gabriel_Sas_PhD_Thesis.pdf

SB Strengthening (2007): *Repair and Strengthening Methods for Railway Bridges - Guideline,* "Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives". A European FP 6 Integrated Research Project during 2003-2007.139 pp. Available at http://www.sustainablebridges.net/main.php/SB6.1_Guideline_STR.pdf?fileitem=14043927

Schmidt, Michael and Fehling, Ekkehard (2004): Ultra-High-Performance concrete; Research, Development and Application in Europe. Available at http://download.contec-aps.com/uploads/tx_mpdownloadcenter/pp_fp_2005_003_eng_01.pdf

SEI (2010): Fibre Reinforced Polymer Composites, Special Issue, Structural Engineering International, No 4, 2010, pp 359- 484. Available at http://www.scribd.com/doc/113672389/SEI-november-2010-journal

SETRA-AFGC (2002):Bétons fibres à ultra-hautes performances. Recommendations provisoires. - Ultra High Performance Fibre-Reinforced Concretes. Interim Recommendations. In French and English. Service d'études techniques des routes et autoroutes (SETRA) and Association Francaise de génie civil (AFGC). 98 + 55 pp. Available at http://www.afgc.asso.fr/images/stories/pub/Betons_fibres.pdf, Revised Edition, compatible with the Eurocodes, June 2013, 358 pp. Can be obtained from http://www.afgc.asso.fr/images/stories/pub/Bon-de-commande-BFUP-2013.pdf

Shave, Jonathan; Denton, Steve and Frostick, Ian (2010): Design of rthe Austell Fibre Reinforced Polymer Footbridge, UK. Structural Engineering International, No 4, 2010, pp

427-- 429. Available athttp://www.scribd.com/doc/113672389/SEI-november-2010-journalDesign of the St Austell Fibre-Reinforced PolymerFootbridge, UK

Shim, C.S., Yun, N.R., and Song, H.H., 'Application of 3D Bridge Information Modelling to Design and Construction of Bridges', Proceedings of the 12th East Asia-Pacific Conference on Structural Engineering and Construction – EASEC12, Volume 14, 2011. pp 95-99.

Tuakta, Chakrapan (2005): Use of Fiber Reinforced Polymer Composite in Bridge Structures. MSc Thesis, MIT, Boston, 50 pp, Available at http://dspace.mit.edu/bitstream/handle/1721.1/31126/61165353.pdf

Van Erp, G., and Rogers, D. (2008). A Highly Sustainable Fibre Composite Building Panel. Proceedings of the International Workshop on Fibre Composites in Civil Infrastructure – Past, Present and Future, 1-2 December 2008, University of Southern Queensland, Australia.