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TOWARDS SLENDER, INNOVATIVE CONCRETE STRUCTURES FOR REPLACEMENT OF EXISTING VIADUCTS

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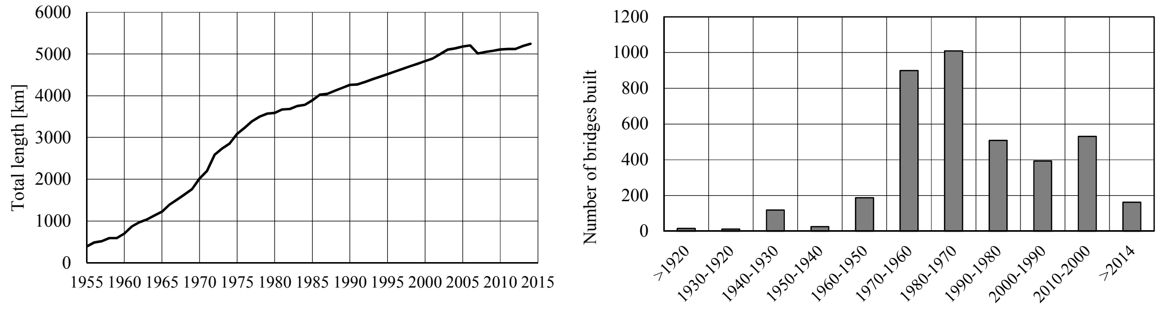
ABSTRACT

A majority of the bridges and viaducts in the Netherlands were built in the sixties and seventies of the last century and many of them will need to be replaced in the near future due to technical or functional reasons. This is a replacement issue, faced by many countries worldwide. But what about the concrete structures? Should we replace them with the same structural systems and by using the same conventional concrete as used before? Or do we apply the newly developed concrete types, such as Ultra High Performance Concrete (UHPC) and Strain Hardening Cementitious Composites (SHCC) and install them with structural health monitoring techniques? In the paper the findings of several exploratory studies, performed at Delft University of Technology, are presented. In general, but especially for the replacement of existing structures, there is a tendency for increasing the slenderness of the concrete structures. In tenders it is even seen that contractors can get an increased bonus when building with reduced heights. A driving force is the fact that piers in roads are highly undesirable (freedom in space), while, in order to reduce additional costs, the new bridge should stay aligned with the existing roads. Most of the existing viaducts in the Netherlands are three or four span plate bridges with a total span between 20 and 60 m. Is it feasible to replace these by single span bridges with slenderness as high as 60? In a feasibility study, the possibilities for this are investigated and steps to be made are addressed. The exploratory study focuses on long, slender concrete structures, which can be obtained by applying Advanced Cementitious Materials (ACMs) while furthermore new building methods are explored. In general, the idea is to make steps towards our future SMART bridges for which structural health monitoring, sustainability, no hinder, zero-energy, no maintenance and aesthetics are keywords.

Keywords: Slender UHPC bridges, Innovative bridge design, SMART bridge.

1. Introduction

In the Netherlands, country with Europe's largest port in Rotterdam, transport infrastructure has always been important. The first official highway in the Netherlands, as being the third country in Europe to have a highway, was the A12 between Voorburg and Zoetermeer which opened in 1937. Nowadays a total of 5075 km highway is constructed making the Netherlands the country with the highest highway density in the European Union (57.5 km highway per 1000 km^2) (Wegenwiki, 2016). Since the Dutch highway network is one of the busiest in the world, the traffic demands are high. Some highways cope with over 200.000 vehicles passing on daily base. This makes our infrastructure susceptible to maintenance and construction works which can easily lead to undesirable traffic hindrance and safety issues. With regard to the historical growth of the Dutch road network (Fig. 1a), it is noticeable that a large expansion took place between the sixties and the eighties of the last century (CBS, 2015). Simultaneously with the expansion of our road network, also a large number of bridges (and viaducts) were constructed (Fig. 1b). Almost 50% of existing bridges are built in this time period (RWS, 2015). Keeping in mind that many of the bridges are constructed for a design service life of 50 years, a large infrastructural replacement task in the near future may be faced by the Dutch ministry of infrastructure (Polder et al., 2012). Many countries worldwide face a similar problem and solutions for dealing with it are urgently needed. Should existing bridges be replaced using the same structural systems and the same materials used in the past? Will this conventional way of building satisfy current requirements or do we need to apply new and innovative techniques and Advanced Cementitious Materials (ACMs) such as UHPC (Ultra High Performance Concrete), SHCC (Strain Hardening Cementitious Composite) and many others?

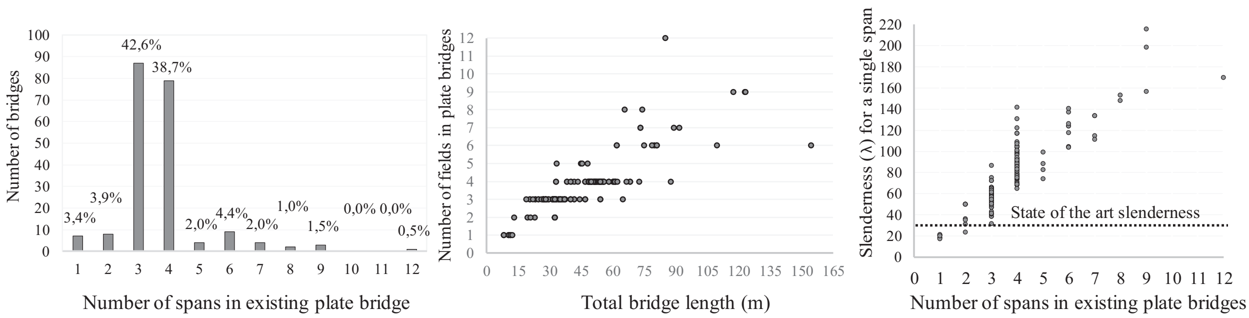


(a) Historical overview of length of Dutch main road network. (b) Historical overview of constructed Dutch bridges in last decades.

Fig. 1. Historical development of Dutch highways.

2. Future replacement task

In the past, mainly cast in-situ reinforced concrete plate bridges were built. Prior to the increasing use of prefabricated concrete, this bridge type was, for a long time, the most attractive. Mostly the plate bridges were built with three or four spans (Fig. 2a). Bridge length for the three span bridges was mainly between 20 m and 40 m. For the four span bridges the total bridge length was mostly between 40 m and 60 m (Fig. 2b). An advantage of a plate bridge with multiple intermediate supports over a single span bridge is the possibility to achieve higher slenderness. This is due to the more favorable distribution of the bending moments in multiple span bridges. A disadvantage of building a cast in-situ plate bridge is that more on-site construction time is needed for mounting the formwork, placing the reinforcements, and pouring and hardening of the concrete. Nevertheless, at the time when most of the plate bridges were built, the construction time was not an issue since bridges were built in new highways where traffic hindrance was irrelevant. However, when considering the future replacement task, rebuilding cast-in situ plate bridges is, due to its impact on traffic, undesirable and should be avoided. This makes the use of prefabricated girders more favorable. Furthermore, rebuilding the intermediate supports is undesirable due to traffic hindrance and safety issues such as vehicle collisions. In addition, when building without the intermediate supports, more traffic lanes can be created in the available space under the bridge (traffic profile). In order to replace an existing cast in-situ plate bridge without using the existing intermediate supports and in order to keep the current traffic profile, a high slenderness is needed. However, the state of the art slenderness with prefabricated prestressed concrete box girders is merely 30 and this is not sufficient for the replacement task (see Fig. 2c).



(a) Existing plate bridges (n=204) and the number of spans. (b) Total length of existing plate bridges with the number of bridge fields. (c) Slenderness required to replace existing plate bridges with a single span bridge.

Fig. 2. Identification of bridges within the Dutch main road network.

Therefore, with the state of the art technology regarding prefabricated concrete bridges, when a single span bridge is desired, three options (marked in Fig. 3) are feasible:

1. Increasing the height of an existing highway in order to align it with the new viaduct under which the traffic profile stays the same;
2. Lowering the underlying road so that the traffic profile under the viaduct stays the same;
3. Reducing the existing traffic profile under the viaduct.

The first and second options are not desirable due to traffic hindrance. Also, apart from costs needed to replace the bridge deck, additional costs are needed for the groundwork to keep the same traffic profile below the viaduct. For the third option, safety issues regarding collisions for higher vehicles may arise as the existing traffic profile is reduced. Therefore, none of the existing solutions regarding the replacement of existing cast in-situ plate bridges, provides that the traffic impact during construction is reduced to a minimum. This means that an innovative slender and lightweight bridge type is needed.

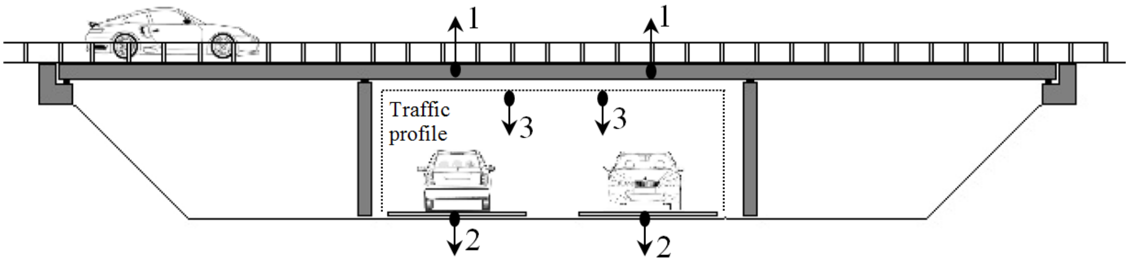


Fig. 3. Replacement of an existing three span concrete plate bridge.

At the moment, the Ministry of Infrastructure and the Environment in the Netherlands (RWS, 2015) manages around 4000 bridges in the Netherlands. Hereof, in total 3000 concrete bridges are within or over a highway. In a dataset provided by RWS it is found that, out of the 3000 bridges in or over highways, 1300 are built before 1974. Bridges constructed before 1974 are built with less conservative design recommendations regarding the shear capacity of concrete. Out of these bridges it is estimated that 750 bridges are three or four span plate bridges. So, in total about 18% of the existing bridges managed by RWS are three or four span plate bridges built before 1974, in or over a highway.

3. Low traffic hindrance bridge replacement methods

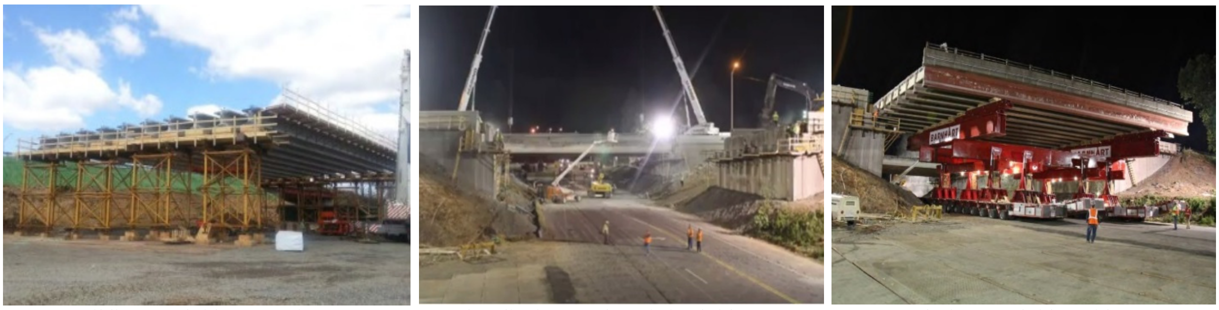
3.1 General

In current projects it has been observed that there is an increasing interest for both the client and the contractor as well the society for decreasing the total project delivery time. This is in order to limit the traffic impact, avoid weather-related time delays and reduce the onsite construction time when an increased work site safety, quality and durability of the structure are required. To decrease the total project delivery time an Accelerated Bridge Construction (ABC) method can be used in combination with a slender and lightweight bridge.

3.2 Accelerated Bridge Construction (ABC)

In an international context, an effective method to replace existing infrastructure is found in America where a concept called ABC is used. ABC uses innovative planning, design, materials, and construction methods in a safe and cost-effective manner to reduce the on-site construction time needed for building new bridges, or replacing and rehabilitating the existing ones. A common reason to use ABC is to reduce traffic hindrance. Namely, safety of the traveling public and the flow of the transportation network are directly impacted by on-site construction related activities. Another common and equally viable reason to use ABC deals with site constructability issues. Often long detours, costly use of a temporary structures, remote site locations, and limited construction periods are opportunities where the use of ABC methods can provide more practical and economical solutions compared to those offered by conventional construction methods (Culmo, 2011).

An example of using ABC for the replacement of interstate highway bridges, which typically can take months, or even a year or more using traditional construction methods, is the project I-84 bridges over Marion Avenue in Southington, Connecticut (Atkinson, 2015). The replacement project consisted of two existing bridges that are built in 1964. The scheduled replacement of the bridges anticipated that the highway will be closed from 9 p.m. Friday, June 27, 2014 to 5 a.m. the following Monday. However, the project progressed smoothly so that one bridge was reopened at 4:30 p.m. and the other at 8:30 p.m. Sunday. After demolition of the existing bridges (see Fig. 4b), new spans were set in place on the existing abutments. These superstructures were built at a nearby staging area (see Fig. 4a) and moved into place using Self-Propelled Modular Transporters (SPMT) which are platform vehicles that can lift and carry large structures, such as bridge section (Fig. 4c). The bridge is built up with prefabricated bulb-tee beams. When considering a construction method such as ABC an important requirement is to reduce bridge weight.



(a) Building new bridge at staging area. (b) Clipping out the existing bridge. (c) Placing new bridge with SPMT.

Fig. 4. Replacement of the two I-84 bridges over Marion Avenue (Atkinson, 2015).

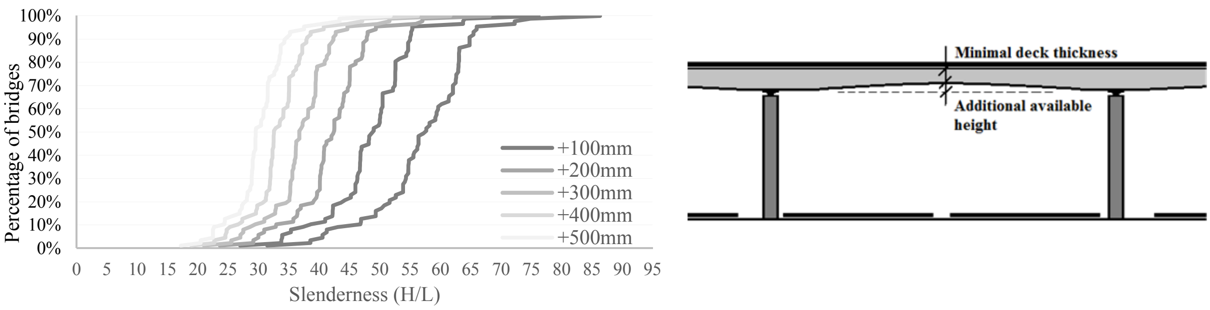
3.3 Innovative slender and lightweight bridge

Concerning the future replacement task there is a need for an innovative slender lightweight bridge that can be placed with a minimum traffic impact. Therefore, the following preconditions apply for the development of this new type of bridge:

1. Slenderness larger than λ=45 with the ability to make a bridge length of at least 40 m.
2. A lightweight bridge type so that the existing foundations can be maintained.
3. A lightweight bridge type to make an easy construction process when using ABC.
4. Ability to join separate elements to each other to form a whole bridge.
5. Suitable geometry for transportable bridge elements with a low traffic impact.

3.3.1 Slenderness

With regard to the required slenderness for replacing an existing concrete three span plate bridge with a single span bridge, a graph based on 87 existing bridges built before 1974 is made, see Fig. 5a.



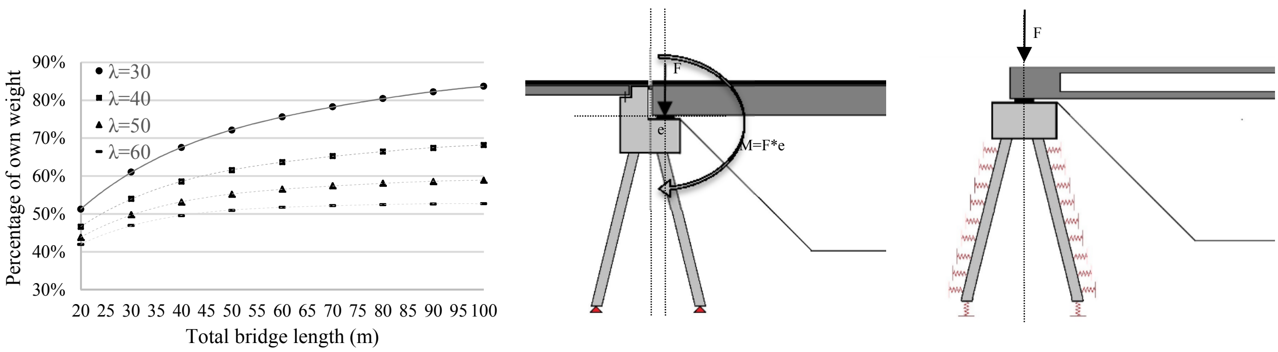
(a) Slenderness needed for a single span bridge. (b) Extra available space compared to deck thickness.

Fig. 5. Identification of slenderness needed to replace existing three span plate bridges.

Here, the needed slenderness depends on the existing space available for building in the new girder. For some of the existing plate bridges extra design height, in addition to the minimal bridge deck thickness, is available (+100 mm, +200 mm). A curved deck is used in some plate bridges (Fig. 5b). If only the existing height of the concrete deck is available, then with a bridge slenderness of λ=45, 10% of the existing bridges can be replaced with a single span bridge (Fig. 5a). When an additional 200 mm is available to build in, with a slenderness of λ=45, 60% of the existing three span plate concrete bridges can be replaced with a single span. Out of Fig. 5a it is clear that a bridge slenderness larger than λ=55 is too high, and a slenderness of λ=35 does not lead to significant percentage of bridges to be replaced.

3.3.2 Keeping existing foundations

In order to further reduce the traffic impact when replacing an existing three span concrete plate bridge with a slender single span bridge, the most favorable is to keep the existing foundation. Then, only the existing bridge deck and the existing intermediate supports need to be demolished and removed before placing the new bridge. However, this may cause forces in the foundation piles in the new situation to exceed the forces in the existing situation. Therefore, not only slender but also a lightweight girder is required. For most of the bridges large capacity is needed to carry its self-weight, see Fig. 6a. For a 20 m span bridge built up with prestressed box girders with slenderness λ=30, the self-weight is equal to the variable load. For longer bridge lengths the bridge self-weight becomes even more dominant. However, with increasing a box girder slenderness from λ=30 to λ=60, for example, the self-weight and variable load become equal again. Besides using slender and lightweight girders modifications on the foundations may be necessary to ensure a safe design. Here various techniques can be used. When analysing the design method used for bridge foundations built between the sixties and eighties it can be concluded that, at that time, more simple design techniques where used. When considering modern design techniques such as FEM, it can be noted that making design calculation with the use of spring stiffness's (vertical and/or horizontal Menard springs) reduces the forces in the piles. By using FEM for redesign of existing foundations, a larger bearing capacity of existing foundations is estimated compared to the initial situation. Another option for redesigning an existing bridge foundation for increasing the design capacity is replacing a bridge girder concentrically (Fig. 6c) on the abutment instead of eccentrically (Fig. 6b). This makes that the bending moment occurring as a result of the abutment support reaction is removed. This reduces the compression force in the frontal piles.



(a) Ratio of bridge own weight against variable load. (b) Existing bridge foundation design. (c) New foundation design.

Fig. 6. Calculation methods for the maximum forces in foundation piles.

3.3.3 Weight reduction for ABC

As already indicated, an accelerated construction when placing a bridge can be achieved by using ABC and SPMT. SPMTs are computer-controlled platform vehicles that can move bridge systems (Fig. 7a and 7b). The prefabrication of bridges off-site, under controlled conditions, followed by rapid installation on-site can achieve high quality installations with lower traffic impact (minutes and hours compared to months typically required for conventional on-site bridge construction). SPMTs are used to lift and drive components in the petrochemical, offshore, power, and heavy civil engineering industries. The shipbuilding industry uses SPMTs to move ship components during fabrication and the transportation industry uses them to move bridges. A single SPMT unit has either six or four-axle lines, with each axle line consisting of multiple wheels. The units are connected by a cable and controlled by one driver who operates the controller. The convenience and flexibility of constructing bridges offsite, out of traffic, provide several opportunities to further improved design and construction processes. Weight reduction and other design efficiencies can streamline the move. Consideration should be given to reducing the self-weight of the heavy prefabricated systems that must be lifted and hauled into position (FWHA, 2007).

(A) Placement of new bridge with SPMT.

(b) Using a jack-up to lift and place a new bridge.

Fig. 7. Illustration of placing a new bridge deck with the use of a SPMT with jack-ups (ENERPAC, 2016).

3.3.4 Joining of separate elements of the bridge

If bridge elements should be connected to form a full bridge, it is required to provide features that enable coupling of elements. For the girders post-tensioning cables can be used to span bridge elements together. Furthermore, it would be favorable to place asphalt on top of the prebuilt bridge as well as other road requirements such as lines and guidance rails.

3.3.5 Easily transportable elements

As a bridge staging area can be used for pre-building a bridge, it may be better to carry smaller elements towards it. This ensures that during the transport of these elements no roadblocks are necessary. An example of using prefabricated UHPC bridge elements is the bridge over the Perak River in Malaysia (Voo and Foster, 2016). This 100 m span bridge is constructed using UHPC bridge elements that are placed by putting the elements on a rail that is supported by a temporary steel structure (Fig. 8). After placing all the elements, post tension strands are used to prestress the elements. A main advantage of these elements for building a bridge is that they are easy transportable and that time dependent effects such as shrinkage of the concrete have less influence on the prestress losses. An ideal method for replacing existing concrete plate bridges can be achieved by using bridge elements with a width that is equal to the bridge width.

(a) Prefabricated UHPC bridge elements.

(b) Placing the elements on site.

(c) UHPC bridge with 100 m span.

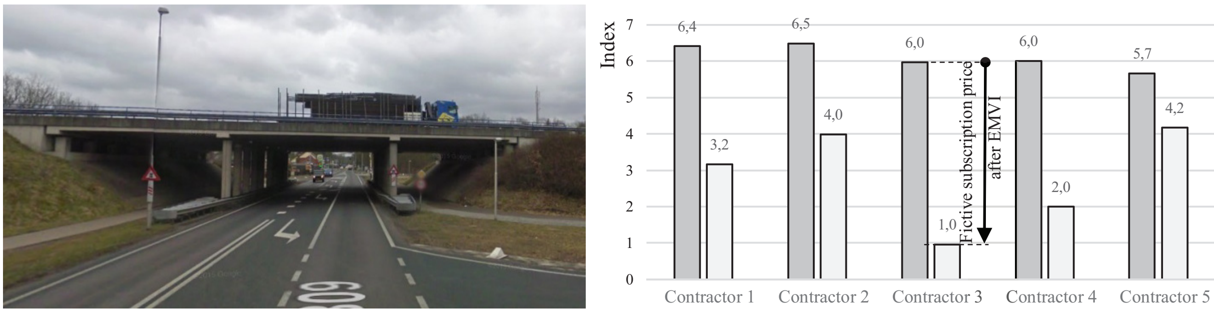
Fig. 8. UHPC bridge spanning 100 m and crossing the Perak River, Malaysia (Voo and Foster, 2016).

4. Proposed solution: innovative slender and lightweight UHPC bridge concept

To obtain a more slender and lightweight bridge there is potential for the many new and innovative ACMs. In recent decennia researchers have successfully put much effort in developing new concrete types. Examples are concrete with properties such as ultra-high performance (UHPC) or bendability/malleability (SHCC), self-sensing concrete, self-healing concrete, etc. However, applications of these ACMs are still limited due to lack of technical and economic feasibility studies, design criteria, large-scale material availability and risk coverage. Hesitance to using ACMs and other well-developed technologies is limiting the advances in building industry and social development. In this respect, aforementioned development towards innovative, slender and lightweight girders can be achieved, for example, by using HPC or UHPC. These concrete mixes, having compressive strengths up to 250 MPa, are much stronger than conventional concrete. Due to this higher compressive strength these concretes can resist a much higher prestress force and enable obtaining higher bridge slenderness. However, there are some restrictions by the production processes of prefabricated concrete girders for using prestressing. Nowadays a limit of 2250 tons of prestress force (110 strands) applies in order to comply with stability demands of the existing retaining blocks. Therefore, when only pretensioned prestressing is applied, the total UHPCs capacity is still not exploited, implying that perhaps a combination of pretensioned prestressing and post-tensioning has to be used.

5. Case study: replacement task A28/N309

To determine the possibilities concerning designing with HPC and UHPC, a feasibility study is elaborated. Here, the objective is to find which slenderness is achievable, and what else is needed for research and development. The elaborated case study deals with the replacement of a three span concrete plate bridge with a total span of 32 m that lies within the Dutch highway A28 (Fig. 9a).



(a) Existing three span plate bridge in A28/N309.

(b) Outcome of tender + EMVI score.

Fig. 9. Tender replacement of existing three span bridge within the A28/N309.

The highway crosses the underlying road N309 with three traffic lanes. The demands of RWS were that the existing bridge is replaced by a new bridge that can serve for the next 100 years, while also the underlying road is widened to five traffic lanes. Special about the project is the Design and Construct (D&C) contract where a large fictive bonus called EMVI (Economical Most Advantageous Registration) is included for the tenderer that has the most favorable traffic model. Also a large bonus was available for using slender bridge girders so that the underlying N309 does not need to be deepened in order to maintain the existing traffic profile under the bridge. Here the bonus of € 250.000 was given for each 50 mm that the bridge was more slender compared to the reference two spans bridge design (each span 24 m) where a 800 mm high box beam girder was used. Therefore, the criteria for choosing the best contractor are directly related to the earned EMVI. In Fig. 5b the result of the tender is shown with the evaluation of five contractors. Here the dark gray column stands for the subscription price ranging from 5.7 till 6.5 (index). After this, the fictive subscription price is calculated based on EMVI. The light gray columns that range from 1 till 4.2 is the fictive subscription price. It can be noted that the EMVI has a very large influence on the final result, meaning that traffic impact and infrastructure alignment is very important factor in this tender. Contractor 3 won the tender with the lowest fictive price of 1 (index).

To determine the advantages of applying a HPC or UHPC bridge for replacement of the existing bridge in the A28/N309 a feasibility study is executed. The bridge in the feasibility study has a single span of 48 m and a bridge width of 16.2 m (two traffic lanes). The first step was to determine the achievable slenderness of a concrete box girder bridge, where the production process and geometry are kept equal to currently produced box girders (Fig. 10, level 1). The concrete strength class was increased. The box girder has a width of 1480 mm, a web thickness of 155 mm, a top flange of 170 mm and a bottom flange of 140 mm. For the prestressing, Y1860 7 wire cables with a diameter of 15.7 mm are used. Besides for shear, no traditional reinforcement is used. The maximum slenderness that can be reached with this box girder is λ=40. In this situation a concrete strength higher than C130 does not give an increased slenderness because of a limitation in the total allowable prestress force of 2250 tons.

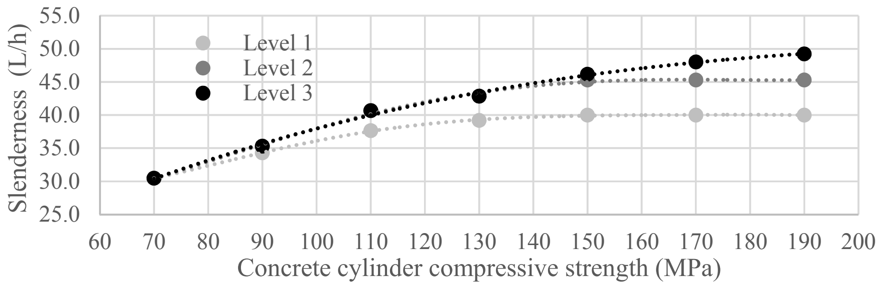


Fig. 10. Achievable slenderness of a box girder bridge with an increasing concrete compressive strength.

The second step consists of the design of a box girder where prestressing and post-tensioning is combined (Fig. 10, level 2). This provides that a larger prestressing force can be applied. In total 110 prestress strands are used for prestressing. The maximum number of post-tensioning strands in this situation is determined with design recommendation for using Dywidag post tension anchors (Dywidag, 2013). However, in this recommendation only anchor edge and in-between distances are given for concrete up to C45. This results in a conservative calculation when using HPC or UHPC. The anchors are placed on the head ends of the box girder. Based on the calculations it is found that, when combining pre- and post-tensioning prestress cables, a maximum slenderness of λ=45 can be achieved. A concrete strength over C150 does not increase the slenderness because of the limitation in the prestress force that can be applied. In Fig. 11 the result of the calculation is shown. Here, on the y-axis the number of strands in the cross section is placed. On the x-axis the height of the box girder is shown. Dashed lines present different concrete strengths. With a more slender box girder, due to equilibrium in the cross section, fewer strands can be used. The light gray area indicates the limit of 110 strands that can be applied in the factory.

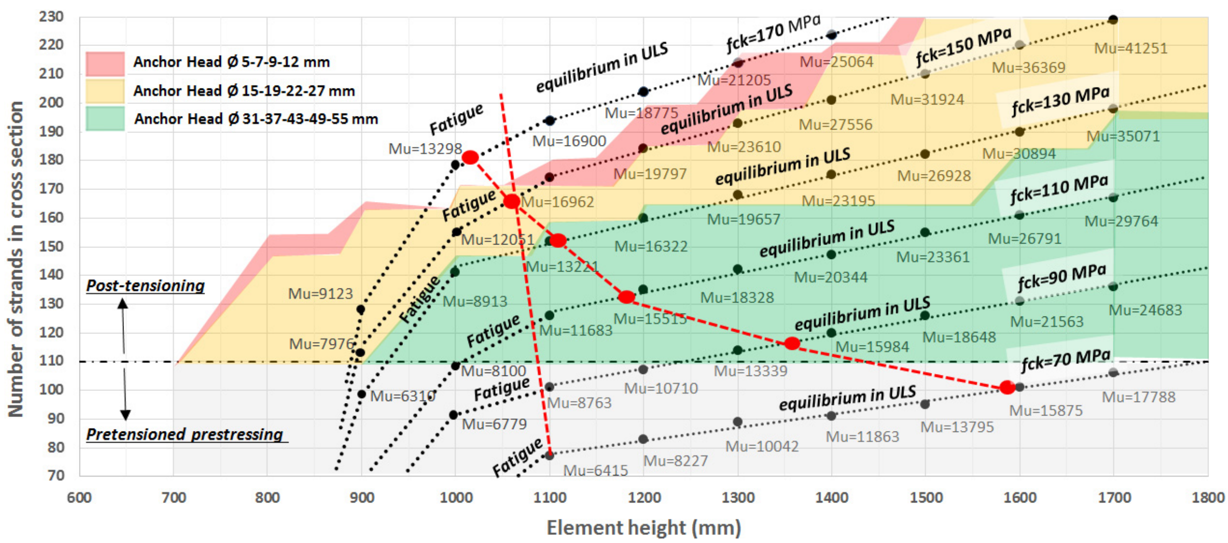


Fig. 11. Combined pretensioned prestressing and post-tensioning in a prefabricated box girder.

The number of post-tensioning strands that can be applied in the cross section is also indicated. In a more slender box girder fewer post-tensioning strands can be placed due to the required anchor distances in the head ends of the box girder. In the graph a line is drawn that is connected by bigger red dots. This line shows the required capacity for a 48 m span bridge. Here it can be observed that when using a C170 concrete the limit is reached to place the post-tensioning strands in the cross section. Therefore, using a concrete strength higher than C150 does not lead to a more slender girder. So, the minimum construction height is a bit more than 1050 mm in which case around 165 strands are required.

The third step was to determine the achievable slenderness when the anchor distances given by Dywidag (2013) (for a maximum C45 concrete) are extrapolated towards HPC and UHPC concrete values (Fig. 10, level 3). For UHPC smaller anchorage distances are assumed to be valid. As a result, using a concrete strength higher than C150 leads to a more slender girder since placing of the post-tensioning strands is not governing for the design anymore. The maximum slenderness that can be reached with this box girder is λ=50. Here the fatigue behavior is governing for the calculations.

With regard to the foundation, calculations were made for the maximum pile force under different bridge types (Fig. 12). The purpose is to check if there is an option where the initial foundation pile force is not exceeded. On the y-axis in Fig. 12 the maximum calculated pile force is shown. The first bridge type on the x-axis is the existing, reference bridge (48 m plate bridge on two intermediate supports). Here a maximum foundation pile force of 694 kN occurs under all acting permanent and variable forces (calculation with partial factors). The second bridge type is a single span box girder with a slenderness of λ=30 that can be produced nowadays. Here the maximum pile forces are calculated with the same method as the pile forces in the existing plate bridge. The maximum occurring pile force is 1290 kN. This is significantly more than the initial situation, which means that additional measures are needed. The first step is that, in the FEM calculations, spring stiffness's both in horizontal and vertical direction are introduced. Here a box girder slenderness λ=30 and λ=50 are used. The acting forces on the foundation piles in these situations still exceed the initial foundation pile forces. The second step is placing the bridge concentrically on the abutment as illustrated in Fig. 6c. Now the calculated maximum foundation pile forces, when using a box girder bridge with a slenderness of λ=50, leads to a situation where the initial maximum pile forces are not exceeded.

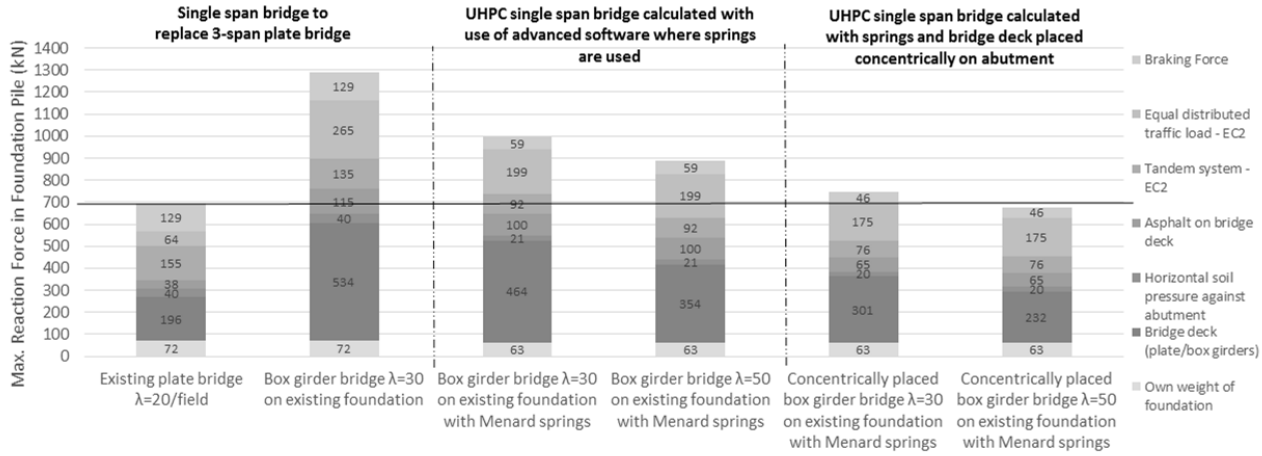


Fig. 12. Maximum reaction force in existing foundation piles obtained by different calculation methods.

The conclusion of the feasibility study for replacing the existing concrete plate bridge within the A28/N309 is that a slenderness of λ=50 can be achieved by using prefabricated C190 prestressed UHPC bridge girders with a combination of prestressed and post tensioned strands. When a slenderness of λ=50 is used to create a single span bridge, calculations show that the existing maximum pile foundation forces are not exceeded with regard to the initial situation. Keeping an existing foundation when using slender UHPC girders can reduce the construction time considerably in many building situations. It has to be highlighted that current approach seems to be promising, but the various assumptions made for the preliminary calculations should be (maybe also experimentally) verified in the future.

6. Future prospective

In this paper an idea is presented for the replacement of existing concrete plate bridges with an innovative bridge type that consists of slender prefabricated UHPC box girders. With preliminary calculations it is shown that a high slenderness of λ=50 can be achieved. For a fast and safe building process, ABC techniques such as keeping the existing foundation and using SPMTs are used to reduce traffic impact. In the elaborated case study new techniques, such as using an increased concrete compressive strength and combining pretensioned prestressing and post-tensioning strands to increase the total prestress force, are used. To obtain an even more slender or lightweight bridge, the following measures may be furthermore taken: removing shear reinforcement to reduce the web thickness, reducing the concrete cover when using UHPC or using high strength strands to increase the bending moment capacity. The future prospective towards utilizing the proposed new bridge type and construction method is to perform research to ensure safe design. To achieve a slenderness of λ=50 a detailed research on the following aspects is necessary:

1) Introducing high prestress forces in a UHPC cross section
2) Determine the failure behavior of heavily prestressed UHPC elements
3) Investigate the shear capacity of UHPC elements without stirrups
4) Investigate the fatigue behavior of UHPC elements
5) Possibilities of reducing the post tension anchor distances in UHPC elements
6) Possibilities of using high strength prestress strands
7) Possibilities of reducing the concrete cover when using UHPC

These aspects will be subject for further research, modeling and experimental verification at Delft University of Technology.

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