# Towards a SMART Bridge: A Bridge with Self –Monitoring – Analysing, and -Reporting Technologies

ir. A.D.Reitsema[1,2], prof.dr.ir. D.A. Hordijk[1]

[1] Delft University of Technology, Delft, the Netherlands
[2] Heijmans, Rosmalen, the Netherlands

ABSTRACT: In recent decennia researchers have successfully put much effort in developing new concrete types. Examples are concrete with properties such as ultra-high performance or bendability/malleability, self-sensing concrete, self-healing concrete, etc. However, applications of these Advanced Cementitious Materials (ACMs) are still below expectations due to lack of technical and economic feasibility studies, design acceptance, large scale material availability and risk coverage. Not using ACMs and other well researched, but unused, technologies is undesirable, both because of the research input already done, as well as opportunities that are lacking where society is concerned. In order to encourage the application of these potential technologies at Delft University of Technology, a visionary overall concept for future bridges has been launched. The idea behind it is placing a point on the horizon (say 2030); bridges then will be smart and intelligent, taking optimal advantage of all possibilities as far as load carrying capacity, durability, aesthetics and monitoring is concerned, in which function integration is normal, and with optimal mobility because of low maintenance. This visionary concept focuses on bridge engineering, and is called SMART bridge. A SMART bridge provides solutions for present-day and future challenges. In the paper the idea of the SMART bridge is elucidated.

Corresponding author's email: a.d.reitsema@tudelft.nl

## 1 INTRODUCTION

As in many other countries, the Netherlands has a large number of structures (bridges, viaducts, tunnels) in its road network that were built in the sixties and seventies (fig.3). These structures have an intended lifespan of at least 50 to 80 years, which may be extended or shortened depending on structural performance, durability aspects, and functionality. If it appears that a structure no longer meets the set of requirements, or that a structure is degrading too quickly under its current conditions, measures for retrofitting can be taken. However, independent of the structure and its protective measures, the aging process will continue and may lead towards a situation where upgrading is economically less feasible than replacement. Nowadays there are many successful efforts to extend the lifespan of infrastructure, but nevertheless it should be envisaged that there will also be a large demand for replacement in the near future. This makes conceptual thinking about shaping future infrastructure essential, and within this process it is important to anticipate known shortcomings, demands and possibilities. This will make newly built infrastructure able to outclass the current infrastructure. At Delft University, a visionary concept about new infrastructure is being developed in which the main focus is on bridge engineering. The overall concept is called SMART Bridge, where SMART stands for Self-

Monitoring, -Analysing and Reporting Technologies. The key characteristic of this concept is that SMART Bridge utilises new but existing and well examined potential technologies such as ACMs, new design and construct methods, and monitoring techniques. In order to use these potential technologies in a well-founded manner, the SMART bridge concept is developed by anticipating an infrastructure's known shortcomings (actual structural health), present-day demands (sustainability, low maintenance, short construction time) and future possibilities (free form design, function integration). To make the concept manageable, all short term possibilities and future opportunities have been identified. These will find application in an actual SMART bridge 2018 version that will be the first prototype towards the 2030 benchmark. After, or perhaps during, completing the SMART bridge 2018 version, research will be done towards the next version. This makes the SMART bridge concept a fast-evolving innovation platform. Besides developing these prototypes, the overall SMART bridge concept's expectations will be shifted due to possibly altering future demand and possibilities (fig.1). The purpose of the SMART Bridge concept is that serves to encourage and convince for all parties involved, e.g. bridge owners, building authorities and contractors. Both society and industry can largely benefit from the utilisation of new techniques.

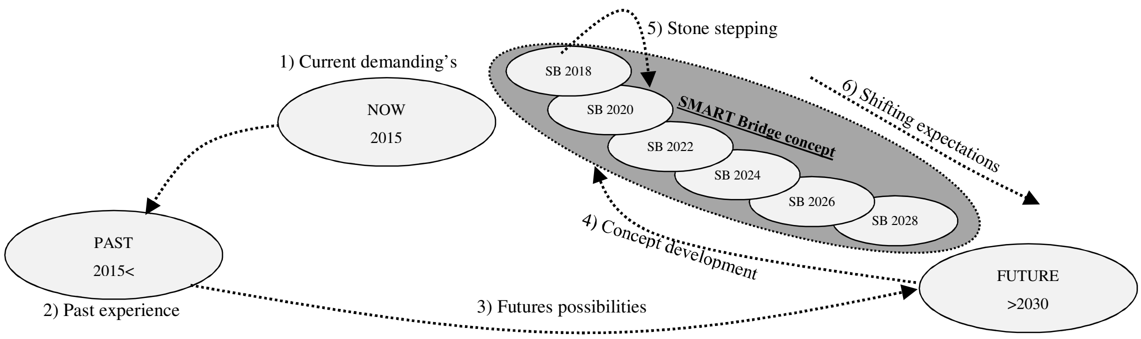
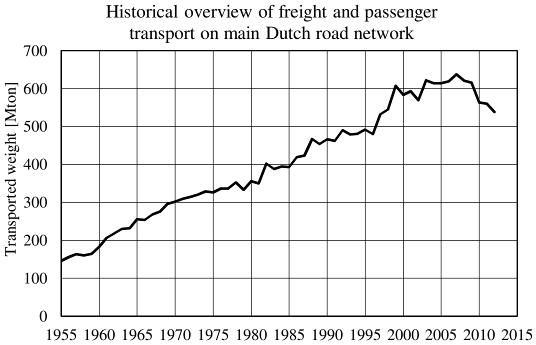



Figure 1. SMART Bridge concept development process.

## 2 KNOWN SHORTCOMMINGS OF PREVIOUSLY BUILT INFRASTRUCTURE

Previously built infrastructure has been made with the construction and material science of its time, and has been calculated with the then existing design standards, available traffic forecasts and vehicle load models. Based on this, these structures have been designed in such a way that they have an intended lifespan of at least 50 to 80 years. However, since the construction of these works, the traffic intensity has greatly increased in both weight and frequency (fig. 2). In addition, for some mechanisms the (safety) requirements for structures over the past decades have become more restricting, and more is known about how materials (steel and concrete) behave over time. It is the combination of increased traffic volume, vehicle load and safety, together with the experience from the regular maintenance regime that made RWS (Dutch Ministry of Infrastructure and the Environment) decide to launch an investigation in 2006 (RWS, 2007). This research answered questions about whether Dutch bridges have a (remaining) lifespan in conformity with the initial design, or if additional life-prolonging measures, or perhaps even accelerated replacement, was needed. A total of 2014 concrete bridges and overpasses were examined. Analysis showed that no further investigation was necessary for 840 bridges and overpasses, and that for 1174 of them a second consideration was needed. Based on the results of the inventory and analysis, there was and is no reason to impose direct restrictions for the use of any of the structures.



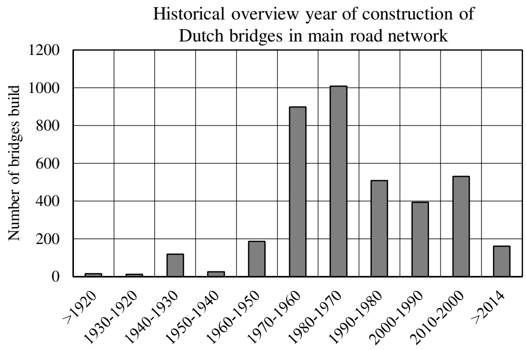




Figure 2. Historical transported weight (CBS, 2015). Figure 3. Bridge construction year (RWS, 2015).

However, it was be noted that the changing environment, safety requirements, material knowledge and degradation of the structure leads to challenges for making reliable determinations about infrastructures actual structural health levels, remaining lifespan, and maintenance needs. This makes it hard to make accurate estimations for maintenance and replacement budgets.

## 3 CURRENT INFRASTRUCTURES DEMANDS

### *3.1 Sustainability*

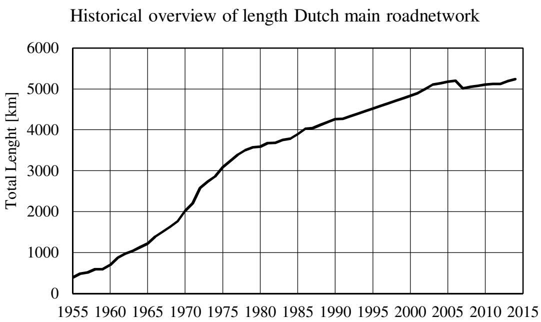
Though concrete structures bring society tremendous benefit, the environmental impact of concrete and its manufacture and applications is significant. A major component of concrete is cement, which has its own environmental and social impacts, and contributes largely to the impact of concrete. The cement industry is one of the primary producers of carbon dioxide (CO2), a major greenhouse gas, and the cement industry produces up to 5% of worldwide man-made emissions of this gas (CSI, 2012). The CO2-emission from concrete production is directly proportional to the cement content used in a concrete mix, and there is a growing interest in reducing carbon emissions related to concrete from both the academic and industrial sectors, especially with the possibility of future carbon tax implementation (ECOFYS, 2011).

### *3.2 Maintenance*

After decades of investments in Dutch infrastructure, such as the main road network, the need to sustain these structures experiences challenges. After a rapid development of the total length of the Dutch main road network (fig.4), it becomes clear that after half a decade the costs of maintaining it are rapidly growing (fig.5). However, because of political pressures, budgets for maintenance are becoming more tight. As a result the life cycle cost of infrastructure, including design, construction, maintenance, upgrading, and replacement, is becoming more important.

#### 3.2.1 Construction time

Building new, or retrofitting existing, infrastructure can lead to traffic disruptions during construction. This is inconvenient for road users who are delayed while traveling, but is also inconvenient because of economic interests. Therefore, various methods of construction are developed. However, the general experience with different methods is that a cheap method usually leads to the worst traffic flow. While this often causes opposing interests among clients, there is however an increasing interest for comparing different design proposals on both cost and traffic disturbance. Generally, there is a strong tendency to increasingly larger precast beams.



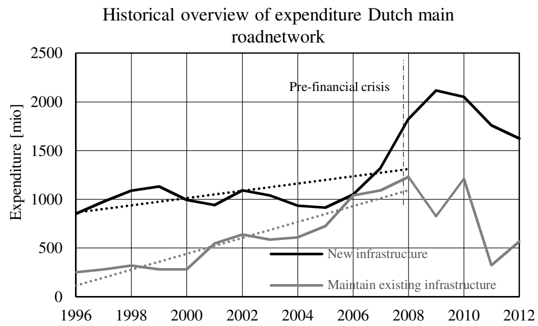




Figure 4. Length of Dutch road network (CBS, 2015). Figure 5. Road networks expenditures (MIRT, 2012).

# 4 FUTURE INFRASTRCTURES POSSIBILITIES

## *4.1 Free form design*

Besides defining topics of interest based on the past and the present, it is important to examine observable trends. One ever-moving and observable trend is aesthetics; with regard to building, aesthetics have always been important because it is a reflection of both knowledge and human development. Current possibilities for changing aesthetics are manifold due to rapidly evolving computer power. On the other hand, knowledge about new construction methods is growing fast. For example, a strong development with a broad interest is 3D printing. Available materials and knowledge about their properties and structural behaviour is also growing swiftly. Combining advanced knowledge about materials, design and construction-methods will lead to an increased development towards freeform structures. An example of a building where construction and design methods which were ahead of its time were used, is the "La Sagrada Familia" in Barcelona (fig.6). Here, Antonio Gaudi set up a model that had strings (for the catenaries) filled with weight in order to find the structure's optimal geometry.

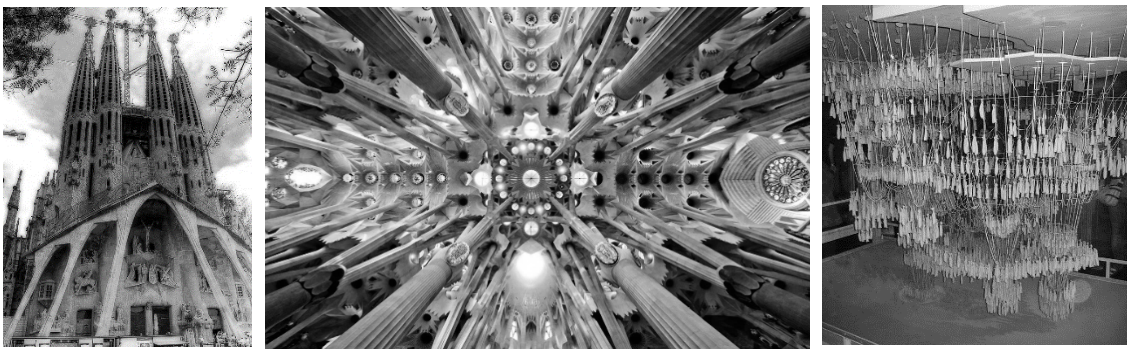


Figure 6. La Sagrada Familia poison façade, roof in the nave, string/bag design model (Sagrada Familia, 2015), (Antoni Gaudí, 2015).

## *4.2 Function integration*

Another globally noticeable trend is the development of smart products. This trend is strongly visible in phones, automobiles and airplanes, to name a few examples, which undergo continuous improvement towards being better able to carry out more than their originally intended tasks. For instance, beside the transportation of goods or persons from one point to another, automobiles are able to provide in information, help ensure safety, entertain, and assist in difficult situations such as parking. In short, present-day cars are able to communicate, and anticipate on changing surroundings and conditions. This is not the case with infrastructure. Most of the bridges built to date only have one purpose: being able to provide in a safe transport route. A clear future need for bridges is function integration; an example of this is a bridge which heats up in the presence of snow, so that no damaging de-icing salts need to be used. Other examples are harvesting solar or wind energy, or kinetic energy from vibrations. Providing information on vehicles using the bridge is also one of the options, such as when a bascule bridge is open so that detours will be faster where necessary, or providing information about required maintenance based on smart decision systems.

## 5 VISIONARY CONCEPT SMART BRIDGE

To anticipate on all mentioned shortcomings, demands and possibilities noted so far, an overall concept for a SMART Bridge has been developed. Four work packages (themes) have been defined in total (fig.7), within which it is intended to perform multiple pilots. An extraction of knowledge and experience from these pilots will have to result in an actual prototype, the 'SMART Bridge 2018 version'. In the second part of this article, the content of the four themes will be explained.

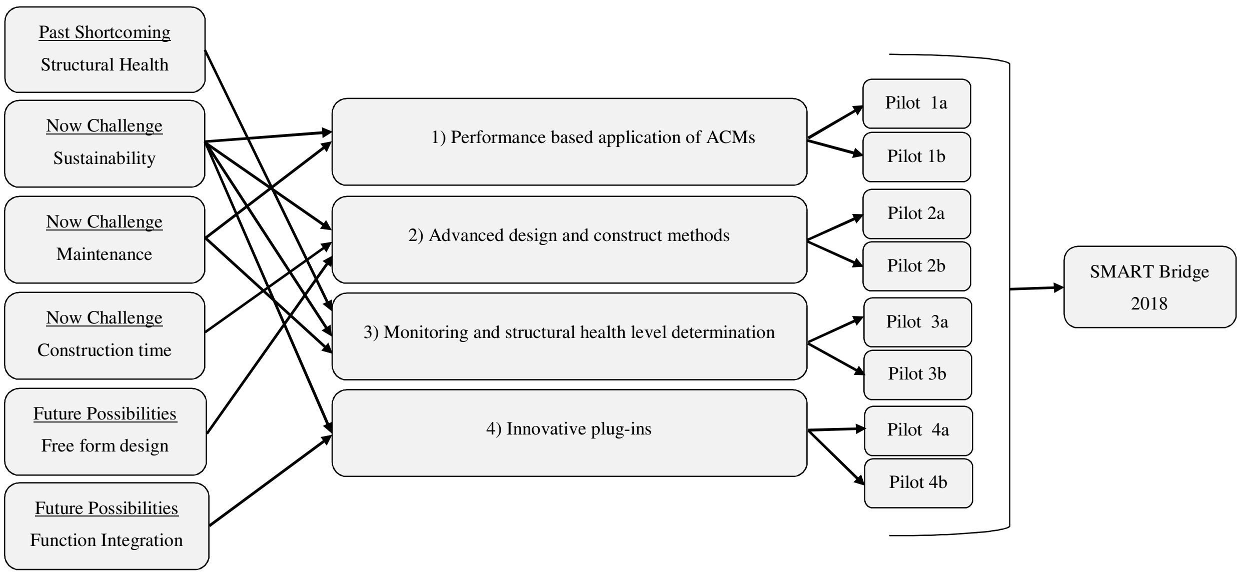



Figure 7. Main themes within the SMART-bridge concept.

### *5.1 Performance based application of ACMs*

In recent decennia a lot of research effort has successfully been put in the development of new concrete types. Properties can be controlled so that the concrete can be classified as self-compacting (SCC), ultra-high performing (UHPC), flexible (SHCC), self-sensing (applying nanotechnologies), self-healing, etc. However, large scale applications of these ACMs are still lacking. Many design studies have been performed to investigate how these ACMs can be successfully utilized. Most of the conclusions drawn are that the high material cost of ACMs make another design philosophy needed for their successful application. Within the SMART bridge concept, ACMs will be applied in a performance based manner. For example, SHCC is known for its bendable behaviour and finely distributed crack pattern (fig.8) that make it suitable as a protective layer for structures in an aggressive environment. Another possibility of performance based application of ACMs, is using UHPC in high compressive zones, for example in a compression arch. The main idea is combining ACMs with ordinary concrete or in other words combining “clever” and “simple” concrete. The advantages of combining different types of concrete is that the expected lifespan of concrete elements are much higher, the maintenance needs are lower, and the structural performance is higher. For the application of hybrid concrete structures, research is needed on the structural performance, scale effects, debonding and time dependent behaviour.

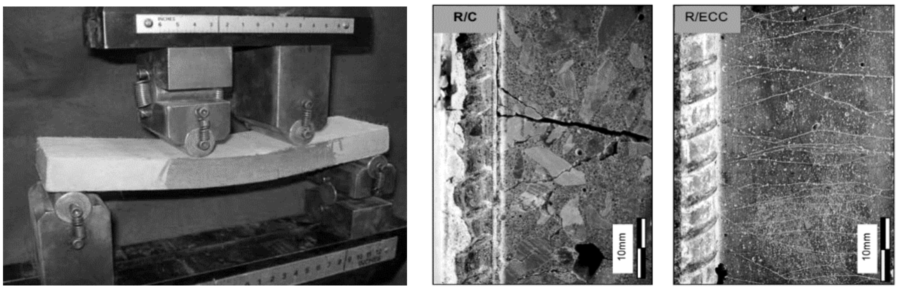



Figure 8. SHCC in four point bending test, crack pattern in ordinary concrete and in SHCC (Li, 2007).

### 5.2 *Advanced design and construct methods*

In order to build a bridge, information on the expected loads during the intended lifespan are required. This is, of course, traffic load, but can also be snow or wind load. Based on these loads, and using a structural scheme, appropriate load combinations and safety factors, the bridge’s safety level can be determined. It may be obvious that for a bridge, its self-weight is an important contribution to the total load. In an optimal situation, the proportion of the self-weight to the total weight is as low as possible. A good example of this is a bicycle with only 10 kg self-weight that is able to carry variable loads that are much larger. This is in large contrast to a bridge. In figure 9, a plot is made of the expected self-weight of a 2x2 lane bridge (based on standard structural capacity charts) that is needed to carry the maximum acting traffic load in accordance with NEN-EN-1991-2. From figure 9 the conclusion can be drawn that, especially at larger spans, the relation between the required self-weight to the maximum acting traffic, is large. In figure 10 the same results are plotted in percentages; here the conclusion can be drawn that for a 2x2 lane bridge with a span length of 70 meters, the self-weight of the bridge is almost 80% of the total. A target for the SMART bridge design is to significantly reduce the percentage of self-weight to the total load. This may be achieved by making use of ACMs in combination with advanced design methods.

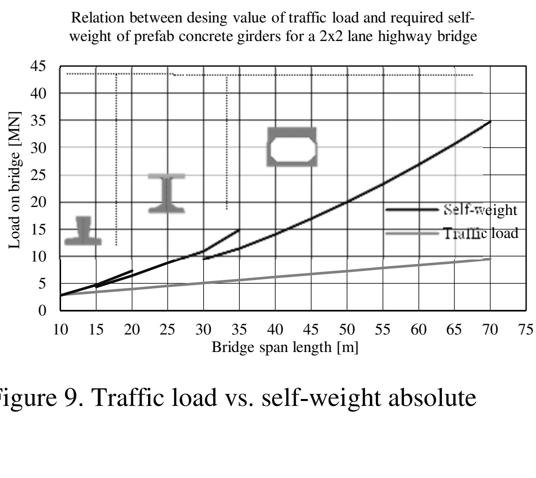



Figure 9. Traffic load vs. self-weight absolute

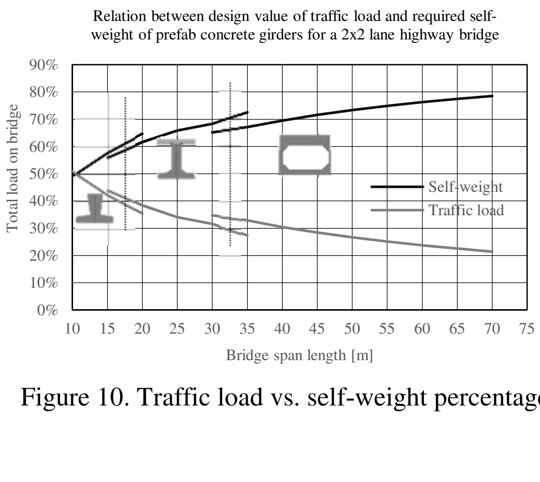



Figure 10. Traffic load vs. self-weight percentage

Examples of the latter are optimization algorithms such as topological optimization. This is a mathematical approach that optimizes the material dispersion within a given design space for a given set of loads and boundary conditions, such that the resulting layout meets a prescribed set of performance targets. Using optimization techniques will lead to freeform structures based on compressive and tensile arches. For the construction of these freeforms, the requirement for the applied material is that there is a phase transition from a liquid state to a solid state, ideally without requiring any additional energy. This makes concrete a very suitable material a opposed to construction steel, aluminium, stone or wood. It may be obvious that ordinary concrete with reinforcing bars to take over tensile forces, does not fit very well in this freeform concept. In that respect the ACM's, like fibre reinforced UHPC offer very good opportunities, especially in combination with prestressing elements. A possible approach is to add the prestressing in the structural freeform element by using post-tensioning tendons through the cross section. In this way, an optimal freedom for structural elements can be achieved. A challenge in obtaining freeform elements is the way in which molds are made. This is because traditional wooden or steel molds are very costly for freeforms. A solution for this can be found in the use of robotics or by applying fabric formwork. The advantages of using advanced design and construction methods is that the total volume of a structural element can be significantly reduced. Due to the reduced weight they can easily be transported and assembled, and also construction time will be reduced. Furthermore, correlating optimal design with freeform molding of elements will lead to aesthetically more attractive structures. The research needed for using advanced design and construct methods for SMART bridge are the application of optimization algorithms for situations where multiple loads and materials are used. Connecting possibilities and recruitments for creating freeform elements by a using advanced design methods, new materials, new production techniques (maybe also 3D-printing) and the structural performance determination is also needed. Furthermore, studies have to be carried out on failure modes which were generally not leading for concrete in the past, such as on vibrations and instability for slender elements.

### *5.3 Monitoring and structural health level determination*

In many technical sectors, monitoring of objects is quite common. Unfortunately, it is almost not done in civil engineering, while knowledge of technologies like wireless sensor networks, fiber optical (embedded) strain gauges, long term monitoring via vibration based methods, non-contact methods (laser), corrosion detection possibilities, and monitoring of environmental loads (Lynch, 2006) are already available and could be included in a SMART bridge. For bridges the monitoring purpose is to conclude on changing load levels in relation to the properties of the elements itself. For a concrete bridge it is possible to predict the current structural health by measuring the bending stiffness (EI) variation of the girders over time. In case of an unexpected significant increase of the load level, a concrete girder can react with an increased crack pattern, resulting in a decrease of stiffness of the element. Apart from increasing load levels there can, on the other hand, be a change in the properties of the element. In that respect the effect of reinforcement corrosion due to a chloride attack can be mentioned. With a significant reduction of the cross section of the reinforcement, deformation may increase, and the measurement of stiffness can possibly be used as an important first level real-time warning. In other words, monitoring stiffness informs us about whether 'something is going on'. What is going on has to be determined by visual inspection or possibly additional testing. By performing long-term concrete bridge girder stiffness measurements, a learning effect may arise. In time, experiences may give insight in relations between changes in stiffness and corresponding causes. For a certain known main cause, monitoring can be done separately (called level 2), in order to more directly respond to a known phenomenon. In a coming pilot project by Heijmans and University of Twente, the measurement of the stiffness of a concrete girder will be done in two ways: on the one hand bridge loadings and girder displacements are measured, while on the other hand bridge vibrations will be recorded. Monitoring the stiffness of a concrete deck with two separate methods can help to determine the accuracy of computations and measurement data. The research needed for the 'SMART bridge 2018 prototype' is the determination of the variation of the bending stiffness over time.

### 5.4 *Innovative plug-ins*

Function integration by using 'innovative plug-ins' can make a SMART bridge even more smart. These plug-ins can be communication systems, bridge cooling/heating products, decision and support systems, energy harvesting sound barriers, or other energy producing systems. These plug-ins can be proposed by each party that wants to introduce a proven existing, used or not yet implemented technology.

## 6 CONCLUSIONS

So far, at Delft University of Technology the SMART bridge is just a concept with the intention of attracting other parties to participate. It is strongly believed that in the future, bridges should no longer be built in the traditional way. The benefits of new technologies with respect to materials, monitoring, design methods, etc., has to be explored. During the development of the SMART Bridge concept, much knowledge and experience can be used in spin-off developments. An example of this is retrofitting of existing structures where ACMs can be used as spraycrete or prefab panels for strengthening and for durability protection. Issues with respect to debonding, or time-dependent effects are also present here. Another spin-off is the application of advanced design and construct methodologies and monitoring for non-bridge structures. The SMART bridge concept is intended for the development of a new type of bridge, but many other structures will change with it based on results and successes.

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