NOVEL DEVELOPMENTS TO PRECAST BRIDGE GIRDER TECHNOLOGY BY THE BME-ZÁÉV RESEARCH COOPERATION

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Abstract
The Competence Center on Safety Science and Technology joints significant research effort of the Budapest University of Technology and Economics (BME) and the potential industrial partners on several fields of industrial safety. On the building industry branch of this project novel bridge girder technologies have been developed by the cooperation of the Civil Engineering Faculty of BME and the ZÁÉV Construction Co Ltd. (ZÁÉV). These technologies aim to reduce the production time and cost, utilize the structural benefits of post-tensioning and ensure sufficient durability for products subjected to extreme chloride and freeze-thaw effects. The main outcome of the project is the full development of a brand-new, 0,9 m high bridge girder family made of self-compacting concrete. The use of self-compacting concrete is completely new in bridge girder technology in Hungary where high compressive strength both at young age and sufficient durability during 100 years of service life are the major demands to complete. For this purpose two mixes including limestone powder and CEM III type cement as additions were developed and tested in laboratory and factory conditions. The practical applicability of internal bonded and unbonded as well as external unbonded types of post-tensioning with various layouts were tested on two-span prototype systems. Following the international trends to extend service life or to further improve the durability of bridges subjected to extreme environmental conditions, possible solutions can be either to use embedded fibre reinforced polymer (FRP) bars instead of traditional steel ones as reinforcement in concrete or to structurally combine them with post-tensioning of full corrosion protection in hybrid-type bridge girders. The applicability of all these developments were demonstrated by failure load tests on full-scale prototype units of the girder family using an exclusive loading platform built on the storage area of the manufacturer. The developed bridge girder family already has CE marking.

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Keywords: bridge girder, bonded and unbonded post-tensioning, fibre reinforced polymer, self-compacting concrete, digitalization.

1. Introduction
To strengthen cooperation between academic research and economy, the Competence Center on Safety Science and Technology has been established at BME in 2021 in frame of the 2019.1.3.1-KK-2019-00004 project by the National Research, Development and Innovation Office. The aim of the project is to manage and optimize the risks occurring in the typical operational areas of the construction industry by applying a safety-oriented approach that meets the needs of the profession and the achieved technological level. The project joints research effort of the BME and the cooperating potential industrial partners in fields of the oil and gas industry, the mission critical systems in vehicle and traffic safety and the building industry as well as aims to develop the necessary IT platform including the technologies of AI, IoT, Big Data.
The building industry branch of the project is represented by the cooperation of the BME Faculty of Civil Engineering and the ZÁEV and divided into two subprojects. One initiates novel product developments and related technological improvements in production and, hereby, aims progress in field of traffic safety. The other focuses on construction industry process management by making developments related to the construction industry digitalization and thus, increase the safety level of the construction industry services. In both fields, the planned developments are realized by combining the competences of the BME Faculty of Civil Engineering and the ZÁEV in the given area. The primary location of these developments is the precast concrete plant of ZÁEV in Bóly.

This paper introduces the results and progress of the first subproject that has completed the first two out of the three milestones until the end of 2022.

2. Development of bridge girders using new technologies

The main goal of this subproject was to develop a bridge girder family applicable in bridges as well as other related prototype bridge girders by using new technologies that are unique both in the domestic and the foreign bridge girder industry. The following three milestones were set as result items:

- Milestone 2. (2022) Development of prototype precast bridge girders and related prototype bridge superstructures using the combination of traditional straight-line, factory made pre-tensioning and several types of post-tensioning
- Milestone 3. (2023) Development of durable prototype precast bridge girders using fiber reinforced polymer (FRP) bars as embedded reinforcement

Bringing the developed new bridge girder family to market within the frame of the project was set as a TRL9 indicator in the Competence Center project. Thus, several activities above research and design tasks had to be completed to make the product marketable.

Using bridge girders developed until Milestone 1 as basic units, high performance prototype bridge girders either suitable for meeting higher structural or durability demands or containing unique structural and technological solutions compared to ordinary applications were developed until Milestone 2 & 3. The primary purpose of these developments was to exploit the applicability of these new technologies. Thus, they are going to be developed to the level of a prototype product but are not intentionally moved to the market. Using self-compacting concrete for these prototype beams help further improving the related concrete technology already developed until Milestone 1.

Fig. 1. (a) Cross-section and (b) 3D view of the ZBI-90 type bridge girders.
2.1. Development of a new precast bridge girder family with traditional straight line pre-tensioning and made of self-compacting concrete (Milestone 1)

A family of prefabricated, high-performance bridge girders (ZBI-90) with a factory-made straight-line pre-tensioning and made of self-compacting concrete with a height of 0.9 m and a length range of 8.8-26.8 m has been developed (Fig. 1). Ordinary prestressing and reinforcing steel was applied as reinforcement. Safety-wise, the bridge girder family represent a reliability level that fully complies with the Eurocode and, consequently, the technical regulations for roads and associated road bridges to be introduced in Hungary in 2024 and the already operative MÁV regulations for railway bridges. To support designers in applying these products in new design projects, a product catalogue (design manual) on the structural details of the girder family as well as “sample” production plans of each element with subsequent lengths of 1 m are under elaboration.

2.1.1. Concrete design

To reduce energy and time consumption during production, high performance self-compacting concrete instead of traditional normal weight concrete has been implemented into the manufacturing process. Its applicability has been demonstrated for years in building construction. Several mixtures of self-compacting concrete containing normal aggregate and one or combination of four types of additions (limestone powder, basalt powder, CEM III type cement, metakaolin) were elaborated and then optimized through several laboratory and production site mixings. The optimization focused primarily on the consistency of fresh concrete ensuring workability (Fig 2(a)) and those hardened concrete properties which are determinant on durability (Fig. 2(b)). The target strength class was set as C50/60 (Fig. 2(c)). As result, two recipes containing limestone powder (G2) and CEM III type cement (G2/1) were selected, tested both in laboratory and on factory site and then further optimized (to G2 M and G2/1 M) when an alternative aggregate (sand) supplier was contracted. The initial tests on factory produced G2 M and G2/1 M mixtures ended in 2023 Q1.

![Fig. 2. Results of (a) consistency (b) freeze-thaw and (c) compressive strength tests of the developed concretes.](https://example.com/fig2.png)
The developed high-performance self-compacting concretes satisfy the durability requirements for environmental classes XC4-XD3-XF4(H) which describe the most severe possible environmental exposures (atmospheric corrosion effects, freeze-thaw attack and chloride penetration from de-icing salt) occurring during the intended 100 years long design working life of bridges. Because the recent technical specifications did not allow the use of the elaborated high amount of additions in structural concrete, the modification of the related road technical regulation e-ÚT 07.02.11 was also initiated.

2.1.2. Load tests on prototype beams
To test the structural adequacy of the developed girders, four 10.80 m long prototype beams made of the most promising developed concrete mixes were manufactured in factory building conditions.

After concrete hardening these beams were load tested until failure on the loading platform of the factory (see Sec. 3) During the full loading process the relevant structural parameters (deflection, compressive and tension strains and crack width) of the beams as function of the applied load were simultaneously registered with a digital data acquisition system (Fig 3). Typical bending failure occurred as expected.

2.1.3. CE marking
Based on the evaluation of the initial tests of the developed self-compacting concretes as well as those of the completed load tests of prototype beams, the competent certification body issued the Factory Production Control Certificate (CE license) for the manufacturer declaring that both the developed self-compacting concretes as constituent materials and the developed ZBI-90 bridge girder family were complying with the relevant European standards and ready to trade them on the European market.

2.2. Development of prototype precast bridge girders an related prototype bridge superstructures using the combination of traditional straight-line, factory made pre-tensioning with several types of post-tensioning (Milestone 2)

Post-tensioning has been widely used for long time on its own in many fields of construction industry. The aim of this development was to combine the structural advantages of post-tensioning with pretensioning. Within this period of the project two pairs of bridge girders of Milestone 1 were equipped with two types of post-tensioning.

2.2.1. Prototype beams and prototype superstructures
As part of this, the traditional, straight-line, factory-made pre-tensioning technology was combined in one version with a straight-line, Internally placed, unbonded post-tensioning (iub), while in the other version, with a curved, Internally placed, bonded post-tensioning (ib). Two 10,80 m long products were produced from both versions (Fig. 4 (a) and (b)).
Then, in accordance with the usual arrangement of continuous bridge superstructures comprising of series of precast beams, these pairs were assembled subsequently in longitudinal direction and structurally connected with monolithic concrete top flange of 20 cm thickness to produce a composite, two-span continuous prototype structure. Thereafter, these prototype structures were equipped with a polygonal, externally placed, unbonded post-tensioning (eub) (Fig. 4 (c)).

**2.2.2. Challenges in structural design and manufacturing**

During design it was extremely challenging to determine the necessary amount and the time of stress release as function of concrete age for both types of prestressing during the manufacturing process as well as to numerically follow the structural effects of each type of prestressing on both the concrete product and each other.

In order to form places to deviate the external tendons and to anchor the „iub“ tendons, it was inevitable to locally modify the geometry of girders by designing two collar-like blocks positioned symmetrically along the length of each prototype girder. The formwork of these deviation blocks had to be individually produced and included as supplementary parts into the existing formwork system used in Milestone 1.

**2.2.3. Testing the prototype structures**

The prototype structures were built above the loading platform and positioned such that one span could be loaded until failure (Fig. 5). The general process of these tests such as the loading and measuring system as well as the applied test protocol and the evaluation process were similar to those used for the Milestone 1 girders (Sec. 2.1.2) with appropriate changes in load intensity.

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Fig. 4. Internally post-tensioned prototype beams (“iub” and “ib”) and the externally post-tensioned prototype structure (“eub”).

Fig. 5. Testing the “eub” type prototype structure and typical damage places at failure.
2.3. Development of durable prototype precast bridge girders using fiber reinforced polymer (FRP) bars as embedded reinforcement

In this part of the project, following the international trends [1]-[2], the structural applicability of recent technologies presumably suitable for extending the design working life (above 100 years) of concrete bridge girders subjected to extreme environmental effects under normal service conditions are focused. Many of these solutions are not yet elaborated to a level which makes them compatible with recent standards but are hot research topics of this field.

One of these technologies aims improving the durability of concrete members by replacing the traditional mild steel reinforcement with glass (GFRP) or basalt-based (BFRP) fibre reinforced polymer bars in order to avoid steel corrosion. For bridge girders this would lead to significant loss in stiffness therefore, an unbonded post-tensioning system with a factory-made corrosion protection which completely separates steel components from the concrete environment is designed as part of the hybrid reinforcement of the prototype bridge girders to be developed until Milestone 3. The biggest challenge of this development is to structurally harmonize the mechanical properties of FRP bars with the structural behaviour of bridge girders to comply with the relevant design requirements. A particular difficulty is that many types of FRP products available on the market are not quality certificated. Thus, laboratory testing will be inevitable to experimentally determine the mechanical properties that play a key role in structural design and behaviour.

The testing of these prototype bridge girders with hybrid reinforcement is expected until the end of 2023.

3. Technological modernization of the equipment

An integral part of the project was directed to the technological modernization of the participants’ accessories. Beside the acquisition and installation of new assets in the BME Materials Testing Laboratory for research and educational purposes and in the factory buildings to improve the effectivity of the manufacturing process, one of the major investments, in close relation to the developed bridge girder product, was made on a brand new, complete formwork system also equipped with heat curing facilities. Of this, a 60 m long set was purchased at the expense of the project for trial productions and for the production of the prototype beams, while an additional 150 m required for continuous production after the physical completion of the project under market conditions will be covered by the ZÁEV from its own resources.

As another investment of the project, a loading device (loading platform) was built at the production site together with the related energy supply and assess paths. This platform consists of a concrete bench as foundation lowered into ground, a steel loading frame and a 2×1000 kN capacity hydraulic loading equipment that make it suitable for 1:1 scale load tests of all products manufactured in the plant (as shown in Fig. 3). This allows either making experimental tests for research and development purposes or conducting presentations for marketing purposes or expanding the portfolio with market-based leasing. The loading equipment is fully compatible with that of the BME Structural Testing Laboratory, thus, it enables further research or project-based cooperation with BME.

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References