Optimization of Prestressed Precast Girders with Ultra High-Performance Concrete

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Abstract
Advances in research, several demands, and challenges of modern construction motivated the Ultra High-Performance Concrete (UHPC) development. High compressive and tensile strength, ductility, self-compacting, and high durability are characteristics of the UHPC. The mentioned material allows more durable structures with high possible slenderness and enables the reduction or elimination of passive flexural and shear reinforcements. In this context, this study presents a case study and a comparative analysis of prestressed girders with UHPC and with a 45-MPa concrete. The section height and area, material volume and weight, reinforcement, ultimate resistance bending moment, shear, deflections, and costs were assessed. It was possible to reduce the volume and weight by 48% and 42% for the beams designed with UHPC with nominal lengths of 20m and 35m, respectively. A total elimination of passive reinforcement the UHPC was considered, which is an essential factor to consider regarding cost. Although the initial cost of UHPC solution is relatively higher when compared to conventional concretes analyzing in the short term, its use has some advantages in relation to prestressed beams in class C45 concrete. Considering a long-term economy, it is believed that the high initial cost may dissolve with the lowest maintenance and repair needs over the structure lifetime, due to its high durability.
Keywords: UHPC. Prestressed concrete. FRC.

1. Introduction

Ultra-High-Performance Concrete (UHPC) is a cementitious composite material obtained from optimizing its granular components, with a water/cement ratio of less than 0.25 and a high percentage of fibers discontinuously arranged in the cementitious matrix (FHWA, 2018). Regarding the main mechanical characteristics, the publication defines that the material must present compressive and post-peak tensile strengths greater than 150 MPa and 5 MPa, respectively. Its high tensile strength and dubious behavior make it possible to design and produce structural elements without other reinforcement (Eurocode 2, 2016; Cesari *et al*., 2021). In addition to its remarkable mechanical characteristics, UHPC allows improved durability, with potential in structural applications, especially in use in prestressed concrete structures, such as bridges. It enables significant reductions in the cross-sectional area and elimination of passive reinforcement, allowing an appropriate solution for designing bridges that require slenderness, lightness, and complex shapes (Ngo, 2016). Also, according to Buttignol *et al.* (2017), structure rehabilitation is one of the most promising uses of UHPC, such as bridges located in highly aggressive environments, highlighting its very low porosity. In this paper we describe a study case to optimize bridge girders projects using local materials and specifications and assessing local Brazilian costs.

2. Case study

Migliore (2018) analyze the design of precast girders of bridges built with conventional concrete (C45) and the prestressing steel CP-210 RB (2.100-MPa yield strength). The number of girders and the deck width were determined according to the local Department of Highways of the State of São Paulo (DER-SP) specification for road bridges. This study considered the bridge design concept using five prestressed girders, with a spacing of 3.24m obtaining a deck width of 14.10 m (Figure 1), with nominal lengths of 20 or 35 m. The original bridge design considered concrete compressive strengths of 45 MPa (C45), CAA II (moderate) Brazilian environmental aggressiveness class, concrete cover of 3 cm, and a 10-cm asphalt cover (Figure 1). The local design code ABNT NBR 7188 (2013) for highway bridges in Brazil presents a live load model named TB-450, which specifies the design load of a 450 kN weight vehicle and a distributed load p of 5.0 kN/m^2, before increased by an impact factor.

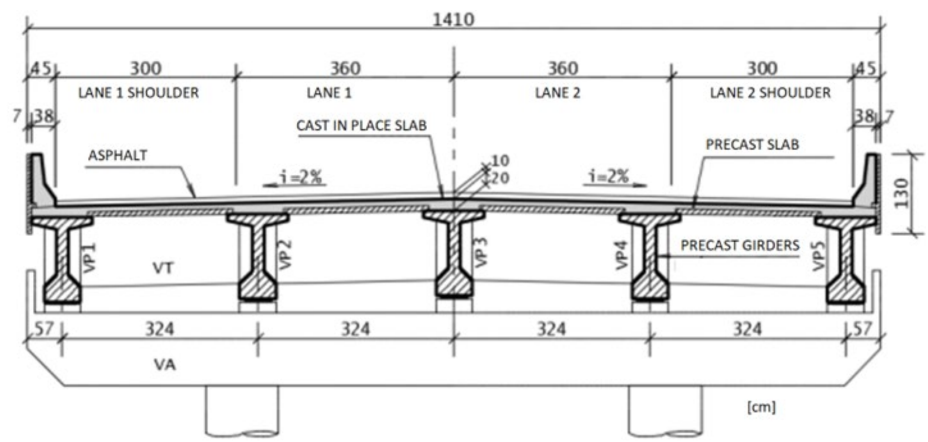

Figure 1- Migliore (2018) and Barbosa (2021) adapted from IP-DE-C00-001 DER-SP (2005)

The conventional concrete bridge design is presented in Migliore (2018). The elements with conventional concrete are identified as C45-20m and C45-35m, for the spans of 20 and 35 meters, respectively. The girders were then designed with UHPC and identified as UHPC-20m and UHPC-35m. The UHPC design is presented in Barbosa (2021). The mechanical properties of the C45 and of the UHPC are presented in Table 1. For the UHPC the volume of fibers considered is 2%.

The beams designed with UHPC have a similar design bending moment to the ones with conventional concrete (Table 2). To simplify the study the same design self-weight load is considered in all cases, although the UHPC section weight is smaller. The equivalent sections were determined by using the theory of the transformed-section method, in which sections composed of two different materials (UHPC and C35 conventional concrete in the slab) are converted into homogeneous sections. The cross-section area of the girder with UHPC was reduced to the minimum capable of supporting the loads and checking if the cross-section has a minimum thickness capable of accommodate the prestressing cables, obeying the minimum design cover adopted for UHPC. An area sufficiently capable of supporting the shear load was checked and the lower flange dimensions should also be sufficient to accommodate the prestressing cables with proper spacing and covering (NF P 18-710, 2016).

Table 1 – Mechanical properties of C45 and UHPC

Characteristic compressive strength	f_{ck}	150 MPa
Ultimate compressive strain	ε_{cud}	2.7×10^{-3}
Characteristic tensile strength (elastic limit)	$f_{ctk,el}$	8 MPa
Characteristic tensile strength post-cracking	f_{ctfk}	8 MPa
Modulus of elasticity	E_{cm}	50 GPa
Fiber orientation factor (global effects)	K_{global}	1.25
Fiber orientation factor (local effects)	K_{local}	1.75
UHPC reduction factor	γ_c	1.5
UHPC retraction (no heat treatment)	$\varepsilon_{cs,nht}$	700 µm/m
Creep factor (no heat treatment)	φ_{nht}	0.8
Length of fibers	l_f	12 mm
UHPC density	ρ	2,500 kg/m³

Table 2 – Verification of flexural, shear and torsional loads demand and capacity, and maximum displacement: girders with (a) C45 (Migliore, 2018) and with (b) UHPC (Barbosa, 2021)

DESCRIÇÃO	**C45-20M**	**C45-35M**	**UHPC-20M**	**UHPC-35M**
Moment Load - M_{sd} (kN·m)	5,320	15,435	5,320	15.435
Shear Load - V_{Sd} (kN)	1,221	1,976	1,221	1,976
Ultimate Moment Capacity- M_{ud} (kN·m)	6,465	19,398	5,855	15.552
Shear Capacity V_{Rd} (kN)	reinforced		4,805	7,320
Counter deflection (cm)	-1.40	-3.60	-4.97	-9.05
Long-term deflection (cm)	0.10	0.80	-4.86	-6.40

Figure 2 shows an example of the parabolic cables positioning along the girder. The geometry of the analysis beams with conventional concrete (compressive strength of 45 MPa – C45) or with UHPC is presented in Figure 3.

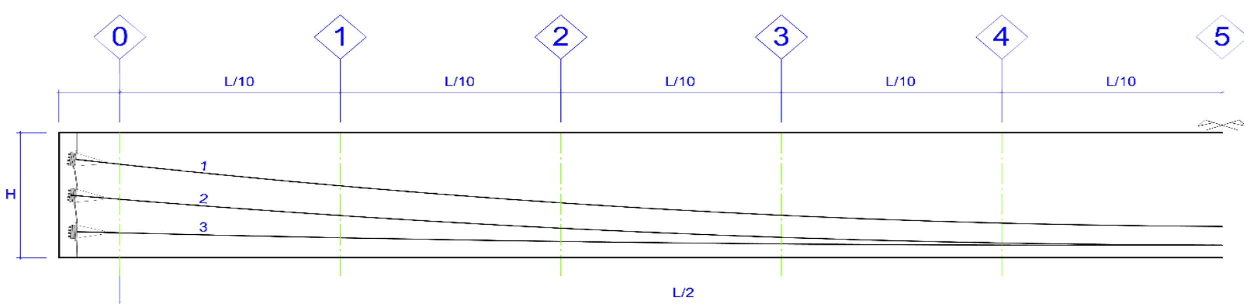

Figure 2 – Cable displacement for the regular reinforced concrete 20-m girder.

The prestressed isostatic beams of UHPC were designed to resist the bending, shear, and torsion loads only by the resistant capacity of the composite material section, without the addition of passive bending and shear reinforcement, with only prestressing cables, exploring to the maximum the characteristics and advantages of this material. Table 3 presents the cable arrangements, the area of each cable and the designed prestressing loads.

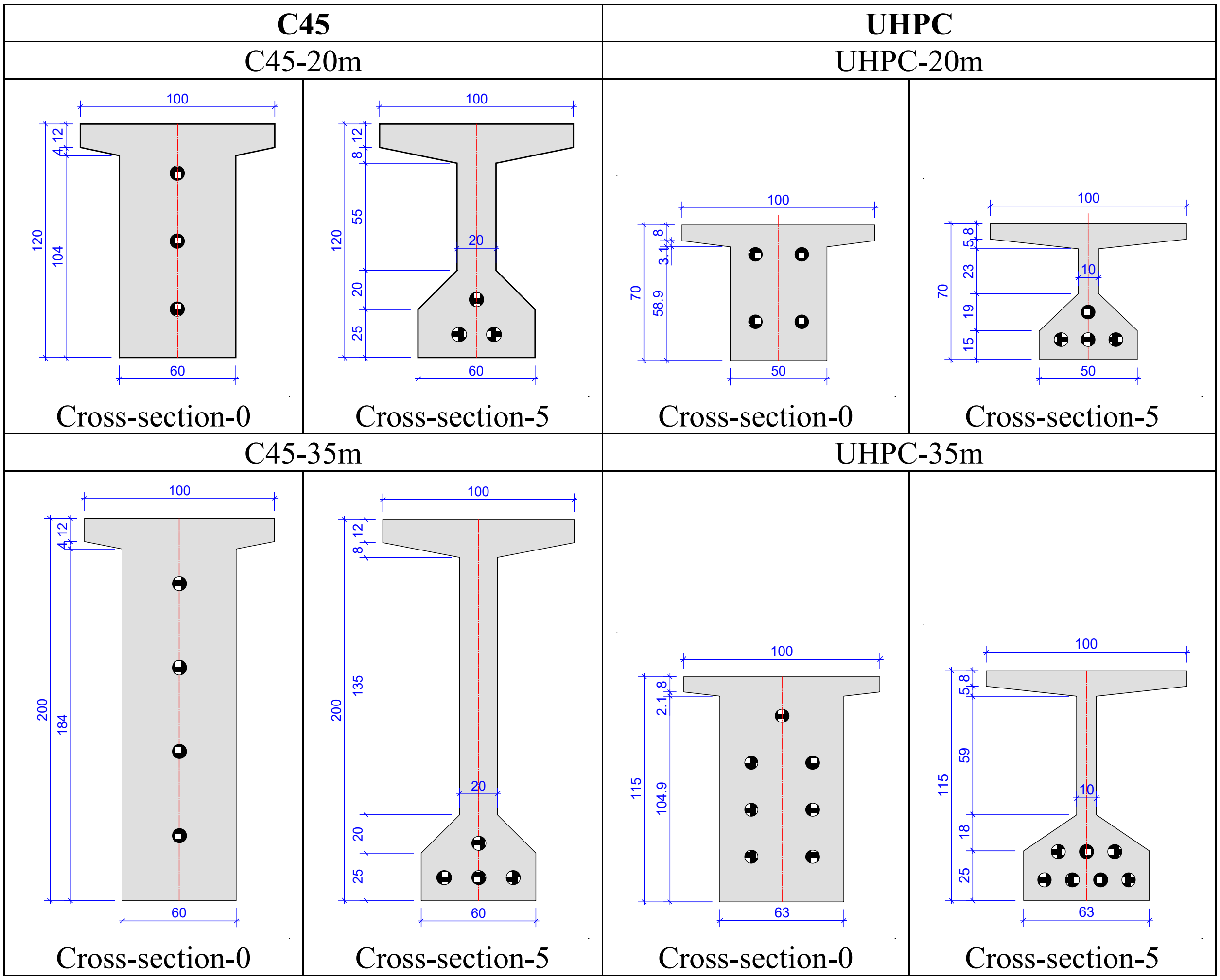

Figure 3 - Cross-sections of the analyzed beams (dimensions in cm).

Table 3 – Cables and prestresing loads

BEAM	NUMBER OF CABLES	# STRANDS	STEEL AREA (CM²/ CABLE)	INITIAL PRESTRESSING LOAD (KN/ CABLE)	LONG-TERM PRESTRESSING LOAD (KN/CABLE)
C45-20m	3	11 Φ 12.7	11.11	1,700	1,213
C45-35m	4	15 Φ 12.7	15.15	2,200	1,495
UHPC-20m	4	8 Φ 15.2	11.44	1,689	1,215
UHPC-35m	7	8 Φ 15.2	11.44	1,693	1,314

3. Results and discussions

A comparison was made between the precast prestressed girders with conventional concrete (C45) and with UHPC considering the lengths of 20 and 35m. The comparative analysis was performed considering geometric, physical, and mechanical parameters: section height, area, concrete volume, beam weight, cable arrangement, prestressing steel area adopted, ultimate resistant moment, shear, and final vertical displacements. Last, a comparative analysis of the cost of the beams was performed for the two materials and the two girder lengths.

3.1 Girders with 20 m

With the use of UHPC, it was possible to reduce the height of the girder up to 42%, obtaining an element with a height of 70 cm. In addition to the height of the beam, the thickness of the web and of the upper and lower flanges was also reduced. Thus, there was a decrease in the section area at the ratio of 48% and, consequently a reduction of volume and the total weight of the beam.

The reduction of the height of the section caused a smaller eccentricity of the prestressing cables, which leads to the need for more significant prestressing to resist the same loads. Thus, the prestressing load was increased by 34% for the section in UHPC with demanded the use of 4 cables with 8 tendons of 15.2 mm each. For the regular concrete C45, the arrangement adopted was 3 cables with 11 tendons of 12.7 mm each (Table 4), which results in a prestressing steel area 37 % greater for the beam in UHPC.

Considering the ultimate resistant moment, the one designed with UHPC presents a moment of about 9% lower than the one with C45 due to the lower height of the section, which despite the larger active reinforcement area, has relatively lower eccentricity. However, the safety condition $(M_{ud} \geq M_{Sd})\ is$ still satisfied.

For the dimensionless shear analysis, the load/capacity ratio of 0.21 was calculated for the UHPC section. Thus, the UHPC shear-resistant is far from the section limit without additional reinforcement and presents a high shear capacity, even with reduced cross-section. For the vertical deflection analysis, the girders with C45 and UHPC present values of 0.1cm (positive) and -4.86cm (negative), respectively. So, the total load is not able to reduce the vertical counter displacement caused by the prestressing force, resulting in negative displacement, but within the limit of the span length over 300.

3.2 Girders with 35 m

As well as the UHPC-20m girders analysis, the same proportion of height reduction was obtained, obtaining a height of 115cm for the UHPC-35m. The thickness of the upper flange and the web was also reduced, while for the lower flange it was necessary an increase of 3 cm depending on the allocation of the prestressing cables. Comparing the cross-section areas, it is observed am area reduction of 42% when using UHPC, which led proportionally to the same value of the reduction in the volume and weight of the section.

Also, a higher prestressing load was necessary to resist the same loads, leading to an increase of 54%, which resulted in the arrangement of 7 cables with 8 tendons of 15.2 mm each. In the regular concrete C45 case the arrangement of 4 cables with 15 tendons of 12.7 mm each was necessary. Therefore, it resulted in a 32% larger prestressing steel area for the beam in UHPC.

Considering the ultimate resistant moment, the one designed with UHPC presents a moment of about 20% lower than the one with. However, the safety condition $(M_{ud} \geq M_{Sd})\ is$ still satisfied. For the shear load is about to only 27% of the shear capacity for the UHPC section with reinforcing stirrups. For the vertical deflection analysis, the girders with C45 and UHPC present values of 0.8cm and -6.4cm (span over 547), respectively.

3.3 Comparative cost analysis

Tables 5 and 6 show the direct costs of the materials to produce each precast girder, as well as the indirect costs such as the transport and lifting services. All prices were obtained through the Unit Price List (TPU) according to the Department of Highways of the State of São Paulo, DER-SP (2016, 2021), for June 2021. Unit prices include the costs related to labour, taxes, and all the equipment necessary for the execution of services. The costs of the UHPC were obtained considering the mix design and cost presented in Table 4 and by quoting suppliers in the State of São Paulo in July 2021. The values of transportation and lifting services were obtained through price compositions of a construction company in precast elements. For transport costs, a distance of 150km was considered on a paved highway for all girders.

Table 4 – UHPC mix design and local cost (1.00 R$ ~ 0.20 USD)

Material	Consumption (kg/m³)	R$/kg	R$/m³	%
Cement	1185.75	R$ 0,74	R$ 877,46	11,60%
Sand	875.81	R$ 0,23	R$ 201,44	2,66%
Superplasticizer	35.57	R$ 19,06	R$ 677,96	8,97%
Water	237.15	-	-	-
Silica fume	108.86	R$ 2,85	R$ 310,25	4,10%
Steel fiber	157.00	R$ 35,00	R$ 5.495,00	72,66%
		Total	R$ 7.562,11	100,00%

Table 5 – Production costs: girders with 20m length (1.00 R$ ~ 0.20 USD)

Materials/services	Unit	Amounts		Costs	
		C45-20m	UHPC-20m	C45-20m	UHPC-20m
Concrete	m³	10,94	5,65	R$ 9.343,58	R$ 42.725,92
Steel formwork	m²	53,16	39,78	R$ 6.849,39	R$ 5.124,61
CA-50	kg	836,00	-	R$ 16.101,36	-
CP-210 RB	kg	489,61	684,95	R$ 16.524,34	R$ 23.116,95
Anchor	unit	6,00	8,00	R$ 11.068,62	R$ 18.256,56
Transport (150km)	vb	1	1	R$ 5.000,00	R$ 2.500,00
Lifting	vb	1	1	R$ 3.500,00	R$ 1.250,00
			Total cost	R$ 68.387,29	R$ 92.974,04

Table 6 – Production costs: girders with 35m length (1.00 R$ ~ 0.20 USD)

MATERIALS/SERVICES	UNIT	AMOUNTS		COSTS	
		C45-20M	UHPC-20M	C45-35M	UHPC-35M
Concrete	m³	27,30	16,13	R$ 23.318,29	R$ 121.976,83
Steel formwork	m²	125,84	94,34	R$ 16.213,48	R$ 12.155,20
CA-50	kg	1679,50	-	R$ 32.347,17	-
CP-210 RB	kg	1605,23	2144,60	R$ 54.176,51	R$ 72.380,38
Anchor	unit	8,00	14,00	R$ 20.124,80	R$ 31.948,98
Transport (150km)	vb	1	1	R$ 25.000,00	R$ 12.000,00
Lifting	vb	1	1	R$ 30.000,00	R$ 5.000,00
			Total Cost	R$ 201.180,25	R$ 255.461,39

It is observed that, compared to the concrete girders with conventional, there is a significant difference in the total cost of the two beams in UHPC, which are 40% and 30.9% higher than the ones in C45, for the span lengths of 20m and 35m, respectively.
Although the UHPC girders use a lower volume of concrete (of about 48.4% and 40.9% for the UHPC-20m and UHPC35m beams, respectively), they presented a total concrete cost of 153.6% and 168.6% higher in comparison with the ones with C45. Another factor to be highlighted that contributed to the high cost of the girders in UHPC, even with the elimination of passive reinforcement, is the use of the largest active reinforcement area (40.0% for the UHPC-20 beam and 33.6% for the UHPC-35m beam). Despite the lower volume of concrete, the UHPC presents a considerable amount of the total cost of the girder, attaining 36% for the UHPC-20m beam and 27% for the UHPC-35m beam.
A more correct comparison of costs can be done by considering the entire production chain. Due to its high durability, the maintenance costs, considering a design life of up to 100 years, will be shorter when comparing the use of C45 and UHPC. Due to the cross-section reduction and, consequently, the reduction of the weight of the elements, it should also be considered the reduction in the foundation cost.
It is punctuated by the continuous need for research on Ultra High-Performance Concrete to reduce the value of the unit cost of the material.

4. Conclusions

With the comparative analysis of the prestressed girders, it was noticed that it was possible to reduce the volume and weight by 48% and 42% for the beams designed with UHPC with nominal lengths of 20m and 35m, respectively. This has significant advantages in some aspects, such as the reduction of the element's cross-section, attaining half the weight compared to the conventional concrete girders, also reducing transportation costs, reductions related to the lifting in the construction phase, with the requirement of lower capacity equipment, reduction in columns and foundation elements.
Through the examples, it is evident that there is the possibility of total elimination of passive bending reinforcement and shear reinforcements using the UHPC, which is an essential factor to consider regarding cost. Although the initial cost of UHPC material is relatively higher when compared to conventional concretes analyzing in the short term, its use has some advantages in relation to prestressed beams in class C45 concrete. Considering the long-term economy, it is believed that the high initial cost may be compensated by the lowest maintenance and repair needs over the structure lifetime, due to its high durability.

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6. References

- FEDERAL HIGHWAY ADMINISTRATION (FHWA). FHWA-HRT-18-036 – U. S. Department of Transportation. *Properties and Behavior of UHPC-Class Materials*, Publication No. FHWA-HRT-18-036. United States. FHWA, 2018.

- FRENCH STANDARD INSTITUTE (FSI). NF P 18-710. National addition to Eurocode 2 – Design of concrete structures: specific rules for Ultra-High Performance Fibre-Reinforced Concrete (UPHFRC), France, 2016.
- CESARI, V. F. et al. "*Effect of water/cement ratio on micro-nanomechanical properties of the interface between cementitious matrix and steel microfibers in ultra-high performance cementitious composites*". Revista IBRACON de Estruturas e Materiais, vol. 14, n. 4, e14413, 2021, https://doi.org/10.1590/S1983-41952021000400013.
- NGO, T. 2017, *Application of UHPC in Long Span Bridge Design*, Master Thesis, Delft University of Technology, Delft, Netherlands, 2016.
- BUTTIGNOL, T.E.T.; SOUSA, J.L.A.O.; BITTENCOURT, T.N. "*Ultra High-Performance Fiber-Reinforced Concrete (UHPFRC): a review of material properties and design procedures*". Revista IBRACON de Estruturas e Materiais, v. 10, n. 4, p. 957-971, 2017, https://doi.org/10.1590/S1983-41952017000400011.
- MIGLIORE, G. M. *Viabilidade de uso de cordoalha de aço CP-210 RB em viga pré-moldada para pontes (Feasibility of using CP-210 RB prestresing steel in precast girders for bridges),* Master Thesis (in Portuguese) - Universidade Federal de São Carlos, São Carlos, São Carlos, SP, 2018. Available at https://repositorio.ufscar.br/handle/ufscar/10823.
- ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). NBR 7188: *Carga móvel rodoviária e de pedestres em pontes, viadutos, passarelas e outras estruturas (Road and pedestrian mobile load on bridges, viaducts, footbridges and other structures)*. Rio de Janeiro, RJ, 2013.
- BARBOSA, J. S. *Aplicação do Concreto de Ultra Alto Desempenho em Viga Pré-moldada Protendida para Ponte*s (*Application of Ultra High Performance Concrete in Precast Prestressed Beam for Bridges*). Master Thesis (in Portuguese) – Universidade Federal de São Carlos. São Carlos, SP, 2021. Available at https://repositorio.ufscar.br/handle/ufscar/15317.
- DEPARTAMENTO DE ESTRADAS DE RODAGEM DO ESTADO DE SÃO PAULO (DER-SP). IP-DE-C00-001_A – *Instrução de projeto de estrutura de obra de arte especial*, IP-DE-C00-001_A *(Special structure design instruction*). São Paulo: DER, 2005. Available at <http://www.der.sp.gov.br/WebSite/Documentos/Tecnicas.aspx>, accessed in February 20th, 2021.
- DEPARTAMENTO DE ESTRADAS DE RODAGEM DO ESTADO DE SÃO PAULO (DER-SP). TPU – *Tabela de preços unitários*, TPU ("*Unit Cost Table"*). São Paulo: DER, 2018. Available at <http://www.der.sp.gov.br/WebSite/Documentos/DocumentosDER.aspx#>, accessed in August 13th, 2021.