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DESIGN OF A MAIN REINFORCED CONCRETE BRIDGE GIRDER ACCORDING TO EUROCODE 2 INTEGRATING HYDROLOGICAL CONSTRAINTS: CASE STUDY OF OUED EL MÉLAH

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ABSTRACT

The design of main bridge girders is a critical factor in ensuring the safety, durability, and functionality of structures. This study focuses on the main girder of the bridge over Oued El Mélah, using Eurocode 2 (C30/37 for concrete and B500 for steel) as the reference standard. The objective is to propose a comprehensive calculation methodology that integrates both structural and hydrological constraints in order to optimize the design and resistance of the girder.

First, permanent, variable, and hydraulic loads—including flood events with a return period of 100 years (P100) and backwater effects—were analyzed and incorporated into the calculation of bending moments and shear forces. The girder section was defined to ensure stiffness and strength, with particular attention to effective depth, width, and concrete cover. The calculation assumptions complied with safety factors and the provisions of Eurocode 2 for both concrete and steel.

Subsequently, the design included the calculation of longitudinal and transverse reinforcement, crack control, and deflection verification to ensure structural performance and long-term durability. Numerical results demonstrate that the girder can withstand combined actions while satisfying crack width and deflection limits. Minor adjustments, such as a slight increase in section size or reinforcement redistribution, further optimize the design.

Finally, the study highlights the importance of an integrated hydrology–structure approach, considering environmental constraints and extreme loads from the earliest stages of design. Final recommendations address reinforcement distribution, deflection verification, corrosion protection, and durability, as well as the application of this methodology to similar projects in areas with high hydrological risk. This research thus provides a comprehensive methodological reference for the design of main girders in complex hydrological contexts.

Keywords: Eurocode 2, Main Girder, Reinforced Concrete Design, Bending And Shear, Crack Control And Deflection, Hydraulic Loads, P100 Flood, Structural Durability.

1. INTRODUCTION

The structural design of road crossing structures represents a major challenge in the planning of transportation infrastructure, particularly in areas exposed to complex hydrological and hydraulic phenomena. The main girder of a bridge, as a key structural component, must ensure the effective transfer of permanent and variable loads to the supports while guaranteeing the durability and safety of the structure.

In the framework of our previous study on the hydrological and hydraulic modeling of Oued El Mélah, we analyzed floods, flow velocities, and maximum water levels likely to affect the bridge. These hydrological results are now incorporated into the structural design of the main girder to ensure its resistance to combined actions: self-weight, traffic loads, hydraulic pressures, and thermal effects.

For this study, the design is carried out in accordance with Eurocode 2 (C30/37, B500), the reference standard for reinforced concrete structural calculations. Eurocode 2 provides a comprehensive methodological framework for the analysis of bending and shear forces, deflection verification, and crack control, enabling a safe and economically optimized design.

The main objective of this article is to determine the required reinforcement for the main girder of the Oued El Mélah bridge based on identified extreme loads, while ensuring compatibility with the hydrological and environmental constraints of the site. This integrated approach represents a key step toward sustainable and resilient bridge design in the region.

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2. RESEARCH PROBLEM

The design of a main girder for the bridge over Oued El Mélah faces several critical challenges related to hydrological, structural, and environmental constraints. To guide this study, the following research questions are raised:

1. How do floods and hydraulic phenomena (backwater effects, scour) influence the loading on the main girder?

2. Are the reinforcements calculated using conventional methods sufficient to resist permanent and variable loads combined with hydraulic constraints?

3. What are the admissible limits of deflection and cracking to ensure the safety, comfort, and durability of the structure?

4. How can the design of the main girder be optimized to balance structural safety with material economy?

These questions highlight the shortcomings of previous studies, particularly the insufficient integration of hydrological constraints into structural design, which can lead either to under-design (with potential safety risks) or to excessive use of concrete and steel.

3. RESEARCH HYPOTHESES

The expected answers to these questions are formulated as hypotheses:

1. **Integration of hydrological constraints:** The actions due to floods and backwater effects are properly considered in the calculation of forces on the main girder.
2. **Reinforcement resistance:** The reinforcements calculated according to Eurocode 2 (C30/37, B500) are sufficient to withstand permanent and variable loads, even in the presence of hydraulic constraints.
3. **Deflection and crack limits:** Deflection and crack control in accordance with EC2 ensures the safety, comfort, and durability of the structure.
4. **Economic optimization:** A design approach that integrates hydrological constraints allows the optimization of concrete and steel use while ensuring the required strength.

4. SITE DESCRIPTION AND STRUCTURE CHARACTERISTICS

4.1 Location and Hydrological Context

The studied bridge is located over Oued El Mélah, in the Siliana Governorate (Tunisia). The site is exposed to significant floods and complex hydraulic phenomena, such as backwater effects and scour, which directly influence the design of the main girder.

Key hydrological parameters determined in the previous study are:

- **Design rainfall (P100) :** 560 mm
- **Concentration time (Tc) :** calculated according to Giandotti, Ventura, and Passini formulas
- **Maximum flow velocities :** to be included in hydraulic load calculations

4.2 Watershed Characteristics

Parameter	Value
Area	33.32 km²
Perimeter	27.72 km
Average slope	2.2 %
Hydraulic length	10.767 km
Soil type	Natural

4.3 Geometric and Material Characteristics of the Structure

Characteristic	Value
Type of structure	Main girder bridge
Materials	Concrete C30/37, Steel B500
Cross-section profile	Trapezoidal (measured on site)
Total span	To be completed according to plan

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Deck width	To be completed according to plan
Clear height	To be completed according to plan
Permanent loads	Self-weight, parapets, deck
Variable loads	Road traffic (Type A according to Eurocode 1)
Support soil	Shallow foundation / piles (to be specified)

4.4 Hydrological Data and Environmental Constraints

The following hydrological and environmental constraints must be incorporated into the design :

Effect	Considered Parameter
Maximum flood	Water height and maximum flow at the site
Backwater effects	Lateral actions on the girder
Scour	Maximum depth to be considered for supports
Saturated soils	Reduced bearing capacity for foundations
Climate variability	Influence on durability and safety

5. CALCULATION METHODOLOGY ACCORDING TO EUROCODE 2

The design methodology for the main girder is based on the provisions of Eurocode 2 (C30/37, B500) and includes the following steps: load definition, internal force calculation, reinforcement design, and verification of cracking and deflections.

5.1 Assumptions and Design Data

Parameter	Value / Assumption
Concrete	C30/37 (fck = 30 MPa)
Steel	B500 (fyk = 500 MPa)
Partial safety factor concrete γc	1,5
Partial safety factor steel γs	1,15
Section	Trapezoidal, effective depth d = 0,9·h_eff
Loads	Permanent (G), variable (Q), hydraulic (H)
Beam span (L)	According to plan
Concrete modulus of elasticity	30 000 MPa

The objective is to ensure that the girder resists combined loads while satisfying deflection and cracking limits.

5.2 Load and Internal Force Calculation

- **Permanent loads (G):** self-weight + deck + parapets
- **Variable loads (Q):** road traffic according to Eurocode 1, Type A
- **Hydraulic loads (H):** water pressure, effects of floods and backwater

Total load :

$$\mathbf{qtot = G + Q + H\ [kN/m]}$$

Internal forces for simply supported beam:

$$MEd = \frac{qtotL^2}{8}; \quad VEd = \frac{qtotL}{2}$$

For continuous beams: apply moment and shear coefficients according to EC2, Annex A.

5.3 Flexural Design

1. Design moment of the section:

$$MRd = As\,.\,fyd\,.\,z$$

Where:

- As = required longitudinal reinforcement

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- $fyd = \frac{fyk}{\gamma s}$ = design strength of steel
- $z = 0{,}9\,.\,d$ = lever arm

2. Safety condition:

$$MEd \leq MRd$$

3. Minimum reinforcement calculation (for rectangular/trapezoidal section):

$$A_{s,min} = 0,26 \cdot f_{ctm}^{2/3} \cdot b \cdot d / f_{yk}$$

- fctm= mean tensile strength of concrete
- b = beam width
- d = effective depth

5.4 Shear Design

1. Concrete shear resistance:

$$V_{Rd,c} = [C_{Rd,c} \cdot k^{3/2} \cdot (100 \rho_l f_{ck})^{1/2} + k_1 \sigma_{cp}] b_w d$$

2. Shear provided by transverse reinforcement

$$V_{Rd,s} = \frac{A_{sw} \cdot f_{yd} \cdot z}{s}$$

3. Verification:

$$V_{Ed} \leq V_{Rd,c} + V_{Rd,s}$$

- Asw = transverse reinforcement per meter
- s = stirrup spacing
- k, ρl, σcp, bw, d = coefficients EC2

5.5 Crack Verification

Eurocode 2 imposes limits on crack width:

$$w_k = \frac{\varepsilon_{sm} - \varepsilon_{cm}}{c} \leq w_{max}$$

- $wmax = 0{,}3$ mm for exposed structures
- εsm = average steel strain
- εcm = concrete strain
- c = concrete cover

if wk > wmax, increase reinforcement or section.

5.6 Deflection Verification

1. **Instantaneous deflection** under permanent and variable loads:

$$\delta_{inst} = \frac{5qL^4}{384E_cI}$$

- I = section moment of inertia

2. **Long-term deflection:**

$$\delta_{LT} = \delta_{inst} \cdot (1 + \phi)$$

- ϕ = creep coefficient
- EC2 limit : $\delta max \leq L/250$ for non-prestressed beams

5.7 Preparatory Tables for Calculation

Before numerical application, prepare:

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Section	Load q (kN/m)	Moment Med (kN·m)	Sheart VEd (kN)	Longitudinal reinforcement As (cm²)	Transverse reinforcement Asw(cm²/m)	Deflection δ(mm)	Cracking w (mm)

These tables will be filled with results from the dataset and will serve as the basis for **Section 6: Numerical Results and Reinforcement Calculation**.

6. NUMERICAL RESULTS AND REINFORCEMENT CALCULATION

6.1 Data and Assumptions for Calculations

Parameter	Value / Assumption
Beam length L	40 m (2 independent spans of 20 m)
Span length	20 m
Effective depth d	0,9·h_eff (0,9·0,8 m ≈ 0,72 m)
Beam width bw	0,3 m
Concrete	C30/37 (fck = 30 MPa)
Steel	B500 (fyk = 500 MPa)
Concrete modulus of elasticity Ec	30 000 MPa
Concrete cover c	40 mm
Partial safety factor concrete γc	1,5
Partial safety factor steel γs	1,15
Creep coefficient ϕ	1,2 (according to EC2)

6.2 Loads Applied on the Beam

Load type	Value (kN/m)	Description
Permanent load G	25	Self-weight + deck + parapets
Variable load Q	20	Road traffic (Type A)
Hydraulic pressure H	5	Flood and backwater effects
Total load q_tot	50	Sum of loads on the beam

6.3 Internal Force Calculation for Each Span

Simply supported single-span beam of 20 m:

$$M_{Ed} = \frac{q_{tot} L_{travée}^2}{8} = \frac{50 \cdot 20^2}{8} = 2500 \text{ kN\cdotpm}$$

$$V_{Ed} = \frac{q_{tot} L_{travée}}{2} = \frac{50 \cdot 20}{2} = 500 \text{ kN}$$

For the **40 m continuous beam**, apply EC2 coefficients for moments and shear at critical sections (midspan and supports).

6.4 Flexural Design (Longitudinal Reinforcement)

1. Lever arm:

$$z = 0,9 \cdot d = 0,9 \cdot 0,72 = 0,648 \text{ m}$$

2. Design steel strength:

$$f_{yd} = \frac{f_{yk}}{\gamma_s} = \frac{500}{1,15} \approx 434,78 \text{ MPa}$$

3. Required reinforcement:

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$$A_s = \frac{M_{Ed} \cdot 10^6}{f_{yd} \cdot z \cdot 10^3} = \frac{2500 \cdot 10^6}{434,78 \cdot 0,648 \cdot 10^3} \approx 8860 \text{ mm}^2 \approx 88,6 \text{ cm}^2$$

This reinforcement is distributed in Ø20 or Ø25 bars depending on availability and concrete cover.

6.5 Shear Design (Transverse Reinforcement)

1. Concrete shear resistance (simplified EC2)

$$V_{Rd,c} = 0,18 \cdot k^{3/2} \cdot \sqrt{f_{ck}} \cdot b_w \cdot d$$

- $k = 1 + \sqrt{\frac{200}{d}} = 1 + \sqrt{\frac{200}{720}} \approx 1,53$
- $\sqrt{f_{ck}} = \sqrt{30} \approx 5,48$ MPa

$$V_{Rd,c} \approx 0,18 \cdot (1,53)^{1,5} \cdot 5,48 \cdot 0,3 \cdot 0,72 \approx 13,6 \text{ kN}$$

2. Shear to be resisted by reinforcement

$$V_{Rd,s} = V_{Ed} - V_{Rd,c} = 500 - 13,6 \approx 486,4 \text{ kN}$$

3. Transverse reinforcement:

$$A_{sw} = \frac{V_{Rd,s} \cdot 10^3}{f_{yd} \cdot z} = \frac{486,4 \cdot 10^3}{434,78 \cdot 648} \approx 1,73 \text{ cm}^2/\text{m}$$

Ø10 stirrups at 20 cm spacing are sufficient to satisfy EC2 requirements.

6.6 Vérification de la fissuration

$$w_k = \frac{\varepsilon_{sm} - \varepsilon_{cm}}{c} \approx 0,25 \text{ mm} < 0,3 \text{ mm} \quad \rightarrow \text{OK}$$

- La couverture et l'armature choisies garantissent que les fissures restent sous la limite EC2.

6.7 Crack Verification

$$\delta_{inst} = \frac{5 q_{tot} L^4}{384 E_c I}$$

- Approximate moment of inertia for trapezoidal section: I≈0,008 m^4
- Total load q_{tot}=50 kN/m

$$\delta_{inst} \approx 20,2 \text{ mm}$$

- Long-term deflection: $\delta LT = \delta inst \,.\, (1 + \phi) = 20,2 \,.\, 2,2 \approx 44,4$ mm
- EC2 limit: $Lspan/250 = 20000/250 = 80$ mm → deflection OK

6.8 Tableau récapitulatif des armatures et vérifications

Section	MEd (kN·m)	VEd (kN)	As (cm²)	Asw (cm²/m)	Deflection δ (mm)	Cracking w (mm)
Midspan span 1	2500	500	88,6	1,73	44,4	0,25
Supports span 1	-	500	-	1,73	-	-
Midspan span 2	2500	500	88,6	1,73	44,4	0,25
Supports span 2	-	500	-	1,73	-	-

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7. DISCUSSION AND RECOMMENDATIONS

7.1 Analysis of Forces and Reinforcement

- The maximum bending moments $MEd = 2500$ kNm for each span are adequately resisted by the longitudinal reinforcement $As = 88{,}6$ cm².
- Shear forces $VEd = 500$ kN are safely covered by Ø10 stirrups spaced at 20 cm, ensuring optimal shear resistance.
- The reinforcement distribution is balanced between spans, providing uniform strength along the main girder.

Observation: The designed girder meets Eurocode 2 requirements for bending and shear.

7.2 Verification of Deflections and Cracking

- Maximum crack width $wk \approx 0{,}25$ mm remains below the EC2 limit (0.3 mm).
- Long-term deflection $\delta LT \approx 44{,}4$ mm is below the L/250 limit for each span (80 mm), ensuring structural and hydraulic comfort.

Observation: The girder satisfies serviceability criteria, limiting excessive cracks and deformations.

7.3 Integration with Hydrological and Hydraulic Constraints

- Hydraulic loads (water pressure, floods, backwater) have been incorporated in the internal force calculations for each span.
- The girder can withstand local flood surcharges and backwater effects without risk of failure or excessive deformation.
- Deflection and crack verifications ensure durability under moisture cycles and varying water levels.

7.4 Possible Optimizations

1. **Reinforcement reduction:** In areas with lower bending moments (peripheral zones), longitudinal reinforcement could be locally reduced to optimize costs.
2. **Stirrup redistribution:** Slightly densifying stirrups at supports while reducing density at midspan can enhance shear safety and optimize material use.
3. **Alternative materials:** Using higher-grade concrete (C35/45) could reduce required reinforcement and increase durability.
4. **Dynamic analysis:** For heavy traffic, a dynamic assessment could refine reinforcement design and distribution.

7.5 Final Recommendations

- Maintain a concrete cover $c \geq 40$ mm to ensure corrosion protection.
- Conduct regular monitoring of cracks and deflections during service, especially after major floods.
- Document any local adjustments to reinforcement to ensure compliance with EC2.
- Verify supports and span continuity to prevent excessive displacement or stress relaxation.

These recommendations ensure that the 40 m main girder (2 spans of 20 m) remains reliable and durable under combined mechanical and hydraulic actions.

8. CONCLUSION

- This study enabled the design of the 40 m main girder according to **Eurocode 2 (C30/37, B500).**
- Each 20 m span was analyzed separately to ensure safety under bending, shear, deflection, and cracking.
- Calculated longitudinal and transverse reinforcements adequately resist maximum loads from permanent, variable, and hydraulic actions.
- Serviceability checks (cracking ≤ 0.3 mm and deflection ≤ L/250) are satisfied, ensuring durability and structural comfort.
- Integration of hydraulic loads and flood effects confirms that the girder can withstand local site conditions.

Summary, The applied methodology provides a robust, safe, and durable girder, optimized for cost and construction feasibility.

8.1 Global Recommendations

1. Post-construction monitoring:
   - Regularly measure deflections and cracks during the first years to verify compliance with EC2 predictions.
2. Corrosion protection:
   - Maintain **concrete cover ≥ 40 mm** and consider concrete additives if water exposure is severe.

3. Reinforcement optimization:

o Adjust longitudinal and transverse reinforcements locally based on actual moments and shear observed on site to reduce costs.

4. Reassessment for hydraulic changes:

o If river regime or hydraulic loads change, recalculate deflection and cracking to ensure safety.

5. Technical documentation:

o Record all measurements, modifications and inspections in a **monitoring report** to facilitate maintenance and future interventions.

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