AICAP

DESIGN OF LONG INTEGRAL ROAD BRIDGES

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A cura di AICAP
Promosso da AITEC

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1. Introduction

1.1. Purpose and organization of study

Expansion joints and supports installed in conventional bridges can cause maintenance problems and integral construction is one of the most efficient solutions. However many countries have imposed restrictive limits on the length of these structures, trying to reduce stresses caused by thermal variations. This document aims to identify the maximum length of integral bridges, in relation to the particular boundary conditions considered in the case study.

First, the theme of integral bridges is introduced, presenting advantages and disadvantages of this type of construction, the different types of abutments, and aspects to be analysed with particular attention. Then, the reinforced and prestressed concrete integral bridge under study is described. The following chapters include the load analysis, the principles adopted in numerical modelling, and the design of structural elements, the latter carried out paying attention to guarantee the necessary flexibility to the structure. Finally, the conclusions of the work and a detailed study on the transition zone behind bridge abutments are presented.

For numerical modelling and structural analysis MIDAS Civil 2017 (v1.1) has been used.

1.2. Integral bridges

Traditionally, between superstructure and abutments of conventional bridges, expansion joints and supports are installed to facilitate relative displacements and prevent the occurrence of stresses caused by thermal variations. However such components can cause maintenance problems.

It has been observed (1) that deicing salts (normally used for roads maintenance in winter season) are the most important source of damage: they penetrate through the joints of the bridge deck and reach the substructures. This process causes corrosion of joints and supports located on abutments and between adjacent spans, becoming essential in defining costs of maintenance in conventional road bridges.

Therefore, considering problems associated with expansion joints and supports in traditional bridges, the idea of physically connecting superstructure and substructure to create what is commonly called *integral bridge* is becoming increasingly popular. This concept avoids all the problems associated with connecting and supporting devices because it considers a structure with one or more spans without expansion joints or supports: piers, deck and abutments are connected monolithically to create a complex structural and geotechnical interaction.

However, due to the connection between superstructure and substructure, abutments are forced to move away from the embankment when the temperature decreases and the deck contracts (i.e. in winter), and to move towards the embankment when the temperature increases and the deck expands (i.e. in summer). Consequently, the backfill soil behind

4. Materials

The following tables show the characteristics of the materials used:

Girders:

Concrete - C50/60			
Characteristic value of cylindrical resistance	f_{ck}	50	N/mm^2
Characteristic value of cubic resistance	R_{ck}	60	N/mm^2
Design value of tensile resistance	f_{ctm}	4.1	N/mm^2
Characteristic value of tensile resistance	$f_{ctk(5\%)}$	2.9	N/mm^2
Partial factor for materials and actions	γ_c	1.5	-
	α_c	0.85	-
Design value of compression resistance ULS	f_{cd}	28.3	N/mm^2
Design value of tensile resistance ULS	f_{ctd}	1.9	N/mm^2
Poisson's ratio	ν	0.2	-
Modulus of elasticity	E_c	37278	N/mm^2
Exposure class		Girders: XC4+XD1	
Minimum concrete cover		25 mm	

Abutments, Piers, Foundations, Structural slab:

Concrete - C32/40			
Characteristic value of cylindrical resistance	f_{ck}	32	N/mm^2
Characteristic value of cubic resistance	R_{ck}	40	N/mm^2
Design value of tensile resistance	f_{ctm}	3.0	N/mm^2
Characteristic value of tensile resistance	$f_{ctk(5\%)}$	2.1	N/mm^2
Partial factor for materials and actions	γ_c	1.5	-
	α_c	0.85	-
Design value of compression resistance ULS	f_{cd}	18.1	N/mm^2
Design value of tensile resistance ULS	f_{ctd}	1.4	N/mm^2
Poisson's ratio	ν	0.2	-
Modulus of elasticity	E_c	33346	N/mm^2
Exposure class		Piers and abutments: XC4+XD1 Foundations: XC2 Structural slab: XC3+XD1	
Minimum concrete cover		Abutments: 50 mm Piers: 30 mm Pile caps: 50 mm Piles: 70 mm Structural slab: 30 mm	

Passive reinforcement:

Steel - B450C				
Characteristic yielding strength	f_{yk}	>	450	N/mm^2
Characteristic ultimate strength	f_{tk}		540	N/mm^2
Modulus of elasticity	E		210000	N/mm^2
Partial factor for materials	γ_s		1.15	-
Design strength ULS	f_{yd}		391.3	N/mm^2
Poisson's ratio	ν		0.3	-

Active reinforcement:

Strand			
One strand area	139 mm^2		
Characteristic strength	f_{ptk}	1860	N/mm^2
Characteristic strength (1% deformation)	$f_{p(1)k}$	1670	N/mm^2
Design strength ULS	f_{pyd}	1452.2	N/mm^2
Modulus of elasticity	E	201000	N/mm^2
Partial factor for materials	γ_s	1.15	-

DYWIDAG plain bars:

Plain bar 32WS			
Characteristic strength	f_{ptk}	1000	N/mm^2
Characteristic strength (1% deformation)	$f_{p(1)k}$	800	N/mm^2
Design strength ULS	f_{pyd}	695.7	N/mm^2
Modulus of elasticity	E	205000	N/mm^2
Partial factor for materials	γ_s	1.15	-

5. Load analysis

5.1. Permanent actions

5.1.1. Structural permanent loads

The calculated structural permanent loads are as follows:

I Precast girder ($L = 30\ m$, $\gamma = 25\ kN/m^3$)	$22\ kN/m$
In situ concrete slab + Predalles ($t = 0.27\ m$, $\gamma = 25\ kN/m^3$)	$6.8\ kN/m^2$

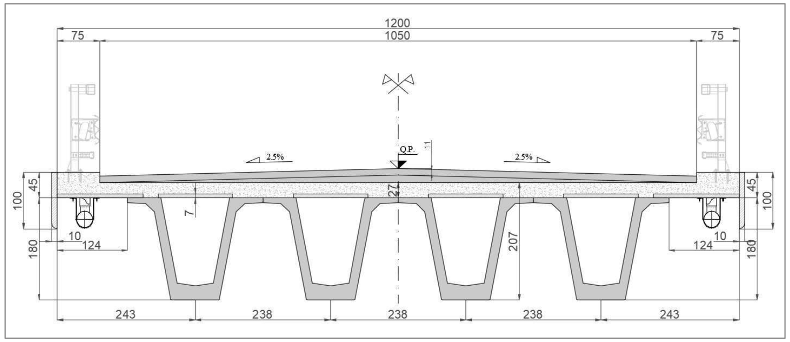


Figure 34 - Bridge deck: cross section at midspan.

5.1.2. Non-structural permanent loads

The calculated non-structural permanent loads are as follows:

Road pavement ($\gamma = 24\ kN/m^3$)	$3\ \ kN/m^2$
Kerb ($18\ cm\ \times 75\ cm$, $\gamma = 25\ kN/m^3$)	$3.4\ \ kN/m$ *(each)*
Lateral vertical panel ($10\ cm\ \times 100\ cm$, $\gamma = 25\ kN/m^3$)	$2.5\ \ kN/m$ *(each)*
Traffic barriers	$1.5\ \ kN/m$ *(each)*
Drainage pipe	$0.6\ \ kN/m$ *(each)*

6. Modelling

In integral bridges the analysis of soil-structure interaction is essential because of the earth pressures which develop following the thermal expansion and contraction of the deck. Therefore it is important to properly model the soil and its ability to react to certain stress states.

In structure modelling, the possible presence of compressible inclusions and geogrids behind abutments is not considered as their benefit is not quantifiable.

In the following paragraphs the soil-structure interaction is first examined, and then implementation and validation of the numerical model are illustrated.

6.1. Soil-structure interaction

6.1.1. Method of analysis

In the design of integral bridges the soil-structure interaction due to temperature changes needs to be dealt with carefully.

The British Standards (13) presents two different methods of analysis:

a) Limit equilibrium method

b) Soil-structure interaction method

The limit equilibrium method does not depend on soil characteristics and is applicable to abutments where:

- the characteristic thermal movement of the end of the deck does not exceed 40 mm;
- the skew does not exceed 30°;
- the depth of soil affected by the abutment movement can be identified without recourse to a soil–structure interaction analysis.

Instead it is not appropriate for:

- abutments founded on a single row of piles;
- embedded wall abutments;
- over-consolidated backfill material;
- cohesive soils;
- layered soils.

This type of analysis provides formulas to calculate the design value of the earth pressure coefficient for expansion K^*_d depending on the abutment's geometry, and suggests the force distribution with which the designer can simulate the earth pressure acting behind abutments.

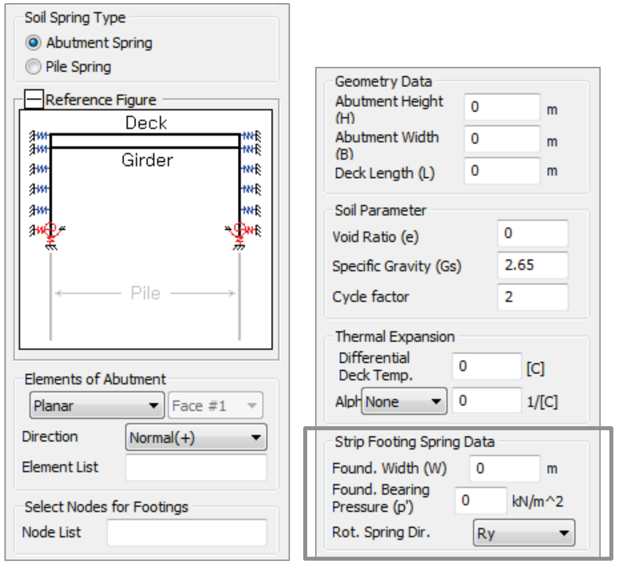


Figure 60 - Parameters to be entered for Abutment Springs (MIDAS Civil).

Strip footing spring data (highlighted in the figure) have to be neglected in case of pile foundations.

Numerical values used for design are presented in paragraph *"Description of the model"*.

Pile springs

The soil-structure interaction between piles and foundation soil is modelled using lateral springs and vertical springs.

For vertical linear elastic springs, the stiffness is calculated using the following expression (for sand, soft clay and stiff clay):

$$K_{vert} = (K_h \cdot D \cdot i) \ / \ K_0$$

where:

K_{vert}	stiffness of the vertical spring;
K_h	coefficient of subgrade reaction of foundation soil;
D	pile diameter;
i	spring's competency length;
K_0	coefficient of earth pressure at rest of foundation soil.

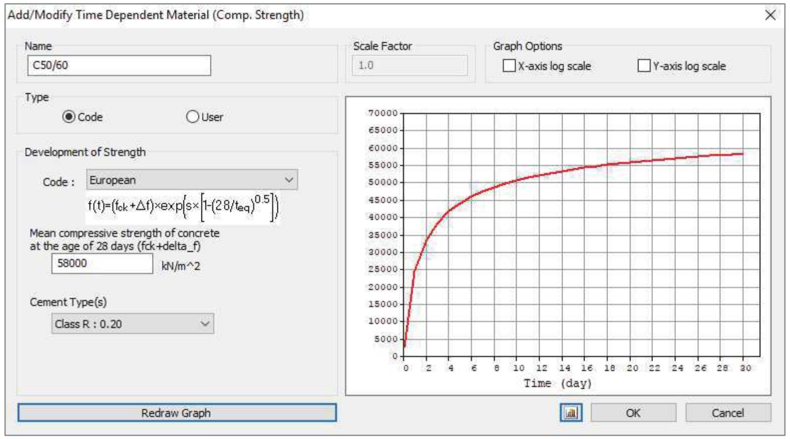


Figure 65 – Variation of modulus of elasticity with time: time dependent material properties for C50/60.

6.2.2. Sections and general modelling

For sections of structural elements refer to paragraph *"Description of the bridge"*.

Girders, slab, piers and foundation piles are modelled using beam elements, while abutments are represented by shell elements.

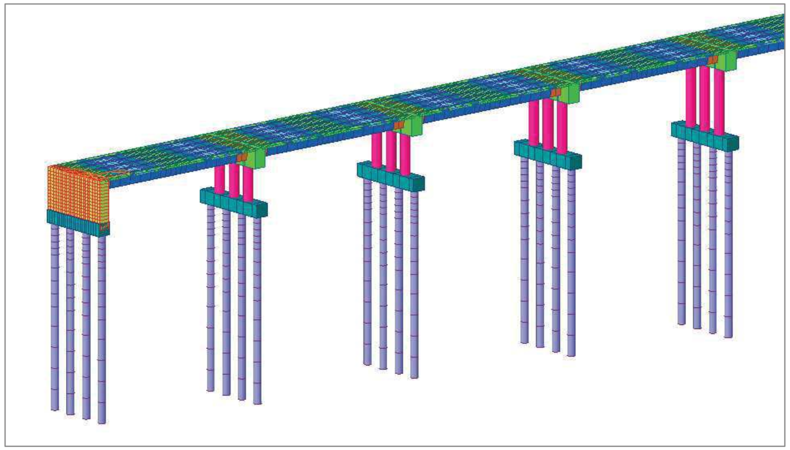


Figure 66 - Extruded view of a part of the model.

In conclusion, a scale factor equal to 20 is applied to the torsional stiffness of girders (composed section), in order to obtain the same transverse deformation in grid and solid model:

$$I_{xx,manual} \cong 0.4\ m^4$$

$$I_{xx,MIDAS} \cong 0.02\ m^4$$

$$I_{xx,manual}/I_{xx,MIDAS} \cong 20$$

where:

$I_{xx,manual}$ torsional stiffness of composed section (precast girder and collaborating structural slab) calculated with geometric formulas;

$I_{xx,MIDAS}$ torsional stiffness of composed section (precast girder and collaborating structural slab) calculated by MIDAS Civil.

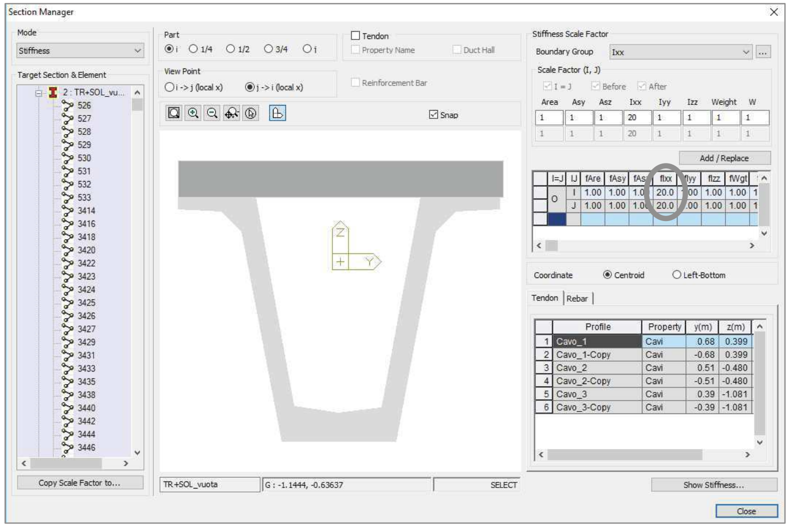


Figure 84 – Scale factor applied to the torsional stiffness of the composed section.

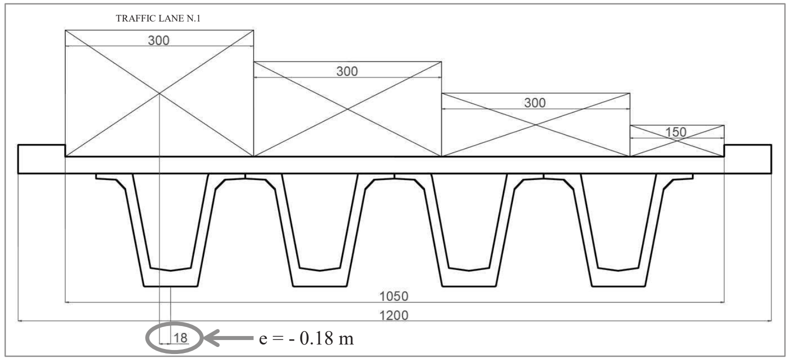


Figure 91 – Traffic line lanes: eccentricity.

Wheel Spacing distance between the wheels of the vehicle;

Vehicular Load Distribution If *Lane Element* is selected, MIDAS applies loads to the traffic line lane elements reflecting the eccentricity (the vertical load components and the moment due to eccentricity is assigned only to the line lane element); on the other hand, if *Cross Beam* is selected, MIDAS applies the traffic load to the cross beams (the eccentricity is used only to locate the lanes from the line lane element; vehicle loads are distributed to girders by cross beam elements defined as *Cross Beam Group*).

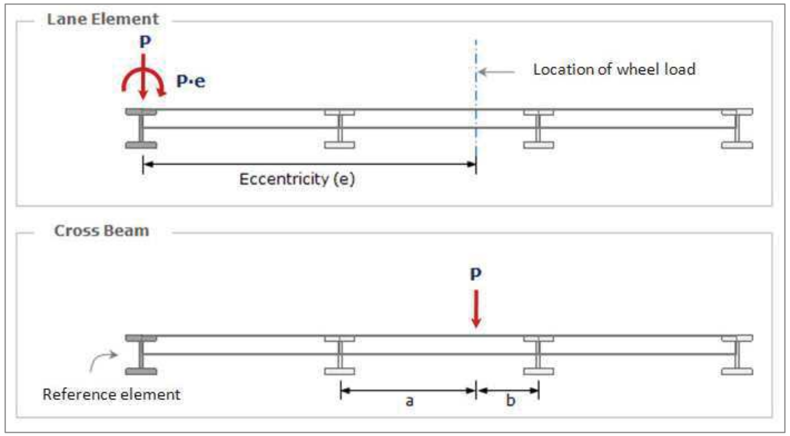


Figure 92 – Vehicular load distribution: difference between Lane Element and Cross Beam (MIDAS Civil manual).

Skew skew angles at the start and end of the bridge;

Moving Direction MIDAS considers both directions (forward and backward):

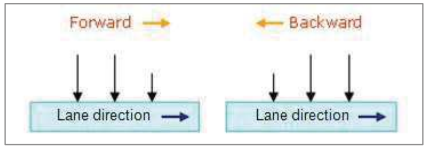
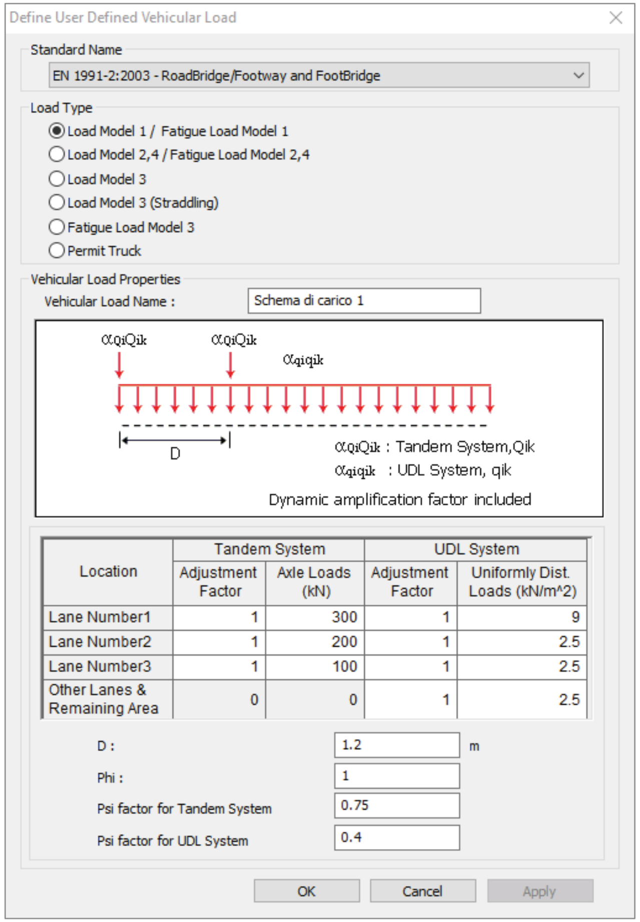


Figure 93 – Moving direction (MIDAS Civil manual).

Therefore, load of vehicles can be defined as follows:


Define User Defined Vehicular Load

Standard Name

EN 1991-2:2003 - RoadBridge/Footway and FootBridge

Load Type

- Load Model 1 / Fatigue Load Model 1
- Load Model 2,4 / Fatigue Load Model 2,4
- Load Model 3
- Load Model 3 (Straddling)
- Fatigue Load Model 3
- Permit Truck

Vehicular Load Properties

Vehicular Load Name : Schema di carico 1

$\alpha_{Qi}Q_{ik}$ $\alpha_{Qi}Q_{ik}$ $\alpha_{qi}q_{ik}$

D

$\alpha_{Qi}Q_{ik}$: Tandem System,Qik

$\alpha_{qi}q_{ik}$: UDL System, qik

Dynamic amplification factor included

Location	Tandem System		UDL System	
	Adjustment Factor	Axle Loads (kN)	Adjustment Factor	Uniformly Dist. Loads (kN/m^2)
Lane Number1	1	300	1	9
Lane Number2	1	200	1	2.5
Lane Number3	1	100	1	2.5
Other Lanes & Remaining Area	0	0	1	2.5

D : 1.2 m

Phi : 1

Psi factor for Tandem System 0.75

Psi factor for UDL System 0.4

OK Cancel Apply

Figure 94 – Vehicular load.

7.1.2. Shear resistance - ULS

For ultimate limit state of shear resistance, the following condition must be verified:

$$V_{Rd} \geq V_{Ed}$$

where:

V_{Rd} shear resistance;

V_{Ed} design shear force.

Shear resistance is calculated considering dimensions of the structural element (see previous figures), characteristics of materials (concrete C50/60 for girder, C32/40 for structural slab and concrete casting, and steel B450C), and a transverse reinforcement of ϕ 16 / 15 cm (considering 4 legs every 15 cm):

$$V_{Rd} = 3969\ kN$$

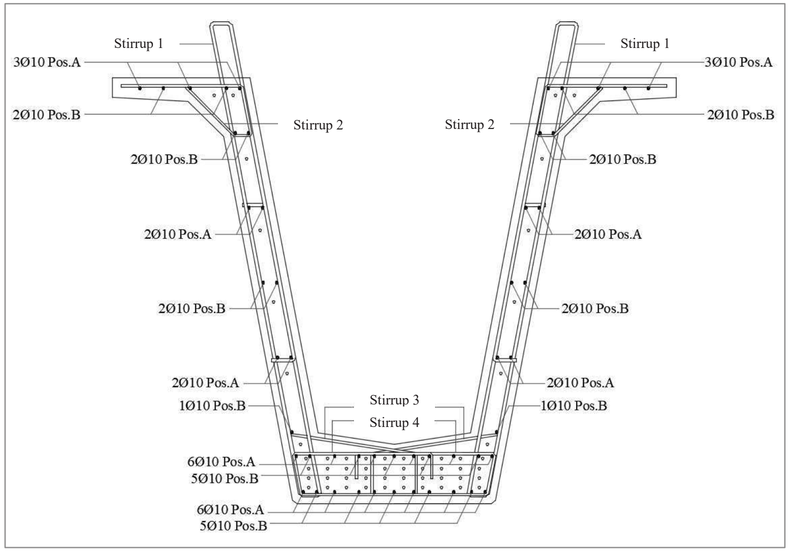


Figure 115 - Section 1: final section of girder near abutment (detail).

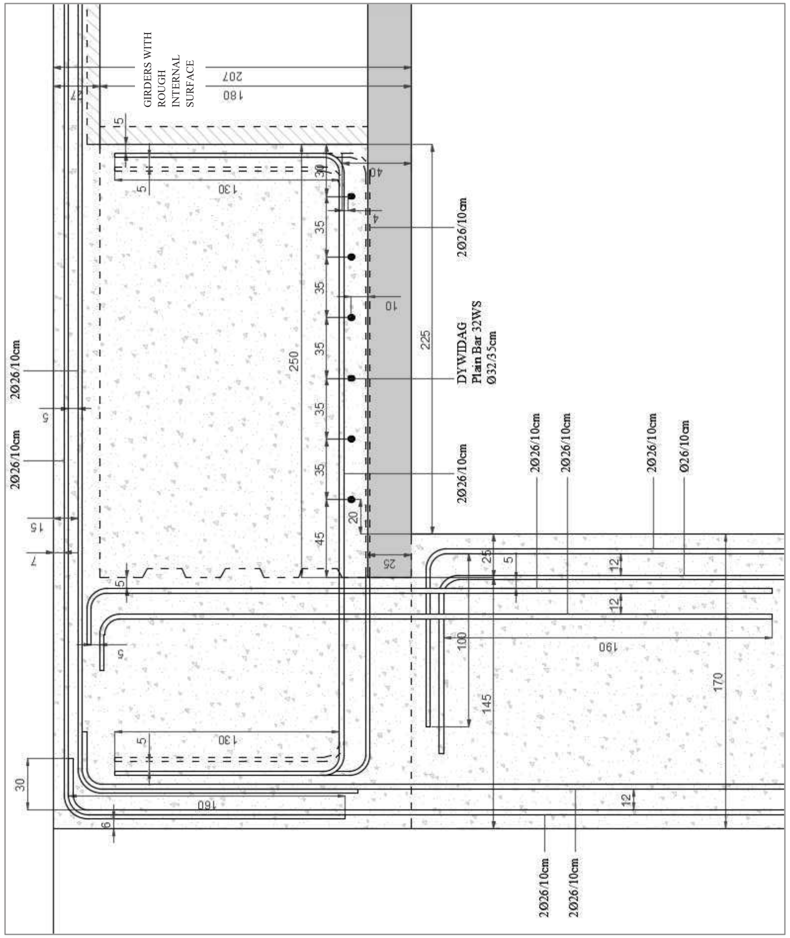


Figure 123 - Section 3: node at abutment (detail).

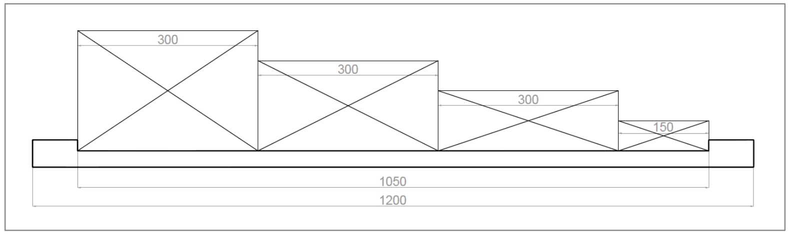


Figure 139 – Transverse configuration for live loads.

The following figures show some diagrams of bending moment per unit length obtained from the model:

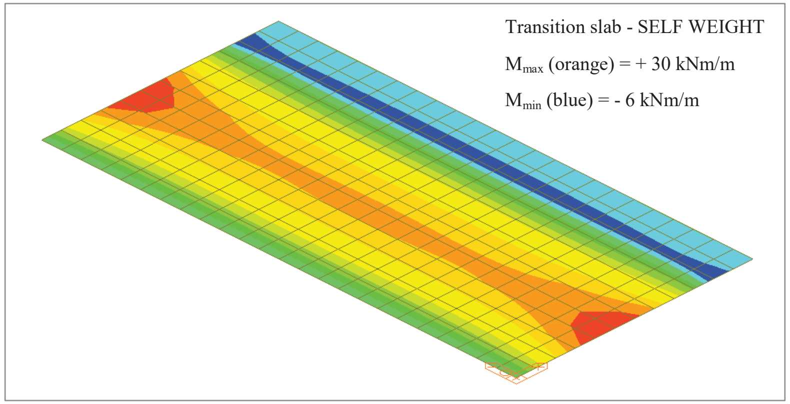


Figure 140 – Transition slab: bending moment per unit length for self weight.

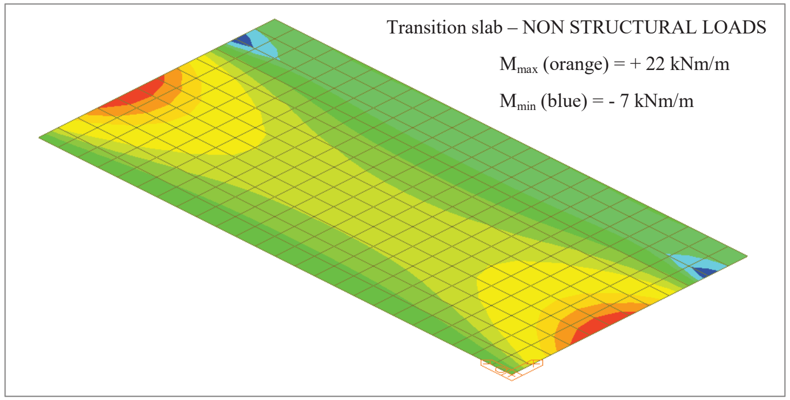


Figure 141 – Transition slab: bending moment per unit length for non structural permanent loads.

Bibliography

1. **Wallbank, E.J.** The Performance of Concrete in Bridges. A Survey of 200 Highway Bridges. A Report Prepared for the Department of Transport by G.Maunsell & Partners. 1989.

2. **Design Manual for Roads and Bridges.** The design of integral bridges. 2003.

3. **Design guide.** Economic and durable design of composite bridges with integral abutments. 2010.

4. **England, G.L., Tsang, N.C.M., Bush, D.I.** *Integral bridges - A fundamental approach to the time-temperature loading problem.* London (UK) : Thomas Telford Ltd, 2000.

5. **Horvath, J.S.** Integral abutment bridges: problems and innovative solutions using geofoam and other geosynthetics. 2000.

6. **Dreier, D., Burdet, O., Muttoni, A.** Transition slabs of integral abutment bridges. *Structural Engineering International.* 2011, Vol. 21, 2.

7. **RWTH Aachen University.** Design guide - Economic and durable design of composite bridges with integral abutments. Aquisgrana (DE) : s.n., 2010.

8. **Eurocode 1 - Actions on structures.** Part 1-5: General actions - Thermal actions.

9. **Eurocode 7 - Geotechnical design.** Part 1: General rules.

10. **Norme Tecniche per le Costruzioni (NTC).** DM 17/01/2018.

11. **Eurocode 1 - Actions on structures.** Part 1-4: General actions - Wind actions.

12. **Eurocode 8 - Design of structures for earthquake resistance.** Part 2: Bridges.

13. **British Standards Institution.** Recommendations for the design of structures subject to traffic loading to BS EN 1997-1:2004. 2011.

14. **Lehane, B.M.** Geotechnical recommendations for MIDAS Civil. 2006.

15. **Lehane, B.M.** Predicting the restraint provided to integral bridge deck expansion. *Proc. 12th European Conf. on Soil Mechanics and Geotechnical Engineering.* 1999.

16. **Lehane, B.M., Cosgrove, E.** Applying triaxial compression stiffness data to settlement prediction of shallow foundations on cohesionless soil. *Geotechnical Engineering.* 2000.

17. **Cosgrove, E., Lehane, B.M., Ng C, W.W.** Sand tested under cyclic triaxial conditions with constant radial stress. *Proc. XV Int. Conf. on Soil Mech. and Fdn. Engng.* 2001.

18. **Atkinson, J.H.** Non-linear soil stiffness in routine design. *Geotechnique.* 2001.

19. **Cosgrove, E.** Cyclic loading of sand behind integral bridge abutments. *PhD Thesis. University of Dublin (Trinity College).* 2001.

20. **Lock, R.J.** Integral bridge abutments. *M.Eng. Project report CUED/D-SOILS/TR320, University of Cambridge, Dept. of Engineering.* 2002.

21. **Matlock, H.** Correlations for Design of Laterally Loaded Piles in Soft Clay. *Proceedings Offshore Technology Conference.* 1970.

22. **Reese, L.C., Cox, W.R., Koop, F.D.** Analysis of Laterally-Loaded Piles in Sand. *Proceedings of Offshore Technology Conference.* 1974.

23. **Sullivan, W.R., Reese, L.C., Fenske, C.W.** Unified Method for Analysis of Laterally Loaded Piles in Clay. *Proceedings of Conference on Numerical Methods in Offshore Piling.* 1980.

24. **Lehane, B.M., Keogh, D.L., O'Brien, E.J.** Simplified elastic model for restraining effects of backfill soil on integral bridges. *Computers and Structures.* 1999.

25. **Eurocode 2 - Design of concrete structures.** Part 1-1: General rules and rules for buildings.

26. **Bransby, P.L.** General theories of earth pressures and deformations. *Proc. 5th European Conf. on Soil Mechanics and Foundation Engineering.* 1972.

27. **Burghignoli, A.** *Lezioni di meccanica delle terre.* Roma : ESA Editrice, 1985.

28. **DIN 1054.** Subsoil - Verification of the safety of earthworks and foundations. 2005.