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Value engineering creation with steel sheet pile bridge abutments

Daniel Neto
ArcelorMittal, Luxembourg, daniel.neto@arcelormittal.com

ABSTRACT: Bridge abutments account for around 40% of the total construction cost of a typical two-span road bridge without temporary retaining walls, rising to 55% if such walls are required. Temporary retaining walls are necessary to retain ground during foundations work, particularly below the groundwater table or to prevent flooding. In these scenarios, steel sheet pile abutments are a sustainable and cost-effective alternative to traditional concrete solutions. They effectively transfer vertical loads into the ground or deeper soil layers but require careful load distribution to avoid added costs from discrete bearings. The use of sheet piles together with the so-called knife edge support (KES) method has emerged as an effective solution in modern bridge abutment design. The KES is a simple and efficient capping beam system designed for load transfer, cast directly on top of the steel sheet pile wall, and approved by the German Institute for Construction Technology (DIBt). It withstands and transmits vertical and horizontal static loading as well as fatigue loads to the sheet pile wall. A description of the KES empirical design approach will be presented including a design calculation. A comparison between a sheet pile abutment solution and a correspondent concrete solution will be presented, to highlight the major benefits of steel sheet piles in bridge abutments as permanent structures.

KEYWORDS: Bridge abutments, Steel sheet piles, Knife Edge Support (KES), Load distribution, Sustainability.

1 INTRODUCTION

Bridge abutments are fundamental substructures responsible for transferring both static and dynamic loads from the superstructure to the foundation while ensuring overall structural stability. Conventional reinforced concrete abutments, although widely utilized, often present challenges such as high material and labour costs, extended construction durations, and long-term maintenance requirements.

Alternatively, steel sheet pile abutments provide a cost-efficient and sustainable solution, optimizing value engineering by reducing construction time, material usage, and environmental impact. The overall cost of abutment construction is influenced by factors such as geotechnical conditions, structural complexity, material selection, and site-specific constraints, with the inclusion of temporary retaining structures further contributing to project expenditures.

Using steel sheet piles, especially those produced from 100% recycled steel using 100% renewable electricity (EcoSheetPiles™ Plus) in ArcelorMittal (2023), reduces material and installation costs while improving constructability and sustainability.

Choosing designs with reduced construction times and minimal maintenance requirements emerges as a priority, particularly when considering the cost of external effects (Zinke, 2016; Zinke, 2020; ArcelorMittal, 2024a). This becomes even more crucial with the anticipated increase in construction sites, as infrastructure investments in Europe are expected to surge in the coming years.

2 VALUE ENGINEERING

2.1 *Knife Edge Support (capping beam)*

The Knife Edge Support (KES) is a capping beam system with a verified reinforcement design method covering the transfer of vertical and horizontal static loads plus vertical non-predominantly static loads (cyclic) from the concrete capping beam into the steel sheet pile section. It is an empirical design approach based on experimental test campaigns, achieving an optimised degree of reinforcement compared to Eurocode 2 (EN 1992-1-1:2004) without the need of reinforcement welded to the sheet pile or go through cut holes, nor the requirement of welded studs to the steel sections (Figure 1).

These advantages ensure an economic design as well as a fast and easy installation on site. Traditional methods for transferring vertical loads into sheet pile walls, such as concrete or steel capping beams, have been documented since 1938 in the German Larssen Handbook (Larssen, 1938) and later recommended in Lackner (1973) technical review. However, these approaches were deemed overly conservative.

In 2004, ArcelorMittal initiated the process for national technical approval to develop a more efficient capping beam design, aiming to reduce reinforcement steel usage, cutting construction time and material costs while still supporting high vertical loads. The German National Technical Approval (NTA), known as *Allgemeine Bauartgenehmigung* was granted by the German authorities with the reference number Z-15.6-235 (DIBt, 2021).

The method was derived by an extensive research and development programme lead by ArcelorMittal's R&D department in Luxembourg and conducted in collaboration with the University of Darmstadt and engineering consultants Hegger + Partner from Aachen, Germany. The rules given in the NTA are to be considered as minimum requirements to follow.

A capping beam designed in accordance with the German standard DIN 1045-1:2023-08 or Eurocode 2 (EN 1992-1-1:2004) allows a maximum vertical load of 625 kN/m. In contrast, the same capping beam designed according to the NTA supports a vertical load of 1,475 kN/m – an increase of 136% (ArcelorMittal, 2022a).

Figure 1. KES section and mockup.

To assess the compressive strength of the concrete placed over the steel sections, more than 20 small-scale samples were tested, considering two different sheet pile thicknesses and two concrete classes (Barcelo, 2019). These test results were used to determine the tensile splitting reinforcement calculation formula over the steel sheet pile. To determine the reinforcement needed to withstand the horizontal loads, the vertical cyclic loads, and to verify the load distribution models, a total of 10 large-scale tests were conducted by the University of Darmstadt. These tests were performed with PU 6 and PU 32 profiles and a C20/25 concrete, and a load-controlled sequence (20 kN/min).

Failure occurred when the steel - concrete interface collapsed, or the stresses and cracking in the concrete caused a drop on the load and an increase in the deformations.

Furthermore, these tests were performed, to analyse the vertical and horizontal load transmission throughout the connection, and to compare its behaviour to a standard reinforced capping beam.

The KES method has been tested and approved for static and vertical cyclic loads along with static horizontal loads; although, it has not been verified for uplifting forces, nor for external torsional moments. The reinforced concrete body should always fulfil the minimum reinforcement criteria required in the national standards and regulations.

2.2 *Capping beam types*

It is necessary to differentiate two types of the KES when designing in accordance with and the NTA. The two cases are shown in Figures 2 and 3 (ArcelorMittal, 2022a):

1. Pinned connection – capping beams are not able to transmit bending moments. Therefore, it can only be used if the external loads transmitted to the sheet pile wall are vertical and centred on the neutral axis of the sheet pile.
2. Fixed connection – capping beams are required in situations with horizontal loads and/or where eccentric vertical loads occur (vertical load not aligned with neutral axis of the sheet pile).

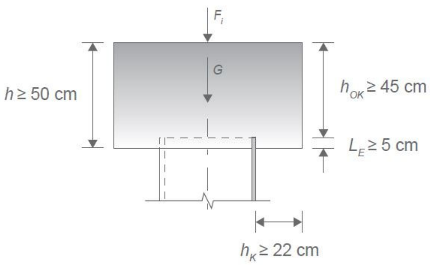

Figure 2. Pinned connection.

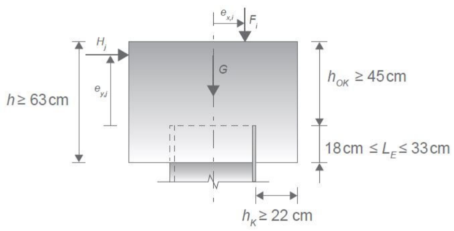

Figure 3. Fixed connection.

Geometrical requirements apply to both types, as follows:

- Minimum height of the capping beam above top of the sheet pile:
  $h_{OK} \geq 45\ cm$
- Minimum recommended concrete cover[¥]:
  $c_{min} \geq 40\ mm$; tolerance $\Delta c \leq \pm 15\ mm$
- Concrete lateral overhang:
  $h_k \geq 22\ cm$

[¥] These values are minimum recommendations from the NTA, but the design may have to comply with more stringent requirements of national standards and regulations.

2.3 *Mechanical models for load transmission in capping beams*

Load transfer in capping beams supported by steel sheet piles follows well-defined mechanical principles to maintain structural integrity. Vertical loads are transmitted through a controlled mechanism, requiring upper and lower splitting tensile reinforcement to prevent localized failure at the connection. The unique geometry of sheet piles distributes loads across both the web and flanges, requiring longitudinal and transverse reinforcement, with a maximum load propagation angle of 35°. Horizontal load transfer is governed by the wall's asymmetry, demanding distinct models for bending moment distribution while ensuring structural stability through continuous sheet pile restraint (Barcelo, 2019).

Analytical models confirm that vertical load transfer into the sheet pile relies solely on splitting tensile reinforcement, while horizontal loads necessitate a minimum embedment depth of the sheet pile into the concrete, along with vertical reinforcement. The required embedment depth depends on the interaction between vertical and horizontal loads and the induced moments. A suitably designed connection must account for the sheet pile's axial bearing (GEO) resistance, stress distribution at the sheet pile-concrete interface, and the required reinforcement within the capping beam to ensure structural performance (Barcelo, 2019). Figure 4 shows the effect of the combination of horizontal and vertical forces (including their eccentricities) that would result in the three load transmission diagrams.

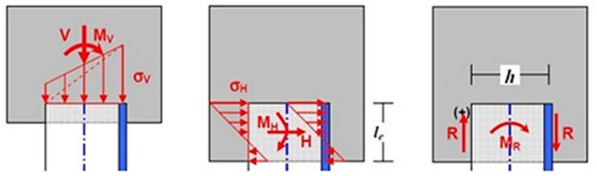

Figure 4. Stress distribution due to $V + M_V$ (left), $H + M_H$ (center), $H+M_R$ (right).

2.4 *Verification of the KES method*

A key aspect of design verification is understanding how vertical and horizontal loads interact in the KES. The mechanical behaviour of this connection can be summarized using interaction diagrams (Figure 5), where $M_{Rd,K}$ represents the maximum bending moment resistance in the absence of vertical loads, while $F_{Rd,m}$ denotes the maximum vertical bearing resistance when there is no bending moment interaction. These values, which depend on the sheet pile section, embedment depth, and concrete class, are provided in Annex II of the NTA. Additionally, the parameter $M_{Rd,KS}$ defines the bending moment resistance when subjected to a vertical load equal to 50 % of $F_{Rd,m}$ (Barcelo, 2019). The diagrams reveal that an increase in vertical loads can initially enhance design resistance, up to a certain limit (50 % of $F_{Rd,m}$), beyond which bending moment resistance begins to decline. Moreover, the bending resistance of the embedded depth is always reduced when vertical loads interact with horizontal loads (Figure 5). The verification diagram, considering reductions due to fatigue effects (Figure 6), follows a similar pattern, ensuring that long-term performance under cyclic loading remains within safe limits (DIN 1045-1:2023-08).

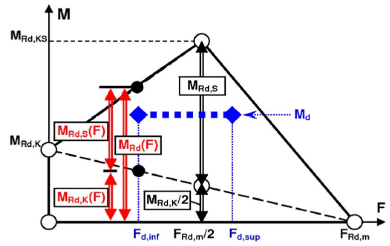

Figure 5. Interaction diagram for verification of the KES.

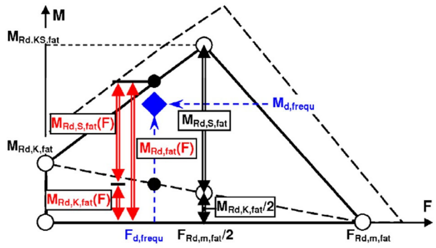

Figure 6. Interaction diagram for verification of the KES due to fatigue effects.

2.5 *Reinforcement layout and design recommendations*

To ensure structural integrity, the reinforcement layout must satisfy several key requirements, with five distinct types of reinforcement specified (Figure 7):

- Pos. 1: Stirrups – Provide shear reinforcement to counteract vertical and horizontal loads.
- Pos. 2: Transversal Splitting Reinforcement – Prevents cracking at the interface between the concrete and the steel sheet pile section.
- Pos. 3: Longitudinal Splitting Reinforcement – A minimum of three bars placed over the depth of the sheet pile to prevent cracking along the joint.
- Pos. 4: Longitudinal Reinforcement – Includes at least three bars on the lateral side and five bars on the top to enhance load-bearing resistance.
- Pos. 5: Longitudinal Corbel Reinforcement – At least two bars on each side of the overhang to prevent cracking.

The diameter of the longitudinal bars and stirrups ranges from 10 mm to 16 mm, while the maximum allowable spacing between them does not exceed 150 mm. These reinforcements ensure that both vertical and horizontal loads are effectively transferred into the steel sheet pile while maintaining the structural integrity of the connection. The interplay between reinforcement positioning, embedment depth, and load transmission mechanisms forms the foundation of a reliable and durable capping beam design (Barcelo, 2019).

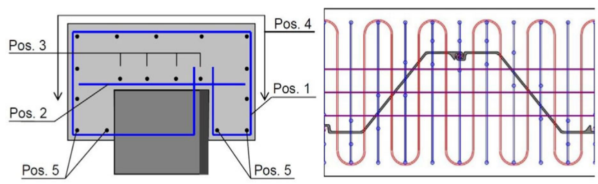

Figure 7. Reinforcement positions.

2.6 *Steel sheet piles axial bearing resistance*

In bridge abutment design, the capping beam must account for superstructure reactions (KES) and verify axial ground bearing resistance (GEO). Vertical load transfer in steel sheet piles occurs mainly through shaft friction and toe resistance, which may be enhanced by plugging during driving if confirmed (ArcelorMittal, 2022b). For axially loaded abutments, a conservative assumption is that friction is mobilized only along the passive soil side from excavation level to pile tip (Yandzio, 1998). The required embedment length is determined through soil-structure interaction analysis using subgrade reaction or p-y models, followed by iterative checks for all bridge actions. Bearing resistance depends primarily on the quality of ground investigations, which is more critical than calculation precision. A key advantage of sheet pile abutments is the ability to confirm bearing resistance during installation using driving refusal or a Pile Driving Analyzer (ArcelorMittal, 2024b).

3 VLOAD® SOFTWARE

The VLoad® software tool, available from ArcelorMittal (2023a), facilitates the analytical assessment and preliminary design of the interface between concrete capping beams and sheet pile sections. Additionally, it supports the development of preliminary drawings for the capping beam geometry and the specification of minimum steel reinforcement requirements (Figure 8). In bridge abutments, a fixed connection is always preferable over a pinned connection. A fixed connection ensures that both bending moments and shear forces are effectively transferred into the abutment structure, providing greater stability and rigidity.

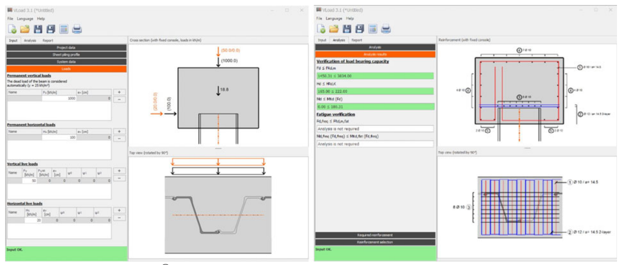

Figure 8. VLoad® software input and analysis results interface.

4 ROAD UNDERPASS – CASE STUDY

The road underpass, constructed in 2018, crosses the motorway 748 at the Juigné-sur-Loire junction (Junction 49) in France (Figure 9). The underpass was built using permanent PU 18 sheet piles in S 240 GP steel, installed to +44.50 mNGF, with a total steel quantity of approximately 100 tonnes.

Figure 9. Road underpass in Juigné sur Loire, France (©ArcelorMittal).

This solution was selected to facilitate traffic management during construction and ensure rapid installation, minimizing disruption to motorway traffic while providing a robust and durable retaining system for long-term performance.

4.1 *Ground conditions*

The ground model and design geotechnical parameters selected for the design of the structure foundations using steel sheet piles are shown in Table 1. The groundwater level was considered 7.70 m below ground level.

Table 1. Ground model and design geotechnical parameters.

Strata	Top Level	Thickness	Limit Pressure, Pl*	Menard Modulus, EM
	mNGF	m	MPa	MPa
Silt	+55.00	1.50	0.2	3
Clayey Sand to Sandy Clay	+53.50	3.00	0.7	10
Weathered Schist	+50.50	Not proven	2.0	25

4.2 *Design aspects*

Soil reactions were represented by non-linear springs to capture elasto-plastic behavior, and construction phasing was considered. Corrosion protection was addressed by applying a sacrificial thickness in accordance with EN 1993-5 for a 100-year service life. Reaction modules were derived from geotechnical investigations following NF P 94-264, and axial bearing resistance was determined in accordance with NF P 94- 262. Although the KES method was not applied in this case, this project case demonstrates the advantages of bridge abutments supported by sheet piles, forming a permanent structure capable of withstanding and transferring bridge loads. The VLoad® tool can be used for preliminary assessment and further refinement of the capping beam design.

5 LIMITATIONS OF THE KES METHOD

The KES method offers efficiency and cost benefits but is subject to strict technical and regulatory constraints. It applies only to ArcelorMittal hot-rolled sheet pile profiles approved under German NTA Z-15.6-235, with regulatory validity mainly in Germany. Additional approval is required elsewhere. The method is designed for static and non-predominantly static loads, excluding dynamic and seismic actions. Capping beam slopes are limited to 5% longitudinal and must remain horizontal transversely. Accurate assumptions about connection type are essential, and fatigue verification for high-cycle loading is not fully addressed. VLoad® software supports only standard KES configurations, so non-standard geometries require manual checks. Finally, precise alignment during installation is critical for effective load transfer.

6 CONCLUSION

Steel sheet pile bridge abutments offer clear advantages in construction speed, cost efficiency, and material optimization. The case study demonstrates value engineering by enabling continuous vehicle operations during construction, which is often challenging with traditional reinforced concrete abutments. With growing emphasis on sustainability and resilient infrastructure, integrating sheet piles with the KES method enhances load transfer efficiency and structural performance, allowing for compact and durable designs. However, its application is subject to limitations, including profile-specific approval under NTA Z-15.6-235, exclusion of dynamic and seismic load cases, slope restrictions, and the need for precise alignment. Fatigue verification and broader regulatory acceptance remain areas for improvement, highlighting the importance of careful design verification for complex loading conditions or non-standard geometries.

7 ACKNOWLEDGEMENTS

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