Technical solution for frame rail viaduct that can guarantee durability and safety exploitation

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Abstract. Bridge constructions with frame static scheme are proven solution for railway viaducts, which guarantees durability, trouble free maintenance, appropriate behaviour ensuring the assumption and transmission of vertical and horizontal efforts, redistribution of deformations occurring during the exploitation. The lack of bearings and expansion joints, makes them extremely reliable and adaptable to both the loads and the deformations that occur during the exploitation. An example of such a construction, with a seamless period of operation for more than 30 years, is the bridge in railway area of Station – Poduyane. It is a 3 spans frame structure, with a total length of 105m, with 18 track lines at the Railway Yard Area. In the current article, 2 railway viaducts will be presented – part of the Modernization of the Railway line Sofia – Plovdiv, railway section Elin Pelin – Ihtiman. Specific issues of the design process have been considered, with particular attention to the element stiffness proportion ratio, details of the joints, the effects of temperature, the shrinkage and creeping of the concrete, isolating the abutments from the soil effects / pressure.

1. Structure and foundation types for frame rail viaduct - overview

1.1. Regarding the superstructure
Usually a prefabricated-monolithic superstructure is used, where the beams are from plain reinforced concrete. After their mounting, in-situ concrete is casted over the supports, which embeds the beams in the respective sectors. This way it is possible to achieve spans’ lengths which are significantly longer than the beams’ length. The beams themselves are unified in transversal direction in a grillage structure with the help of a monolithic slab [1], [2], [3], [4].

1.2. Regarding the foundation
The foundation can be of direct / spread type and pile type.

Direct foundations are modelled with the help of springs, which stiffnesses’ values depend on the soil layer properties, on which the foundation is positioned. It is not correct to place a spread foundation directly onto a solid rock layer. In this case at least 0,50 m of the solid rock layer are removed and subsequently replaced with coarse sand layer. The obtained sand bed is functioning as an elastic environment with its respective properties [5] [6].

Pile foundations, when needed, could be implemented with friction piles or standing piles. The calculation model which defines their structural behaviour is again achieved with the help of springs, which stiffnesses’ values depend on the soil layers properties, through which the piles are penetrating.
2. General information about the present two structures
As a static scheme the viaducts are frame structures. The 8 no. of spans consist of prefabricated reinforced beams with length of 22m and weight of 35t each, which are unified with cast in-situ concrete slab thus creating a common structure. In longitudinal direction the beams are embedded with cast in-situ concrete over the supports and abutments, thus creating the frame structure. All the loads and actions on the structure are according to the Eurocodes. The abutments themselves are part of the frame structure. They are not subjected to passive and active soil pressure, because are protected by a retaining wall, which is founded on the same pile cap – Figure 10.

![Visualization](image1.png)

**Figure 1.** Visualization.

![General plan](image2.png)

**Figure 2.** General plan.
2.1. Viaduct at km 30+217
The railway viaduct consists of two tracks with 6 no. of middle spans with length of 30m each and 2 no.
outermost spans with length of 27m each. The overall length is 234m. The viaduct is positioned in a
curve with R=1500m for the left track in direction of Ihtiman and R=1504m for the right track. It crosses
both a coulee, for which a correction is envisioned, and 2 no. of 20kW power lines, one of which requires
a dislocation.
The dilatations between the frame structure and the retaining wall are with overall value of about 8 cm
(from -5 to +3 cm).

2.2. Viaduct at km 30+765
The railway viaduct consists of two tracks with 12 no. of middle spans with length of 30m each and 2
no. outermost spans with length of 27m each. The overall length is 414m. The viaduct is positioned in
a curve with R=1500m for the left track in direction of Ihtiman and R=1504m for the right track. The
dilatations between the frame structure and the retaining wall are with overall value of about 15 cm
(from -6 to +9 cm).

2.3. Construction technology
The following technological order will be maintained during the construction of the facility:

2.3.1. Casting the in-situ piles with diameter of 120cm and length of 20m. During the casting, the
following should be done:
- conducting tests for bearing capacity of a single pile of the pile groups positioned at the
  beginning, middle and end of the viaduct;
- running a check and recording an ultrasound scan of the achieved concrete density of all piles,
  which should remain as a project documentation.

2.3.2. Formwork mounting, reinforcement placing and concrete casting for all the middle
supports' and abutments' pile caps;

2.3.3. Formwork mounting, reinforcement placing and concrete casting for the abutments to level
top edge of predalle and all piers to level 25cm beneath top edge monolithic in-situ slab;
2.3.4. Mounting of the prefabricated and pre-transported to the construction site reinforced concrete beams with length of 22m and weight of 35t each;

2.3.5. Formwork mounting, reinforcement placing and concrete casting for monolithic sectors and in-situ slab. During the reinforcement placing the overlapping of both horizontal and vertical bars to be achieved with front contact welding or with rebar couplers;

2.3.6. Mounting of the dilatation joint between the viaduct and the retaining wall;

2.3.7. Concrete casting for the sidewalks’ sections, with leaving of openings for the handrail sceptres;

2.3.8. Mounting of the gullies and casting the concrete for dewatering inclination, which is with maximal thickness of 5cm. After a while, depending on the type of insulation used, the hydro insulation of the slab along with the protective layer is implemented;

2.3.9. At both ends of the viaduct, at the connection with the backfill, two types of connections could be implemented:
- first variant – implementation of two curtain walls, which has sleepers installed subsequently before and after them;
- second variant – implementation of transitional devices to prevent falling out of the ballast bed onto the dilatation joint.

The advantage of the second variant is that it prevents the lifting of the heavy machine for sieving of the ballast bed during operation and maintenance of the railway [7].

3. Specific points of the design for the presented rail viaducts

3.1. Elements’ stiffness proportion ratio
With long viaducts the separate elements’ stiffness proportion ratio is crucial for optimizing the structural behaviour. For the correct proportions to be obtained the respective analyses should be made. The final goal is to get a structure with optimal behaviour in all of the standardized limit states. The parameters for the limits of the desired structural behaviour are the minimal and maximal stiffness for specific elements. In the superstructure the minimal stiffness is required, based on the desired deformation in horizontal and vertical direction to be in standardized limits. These factors can be influenced with the cross-section to span length ratio. The goal is a structure, which is not susceptible to severe deformations. Suitable and easy method for determining the dimensions is established by years of practice and the indicative proportions of structural height to span length are varying from 1/8 to 1/24, depending on the type and purpose of the structure [3], [4], [6].

During the design of the connection for the joints between superstructure and substructure elements in the particular case a proportion is sought where the superstructure has greater bending stiffness than the substructure elements, which are connected to it.

![Figure 4. Stiffness proportions](image)

The following dependency is sought: 
\[ E_C \cdot l_{bas} < E_C \cdot l_{pas} \]

The rotational stiffnesses of the section are directly influenced by this dependency. The lengths are assumed to be proportional.

\[ E_C \cdot l_{pas} \]

- Elasticity module of concrete

\[ l_{bas} \]

- Moment of inertia of the superstructure

\[ l_{pas} \]

- Moment of inertia of the passtruction
This way a behaviour is provided for the superstructure beam, which is very close to the classic continuous beam behaviour. Thus two connected structures are obtained which don’t affect drastically each other. The final result is that the bending moments caused by the superstructure shortening / lengthening deformations are drastically decreased both in the substructure elements themselves and in the joints’ equilibrium. Other important aspect of this design is that loadings on the bridge superstructure don’t create critical bending moments for the substructure and vice-versa. For determining the correct ratio several options for the joints have been analysed, all with different geometric proportions of the substructure elements. The last critical aspect is the equalization of the stiffness properties of the substructure elements.

![Weakened section](image)

**Figure 5.** Weakened section

The main factor participating in this is the height of every single pier. Leaving different supports’ heights without taking into consideration their different stiffness properties could lead to critical situations. Increased second order effects, uneven dynamic loadings distribution and a number of other problems could prove to be critical. Such parameters are often avoided and rarely are being left to be leading for the design, because of their time consuming and often unreliable analysis. This problem could be solved with a number of methods, like using a typical cross section with reliable stiffness in horizontal / transversal direction – a box, for example.

In the particular case a decision has been made for all the piers to be designed in a way to guarantee high stiffness below a particular level. For determining the level a quick proportions determining is enough as a start and it is updated after initial analyses. The determining criterium is uniform behaviour of the structure under dynamic effects / horizontal loadings, which eliminates the overloading of certain elements.

![Static scheme](image)

**Figure 6.** Static scheme of the structural behavior under horizontal loading

The stiffness should be in the limits – from minimal stiffness, which is dictated by allowable deformations outside the structural plane, to maximal stiffness, which leads to critical states from superstructure shortening / lengthening effects in horizontal longitudinal direction.
3.2. Joint detailing for substructure – pier connection

The joints’ detailing and their implementation are important for the desired behaviour of the structure. In the particular case a prefabricated-monolithic solution is sought. For this purpose, a detail has been designed, which provides the possibility for mounting the beams in their design positions without the help of temporary supporting elements. For all elements’ reinforcement quantities have been predetermined, which need to be correctly anchored in the joint. For the reinforcement baskets to be correctly assembled, all of the waiting reinforcement is selected to be anchored in free zones with open access for work.

3.3. Isolating of the abutments from the backfill

A vertical reinforced concrete retaining wall is positioned behind each of the abutments for protecting the endmost support from direct contact with the backfill.

The aim is the effects from soil pressure on the structure to be eliminated. Due to the large uninterrupted structure length the displacements at the end supports are expected to be quite big. Such displacements of the abutment could lead to varying of the active and passive soil pressure, which respectively are influencing the structure. Such varying on the other hand could lead to interrupted contact between structure and backfill [8].

Figure 7. “Reinforcement basket” of the frame joint superstructure - pier

Figure 8. Behavior of the abutments and the retaining walls behind them
This interruption is critical for the structure’s durability, due to it causing soil settlements, active corrosion zones and overall problems with the structure behaviour, as well as considerable stresses in the superstructure itself. For the particular case, a retaining wall is designed within direct proximity to the endmost bridge supports. The two structures are stepping on the same foundation. When designing such a structure it is necessary the possible displacements in both elements to be taken into account and the needed distance between them to be provided. Also, the common foundation should be designed for the cooperative behaviour of the two elements.

3.4. Thermal effects
The thermal effects should be taken into account with their full capacity since they are important critical effect for continuous structures. They usually lead to significant deformations and can dictate the division of the structure to separate blocks. With the correct stiffness proportion ratio, the thermal effects could be lowered to their minimal values, but they are still critical for certain elements. Load combination with dominant thermal effects is taken into account for every structural element.

3.5. Creep and shrinkage of concrete
The creep and shrinkage of concrete are effects which are difficult to be defined precisely. Because of this every design normative has them included with their maximal values. These values in most of the cases are on the conservative side and can be reduced by more precise analyses and building conditions, time for construction, care for concrete, quality of the materials. Due to the susceptibility of the continuous structures for the particular case is decided in favour of the Eurocode values, which are on the conservative side. The design of the structures is made with the maximal values of creep and shrinkage and their effects are added in every load combination for which they prove to be unfavourable. The deformations due to creep and shrinkage are critical parameter for determining the maximal and minimal dilatations and are also taken into account when defining the joints’ dimensions and their location.

4. Advantages of the presented technical solution to other common methods
The presented structure has considerable amount of positive and negative compared to the traditional simply beam style static scheme, common for railway bridges. On the side of the design, a frame structure provides significant complexity to the structure behaviour. The static flow of the forces often cannot be determined as directly as in the simply supported structures. Effects like a creep, shrinkage, thermal deformations have a significant impact on the frame structure, compared to the simply supported
static conditions, where those effects are significantly simplified or straight out ignored. However, the frame structure provides option of forces transfer in directions that the standard solutions do not. Having stiff connections between the substructure and the superstructure provides better mechanism for horizontal force distribution. In the traditional solutions, horizontal forces, bridge stability, and durability are provided via the usage of bearings, construction joints, dampers, and other devices. Those devices are expensive, especially the ones that can guarantee a good quality and low maintenance, negating the price difference between the frame and the traditional beam structures. Even more so if the devises used, have to be overengineered to withstand and maintain stability in case of accidental horizontal loads, such in earthquakes or severe wind action. The frame structures do put out more strain on the substructure itself. However, this trade of is often more than ideal as substructures of bridges tend to have design that can be utilized significantly better and be able to withstand the additional forces easily. In the frame static solution significant strain on the structure can occur due to the soil-abutment interaction, however a good solutions for isolation of the structure from the soil are optional, like the presented double wall abutment.

5. Conclusion
The use of frame structure reduces a lot of the critical key point, that are common to failure, high maintenance, and excessive costs. The modern solutions for bearings, joint connections are becoming more and more advanced, increasing the lifespan of the element, but still lack the durability index of the frame structures. The increased lifespan such elements is achieved by increased complexity, reflecting on their cost for the product itself and its application is inevitable. In the modern bridge development, most of the setback of the frame structure are avoided by the state of the construction quality. The modern constructor has arsenals of utilities and tools to easy the issues like complexity, quality of elements and connection, logistics, scaffolding, framework, and reinforcement. For most construction, the above-mentioned setbacks of the frame structures are irrelevant as the methods used are not significantly affected by them. Even more so, application of good design solution for isolation of the abutments from soil pressure, like the double walled abutments, further improve the general behaviour of the structure. This leads to the costs for a frame structure to be quite comparative compared to traditional solution where quality joints, bearings, and dampers must be used.

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