ARCH VIADUCT IN POMERANIA METROPOLITAN RAILWAY – FORM FINDING AND IDEA OF PRESTRESSING

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SUMMARY

The paper presents the historical background and final concept of design of railway concrete arch bridge with the span of 80 m. Interesting architectural effect was reached as a result of precise analysis of internal forces in structure.

Additionally a special prestressing without tendons was developed to reduce effect of bending moments in concrete arch. Finally results of load test are presented. Arch viaduct was opened to service in 2015. Detailed information, drawings and photos are included.

Keywords: *Arch bridge, concrete, FEM analysis, construction, load test.*

1. VIADUCT WK11, PRELIMINARY STUDY

Conceptual works has been done during preliminary Feasibility Study of Metropolitan Railway. Classic arch with tie and carriage way on the top was considered. However, visualization revealed that this design too dominates the surrounding environment.

First complete concept of viaduct was design by PBK SA (Fig. 1). They proposed two span, multi-beam construction with a pillar at the waist section of the street. An important element of the concept has become a vision of red bus shelters.

The final form of the object was formed in Transprojekt Gdanski within the contract "Design and Build". It was decided, referring to the historical demolished viaduct and due to the collision of underground infrastructure in the street below, that WK 11 will be single-span arch with carriageway on the top. Pre-designed span of the arches in the form of four steel box girders and roadway composite steel and concrete. Visualization of the object is shown below (Fig. 2).

Finally contractor (Budimex SA) decided that the arch has to be constructed as a pure reinforced concrete structure. This decision with the clear economic background has become a challenge for the project team.

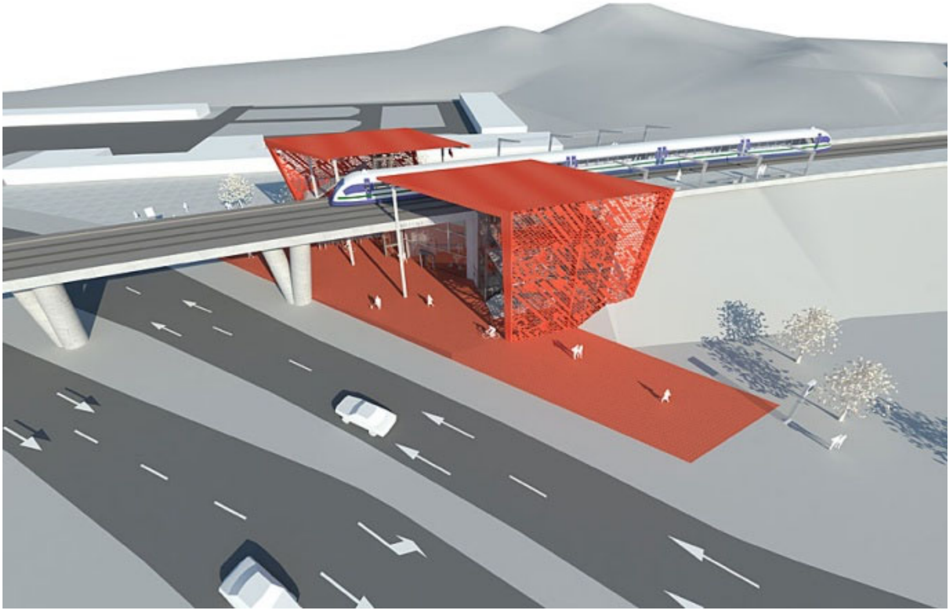

Fig. 1. *Concept of WK-11 viaduct and train station „Niedźwiednik”.*

Fig. 2. *WK-11 viaduct. Primary concept, Transprojekt Gdańsk.*

2. VIADUCT WK 11, THE FINAL CONCEPT

Designing of concrete arch is nothing extraordinary. However, in the case of the viaduct WK 11 there were several reasons to wonder. This was a reason of advanced numerical analysis of structure. The most important problem was the small camber of arc (f = 7.2 m for a span of l_t = 74 m). The consequence of such a ratio is very big (~55000 kN) horizontal force acting to abutment. That means that prediction of horizontal deflection of abutments and its influence to arch is burdened with uncertainty. In addition with rheology and railway traffic load it was clear that we cannot exclude bending moments in superstructure. In classic arch bridges we have two ways to carry bending moments: designing a stiff arch girder or stiff carriageway above the arch. In case of concrete structure we assumed that the best element to carry bending moments is the concrete prestressed section. That means that the viaduct should be a composition of naturally pressed solid arches and delicate carriageway supported on the arches by slender columns. Carriageway is based on the arch by concrete columns with classic concrete reinforced hinges on both ends. Because of big normal force in the arch, cast steel hinge bearings were implemented in both ends.

In primary designing stage, a series of FEM analysis with beam and membrane models were done. Finally revealed a familiar arc shape designed many years ago by brilliant Swiss engineer and architect Robert Maillart (1872-1940) [1] (Fig. 4).

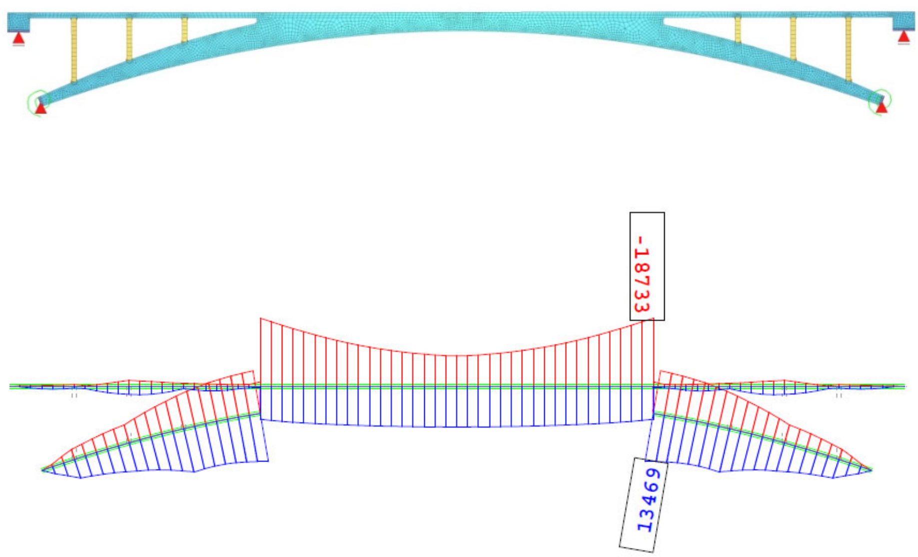

***Fig. 3**. Plane model of WK11 viaduct prepared in FEM SOFiSTiK, Envelope of bending moments [kNm].*

Fig. 4. *Bridge over Salgina valley designed by Robert Maillart in 1929 (wikipedia.org).*

Final dimensioning was carried out on the beam model previously verified by the membrane one. Superstructure consists of two separated arches and above continuous road carriageway plate (Fig. 5). Abutments are designed as reinforced concrete chamber corresponding to the original, historic form. The result is a slim design harmoniously fitted into the hilly surroundings (Fig. 6, 7).

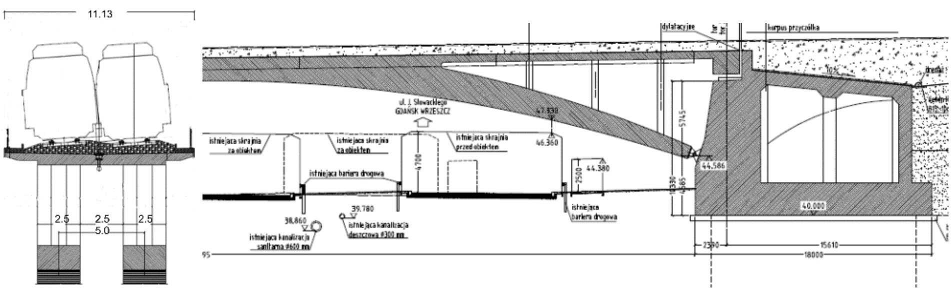

Fig. 5. *Cross and longitudinal section of the viaduct [2].*

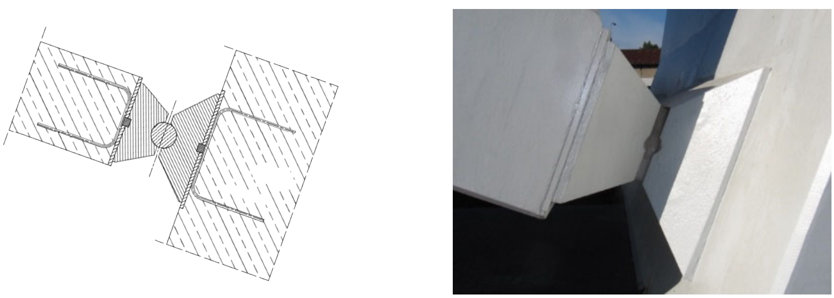

Fig 6. *Cast steel hinge.*

Fig. 7. Test load (photo – archive of PG).

3. FEM ANALYSIS – DEVELOPMENT OF ADDITIONAL PRESTRESSING IN EARLY STAGES

Tension stress in the concrete arch was a reason to develop the simple method of additional local prestressing of the arch in bottom zone. Standard solution based on a third hinge in the middle of the arch (only in dead weight stage) was implemented and modified by eccentricity of the hinge position in cross section. This simple idea was studied with FEM models. Two cases were considered. One without third hinge and one with a hinge in early construction stages.

3.1. Analysis of case 1

3.1.1. Model and construction stages

The numerical model of the superstructure has been defined with plane elements and beams used as columns, as it is shown in Fig. 8.

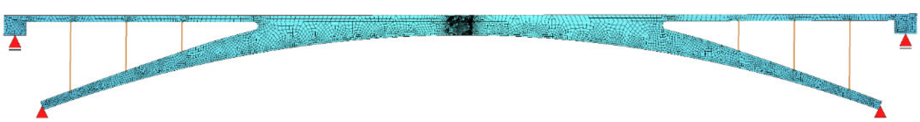

Fig. 8. Visualization of numerical model.

The construction stages in numerical model has been defined as follows:

- concreting the arch (Fig. 9a) ,
- creep and shrinkage lasting 14 days,
- horizontal movement of abutments with value of 13mm on both sides (total 26 mm),
- applying formwork and fresh concrete of carriageway on both sides (Fig. 9b),
- applying equipment on carriageway (Fig. 9c),
- applying traffic load.

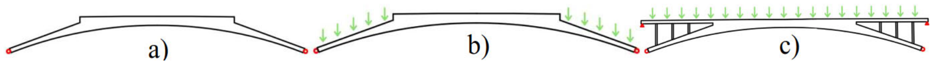

Fig. 9. *Construction stages considered in numerical analysis – case 1.*

On the base of explained above construction stages, numerical simulation has been performed. Analysis was focused on the level of inducted tension stress (marked as blue in following drawings).

3.1.2. Results of analysis – case 1

On figures below, the stresses of the structure in the first main direction in four stages have been presented – after casting the main arch (Fig. 10), after horizontal displacement of abutments (Fig. 11), complete deadweight stage (Fig. 12) and service stage – most unfavourable traffic load position (Fig. 13).

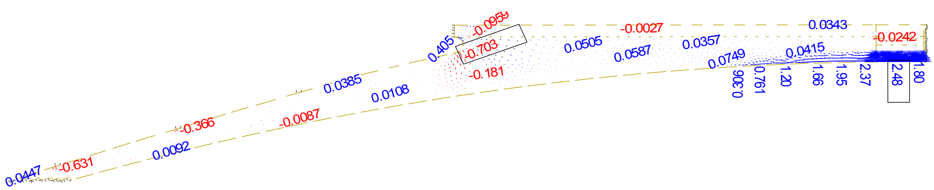

Fig. 10. *Stress level in the arch after removing the formwork [MPa].*

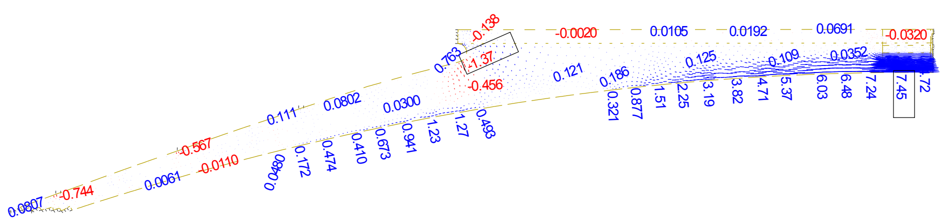

Fig. 11. *Stress level in the arch after horizontal movement of abutment (2 x 13 mm) [MPa].*

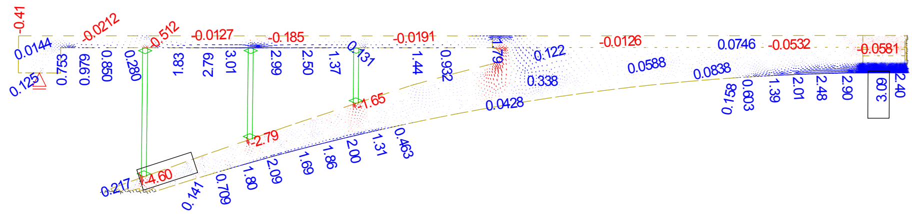

Fig. 12. Final stresses in main direction (longitudinal) in the arch – deadweight [MPa].

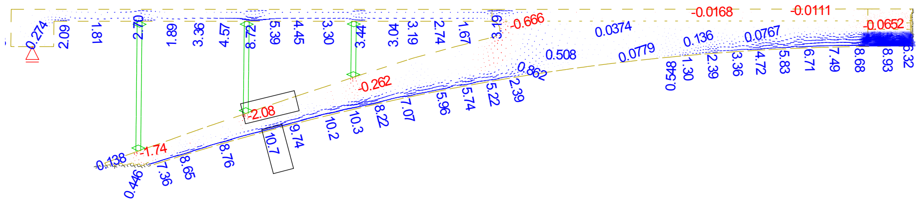

Fig. 13. Final stresses in main direction (longitudinal).
Envelope, service stage and deadweight [MPa].

After analysis several conclusions can be formed:

- The horizontal movement of abutments increases the value of tension stresses in the centre of the arch up to 7.6 MPa (Fig. 11).
- The zone where the tension stresses at the bottom were identified, is about 20 m long and may require heavy reinforcement (Fig. 11).
- The carriageway's load reduces tension stresses in the centre of the arch, but also increases tensioning in quarter of span (Fig. 12).
- The traffic loading can increase tension stresses in the arch, with maximum value of 10.7 MPa in quarter part of span (Fig. 13).

3.2. Analysis of case 2

3.2.1. Model and construction stages

Because of the danger of unexpected horizontal movements of abutments, an alternative way of constructing has been developed. The main aim was to reduce the zone of tension stresses identified in case 1 study. The developed procedure assumed the work of the arch with additional hinge in its early stages (Fig. 14).

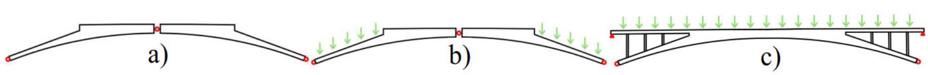

Fig. 14. Construction stages considered in numerical analysis – case 2.

The analysis was performed with the same numerical model as in case 1, where specific groups of elements have been activated in different stages:

- casting the arch with a hinge in the middle (Fig. 14a),
- creep and shrinkage lasting 14 days (Fig. 14a),
- horizontal movement of abutments with value of 13 mm on both sides (total 26 mm) (Fig. 14a),
- applying formwork and fresh concrete of carriageway on both sides (Fig. 14b),
- applying equipment on carriageway (Fig. 14c),
- concreting of hinge zone in the middle of the arch,
- applying traffic load.

The idea and implementation in FEM model is presented in the Fig. 15.

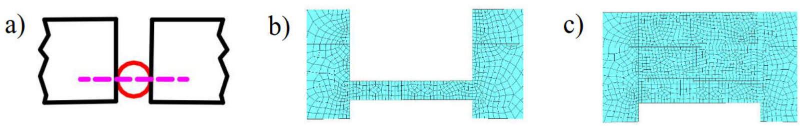

Fig. 15. *Design of hinge in the middle of the arch a) idea, b) early and c) final stages in FEM.*

3.2.2. Results of analysis – case 2

In figures below, the stresses in first main direction are presented as it was in case 1.

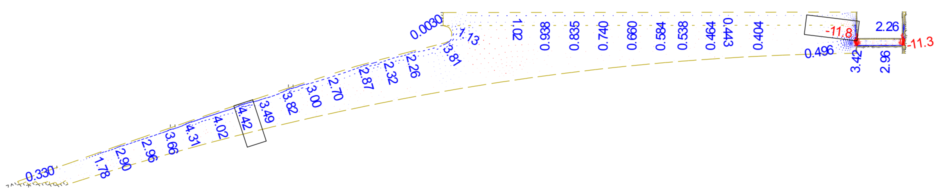

Fig. 16. *Stress level in the arch after removing the formwork [MPa].*

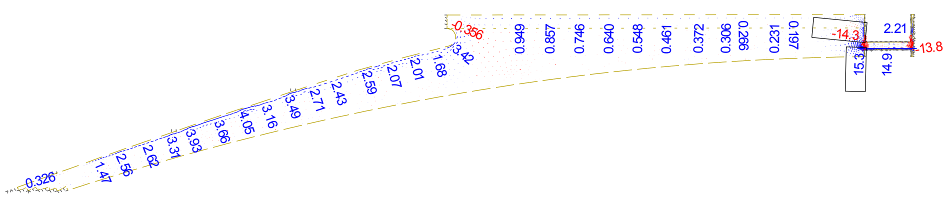

Fig. 17. *Stress level in the arch after horizontal movement of abutment (2 x 13mm) [MPa].*

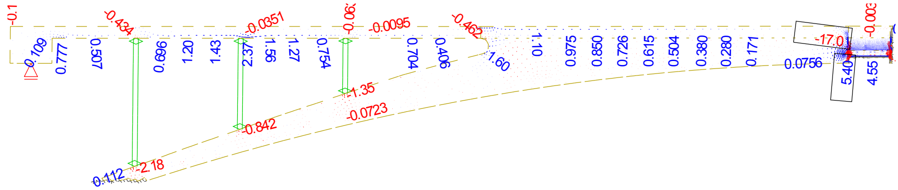

Fig. 18. Final stresses in main direction (longitudinal) in the arch – deadweight [MPa].

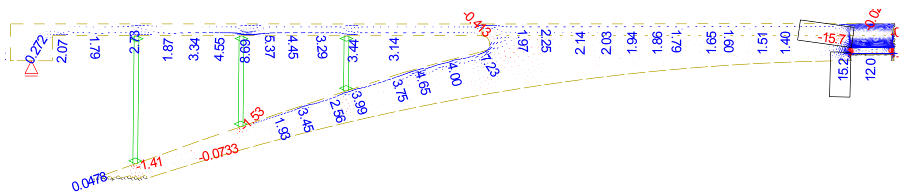

Fig. 19. Final stresses in main direction (longitudinal).
Envelope, service stage and deadweight [MPa].

After analysis several conclusions can be formed:

- The developed procedure greatly reduces tension stress in the arch.
- The tension stress with values up to 4.0 MPa is identified in early stages (Fig. 16 and 17), in upper fibers of the arch and are later eliminated by the weight of deck and equipment.
- The traffic loading causes tension stresses with values of 4.6 MPa (Fig. 19), but they are far lower than values obtained in case 1 (Fig. 13).
- The hinge zone in early stages gets tension stress up to 15.2 MPa (effect of local bending). This part of structure would require heavy reinforcement or even usage of steel detail.
- Nevertheless, the tension zone in the arch has been greatly reduced (Fig. 19), what makes the whole procedure worth considering.

4. CONCLUSIONS

Finally, the contractor has resigned of additional hinge in early construction stages after positive results of horizontal load test of abutments. Identified tension in concrete was undertaken by standard reinforcement. However, applying an additional eccentric hinge during construction stages can be an effective way to reduce tension stresses in the structure.

The WK-11 viaduct has been built and the test load has confirmed its correct work. The attractive shape of the arch was reached by the optimization process using advance FEM structural model. This brand new viaduct can be the next tribute to the knowledge and art of Mr Robert Maillart.

REFERENCES

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[2] TRANSPROJEKT GDAŃSKI, *Preliminary and detailed design of viaduct WK-11 - Pomeranian Metropolitan Railway, 2013*.