# STRAIN GAUGES MONITORING OF ARCH BRIDGE OVER THE VISTULA RIVER IN TORUŃ DURING CONSTRUCTION

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## SUMMARY

In 2013 one of the biggest Polish road bridges over the Vistula was built in Torun. Considering the use of original engineering solutions and innovative assembly it was decided on monitoring of strain gauges and assessment of building's behaviour during its construction. The research was aimed at determining the degree of strain and the assessment of proper work of main arch girders during assembly phases. This work presents the assumptions of a monitoring system, methodology and representative results of the research.

**Keywords:** *Arch bridge, innovative assembly, FEM analysis, monitoring,*

## 1. INTRODUCTION

Significant development of communication infrastructure means for architects and contractors of bridges new challenges which results in more and more innovative and unusual facilities. Their design and construction provides for systematic overcoming construction-related, technical and technological barriers. Introduction and application of new solutions requires the knowledge of real behaviour of structures and verification of acquired theoretical and design assumptions. Unified description of real behaviour of a building may be achieved on the basis of results of well-prepared and conducted monitoring of a facility during phases of its construction, final hand-over tests and its destined use. [1÷6].

One of the biggest Polish road bridge over the Vistula was built in Torun. Considering the use of original engineering solutions and innovative assembly it was decided on monitoring of strain gauges and assessment of building's behaviour during its construction. The task was entrusted to the team of Laboratory of Field Research at Gdansk University of Technology, an entity of over 60-years-experience in diagnostics and researches on bridges.

## 2. THE DESCRIPTION OF THE FACILITY AND THE TECHNOLOGY OF CONSTRUCTION

### 2.1. Description of the facility

A road arch bridge over the Vistula in Torun named after Elżbieta Zawacka is the structure of two bays (Fig. 1, 2), which span width is a record in Poland 2 x 270 m, and which constitutes the part of a new route equalling in total 4.100 m. Main girders are two inclined towards one another arch box girders, of a closed hexagonal cross-section. They are braced in each bay with six transverse box rafters.

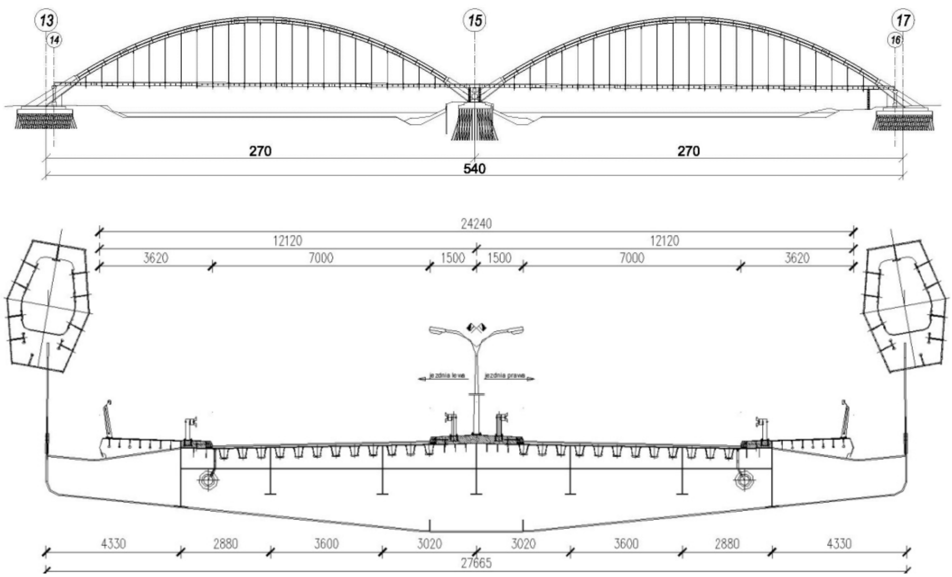


***Fig. 1.*** *Chart and cross-section of arch bridge over the Vistula in Torun.*

Head section of arches was made as a mixed combined system: made of steel and reinforced concrete. On the top, steel boxes of arch girders are braced with a corpus of head sections made of reinforced concrete with the use of steel pins. The bottom part of head sections is a monolithic structure made of reinforced concrete joined with foundation plate placed on poles.

The platform of steel structure is made by longitudinal and transverse girders with orthotropic plate situated in a plane of their top lanes. The platform suspended to arches with stiff pipe hangers which is 24 metres wide has got two traffic lanes in each of directions.

The structure is located on two supports, including one hydrotechnical support placed on an artificial island, which is to secure the support against the current of the Vistula.

## 2.2. Bay assembly technology

During the execution of the enterprise the innovative way of assembly of main girders was exercised considering the size of the facility. Assembly sections of arch girders were braced on shore as a whole of total length 230 m and total weight about 5.500 tons, then they were transported on pontoons and special supports to the intended place of construction.

Then, the arches were raised from pontoons and before permanent continuity placed on specially-constructed assembly tables (Fig. 2b, c, d) on braced parts of formerly performed head sections. At first, the arch girders of a bay 13-15 were mounted, then – after bracing arches with head sections – suspension of platform sections was begun. Upon suspension of three platform sections in a bay 13-15 the operation of assembly of arch girders in a bay 15-17 was performed. Subsequent phases covered suspension and bracing of platform assembly sections (Fig. 3). A whole platform was divided into 19 assembly sections, which weight was from 72 to 88 T.


***Fig. 2.*** *a) Bridges of Torun; b) assembly of bay arch girders 13-15; c) assembly of bay arch girders 15-17; d) assembly table for placing an arch girder on a head section*

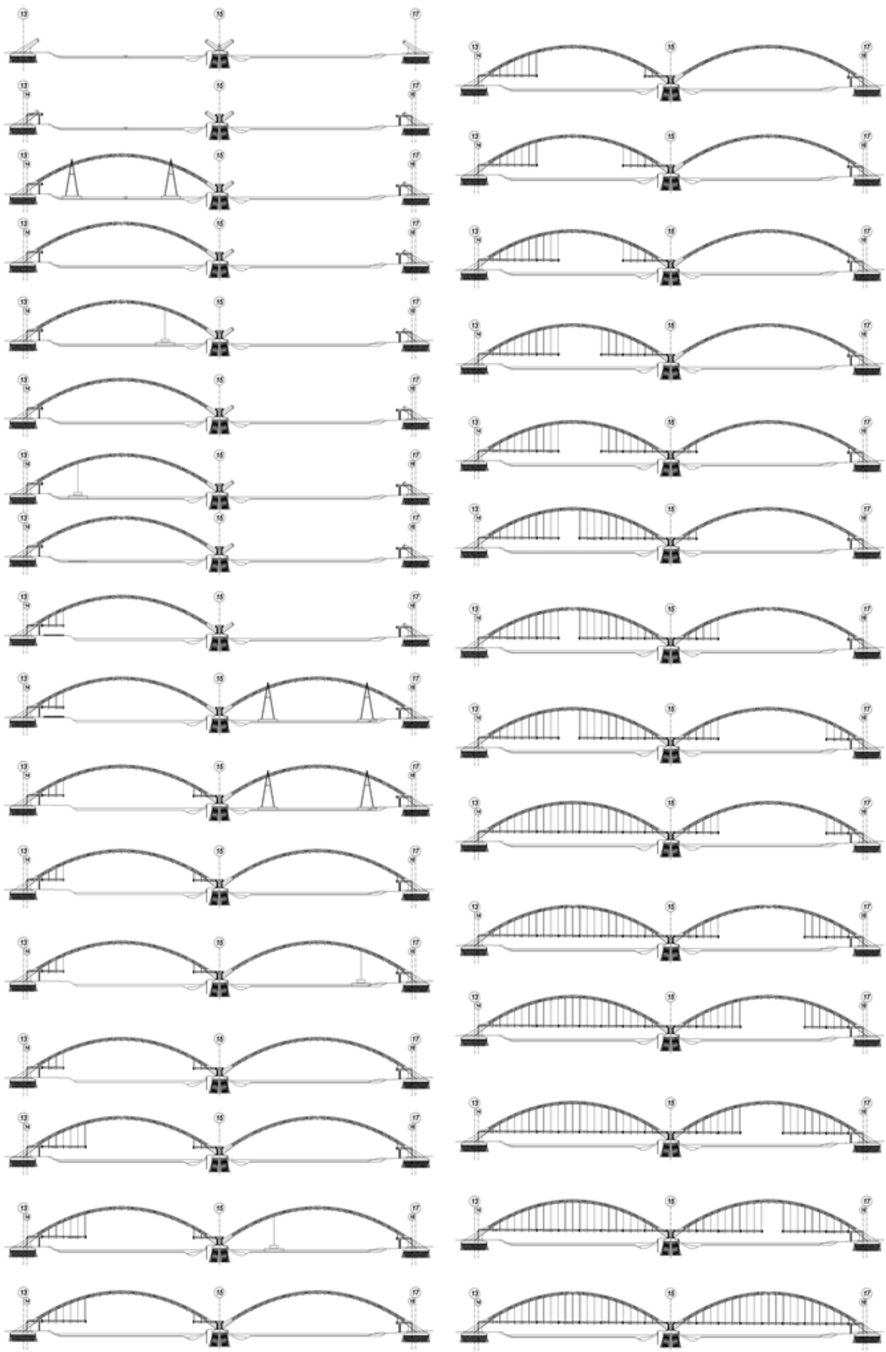

***Fig. 3.** Phases of assembly of arch bridge over the Vistula in Torun.*

## 3. STRAIN GAUGE MONITORING SYSTEM

### 3.1. Aim and scope of research

Because of uniqueness of the structure and innovative application of technological solutions the construction of Torun bridge was monitored during its erection. The aim was to determine the degree of strain and the assessment of work of main arch girders during assembly phases [7].

### 3.2. Methodology of research

The monitoring system covered cyclical measurements of gauge strain/deformation in steel parts of arch girders in four representative head sections and on pins/tenon joints of assembly tables. Simultaneously, the measurement of the temperature within the structure was taken. Proper layout of sections and measuring points in tested head sections in certain assembly phases provided for current tracing and reconstruction of maps of supporting zone and the assessment of appropriateness and interaction between steel parts and reinforced-concrete parts in head sections. As an example, the layout of sections and measuring points for a representative head section no. 13 was presented on Fig. 5, 7.

### 3.3. Numerical analyses

Theoretical behaviour of the structure was analysed on the basis of calculations on advanced spatial FEM models.

The global calculation model of a bridge (Fig. 4) was a spatial system of surface and beams. The plate of the platform, walls of head sections and supports were modelled with 4-nod, coating finite elements. Arch girders, transverse braces of arches, head sections, crossbars, girders and longitudinal fins of the platform and poles were modelled with 2-nod beam elements including eccentrics. Hangers were modelled with grid elements.

Geometric and material parameters of the structure were acquired on the basis of facility documentation. Generated model of the bridge consisted of:

- grid 155 544 nods,
- 101 714 beam elements,
- 158 284 coating elements,
- 92 grid elements,
- 19 supporting nods of the platform.

In order to analyse and determine the degree of strain and interaction between steel part and reinforced-concrete part of head sections detailed section models were performed for head sections (Fig. 5). The possible scheme of load transfer from a bay part to support part were also taken into account, i.e. through assembly tables or arch girders just after continuation. For each analysed head section there were 2 models assumed made of coating elements (steel part) and solid elements (reinforced-concrete part) at boundary conditions considering global interaction between parts of the structure during subsequent phases of the assembly. (Tab. 1).

*Fig. 4. Visualisation of a global calculation model.*

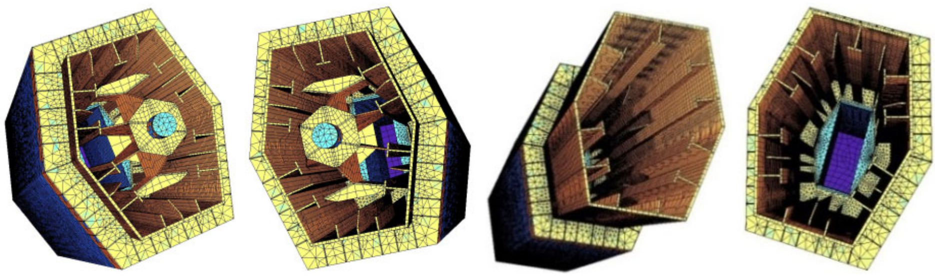

*Fig. 5. Visualisation of detailed section models of bridge head sections.*

*Table 1. Parametric description of detailed section models of head sections.*

| No. of head section/variant | Nods | Coating elements (steel part) | Solid elements (reinforced-concrete parts) |
|---|---|---|---|
| W13/table | 58 179 | 40 826 | 188 438 |
| W13/extended | 65 487 | 48 540 | 185 903 |
| W15_13/table | 56 978 | 41 165 | 179 627 |
| W15_13/extended | 64 604 | 48 839 | 178 658 |
| W15_17/table | 58 816 | 41 381 | 190 445 |
| W15_17/extended | 66 539 | 49 040 | 190 287 |
| W17/table | 49 207 | 38 501 | 140 343 |
| W17/extended | 56 223 | 45 856 | 136 746 |

Measured strain values were compared to theoretical results for a certain load scheme – assembly phase (Fig. 3) considering the influence of temperature of the system (results of measurements) onto a mounted part of structure.

## 4. RESULTS OF THE RESEARCH

Considering limited capacity of work the results of the research were presented for two phases of the assembly of a bay 13-15.

Representative results for assembly phase: placing on assembly tables of bay part 13-15 (Fig. 6, 7) presented in Tab. 2 and 3.

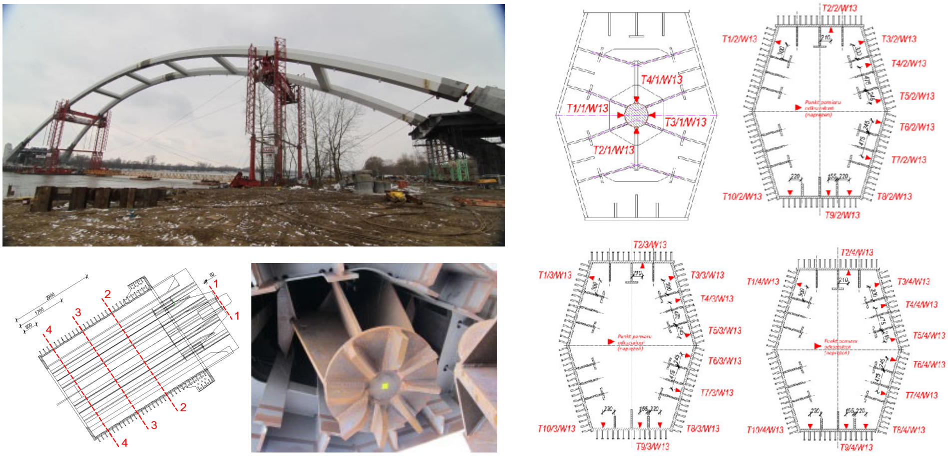


***Fig. 6.*** *General view of the structure after placing arches of a bay 13-15 on assembly tables; layout of cross-sections and strain gauge measuring points of a head section no. 13 (till the moment of bracing of bay part with supporting part of arches).*

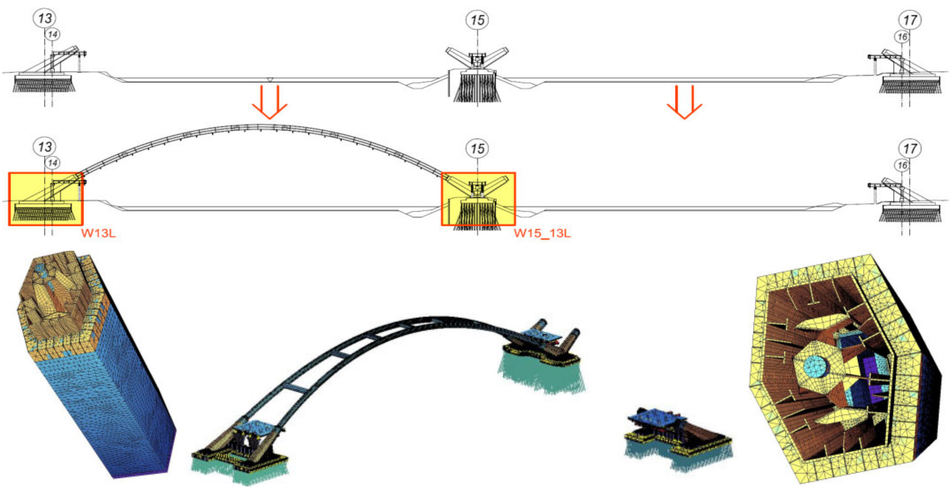


***Fig.*** *7. Chart and visualisation of a global and detailed calculation model for the bridge and head section no. 13 for assembly phase: placing arches of a bay 13-15 on assembly tables.*

***Table 2.*** *Results of stresses σ in the element of assembly table no. 13 for assembly phase: placing of bay arches 13-15 on assembly tables.*

| | VALUES OF INCREMENTS OF STRESSES σ [MPa] W13 MEASURING SECTION _1-1 _ TENON JOINT | | | |
|---|---|---|---|---|
| | **T1/1/W13** | **T2/1/W13** | **T3/1/W13** | **T4/1/W13** |
| Measured | -140,0 | -250,0 | -38,0 | 8,0 |
| Theoretical | -138,0 | -250,2 | -41,1 | 16,6 |
| % | 101 | 100 | 92 | 48 |

***Table 3.*** *Results of stresses σ in steel structure of braced part of head section no. 13 for assembly phase: placing of bay arches 13-15 on assembly tables.*

| | VALUES OF INCREMENTS OF STRESSES σ [MPa] W13_ MEASURING SECTION _2-2 – MEASURING POINTS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **T1/2 /W13** | **T2/2 /W13** | **T3/2 /W13** | **T4/2 /W13** | **T5/2 /W13** | **T6/2 /W13** | **T7/2 /W13** | **T8/2 /W13** | **T9/2 /W13** | **T10/2 /W13** |
| Measured | -6,1 | -3,4 | -5,9 | -9,0 | -10,9 | -11,1 | -8,6 | -4,2 | -0,8 | -1,3 |
| Theoretical | -5,4 | -2,2 | -5,2 | -8,2 | -9,4 | -10,1 | -10,5 | -3,0 | -3,0 | -3,2 |
| % | 113 | 153 | 114 | 110 | 116 | 110 | 82 | 140 | 27 | 41 |
| | **VALUES OF INCREMENTS OF STRESSES σ [MPa] W13_ MEASURING SECTION _3-3** | | | | | | | | | |
| | **T1/3 /W13** | **T2/3 /W13** | **T3/3 /W13** | **T4/3 /W13** | **T5/3 /W13** | **T6/3 /W13** | **T7/3 /W13** | **T8/3 /W13** | **T9/3 /W13** | **T10/3 /W13** |
| Measured | -6,7 | -6,1 | -6,9 | -5,9 | -7,6 | -4,5 | -6,0 | -4,7 | -6,6 | -7,9 |
| Theoretical | -5,6 | -3,5 | -4,7 | -6,1 | -7,0 | -7,2 | -6,9 | -4,0 | -4,0 | 4,4 |
| % | 120 | 174 | 147 | 95 | 109 | 62 | 87 | 118 | 163 | -179 |
| | **VALUES OF INCREMENTS OF STRESSES σ [MPa] W13_ MEASURING SECTION _4-4** | | | | | | | | | |
| | **T1/4 /W13** | **T2/4 /W13** | **T3/4 /W13** | **T4/4 /W13** | **T5/4 /W13** | **T6/4 /W13** | **T7/4 /W13** | **T8/4 /W13** | **T9/4 /W13** | **T10/4 /W13** |
| Measured | -2,4 | -3,9 | -1,3 | -2,4 | -1,4 | -1,2 | -3,2 | -5,0 | -0,9 | -2,6 |
| Theoretical | -5,0 | -4,1 | -4,3 | -4,6 | -5,6 | -5,6 | -5,3 | -4,3 | -4,5 | -4,8 |
| % | 47 | 96 | 31 | 52 | 25 | 21 | 61 | 117 | 19 | 55 |

Representative results for assembly phase: suspension of section JMP6 of the platform of a bay 13-15 (Fig. 8, 9) is presented in Fig. 10, 11 and in Tab. 4.

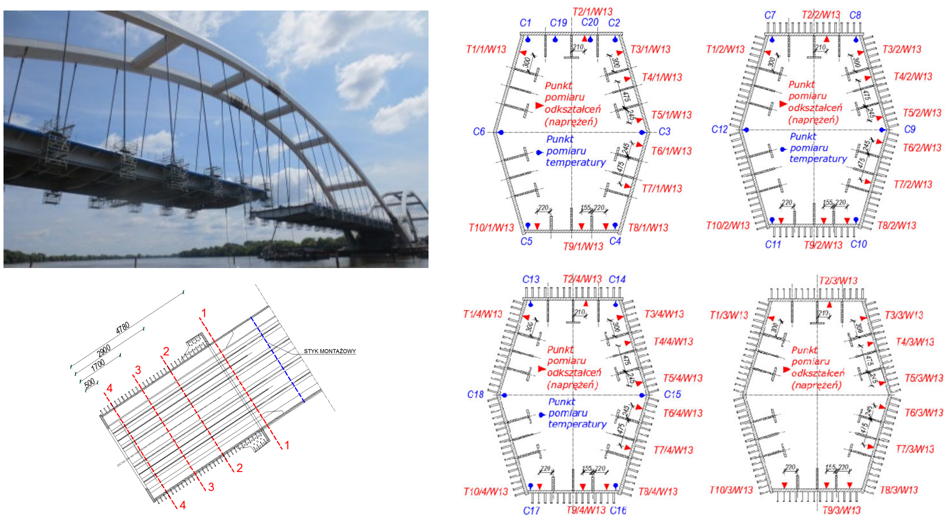


***Fig. 8.*** *General view of the structure after suspension of platform segment JMP6 of a bay 13-15; layout of cross-sections and measuring points of a head section no. 13.*

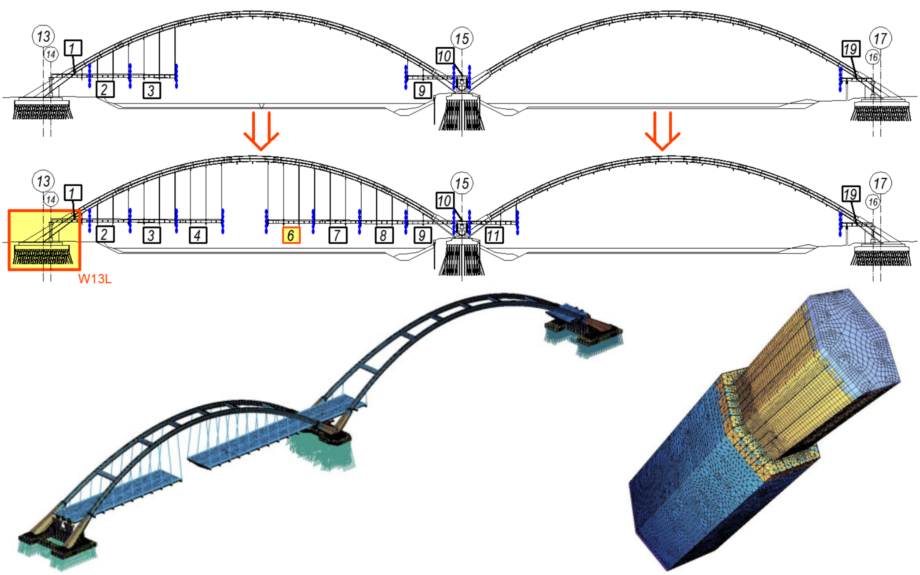


***Fig. 9.*** *Chart and visualisation of a global and detailed calculation model for a bridge and head section no. 13 for the assembly phase: suspension of a platform segment JMP6 of a bay 13-15.*

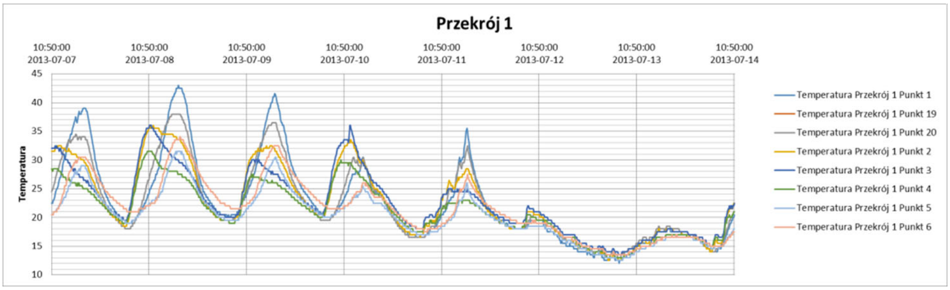


***Fig. 10.*** *Chart of temperature changes within steel structure in a cross-section 1-1 of a head section no. 13 at the assembly phase: suspension and joining with the remaining platform segment JMP6 of a bay 13-15.*

***Table 4.*** *Results of stresses σ w in steel structure of head section no. 13 for the assembly phase: suspension of platform segments JMP6 of a bay 13-15.*

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **VALUES OF STRESS INCREMENTS σ [MPa] W13_MEASURING CROSS-SECTION_1-1** | | | | | | | | | |
| | | **T1/1 /W13** | **T2/1 /W13** | **T3/1 /W13** | **T4/1 /W13** | **T5/1 /W13** | **T6/1 /W13** | **T7/1 /W13** | **T8/1 /W13** | **T9/1 /W13** | **T10/1 /W13** |
| Measured | | -47,0 | -47,3 | -46,5 | -31,9 | -19,0 | -7,6 | 11,1 | 24,5 | 18,4 | 29,2 |
| Theoretical | c.w.+Δt | -43,5 | -50,8 | -48,2 | -33,3 | -17,6 | -6,6 | 11,0 | 32,7 | 31,6 | 37,2 |
| % | c.w.+Δt | 108 | 93 | 97 | 96 | 108 | 115 | 101 | 75 | 58 | 78 |
| | | **VALUES OF STRESS INCREMENTSσ [MPa] W13_MEASURING CROSS-SECTION_2-2** | | | | | | | | | |
| | | **T1/2 /W13** | **T2/2 /W13** | **T3/2 /W13** | **T4/2 /W13** | **T5/2 /W13** | **T6/2 /W13** | **T7/2 /W13** | **T8/2 /W13** | **T9/2 /W13** | **T10/2 /W13** |
| Measured | | -12,7 | -17,8 | -14,3 | -11,5 | -6,3 | -2,2 | 3,1 | 9,0 | 8,5 | 10,7 |
| Theoretical | c.w.+Δt | -13,3 | -18,0 | -14,9 | -12,8 | -6,5 | -2,0 | 3,2 | 9,5 | 10,6 | 10,4 |
| % | c.w.+Δt | 96 | 99 | 96 | 90 | 96 | 106 | 96 | 94 | 80 | 103 |
| | | **VALUES OF STRESS INCREMENTSσ [MPa] W13_MEASURING CROSS-SECTION_3-3** | | | | | | | | | |
| | | **T1/3 /W13** | **T2/3 /W13** | **T3/3 /W13** | **T4/3 /W13** | **T5/3 /W13** | **T6/3 /W13** | **T7/3 /W13** | **T8/3 /W13** | **T9/3 /W13** | **T10/3 /W13** |
| Measured | | -14,5 | -11,2 | -10,3 | -9,5 | -4,0 | -2,1 | 1,5 | 6,6 | 6,1 | 9,1 |
| Theoretical | c.w.+Δt | -12,3 | -16,0 | -14,0 | -11,5 | -6,3 | -2,5 | 2,3 | 7,9 | 7,1 | 8,7 |
| % | c.w.+Δt | 118 | 70 | 74 | 83 | 64 | 85 | 65 | 84 | 85 | 105 |
| | | **VALUES OF STRESS INCREMENTSσ [MPa] W13_MEASURING CROSS-SECTION_4-4** | | | | | | | | | |
| | | **T1/4 /W13** | **T2/4 /W13** | **T3/4 /W13** | **T4/4 /W13** | **T5/4 /W13** | **T6/4 /W13** | **T7/4 /W13** | **T8/4 /W13** | **T9/4 /W13** | **T10/4 /W13** |
| Measured | | -5,8 | -7,6 | -8,3 | -8,6 | -3,8 | -1,6 | 1,4 | 6,4 | 6,1 | 9,5 |
| Theoretical | c.w.+Δt | -11,8 | -14,3 | -12,6 | -10,7 | -5,7 | -2,7 | 2,0 | 6,9 | 7,1 | 7,6 |
| % | c.w.+Δt | 49 | 53 | 66 | 80 | 67 | 58 | 70 | 93 | 86 | 125 |

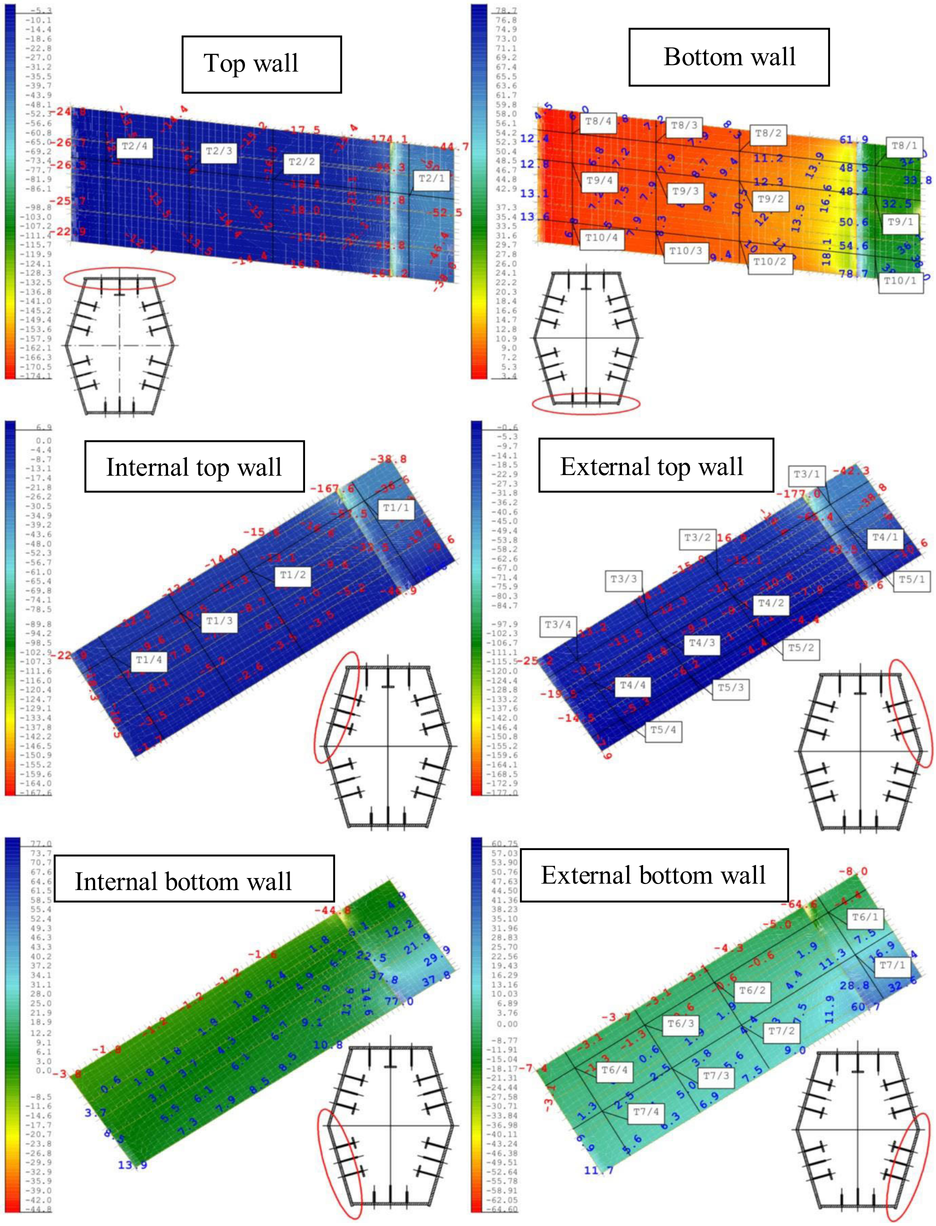


***Fig. 11.*** *Maps of theoretical values of stresses σ [MPa] in a steel part of a head section no. 13 for the assembly phase: suspension of a platform section JMP6 of a bay 13-15(considering the influence of temperature of the structure at the moment of measurement).*

## 5. CONCLUSIONS

The designed, implemented and functional, during whole process of assembly monitoring, system of arch girders turned fit for the purpose. Results of conducted research and analysed numerical calculations (considering temperature of the structure) provided for the possibility of tracing real behaviour of the structure in certain phases of bridge assembly and the assessment of appropriateness and degree of interaction between steel part and reinforced-concrete part in head sections.

Measuring points from monitoring were also used for tests during test loading of a bridge [8,9].

Results of performed tests and numerical calculations confirm the profound sense of simultaneous conduct of in situ tests supported by theoretical apparatus of well-identified parameters of calculation model. Advanced numerical analyses supported by well-scheduled in-situ tests provide for unified identification of behaviour of even the most complicated structures and constitute valuable base of data and experience for architects and contractors of the future non-standard bridges.

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