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EXPERIMENTAL ANALYSIS OF THE RAILWAY TRUSS BRIDGE USING MODERN METHODS

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Abstract. Experimental analyses of civil engineering structures have been carried out for decades. While in the past, mainly static load tests of new structures were performed, a few severe accidents with fatal results caused a lot of emphasis to be given to monitoring existing structures recently. The need for continuous or periodical evaluation of static or dynamic behaviour of structures in operation led to a good progress in the development of modern methods for experimental analysis. The paper deals with one of the modern methods of experimental analysis – the DIC method. Possible application of the DIC method was verified by an experimental analysis of a railway truss bridge in Rataje nad Sázavou. The experiment was divided into two stages. During the experiment, deflections of the bridge measured by LVDT sensors and the DIC method were compared. Technological problems of the DIC method were found in the first stage. One of the problems was related to stability of the camera tripod. A solution was proposed and verified during the second stage.

Keywords: Experimental analysis, digital image correlation, LVDT sensors, railway bridge.

1. Introduction

Experimental analyses of civil engineering structures have been carried out for decades. While in the past, mainly static load tests of new structures were performed, a lot of emphasis has been given to monitoring existing structures recently. By the monitoring is meant continuous or periodical evaluation of static or dynamic behaviour of structures in operation. This is the consequence of a few severe accidents which had fatal results. For example, it is possible to mention the collapse of Morandi Bridge (Italy) with 43 victims in 2018 [1] or the collapse of Nanfang'ao Bridge (Taiwan) with 6 victims in 2019 [2]. However, collapses of civil engineering structures happen in the Czech Republic too. Almost every citizen has heart about the collapse of the pedestrian bridge over Vltava (Trója, Prague, the Czech Republic) in 2017. There were no victims but it has stimulated the discussion on other bridges and pedestrian bridges in a state of disrepair in the Czech Republic.

While the reason of collapses of civil engineering structures usually is a combination of many factors, it is indisputable that the actual condition of many bridges and pedestrian bridges in the Czech Republic is not good. One of the main reasons is neglecting regular maintenance. Since there is not enough financial resources and workers for the immediate repair of all the constructions in unsatisfactory condition, it is necessary to control these constructions regularly. Some of them may need continuous monitoring of construction condition. After that, it is possible to evaluate which construction is in a state of disrepair, and therefore have to be closed and repaired or demolished immediately, and which is possible to operate with restrictions or after small repairs.

Because of the reasons above, good progress has been made in the development of modern methods for experimental analysis and monitoring of civil engineering structures. Focusing on construction (especially bridges and pedestrian bridges) displacements, it is necessary to mention two methods – **terrestrial radar interferometry** and **digital image correlation**. These methods have some advantages compared to classical methods for experimental analysis, such as velocity sensors, acceleration sensors and strain gauges. The main advantage is that the modern methods are non-contact so the experiments can be prepared and held without traffic disruptions which negatively influence its total costs. The next advantage is possibility to monitor parts of constructions which are uneasily accessible. As a counterweight to the benefits, there are disadvantages, such as lower precision, a lack of experience of the experimenters etc.

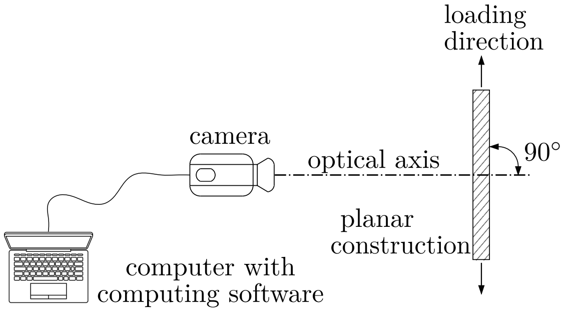
The paper deals with one of the modern methods of experimental analysis – the DIC method. Possible application of the DIC method is verified by the experimental analysis of the railway truss bridge in Rataje nad Sázavou. At the beginning, the DIC method is briefly introduced. It is followed by the description of the experiment which was divided into two stages. Technological problems of the DIC method were found in the first stage. The proposed solution was verified during the second stage. The results of both stages are shown in Section 4. The idea of the future work, such as mathematical model, is given at the end.

1.1. DIGITAL IMAGE CORRELATION

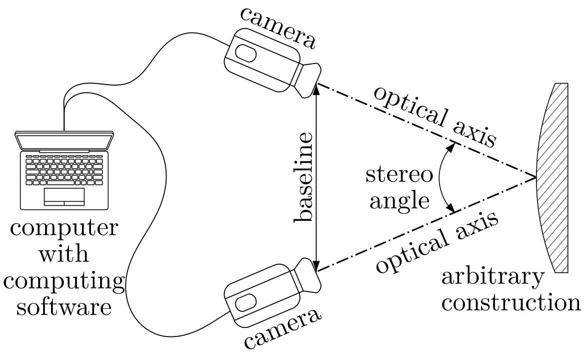
Digital image correlation (DIC) is another modern non-contact method for experimental analysis or long-term monitoring of civil engineering constructions. This optic method is based on the correlation between the digital images performed before, during, and after the construction deformation. The DIC method was used for a displacement and relative displacement analysis of small laboratory samples in the past. Today, with development in technique, it can also be used for monitoring of large civil engineering constructions, such as bridges, building etc.

It is hard to appoint the only inventor of the DIC method. The initial studies which were closely lined to the DIC method can be found mainly in the area of digital photogrammetry. Gilbert Hobrough dedicated to the digital photogrammetry from the beginning of 1950s. But the American researchers, Peters and Ranson, are considered to be the pioneers of the DIC method. Peters and Ranson [3] presented a new technology how to measure deformation of a simple object using the image correlation in 1983. The technology was based on computing solution. The technology was further improved in cooperation with Sutton [4].

The DIC method has gone through great development during the last 40 years. The development was supported by technical advance in the area of cameras and computing systems. The transition from 2D [5] to 3D [6] DIC can be considered one of the main milestones. While the only camera can be used for displacement and relative displacement measurement in a plane parallel to the sensor plane (Figure 1a), it is possible to determine 3D displacement captured by pairs of cameras (Figure 1b). 3D DIC is also necessary to use in the case of construction without flat surface. A higher sampling rate of the cameras enables monitoring of dynamic behaviour of the constructions [7, 8], even during extreme situations, such as earthquakes [9]. In addition, a higher camera resolution enables the more precise measurement and the usage of the construction natural surface instead of artificial speckle patterns. Thanks to increased computer memory and faster calculations, it is possible to monitor extensive areas of interest. The DIC method has the ability to partially substitute visual inspections of the constructions because it is possible to detect concrete spalling [10] or cracks, even the cracks which are not readily seen [11].



(A). 2D DIC.



(B). 3D DIC.

FIGURE 1. Experimental setup and necessary equipment for the DIC method – a camera and a computer with computing software.

The main advantages of the DIC method are non-contact measurement and possibility to measure displacements of more points simultaneously. The non-contact measurement is particularly important for constructions or its parts which are uneasily accessible. On the other hand the constructions has to be clearly visible – there cannot be any barriers between the cameras and tracked points of the construction. It can be problem for monitoring constructions such as bridges with more spans where piers can hide part of the constructions. In addition, the constructions has to be to be made out of material with speckle pattern, such as concrete. In other cases, the speckle pattern has to be sprayed on the constructions or desks with the speckle pattern has to be installed. The great advantage is that the DIC method allows to monitor the whole displacement fields. The field size is limited only by the camera resolution and the computer memory. However, amount of data has to be processed within a reasonable time.

The next important competitive advantage, compared mainly to other modern methods such as radar interferometry, is a lower price. The necessary equipment, on a practical level, is only a camera and a computer with computing software. A type of the camera and, therefore, the price depend on required accuracy. High-speed cameras are used most frequently. But it is possible to use macroscopes and microscopes (electronic, atomic) too. During the experiment, the cameras are taking pictures/video which can help to detect undesirable phenomenons affecting the results (e.q. people passing in front of the camera) or cause of the acquired results (e.q. cracks in the construction). Installation and set-up of the equipment is fast and easy. B. Pan et al. [5] mention a comparison of the DIC method with interferometric optical methods in their work.

Figure 2. The historical railway bridge in Rataje nad Sázavou. The photo was taken during the second stage of the experiment.

2. Description of the bridge

A historical steel railway bridge in Rataje nad Sázavou is a part of railway line called “Posázavský Pacifik”. The railway line No. 212 runs from Čerčany to Světlá nad Sázavou. On the way to Čerčany, there is a tunnel in close proximity to the bridge. On the other side of the bridge, there is a branch line No. 14 running to Kolín. The bridge crosses river Sázava and a private road. Figure 2 shows photo of the bridge taken in 2022.

The bridge was build at the beginning of 20th century. The supplier of the steel construction was První Českomoravská továrna na stroje in Libeň. The abutments and the bridge completion in situ was done by the firm owned by Ing. Osvald Životský. This firm was in charge of the whole railway line. A load test of the bridge was performed on 29th of June 1901 [12]. In the same year, the railway line was put in operation. But the whole railway line was completed as late as 1903. The bridge was restored and renovated twice, in 1961 and 2021.

It is a riveted truss bridge with the only span which is 72.0 m long. The clear perpendicular distance between abutments is 70.0 m. The total length of the bridge is 86.2 m. The load-bearing superstructure is composed of two trusses with parabolic upper chords. The roadbed is carried at the bottom of the trusses. The width of the load-bearing structure is 5.23 m. The width of the free space for passing train is 4.12 m. The height of the superstructure is 0.88 m. The clear height of the bridge is 4.12 m. The railway line and the bridge are straight.

It was said above that the span of two main trusses is 72.0 m long. The trusses are 4.65 m apart. The height of the trusses is variable because of the parabolic upper chords. Each truss consists of upper chord, bottom chord, verticals (struts) and diagonals. The elements are connected in joints. The upper chords are composed of 2 webs, 1–3 flanges and angles riveted together. The bottom chords are composed of 2 webs, 0–5 flanges and angles riveted together. The verticals above the abutments consist of 12 angles a 3 sheet metals riveted together. All the other verticals consist of 4 angles. Diagonals consist of 4 sheet metals or 4 angles. The stiffeners between the bottom chord are made of steel sections U200. The stiffeners between the upper chords consist of lattice girders and upper frame stiffeners.

The roadbed is on wooden crossbeams which lay on two stringers. The stringers are 1.80 m apart. The stringers are welded from sheet metals to form ’I’ shape. The height of the stringers is 500 mm except the stringers in panel 1–3 and 10 which are higher (580–630 mm). Floor beams are riveted to form ’I’ shape. There are 6 different cross sections of the floor beams. The floor beams height vary 720–724 mm. There are the stiffeners U140 between the stringers.

The horizontal load-bearing structure is supported on the abutments by bearings from steel and cast iron elements. The stone masonry abutment are made of blocks of the same size. The wing walls are parallel. The wing walls and adjacent slopes are also made of blocks of the same size.

The description of the bridge mentioned above corresponds to the current conditions and therefore to the second stage of the experiment. The first stage was realized before the last renovation so there were some differences in components. The stringers were riveted from web, flange and 4 angles to form asymmetrical ’I’ shape. The height of the stringers was 560 mm. The stiffeners between the stringers consisted of lattice girders. Also the stiffeners between the bottom chord differed from the current conditions. It consisted of 2 angles.

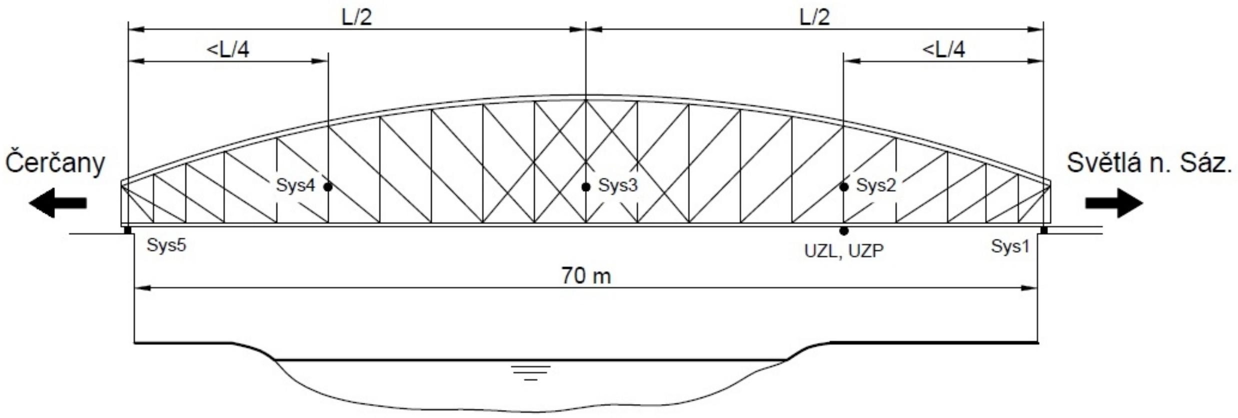


Figure 3. Cross section of the bridge in Rataje nad Sázavou. Deflections of points UZL, UZP were measured by the standard method of experimental analysis – the LVDT sensors. Displacements of points Sys2, Sys3 and Sys4 were measured by the modern method of experimental analysis – the DIC.

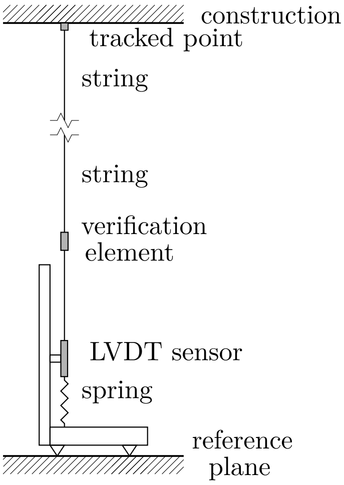


Figure 4. The scheme of the measuring system – the steel string, the verification element, the core of LVDT sensor. The figure has been taken over with minor changes from [13].

Figure 5. The real photo of the measuring system.

3. Equipment and experimental setup

The experiment was divided into two stages. The first stage took place in July 2021. The second stage was planned almost one year later – in June 2022. Because of the possible comparison, the aim was the same experimental setup in both stages. But problems in the first stage resulted in some differences which are described below.

3.1. Standard method of experimental analysis

LVDT sensors were used to measure deflections of the bridge by standard method of experimental analysis. The sensors measured deflections in two points of the bridge. Figure 3 shows scheme of the tracked points and how it is marked (UZL,UZP). Both points measured by the LVDT sensors were placed in the same cross section of the bridge (≈ 1/4 of the bridge span). The point UZL was placed on the bottom chord of the left main truss. The point UZP was placed on the bottom chord of the right main truss.

The LVDT sensors ISDL 50-KD-2405 (Inelta Sensorsysteme, Germany) were used for the experiment. Serial numbers of the sensors were 84801 and 84803. Steel frames with the fixed LVDT sensors were placed in reference points under the bridge. Cores of the sensors were attached to verification elements which were connected to the tracked points by steel string. Figure 4 shows scheme of the measuring system and Figure 5 shows photo of the real measuring system used in the experiment. The measuring system, the steel string – the verification element – the core of the LVDT sensor, were prestressed by steel spring fixed to the other side of the steel frame. The LVDT sensors were connected to data acquisition system EMS Pohl. Before start of the measurement, adjusted sensitivity

Figure 6. The desks with artificial speckle pattern were used to the achieve exact location of the tracked points.

of the used LVDT sensors was verified by simulating deflection of 10 mm realized by verification element.

3.2. Digital image correlation

The DIC method was used to measure deflection of the bridge by modern method of experimental analysis. Three points, which were placed on verticals of the right main truss, were tracked by the DIC method in the first stage. Figure 3 shows that the tracked point were placed in ≈ 1/4, 1/2 and 3/4 of the bridge span. Desks with artificial speckle pattern were used to achieve the exact location of the tracked points. Figure 6 shows that the desks were attached to the verticals by clamps. The distance between the tracked points and the cameras was: Sys2 ≈ 15 m, Sys3 ≈ 30 m, and Sys4 ≈ 45 m.

Three cameras Basler acA4096-30um USB 3.0 (8.9 MP; 32 fps) were used for the experiment in the first stage. The cameras were equipped with different cameras lens: Sys2 – f = 50 mm; Sys3 – f = 75 mm, and Sys4 – f = 75 mm. The cameras were attached to two tripods 475 Pro Geared Tripod and connected to a notebook by USB 3.0 cables. Figure 7 shows the whole measuring system of the DIC method. Software VIC-Snap – Correlated Solution was used for measuring and synchronization of the data. Subsequently, software VID-2D – Correlated Solution was used for the data evaluation. Three floodlights AKU PARKSIDE served to lighting the desks during reduced visibility, especially at night.

There were problems with stability of the tripods, particularly the tripod carrying the camera tracking point Sys2, in the first stage of the experiment. Because of that problems, five cameras were used in the second stage. Two additional cameras were aimed at two points located on the abutments – Sys1 and Sys5 (Figure 3). It was supposed that these points were fixed and there should not have been any measurable displacements. The cameras were equipped with different cameras lens: Sys1 – f = 50 mm; Sys2 – f = 50 mm; Sys3 – f = 50 mm, Sys4 – f = 75 mm, and Sys5 – f = 75 mm. All the cameras were attached to only tripod. Figure 8 shows the whole measuring system in the second stage.

Figure 7. The measuring system of the DIC method in the first stage of the experiment.

Figure 8. The measuring system of the DIC method in the second stage of the experiment.

3.3. Additional equipment

To consider the influence of temperature on quasi-static deflection of the bridge, it was important to record temperature of the construction and the air. A temperature sensor T1 was placed on the bottom chord of left main truss and it measured temperature of the construction near the point tracked by the LVDT sensor. A temperature sensor STV was placed under the bridge near a table with the notebook and the data acquisition system EMS Pohl. The sensor

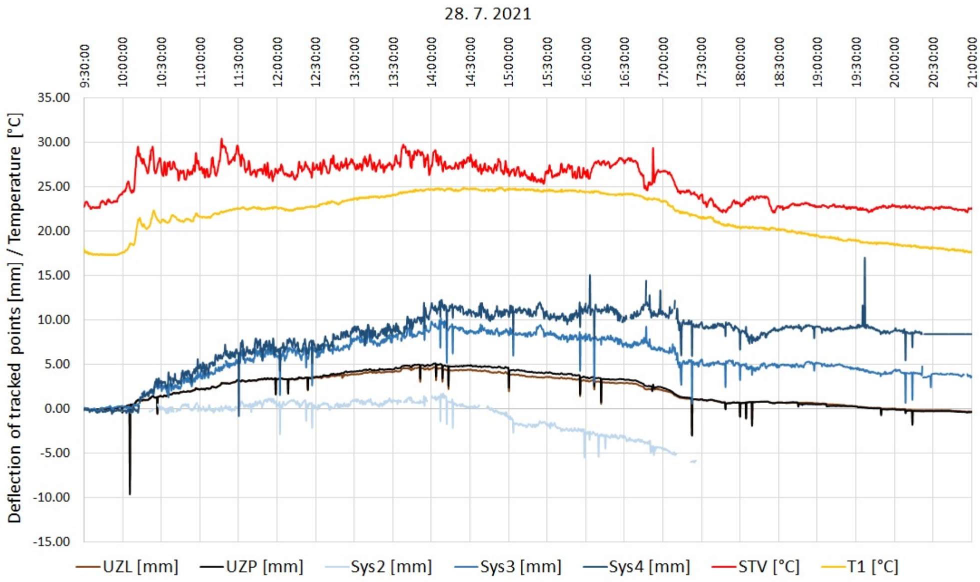


FIGURE 9. Influence of temperature changes on deflections of the tracked points during the first stage of the experiment. Deflections of points UZL, UZP were measured by the LVDT sensors. Deflections of points Sys2, Sys3, and Sys4 were measured by the DIC method. Temperature T1 responds temperature of the construction near the point tracked by the LVDT sensor. Temperature STV responds temperature of the air.

STV measured temperature of the air. In the second stage of the experiment both sensors T1 and T2 measured temperature of the air.

During both stages of the experiment, next classical and modern methods for experimental analysis were used. High sensitive piezometric accelerometers served to an experimental modal analysis of the bridge. The modern method of radar interferometry measured quasi-static and dynamic response of the bridge. These methods are not described in the paper because the results has not been available until that time. Both methods were also used during our last experiment [14].

4. RESULTS

4.1. FIRST STAGE OF THE EXPERIMENT (2021)

The first stage of the experiment took place in July 2021. It was mostly sunny during the experiment. The LVTD sensors measured the deflections of two points (UZL, UZP) located on the bottom chord of the main trusses. The measurement performed by the LVDT sensor lasted almost 24 hours – from 28th of July 2021 8:22 to 29th of July 2021 7:57. Sampling rate of the sensors was 50 Hz. The deflections of three points (Sys2, Sys3 and Sys4) located on the verticals of the right main truss were measured by the DIC method. The measurement performed by the DIC method lasted from 28th of July 2021 8:22 to 28th of July 2021 21:26. Sampling rate of the cameras was 10× lower that the sampling rate of the LVDT sensors, i.e. 5 Hz.

Figure 9 shows influence of temperature changes on deflections of the tracked points. The figure shows a part of the experiment from 28th of July 9:30 to 28th of July 21:00 when both methods were in operation. It can be seen that the temperature changes had an effect on deflections of the lower chords and the verticals of the main trusses. Compared to initial time 9:30 ($u_{9:30} = 0$), the upward deflection of points UZL, UZP, Sys3, and Sys4 was dominant. It was most likely caused by different temperatures of the bottom and the upper chords of the main trusses. During a daytime the upper chords are more exposed to the sun than the lower chords that results in higher temperature.

The different behaviour of point Sys2 and visual observation of the DIC equipment during the experiment confirmed concerns about external factor affecting the results. Uneven settlement of feet of the tripod carrying the camera tracking point Sys2 was observed. It resulted in inclining of the camera and consequently the incorrect results. The solution of this problem was proposed and verified during the second stage.

Figure 9 also shows dynamic behaviour of the bridge. While the significant deflection of points UZL and UZP measured by LVDT sensors were downward, which responds to passing trains, some significant deflections of points Sys2 and Sys 3 measure by the DIC method were upwards. It can be seen from 16:00 to 17:00 and at 19:37. It is assumed that it was most likely caused by manipulation with the cameras, for example during setting up aperture. This can be another problem of the DIC method during long-term measurement.

4.2. SECOND STAGE OF THE EXPERIMENT (2022)

The second stage of the experiment took place in June 2022. It was cloudy with occasional heavy rains

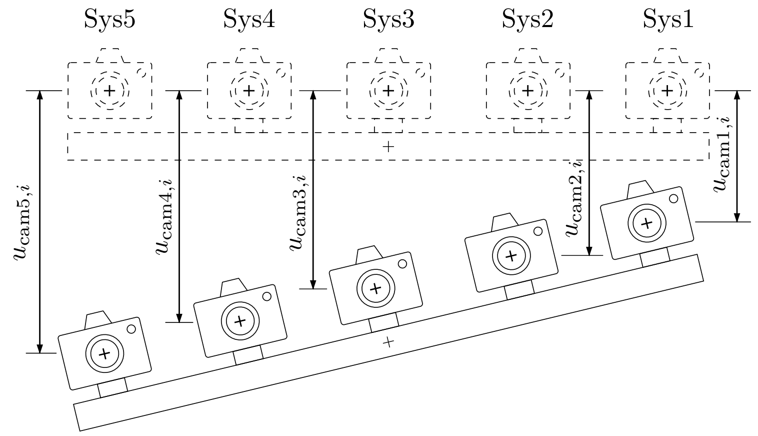


Figure 10. The simplified scheme showing 2D movement of cameras without rotation caused by uneven settlement of tripod feet. The vertical movement ($u_{\mathrm{cam}2,i}$;$u_{\mathrm{cam}3,i}$;$u_{\mathrm{cam}4,i}$) can be calculated and used for the correction of results.

and thunderstorms. As in the first stage, the LVTD sensors measured the deflections of two points (UZL, UZP) located on the bottom chord of the main trusses. The measurement performed by the LVDT sensor lasted more than 24 hours – from 28th of June 2022 18:58 to 29th of June 2022 20:28. Sampling rate of the sensors was 50 Hz. The deflections of three points (Sys2, Sys3 and Sys4) located on the verticals of the right main truss were measured by the DIC method. Additional two points (Sys1 and Sys5) located on the abutments were also measured by the DIC method. The measurement performed by the DIC method lasted from 28th of June 2021 21:20 to 29th of June 2022 15:48. Sampling rate of the cameras was lower than in the first stage, i.e. 0.1 Hz. The lower sampling rate and the shorter period of measurement was chosen with regard to large amount of data to process. The remaining time of the experiment was used to measure the bridge response to passing trains. For this purpose, the sampling rate of the cameras was higher, i.e. 10 Hz.

The uneven settlement of the tripod feet was observed during the first stage. It resulted in observable inclining of the camera tracking point Sys2 and consequently the incorrect result. The proposed solutions was to measure two additional points (Sys1 and Sys5) which were located on the abutments, and therefore these points were considered to be fixed. The measured displacement of these points was not largely real and was caused by movement and rotation of the cameras. The displacement could be used for correction of the results. A method of correction is explained by simplified 2D scheme in Figure 10 and Equations (1) and (2).

$$\begin{aligned}
u_{\mathrm{cam}2,i} &= u_{\mathrm{cam}1,i} + \{(u_{\mathrm{cam}5,i} - u_{\mathrm{cam}1,i})) * \frac{1}{4}\} \\
u_{\mathrm{cam}3,i} &= u_{\mathrm{cam}1,i} + \{(u_{\mathrm{cam}5,i} - u_{\mathrm{cam}1,i})) * \frac{2}{4}\} \\
u_{\mathrm{cam}4,i} &= u_{\mathrm{cam}1,i} + \{(u_{\mathrm{cam}5,i} - u_{\mathrm{cam}1,i})) * \frac{3}{4}\} \qquad (1)
\end{aligned}$$

$$\begin{aligned}
u_{2,i,\mathrm{corr}} &= u_{2,i} - u_{\mathrm{cam}2,i} \\
u_{3,i,\mathrm{corr}} &= u_{3,i} - u_{\mathrm{cam}3,i} \\
u_{4,i,\mathrm{corr}} &= u_{4,i} - u_{\mathrm{cam}4,i} \qquad (2)
\end{aligned}$$

In Equation (1) $u_{\mathrm{cam}1,i}$ and $u_{\mathrm{cam}5,i}$ are measured displacements of points Sys1 and Sys5. These points are supposed to be fixed and therefore in the simplified situation (2D movement of the cameras without rotation) the displacements should correspond to vertical movement of cameras caused by uneven settlement of tripod feet. In Equation (2) $u_{2,i}$, $u_{3,i}$ and $u_{4,i}$ are measured deflections of points Sys2, Sys3 and Sys4. $u_{2,i,\mathrm{corr}}$, $u_{3,i,\mathrm{corr}}$ and $u_{4,i,\mathrm{corr}}$ are corrected results involving the influence of uneven settlement of tripod feet. Equation (1) can also be used for more complex situations (3D movement and rotation of the cameras) if all the tracked points are located in one line. During the experiment, it was taken advantage of this fact.

Figure 11 shows the influence of temperature changes on deflections of the tracked points during the second stage of the experiment. The picture shows the part of the experiment from 28th of June 22:00 to 29th of June 8:00 when both methods were in operation. There are a lot of gaps in measurement by the DIC method from 8:00 to 15:48 caused by lack of free disk space, changing weather conditions etc. so the results are not presented here. Unfortunately, during the 10-hour period showed in Figure 11 there were not significant changes in temperature. What is more important, Figure 11 shows a difference between the original (Sys2, Sys3 and Sys4) and the corrected results (Sys2_corr, Sys3_corr and Sys4_corr), or deflections, acquired by the DIC method. It can be seen that the difference between the original deflections measured by the DIC method and deflections measured by the LVDT sensor is increasing over time. This trend is not observable for corrected results. On the other hand, Figure 12 shows that the points which were supposed to be fixed (Sys1 and Sys5) also vibrated. Strong vibration of point Sys5 can be seen

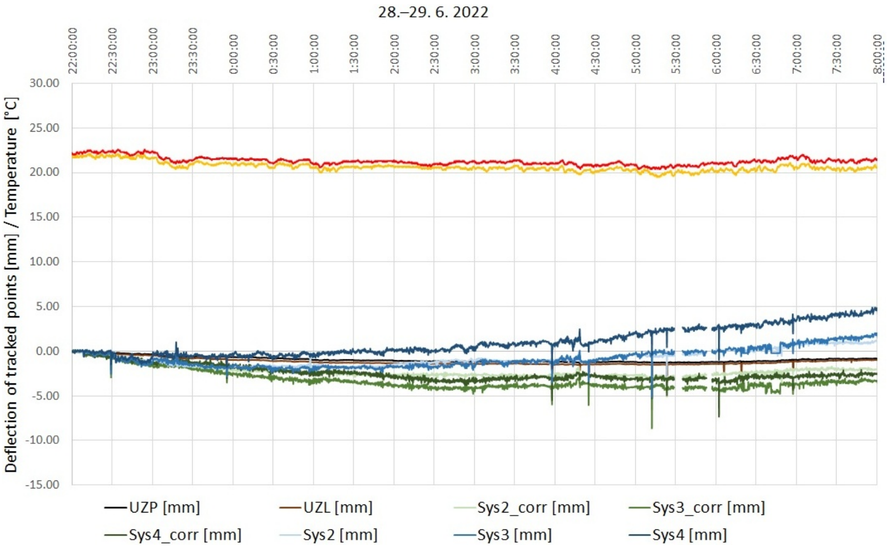


FIGURE 11. Influence of temperature changes on deflections of the tracked points during the second stage of the experiment. Deflections of points UZL, UZP were measured by the LVDT sensors. Deflections of points Sys2, Sys3, and Sys4 were measured by the DIC method. The corrected results Sys1_corr, Sys2_corr and Sys3_corr involve influence of uneven settlement of the tripod feet.

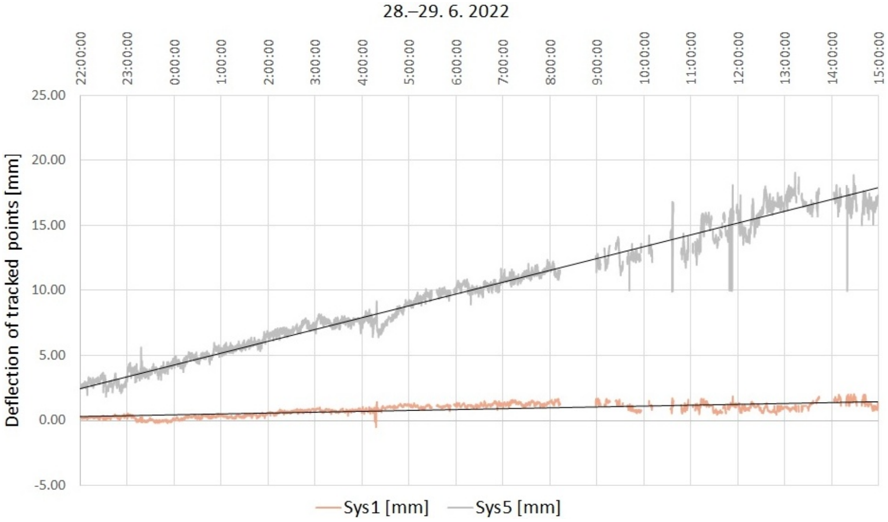


FIGURE 12. Measured displacement of points Sys1 and Sys5 which were supposed to be fixed. The black lines are linear trend lines. Strong vibrations of point Sys5 can be seen from 9:00. The vibrations were likely caused by multiple reasons – passing trains, diffraction of light, air shimmering etc.

from 9:00. The vibrations can be caused by multiple reason – passing trains, diffraction of light, air shimmering etc. This fact stimulates a discussion whether the position and fixation of these points was chosen right.

5. CONCLUSIONS

The experimental analysis of the railway truss bridge in Rataje nad Sázavou was carried out in 2021 and 2022. Apart from classical methods of experimental analysis (LVDT sensors), one of modern methods (the DIC method) was also used.

During the first stage of the experiment, it was observed by both methods that the temperature changes had an effect on deflections of the lower chords and the verticals of the main trusses. Since the DIC method has been used for experimental analysis in field only several times, problems were expected. One of the found problems was uneven settlement of the tripod feet. The solution of this problem was proposed. The other problem was necessary manipulation with the cameras (setting up aperture) which caused false upward deflections.

During the second stage of the experiment, the proposed solution of uneven settlement of the tripod feet was verified. The results showed that the difference between the original deflections measured by the DIC method and the deflections measured by the LVDT sensor had been increasing over time. This trend was not observable for the corrected results. Unfortunately, the fixed points (particularly further point Sys5) whose measuring was necessary for the correction of results also vibrated. The vibrations were greater during a day while there were changing weather conditions, passing trains over the bridge and other negative effects. This fact stimulates a discussion whether the position and fixation of these points was chosen right. It would be likely better to choose points outside the bridge construction which are closer to the cameras than point Sys5. On the other hand, the locations of the points in one line enabled to use simplified situation (2D movement of cameras without rotation) and the related equations. Evaluation of the corrections for complex situation (3D movement and rotation of the cameras) would be more difficult.

To sum up, there are still problems with long-term monitoring by the DIC method which are necessary to deal with. We would like to readjust and verify the solution of uneven settlement of tripod feet during next experiments. The problem of necessary manipulation with the cameras during long-term experiments has also to be solved.

We would like to aim our future work at a dynamic response of the bridge. For this purpose, a mathematical model of the bridge will be made. Results measured by the DIC method, the LVDT sensors and high sensitive piezoelectric accelerometers will be compared to results calculated from the mathematical model.

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