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Analysis of Displacements and Deformations of a Steel Footbridge

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Abstract. In in-service structural diagnostics, besides the monitoring of changes in physical properties of materials, it is essential to determine the dimensional stability of the structure as a whole. This is particularly important in the case of non-building structures exposed to variable and dynamic loading, such as overhead cranes, bridges, flyovers, telecommunications towers etc. Moreover, precise determination of the extent of deformation of structural elements allows for quick identification of any weak points or damaged areas which need to be further tested and assessed. The object of the analysis carried out in this article is a steel footbridge over the Brda River in Bydgoszcz. The main part of the structure stretching between the river banks comprises nine pin-jointed bridge decks suspended on pylons using steel cable stays. The jointed bridge decks make up the top slab. The structural design of the footbridge is simple and clear. The footbridge is rather susceptible to static loading and dynamic ambient excitations.

The research involved displacement and strain gauge measurements of the footbridge subjected to a test load. The test loading was applied by moving a loaded hand truck along the centre line of the footbridge deck and stopping it at predefined locations on deck segments. Vertical displacements were measured for each load setting at selected specific points of the bridge and the strain of the cable stays was determined on the basis of the measured values of the displacement. Precise surveying technology was applied to measure the vertical displacement, enabling the location of control points with an accuracy of 0.25mm in three dimensions, whereas deformations and strains were determined using strain gauges. This article also includes an account of changes in the geometric features of the footbridge resulting from its long-term use. A simplified static load analysis of the load-bearing system of the footbridge was performed (2D model) with simulated test loads. The loads applied in the FEM model were equivalent to the load values determined through geodetic measurements. The developed model was then used to identify a displacement of control points. A comparison of the measurement results with the results of the numerical analysis revealed inconsistencies, both as regards vertical displacements of footbridge deck segments and cable stay strains. An attempt was made in the article to explain the differences.

1. Introduction

Structures must be inspected for their technical condition on a periodic basis. In structural diagnostics, apart from testing changes in physical properties of materials, it is essential to determine the dimensional stability of the structure as a whole. This is particularly important for buildings exposed to variable and dynamic loading (overhead cranes, bridges, flyovers, telecommunications towers, high buildings, etc.) [1].



Complete, precise and clear determination of the technical condition of the structure requires a number of tests and analyses to be performed, and this may be a difficult and complex task. [2, 3]. One of relatively simple tests, which can support assessment of the technical condition of the structure, are measurements of displacements based on geodetic techniques. A possibility to compare a structural displacement with results of other tests (e.g. with deformations determined with tensometric measurements) and numerical simulations is also valuable. The right interpretation of results and translation of the same into an assessment of the technical condition require proper engineering knowledge combined with information on the actual structural movement.

The geometry, displacements and deformations of structural components can be tested with precise optical devices combining laser scanning systems with photogrammetric image processing. This technique is commonly used today, both in metrological industrial measurement [4, 5], survey and monitoring of structures [5, 6, 7, 8].

As part of the tests, a trial load of the footbridge was applied along with geodetic and tensometric measurements. A simplified static analysis of the footbridge structure (2D model) was also carried out to simulate individual settings of the trial load. The scheme of loads taken in the FEM model was equivalent to the trial loads applied during the geodetic measurements. On the basis of that model, displacements of control points and forces in cable stays of the footbridge structure were determined. A comparison of the measurement results with the results of the numerical analysis revealed inconsistencies, both as regards vertical displacements of footbridge deck segments and cable stay strains. An attempt was made in the article to explain the differences.

2. Tested object characteristics

The tested object is a steel footbridge over the Brda River. It is an object of a suspended (cable stay) structure comprising three spans of the following lengths: 8.00 m + 50.0 m + 8.0 m. The extreme spans are designed as spans freely supported by reinforced concrete supports. The central span consists of eight segments, each 5.5 m long, and one central segment of 6 m in length. The segments are connected with joints and suspended on cable stays attached to the pylon tops. An expansion joint that allows for longitudinal movement has been provided between the central segment and the right-bank pre-central segment. Steel pylons are inclined toward the central span at an angle of approx. 65° from the horizontal plane and supported by intermediate supports using joints, whereas their heads are connected with extreme supports using stays. Total deck width is equal to 4.10 m and the width between handrails is equal to 3.40 m.

The footbridge was commissioned in 1979. Unfortunately, no archival documentation from that period has been preserved. In 1992, the technical condition of the footbridge was surveyed. Conclusions and final recommendations suggested that the longitudinal profile of the footbridge be corrected by shortening the cable stays, etc. Cable stay adjustment was performed between July and September 1994. Following this, precision levelling of the footbridge longitudinal profile was performed. In 2017, the footbridge profile was measured again [9]. Eventually, research material has been obtained covering results of the following measurements:

- designed condition of the footbridge (by estimation),
- condition of the footbridge before the renovation of 1992-94,
- condition of the footbridge after the renovation combined with adjustment of the geometry of its deck,
- current condition of the footbridge.

In 2017, the authors of this paper also performed measurements of vertical displacements of the deck and strains in the footbridge cable stays. At the same time, a structural model was developed using the finite element method [10].

3. Change of the footbridge geometry in the operation period

On 12.10.2017, elevation measurements of the footbridge were performed with the trigonometric method and using the TDRA6000 laser station from Leica. The device provides accurate measurement to 1.5" RRR prism that allows for determination of vertical displacements with an average measurement error of 0.2 mm [4]. Controlled points, according to the existing technical documentation, were arranged at the outer edges of the footbridge spans, above cable stay fixing points (figure 1).

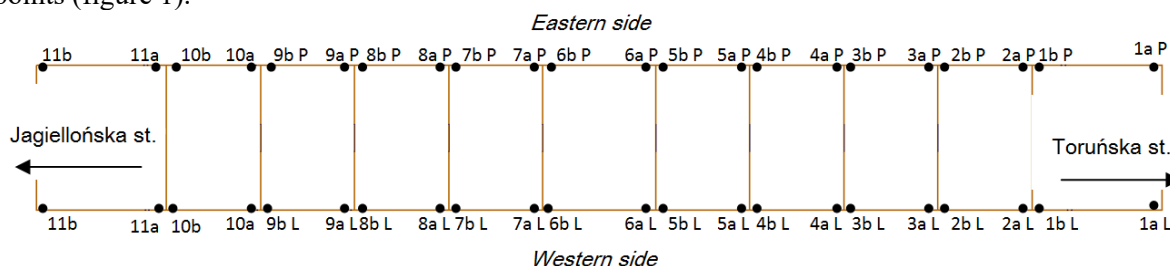


Figure 1. Layout of control point arrangement during levelling measurements [10]

The control network was referred to the benchmark located in the vicinity of point 11bP. For the purpose of analyses carried out in this article, values of theoretical ordinates of the control points (elevation above chords connecting abutments of the footbridge) were calculated, and then the differences between measured ordinates and theoretical ordinates were calculated. The analysis was performed for three measurement sessions of: 09.07.1994 (measurement 1) – before cable stay adjustment, 03.09.1994 (measurement 2) – after cable stay adjustment, and 12.10.2017 (measurement 3) – after 23 years of operation. Differences of ordinates measured between measurements 2 and 3 were also calculated. Values of the differences are shown in table 1. Their graphical representation is presented in figure 2, 3 and 4.

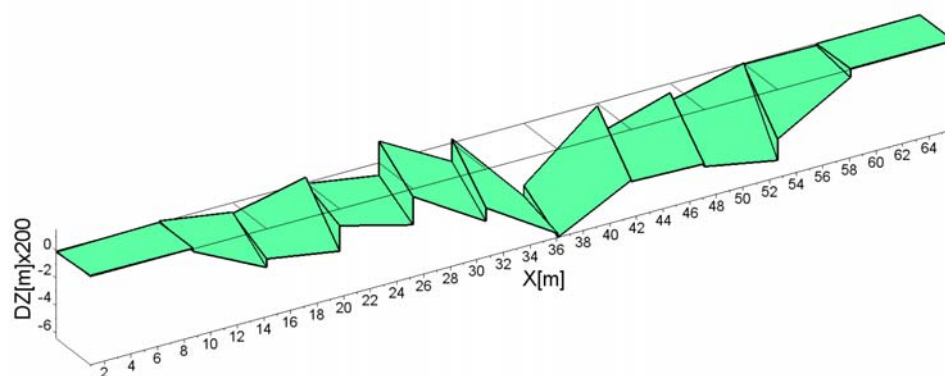
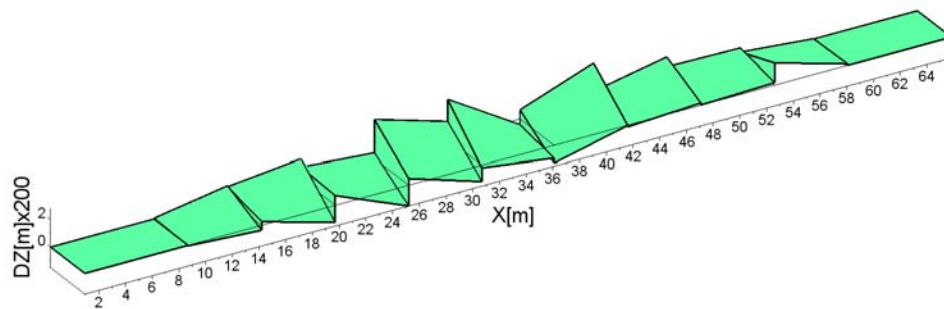


Figure 2. Graphical representation of differences between the measured ordinates and the theoretical ordinates for measurement 1 [11].

Table 1. Differences between the ordinates [11]

Point No.	Differences between the measured ordinates and the theoretical ordinates [mm]				Differences of ordinates measured between measurements 2 (03.09.1994) and 3 (12.10.2017) [mm]	
	Measurement 1 – 09.07.1994		Measurement 2 – 03.09.1994			
	L	P	L	P	L	P
01a	-	-	-	-	-1.9	0.3
01b	-	-	-	-	0.1	0.0
02a	0.0	0.0	0.0	0.0	-1.5	-4.2
02b	-4.2	-12.8	4.3	-1.6	-1.7	-3.7
03a	-4.6	-9.6	3.9	1.5	-1.7	-3.1
03b	1.5	-13.6	6.8	-5.8	-4.7	-5.9
04a	-0.9	-4.4	3.8	3.9	-2.8	-5.9
04b	-4.9	-11.8	1.7	-7.9	-7.2	-7.7
05a	7.5	-1.6	13.8	2.0	-3.1	-10.3
05b	-6.9	-17.3	5.9	-6.2	-5.0	-5.0
06a	1.5	-12.4	14.0	-1.2	-7.1	-1.8
06b	-26.4	-28.4	-2.3	-4.7	-16.1	-7.6
07a	-22.5	-29.8	3.1	-6.5	-15.3	-10.5
07b	-0.5	-15.8	12.9	0.0	-13.1	-11.8
08a	-11.0	-16.3	2.6	-0.5	-13.6	-11.3
08b	-2.9	-17.7	8.0	0.1	-9.8	-7.0
09a	-5.8	-18.6	4.4	-0.6	-10.7	-6.9
09b	0.8	-23.2	4.0	0.3	-7.4	-4.1
10a	0.4	-15.5	2.6	7.6	-7.4	-4.1
10b	0.0	0.0	0.0	0.0	-8.4	-3.5
11a	-	-	-	-	-2.1	2.9
11b	-	-	-	-	0.3	2.4

**Figure 3.** Graphical representation of differences between the measured ordinates and the theoretical ordinates for measurement 2 [11].

Values of ordinate differences for measurement 1 showed that there are divergences relative to the geometry assumed to be theoretical. Therefore, the bridge geometry was corrected after this measurement (cable stay length adjustment, and a control measurement 2 was performed after the correction. The analysis of ordinate differences for measurement 2 shows significant improvement in the bridge geometry after its correction. It is notable that the correction of the geometry in points with significant divergence from the theoretical geometry negatively affected neighbouring points. However, values of these differences are visibly lower from those from before the correction.

The bridge geometry had not been tested between measurement 2 and 3 (a period of 23 years). In order to check how the bridge geometry had changed during these years, a difference between the measured ordinates was calculated. A graphical representation of the change in ordinates measured in measurements 2 and 3 was shown in figure 4.

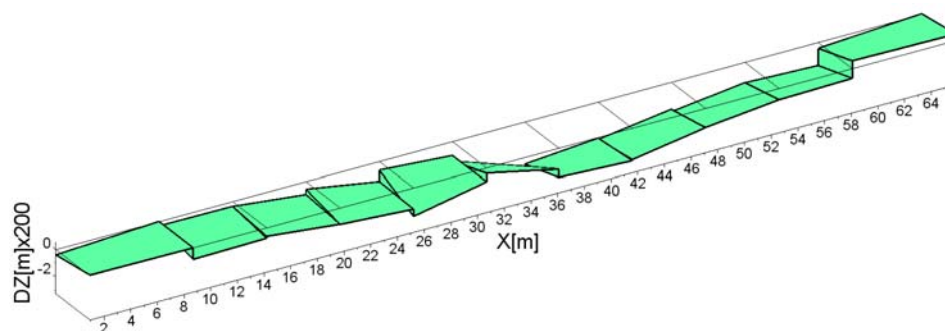


Figure 4. Graphical representation of the difference between ordinates measured in measurement 2 and 3 [11]

Values of the differences obtained are half as big as those during the initial period of operation (the years 1979-1992). Maximum permanent displacements of the suspended footbridge from its erection (1979) to the renovation and adjustment (1994), i.e. in the period of 15 years, were approx. 30 mm (without considering unknown workmanship errors). Maximum permanent displacements from the adjustment of the footbridge to 2017 (the period of 23 years) were approx. 15 mm. This indicates that the greatest displacements occurred in the first years of operation.

4. Vertical displacements of the footbridge on the basis of measurements and a model analysis

Measurements of vertical displacements of the footbridge for eight trial load settings were carried out in the research. A load of 1600 kg was applied statically to the footbridge axis in connection points of its segments. The measurements were performed with the trigonometric method from two stands located on both abutments, using the TDRA6000 laser station from Leica. Figure 5 presents load application points (from A to H) and control points of the left (L) and right (P) footbridge section.

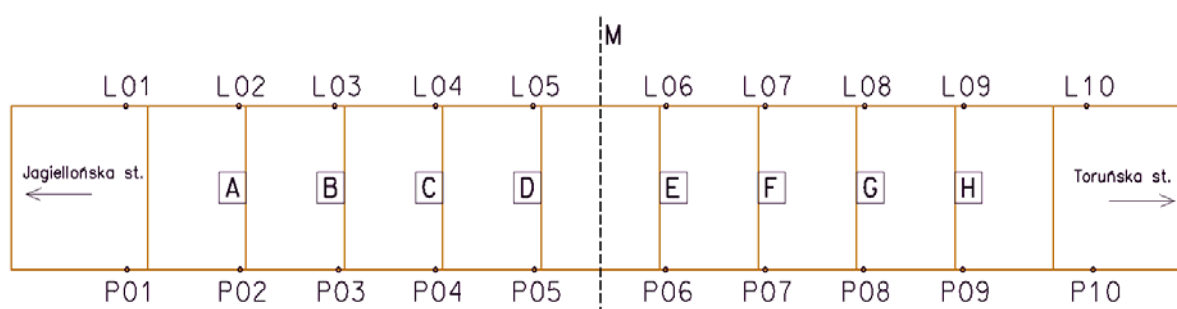


Figure 5. Layout of control point and trial load application point arrangement [10]

The values of footbridge axis displacements (average from measurements L and P) for individual cross sections were taken into account in the analysis. The symmetry of displacements relative to the M plane (figure 5) was examined. Displacements of the control points under loading is shown in charts (figure 6).

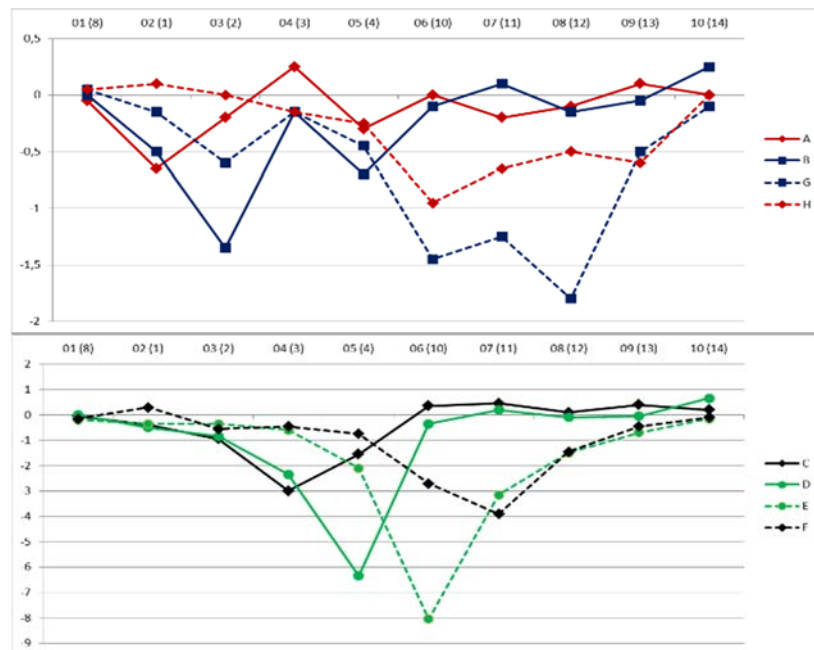


Figure 6. Displacements along the footbridge axis [10]

Charts of the same colour should be symmetric to each other, e.g. the chart for load A (continuous red) should be symmetric to the chart for load H (dashed red), etc. In fact, the expected symmetry is not observed. One may notice, however, that values of displacements of the footbridge loaded from Toruńska street (E÷H load schemes) are higher than values of displacements due to its loading from Jagiellońska street (A÷D load schemes).

Another stage of the test was to develop a structure model using the finite element method. Due to the symmetry of the object, a flat numerical model was applied covering half of the structure. On the basis of this model, displacements of the control points were determined. The load schemes taken in the FEM model were equivalent to the trial loads applied during the geodetic measurements. The footbridge model and a sample layout of displacements are shown in figure 7. Results obtained from numerical calculations were compared with results of the geodetic measurement. Results of displacements of the control points are shown in table 2.

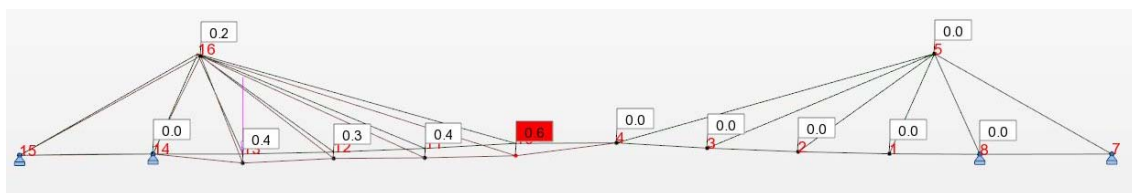
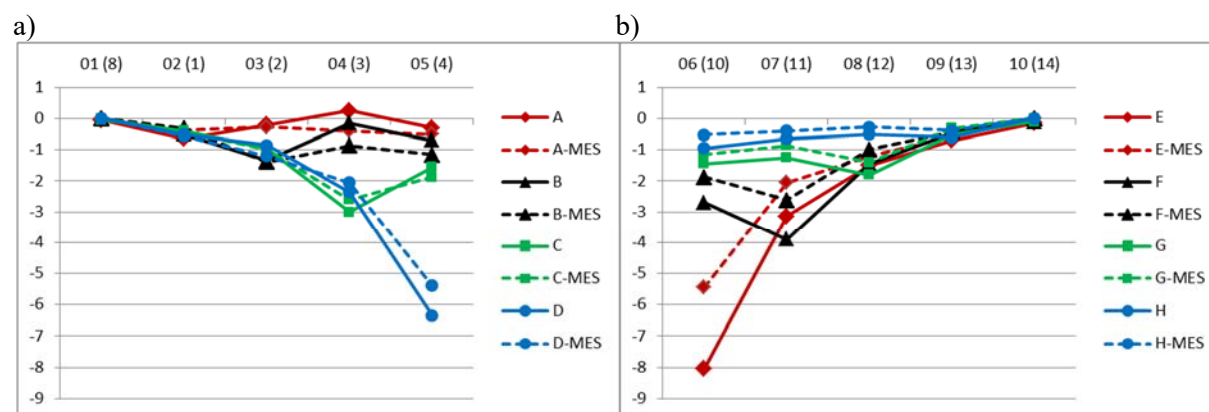


Figure 7. The footbridge model with a sample layout of displacements (a trial load in point A) [10]

Table 2. Vertical displacements of the control points of the theoretical model A - H – load application points; 01-10 – control point numbers – see figure 5 [10]

Points (joints)	Load scheme							
	A	B	C	D	E	F	G	H
01	0	0	0	0	0	0	0	0
02	-0.38	-0.31	-0.42	-0.56	0	0	0	0
03	-0.27	-1.39	-0.98	-1.19	0	0	0	0
04	-0.39	-0.87	-2.61	-2.05	0	0	0	0
05	-0.51	-1.15	-1.88	-5.39	0	0	0	0
06	0	0	0	0	-5.45	-1.88	-1.16	-0.52
07	0	0	0	0	-2.05	-2.62	-0.87	-0.39
08	0	0	0	0	-1.2	-0.99	-1.4	-0.27
09	0	0	0	0	-0.57	-0.43	-0.31	-0.38
10	0	0	0	0	0	0	0	0

Analysing the values of calculated vertical displacements shown in table 2, one may notice that these displacements are symmetric to the M plane perpendicular to the footbridge. Values of displacements obtained from geodetic measurements are not symmetric to both planes of symmetry of the footbridge. A tendency of the deck segments to oscillate around its axis was also observed, as this was indicated by different values of vertical displacements of the left and right side of the footbridge in the same cross sections. Values of measured vertical displacements were also compared with that measured with the finite element method. This is shown in figure 8.

**Figure 8.** Comparison of measured and calculated displacements, a) on the half of the footbridge from Jagiellońska street, a) on the half of the bridge from Toruńska street [10]

One may notice that the values of measured displacements are higher than that of displacements calculated numerically. These differences are greater on the half of the footbridge from Toruńska street.

5. Tensometric measurements

During the trial load of the footbridge, tensometric measurements of cable stay deformations were also performed. On the basis of the deformations, axial forces occurring in them were calculated. A tensometric sensor was attached to each cable stay. Changes in ambient temperature were compensated during the measurements. With every load applied, indications of sensors located on the loaded half of the structure were read only.

A numerical simplified structure model (created with the finite element method) was used to compare results of tensometric measurements with numerical simulations. This article presents results

for three trial load positions – marked E, F and G in figure 9. Charts of normal forces calculated numerically were also drawn up for the said schemes.

Values of normal forces in cable stays determined numerically (marked FEM) and values resulting from tensometric measurements (marked L and P, depending on the bridge side) are shown in figure 10. With a visual comparison of the force charts, it is easy to notice that for the FEM simulation a trial load is carried mainly by cable stays closest to the position of that load. This results from a static scheme assumed in the structure design phase and taken for the purpose of these analyses, in which individual segments of the footbridge are articulated. However, charts of tensometric measurements reflecting the actual behaviour of the structure show different force distribution. The loading force is carried by many cable stays (it is particularly visible in figure 10b), which is possible only in a situation when deck connection points are not articulated. This means that the actual footbridge deck movement, thus its static scheme, is different – much more complex than the theoretical model.

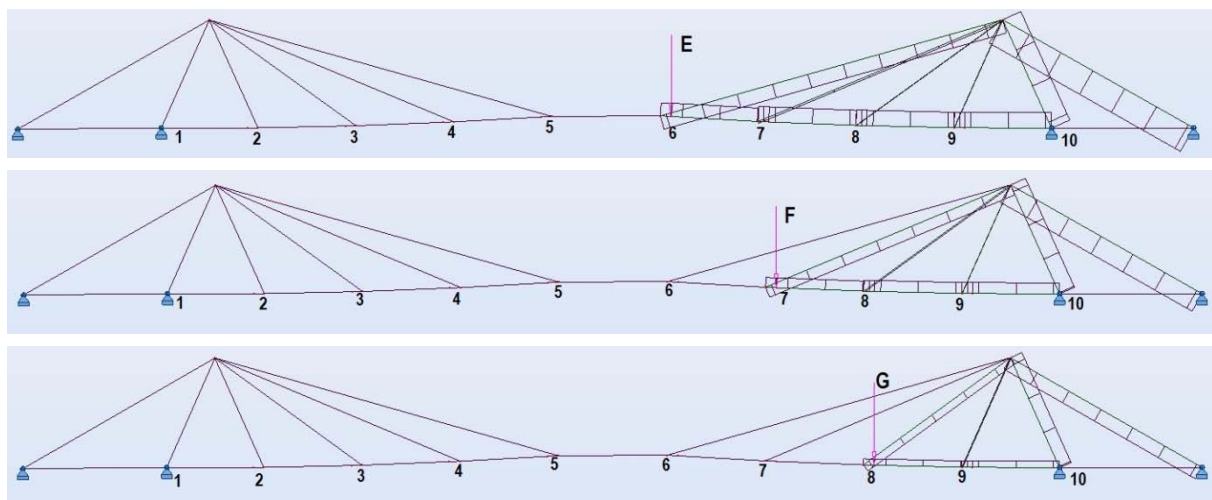
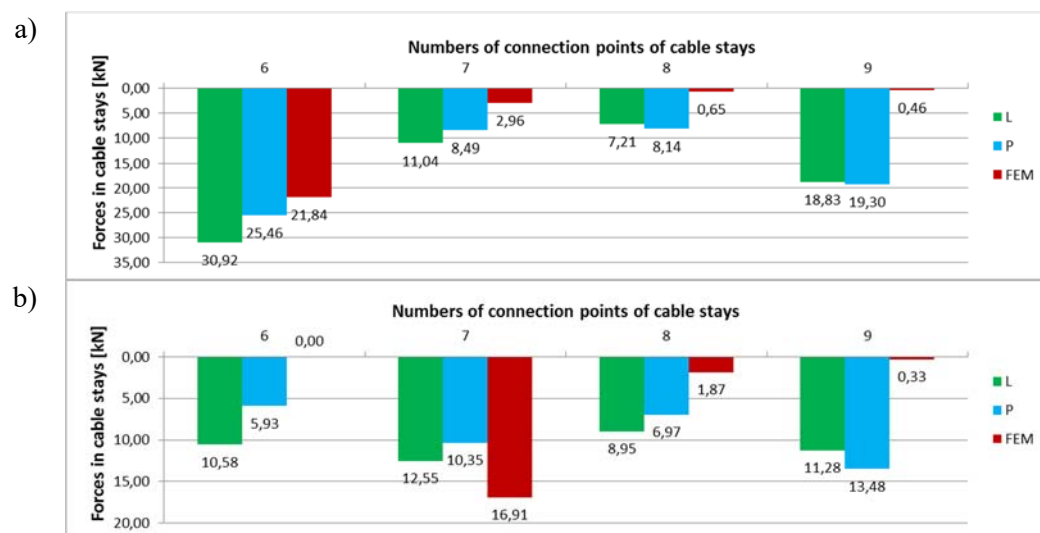


Figure 9. Charts of normal forces in footbridge components in three trial load positions



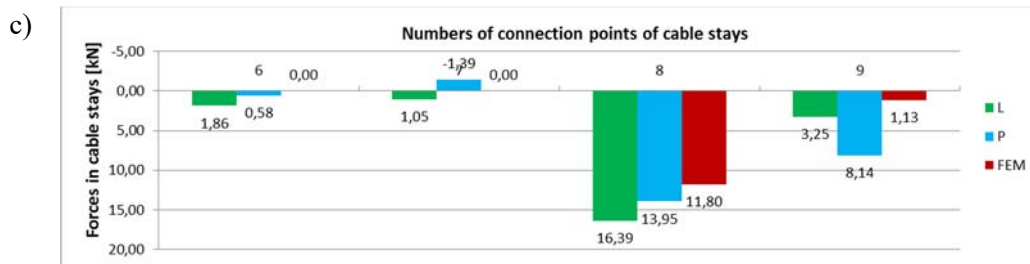


Figure 10. Charts of values of forces in cable stays from tensometric measurements (L, P) and the FEM simulation, for load schemes: a) position E, b) position F, c) position G

A quantitative comparison of the values of forces in cable stays indicated a nonconformity, i.e. forces determined on the basis of tensometric measurements are too high in comparison to the applied trial load. An estimation analysis (without considering changes in forces transmitted from the deck to the abutments) was carried out. According to this, the sum of forces to the vertical direction in cable stays for each case of a load is higher than the value of the trial load. While searching for causes of this nonconformity, attention was paid to the fact that in the theoretical model cable stays are treated as rectilinear components, whereas they are actually curved. This curvature results from their dead weight and applies only to the longest cable stays which are least inclined. Deflections of the cable stays were measured – for the longest ones, they were 11.3 to 18.2 cm, 15.0 cm on average. The curvature of cable stays is significant, since tension meters were attached to the top surfaces of cable stays rods from the internal side of their curvature (such location was easiest to make). This caused them to stretch and straighten simultaneously at the time the forces started to grow. In order to estimate the relevance of the effect of the straightening of the cable stays on results of tensometric measurements, additional calculations were made. Assuming that the cable stays are roughly in the shape of circular arches of specific parameters and knowing the diameter of the cable stay rods (which is 38 mm), it is possible to calculate unit shortening of their extreme fibres (from the curvature side) relative to the central fibres. Taking the arch span of 19.00 m and the rise of arch of 15.0 cm, this unit shortening was calculated to be 63×10^{-6} . The maximum reading from the tensometric sensors was approx. 130×10^{-6} . This implies that the cable stays straightening effect accompanying the increase of forces could have caused an increase of sensor readings. The most effective way to avoid this problem is to attach tensometric sensors to the opposite surfaces of the cable stay rods.

6. Conclusions

Research and analysis allowed to formulate the following conclusions:

- Maximum vertical displacements of suspended footbridge segments in the initial period of its operation (the years 1979-1994) were 30 mm, whereas displacements from the time when the footbridge had been adjusted to 2017 (a period of 23 years) were 16 mm. This results from the fact that the largest displacements of the footbridge occurred in the first years of its operation.
- Geodetic measurements of the footbridge made after its adjustment in 1994 indicated that the adjustment had not brought entirely positive results compliant with theoretical assumptions. During the adjustment, much of the deck was raised without changes to transverse inclination (crosslevels). This can be explained by a relatively high spatial rigidity of the deck segments that prevented these segments from twisting around the longitudinal axis of the deck. The shortening of cable stays from the right side of the footbridge resulted in rising of a large stretch of the entire deck and simultaneous unloading of the cable stays on the left side of the footbridge.
- In theoretical calculations, footbridge displacements were obtained only on this half to which a load had been applied (for all cases). The image of displacements differs from the theoretical one. The expected symmetry of measured footbridge displacements has not been observed (this regards the symmetry along and across the structural unit). In particular, this applies to

the cross direction where the footbridge rotates. Such rotations are different in respective sections, therefore they cause slight twisting of the deck segments.

- It should be stated that the actual nature of operation of the footbridge is other than that in the assumed FEM model (static scheme). An assumption can be made that the differences concern behaviour of the footbridge structure joints. Probably, connections of the deck segments are not completely articulated (they feature a certain rigidity) or the expansion joint of part of the deck does not fulfil its function.
- Errors of tensometric measurements are too large to use the obtained results in quantitative analyses. However, it was decided that the results are useful for observation of general behavioural tendencies of the footbridge structure. The distribution of forces in the cable stays observed on the basis of tensometric measurements indicates that the actual structure of the footbridge differs from its theoretical model in which connections of individual deck segments are articulated.
- Tensometric tests of the footbridge demonstrated how measurement results can be affected by relatively insignificant, usually ignored differences between actual structural units and their theoretical models. In the analysed case, failure to consider the curvature of cable stays combined with the application of single tensometric sensors on cable stay curvature planes resulted in substantially distorted readings. It is a lesson for the authors of this article (the tests are going to be performed again) and a caution for other researchers.
- The image of footbridge displacements measured during the tests proved to be complex enough and different from theoretical displacements, so the footbridge has to be further tested and analysed, to include measurements of displacements of other characteristic joints of the footbridge and additional numerical analyses (a spatial model) with consideration of the rigidity of joints treated previously as articulated.
- It is recommended to readjust the footbridge cable stay tension in the near future. For this purpose, an approach other than that of 1992-94 should be applied. The expected outcome of such adjustment should be a proper geometry of vertical alignment of the footbridge, not its both edges, and balancing of forces in the cable stays. This will help restore static work of the footbridge, in accordance with the original design assumptions.

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