ORIGINAL ARTICLE

Investigations on the historical Széchenyi chain bridge

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Abstract

The Széchenyi chain bridge is an almost 170-year-old historical structure located in the downtown of Budapest, which has been reconstructed between 2020-2022. The chain system of the bridge is more than 100 years old, and the rotational capacity of the pins is questionable due to corrosion and friction. This phenomenon significantly influences the static behavior of the chain elements and the entire suspending system. Therefore, connected to the renewal process, the Budapest University of Technology and Economics, Department of Structural Engineering investigated the rotational capacity of the pins of the chain elements, and the corrosion grade of the chain bars. To investigate these two issues, three on-site measurements are executed: (i) loading test to measure the bending moments in the chains and checking the rotation of the pins, (ii) one-year-long monitoring system operating during the renewal process and checking the internal force distribution of the structure during the reconstruction phases, and (iii) corrosion measurements on the chain bars. The paper introduces the measurement results, the main conclusions, and their practical application possibilities in the renewal process.

Keywords

chain bridge, historical structure, on-site measurements, advanced numerical modelling, corrosion, probabilistic analysis

1 Introduction

The Széchenyi chain bridge (Figure 1) in Budapest was originally built between 1839-49. It was reconstructed several times in the history, but chain elements reached their 100-year-lifetime and the deck system was more than 70-year-old. The latest renewal process on the bridge executed within the last years has been designed by the Főmterv Co. and MSc Ltd. [1] The strategy of the current reconstruction was that the old bridge deck system (concrete slab and longitudinal steel stringers) has been replaced by a new orthotropic steel deck. The chain elements, the steel stiffening girder and the cross-girder system remain unchanged, only the corrosion protection is planned to be renewed. It is well known, stuck pins can change the structural behavior of the chain system, which could lead to damage of the bridge. One of the most serious chain bridge failures occurred in the USA in 1967 resulting in the death of 46 people [2]. The Silver Bridge collapsed due to a single chain element failure initiated from a fatigue crack resulting the total collapse of the chain system. Therefore, the evaluation of the structural condition of the remaining elements is an important task of the renewal process to determine their load carrying capacity and remaining lifetime. Therefore, connected to the current renewal process, the corrosion grade of the structure and the condition of the chain bars was investigated in a detailed manner and its effect on the load-bearing capacity was evaluated by the Budapest University of Technology and Economics, Department of Structural Engineering. During the investigations two issues are studied: (i) rotational capacity of the pins of the chain elements – which could be fixed by corrosion causing bending moments, and (ii) material loss of the chain bars causing reduced tensile resistance leading to inappropriate ultimate resistance.

Figure 1 The Széchenyi chain bridge under reconstruction

To investigate these issues, three different on-site measurements are executed on the bridge: (i) loading test to measure the bending moments and rotation grade of the pins, (ii) one-year-long monitoring system operating during the renewal process to check the static behaviour, rotation and stress distribution of the chain elements, and (iii) corrosion measurements and damaged surface detection on the chain bars. The paper presents the investigation strategy and results of these on-site measurements.

2 On-site measurements

2.1 Investigation strategy

The first point was to investigate the rotational capacity of the pins and to decide if they can rotate or not. The rotational capacity has been checked under traffic loads and under the reconstruction work, while the reinforced concrete deck system has been removed and the new steel deck system has been erected, causing large internal force change in the chain system. The rotational capacity under the traffic load has been analyzed by loading test. The rotational capacity under reconstruction is tested by a one-year-long monitoring system, which delivered essential information and highlights important characteristic properties of the structural behavior of the historic structure. The second point was the determination of the corrosion damage of the chain elements. Based on the corrosion surface measurements, the corroded surface of the chain elements could be determined on many chain bars and the measurement results could be statistically evaluated. A stochastic corrosion model is developed characterizing the corroded shape of the chain elements, which is implemented into advanced three-dimensional (3D) finite element (FE) models to determine the resistance of the chain element more accurately.

2.2 Loading test

The aim of the loading test was to determine the change in the normal force and bending moment diagrams within the chain elements due to live load. Numerical model (developed in ANSYS [3]) results shown in Figure 2b demonstrate, if all pins are stuck (fixed connections are assumed in the numerical model) the typical bending moment diagram has large values only at the location where the suspension system has knick-points (at the abutment and at the pylon). It means significant bending moment can develop only at these two places. Therefore, stress changes were measured at these two locations during the loading test.

The bridge was loaded by 12 trucks (Figure 2a) with an average weight of ~200 kN, placed in 13 different loading arrangements simulating partial and total loading situations. The loading schemes were selected to create the largest possible bending moment change in the pins to make them rotate (if they can). During the test program the following measurements are executed:

- deflection measurements to check the global behaviour of the system,
- strain measurements at 8 chain elements to determine the normal stress changes (normal force and bending moments separately),
- influence line measurements on the chain to check the global structural behaviour due to moving loads,
- eigenfrequency measurements.

In the current paper only the strain measurement results are presented.

a)

b)

Figure 2 a) On-site loading test and b) calculated bending moment diagram with fixed pins

Strain gauges are placed on the chain elements where significant bending moments were expected, and on the neighbouring chain elements, where dominant tension force was expected, giving reference measurements to clearly separate the tension force and bending moment changes. Normal force and bending moment changes are determined in each investigated chain elements. The measurements are also compared to the numerical results, which proved that from the 8 measured pins only one could rotate under the applied load. All the other pins got stuck and did not rotate under the applied test load. One example for the measured normal stresses is presented in Figure 3. The diagram shows the strain measurement results during 3 trucks are moving on the bridge and take their planned position. 10 strain gauges are placed on the chain elements at each measuring location (resulting the code of the strain gauges e.g., H3/1, H3/2, etc. – where #3 means the third measuring location). Strain gauges H3/1 – H3/6 are placed on the extreme fibre of the first chain element next to the abutment and others are located on the second one, serving as reference measurements. Results give evidence on the developed bending moment around the pins as shown in Figure 3.

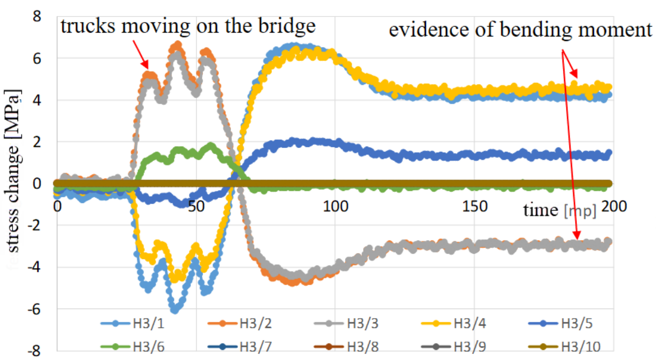


Figure 3. Stress changes in one chain element due to loading by 3 trucks

It could be concluded that the applied load was not large enough to overcome the friction between chain elements which significantly increased due to corrosion. Therefore, measurements were continued under the reconstruction work where larger internal force changes were expected coming from the self-weight change of the bridge.

2.3 Monitoring measurements under reconstruction

The goals of the monitoring system measurements were twofold, but the main objective was to investigate the rotational capacity of the pins. Therefore, strain gauge measurements are executed continuously at the four abutments and at 4 different locations around the pylons, where the large bending moments were identified during the on-site loading tests. The schematic drawing of the strain gauge locations can be seen in Figure 4.

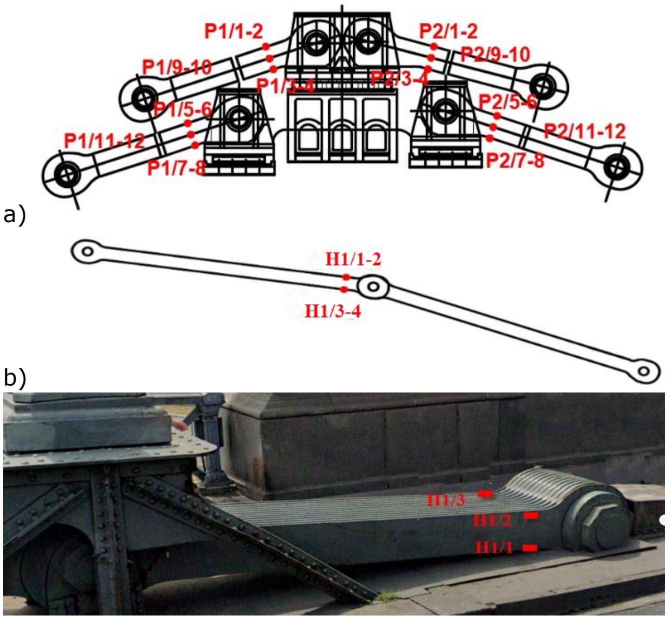


Figure 4 Location of strain gauges a) at the pylon, b) at the abutment

Figure 5 shows the measured strains and accompanying temperatures for one specific location at the abutment (H1 – shown in Figure 4b). The horizontal axis shows the measuring time period (8 month long) and the two vertical axis shows the measured temperatures and the changes in the axis strains of the chain elements at the locations shown in Figure 4b).

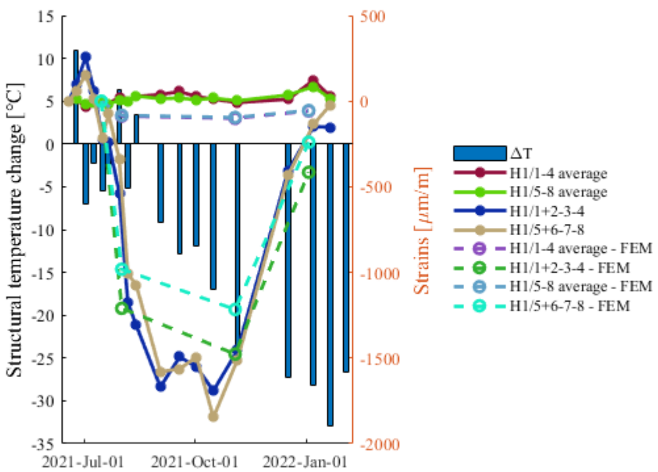


Figure 5 Measurement results of the strain gauges at the abutments during reconstruction

The diagram shows the average strains measured in the 4 extreme fibres of the chain elements (representing the measured normal force change) and the strain changes between the lower and upper extreme fibres (representing the measured bending moment). Based on the results three observations can be made: (i) the stresses coming from the bending are more significant than strains coming from the tension force change, (ii) the measured strains fit quite well with the strains calculated with the numerical model following the erection phases of the bridge during reconstruction and considering the actual temperature values measured at the bridge, and (iii) there is no sudden drop in the diagram representing the bending moment change, which means, the pin under investigation did not rotate within the measuring period. The pins are stuck. Similar diagrams are observed at all the other measured locations, meaning, the pins did not rotate during the reconstruction process of the bridge.

The measurements shown in Figure 4a could be also used to determine the tension force change within the chain elements at the two sides of the pylon. The measured normal force changes at the four investigated locations are summarised in Table 1. The first column shows the measuring location. The second column shows the measured normal force changes. The third and fourth columns show the difference at the two sides of the pylon in [kN] and in [%], respectively. The results show that a horizontal force about ~450 – 760 kN remains in the pylon.

Table 1 Measured tension force changes within the chain elements at the two sides of the pylon

	ΔN [kN]	$\Delta N_{i\text{-}j}$ [kN]	$2\Delta N_{i\text{-}j} / (\Delta N_i + \Delta N_j)$ [%]
P1 upper	1822.737	577.941	37.7
P2 upper	1244.796		
P1 lower	1133.6535	689.0835	87.3
P2 lower	444.57		
P3 upper	1711.5945	466.7985	31.6
P4 upper	1244.796		
P3 lower	1222.5675	755.769	89.5
P4 lower	466.7985		

These results mean the roller supports at the top of the pylon has a friction resistance approximately equal with the measured values. These normal force differences are step-by-step eliminated when the roller supports are moving due to the temperature change of the bridge. Therefore, to check the correct rolling mechanism of the bearings, the actual location of the roller bearings is also measured and evaluated. Figure 6 shows the measured displacements on the four roller bearings during the measured time period (9 months). The results show, all the four roller bearings are moving. Three of them had almost the same displacement in all time and one had a slightly (~1 mm) larger one, which had the reason, that the reference value has a certain uncertainty coming from the unequal movement of the roller bearings. It means the observed friction force does not reach their maximum value in the same time at all the four bearings; therefore, the movement of the bearings do not happen at the same time. So, it can happen, that one bearing has been slightly moved and all the three were still before the movement at the time of the measurement.

In Figure 6 characteristic points are also marked with numbers #1-#6 showing when large changes happened in the stiffness or loading of the bridge during the renewal process. The measurement results showed, the erection did not have significant effect on the roller bearings. It proves that the largest effect causing the bearing movement is the temperature change and the deck system reconstruction did not have significant effect on the structural behaviour of the chain system.

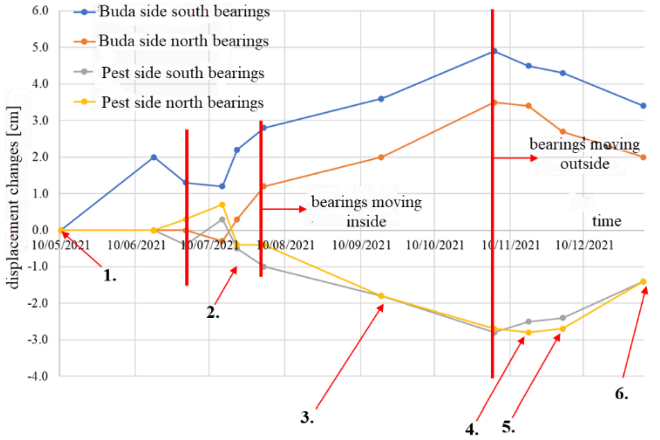


Figure 6 Measurement results of the roller bearings: time-displacement diagram

2.4 Corrosion measurements of the chain bars

Knowing that all the pins are stuck, and the chain elements should be checked for normal force and bending interaction, the second question was how much the corrosion grade of the chain elements is and how large is the remaining cross-sectional area of the chain bars to be considered in the static check. To answer these questions corrosion measurements are executed on the chain elements in the anchoring chambers and in the abutments where the bending moments have their maximum values, as shown in Figure 7.

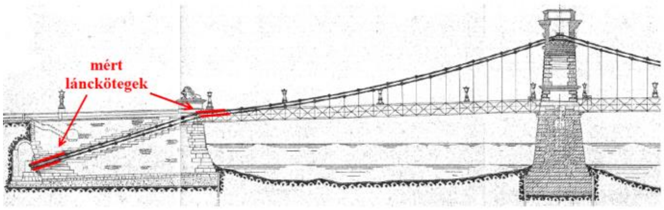


Figure 7 Location of the corrosion measurements

Before the measurements all the chain elements were cleaned by sand shooting to create a surface which could be scanned with high accuracy using a specific measuring device developed specially to the chain elements of the Széchenyi chain bridge. The typical corroded surface of the chain elements and the measuring device is presented in Figure 8. The measuring device could produce continuous measurements at 7 straight lines along the longitudinal axis of the chain elements. One example for one specific chain bar is shown in Figure 9, where the horizontal axis shows the longitudinal axis of the chain bar and the vertical axis shows the measured thickness. It can be seen the largest cross-section loss is located at the end of the chain bars. Its reason is that the rain flows alongside of the entire element, and it drops down at the end of the member.

Figure 8 Typical surface of the corroded and cleaned chain elements

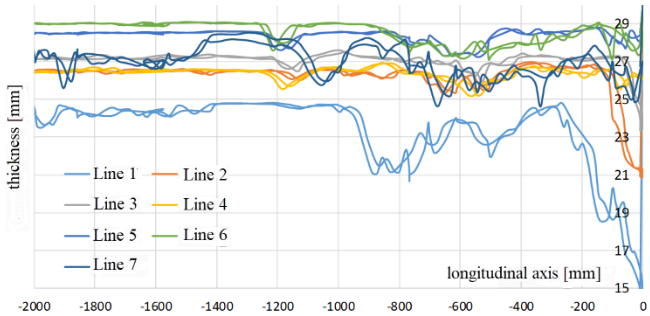


Figure 9 Measured thicknesses at 7 lines along the longitudinal axis of the chain elements

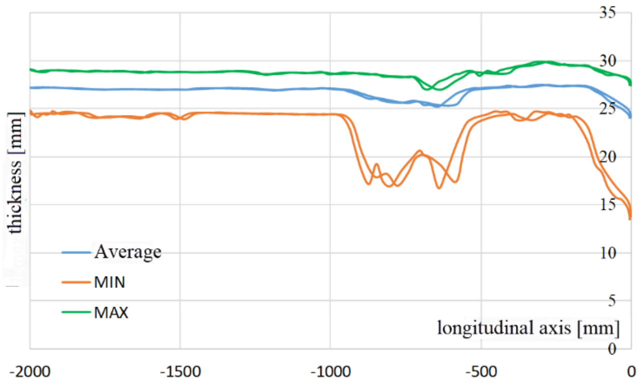


Figure 10 Statistically evaluated measurement results for one specific chain element

The measured results also show, there are smaller or larger holes on the chain elements which has a large variety. Therefore, a statistical evaluation is executed to identify the minimum, the maximum, and the average material loss and to determine the statistical characteristics of the actual corrosion grade of the chain elements. Based on the measured results, at first the largest average thickness loss is determined on the chain elements taken from the weighted average of the 7 measuring lines. The weighted average for each cross-section was used to determine the average plate thickness of each cross-section along the length of the chain elements. The minimum, average and maximum values of these averages over a length (measurement range) were then calculated for each plate separately (for one specific case it is shown in Figure 10). The percentage reduction in plate thickness was then determined from the minimum values of the averages, since the minimum average plate thickness for each plate is required for determining the tensile resistance of a tension member. Using this method, the minimum, maximum and average values of the cross-sectional material losses are determined for all the 11 chain elements, which forms one row of the chain system. This evaluation procedure is made for all 12 measured locations in the anchorage chamber and at the abutment.

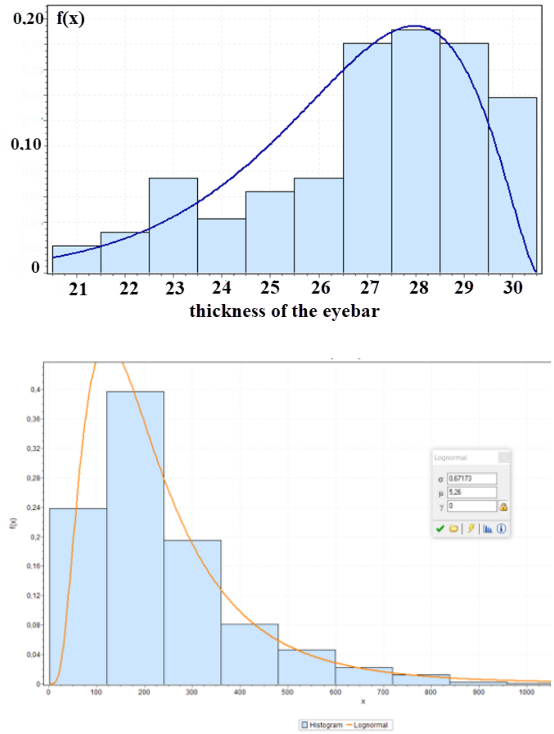
Based on the measured values, it is determined, that the remaining cross-sectional area to be taken into account in the static check varies between 79-90% in the case of 8 chain element groups measured in the anchorage chamber. The same value varies between 94-102% on the chain elements next to the abutment. Note that the thickness of the original chain plate may have been slightly greater than its nominal value (29 mm taken into account in the static calculation), which accounts for the measured values above 100%. The evaluation strategy used is the same as that used in 1986 and 2002 at the previous corrosion measurements on the chain bridge. At the same time, note that a direct comparison with previous measurement results can be misleading in terms of determining the corrosion rate due to the surface cleaning methods used in different ways (e.g. during the measurement carried out in 2002 on chain plates where the measurement was performed on plates already equipped with a corrosion protection coating, the coating was considered with a nominal thickness of 2 x 0.30 mm; the same value during the measurements in 2022 was 2 x 0.595 mm, which was deducted from the measurement results).

The measurement results taken in 2022 prove, 21% average material loss should be considered for the determination of the tensile resistance of the chain elements. In the cross-section where the interaction of normal force and bending moment should be checked, the average material loss to be considered is only 6%.

3 Probabilistic model of the chain bar

The second evaluation process executed based on the corrosion measurements was that the hole sizes (length, width and magnitude) are statistically evaluated. The reason for it is to determine a specific corrosion model because the applicability of the previously developed corrosion models [4]-[6] are questionable on this bridge. Therefore, each measurement lines are studied independently, meaning that all the 7 measurement lines on all 11 chain bars for all the 16 measured chain elements are separately evaluated. It means that 1232 measurement lines are statistically evaluated to create a statistical measure for the corroded surface. The statistical evaluation showed the following results:

- beta distribution could be applied for the description of the maximum corrosion loss (hole depths) with parameters of $\sigma=2.5$; $\beta=1.4$; as shown in Figure 11a;
- lognormal distribution could be used for the description of the hole diameters of the corroded surface with parameters of $\alpha=0.67$; $\mu=5.26$ as shown in Figure 11b).



a)

b)

Figure 11 Statistical measures of the corrosion model: a) beta distribution for the maximum corrosion loss (hole depths), b) lognormal distribution for the hole diameters

Regarding the material properties it is known, the main part (76%) of the chain elements was manufactured in 1915 [7] having the characteristic of the contemporary steel manufacturing techniques. Results of 702 coupon tests taken in 1912 are found by the authors in the literature. So, the mean and characteristic values of the steel material could be determined by statistical evaluation and probabilistic curve fitting as shown in Figure 12. The mean value of the yield strength is 525 MPa with a CoV of 0.03.

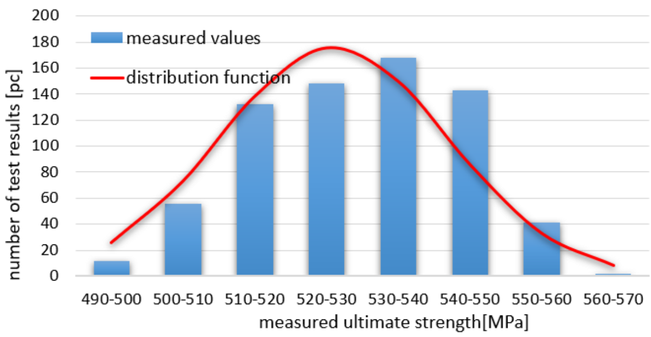


Figure 12 Statistical distribution of the yield strength

To determine the resistance of the chain elements an advanced solid element based numerical model is developed in which the corroded surface can be accurately implemented. Contact elements are applied between the connected surfaces considering friction and sticking effect. The developed numerical models have the following capabilities:

- elastoplastic material behaviour using damage criteria to model tensile fracture of the material,
- friction and sticking between the pin and chain elements,
- considering the measured corrosion grade based on the measured surface properties and its probability on the surface of the chain elements,
- ultimate load is determined using geometrical and material nonlinear analysis using imperfections (GMNI analysis) according to EN 1993-1-5 Annex C [8],
- coupling GMNI analysis (numerical simulations) with the probabilistic design approach using the design rules of EN 1990 [9].

Considering corrosion of the chain elements measured mean surface is implemented into the numerical model, as shown in Figure 13.

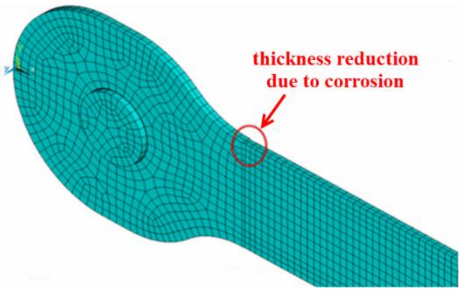


Figure 13 Numerical model of the corroded surface

Probabilistic analysis is carried out on the numerical model using Monte-Carlo simulation technique, generating pseudorandom values for the defined variable parameters using Latin hypercube sampling. In each single case the ultimate resistance is determined using GMNI analysis by evaluation of the obtained load-displacement curve. During probabilistic analysis the following variables are considered:

- depth of the chain elements (using CoV =0.005),
- thickness of the chain elements (using CoV =0.05),
- yield strength of the steel (using CoV=0.03 - based on measurements),
- corrosion depth (using Beta distribution function - based on measurements).

Using the probabilistic model which results are presented in Figure 14 the design value of the ultimate resistance could be determined and the static check could be performed on the corroded chain elements. Finally, it could be proven, the bridge can operate with adequate safety according to EN 1990 [9].

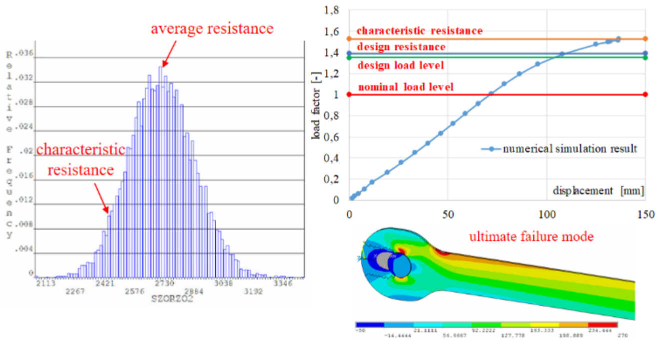


Figure 14 Result of the combined probabilistic design method with the GMNI analyses

4 Conclusions

Based on the on-site measurements, the following conclusions could be drawn regarding the bridge behaviour:

- all the measured pines are stuck, no rotations are expected coming from the live load on the bridge;
- normal stresses coming from bending are significant; the bending component should always be considered in the static check of the chain elements;
- the measured normal stresses show good agreement with the numerically calculated values using a model where all pins are assumed as fixed;
- the roller bearings of the bridge have a significant friction resistance, which makes the tension forces at the two sides of the pylon different;
- even if the roller bearings have significant friction, due to temperature change they are moving, and the bridge behaviour is quasi-symmetric;
- based on the corrosion measurements it has been determined that the average material loss of 21% should be considered in the tension resistance calculation of the chain elements;
- on the cross-section, where the interaction of tension and bending moment should be checked, a maximum of 6% material loss should be considered;
- based on the statistical evaluation of the corroded surface of the chain elements the statistical measures could be determined, which are implemented into a probabilistic numerical model determining the design resistance of the chain elements.

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References

[1] 10-I-002-01 *Static calculation of the superstructure of the Széchenyi chain bridge*, MSc Ltd., Főmterv – MSc – Céh Consortium, 8300, 2016.08.23, Shop drawings.
[2] Åkesson, B.: *Understanding Bridge Collapses*, 139-148, Taylor & Francis Group, 2008.
[3] ANSYS® v15.0, Canonsburg, Pennsylvania, USA.
[4] Tohodi, S., Sharifi, Y.: *Load-carrying capacity of locally corroded steel plate girder ends using artificial neural network*, Thin-Walled Structures, 100, 48-61, 2016.
[5] Paik, J.K, Kim, D.K: *Advanced method for the development of an empirical model to predict time-dependent corrosion wastage*, Corrosion Science, 63, 51-58, 2012.
[6] Wang, Y., Xu, S., Wang, H., Li, A.: *Predicting the residual strength and deformability of corroded steel plate based on the corrosion morphology*, Construction and Building Materials, 152, 777-793, 2017.
[7] Domanovszky, S.: *One hundred years ago, on November 27, 1915, the reconstructed Chain Bridge was opened for traffic*, TEXT Nyomdaipari Kft., 2015 (in Hungarian).
[8] EN 1993-1-5 Eurocode 3: Design of Steel Structures – Part 1-5: General rules - Plated structural elements, 2006.
[9] EN 1990. Eurocode – Bases of structural design, 2002.