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Research paper

Nonlinear modelling of a bridge: A case study-based damage evaluation and proposal of Structural Health Monitoring (SHM) system

Muhammad Fawad[1], Kalman Koris[2], Marek Salamak[3], Michael Gerges[4], Lukasz Bednarski[5], Rafal Sienko[6]

Abstract: Monitoring and structural health assessment are the primary requirements for performance evaluation of damaged bridges. This paper highlights the case-study of a damaged Reinforced Concrete (RC) bridge structure by considering the outcomes of destructive testing, Non-Destructive Testing (NDT) evaluations, static and 3D non-linear analysis methods. Finite element (FE) modelling of this structure is being done using the material properties extracted by the in-situ testing. Analysis is carried out to evaluate the bridge damage based on the data recorded after the static linear (AXIS VM software) and 3D non-linear analysis (ATENA 3D software). Extensive concrete cracking and high value of crack width are found to be the major problems, leading to lowering the performance of the bridge. As a solution, this paper proposes a proper Structural Health Monitoring (SHM) system, that will extend the life cycle of the bridge with minimal repair costs and reduced risk of failure. This system is based on the installation of three different types of sensors: Liquid Levelling sensors (LLS) for measurement of vertical displacement, Distributed Fiber Optic Sensors (DFOS) for crack monitoring, and Weigh in Motion (WIM) devices for monitoring of moving loads on bridge.

Keywords: bridges, reinforced concrete, finite element method, non-destructive techniques, structural health monitoring, sensors

[1]MSc, Eng. Silesian University of Technology, Faculty of Civil Engineering, ul. Akademicka 2A, 44-100 Gliwice, Poland, e-mail: muhammad.fawad@polsl.pl, ORCID: 0000-0003-4729-7289
[2]Assoc. Prof., Budapest University of Technology and Economics, Faculty of Civil Engineering, Műegyetem rkp. 3,1111 Budapest, Hungary, e-mail: koris.kalman@emk.bme.hu, ORCID: 0000-0002-6571-5555
[3]Assoc. Prof., Silesian University of Technology, Faculty of Civil Engineering, ul. Akademicka 2A, 44-100 Gliwice, Poland, e-mail: marek.salamak@polsl.pl, ORCID: 0000-0003-3602-0575
[4]Associate Dean, University of Wolverhampton, Wulfruna St, Wolverhampton WV1 1LY, United Kingdom, UK, e-mail: Michael.gerges@wlv.ac.uk, ORCID: 0000-0001-5986-7301
[5]Assist. Prof., AGH University of Science, Mechanical Engineering and Robotics, ul. Mickiewicza 30, 30-059 Kraków, Poland, e-mail: lukaszb@agh.edu.pl, ORCID: 0000-0002-5404-9921
[6]Assist. Prof., Cracow University of Technology, Faculty of Civil Engineering, ul. Warszawska 24, 31-155 Kraków, Poland, e-mail: rafal.sienko@pk.edu.pl, ORCID: 0000-0002-2751-7558

1. Introduction

Structural health monitoring (SHM) framework is utilized to observe and evaluate the existing condition of civil infrastructure, which has been broadly evolved to monitor the safety, serviceability, and sustainability of existing structures like bridges [1]. Deterioration and damage of bridges are results of ageing and downgrading of the structure. The reasons for this may be environmental factors, improper design, poor construction quality, lack of proper maintenance, and natural disasters like earthquakes, floods or strong winds [2, 3]. Increasing decay of infrastructure calls for a structural evaluation to make them in line with the exact design requisites [4].

Many methodologies are in practice for detailed evaluation of bridges. In this regard, in-situ measurements and non-destructive testing (NDT) evaluations have been the most adaptable methodologies since long [5, 6]. These evaluations have provided us with the specifications and properties of the material and information about significant deterioration effects phenomenon [7, 8]. It further involves numerical models for static and dynamic analysis of bridges. In addition to strength and stability issues, special consideration should be given to a broad range of important factors such as dynamic and seismic behavior, long-term deformations, fatigue, and durability (functional efficiency) issues, that can be effectively analyzed using the 3D nonlinear FE modelling technique [9–11]. Safety assessment procedures using Finite Element (FE) modelling represent the sound basis for selecting intervention techniques and controlling the efficiency of the applied interventions [12]. Numerous deficiencies of existing Reinforced Concrete (RC) bridges are due to the absence of detailed durability rules in the original design, which can be verified by carrying out static and 3D nonlinear structural analysis [13]. In current practices, FE analysis is also used to design the SHM systems and identify the locations of sensors [14]. The effects of influencing factors such as live-load, temperature, and wind can be analyzed in the numerical model determining the type and location of sensors in the planned SHM system [15, 16]. This approach allows the selection of optimal and efficient sensors [17]. For example, strain needs a special measurement method for testing and early identification of structural defects in bridges [18].

Different novel techniques, including infrared (IR) thermography and digital image correlation (DIC), are preferable when it comes to measuring strain [19]. Furthermore, Fiber Bragg Grating (FBG) using fiber optic sensing techniques are widely used and highly efficient to measure strain under the effects of dynamic loads [20, 21]. Displacement is another essential parameter in the case of bridges as it reflects the overall stability and behavior of a bridge [22]. An efficient measurement of deflection is carried out by using inclinometer because of their high precision and easy handling [23]. However, these inclinometers have special hardware requirements, which limits their use for special bridge sites. Therefore, to overcome the limitations of certain contact sensors, and the measurement of vertical displacements, the use of special Liquid Leveling Sensors (LLS) is vital [24]. This is also because these Liquid Leveling Sensors (LLS) offer contactless services with the measurement of 3D field dynamic deflection [25].

Another critical problem in RC bridges is monitoring of the cracks, which can be caused by overloading, carbonation process, and corrosion of rebars in an ageing bridge structure [26, 27]. The formation of new cracks and the propagation of existing ones do not only reduce the stiffness and load-bearing capacity and durability but also shorten the service life of bridges [28, 29]. Many traditional mechanical methods allow for spot measurement of cracks up to 7 mm at the places where cracks have already been identified [30]. However, simple crack scales or gauges are inefficient for the detection of new cracks along with the propagation of cracks in new areas [3]. Many smart deformation monitoring techniques are in practice nowadays, among which smart film for crack monitoring is an effective one [32] but their high sensitivity limits their applications for some typical usage in bridges. Distributed Fiber Optic Sensing (DFOS) is found to be the most effective method for deformations monitoring of RC bridges [33]. It can effectively detect length, width, shape, location, and propagation of cracks in an existing bridge along with the measurement of the deformation parameter [34, 37]. Some researches [38, 39] have highlighted the monitoring of cracks using deep machine learning algorithms that involve the basics of fiber optic sensing. These sensors provide a continuous profile of light scattering processes, over a certain optical fiber range, that allow users to set the parameters for measurements of deformations as per their requirements [40, 41]. In addition to that, another important parameter in bridges is the measurement and monitoring of moving weights especially when the load bearing capacity of the structure is under design [42]. Imposing proper regulations of truck weights reduces the surface damage in bridge structures which in turn reduces the pavement maintenance costs and provides a check over the load-bearing capacity of bridges [43, 44]. Consequently, the mentioned literature provides a data set of most advanced sensors that can give rise to SHM systems, as proposed in this research paper.

Considering the above citations; this paper uses NDT evaluations, static linear, and 3D nonlinear analysis methods to analyze the existing condition of bridge, also by providing the basis for SHM of the considered bridge.

The novelty of presented work includes the comparison of different techniques for damage assessment of the bridge and recommendations for the most accurate and suitable techniques. Besides this, use of smart damage measurement devices like FBG and DFOS sensors is suggesting something new for practical implementation on a real-life damaged bridge structure.

2. Description of the case-study bridge

Existing problems of a 50-year-old box girder bridge, situated over a dam in Eastern Hungary, has been considered as a case-study in this research paper. Overall, the bridge structure contains five spans, each of 27.6 m making the total length of 138 m. The superstructure is a continuous RC double box girder having a 20 cm top slab (separated by the expansion joints at each support) and 16 cm bottom slab, joined together using the 40 cm thick deck walls. These walls are additionally the elements of the hydrotechnical infrastructure providing the access for inspection of hydrotechnical works. For this reason, the outer deck walls of the webs have openings located above the support walls. This results in a local reduction of the girder stiffness in the area of the support walls connections. The girder is supported on concrete support walls of 20 cm via the set of three steel plate bearings placed under the box webs. The cross section and spans layout is shown in Figure 1. The first two spans (A–C) of the bridge, over the water-bed are considered in this research work because on one side, maximum moment is experienced at the central support while on the other side, different crack patterns can be observed in both the spans.

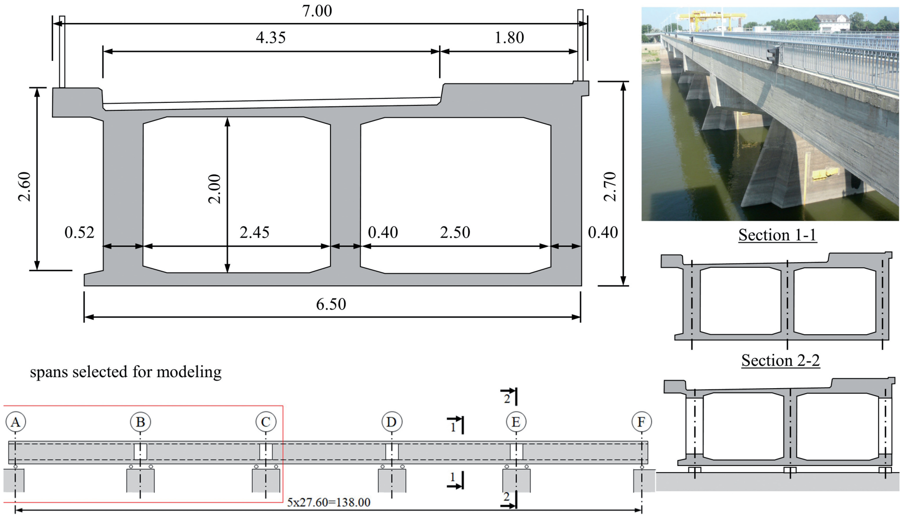

Fig. 1. Bridge cross section and spans layout

The bridge's hidden capacities and their predictive models have been developed in the past but similar defects are addressed in every archival report. These reports suggested certain strengthening or complete dismantling. The archival reports from 1998 showed the presence of cracks for the first time, since then every report has mentioned these cracks, with a significant increase in the location of cracks. The technical condition has not been improved so far. As the infrastructure is to be used only for the next 15 years, the overall reconstruction is economically and technically irrational in this case. Therefore, implementation of SHM system is found to be a viable solution for the above-mentioned case. This system would enhance safe bridge operation for the next 15 years, reduce inspection costs, and monitor certain defects, especially cracking.

3. Evaluation of concrete properties

In-situ measurements are carried out for strength-based evaluation of concrete. It also helps to determine the material nonlinearity and its basic properties. Concrete compressive strength testing was done on seven cores (90×180 mm) that were extracted from the structure. Core testing yielded the average compressive cylinder strength of concrete as 17.5 N/mm^2 with the relative spread of 27%. The characteristic compressive strength was measured as 10 N/mm^2, showing the concrete class as C10/12. The concrete strength is found to be less than the design value, due to extensive cracking of concrete. To further explore this issue, NDT evaluation was also performed. Total nine tests (216 measurements) were performed with the help of Rebound Schmidt hammer. The average compressive strength value of the concrete was measured to be 17.5 N/mm^2 with an average rebound value of 48.4. The relative variance was found to be between 22–27%. The results of the NDT evaluation verify the core testing as lower concrete strength is observed in both cases. This strength is insufficient even for small structures, according to Eurocode-2 (EC) [45], and so as for the RC bridges, like the one mentioned in this case study. Signs of this weak strength were also observed from the broken pieces of the test specimen. The on-site crack evaluation showed that most of the cracks were along the bridge's top and bottom slabs. The damaged expansion joint was clearly visible; having a critical crack width, which could lead to restrained heat motions, causing further cracking on the deck walls. Major cracks were observed on the external sides of the deck walls, having different crack pattern on both sides due to exposure to the sunlight (Figure 2). However, inside the box-girder, both sides of the webs somehow have a similar crack pattern. The on-site measured crack

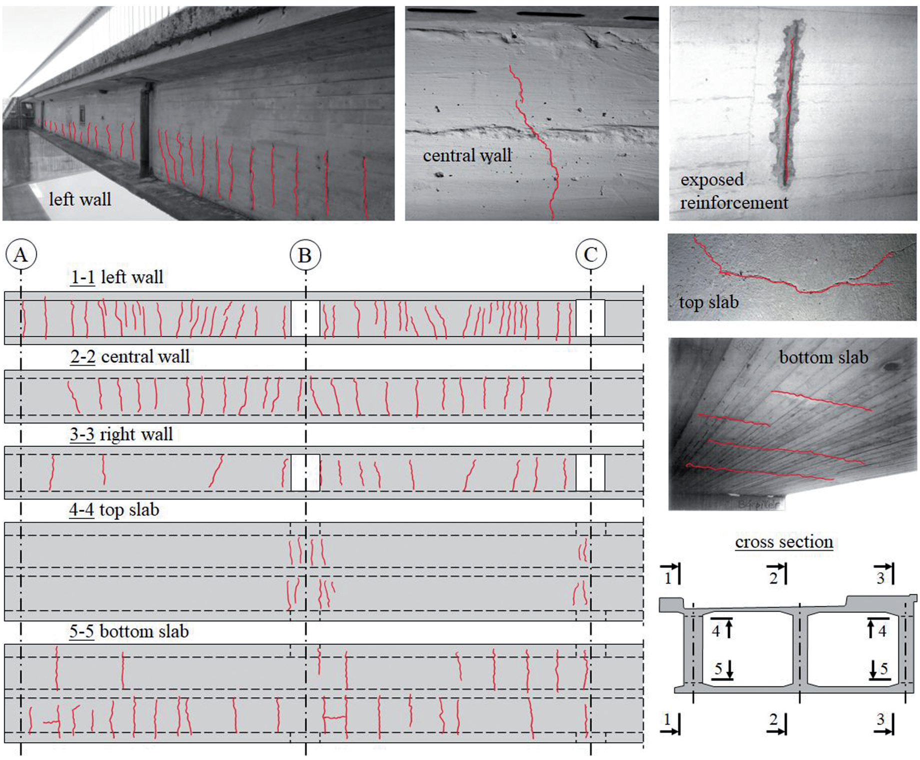

Fig. 2. Identified cracks at different locations

width exceeds the value of 0.6–0.8 mm in many cases (at the joint of webs and slabs of the box section), which is above the limit value of 0.3 mm [45]. These pre-existing cracks are considered in the numerical models by using the decreased elastic modulus of concrete. There is no direct way to use these cracks in the AXIS VM software so reduced elastic modulus (reduction of 0.6) was used to fulfill this purpose.

4. Finite Element Modelling (FEM) based analysis

4.1. Preliminary static analysis

Static linear analysis is carried out using AXIS VM software to calculate internal forces and check for the displacement capacity of the bridge, as per the EC. So, for this strength-based design an elastic model of two spans (A–C) is developed as a shell element. Loading of the structure includes the application of live loads as 7 kN/m^2(taken from the standard load given in the EC for this type of bridge structures), permanent loads (besides self-weight) as 1.9 kN/m^2, moving loads (vehicular load) as a concentrated and a distributed load of 300 kN and 4 kN/m^2 respectively, and the temperature loads as +20/–60°C by considering the thermal expansion effects. The supports' (bearings) stiffness is considered to be quite stiff against the vertical movements without any calculations, because there is a solid concrete structure under it. These bearings are supported by 20 cm thick support walls. Connections between the deck walls and bearings are kept pinned at support A while the roller at B and C, as per the actual conditions at the bridge. The supporting walls have a fixed connection with maximum stiffness at support A and relatively less stiff supports at B and C. Actual reinforcement is added to the bridge model, just to analyze the internal forces and cracking in the bridge (Figure 3).

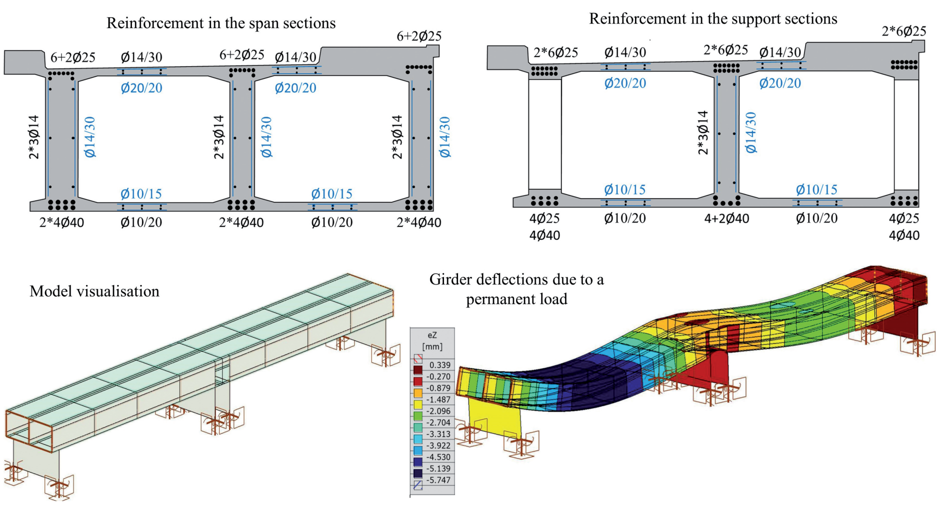

Fig. 3. Static linear model created in AXIS VM software

4.1.1. Static analysis results

As the current analysis is aimed at finding displacement, so, the results of displacement rather than the forces are required to fulfill the damage limit state. A detailed analysis shows that the maximum vertical deflection is almost 6 mm at the center of the span AB (Figure 3). Bridge condition assessment is based on displacement comparisons between calculated results and the code criteria, therefore, by applying the maximum deflection criteria as per the EC ($L/400 = 27600/400 = 69$ mm) maximum deflection is found to be less than the limit value. Thus, the bridge is showing satisfactory performance against displacement damage.

However, cracking is observed as one of the major problems. The complete crack profile (with ranges) in the top and bottom slab (wk.(t), wk.(b)) is shown in Figure 4. The cracks at the middle of the span in the bottom slab (0.80–0.99 mm), and at the support in the top slab (0.10–0.33 mm) seem to be reasonable because these are the locations of highest bending moment. Cracks in the side wall of deck below the top slab, at the end of span, are critical (reaching up to 1.54 mm), as thermal changes are applied to the bridge. Moreover, these are the places where the highest shear stresses are transferred from the slab to the deck wall producing cracks of maximum width. This maximum crack width is due to several reasons. First, in the numerical model there is a peak stress at some points, however in the real structure these stresses will be lower e.g., if a small crack appears, the stiffness will be reduced there, and the internal forces will be redistributed because of that, furthermore, having actual structural thicknesses will result in different internal forces than in the numerical model, where everything is represented by single lines or surfaces).

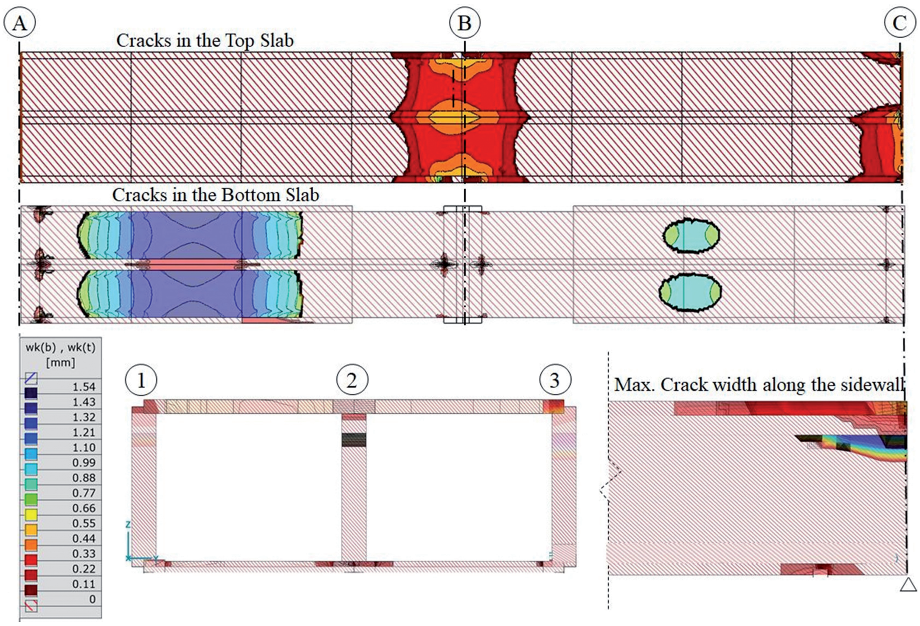

Fig. 4. Visualization of critical crack width

Secondly, in the model, numerical calculations are done at design level, considering weaker material properties and higher design loads. These loads are giving consideration to the fact that the bridge is operated under full traffic, and to be satisfactory according to EC. Therefore, by comparing these results with the EC criteria, it is observed that the results are far above the allowable crack width of 0.3 mm (for the frequent combination of loads), confirming that the structure needs special attention against the crack width issue.

4.1.2. Static analysis results summary

Static analysis results conclude that the bridge is experiencing satisfactory shear resistance. The bridge was originally designed using the Hungarian Road Bridge Regulations Part-I&II- KPM HI W/1-67 (MSZ–07–3701–67) [46]. According to these regulations, most of the shear resistance is provided by bent up steel bars and stirrups. If both the applied shear reinforcements are considered, then half of the shear force is taken by the stirrups, making the structure strong enough to resist the design shear forces acting on the bridge. The resistance of the bent steel bars is well above the shear force derived from a standard load, which is providing sufficient shear resistance to the bridge structure. Surface stresses in the tensioned zones are slightly higher than the tensile strength of concrete, but the reinforcement will take these higher stresses, making them comparable with internal forces. Moreover, the bending capacity of the bridge at the midspan and supports is also satisfactory. Furthermore, all the stress controls are also observed in the satisfactory range. However, the bridge has only a small capacity to bear additional loads even after retrofitting [47].

4.2. Non-linear 3D analysis

3D Non-linear analysis is carried out using ATENA software based on non-linear material properties. This analysis overcomes the limitations of static analysis and provides the more accurate results. Geometric model starts with the material selection followed by macro-element generation, material assignment, loading of structure, meshing, and analysis set up.

In this analysis, modelling is done on the principle of shell element theory with the cross section of 2D macro-elements. Smeared cracked material approach is used for the concrete. As per the findings of in-situ measurements, concrete with the elastic modulus of lower range value (31.7 GPA) is selected. This material selection is based on the applications of Biaxial Compression-Tension Failure, where the tensile strain is experienced within the concrete under the effect of poison ratio (0.2) in $x - y$ directions. In this way, the selected concrete is fully complying with the nonlinear biaxial stress-strain law. Cracked concrete is supposed to be a homogeneous material with orthotropic behavior. At different section levels of structural damage, a shear-sensitive model accounts for the axial force-bending-shear interaction (N-M-V). This methodology is very effective as it is based on a hybrid approach. On one side, it considers the multiaxial stresses generation in macro-elements, and on the other side accounts for the nonlinearities produced by cracking and the anisotropy of concrete.

Loading of structure is done in 40 intervals of nine load cycles (different load types) starting from zero to their maximum value. Load values are the same as defined in case of static analysis. Thinner mesh of size 0.05 m is used to get refined results. The analysis is carried out within the framework of Newton-Raphson method with tangent stiffness properties of finite elements. In this method non-linear algebraic equations are used to solve the non-linear finite element problems using the selected iterations.

4.2.1. 3D non-linear analysis results

After running the analysis, results are obtained in the post-processing phase. Maximum deflection is calculated to be 20 mm, while the minimum deflection is 5.4 mm. As the maximum deflection is less than the allowable value, thus the structure satisfies the deflection criteria [45]. Cracking is critical in this analysis. Maximum crack width is found to be 0.62 mm along the sidewall of deck at support C, which is higher than the limiting value of 0.30 mm. These results are comparable with static analysis where the critical crack width is found exactly at the same location.

The Load Displacement (LD) curve highlights the overall response of the bridge against the applied loads. As the shear is considered to be linear and bending is due to non-linear interactions, so the load-bearing capacity of the bridge keeps on increasing linearly until the appearance of shear cracks. These cracks appear when the structure experiences a higher load level (around 14.7 kN/m^2). At this the stage, the model experiences bending failure not only because of the crushing of concrete but also due to yielding of longitudinal reinforcement. So, the load value suddenly falls to 11.2 kN/m^2. After this, a resuming mechanism takes place which tries to stabilize the load-bearing capacity of concrete but fails to do so. Thus, the fractured concrete and yielded steel reinforcement cause an increase in displacements without further increase of load-bearing capacity of the bridge until stirrups fail, leading to the attainment of maximum displacement. In general, the extracted LD curve (Figure 5) represents the experimental behavior of materials precisely

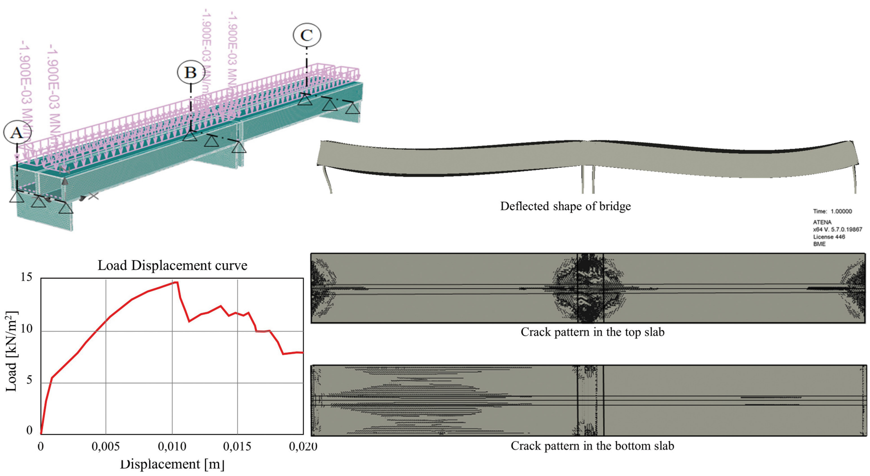

Fig. 5. Nonlinear analysis results and deflected shape of bridge

until the cracking of concrete and yielding of steel. Cracking pattern and deflected shape of bridge with LD curve is shown in Figure 5.

4.2.2. 3D non-linear analysis results summary

Conclusively, two major concerns are highlighted by 3D non-linear analysis results. One of them is cracking, and the other one is displacement. The bridge has sufficient bending and shear capacity in Ultimate Limit State; therefore, analysis results are satisfactory here as well. This analysis also proves the safety of the bridge against the deflection damage as maximum value (20 mm) is below the allowable limit ($L/400 = 69$ mm). Verification of stresses in SLS is also exhibiting satisfactory values. The cracks at the mid supports of two spans are very critical due to a stiff resistance against the vehicular loads. Finally, the extracted crack pattern of slabs is quite similar to the crack's profiles drawn by static analysis. These results are more accurate and closer to the conclusions of the in-situ measurements. Considering the outcomes of this assessment, the next step is to install sensors along the full length of the bridge for future monitoring.

4.3. Discussion of NDT and FEM analysis results

In-situ measurements provided the material properties, which are further used by static linear and 3D nonlinear analysis in this case study. These measurements highlight the strength and stability issues of the bridge and report the out of limit crack widths at certain places while mapping the cracks along the full length of bridge. These observations are then verified by static linear and 3D non-linear analysis. So, all these analysis methods highlighted the same and the only issue associated to this bridge which is observed as the major problem. This is a commonly observed issue of concrete structures built over the water-bed due to exposure to moisture and dense humidity. The reason for these cracks is that in the numerical model we have peak stresses in some points, but in the real structure, these stresses will be lower (e.g., if a small crack appears, the stiffness will be reduced in that area, and the internal forces will be redistributed, or having actual structural thicknesses will result in different internal forces than in the numerical model, where everything is represented by single lines or surfaces). Moreover, the numerical calculation is done on the design level, considering weaker material properties and higher loads than the ones in reality. When the calculations are done on mean level (using the mean values of material properties and loads), its possible to compare the results to the real bridge better. Infact the real bridge does not experience as much load as applied in the calculation, but this is done to see the operationality of bridge under full traffic, and to be satisfactory according to EC.

5. Proposal of the SHM system

Based on the inspection results, material tests, and assessment of the technical condition of the bridge described above, it is observed that the structure exhibits considerable damage, indicating a reduced load-bearing capacity of the box girder. Therefore, with such reduced functional properties and durability, the structure's degradation level will accelerate over time, which either calls for an extensive renovation or the complete replacement of the spans. Therefore, long-term plans assume the reconstruction of the entire infrastructure, however, until then, the bridge must guarantee safety. Furthermore, the assumed operating life of the existing components is approximately 15 years. Therefore, replacing spans or a thorough repair with reinforcement is not an economical solution. Thus, the authors proposed a solution that will extend the life cycle of the bridge with minimal repair costs while reducing the risk of failure.

The proposal is to install a Structural Health Monitoring (SHM) system. Several assumptions are made while planning this system. First, the system should be in operation for 15 years and be able to alert the authorities when a sudden drop in the load-bearing capacity is observed. The second assumption applies to the restrictions on traffic organization on the bridge by determining the load limit (up to 300 kN), speed (up to 30 km/h), and the weight monitoring of passing vehicles. The third provides information about the load-bearing capacity that will be obtained using at least two different techniques in several critical places like deck connections with its walls, opening of the deck walls and supports. Lastly, it is assumed that together with the installation of the SHM system, protective work should be performed, particularly anti-corrosion protection of the exposed reinforcement and injection of the indicated cracks. Therefore, it is proposed that the planned system should record the deformation of the structure by measuring the vertical displacements of the spans and the deformation of the box girder at the places highly exposed to cracks. This system consists of a set of sensors, weigh in motion system on both sided access roads of the bridge, power wirings, and electronic gadgets data acquisition. Another integral part of this system is the software data analysis, providing the visualization and tracking of crucial information associated with the behavior of the structure.

The proposed SHM system provides for the installation of two essential measuring devices. The first are sensors for measuring vertical displacements. Their task is to monitor changes in the grade line. For this purpose, a series-connected Liquid Levelling Sensor (LLS) has been proposed; that uses the communicating vessel principle (Figure 6). Together

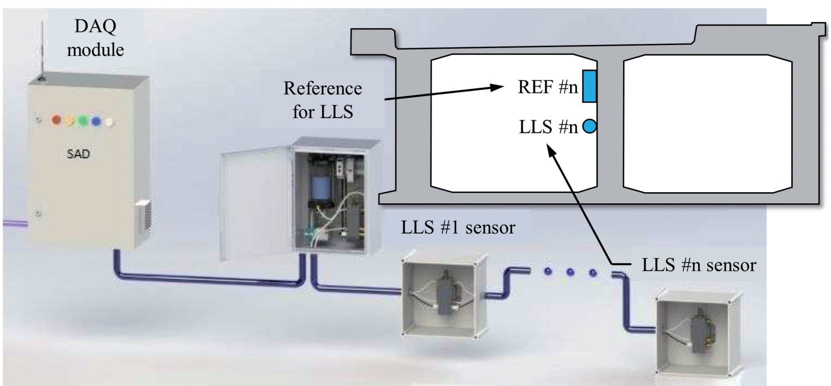

Fig. 6. Liquid Levelling Sensors for measuring vertical displacements of spans

with the reference station, they will form a hydrostatic system for measuring changes in displacement in relation to the reference point on the extreme supports.

The second device will be fiber optic sensors for geometrically continuous measurements, type DFOS (Distributed Fiber Optic Sensing). These are sensors in the form of composite reinforcing bars with a diameter of approx. 5–6 mm called Epsilon Rebar. The key feature of the Epsilon Rebar is that it is made of one composite material. Its cross-section is monolithic, without any intermediate layers. They guarantee accurate strain transfer from the concrete to the optical fiber inside the sensor. In addition to that its external surface is ribbed to provide appropriate mechanical bonding with the surrounding concrete. Sensors will be placed in grooves approx. 7–8 mm wide and of the same depth. Their location on the cross-section of the box girder is shown in Figure 7.

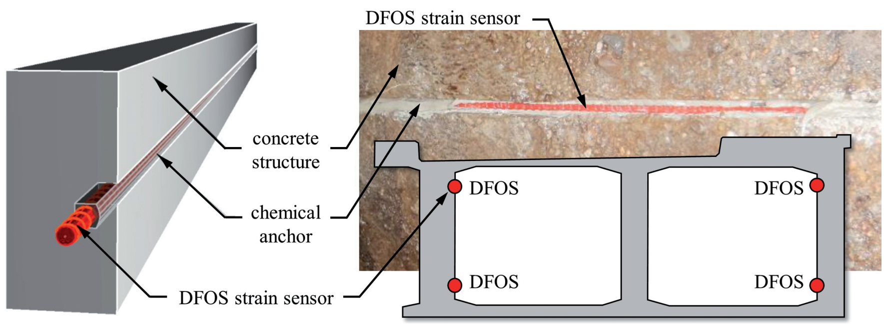

Fig. 7. DFOS sensors on the cross-section of a box girder

The four outer corners of the girder box are indicated at the contact of the outer webs with the upper and lower plate. The final location of the bar sensors should be determined in situ. It should fit in the concrete cover during installation without damaging the existing reinforcement. The resin adhesive composition carries out the transfer of deformations from concrete to the sensors. Therefore, the sensors should enable the measurement of strains, i.e., because of changes in the width of the cracks and temperature. Moreover, using the knowledge of the distance between the sensor axes, it is possible to determine the deformation of bridge spans understood as its displacement Epsilon Rebars.

In addition to the described set of sensors, two Weigh in Motion (WIM) devices are also planned to be used. To initiate and close measurement sessions, they should be integrated with the main data acquisition system (DAQ). Each vehicle passing the WIM device can force the entire system to record the measurement data. In turn, driving through the second WIM device will end of the registration process. Locations of all significant components of a planned SHM system are shown in Figure 8.

So, the recorded data must be pre-processed in order to determine the extreme values and to be archived. Subsequently, SHM system management software modules will later make use of such reduced signals and will be transferred to the reporting and visualization module. Users will receive periodic reports via email. They will also have authorized access to the running application that will be used to clearly present data in tabular and graphical

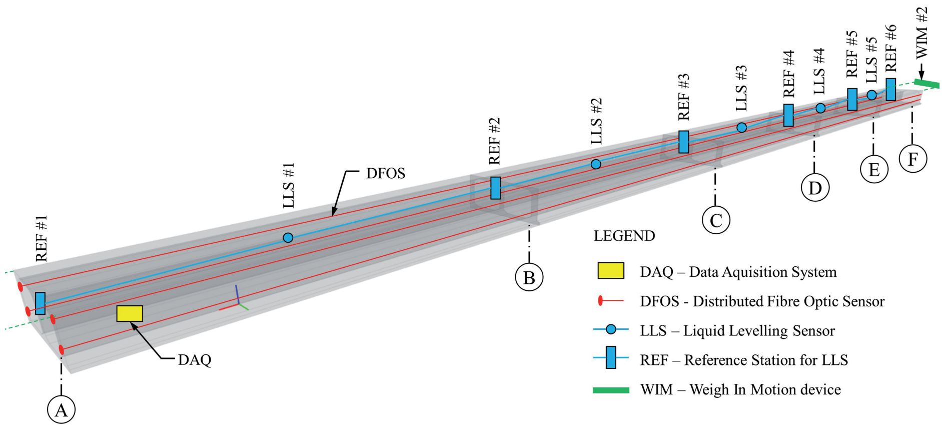

Fig. 8. Location of the essential elements of the SHM system

form over time. It will also show alarm conditions and threshold violations. Later, the data will be synthesized according to a specific conversion algorithm in additional modules – diagnostic, alarm, and expert.

6. Conclusions

The findings of this whole research can be concluded with the comparison of results extracted from three different types of analysis methods and their recommendations for the development of SHM system that can be installed on RC bridges having a similar situation as considered in this case-study. Analysis results yields following observations:

- Out of limit crack width, calculated as 0.4 mm in case of in-situ investigations, 1.5 mm in case of static analysis and 0.6 mm in case of non-linear analysis, exceeds the EC limits (0.3 mm).
- High values of temperature and humidity variations cause cracking and weathering of concrete.
- Extensive corrosion of steel bars was observed which is due to small concrete cover.
- Bridge deflection is observed in the safe zone as it is calculated to 6 mm in case of static analysis and 20 mm in case of non-linear analysis, so both values are below the EC limits (69 mm) bridge.
- Bending and shear capacity of the bridge in Ultimate Limit State and stresses in Serviceability Limit State, are satisfying the criteria as per the guidelines of EC.

Above results are more refined in 3D non-linear analysis and have closer values to the in-situ investigation. Hence, a 3D non-linear analysis is highly recommended for the damage assessment and evaluation of bridge.

Further, to monitor associated damage and to ensure safer operations of the bridge, a SHM system is proposed in this study. This system includes the installation of Liquid

Levelling Sensor (LLS) for measurement of vertical displacement, Distributed Fiber Optic Sensors (DFOS) for deformation monitoring and Weigh in Motion devices for monitoring of moving loads on bridges. Installation of this system is subjected to following measures.

- The system will be in operation for 15 years and will alert the authorities when a sudden drop in the load-bearing capacity is observed.
- Load (up to 300 kN) and speed limits (up to 30 km/h) are recommended with a monitoring of passing vehicle weight.
- One directional traffic flow to be implemented on the bridge.
- Together with the SHM system, protective works, particularly anti-corrosion protection of the exposed reinforcement and injection of the indicated cracks should be performed.

So SHM system with the practical implementation of above restrictions will enhance safe bridge operations for the next 15 years, reduce inspection costs, and monitor certain defects, especially cracking.

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