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Evaluation of Fatigue-sensitive Details in a Railway Danube Bridge by FE Analysis and SHM Measurements

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Abstract

Structural health monitoring system (SHM) has an essential role in the prediction of steel bridges behavior and damage detection. Due to site difficulties and economic reasons, it is not possible to instrumenting all sensitive details within the structure. Finite element modelling is an effective tool for analyzing fatigue-sensitive details, as it enables the extension and interpretation of measured data. This study investigates the structural health monitoring (SHM) system of Southern Railway Danube bridge located in Budapest from fatigue sensitive details point of view. The research applies load testing data for the validation of finite elements models (FEM) which are to be used for specifying the sensitive details. Based on a detailed stress analysis, three fatigue-sensitive areas were identified in the bridge, as follows: 1. the cutout holes of cross girder, 2. the cope-holes, and 3. the transvers welding of bottom flange. Artificial cracks are applied in these details separately to investigate the efficiency of SHM system for crack detection. Stress values at the location of strain gauge points of the SHM system are calculated continuously as cracks size increased, simulating the propagation. The results show that the SHM strain gauges in the current placements not highly efficient to detect the cracks of the investigated details. The study extended to propose strain gauge positions to recognize the crack initiation and propagation in these details.

Keywords

railway bridge, structural health monitoring, finite elements model, fatigue

1 Introduction

In the last century by the rapid development of the road and railway infrastructures, huge number of steel bridges were built to support the increasing of traffic volumes and expansion of railway networks. Most of these bridges are still in service reaching their design life [1]. Regarding steel railway bridges, a survey by the European Project on Sustainable Bridges found that the majority of railway bridges are between 50 and 100 years old. The 75% of steel railway bridges are over 50 years old, and nearly 35% are over 100 years old [2]. A research conducted by the American Society of Civil Engineers (ASCE) reveals that 80–90% of failures in steel structures are attributed to fatigue and fracture [3]. Moreover, due to numerous bridge collapses worldwide in the past, it became evident that relying solely on visual inspections might be insufficient for accurately assessing bridge condition [4] so that, structural health monitoring (SHM) is essential in the assessment of steel bridges, given the critical importance of their safety and integrity [5]. Fatigue is a crucial phenomenon, a recent research report [6] revealed that 38% of metallic bridges failure as a result of fatigue. Moreover, assessing the fatigue life of structural components in metallic bridges is a significant challenge for bridge engineers, to ensure proper maintenance and management of these structures [7]. However, due to field restrictions and difficulty of access to some structural details, the required time for install of measurements for entire structure may be take 75% of testing time, furthermore the cost of installation may be over than 25% of testing cost [8]. The above-mentioned drawbacks make it impossible to instrument and monitoring all fatigue critical details. Recently, a combination of in-situ measurements with FE analysis for accurate simulation of structural behavior, with minimal number of measurement points in demand. A novel procedure proposed by [9] which integrates real measurements from sensor with FE analysis to

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predict hot spot stress at uninstrumented points. On the other hand, a laboratory tests and field measurements carried out to develop and validate an analytical model which is then used to assess the capacity of steel bridge to support heavier train loads [10, 11]. In addition, a case study was presented for a steel railway bridge in which dynamic and quasi-static measurements were utilized to calibrate a FE model and propose a strengthening scheme [12]. Consequently, attention in constructing and applying an effective SHM system for evaluating health condition of the structures has considerably increased over the last decades. The goal of most previous studies is to detect damages by utilize the deterioration in the dynamic characteristics of the bridge [13]. Likewise, a virtual monitoring system combined Bridge Weighing-Motion (B-WIM) measurements with the structural health monitoring for fatigue damage calculations [14]. Similarly, a field implementation of wireless large area strain sensors used for fatigue crack detection in extended area [15]. Due to the trend of automation, machine learning tools are also used for locating of fatigue damages in steel railway bridge by enabling automatic analysis of raw strain measurements [16]. A combination of validated FE and experimental results used to propose a novel hybrid SHM system for damage detection in steel bridges [17].

Despite the structural health monitoring studies thrive, there remains a significant shortage in the literature concerning the evaluation of SHM efficiency for crack detection in steel structures. Exploring this gap, it is essential to design more reliable SHM system that can ensure early detection of cracks which leads to an increasing of safety and durability. The current research at the Department of Structural Engineering of BME has a focus on this problem, and this paper presents the results of the first phase of the research. This research adopts a dual-methodology approach to achieve its objectives. The first methodology involves developing and validating a multi-level Finite Element (FE) model of the Southern Railway Danube Bridge using load testing results. This model is then utilized to identify fatigue-prone features within the cross girder of the floor system. Furthermore, the FE model is applied to assess the performance of the Structural Health Monitoring (SHM) system in detecting cracks in these critical details. This evaluation is conducted by analyzing variations in stress values calculated at the SHM measurement points located within the cross girder.

The second methodology focuses on optimizing sensor placement to enhance monitoring capabilities. New sensor positions are proposed to facilitate the prediction of damage progression by observing changes in sensor measurements. This approach aims to provide a deeper insight into the structural behavior of the bridge over time.

2 The Southern Railway Danube bridge

The new Southern Railway Danube bridges built in 2021 in Budapest. The bridge consists of three identical and separated superstructures, linking two sides of Hungary's capital and has a vital role for international railway traffic, as shown in Fig. 1. The bridge is a symmetric through-truss structure that works in conjunction with the orthotropic deck system. The spans of the truss are adapted to the existing substructures, measuring 49.26 + 4 × 98.52 + 49.26 m; the total length of the structure is 492.6 m. The upper chords of the trusses are hat sections, while the truss members are welded I-sections. The width of the hat sections remains constant at 680 mm along the entire length of the bridge, and the dimension between the web plates is also constant at 550 mm, which is the height of the truss members. The lower chord is a welded I-section placed in the plane of the inner web plates of the truss members, working together with the longitudinal girders, deck plate, and longitudinal stiffeners. The lower flange plates of the longitudinal and transverse girders are in the same plane. The transverse girders match the nodal arrangement of the lower truss, with 8210 mm between the joints of the truss. The cross-section of orthotropic deck system is shown in Fig. 2 consists of a 16 mm thick deck plate supported by longitudinal stiffeners with a profile of 240-20 mm. These longitudinal stiffeners pass through the cut-outs in the transverse girders and are welded to the web of the transverse girders. The longitudinal girders' web size is 950-16 mm, the lower flange is 500-30 mm. The web plates of the general transverse girders are 950-16 mm, and the lower flange plates are 500-30 mm. The web plates of the support transverse girders are increased to 20 mm, and the lower flange plates to 40 mm. The truss is designed with an upper wind bracing system. The orthotropic deck includes

Fig. 1 Aerial view of Southern Railway Danube bridge

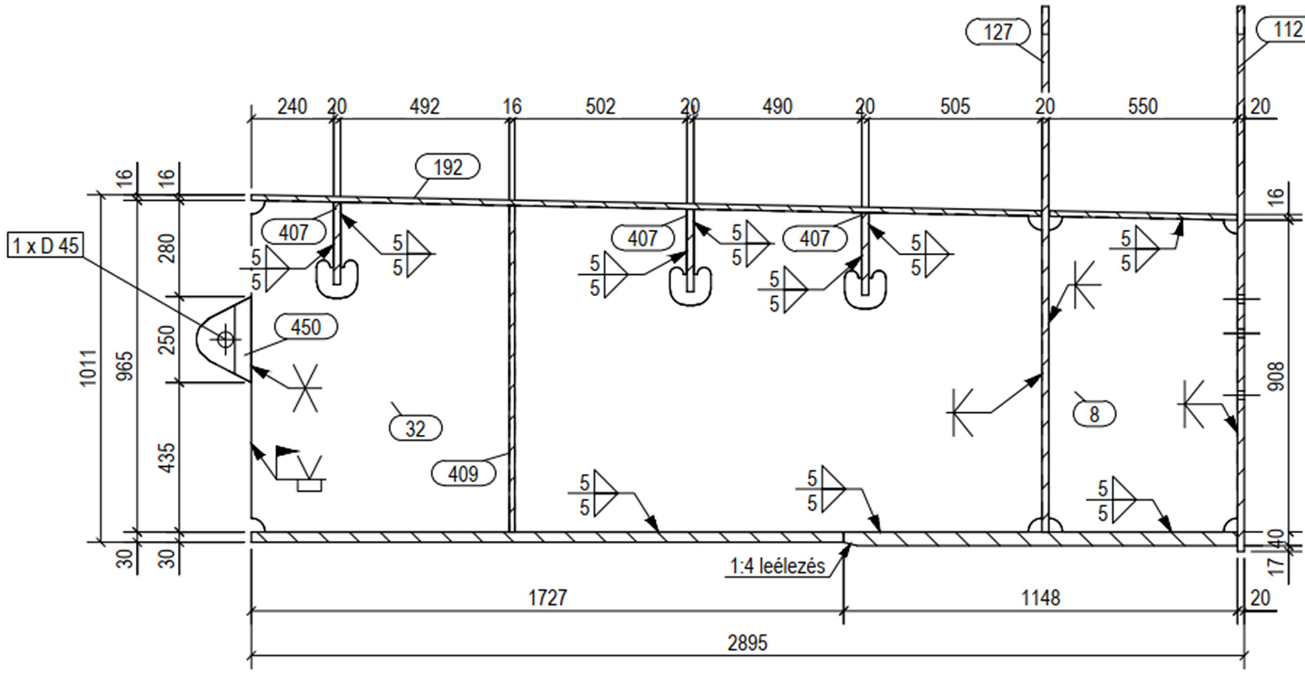

Fig. 2 Cross-section of orthotropic deck system

a continuously supported, elastically fastened railway track system. A cantilevered inspection walkway is constructed on one side of the cross-section. The general design and characteristic of the structure are shown in Fig. 3.

3 Load test

Load test of the bridge was completed by the Department of Structural Engineering, Budapest University of Technology and Economics. The static load test was conducted by one locomotive and wagons with measured weights. Locomotive of type M62 with known geometry and axle loads with a total weight of 1120 kN, and wagons with four axles loaded with crushed stones were used to conduct a series of load cases. Bridge investigated under several load cases and four of them were selected for the model validation, as shown in Fig. 4. The first two load cases consist of one locomotive and 6 wagons (#6 & #7); the third load case represented by 4 wagons acting on the end span of the bridge (#8), while the fourth applied load case (#14), consists of one locomotive and 13 wagons acting on two consecutive spans. Wagons weights range from 475 to 627 kN.

In parallel of deflection measurements, strains were measured in specified points for all load cases. The purpose of strain measurements to determine normal stresses which are developing in the critical sections of the structure. Measurement process accomplished by using 110 KMT-LIAS 3/350 type uniaxial strain gauges with gauge length of 3 mm through the entire bridge. Bridge behavior checked globally by strain measurements of truss members and locally measurements in the orthotropic deck system, as illustrated in Fig. 5.

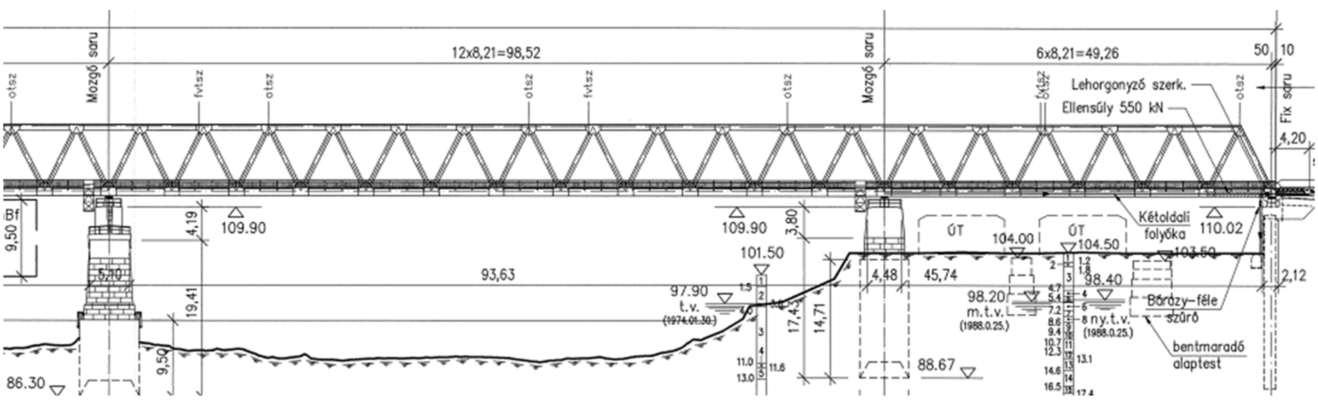

Fig. 3 Side view of the bridge end spans

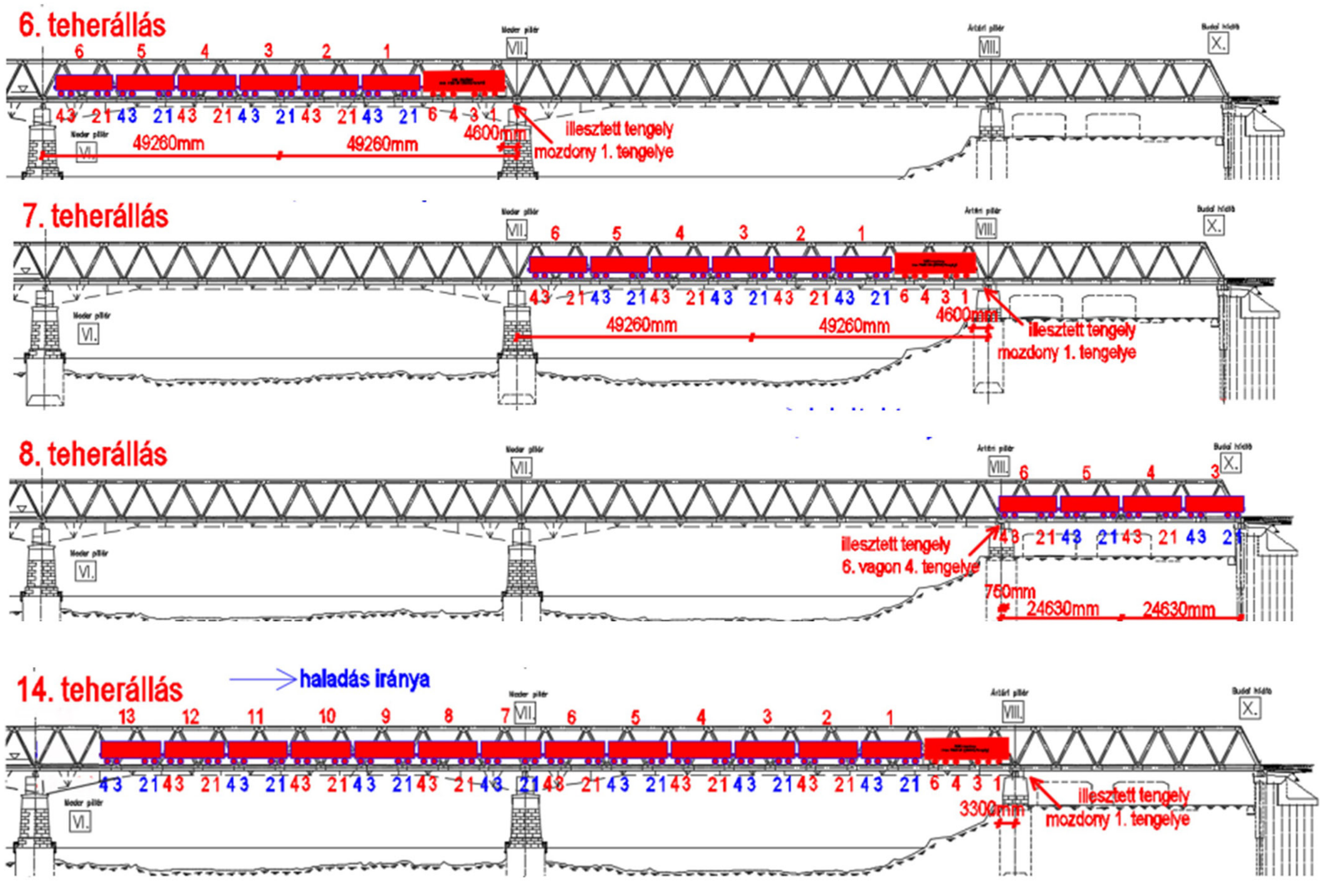

Fig. 4 Load cases

4 Finite element model

The FE models of the bridge are developed using the ANSYS general purpose FE analysis software [18]. This part of study focusing on the verification and validation of the models. The global model is basically built-up by shell element of type SHELL181. Beam188 elements are used to model the upper wind bracings. The details of the global model can be seen in Fig. 6. Weld fillets, cutouts, cope-holes, walkway, rail and sleepers were omitted from the global model. The size of elements should be determined to make a balance between accuracy and computational efficiency [19]. A global model is developed by three mesh densities, as follows:

1. 1502245 shell elements of size 100 mm and 17032 beam elements of size 100 mm,
2. 472217 shell elements of size 200 mm,
3. 228312 shell elements of size 300 mm.

The structural steel material properties of 210000 MPa elastic modulus and Poisson's ratio 0.3 are applied. Boundary conditions of the model were adopted to align with the support conditions of real structure; support on the first pillar was constrained in longitudinal, transverse, and vertical directions, while the supports of other pillars were constrained in the transverse and vertical directions only, allowing for longitudinal movement. Train axle loads applied as concentrated loads subjected to deck plate at points matching load positions on the real bridge.

The local model represents a specific segment of the steel bridge, emphasizing critical areas that are susceptible to fatigue or exhibit complex behavior under loading [20]. The focus is on the cross girder of the orthotropic deck positioned at the midpoint of the third span, as depicted in Fig. 7. The investigated cross girder was instrumented with strain gauges at points of section K3 for strain measurements due to train loading, as detailed in Fig. 5. Cutouts and cope-holes of through cross girder web were considered in local level. Local model utilizes the same material properties and element types that used in the global model, it consists of 242898 quadrilateral shell elements of size 20 mm. Degrees of freedom at nodes which connects the local region with the entire structure were calculated from global model, then it used as a boundary condition for analyzing of local model.

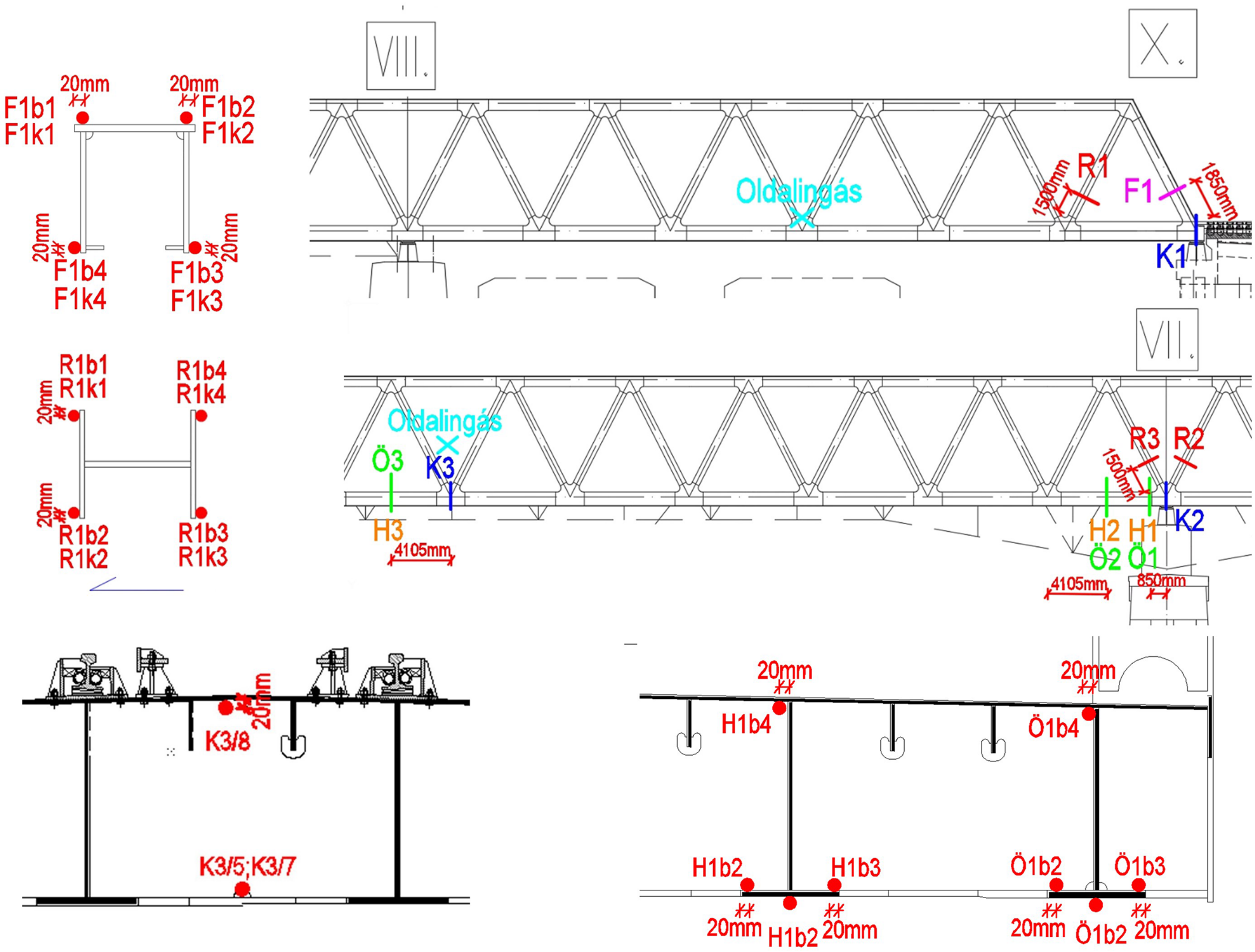

Fig. 5 Measurement points

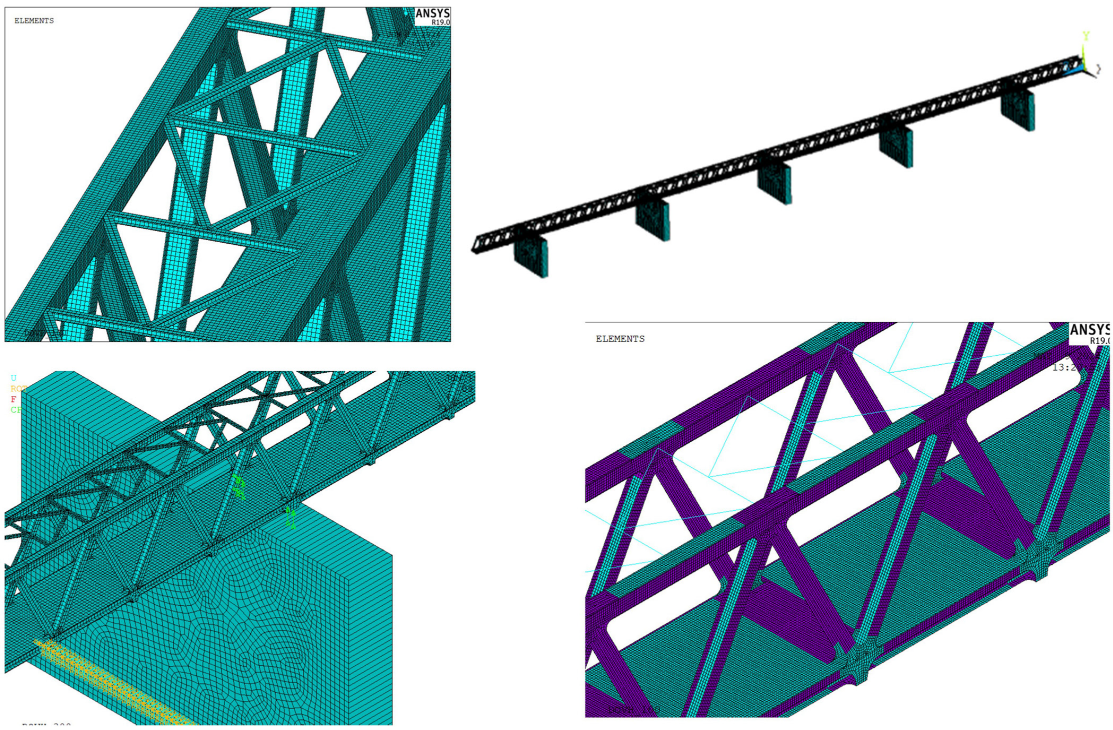

Fig. 6 Details of global model

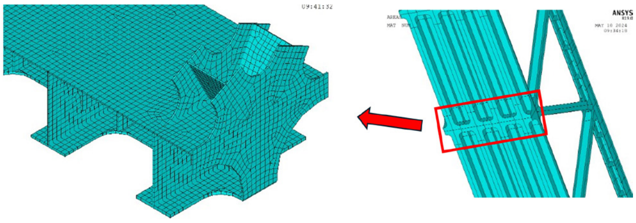

Fig. 7 Details of local model

4.1 Validation of global FE models

Validation is a crucial matter to ensure the accuracy of FE model and predicting the behavior of real bridge. Validation was accomplished by comparing FE results with the load test measurements, using the measured deflections and stresses. Through validation process FE model subjected to similar load conditions as the real structure and the resulting stresses and deflections calculated and analyzed. By comparison with the literature [21, 22], the FE results obtained in this study demonstrate a good agreement, confirming the model's capability to accurately represent the structural behavior under the applied loads. Fig. 8 represents the comparison of FE results with the measured deflection through load test and Figs. 9 and 10 demonstrate the comparison of stress results between FE and load test measurements.

4.2 Local model verification

A systematic mesh convergence study was conducted to determine the optimal mesh size. The study began with a coarser mesh size of 50 mm, progressively refined to smaller sizes of 40, 30, 20, 15, 10, and 5 mm. The mesh sensitivity analysis was performed at three measurement points (K3-5, K3-6, and K3-7) as shown in Fig. 5. At K3-6, the stress variation between successive mesh refinements was below the widely accepted threshold for mesh convergence [23]. K3-6 showed the largest deviation from experimental results by 3.4%, whereas K3-5 and K3-7 demonstrated closer agreement with the experimental data by 0.6% and 0.8%, respectively, as shown in Fig. 11. Based on these findings, a mesh size of 20 mm was chosen as it provides a suitable balance between numerical consistency and experimental accuracy.

5 Specifying of fatigue sensitive details

Due to manufacturing processes, steel structures contain several geometric discontinuities such as notch, holes, welded parts and sharp edges which can lead to stress concentration phenomenon. Most of mentioned discontinuities may considered a fatigue-prone details. In the current study the developed FE model is applied to explore fatigue sensitive details in the region of the investigated

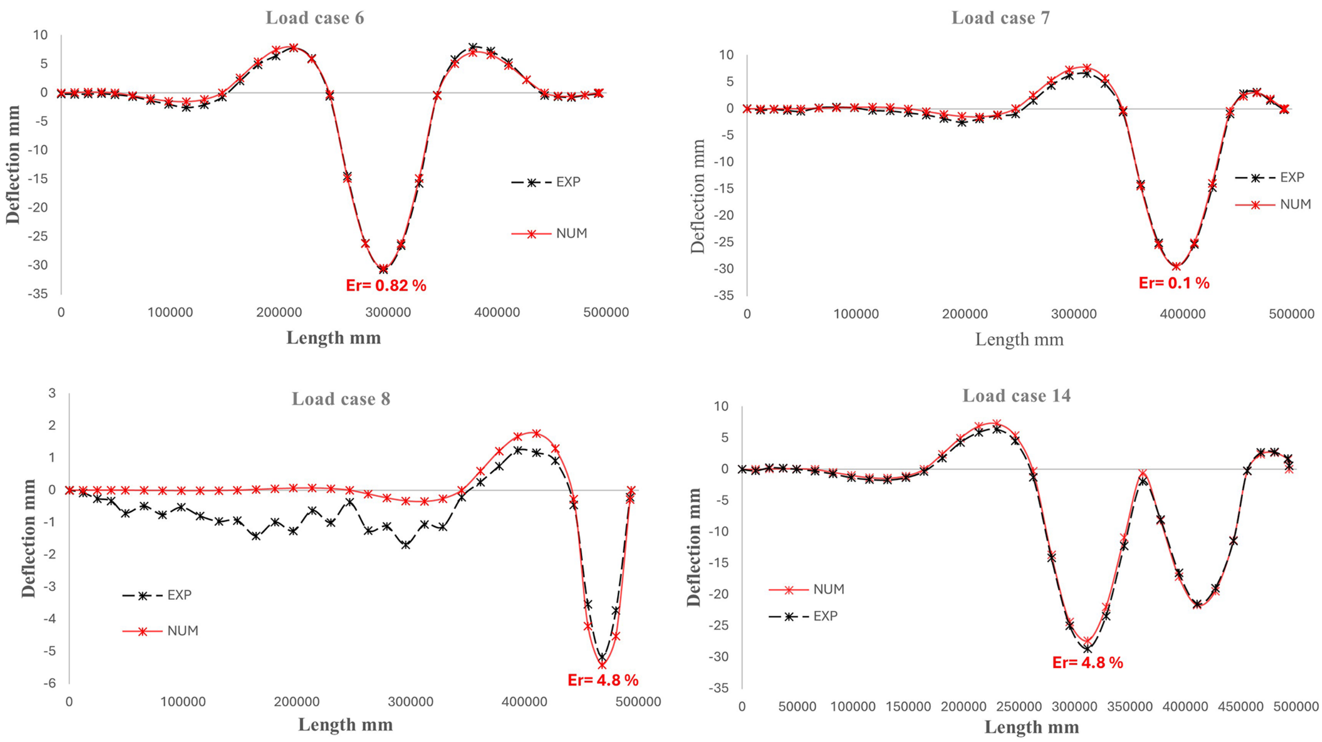

Fig. 8 FE model validation by deflection measurements

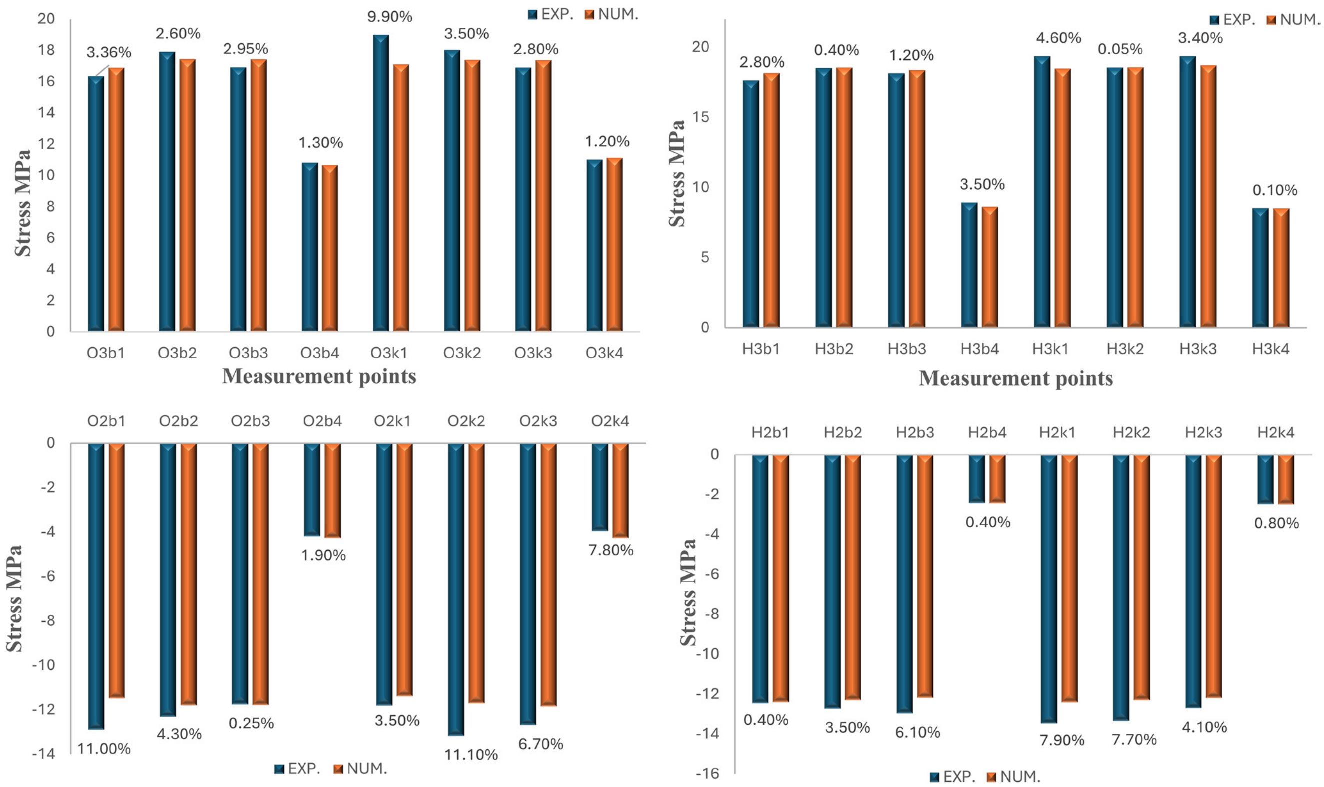

Fig. 9 FE model validation by stress measurements – 1

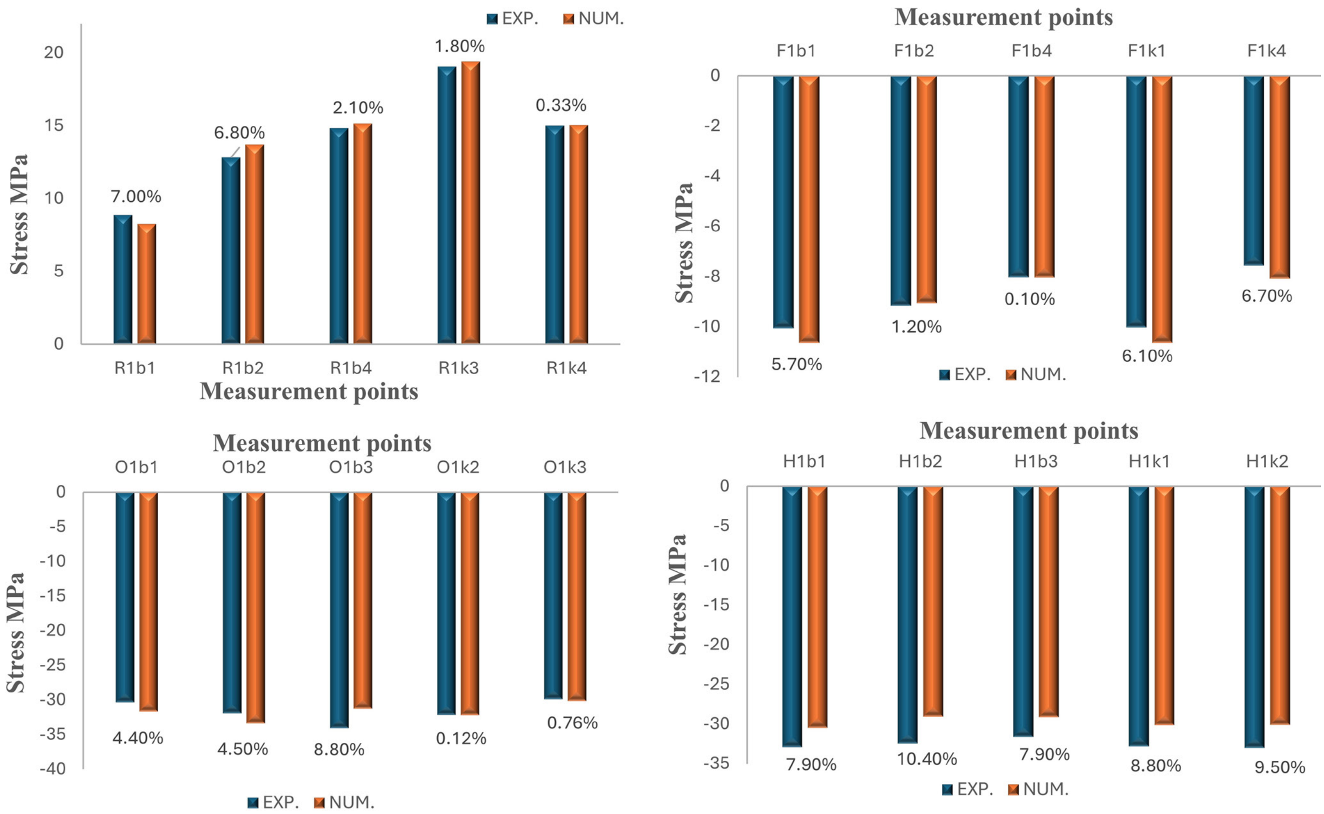

Fig. 10 FE model validation by stress measurements – 2

cross girder. Sensitive details are identified based on stress concentration points and by a comparison with structural components which are standardized as a fatigue- prone details in Eurocode 3 [24].

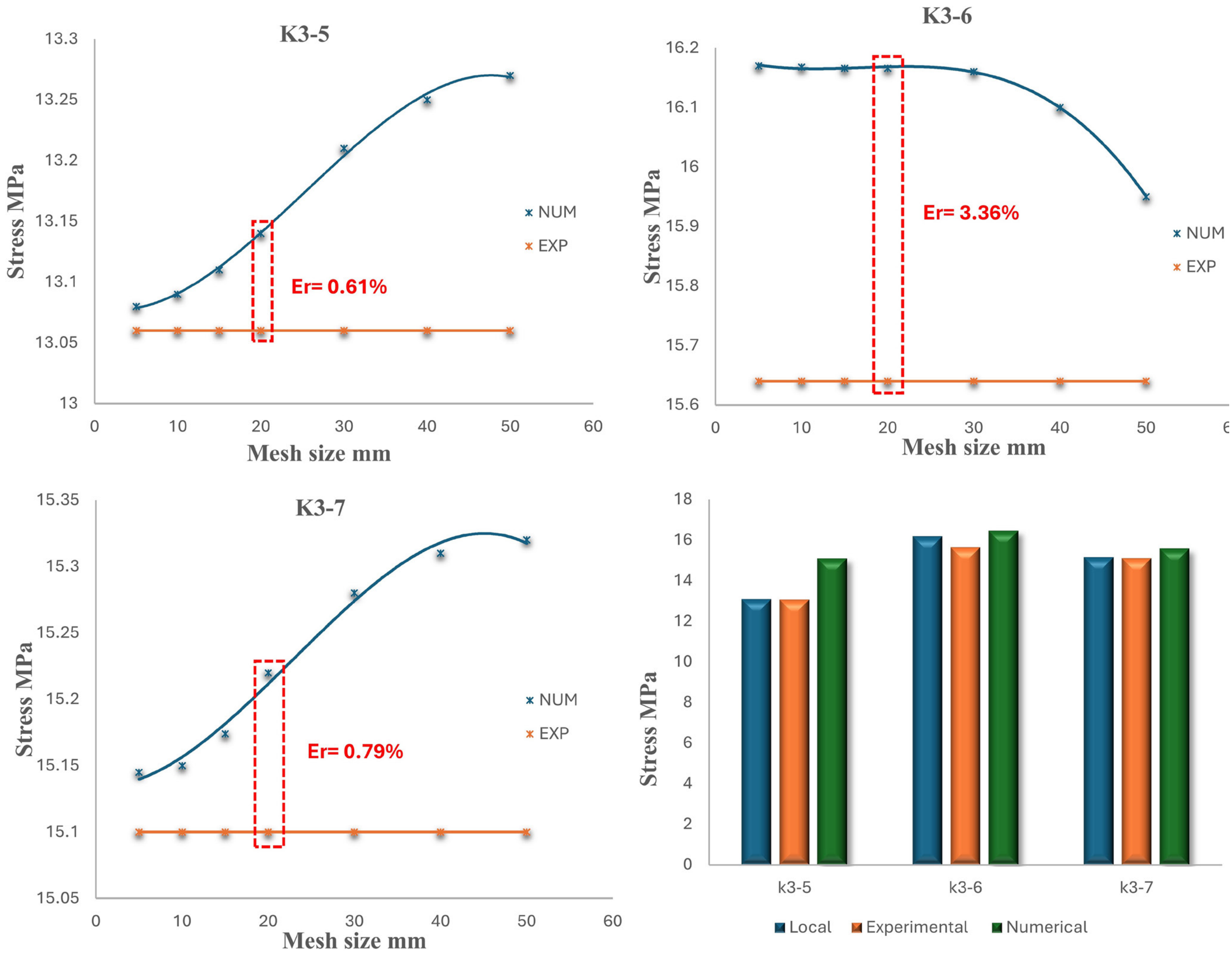

Fig. 11 Verification of local model

Due to these conditions, three fatigue-sensitive details are identified, as shown in Fig. 12:

1. the cutout of cross girder web classified in Eurocode 3 with a fatigue detail category of 56,
2. the lower cope-hole at the mid-span of cross girder classified with a fatigue detail category of 71, and
3. the transverse welding of different thickness plates of bottom flanges classified with a fatigue detail category of 90.

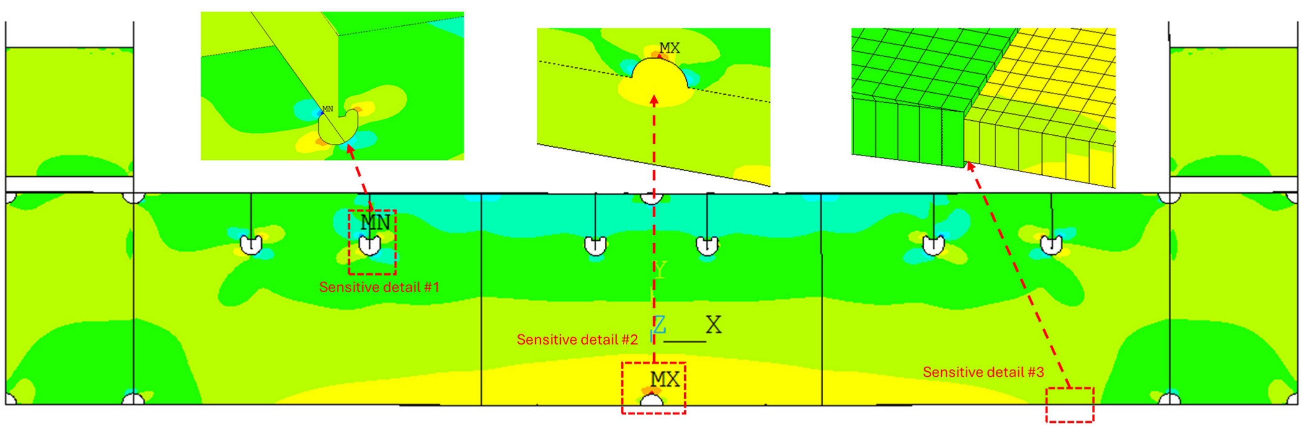

Fig. 12 Fatigue sensitive details

6 Structural health monitoring system of the bridge

Structural health monitoring (SHM) is a critical approach for ensuring the safety and longevity of steel bridges. In the case of the Southern Railway Danube bridge, a comprehensive SHM system was deployed, integrating various types of sensors to facilitate continuous monitoring and assessment of the structural integrity. These sensors are strategically placed throughout the bridge to capture both global and local structural behavior. Sensors positioned on the truss members are primarily used for global structural assessment, providing an overall view of the bridge's performance. Meanwhile, sensors embedded within the orthotropic deck focus on localized assessments, capturing detailed data specific to critical areas of the bridge. Local region (cross girder) was instrumented with 14 two-way strain gauge sensors for in-plane stress measurements, distributed at bottom flange, deck plate, web of internal longitudinal girders, and longitudinal stiffeners. Strain gauges were fixed at sections with 65 mm distance from the plane of cross girder, as illustrated in Fig. 13. The purpose of the further study is to check if these sensors – beside their other tasks – can detect fatigue cracks in the previously defined details.

6.1 Efficiency of SHM system for crack detection

Early detection of cracks in steel structures can prevent catastrophic failures and expensive repairs. The effectiveness of SHM in detecting cracks in steel bridges is influenced by several factors, including sensor types and position, data acquisition methods, and analysis techniques. In this study FE analysis is applied to investigate the sensitivity of SHM systems of the concerned bridge for cracks detecting within the sensitive details. Moreover, a specific region in a real bridge, composed of various geometric discontinuities which may present weaknesses that can initiate cracks. The study focused on three fatigue-prone details, as discussed previously and shown in Fig. 12. FE model is used to show the effects of cracks initiation and propagation in the sensitive details on calculated stress values at points compatible

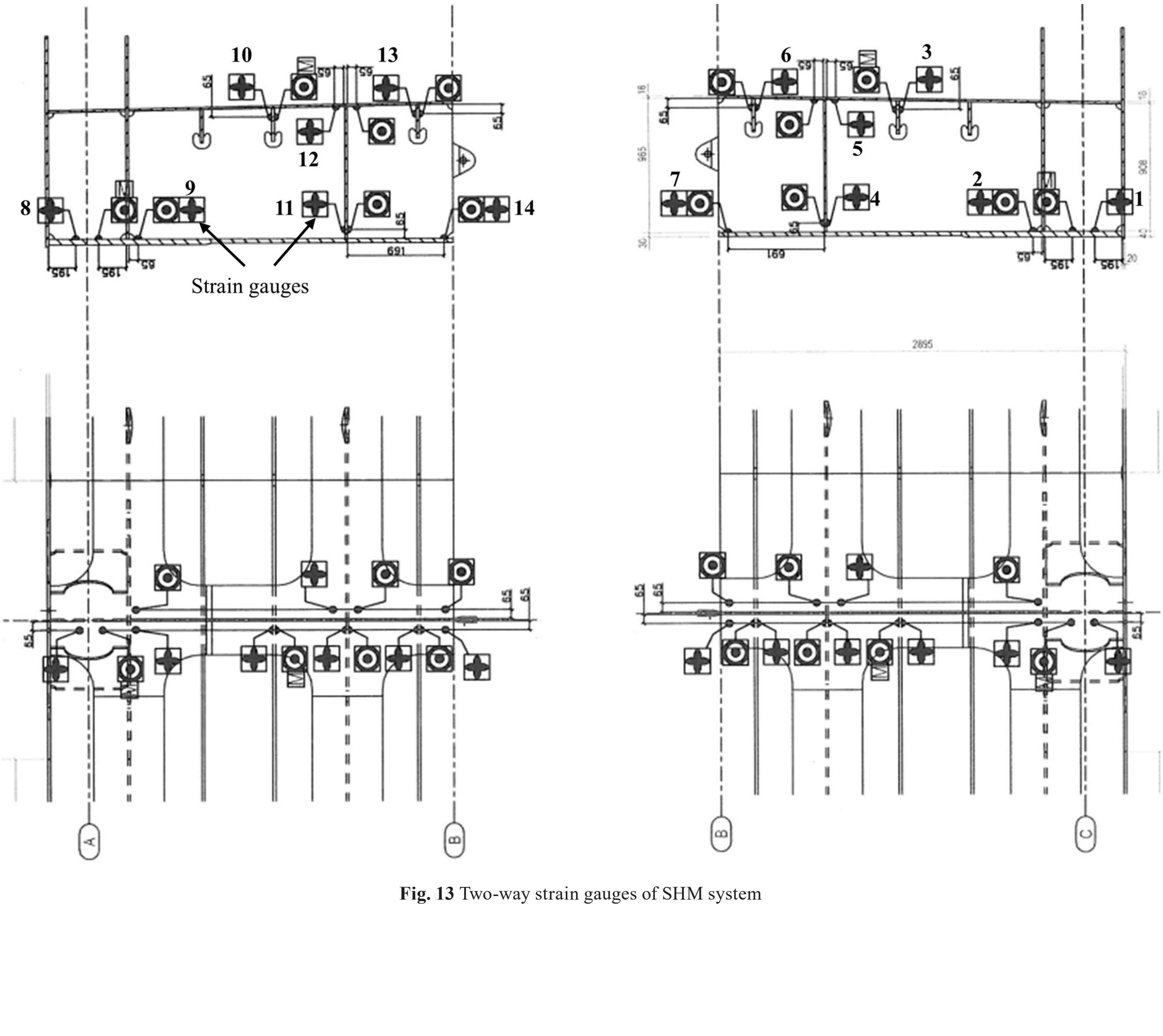

Fig. 13 Two-way strain gauges of SHM system

with SHM sensors. Consequently, changes in the trend of relative stress diagrams may indicate crack initiation and growth. Three artificial cracks are initiated and analyzed separately to investigate the crack detecting sensitivity of the SHM system, as shown in Fig. 14. Crack #1 applied through sensitive detail #1 (cutout), crack initiates at stress concentration point of cutout edge and aligned obliquely in a direction perpendicular to the principal stress. Crack #2 used in the sensitive detail #2 (cope-hole), the crack starts from the highest point of cope-hole and extending through cross girder web in a direction perpendicular to the longitudinal direction of cross girder. Crack #3 initiated from the edge of welded plates (detail #3) and oriented in parallel of welding direction toward the center of bottom flange.

The relative stresses with respect to zero crack values at the positions of SHM sensors are calculated continuously with increasing crack length. Then, the trends of the relative stresses are described against crack lengths for cracks #1, 2, and 3 in Figs. 15–17, respectively. The results revealed that the relative stresses calculated at the positions of strain gauges identified (Sy3, Sz7 and Sx2) are slightly affected. In contrast, the remaining sensor positions are not visibly affected by increasing crack length, showing that the current positions of these SHM sensors are not efficient in detecting fatigue damages of these details. Consequently, the analysis is extended to identify new sensor positions within the real structure to enhance the SHM system's capability for crack detection.

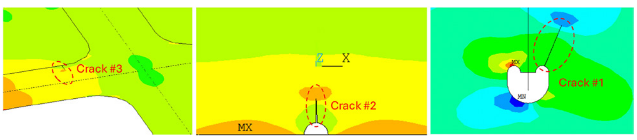

Fig. 14 Crack locations and directions

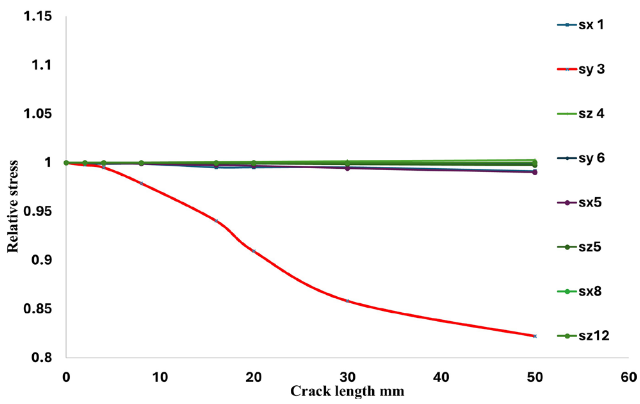

Fig. 15 Relative stress of SHM sensor positions via crack #1 propagation

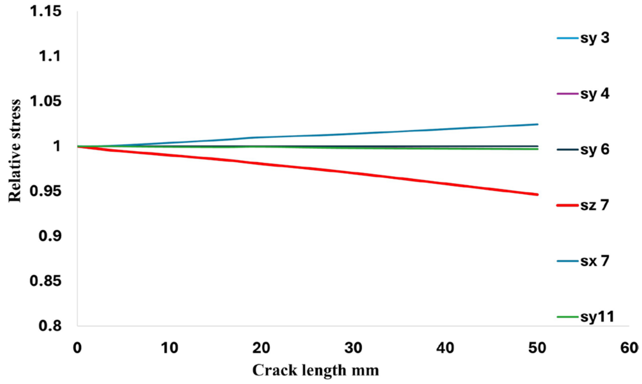

Fig. 16 Relative stress of SHM sensor positions via crack #2 propagation

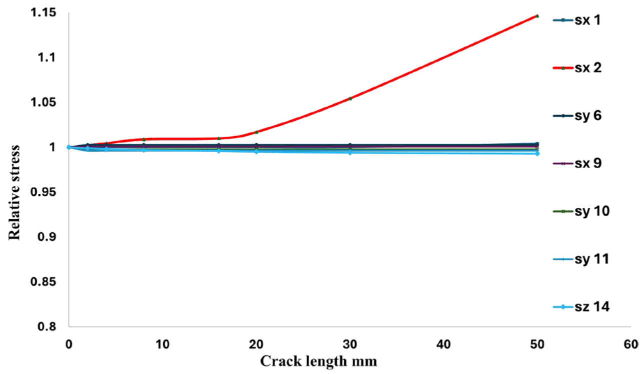

Fig. 17 Relative stress of SHM sensor positions via crack #3 propagation

The methodology for determining the new sensor positions is based on stress analysis conducted using a finite element (FE) model with increasing crack length. The FE model simulated stress distributions and identified areas of significant stress variation associated with crack initiation and propagation.

Sensors A and C were placed at locations where stress decreases were predicted by the FE analysis due to the initiation and growth of cracks #1 and #3, respectively. In contrast, position B was selected to monitor the expected stress increase caused by stress concentration as crack #2 develops and propagates, see Fig. 18. This placement ensures that the sensors effectively capture changes in stress patterns linked to crack progression, providing valuable insights for structural health monitoring, see Fig. 19.

The effectiveness of sensor positions for crack detection is identified by their ability to detect variations in stress caused by crack propagation compared to the stress in the absence of a crack. The effectiveness of proposed positions A, B, and C estimated due to specified crack lengths of 10, 30 and 50 mm. Table 1 compares the efficiency of the proposed positions and SHM placements for crack detection.

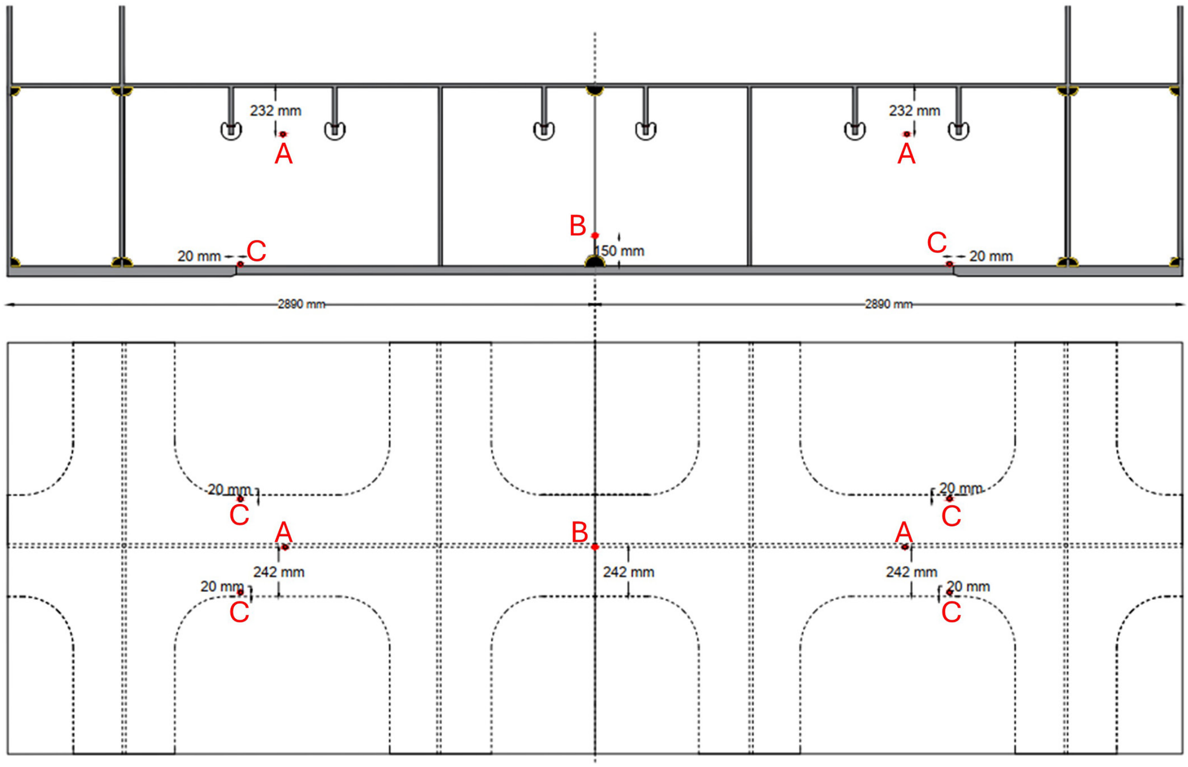

Fig. 18 Proposed sensor positions for crack detection

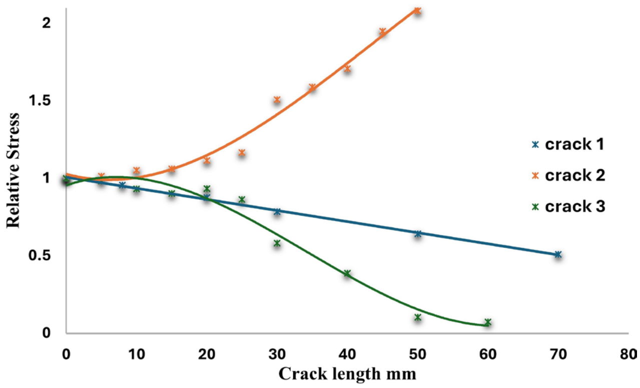

Fig. 19 Relative stress of proposed position via cracks propagation

Table 1 Efficiency of proposed and SHM positions for crack detection

Sensor category	Code	Effectiveness		
		10 mm	30 mm	50 mm
SHM	Sy 3	2.8%	14.2%	17.8%
	Sz 7	0.95%	3.0%	5.4%
	Sx 2	1.0%	5.5%	14.7%
Proposed	A	5.7%	21.5%	35.8%
	B	5.2%	50.8%	108%
	C	6.8%	41.8%	90%

7 Conclusions

The first part of the paper presents the methodology of employing load test measurements for validation and verification of FE model of the Southern Railway Danube bridge in Budapest. FE analyses are applied by different load scenarios to calculate the measurements at the positions of SHM strain gauges. Global model revealed a good agreement with the load test data. Furthermore, cross girder through the orthotropic deck system considered as a fatigue sensitive area and simulated by local model. To assure model accuracy and minimizing the simulation runtime a verification by mesh sensitivity test is carried out. It is found that a 20 mm element size of local model is adequately representing the behavior of the real bridge and the percentage of errors at strain measurement points of K3-5, K3-6, and K3-7 were 0.6%, 3.4%, and 0.8% respectively.

Subsequently, fatigue prone details are investigated by the validated local model. Based on constructional solutions and stress concentrations, three sensitive details are identified. These details represented by the cutout of the web of cross girder, lower cope-hole in the mid-span of cross girder, and transvers welding of different thickness plates of the bottom flange.

By the developed and validated model, the crack detection efficiency of the SHM system of the bridge is studied in the investigated local area of the floor system. Three separated cracks are applied through the identified fatigue sensitive details in the local FE model. The cracks are initiated artificially with stable length in a direction normal to principal stresses. The stresses at the positions of SHM sensors are calculated continuously with the increasing crack length. The results show that the calculated stress values cannot obviously reflect the effects of the crack initiation and propagation in the current positions of SHM sensors. The detection efficiency ratio is introduced by the percentage of stress variation due to specified crack lengths. In the evaluation of the SHM, the detection efficiency ratio in the case of 50 mm crack size is found for strain gauges Sy3, Sz7, and Sx2: 17.8%, 5.4%, and 14.7%, respectively. This means that these gauges are not efficient enough to detect a relatively big crack initiation for the three investigated fatigue-sensitive details.

In the further study based on stress analysis, new SHM strain gauge positions are proposed. These positions demonstrated significant changes in the calculated stress trends with crack propagation. The crack detection efficiency ratios for the 10 mm/50 mm crack sizes are as follows: 5.7/35.8%, 5.2/108%, and 6.8/90% for positions A, B, and C, respectively. The results show the potential applicability the strain gauges in the new positions for crack monitoring and detection. By this observation it is recommended extend the strain measurement sensors of the SHM system for crack detection in the three fatigue sensitive details, for enhancing the safety and durability of the bridge.

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