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Assessment of fatigue behaviour of orthotropic steel bridge decks using monitoring system

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Abstract

During the last decades orthotropic steel decks have become a widely used component of steel bridges, however high numbers of fatigue cracks have been recently detected in these structure types. It is well known, that the orthotropic decks are sensitive to fatigue damage, therefore safe fatigue design is important for the safety assessment of bridge structures. The fatigue damage assessment and life prediction of steel bridges can be carried out by using online structural health monitoring systems (SHM). By using the SHM system, it is possible to detect deterioration, determine anomalies and assess the safety level which will allow optimum maintenance strategies. On-structure long-term monitoring systems have been already successfully implemented on bridges all around the world in order to detect cracks just like on the orthotropic steel deck structure of M0 Háros Danube highway Bridge in Hungary. The purpose of the current research program is the investigation and analysis of the fatigue behaviour of this orthotropic steel bridge deck and the evaluation process improvement of the data rows collected by the monitoring system. Additional laboratory tests are carried out at 6 large scale test specimens at the Budapest University of Technology and Economics, Department of Structural Engineering to determine the fatigue resistance of closed section longitudinal stiffeners. In parallel finite element model is developed to simulate the fatigue behaviour of the analyzed components and to investigate its fatigue behaviour by numerical analysis. The aim of the current study is to analyze and verify the structural behaviour of the orthotropic steel deck on the basis of the executed test results, numerical simulations and the strain-time history data from the online structural health monitoring system implemented on the studied bridge.

Keywords: Orthotropic steel deck; Structural health monitoring system; Fatigue behaviour

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1. Introduction

During the last decades orthotropic steel decks have become a widely used component of steel bridges due to their favorable properties. They consist of a complex network of longitudinal stiffeners, transverse stiffeners and the deck plate itself. However, under traffic high numbers of fatigue cracks have been detected in these structures. One of its main reason is that the deck is directly subjected by cyclic heavy traffic loads which induce high local deformations and stress concentrations. Consequently, the steel deck and the stiffeners are subjected to local stresses which can cause damage due to fatigue. Under the effect of these stress variations, microscopic cracks in structural members can propagate into large cracks, which usually begin around the welded connections where high stress concentration exists [1,2,3]. Thus the orthotropic decks are sensitive to fatigue damage induced by permanent heavy traffic loads, therefore fatigue analysis is a significant task for the safety assessment of these structure types. The fatigue damage assessment and the life time prediction of these bridge deck systems can be carried out by numerical fatigue analysis supported by the online structural health monitoring systems (SHM), what is the focus of the current paper. On-structure long-term monitoring systems have been already implemented on the M0 Háros Danube highway Bridge in Hungary in order to detect cracks and to study the stress history of several predefined structural details of the bridge. The current research aim is the investigation and analysis of the fatigue behaviour of this orthotropic steel bridge deck and the evaluation process improvement of the data rows collected by the monitoring system.

1.1. Investigated structure

In the current study the orthotropic steel deck of the M0 Háros Danube highway Bridge in Hungary is analyzed. The whole bridge structure contains three independent bridges. The flood bridges are continuous three span composite bridges, and the bridge above the Danube river is a continuous three span girder with a one-cell box-section with inclined webs and orthotropic steel deck. The geometrical properties of the studied bridge deck are collected in *Table 1.*

Table 1. Data of the M0 Háros Danube Bridge

Length	770.42 m
Width	21.80 m
Spans	3x73,5 m+ 3x108,5 m+ 3x73,5 m
Thickness of the deck	14 mm
Distance of the stiffeners	300 mm
Width of the stiffeners	300 mm
Height of the stiffeners	300 mm
Thickness of the stiffeners	8 mm
Spacing of the cross-beams	3875 mm
Height of the cross-beams	1000 mm

1.2. Research aims

In the recent years numerous cracks have been observed in the trough splice joints of several orthotropic bridge decks. Many of these connections have low fatigue strength, since the welds must be made in an unfavorable overhead position from outside the stiffener. A considerable part of the observed cracks in the trough splice joints are due to a bad weld quality, and in the same time the crack growth is also sensitive for the quality of the weld [3,4]. That is the reason why more attention will be devoted to the splice joints of the closed section longitudinal stiffeners in the current project.

Laboratory tests are carried out on 6 large scale test specimens at the Budapest University of Technology and Economics (BME), Department of Structural Engineering to determine the fatigue life of joints on closed section longitudinal stiffeners with steel backing plates. In parallel finite element models are developed to simulate the fatigue behaviour of the analyzed components and to investigate its fatigue behaviour by numerical analysis.

The aim of the current study is to analyze and verify the structural behaviour of the orthotropic steel deck on the basis of the executed test results, numerical simulations and the strain-time history data from the online structural health monitoring system implemented on the bridge.

2. Experimental test results

2.1. Laboratory tests

Full scale fatigue laboratory tests *(Fig. 1.a)* are executed at the Budapest University of Technology and Economics, Department of Structural Engineering in order to investigate the fatigue life of the closed section longitudinal stiffeners and to determine their fatigue detail category. In the experimental research program 4 large scale fatigue tests are carried out. Four specimens are loaded by four-point-bending, and on two specimens an additional torsional load is also applied accompanying to the bending moment. The number of the applied loading cycles and the strain values at 4 different locations (where crack initiation points were expected) are measured and recorded continuously during the tests.

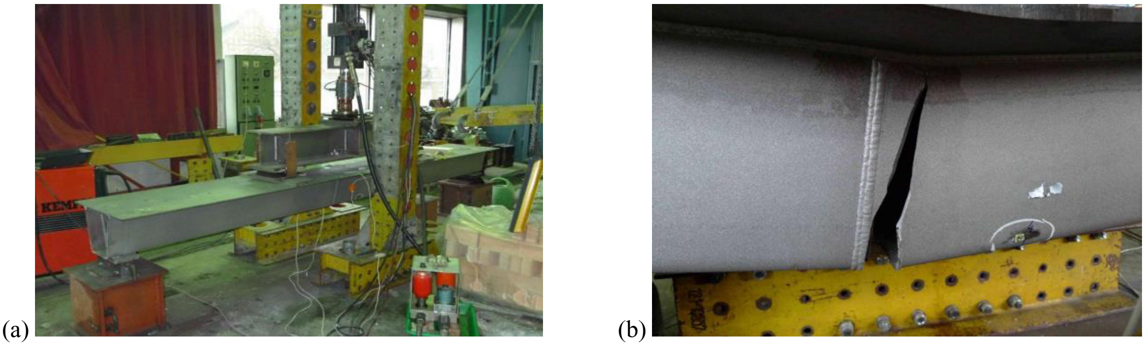


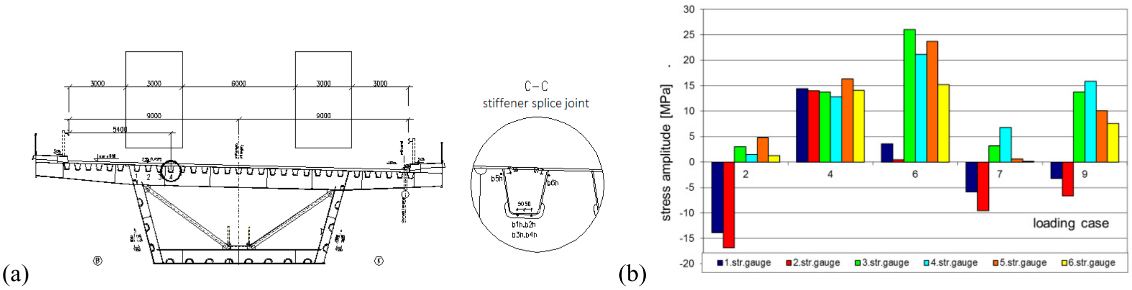
Figure 1 (a) Fatigue test, (b) Failure mode of the stiffener

In accordance with the expectations, the tests proved that the fatigue crack initiates from the weld toe of the stiffener joint *(Fig. 1.b)*. The crack was propagated in the lower flange at first, followed in the web of the stiffener, and finally over the total lengths of the stiffener's webs. According to Eurocode 3 standard this joint belongs to the fatigue detail category 71 ($\Delta\sigma_c$=71 N/mm^2). The statistical evaluation of the test results, however, showed that the design fatigue detail category of 88 could be used for the tested specimens ($\Delta\sigma_c$=88 N/mm^2) [5].

2.2. Loading test of the M0 Háros Danube Bridge

Before finalization of the M0 Háros Danube Bridge erection, the BME Department of Structural Engineering executed the static and dynamic loading test of the bridge. During the investigation the bridge is instrumented and loaded using trucks of known weights and configurations positioned at specified locations on the deck. Beside the check of the global behaviour of the bridge structure, the aim of the load testing is also the local investigation of the structural details which are sensitive against fatigue, such as the longitudinal stiffener splice joint. In the frame of the static load testing six strain gauges are implemented around the 4th stiffener's splice joint in order to measure the local longitudinal normal stresses *(Fig. 2.a)*.

According to the locations of the trucks, directly loaded and not directly loaded cases are separated. In the former case, it is observed that the stresses are coming from the sum of the global effect (tension) and a significant additional local bending effect (compression) as it can be seen from the measured stress amplitudes *(Fig. 2.b)*. During the static loading, the σ_{max} maximum and σ_{min} minimum stresses around the investigated longitudinal stiffener splice joint are measured. The highest measured $\Delta\sigma$ stress amplitude value is 33,9 MPa [6]. The different colors in *Fig. 2.b* present the measured stress values in the different loading cases at the same strain gauge location. The difference in the maximum and minimum values gives the maximum stress amplitude measured on the longitudinal stiffener.

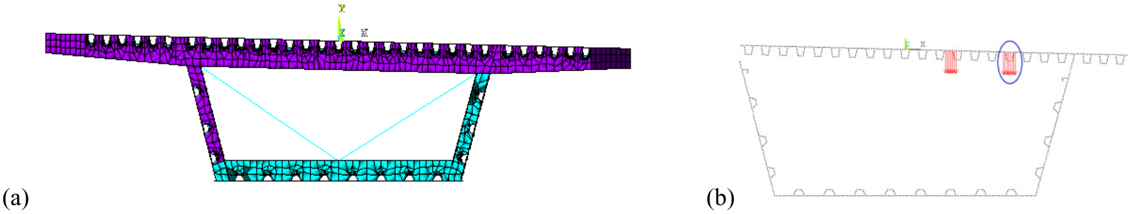


(a) (b)

Figure 2 (a) Investigated cross-section, (b) Stress ranges – directly loaded joint.

3. Applied numerical models

Numerical models are developed to investigate the structural behaviour of the analyzed orthotropic bridge deck system. In the numerical models one part (19.375 m long and 18.64 m wide) of the whole M0 Háros Danube Bridge structure is modelled. It has 31 longitudinal stiffeners in the orthotropic deck and six cross-beams in the transverse direction, which are spaced in a distance of 3.875 m *(Fig. 3.a)*. The investigated stiffener in the current investigation is the 4th longitudinal stiffener counted from the web, therefore the wheel of the model vehicles are situated above the analyzed stiffener *(Fig. 3.b)*. The stiffener has a width of 300 mm, a height of 300 mm and a thickness of 8 mm.



(a) (b)

Figure 3 (a) Built-up model, (b) Load model

Two types of numerical models are developed using ANSYS R14.5 [8] finite element software. The first model is developed by application of thin walled shell elements, and in the second model a two-level modelling technique is used where the studied stiffener is modelled by solid elements and the surrounding part of the structure is modelled by shells. The aims of the numerical models are to determine the longitudinal stress history next to the butt welded splice joint. During the analysis the LM4 fatigue load model is used according to the EN1991-2 [9] with five types of lorry, representing the heavy traffic load, which fits the best the loading conditions of the M0 Háros Danube Bridge. The applied loads are used as uniformly distributed loads on the nodes of the loading surface of the different wheel types (45° load distribution along this layer is considered because of the presence of the asphalt layer). In order to have more accurate results, the investigated 4th longitudinal stiffener and its surrounding model part is equipped with much finer finite element mesh, as shown in *Fig. 4*.

Shell model

In the first model - except the stiffening girders - every element are modelled using SHELL181 type elements of the ANSYS program which is suitable for analyzing thin shell structures. The bracing system, which are placed at every second cross-beam are modelled with BEAM 188 elements which is suitable for analyzing slender beam structures.

Solid model

3D solid elements are usually preferred in the numerical modelling of welded steel structures, since they rarely contain simple details or simple loading conditions. In large structures such as bridges, finite element models having only solid elements can lead to enormous model sizes, very long computational time and huge computational efforts. In order to avoid these and to obtain a more detailed and accurate results in local regions, sub-modelling technique is recommended to analyze smaller parts of the total structure using solid elements [7]. Consequently, in the second numerical model a two-level model is improved. The investigated 4th longitudinal stiffener is modelled using SOLID45 elements between two cross-girders *(Fig. 4.b)*. To connect the shell and the solid elements MPC184 elements (rigid elements) are used in the model around the investigated stiffener in order to transfer rotation from shell elements to the solid elements.

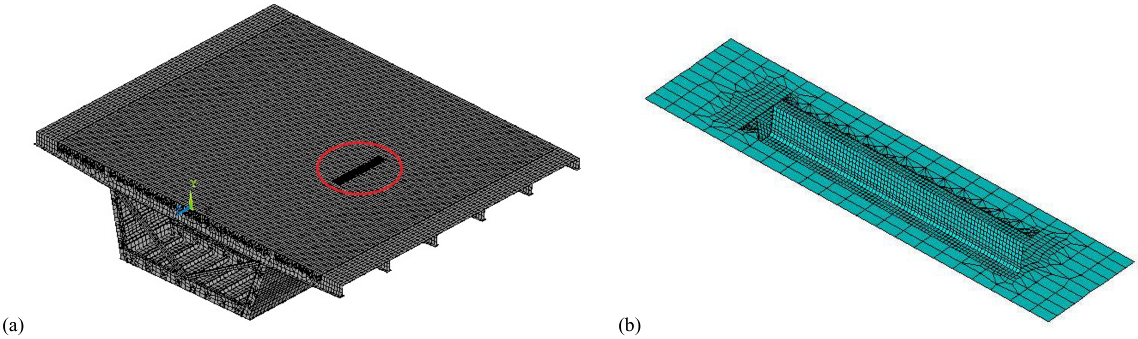

(a) (b)

Figure 4 (a) Investigated part of the bridge, (b) refined mesh around the 4th stiffener.

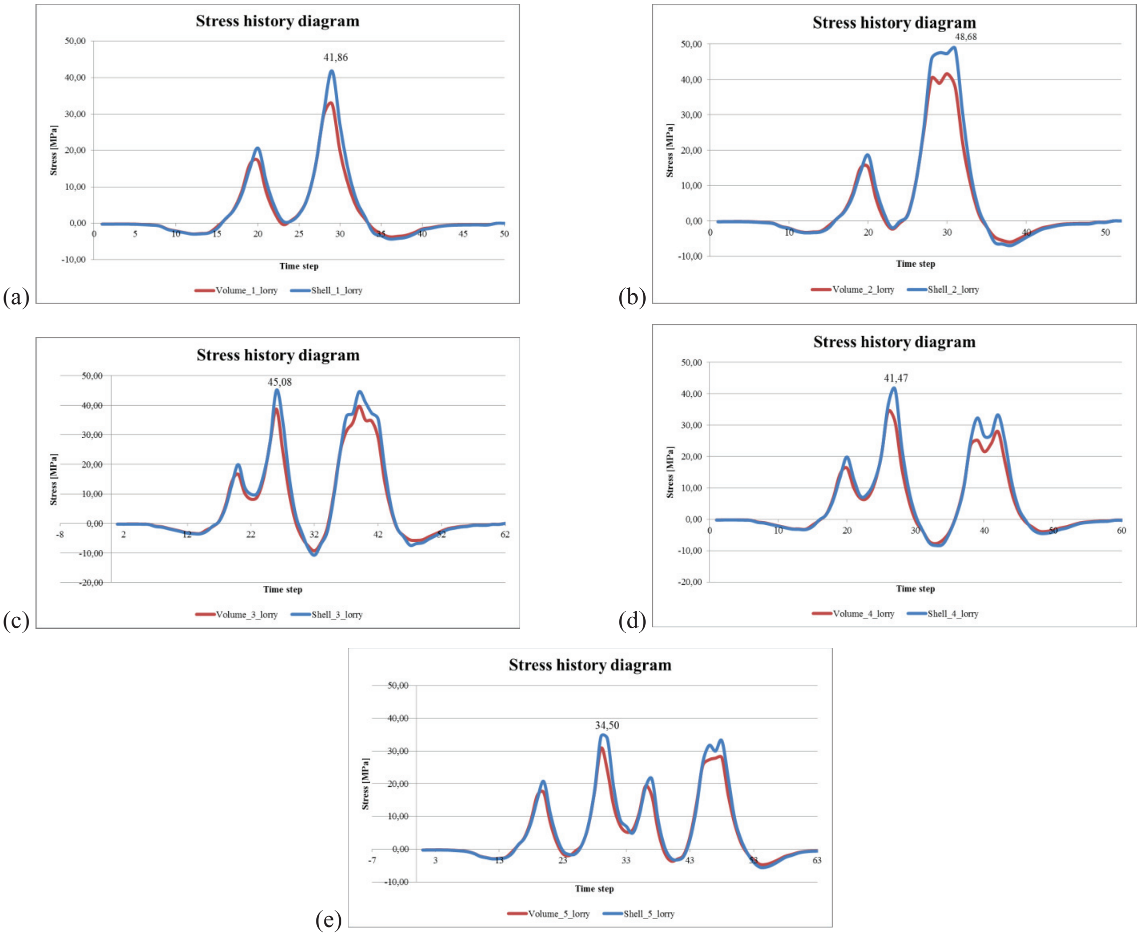
4. Results

After executing the static analysis in ANSYS for all the five specific lorry of the EN1991-2 [9], using the stress history of the longitudinal stresses in the mid-span of the stiffener, the Δσ stress ranges are determined *(Table 2.)*.

Table 2. Maximum stress amplitudes based on the numerical calculations.

max Δσ stress range [MPa]	Shell model	Two-level model
1. lorry type	46.19	36.52
2. lorry type	55.66	47.56
3. lorry type	55.82	48.90
4. lorry type	49.86	42.19
5. lorry type	40.01	35.46

The stress history diagrams are determined for the five different lorries defined in the LM4 on both numerical models. The results are presented in *Fig. 5.* There are no large differences in the tendencies of the different diagrams using shell or volume elements, however 10% difference can be observed between the maximum stress values, which can be treated as a significant effect coming from the accuracy of the model. *Figure 6* shows the stress distribution in case of a directly loaded longitudinal stiffener determined by the numerical model.



(a) (b) (c) (d) (e)

Figure 5 Relevant stress history diagrams for LM4.

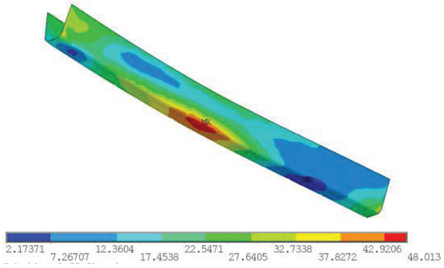


Figure 6 Stress distribution in the numerical model - directly loaded stiffener.

5. Monitoring system

The fatigue damage assessment and life-time prediction of the M0 Háros Danube Bridge is also supported using online structural health monitoring system (SHM). The main aim of the SHM systems is, that they makes possible to detect fatigue cracks, anomalies and to assess and evaluate the safety level of the bridge structure in any time, which can support the decision of the optimum maintenance strategies [10]. The main elements and the set-up of the implemented monitoring system are given in the following list and the number and distribution of the applied equipment are given in *Fig. 7.*

- sensors (accelerometers, bearing displacement sensors, temperature sensors, strain gauges),
- converters and transmitting devices,
- PC – control system, processing equipment,
- wiring between the different elements of the system.

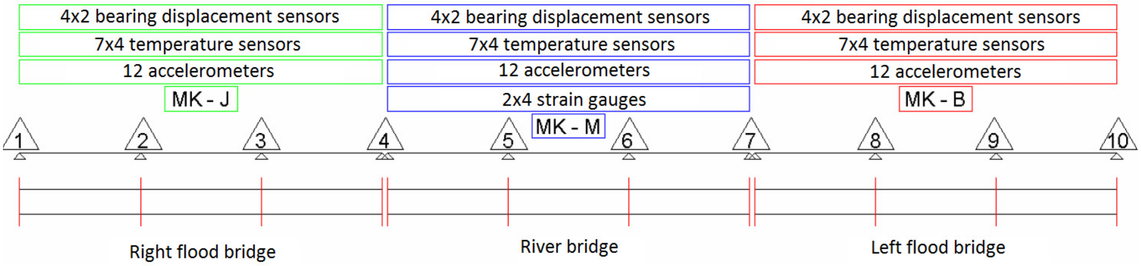


Figure 7 Implemented monitoring system.

By the help of the long-term monitoring system the behaviour of the structure can be continuously studied and evaluated. By processing the measured data it is possible to evaluate the current state and also to optimize the further maintenance works on the structure [10]. The global structural behaviour and the effects of special unexpected events (seismic events, extreme wind effects, accidents, etc.) can be observed by the measured dynamic data of the accelerometers. In addition, to investigate the evolved fatigue cracks and their propagation, a local monitoring system is also implemented around the most dangerous structural details which are the followings [11]:

- connections in the longitudinal stiffener splice joints around the piers,
- connections between the longitudinal stiffener and the cross-beam around the piers,
- connections between the deck plate and the longitudinal stiffener.

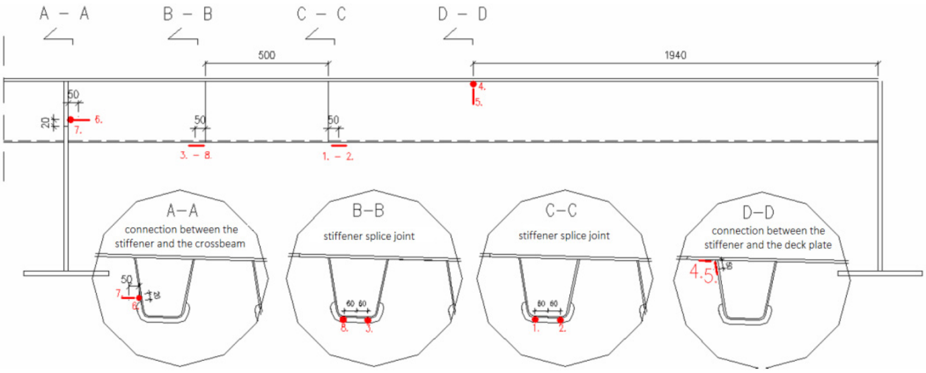


Figure 8 Location of the strain gauges on the orthotropic deck

The location of the 8 uniaxial strain gauges are shown in Fig. 8. Using the strain-time history data measured by the strain gauges the stress spectrum of these details can be calculated under the real traffic loads. Using the data rows collected by the monitoring system the structural life can be estimated. Other elements, such as bearings and dilatations are also observed by the implemented accelerometers and temperature sensors [11].

6. Concluding remarks and further works

The aim of the current research is to analyze and verify the structural behaviour of the orthotropic steel deck on the basis of the executed test results, numerical simulations and the strain-time history data from the online structural health monitoring system implemented on the M0 Háros Danube highway Bridge in Hungary. At the current level of the research, all the four main piers of the research program are independently working: (i) numerical model for fatigue assessment, (ii) monitoring system provides measured data continuously, (iii) reference stress data coming from the static and dynamic loading tests and (iv) improved fatigue detail class coming from large scale test specimens manufactured by the same manufacturer than the real bridge structure.

The next research step is the combination and evaluation of the monitoring data and the stress history calculated by the numerical model. Based on these measured and calculated stress histories an automatic system to be developed which can evaluate and estimate the life-time of the analyzed bridge deck system continuously during the service of the structure. It will support the decision making on the maintenance of the bridge.

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