Monitoring based performance prediction of steel bridges against traffic loading exemplified at the Europabrücke

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ABSTRACT: Bridges are ageing and traffic is growing, which creates a demand for accurate fatigue life assessment. The Europabrücke – a well known Austrian steel bridge near Innsbruck, opened in 1963 - is one of the main alpine north-south routes for urban and freight traffic. It represents a bridge generation, where bridge designers acted on a maxim of building material economisation. A long-term preoccupation of VCE with BRIMOS® (BRIdge MONitoring System) on the Europabrücke (since 1997) with regard to fatigue problems and possible damage led to the installation of a permanent monitoring system in 2003. Since that time a lot of investigations and additional special measurements were devoted to innovative, mainly monitoring-based fatigue assessment. As life-time predictions in modern standards depend on lots of assumptions, the emphasis is to replace those premises – referring to loading - by measurements.

1 INTRODUCTION

In the abstract’s context the present work is focused on three levels:

− Level I: Global behaviour – primary load bearing members (traffic loading observation mainly based on laser-supported global deflection measurement)

− Level II: Cross-sectional behaviour (dynamic traffic-weight registration system, which utilises laser-calibrated accelerometers reproducing vertical cantilever deformations based on pattern recognition.

− Level III: Local systems – e.g. the bottom and top joints of the bridge’s torsional bracings (verification with additional strain gauge measurements)

In each of these levels of analysis the consumption of the structure’s overall-capacity per year is to be determined. A continuitive methodology was prepared, which uses the isolated hot spot areas for detailed fatigue analysis to determine, how grave the present situation is with regard to the remaining service lifetime of the analysed structural members. As the present lifetime calculations are performed in terms of stresses by means of damage-accumulation, comprehensive Finite Element Analysis is necessary to quantify the real fatigue-threat. The calculation’s loading-input is going to be strictly measurement based. This methodology of course implies additional strain gauge measurements for verification purposes.

2 METHODOLOGY

An extensive explanation of the present research work as well as an insight into its methodology in detail is given in [Wenzel et. al 2008] and is visualised in Fig 1. Even if the present methodology represents a tailor-made approach, it can be modified and transferred to other bridge structures. For reasons of a limited extension of the present contribution it is mainly going to be focused on showing the development of a tailor-made loading model for performance prediction.

3 TAILOR-MADE LOADING MODEL FOR PERFORMANCE PREDICTION

Based on the hot spot areas isolated in [Veit-Egerer & Wenzel 2007], detailed fatigue analysis is demanded to determine, how grave the present situation of the relevant structural members is with regard to the remaining service lifetime – using the monitoring based impact. In the following an insight is given into the idea, how the results for a one week lasting measurement campaign are extracted and implemented into the developed methodology for performance prediction. Firstly accompanying video recordings were undertaken to eliminate possible uncertainties and to provide complementary information. Extensive data mining lead to frequency distributions including all different kinds of occurring loading scenarios (Fig. 2). One of these loading configurations - two trucks simultaneously stressing the bridge’s side span by driving in the downhill direction -
was chosen to show its consequence for the three levels of performance analysis (Fig. 5), which have been introduced.

Fig. 1 Detailed flowchart of the methodology

Fig. 2 Typical, exemplary loading scenario – two trucks causing unsymmetrical traffic impact - highlighted in Fig. 4

Fig. 3 Video based observation of relevant loading scenarios

Fig. 4 Video supported classification of loading scenarios and resulting frequency distribution
Global response in terms of vertical deflection due to the chosen scenario was recorded using a transmitter unit at the bridge abutment and a receiver unit located at the southern side span (laser supported global deflection measurement).

In the course of [Wenzel & Veit-Egerer 2007] the main feature of the permanent monitoring system – the DY-GES algorithm (Dynamic Freight Traffic Classification) - was introduced. This feature explicitly provides the truck loads corresponding with the observed global bridge span deflection.

Finally the effective axial forces and bending moments acting on the bracings as well as the occurring stress cycles can be extracted from the monitored strain data recorded at the directly stressed bracings. In the following it is explained, how the established, tailor-made loading model (Fig. 2) is utilised for performance analysis of Level I (Global Impact):

Monitoring based global impact data for a certain, representative time period (one day, one week – e.g. Fig. 6) are assessed using Rainflow Analysis. To express the Damage Rate for this loading function each of the observed, typically occurring loading scenarios (Fig. 4) is implemented one by one into a Structural Finite Element Model using certain truck loads (DYGES). This leads to a corresponding structural stress cycle $\Delta \sigma$. As it has to be dealt with truck traffic causing High Cycle Fatigue, linear elastic material behaviour can be assumed. Stresses and strains are assumed to remain elastic. This facilitates the calculations, as a single load case due to the chosen scenario is to be calculated in terms of stresses, while all other occurring truck loads are automatically included within the Rainflow Matrix. The latter, the calculated stress cycle value and the stress life curve corresponding with the analysed relevant structural detail lead to a Damage Matrix. This assumes only the chosen loading scenario to be occurring. Based on the frequency distribution of the observed loading scenarios (Fig. 2) the chosen entry gets its weighting within all other relevant loading cases to quantify the consumed loading capacity related to a certain observation period. The same procedure is repeated for all other entries of the observed loading scenario distribution leading to an accumulated damage per determined observation period.
In the course of the performed Finite Element calculations - following the consequence for the fatigue resistance of structural details relevant for Level I, a parallel determination for those structural details relevant for Level III can be done. Additionally there is always the possibility to make a crosscheck for those stresses from analytical calculations by comparing them to the ones given by explicit strain measurements at representative positions, which shows the capability of this integral methodology (Fig. 7).

Performance analysis for Level II (Cantilever impact) seems to be less complex, as the consequence on fatigue relevant structural details in terms of principal structural stresses occurs perpendicular to the stress cycles - previously analysed for Level I. The DYGES based truck loading impact (Fig. 8) is again implemented into structural models by means of a deformation constraint load case affecting the cantilever’s outer edges.

4 REMAINING SERVICE LIFETIME BY MEANS OF EXISTING TRAFFIC DATA

The demonstrated damage calculations refer to a sufficient amount of workdays and weekend-days, that enable a representative extraction of a damage rate per week, which consequently enables its extrapolation to enlarged time periods. Thus the assessment of an analysed detail via Damage Matrix calculated for the measuring time of a whole year ( => 'Damage-per year effect’) is possible to determine the consumption of the overall loading-capacity per year for the corresponding detail. The detailed knowledge about the progression of the prevailing traffic from the very beginning up to these days and the implementation of published future trend studies with regard to the next ten years (until 2015) are used for fatigue analysis (variation of traffic volume & variation of the notional truck-weight). Fig. 9 shows the increase of the freight traffic volume at the Europabrücke. According to [Verkehrsentwicklung in Tirol 2006], traffic volume in 2006 increased to an amount of 472 % in relation to 1964 and is expected to grow 2.9% per year until 2015 [Verkehrsprognose 2015].

To derive every considered year’s Damage Matrix affected by the variation of traffic volume, fatigue analysis approximately demands a uniform adaptation of the number of occurrences for all elements of the derived Rainflow Matrix before extrapolation techniques of the measured impact for the whole lifetime - discussed in [Wenzel et. al 2008] - are applied.

Fig. 7 Successively added strain gauges - installed along an assembly of two corresponding torsional bracings; 25.05.2007 11:00 - 27.05.2007 11:00

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Fig. 8 Corresponding pattern of the Dynamic weight registration based on cantilever acceleration measurements (reproduced cantilever deformations via pattern recognition) – a feature implemented into permanent monitoring; 25.05.2007 11:00 - 27.05.2007 11:00

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Fig. 9 Progression of freight traffic volume at the Europabrücke from 1964 until 2015 [trucks/day]

Fig. 10 shows the increase of the effective amount of transported goods compared to a calculated cargo per notional truck. The calculations showed that this truck weight in 2006 increased to an amount of 503 % in relation to 1964 and is assumed to have already reached a maximum. This means, that a further increase of transported goods is likely to be a consequence of the still growing traffic volume. An adaptation for fatigue analysis due to the variation of the notional truck-weight is realised by re-scaling the Rainflow Matrice’s subdivision. The information included in both of these functions can be broadened crucially, as the DYGES based freight traffic classification delivers exact truck weight data for the analysed bridge object – starting with the summer of 2004.
5 CONCLUSIONS AND FUTURE WORK

The present contribution explicitly deals with measurement data and the procedures, how they were provided and conditioned for continuative performance analysis. The methodology provides strictly in-situ based loading input parameters for continuative fatigue analysis leading to a “tailor-made” performance prediction. In addition strain gauge measurements in each of the considered levels of analysis (Level I – Level III) are done for verification purposes of the Finite Element based stress-life approach. Thus the main goal, the substitution of the standard’s premises – referring to loading – has been reached in a quite innovative manner with regard to determine the consumption of the structure’s overall capacity per year by means of a three level approach.

One of the main innovations within the present methodology is the introduced DYGES Algorithm, which is necessarily based on a pattern recognition algorithm by Wenzel & Veit-Egerer [Wenzel & Veit-Egerer 2007] in order to reproduce vertical cantilever deformations from accelerometers (major feature of the permanent monitoring system). The development of the DYGES Algorithm was nominated for the Austrian Award for Telematics, by the Federal Ministry of Transport, Innovation and Technology.

Besides the traffic induced impact, additional monitoring campaigns revealed, that there is a strong influence due to sun-radiation (Fig. 11 & Fig. 12). In addition to the described laser supported global deflection measurements the progression of the offset of the bridge’s reference accelerometer in the lateral direction was transformed into an angle of inclination. The resulting temperature gradient function induces additional axial forces and deformations explicitly into the outer bridge spans. Approximate analysis indicates that this constraint’s intensity level can occur up to the range of the traffic-impact itself. The affection due to temperature and radiation impact needs to be analysed seperately, before it is necessarily going to be superimposed with the strictly traffic induced fatigue impact.

Contrary to the general doctrine in conjunction with structural performance analysis of welded components the authors assume, that the influence of temperature leading to varying mean stresses will have to be considered. The authors are convinced that shrinkage effects that lead to residual stresses in the welds are minimized or already vanished in this almost 45 year old and constantly stressed structure. In that case varying mean stresses become relevant even for welded structural members and demand the application of appropriate correction rules.

Fig. 10 Effective amount of transported goods on the Brenner route compared to a calculated cargo per notional truck

Fig. 11 Integral Assessment of environmental conditions: Steel-temperature and Air-temperature along on a certain cross section (pier V): 23.05.2007 19:00 - 27.05.2007 13:00

Fig. 12 Integral Assessment of Traffic impact and comparison with environmental conditions: Global vertical deformations vs Air-temperature vs. Radiation efficiency vs. Humidity: 23.05.2007 20:00 - 26.05.2007 12:00

Starting with May 2007 the in-situ distribution of temperature impact as well as the sun-radiation itself is assessed via permanent monitoring using a profile of temperature sensors over a certain box-girder’s cross section (Fig. 11). An explicit temperature load case is going to be created and again implemented into the Finite Element calculations.

The implementation of strictly measurement based loading impact into Finite Element calculations strongly supports quantitative estimation of the service-lifetime via separation of fatigue relevant loading cycles from the randomly occurring overall traffic. The Palgrem-Miner based accumulation of all calculated Damage Matrices
from the very beginning of the bridge’s existence up to now leads to the remaining capacity of loading cycles for the analyzed detail. As a superior conclusion in addition to a quantitative estimation of the service-lifetime another key figure FR (Fatigue Relevance) is also derived (eq. (1)). It separates remaining, fatigue relevant loading cycles \( n_i \) (registered by sensors and taken from the Damage Matrix) from the randomly occurring traffic (ADTV = average daily traffic volume). It is obvious that the investigation’s results are going to be improved by progressive stages; the longer the observation period lasts.

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FR = \frac{\sum n_i}{ADTV}
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(1)

This whole conception assures the determination and observation of slowly progressing processes in the structure, which might lead to local damage or to deterioration of the structure’s operational integrity. The results of these hot spot analysis calculations with regard to the fatigue resistance itself are going to be undertaken and discussed in the course of further publications.

6 REFERENCES


