Assessment, Upgrading, Refurbishments and Conservation of Infrastructures

Properties of Early Structural Steel in Old Railway Bridges; Janusz Marek Holowaty; Dr., Poland

The long-term use of steel bridges leads to changes in the mechanical properties of their structural steels. This issue is demonstrated in a study of cast steels from four railway truss bridges built in 1875. The tests for each bridge involved: an analysis of the chemical composition, determination of hardness and toughness, along with yield strength and ultimate strength. The tests made it possible to calculate the current mechanical properties of steels and to estimate their fracture toughness. One of the bridges in the study was built from a low-carbon steel and the others from a high-carbon steel which was not thought to be used at that time. An assessment of the current mechanical properties of the steels allowed the bearing capacities of the bridges to be estimated and following this technical designs for their upgrading and repair to be drawn up.

Keywords: Old railway bridge, historic bridge, truss, cast steel, ageing of steel, durability.

Load-Carrying Capacity Improvement and Seismic Upgrading of a 1914 riveted Steel Bridge; Marco Breccolotti; Carlo Alberto Beffa; Andrea Rapicetta; Fabio Pelliccia; Italy

The paper describes the analyses carried out to evaluate and improve the load-bearing capacity of an old riveted steel bridge locate in the Province of Perugia, in the central part of Italy. The bridge was designed and constructed between the 1914 and 1918 to carry pedestrian and light vehicles loads, well below the current transportation requirements. It is composed by two steel spans with three continuous truss beams and by three masonry arches for an overall length of 116 m. The metallic part of the bridge rests on two unreinforced concrete abutments and on a pier, also made of unreinforced concrete, placed inside the Tiber riverbed. A detailed control on the assemblage of the riveted steel elements put in evidence instability problems that caused a partial buckling in a lower chord close to the inner support. Furthermore, the actual support system, composed of fixed bearings on the central pier and longitudinal sliding bearings on the abutments, concentrates the longitudinal seismic forces on the masonry pier which is unable to carry relevant horizontal loads. In this paper the works carried out to increase the admissible traffic load and those to improve the behaviour of the bridge under seismic actions are briefly described.

Keywords: Riveted steel bridge, assessment, buckling, strengthening, seismic upgrading.

Soil-Structure Interaction in Sidi Rached Masonry Bridge; Marco Petrangeli; Paola Rita Marcantonio; Paolo Tortolini; Italy

The Sidi Rached Bridge was built in the early 20th century across the Rhumel canyon in the centre of Constantine, Algeria. The bridge, with its 27 arcades spanning up to 68 metre, is a famous city landmark and one of the main cultural heritage of Algeria as well as the largest masonry structure of this type in Africa. The 8 spans on the right bank have been suffering for over 50 years, from intermitting slope instability. The problem has been addressed and temporarily solved few times now. After 30 years of relative calm, the landslide peaked again in 2008 causing severe damage to all the piers on the right bank and the near collapse of one arcade. A new campaign of assessment, reconstruction and strengthening has therefore been undertaken. The paper presents the results of the study and the repair works carried out so far while monitoring, studies and strengthening proceed on this historical monument that still provides a vital link in the hearth of one of the most populous cities of North Africa.

Keywords: Masonry bridges, slope instability, numerical modelling, rehabilitation, external post-tensioning.
Post Fatigue Evaluation of a Strengthened Steel Truss Bridge; Chun-Sheng Wang, Qian Wang, Yue Xu, China

Many existing steel bridges in China were strengthened or retrofitted recently to improve the load carrying capacity or to extend the service life span. The effectiveness is investigated by a post evaluation of fatigue life of a strengthened highway continuous steel truss bridge in order to assure the continued safe use and to gain knowledge on repair or replacement. Three-dimensional finite element models of the structure before and after strengthening are established through calibration with in-situ measured stresses and displacement. The traffic condition of the bridge is investigated, and the stress histogram and stress spectrum are simulated by the Monte-Carlo Method. The fatigue life and damage of all fracture critical tension members before and after strengthening of the structure is calculated by using S-N curves and by adopting a fracture mechanics model. Finally, the effectiveness of strengthening and a maintenance strategy are determined based on the results of evaluation.

Keywords: Existing steel bridges, post-strengthening evaluation, fatigue loads, fatigue stress spectrum, remaining fatigue life, fracture mechanics.

On a Partial Factor Approach for Existing Concrete Structures: The Design Value Approach and Adjusted Partial Factor Method; Robby Caspeele, Belgium; Miroslav Sykora, Czech Republic; Diego Allaix, Italy; Raphael Steenbergen, The Netherlands

In contrast to the design of new structures, the assessment of existing structures often relies on the subjective judgement of the investigating engineer. An objective verification format for existing structures based on alternative partial factors is however feasible, enabling a rather simple and straightforward, but objective and coherent safety evaluation of existing concrete structures by practitioners. The proposed framework is compatible with the current Eurocodes for the design of new structures, but additionally enables to incorporate alternative values for the target reliability level, alternative values for the remaining working life and also updated information based on e.g. on-site inspection data and data from testing, as these all considerably influence the partial factors in the structural reliability assessment of existing structures. After introducing the framework for the derivation of partial factors, two suitable methods for developing alternative partial factors for existing structures are described and explained, i.e. the Design Value Method and the Adjusted Partial Factor Method. The performance of both methods are investigated by FORM-based reliability analyses.

Keywords: Existing structures, concrete, partial factors, FORM analysis.

Recommendations from Experiments for the Shear Assessment of Reinforced Concrete Slab Bridges; Eva O.L.Lantsoght, Cor van der Veen, Joost Walraven, Ane de Boer; The Netherlands

Upon assessment of existing reinforced concrete short span solid slab bridges according to the recently implemented Eurocodes, that include more conservative shear capacity provisions and heavier axle loads, a number of these structures were found to be shear-critical. The results from recent experimental research on the shear capacity of slabs indicate that slabs benefit from transverse load distribution. Recommendations for the assessment of solid slab bridges in shear based on these experiments are developed. A load spreading method for the concentrated loads is proposed and the applicability of superposition of loading is studied. The resulting most unfavourable position for the design trucks is provided and implemented in the so-called Dutch “Quick Scan” method. Cases of existing bridges are studied with the previously used “Quick Scan” method as well as with the “Quick Scan” method including the recommendations. As a result of the assumed transverse load distribution, the shear stress to be considered at the support based on the recommendations becomes smaller.
Structural Weaknesses of the Hennebique Early Reinforced Concrete System and Possible Retrofitting; Armande Hellebois, Bernard Espion; Belgium

Up to the First World War, one of the most popular reinforced concrete patterns, used in many countries, was the system of François Hennebique (1842-1921). The best known characteristics of the Hennebique design, which was used in buildings as well as in bridges, are the monolithic structure with continuous T-beams reinforced with bent-up bars overlapping the supports and the use of flat open U-shape stirrups as transversal reinforcements. The reasons for the success of his company have been extensively studied. However, so far, the assessment of the carrying capacity of the system remains incomplete. This first part of the paper deals with the results of experimental bending tests up to failure performed on three full scale T-beam segments removed from a narrow gage railway viaduct built in Braine-l’Alleud (Belgium) in 1904. They aim at identifying the mechanisms of failure. The second part of the paper presents retrofitting actions to counteract the observed principal structural weakness, being the too short overlapping length of the tensile rebars over the supports.

Keywords: Hennebique system, experimental tests, flexural behaviour, RC T-beam, strengthening, externally bonded FRP, steel plate bonding.


In the central part of the Delft railway tunnel project, an underground railway station is being built at very close distance to the existing station building, which is still in operation. Although elaborate sensitivity analyses were made, some unforeseen deformations were encountered during the first phases of the execution process. Especially the installation of temporary sheet pile walls as well as the installation of a huge amount of grout anchor piles resulted in deformations exceeding the predicted final deformations as well as the boundary values defined by a level I limiting tensile strain method (LTSM) approach. In order to ensure the execution process, supplementary analyses were made to predict future deformations, and this for multiple cross sections. These deformations were implemented into a finite element model of the masonry of the building in order to define probable crack formation. This Level II LTSM approach made it possible to increase the initially foreseen deformation criteria and the continuation of the works. Design steps, design models and monitoring results will be explained within this paper.

Lightweight Reinforcement Systems for Fatigue Cracked Orthotropic Bridge Decks; Sofia Teixeira de Freitas, Henk Kolstein, Frans Bijlaard; The Netherlands

Orthotropic bridge decks (OBDs) have been researched: the bonded steel plates system and the sandwich steel plates system. The main idea of these type of reinforcements is to stiffen the existing deck plate, thereby reducing the stresses at the fatigue sensitive details, and thus extending the fatigue life of the OBD. Both reinforcement systems consist of adding a second steel plate to the existing steel deck. The behaviour and the effect of the reinforcement systems on full-scale OBD are investigated. Full-scale static tests and finite element analyses were performed on reinforced deck panels, using realistic wheel loads. The results showed at least 40% of stress reduction close to the fatigue sensitive details after applying both reinforcements. The two suggested reinforcement systems showed a good performance and proved to be efficient lightweight solutions to refurbish orthotropic bridge decks and extend their life span.

Keywords: Orthotropic decks, bridges, reinforcement, refurbishment, sandwich structures, adhesive bonding.
Rehabilitation and Strengthening of Concrete Structures using Ultra-High Performance Fibre Reinforced Concrete; Eugen Brühwiler, Emmanuel Denarié; Switzerland

An original concept is presented for the durable rehabilitation and strengthening of concrete structures. The main idea is to use Ultra-High Performance Fibre Reinforced Concrete (UHPFRC), complemented with steel reinforcing bars to protect and strengthen those zones of the structure that are exposed to severe environmental influences and high mechanical loading. This concept combines efficiently protection and resistance properties of UHPFRC and significantly improves the structural performance of the rehabilitated concrete structure in terms of durability. The concept has been validated by means of field applications demonstrating that the technology of UHPFRC is now well developed for cast in-situ and prefabrication using standard equipment for concrete manufacturing. This novel technology is a step forward towards more sustainable structures.

Keywords: Existing concrete structures, rehabilitation, strengthening, Ultra-High Performance Fibre Reinforced Concrete, composite UHPFRC – RC structures, durability, ultimate resistance.

Performance Assessment and Simulation of Welded Joints in Orthotropic Decks Considering Multiple Sources of Hourly-Based Monitoring Data; Issac Arreras Alcover, Jacob Egede Andersen; Denmark; M.K. Chryssanthopoulos, UK

Orthotropic steel decks can experience fatigue at welded joints, the assessment of which turns out to be a complex task due to their intricate geometry, the stochastic nature of the primary live load (traffic flow) and the temperature-dependent composite action between the pavement and the steel deck. In recent years, the possibility of monitoring, in addition to traditional inspections, has been put forward as a means of improved assessment. Nevertheless, a rigorous framework to (i) enable the effective use of high amounts of multiple/incomplete data provided by distributed data acquisition systems, (ii) improve current monitoring-based assessment methods, and (iii) enhance current simulation and data visualization techniques, is still absent. A theoretical framework is presented in which a strain-related performance indicator is estimated through a multiple regression model with hourly pavement temperatures and heavy traffic intensities as independent variables. The proposed performance indicator is proportional to fatigue damage following the principles of the S-N approach and Miner’s rule. Typical applications of this model include i) analysis of monitoring outcomes for performance assessment, ii) performance simulation of past/future events, and iii) fatigue assessment. To illustrate the proposed approach, model-based performance simulations are benchmarked with real monitoring outcomes from the Great Belt Bridge (in Denmark) and good agreement has been observed. Moreover, model simulations are used to estimate the fatigue life of a monitored welded joint. The new methodology enhances Structural Health Monitoring methods for orthotropic decks and provides a framework to integrate and visualize the multiple outcomes produced by modern monitoring systems as a part of the Bridge Management System or to assess the remaining life of structures.

Keywords: Orthotropic Decks, Structural Health Monitoring, Remaining Fatigue Life Assessment, Monitoring-based Predictive Models, Bridge Management System, Asset Management.

Statistical Deterioration Prediction Model Considering the Heterogeneity in Deterioration Rates by Hierarchical Bayesian Estimation; Daijiro Mizutani, Kodai Matsuoka, Kiyoyuki Kaito; Japan

A variety of uncertainty affects the deterioration processes of infrastructure. Deterioration rates vary significantly according to the differences in the structural characteristics, use, and environmental conditions of infrastructure. In order to overcome the problem of overdispersion of deterioration rates caused by the heterogeneity of structures, the mixed Markov deterioration hazard model has been proposed considering the heterogeneity of deterioration rates among groups of infrastructures. In this study, it is assumed that the overdispersion of
deterioration rates depend on the heterogeneity. Then, the mixed Markov deterioration hazard model that takes into account hierarchical heterogeneity is formulated, and a hierarchical Bayesian estimation method is proposed. Lastly, the validity of the proposed method is discussed through the empirical analysis of the visual inspection data of 823 RC slabs of 151 bridges. Then, the authors found that the expected lifespan of all 823 RC slabs is about 26.9 years and that the expected lifespan of the RC slabs varies from 6.2 years to 72.5 years due to the heterogeneity of each RC slab. Finally, the expected deterioration processes of all 823 RC slabs considering the heterogeneity of deterioration rates are shown.

**Keywords:** Hierarchical Bayesian estimation, mixed Markov hazard model, heterogeneity, statistical deterioration prediction, visual inspection data.

**New Approach for the Assessment of Existing Structures using Probabilistic Analysis Methods in Combination with Non-Destructive Testing Methods:** Thomas Braml; Alexander Taffe, Germany; Sascha Feistkorn, Switzerland; Otto Wurzer, Germany

Increasing daily traffic volume with rising numbers of axles and allowable load per axle, demands appropriate load models for structural analysis. Such models have been developed and incorporated in the latest standards. Using the new load models, the load bearing capacity of many in-service structures is exceeded. Therefore a realistic assessment of the structure especially for the existing bridges is needed. Non-destructive testing (NDT) is being used to give realistic import values for structural analysis. This article outlines a procedure for combining the results of non-destructive testing in civil engineering (NDT-CE) and stochastic models used for probabilistic analysis to quantify the reliability of a structure given by the reliability index. The idea to implement the measurement results as statistic variables in stochastic models is not new. This article presents a novel flexible approach to quantify the uncertainty of measurement according to the GUM (Guide to the Expression of Uncertainty in Measurement). The GUM-approach allows easily updating input quantities and quantifying their effect on the total uncertainty without repeating the whole process. In advance the reliability of a NDT-method can be quantified by conducting carefully designed POD (Probability of Detection) studies. A case study of an existing bridge is presented here, where it will be shown by means of a sensitivity analysis how detailed knowledge – gained from reliable NDT-CE measurements - of the dead loads or the exact position of tendon ducts can influence the reliability index. Combining reliable NDT-CE measurements and probabilistic analysis allows assessing the “true” as-built structure with the purpose to prove its stability based on detailed structural and statistical knowledge.

**Keywords:** Reliability, existing structures, non-destructive testing methods, load-bearing capacity, practical approach, probability of detection, stochastic models.

**Concrete Girders with Exposed Flexural Reinforcement:** Trevor Scott, Michael F. Bartlett, Canada

Deteriorated reinforced concrete highway bridge girders are regularly repaired by replacing existing concrete with new concrete, temporarily exposing the flexural reinforcement. The absence of bond between the concrete and the steel reinforcement makes it difficult to compute the flexural capacity of the girder and current code criteria provide no guidance to assist practitioners. In Canada, it is common for the reinforcement to be exposed for periods of days or even weeks while unrestricted traffic is travelling in the lane supported by the girder being repaired. Two analytical approaches are developed to predict the longest length of exposed flexural reinforcement that ensures a girder will still exhibit a ductile failure with no reduction in yield capacity. A new experimental investigation is reported comprising five 4-metre concrete T-section specimens with reinforcement ratios of 0.37%, and exposed flexural reinforcement, loaded with a simulated uniformly distributed load and a concurrent single-point load to realistically simulate the loading applied to a typical bridge girder. All specimens yielded, exhibited ductile behaviour with no strain hardening, and failed by the crushing of the concrete compression region at applied moments of 75 to 81% of the predicted moment of the original specimen without
exposed reinforcement. The results validated a Strain-Compatibility-based analysis with an average test-to-predicted ratio of 1.00 and a standard deviation of 0.068. A Strut-and-Tie-based analysis could only be indirectly validated. These approaches will assist practicing engineers designing rehabilitations.

**Keywords:** Bridges; girder; reinforced concrete; exposed reinforcement; assessment/repair; rehabilitation.

**Recommended Reliability Levels for the Evaluation of Existing Bridges According to Eurocodes;** P. Koteš, J. Vičan; Slovakia.

Transport infrastructure plays an important role from an economic and management point of view in every country. In developing countries, transport infrastructure has a prominent position in advancing industry and society. Recent developments show attention should be moved from the design of new structures towards the repair and reconstruction of existing ones to ensure and increase their satisfactory structural reliability and durability. The problem is very urgent because many construction projects, especially transport infrastructure, in most European countries are more than 50-60 years old and require rehabilitations based on objective evaluations. Modified reliability levels for the evaluation of existing bridges were derived based on activities in the department of structures and bridges. The levels are used for determining partial safety factors for resistance depending on the age of the bridge and on its remaining lifetime. New modified reliability levels for the evaluation of existing bridges also affect the partial safety factors for load effects.

**Keywords:** Evaluation, bridge, existing structure, reliability level, load, material properties, partial safety factors.

**Assessment of Cable Forces at the London 2012 Olympic Stadium Roof;** Elsa Caetano, Portugal; Rastislav Bartek, UK; Filipe Magalhães, Portugal; Chris Keenan, Glyn Trippick; UK

The London 2012 Olympic Stadium Roof was constructed as a cable net covered by a flat PVC coated Polyester fabric membrane supported by an oval compression truss and an inner tension ring. As part of the geometric and mechanical control of the constructed structure, the forces installed in the most relevant cables were assessed using the vibration method. Particular characteristics of these cables, as the flexibility of anchorages, the short length, low tension and bending effects were among the difficulties found, preventing the direct application of the vibrating chord formula to estimate force on the basis of measured natural frequencies. In order to reduce as much as possible the errors in force estimates, a methodology combining numerical finite element modeling with experimental testing was applied. This comprehended in particular the modeling of the cables with adjustable rotational springs, the corresponding constants being fitted on the basis of the measured natural frequencies. This paper describes the methodology applied in the identification of force in different conditions, showing that the combination of high quality vibration measurements with the finite element analysis of individual cables can provide a robust and powerful identification tool in many situations where the vibrating chord theory fails. Furthermore, the differences of pre-stress to theoretical values are characterised and discussed in face of the sensitivity of structural members to fabrication and erection tolerances.

**Keywords:** Assessment, Olympic stadium, membrane/tensile structures; monitoring, steel, prestressing.

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