CONSECUTIVE MULTI-LEVEL BRIDGE ASSESSMENT

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Abstract

When assessing an existing bridge, the application of conservative design load and resistance models can cause unnecessarily high maintenance costs. On the other hand, sophisticated methods based on probabilistic approach require greater effort and are also demanding for practical application. Consequently, multi-level assessment procedures are considered appropriate, whereby complexity and accuracy increase consecutively through the levels. Namely, if the bridge meets the requirements at the first assessment level - on the safe side, no further complicated steps are needed. Otherwise, a more complex assessment step should be carried out in which we are closer to the real values of the structure's performance and resistance.

In this paper, (i) the multi-level assessment of road bridges for traffic load and (ii) the multi-level seismic assessment of arch bridges, will be overviewed.

In addition, recommendations for further development of assessment procedures will be provided, based on undergoing research. The first research branch explores the value of implementing the Bridge-Weigh-in-Motion measurements together with the probabilistic approach in assessment of existing road bridges. The second research branch aims to reveal seismic resistance of bridge elements with nonstandard sections and smooth reinforcement designed without contemporary rules for ductile behaviour.

Keywords: bridges, arch bridges, multi-level assessment, traffic load, seismic assessment

1. INTRODUCTION

Deterioration of bridge structures occurs due to weathering (eg. corrosion, fatigue) or due to structural defects caused by accidental actions (eg. truck collision on substructure elements). Combination of aggressive exposure conditions, inadequate detailing, neglecting durability issues, construction errors and underestimating the importance of maintenance, may result in serious damages. Furthermore, loads change during lifetime of the bridge (eg. traffic load) or extension of the design life is imposed [1]. In addition, requirements on structures change in terms of development and updating of regulations and normative standards in line with contemporary approaches to safety and serviceability of structures and novel scientific contributions. Therefore, existing structures, often do not satisfy current needs, respectively do not poses adequate safety levels, particularly in relation to seismic performance.

For the successful evaluation of bridge performance in remaining service life, in order to determine whether it requires repair or retrofitting, it is extremely important to properly assess it. Current codes for the design of new bridges do not offer optimum approach for assessment of existing bridges, as they are based on conservative assumptions regarding loads and resistance and could result in extremely large costs for bridge maintenance [2]. On the other hand, sophisticated methods, based on probabilistic approach require additional knowledge and assets, and they are more complicated for practical application.

Therefore, multi-level assessment methods, where accuracy, along with complexity increases on subsequent levels, are considered to be more appropriate for assessment of existing bridges. If the bridge passes the initial level of assessment, no further actions are required. Otherwise, the bridge is revaluated with advanced methods on subsequent levels, in order to determine realistic values of load effects and bridge load carrying capacity.

2. MULTI-LEVEL ASSESSMENT OF ROAD BRIDGES FOR TRAFFIC LOAD

Most often, bridges are assessed in terms of traffic load effect. Traffic load is the basic bridge load, of highly variable characterisation, both in space and in time, so its modelling for the design of new bridges is very conservative. In most of the European countries that have adopted national standards for assessment of existing structures (Switzerland, Austria, Germany), adjusted partial factors method is used with the same reliability levels requirements as for new structures. The exception is the Netherlands, where reduced reliability levels are suggested for existing structures [3].

A large number of road bridges and overpasses of small and medium spans in Croatia, built during seventies and eighties, are designed according to outdated regulations. In order to evaluate their reliability for traffic loading, multi-level method (Figure 1) is developed [4]. If condition assessment based on visual inspection and documentation overview, points to deficiencies which might endanger the safety of the bridge and its users, three-level assessment procedure should start. At each level, adequate checks, based on limit state equation are to be evaluated, thus proving whether the bridge is enough safe/ reliable for continued use [4].

At the initial level, assessment is performed using conservative methods similar to those used when designing new bridge, employing codified partial safety factors for material and load. If the bridge passes the initial level, no further actions are performed.

Otherwise, the bridge should be re-evaluated using advanced non-linear analysis methods at the second assessment level in order to reveal global safety factor γ as shown in Figure 1. Applying non-linear behavior of bridge materials may result in higher levels of bridge resistance compared to those obtained from the first assessment level [3].

Third level of proposed assessment method is based on probabilistic approach, which makes it more demanding for practical use. All variables in limit state equation are modelled as stochastic variables, described with its statistical parameters (mean value μ and standard deviation σ). Probability index β is calculated and compared to target reliability for existing bridges. To carry out this assessment level, data on materials based on in-site and laboratory testing are to be collected to calculate the relevant statistical parameters. Uncertainties in resistance and load effects will not be covered with partial factors as in previous two levels;

namely adequate uncertainty will be joined to each separate variable depending on its type and amount of data. Valuing of uncertainties will highly impact the final assessment result [4].

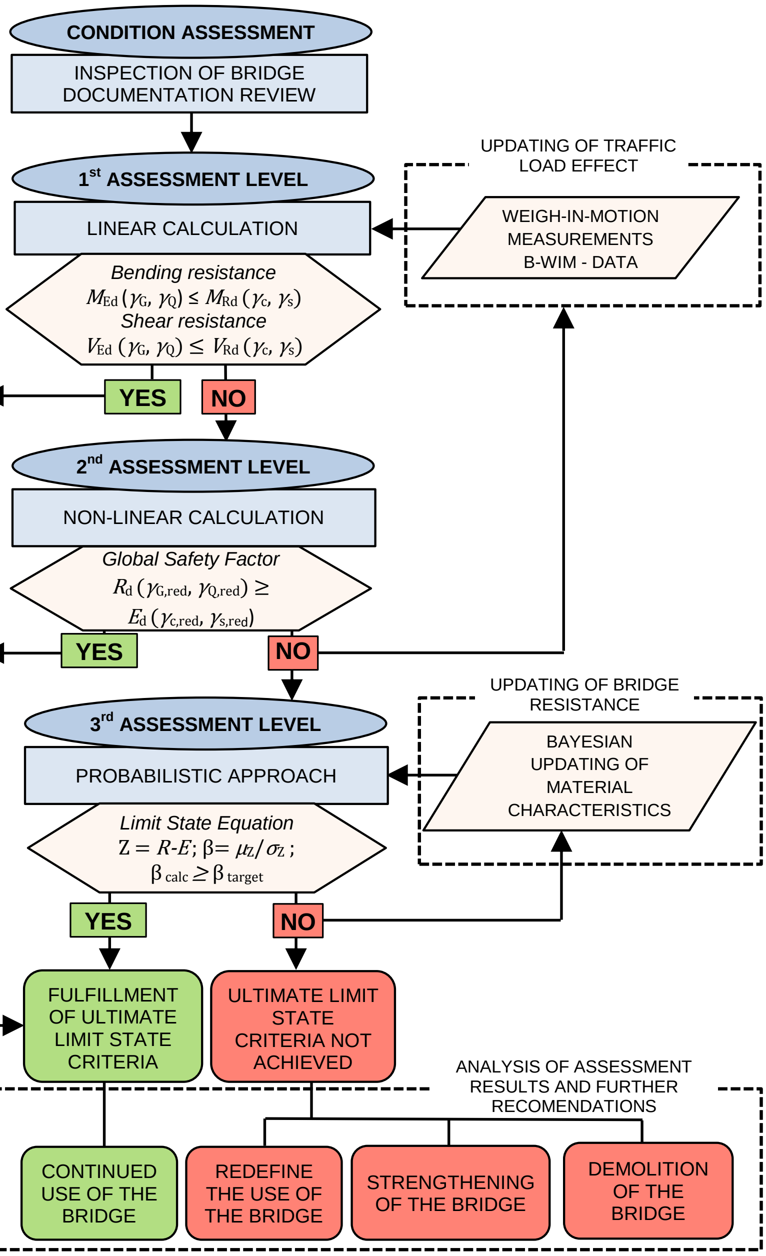

Figure 1: Flow chart diagram of multi-level assessment of road bridges for traffic load

Above mentioned bridge evaluation procedure may be improved by additional methods for determining localised load effects and realistic material/structural resistance indicators. This requires additional research and gathering more data.

Based on measurements of in-service traffic load using Bridge Weight in Motion System, it is possible to reveal exact traffic effect for a certain bridge including changes in bridge boundary condition, hidden degradation and also the values of dynamic amplification factor which may have significant influence in assessment of small and medium span bridges [5, 6].

In probabilistic based approach at the third level of assessment method, material resistance indicators are to be presented as random variables with adequate statistical parameters. Valuing of this indicators is based on inspections and tests which extent greatly depend on the available costs provided by the investor so very often the engineer will need to assess the bridge based on a limited data collection. In these cases, the use of Bayesian method [7] of probability estimation proved to be very effective. It provides reliable values of material characteristics, combining prior information, obtained from literature or past experiments, with test results in order to reduce uncertainties in probabilistic based assessment approach.

Based on the assessment procedure results, we come to the conclusions for further bridge performance. In case the assessed bridge does not meet the ultimate and serviceability limit state criteria, it is necessary to decide whether the traffic should be restricted, bridge strengthened or completely closed or/and removed.

3. MULTI-LEVEL SEISMIC ASSESSMENT OF ARCH BRIDGES

Considering that the whole of Croatian territory is seismically active, earthquake loading is often governing for element design (especially columns), material consumption, detailing, and overall mechanical resistance and stability of bridges.

The current European seismic code does not offer a procedure for seismic assessment of bridges, arch bridges in particular [8]. Non-linear static pushover methods have been the focus of extensive research in the recent years [9], particularly in the direction of extending them to structures with significant higher mode effects as are many bridge types.

Reinforced concrete arch bridges are particular structures owing to their robustness and not much may be found in existing literature about seismic assessment of this type of bridges. The tradition in construction of such structures in Croatia and gathering knowledge on them through their use and maintenance, enabled us to further develop and improve certain aspects of available seismic performance methods and to properly incorporate them in a new procedure dedicated to seismic assessment of reinforced concrete arch bridges, presented at the figure 2. The procedure, running through levels of assessment, is applicable for the whole arch bridge structure and it indicates the most critical bridge details and elements in seismic response [8, 10].

First of all, it is necessary to collect bridge data. To define a correct structural model of the existing structure and to perform adequate structural analysis it is necessary to identify existing and desired knowledge level of the existing structure based on the bridge importance. These knowledge levels may be obtained with adequate data collection on geometrical properties of both structural and non-structural elements which may affect structural response, structural details including amount and detailing of reinforcement, concrete cover, connection between members and the mechanical properties of the constituent materials in conjunction with the appropriate confidence factors [8,10].

The procedure is consisted of two levels and several evaluation checks at each assessment level (table 1). Each evaluation check gives an answer if appointed demand is fulfilled or not. With these answers quite precise guideline for seismic retrofit of assessed arch bridge may be brought, which than can be presented to the bridge owner who will bring the final decision to retrofit the bridge or not.

First level of assessment results with more conservative estimate of the bridge state considering seismic response than the second level. Therefore for bridges that do not fulfill all checks of the first level it is necessary to go through the second level of assessment. As reinforced concrete arch bridges are particular structures owing to their robustness, it is found out that performance of arches under seismic design situation may be proved already at the first level using linear multimodal analysis. For spandrel columns (particularly short ones near the arch crown) it will be necessary to go through the second level of assessment based on non-linear pushover analysis [8,10].

Second level requires more numerical and computational effort but it results with less conservative estimate of bridge state than the first one and thus with economically favourable retrofitting measures. If retrofitting measures will be taken, it is important to apply this same procedure again on the model of retrofitted bridge and evaluate the results following the same steps [8,10].

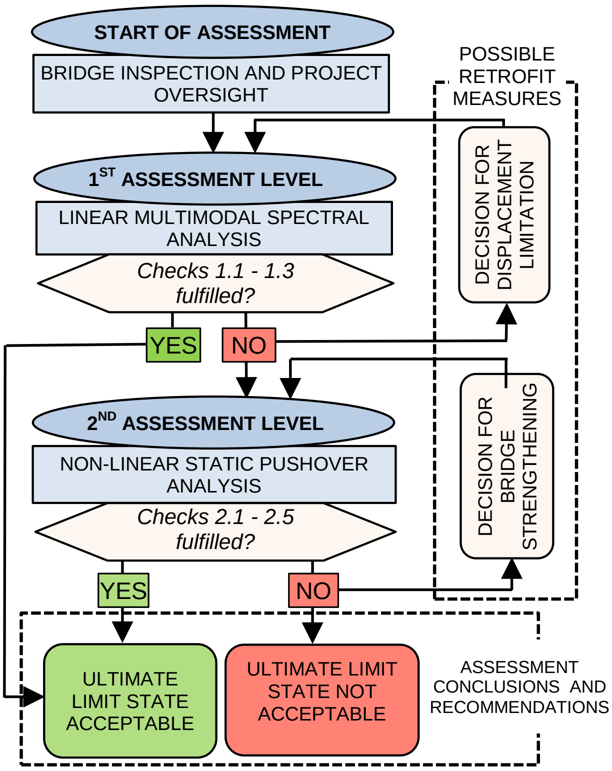

Figure 2: Seismic assessment procedure flowchart

Dynamic specificity of arch bridges is the flexibility of an arch as support for spandrel columns and great amount of the bridge mass located generally in the middle of the bridge, what comes from the position and the mass of arch.

During inelastic response of arch bridge due to the initial seismic stroke, the greatest deformation demands are posed on the shortest columns which results in their excessive cracking and finally after damage causing earthquake the need for their repair or retrofit. Upon the cracking of shortest columns and appurtenant stiffness reduction, deformation requirements are moved following from the crown to the coastal columns which results with their degradation as well. That excessive cracking should be taken into the account appropriately with effective stiffness of column cross sections [8].

Table 1: Assessment checks through consecutive levels

Assessment checks related to linear multimodal spectral analysis	
1.1 Displacements compared to allowable ones at the abutment	$d_{allow} \geq d_e$
1.2 Design resistances for the interaction of axial force and bending moment	$f(N_{Rd}, M_{Rd}) \geq f(N_E, M_E)$; $f_{i,m}$ za $f(N_{Rd}, M_{Rd})$ i $f(N_E, M_E)$
1.3 Seismic shear force demand	$V_{Bd,1}=V_{Rd}/\gamma_{Bd,1} \geq V_E$; $CF \times f_{i,m}$ za V_E; $f_{i,m}$ $/CF \times \gamma$ *za* V_{Rd}
Assessment checks related to non-linear static pushover assessment	
2.1 Rotation capability at locations of potential plastic hinges	$\theta_{ls} \geq \theta_{p,E}$
2.2 a) Stresses of unconfined i b) and confined concrete	$f_{cm}/(CF \times \gamma_{c,acc}) \geq \sigma_{c,E}$ (in elastic regions) $f_{cm,c}/(CF \times \gamma_{c,acc}) \geq \sigma_{c,E}$ (in plastic regions)
2.3 Stresses in reinforcing steel	$f_{ym}/(CF \times \gamma_{s,acc}) \geq \sigma_{y,E}$
2.4 Verification against non-ductile failure through shear	$V_{Bd,1}=V_{Rd}/\gamma_{Bd,1} \geq V_E$; $CF \times f_{i,m}$ za V_E;$f_{i,m}$ $/CF \times \gamma$ *za* V_{Rd}
2.5 Outward buckling of longitudinal compression reinforcement between transverse ties	$A_{t,built}/s_{T,built} \geq \min(A_t/s_T)$

The topic that requires additional research is the rotational capability of elements with unusual section (such is the extended hexagon shown at the figure 3 right), which so far are to be conservatively approximated with rectangular sections.

Accurate evaluation of the ultimate rotational capacity of reinforced concrete members may only be based on experimental data [11] due to numerous geometrical and mechanical parameters and uncertainties involved (loading type: cyclic or monotonic, seismic detailing, concrete confinement, spalling of concrete cover, ribbed or smooth bars, overlapping length, plastic hinge length, bending contribution, height of the section, etc.).

4. UNDERGOING RESEARCH

Further development of assessment procedures will be based on two undergoing research branches.

The first research branch explores the value of implementing the Bridge-Weigh-in-Motion measurements together with the probabilistic approach in assessment of existing road bridges. This is related to the 3rd assessment level after the updating of traffic load effect as presented in the figure 1.

So far this approach is applied at the case study simply supported highway bridge with a single span of 24,8 meters, and superstructure composed of five prefabricated I-type prestressed concrete girders connected with monolithic deck. B-WIM monitoring strategies include (i) short term monitoring, which provides realistic influence lines and girder distribution factors and (ii) long term monitoring, which provides dynamic amplification factors and site-specific load models, along with the data obtained also in short term monitoring.

Results showed that this improvement may reveal hidden bridge reserves and predict bridge reliability development over a specified lifetime. Consequently, such measurements can permit unrestricted use of a bridge over a much longer remaining service life [6].

Undergoing research involves Value of Information analysis, and associated decision trees as convenient tools that can be used to justify initial investments in SHM to bridge owners. Currently modelling of all the associated probabilities, costs and benefits required for the decision tree, along with classification of bridge based on his importance in the infrastructure networks is under progress (Figure 3 left) [12].

The second research branch aims to reveal seismic resistance of bridge elements with nonstandard sections and smooth reinforcement designed without contemporary rules for ductile behaviour [13].

Namely, the question of ductility of such columns, as well as plastic hinge development, and overall nonlinear behaviour, is largely unanswered. Therefore, research into the behaviour of such sections could reveal their ductility levels and show much better performance in seismically active areas. Seismic performance indicators of bridge columns to be revealed are: (i) M/φ diagrams - bending moment and section curvature relationship curves which best show the rotational capability of plastic hinges, (ii) chord rotation capacity as rotational capability of sections and elements in the hinges and (iii) real effective stiffness after cracking near the hinge.

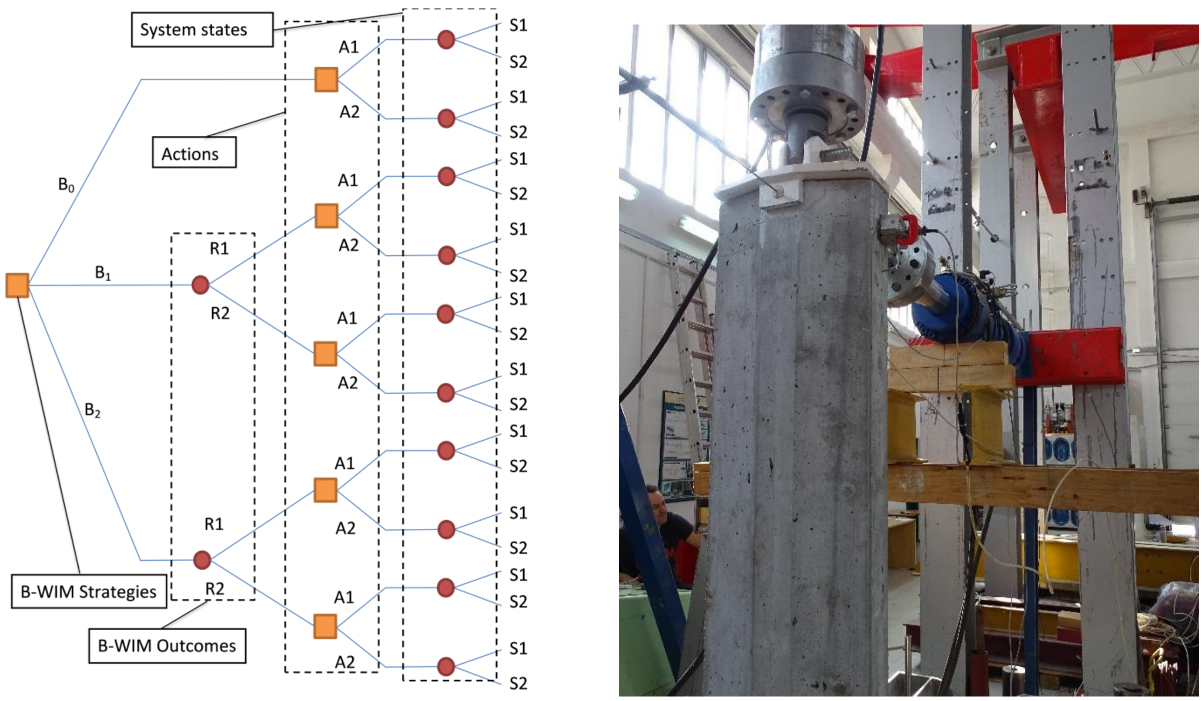

Figure 3: Undergoing research for further development of assessment procedures – Left : implementation of VoI for quantifying the value of B-WIM; Right: testing of piers with nonstandard cross sections and smooth reinforcement for revealing ductility levels

The experiment planned to reveal this indicators for bridge columns of nonstandard sections with smooth reinforcement, designed without contemporary detailing for ductile behaviour, is under progress (Figure 3 right). Experiment will serve to update analytical models and investigate the applicability of existing building code formulas for assessment of seismic resistance of existing bridges with atypical cross sections.

5. CONCLUSIONS

Assessment of existing bridges should be based on consecutive levels becoming more demanding but also more accurate, which are gradually approaching the realistic load effects and structural resistance. Only this way, the application of scientific achievements in practice, resulting in optimal and efficient maintenance of the bridges, will be possible. Two undergoing researches will hopefully (i) prove the value of implementing the Bridge-Weigh-in-Motion measurements together with the probabilistic approach in assessment of existing road bridges and (ii) reveal ductility levels of nonstandard bridge column sections with smooth reinforcement in seismically active areas.

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