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SEISMIC VULNERABILITY ASSESSMENT OF BRIDGES

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Abstract. *This article presents a systematic method for the seismic vulnerability assessment of existing bridge structures depending on the bridge type. The analysis procedure is based on three investigation levels with increasing expenditure of time and has been developed within the framework of a research project funded by the German Federal Highway Research Institute. The method is supported by a management system with database functionality linked to a national bridge database. The practical use of the method is demonstrated by means of an example of the longest suspension bridge in Germany, the Rhine bridge Emmerich.*

1 INTRODUCTION

One of the main causes for a high number of deaths during earthquakes is that rescue measures can often only be accomplished insufficiently and delayed. Strategic important roads are impassable due to collapsed bridges, debris or fires so that rescue forces are not able to attain incident places (Fig. 1). Hence there is a need to assess the seismic vulnerability of existing bridges in order to guarantee their functionality in case of an earthquake. The assessment procedures should consider the demands of the current standards and must be applicable in the engineering practice. Furthermore the forthcoming introduction of the Eurocode 8, part 2 [1] increased the interest for reliable assessment procedures considerably.

In the present paper a general seismic vulnerability assessment system for bridges, developed within the framework of the ongoing research project “Seismic vulnerability assessment of bridges in Germany” funded by the German Federal Highway Research Institute, is introduced. The basis of the system is a hierarchical classification of the bridges into different types. For each bridge type a vulnerability assessment procedure consisting of three different levels with an increasing expenditure of time is provided for the user of the system. The developed system is linked to the national bridge database SIB-Bauwerke [2], which provides information of all strategic important bridges in Germany. The level of assessment can be chosen depending on the scope and the accuracy required.

Figure 1: Collapsed bridge impeding traffic to hospital resulting from 1971 San Fernando Earthquake [3].

2 DESCRIPTION OF THE ASSESSMENT SYSTEM

The vulnerability assessment is based on three investigation levels with increasing expenditure of time and necessary bridge data. The implementation has been carried out in form of a management system linked to an existing national bridge data base. In the following the functionality of the management system and the procedure in the three investigation levels are described.

2.1 Management system

The developed management system provides to the engineer a tool for an efficient execution of the three investigation levels. The system supports the bridge data acquisition, the determination of the seismic site hazard, the generation of the computer models, the evaluation and interpretation of the investigation results and finally the structured storage of the data on a central data base server. Furthermore the system incorporates a hierarchical user management with different levels of data access authorizations.

For the collection of the bridge data the management system is connected to the already existing national bridge data base SIB-Bauwerke [2]. The update of the data is enforced through a secure connection over the intranet or internet. In order to guarantee a simple data exchange, the bridge classification of the national data base was mostly taken over. In accordance to the national database the management system provides the following bridge classes (Fig. 2):

- Beam girder bridge: slab, girder, tee-beam, box girder
- Frame bridge: opened, closed
- Arched bridge: spandrel-braced arch, arched trough
- Suspension bridge: one pylon, two pylons
- Cable-stay bridge: one pylon, more than one pylon
- Cantilever-truss bridge

Each of these upper bridge classes is divided into more detailed subclasses with respect to the type of continuity and the supporting columns.

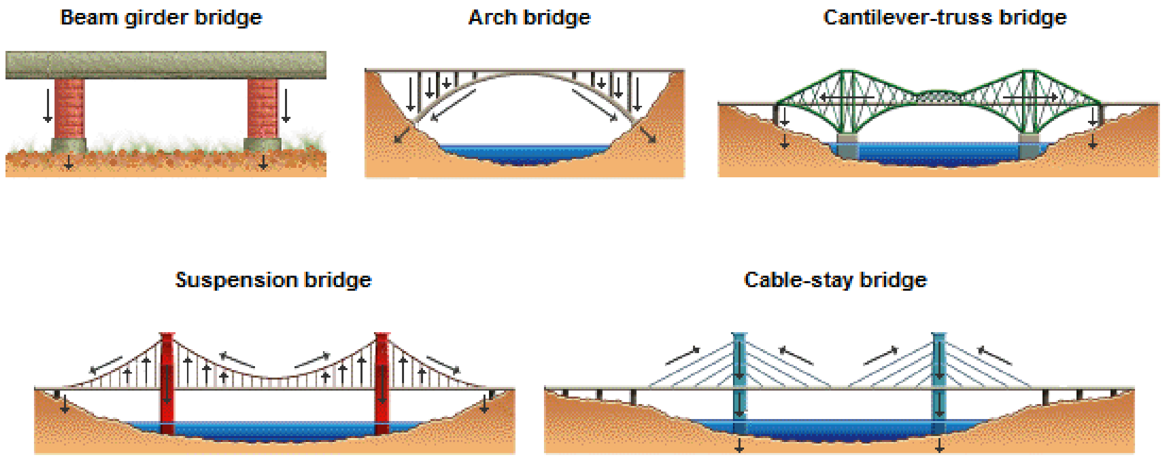

Figure 2: Upper bridge type classification of the management system

The seismic site hazard is described by a design spectrum, which is produced automatically according to the DIN 4149 or the Eurocode 8 specifications depending on the earthquake zone and ground type (Fig. 3). Optionally there is the possibility to introduce site specific spectra instead of using the ones provided by the codes. The synthetic accelerograms for the base excitation in the third investigation level are generated on the basis of these spectra. Furthermore the management system supports the usage of measured site specific accelerograms.

The generation of the finite element simulation model for the second investigation level is realized by the supply of generalized templates for the different bridge types. The templates allow the automatic generation of the simulation models by using the substantial geometry, material and cross-sectional parameters.

The interpretation of the results is facilitated by the detailed presentation of the input data and output data completed with statistical evaluations and result visualizations. As the geographic position has to be entered in the management system, the system offers an interface for the possibility to visualize the results through a Geographical Information System (GIS). Finally, all bridge data and results are stored on a central data base server, so that future events like long-term deterioration effects or rehabilitation measures can be taken into account at a later stage. The advantage of the central data base is furthermore the possibility for a continuously updating of the bridge data base.

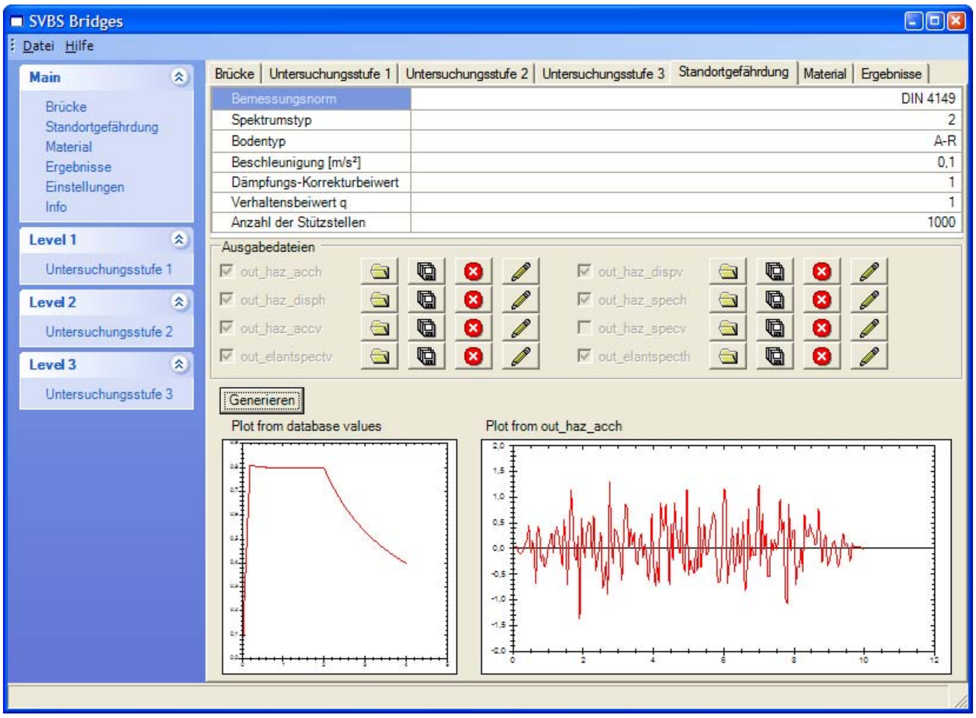

Figure 3: Management system: Definition of the seismic site hazard

2.2 Investigation level I

In the first investigation level the seismic behavior of the bridge is described by fragility curves, which define the relation between spectral acceleration and the probability of occurrence of certain damage states. The curves are obtained with the procedure described in

HAZUS-MH [4]. As input parameters the bridge type, the response spectrum for the specific location and the bridge geometry are required. The procedure is based on expert opinion and statistical data obtained from data acquisitions of damages after earthquakes. The curves included in HAZUS-MH are based on the world-wide most comprehensive statistic evaluation of the seismic damages on bridge structures [5], arisen after the Northridge and Loma Prieta earthquake. The bridge data necessary for calculation of the fragility curves are extracted from the national bridge data base [2].

Additionally for each bridge type, an extensive evaluation system is provided by the management system, based on the evaluation of constructional characteristics. With the results of the evaluation system complementary information is provided to the fragility curves for a better consideration of the individual bridge characteristics. For this evaluation system more detailed bridge data from a bridge inspection, static calculations and construction plans are necessary. The result of the first investigation level represents a first estimation with small expenditure of time. It serves as decision basis for the necessity for further investigation steps.

As result of the evaluation system a priority index P for the analyzed bridge is evaluated by the multiplication of the risk and importance factor I of the bridge, whereas the risk is defined by the multiplication of the vulnerability V and the seismic site hazard S:

$$P = V \times S \times I. \tag{1}$$

The risk represents the probability for a certain damage of the bridge during a certain reference period. The importance factor I of a bridge describes the lower or higher importance of the bridge for the society in case of a crisis with respect to the structural safety and economical effects. The seismic site hazard S characterizes the probability for a seismic hazard to occur in the given region. The probability for a seismic action is the so called “annual return period” of the ground acceleration due to a possible earthquake.

2.3 Evaluation of the importance factor

The Eurocode 8, part 2 recommends the classification the bridges into three different importance classes with a less than average, average and greater than average bridge importance. The values for the importance factors may be found in the National Annexe to the Eurocode 8. If no Annexe is available three values for the importance factors are recommended by the Eurocode. The Eurocode 8 defines that bridges on motorways and national roads as well as railroad bridges belong to the middle importance class. The highest importance class contains bridges of crucial importance for the maintenance of the traffic facilities particularly in the time immediately after the earthquake event. Furthermore bridges whose failure is associated with a large number of presumed victims and major bridges, for which a design life greater than normal is required.

For the engineer this description might in most of the cases be not precise enough as the parameters described before might be not available. Within the development of the evaluation system for the vulnerability assessment of bridges a formula to evaluate the importance of a bridge is proposed [6]:

$$I = 0.7 \cdot \left[ST_{over} \cdot \left(\frac{DTV_{over}}{DTV_{\max over}} \right)^{0.25} \cdot UL_{over} \cdot ESU_{over} \right] + 0.3 \cdot \left[ST_{under} \cdot \left(\frac{DTV_{under}}{DTV_{\max under}} \right)^{0.25} \cdot UL_{under} \cdot ESU_{under} \right] \quad (2)$$

Equation 2 is widely based on a technical report of the MCEER [7], improvement recommendations for this report and the work of Basöz and Kiremidjian [8]. The equation consists of two terms, where the first one describes the importance of the road and traffic on the bridge (index over) and the second the importance and traffic of the crossed road (index under). Both terms are evaluated separately and added, assuming that there is no influence between both. Each term is obtained by the multiplication of the following factors:

- ST: Road type
- DTV: Average daily traffic of the road
- DTV_{max}: Maximum average daily traffic of the road
- UL: Detour = (0.6 + 0.4 · x [km] / 150)
- ESU: Influence of the road type over/under the bridge on the road type of the detour

The resulting importance factor provides a result between 0 and 1 for the lowest and highest importance for a bridge. In order to divide the obtained importance into the three classes defined in the Eurocode 8, following classification is proposed: For an importance factor $I \leq 0.2$ the less than average, for $0.2 < I \leq 0.6$ the average and for $0.6 < I \leq 1.0$ the greater than average importance class. With this conservative range the requirement of the Eurocode 8 to place the highway and railroad bridges into the average importance class is fulfilled.

2.4 Investigation level II

The second investigation level consists of a numerical simulation of the bridge based on an equivalent simplified linear model of the overall system consisting of linear beams connected by (in the case of the suspension bridge) simple tension-only elements. Details are not taken into account in the simplified model. For the determination of the internal forces the modal response spectrum analysis is used. The soil-structure interaction is considered by the use of the truncated cone model of Wolf [9]. This model idealizes the soil as homogeneous, linear elastic, half-infinite medium and can be used for foundations on homogeneous as well as on layered soils. The expenditure of time in this investigation level essentially depends on the accessibility of geometry, material and cross-section parameters. This information is entered into a generalized template of the management system. By using the inputs the simplified numerical model is generated as far as possible automatically. The result of the second investigation level is the evaluation and verification of the earthquake resistance on the basis of simple design checks with the calculated internal forces and deformations. This investigation level is sufficient in most cases, in order to make a reliable statement about the existing earthquake resistance.

2.5 Investigation Level III

The third investigation level is based on an evaluation of the construction documents, on a bridge inspection in combination with measurements of the natural frequencies and on a nonlinear time-history analysis with a detailed numerical model. The numerical model must include all the critical constructional details identified in the preceding investigation levels, in order to take into account all possible failure mechanisms.

The measured natural frequencies are used for the review and calibration of the numerical model by variation of the stiffness distribution. The time-history analysis of the calibrated model is carried out in most of the cases by using synthetic accelerograms generated from the elastic response spectrum. The soil-structure interaction is considered in the same way as in the second investigation level. The model generation in this stage cannot be generalized, so that the expenditure of time is always high in this investigation level. Therefore, an investigation in this level is limited to critical bridge structures, whose earthquake resistance can only be verified considering all system reserves.

3 INVESTIGATION OF THE RHINE BRIDGE EMMERICH

The practical application of the described approach is demonstrated by the Rhine bridge Emmerich, situated near the border to the Netherlands. With a span length of 500 m in the main span and a total length of 800 m, the bridge is the largest suspension bridge in Germany. It is the last crossing possibility of the Lower Rhine on the German side and the direct connection between the motorway A3 west of the river and the motorway A57 on the east side of the river. In case of a bridge failure, traffic would have to be rerouted under considerable difficulties over roads involving a detour of approximately 35 km. Because of the infrastructural importance of the bridge, a comprehensive investigation was carried out on all three levels of accuracy. Since neither the Eurocode 8 nor the revised version of the DIN 4149 include seismic design procedures for suspension bridges, only the seismic hazard given in these codes were used for the investigations.

3.1 Description of the bridge

The Rhine bridge Emmerich (Fig. 4) is a suspension bridge with two pylons and ground-anchored main cables. It was completed in 1965 after a construction period of 40 months. The four-lane federal road B220 crosses the bridge with a pedestrian and bicycle lane on each side of the deck. The deck itself is 22.50 m wide and designed as a steel truss. The girder is supported by rocker bearings, which makes a shift in longitudinal direction possible. The 74.15 m high pylons with rectangular steel box cross-sections are connected by a tie bar thus forming a framework. The main construction material is steel S355. Between the abutments 124 cables of 14 t weight each are present over a length of 922 m. The bridge has a total weight of 10200 t.

Figure 4: Rhine bridge Emmerich

3.2 Definition of the seismic site hazard

Due to the infrastructural importance and the size of the Rhine bridge Emmerich the specific seismic site hazard curve of the bridge location was determined by the Federal Institute for Geosciences and Natural Resources [10] on the basis of probabilistic seismic hazard assessment (PSHA) methods using the German earthquake catalogue considering the local underground conditions. As result the highest possible intensity in the Lower Rhine region was determined to 8.5 MSK. In comparison the highest historically observed intensity amounts to 8.0 MSK. The resulting seismic hazard curve of the location is shown in Figure 5. The standard deviation of the determined hazard curves is 0.5 MSK.

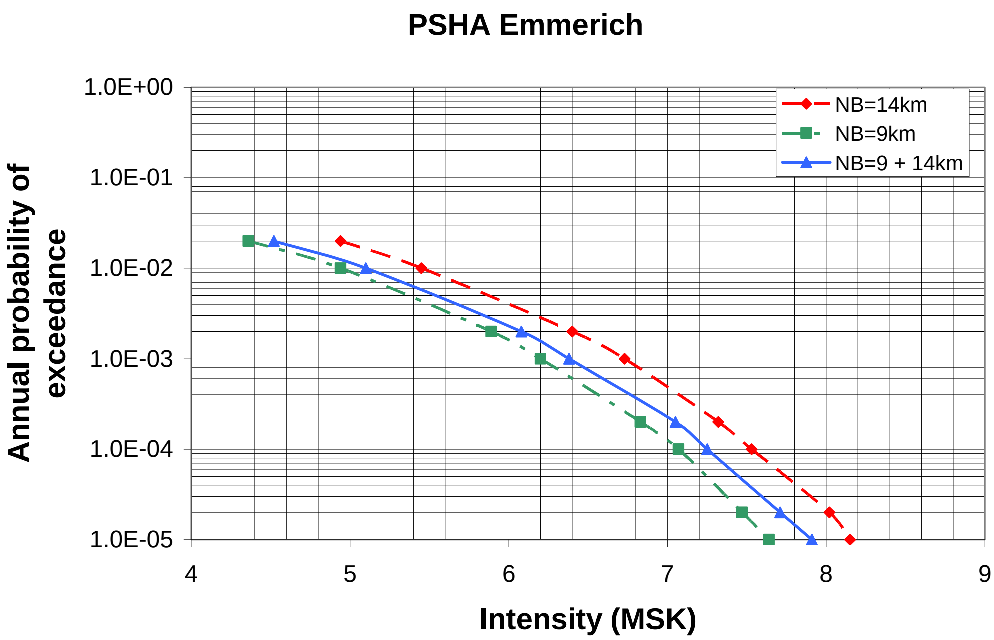

Figure 5: Seismic hazard curve for the Rhine bridge Emmerich [10]

The two exterior curves represent events with characteristic focal depths of 9 and 14 km for the Lower Rhine bay (NB). The curve used here corresponds to a weighing of the two curves by factors of ¼ for the depth of 14 km and of ¾ for the depth of 9 km.

Following the conversion of intensity into soil acceleration according to the relationship of Murphy and O'Brien [11], a relationship between annual probability of exceedance and soil acceleration can be determined. Using this relationship, the response spectra can be set up for deep geology class T and ground type C according to the revised version of the DIN 4149 for different probabilities of exceedance.

3.3 Investigation level II and III computer models

In the simplified linear finite element model, the pylons, the deck and the foundations are modelled by beam elements with equivalent stiffness properties. The rocker bearings are modelled by linear spring-damper elements and tension-only elements are used for the idealization of the cables. The interaction between soil and structure is considered by truncated cone models after Wolf for a homogeneous soil. The entire model consists of approximately 3500 degrees of freedom.

In the detailed nonlinear model (Fig. 6), the bridge deck is represented by shell elements (Fig. 7). The bracing truss which accounts for the torsional rigidity, present only in the main span, is modeled with bars. The rectangular hollow cross-section of the pylon with internal stiffening by IPE profiles is modeled by a thin-walled beam element with equivalent rectangular cross-sectional shape. The detailed model consists of approximately 6000 degrees of freedom. To take into account possible arising physical nonlinearities a bilinear material law for steel according to Eurocode 3 [12] was applied.

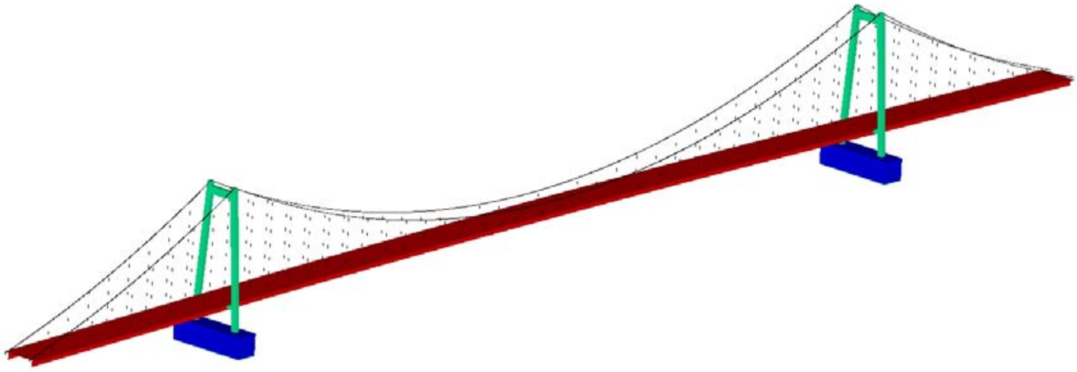

Figure 6: Detailed FE model of the Rhine bridge Emmerich

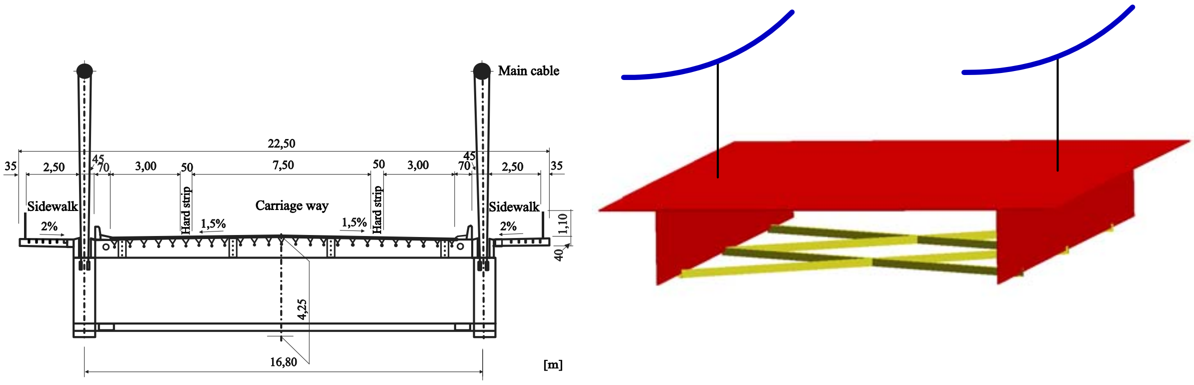

Figure 7: Characteristic cross section in the mid of the bridge

3.4 Investigated seismic actions

The seismic actions for the simplified model of the investigation level II is described by a response spectrum defined according to the revised version of the DIN 4149. For the definition of the spectrum the importance class III and a behavior factor q = 1.0 are chosen. The behavior is chosen in accordance to the Eurocode 8, part 2, which recommends this conservative value for cable systems due to the participation of higher oscillation modes.

The seismic action for the detailed model in the investigation level III is given by an uncorrelated base excitation for the two abutments and the pier foundation. Since no measured acceleration time-history records are available for the given location, they were generated synthetically for the elastic response spectrum provided in the investigation level II for different return periods.

In Eurocode 8, part 2, the combination of the seismic loads with other load cases is described. In case of the Rhine bridge Emmerich the seismic actions have to be combined with the permanent dead loads, the prestress and 20 % of the live load. The live loads are determined according to the DIN-Technical report 101 [13] according to load model 1. This load model consists both of single loads and of uniform distributed loads. It covers the effects from truck and passenger car traffic as well as pedestrian and bicycle traffic. The additional loads of the prescribed load case combination are considered as distributed masses in the bridge deck of the numerical models.

3.5 Model calibration

The calibration was carried out by variation of the stiffness distribution and comparing the computed and the measured first natural frequency. Within the calibration the mass distribution was assumed to be constant. This is justified, since the geometry is normally known exactly. In the case of the Rhine bridge Emmerich, only a slight modification of the stiffness distribution was necessary by adjustment of the cable prestress.

Table 1 includes a comparison of the measured and calculated natural frequencies of the detailed model. Only the natural frequencies which have a relevant effective modal mass are listed. The sum of the effective modal mass of all mode shapes listed in Table 1 is higher than 90% of the total structural mass, so that the requirements of the DIN 4149 and the Eurocode 8 are fulfilled.

Measured and calculated natural frequencies [Hz]					
Torsion		Transversal		Vertical	
Measurement	Calculation	Measurement	Calculation	Measurement	Calculation
0.527	0.525	0.254	0.251	0.234	0.247
0.547	0.553	0.430	0.389	0.273	0.273
0.781	0.635	0.742	-	0.410	0.419
0.898	0.753	1.445	1.147	0.508	0.544
1.269	1.163	1.482	1.305	0.645	0.654

Table 1: Comparison of measured and calculated natural frequencies.

The comparison of the measured and the computed natural frequencies shows a good agreement of the vertical, transversal and torsional natural frequencies. In Figure 8 the first four vertical mode shapes are shown.

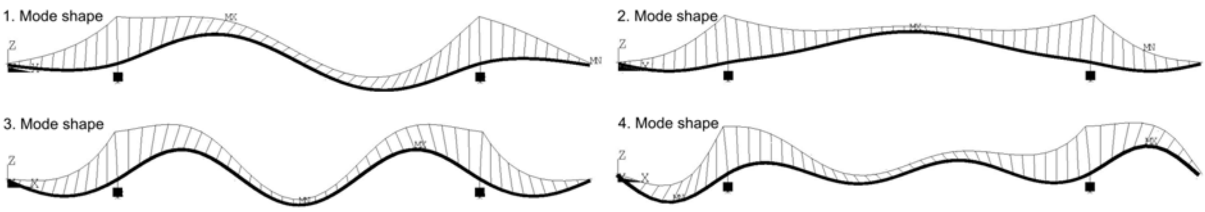

Figure 8: First four vertical mode shapes of the Rhine bridge Emmerich

4 INVESTIGATION RESULTS

4.1 Investigation level I results

In investigation level I, the fragility curves of the suspension bridge were first determined according to the procedure presented in HAZUS-MH. These curves represent generalized mean curves without consideration of the specific structural characteristics (Fig. 9). The occurrence probability of a defined damage state can be read off from the fragility curves to a given spectral acceleration.

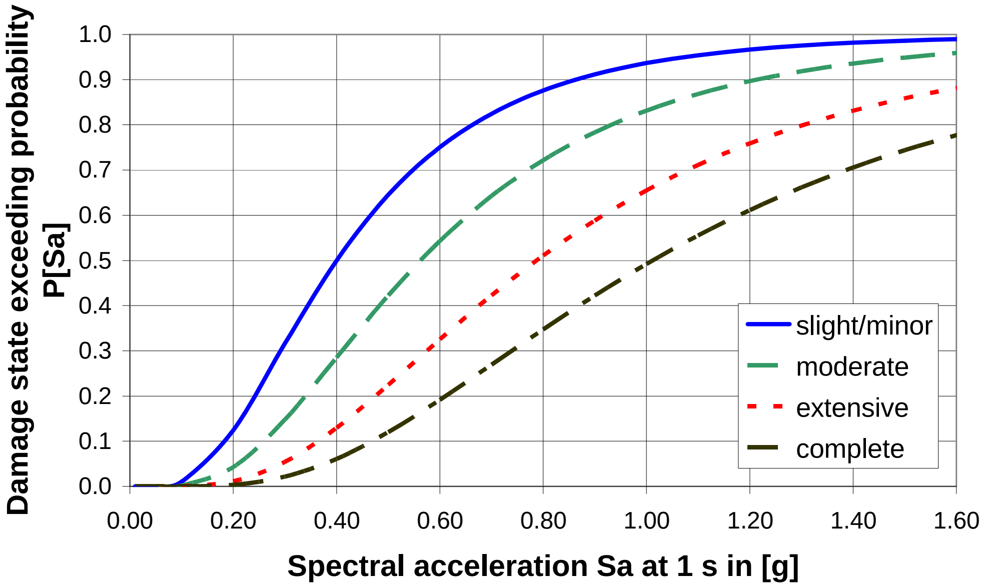

Figure 9: Fragility curves for the Rhine bridge Emmerich

Here the damage states "slight/minor", "moderate", "extensive" and "complete" are differentiated. A slight damage means that only a cosmetic repair is necessary. Moderate damage is defined by moderate movements of the abutments (< 5 cm) and the possibility that it can come e.g. to a failure of the rocker bearing or moderate settlement of the bridge approach. An extensive damage is defined by column damage without complete destruction, by significant residual deformations at connections or by major settlement of the bridge approach. During a complete damage any column collapse or loss of connection for all bearing support, which may lead to imminent deck collapse, can occur. A tilting of the substructure due to foundation failure is also possible in this damage state.

An evaluation of the fragility curves with the maximum spectral acceleration of 0.5 m/s², determined according to the design spectrum of the revised version of the DIN 4149, suggests only slight damage.

Additionally to the fragility curves, the developed evaluation system for suspension bridges provides a more detailed result taking into account the most important construction details. The priority index P for the Rhine bridge Emmerich obtained from the evaluation system is 0.32. Thus only a small damage of the bridge has to be expected. The correctness of this first estimation will be proved in the further investigation levels.

4.2 Investigation level II results

For investigation level II the structural response is evaluated by means of the damage indicators suggested by Dicleli and Bruneau [14]. Additionally, the internal forces and moments due to earthquake are computed with a partial safety factor of $\gamma_M = 1.1$ for material uncertainties and a weighting factor of $\gamma_I = 1.0$ for the seismic action. With the required computed internal forces, stability analysis and stress verification are accomplished according to the Eurocode 3 [12] at the determinant points of the structure. In the following the results of the indicators for the impact of the bridge deck on the abutments and the verification of the axial stresses out at the pylon bottom are exemplarily presented. These criteria proved to be determinant for the Rhine bridge Emmerich in the seismic load case. Figure 10 shows the results for different seismic intensities. The ratio of the calculated longitudinal displacement of the bridge deck compared to the width of the expansion joint as well as the ratio of the apparent to the permissible axial stresses are shown. The analysis considered unfavorable effects of a temperature expansion of the bridge deck during the summer.

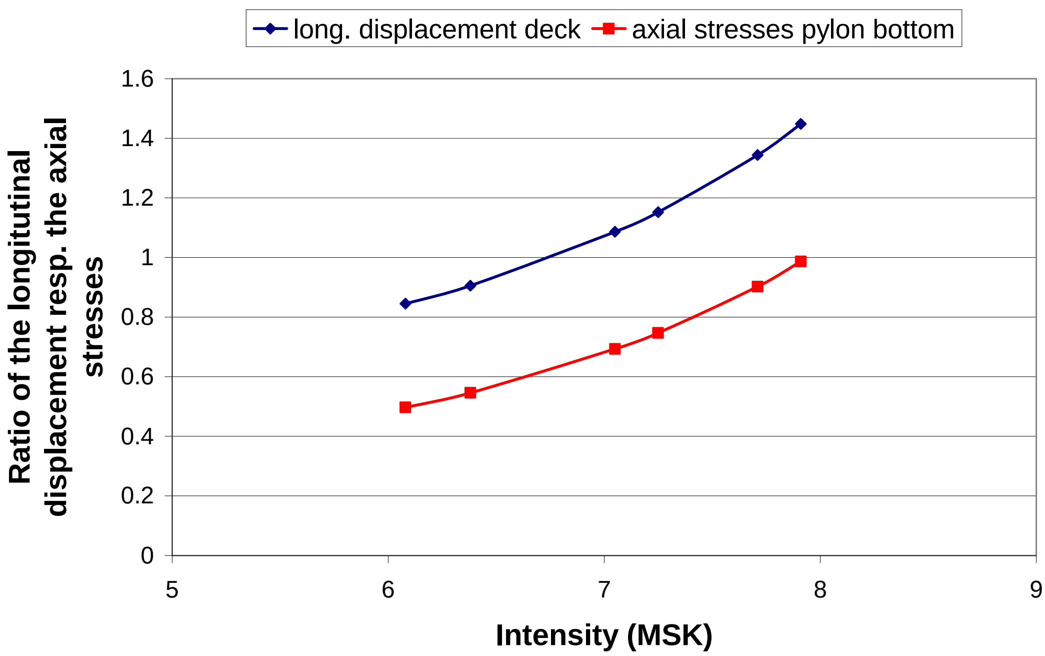

Figure 10: Investigation level II results

The results show that an exceedance of the permissible axial stresses of the pylon arises only due to a seismic intensity higher than VIII. This intensity is to be expected with an annual probability of exceedance of 10^{-5} for the specific location. An impact on the abutments is possible when an earthquake occurs with an intensity of approximately VI-VII, which corresponds to an annual probability of exceedance of $5 \cdot 10^{-4}$. These probabilities are very small compared with the probabilities of 10% in 50 years, as defined in the current codes, which corresponds to an annual probability of exceedance of $2 \cdot 10^{-2}$. This means that the safety level for this bridge can be regarded as sufficient.

4.3 Investigation level III results

For the evaluation of the damage potential, again the indicators of the bridge deck impact on the abutments and the verification of the axial stresses in the pylon bottom are used. Exemplarily the results obtained from three time-history analyses with synthetically generated accelerograms for an earthquake of 10 seconds are presented. Figure 11 shows the determining time-histories of the longitudinal displacement of the bridge deck compared to the width of the expansion joint as well as the ratio of the occurring to permissible axial stresses at the pylon bottom. The here presented time-history records were generated for an earthquake of the intensity VII-VIII, which corresponds to a soil acceleration of 1.5 m/s², converted with the relationship of Murphy and O'Brien.

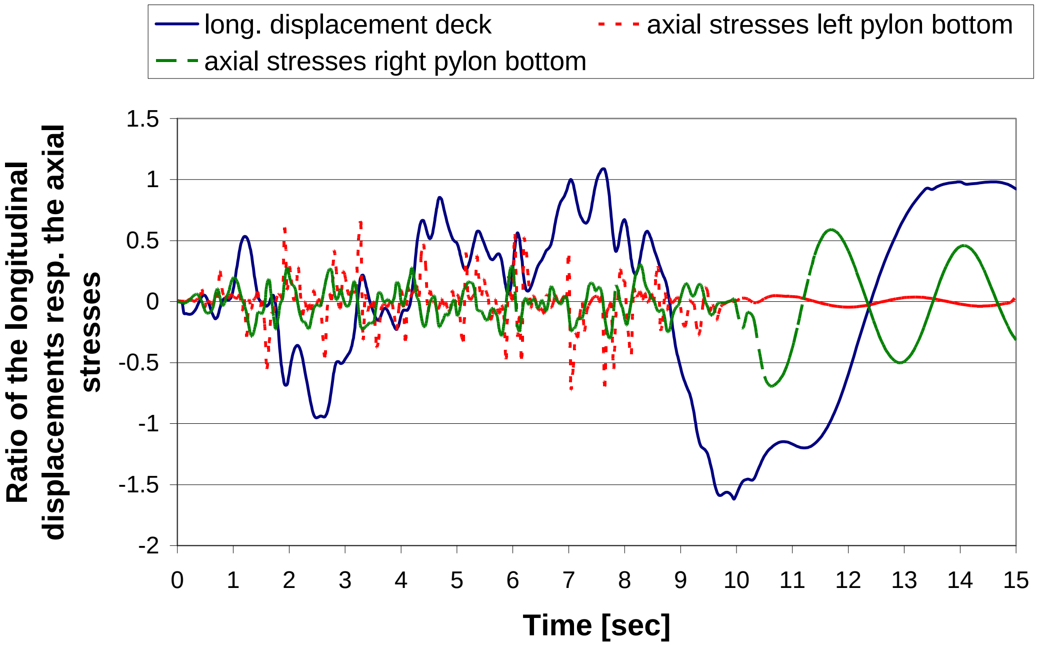

Figure 11: Investigation level III results

The results of investigation level III confirm the results of the level II. The structural design calculation of the axial stresses for the pylon bottom is fulfilled, but at time 7 resp. 7.6 and 9.5 seconds, an impact of the deck against the abutments can arise.

5 CONCLUSIONS

In this paper a systematic three-stepped procedure for the evaluation of the earthquake resistance of existing bridge structures was presented through the example of the suspension bridge Emmerich. The results in the three investigation levels lead to the conclusion that the structural safety of the bridge Emmerich is not endangered. For a probability of exceedance of $2 \cdot 10^{-2}$, which is defined in the Eurocode 8 and in the revised version of the DIN 4149 no damage will occur.

The procedure is supported by a management system with data base functionality and linked to the national bridge data base. The presented three-stepped procedure will be expanded to all bridge types which are defined in the national data base SIB-Bauwerke [2].

ACKNOWLEDGEMENT

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