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DETERIORATION OF BRIDGE DECK ROADWAY MEMBERS. PART II: CONDITION EVALUATION

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Abstract. One of the simplest ways of assessing existing structures is the use of rating marks, classes or grades for each bridge or its components. Different rating systems have been developed and used widely in many countries. Markovian models are often considered to represent the bridge deterioration process. In part I of this two-part paper results of experimental studies on the deterioration of bridge deck ancillary members are presented. This study was conducted to determine the condition assessment procedures and performance characteristics of bridge deck surfacing, expansion joints, and safety barriers. A simple rating system with a scale of 7 to 1 to diagnose the condition of bridge deck members in service is proposed. A Markovian process for physical deterioration of these members is used. Results from a simulation study using the real individual bridge components in City Vilnius are presented.

Keywords: highway bridges, deck members, defects and damages, assessment, serviceability rating, Markovian deterioration process.

1. Introduction

Over the past few decades, bridge management in service has substantially gained importance. The reasons for the growing interest in maintenance, repair and reconstruction works of bridges, can be listed as follows:

- physical obsolescence of building materials;
- rapid increase of traffic volume and heavy vehicles;
- environmental aggression;
- faults of design, materials or workmanship;
- necessity to assure the structural safety and planning of preventative measures;
- necessity to provide feedback of information for designers and constructors.

A very important stage in the bridge management policy is the assessment of all forms of damages, as well as the condition state of existing structures. These factors have a very great importance for establishing the priorities for the long-term maintenance or repair programme and budget planning. Bridge management in service begins with inspections of the present condition of the structure, followed by bridge assessment and evaluation and finally by selection of the appropriate maintenance or repair measures. Bridge management of existing structures is a complex matter with technical and economic consequences.

There are many possible approaches to defining performance and assessing the condition of bridge structures. Currently bridges and their parts are evaluated either through a visual inspection or structural analysis. With an analytical evaluation, the bridge condition is computed based on the load applied and the resistance capacity of bridge components. This approach is frequently used for structural elements of superstructures and substructures. On the other hand, it seems that ratings based on visual inspection are a good choice for those members, for which it is not always possible to determine the resistance factors. When bridge evaluation is conducted by a visual inspection based on the experience of the inspector, a subjective rating is assigned to the bridge component, a bridge as a whole or the bridge stock. Different rating systems typically with a scale of 0 (or 1), complete failure, to 100 (sometimes 5, 10, 30), being a new state, are proposed for evaluating bridge deck, superstructures, and substructures [1–6]. Many rating systems are presented in many guides and manuals. The author's experience shows that it is often a good choice for a smaller, less sophisticated condition rating system. When too many state grades are used in evaluation, it becomes difficult to differentiate between them.

Once the current condition of a component has been assessed, future condition can be predicted using deterioration models. Deterioration of bridge structures is complex reflecting the nature of the physical or chemical processes involving a number of different mechanisms operating simultaneously. Different materials and members have different deterioration processes. Deterioration is a stochastic process. The probability based Markovian models are often considered to represent the bridge deterioration process from the condition ratings data collected during the bridge inspections most effectively. In the majority of countries the BMS (Bridge Management Systems) based on the use of Markovian type deterioration process have been developed [eg 7–10].

This article discusses the condition evaluation of bridge deck components using proposed condition rating system and the condition prediction modeling based on the Markovian deterioration process. This research examines condition assessment data for deck surfacing, expansion joints, and safety barriers. Observed condition states of these members were reported in part I of this paper [11]. The purpose of this procedure was to determine, through visual condition assessment, the condition state and the life span of the bridge deck members in some bridges of City Vilnius.

2. Condition assessment

Condition assessment is a process, which can be summarised in the following general procedures:

- Sub-divide the bridge substructure, superstructure and deck into sets of elements based on their importance for function and safety, maintenance requirements, similar mechanism of deterioration, and relative life spans. Certain structural elements have a life which is less than that of a bridge. It is useful to distinguish between short-term elements which can be easily replaced, and long term, which favor rehabilitation or strengthening.
- Determine for each set of bridge elements the type and extent of current deterioration/damage and their influence on the condition of members.
- Set the scale of parameters that describe the condition of the structure and its constituent elements.
- Carry out a Markov chain for the deterioration process starting from a known current situation. The Markov chain calculates the probability of a typical element being in a particular condition state at a particular age as well as the state transition probability representing the rate of deterioration.
- Compare the Markov model of deterioration prediction with previous records of condition assessment obtained from detailed inspections.

2.1. Condition rating system

After a field inspection of a bridge, and if necessary after analysis of the historic condition state data, a structural evaluation must be made to suit the appropriate maintenance, repair or reconstruction methods. The main problem of decision making procedures is to obtain a true condition state of bridge members and to predict their behavior, especially those which are damaged.

Each bridge deck component is to be assessed for structural and functional deficiency. The primary considerations in classifying deficiencies are the component condition ratings (CR). The elements of bridge deck component condition rating are shown in Fig 1.

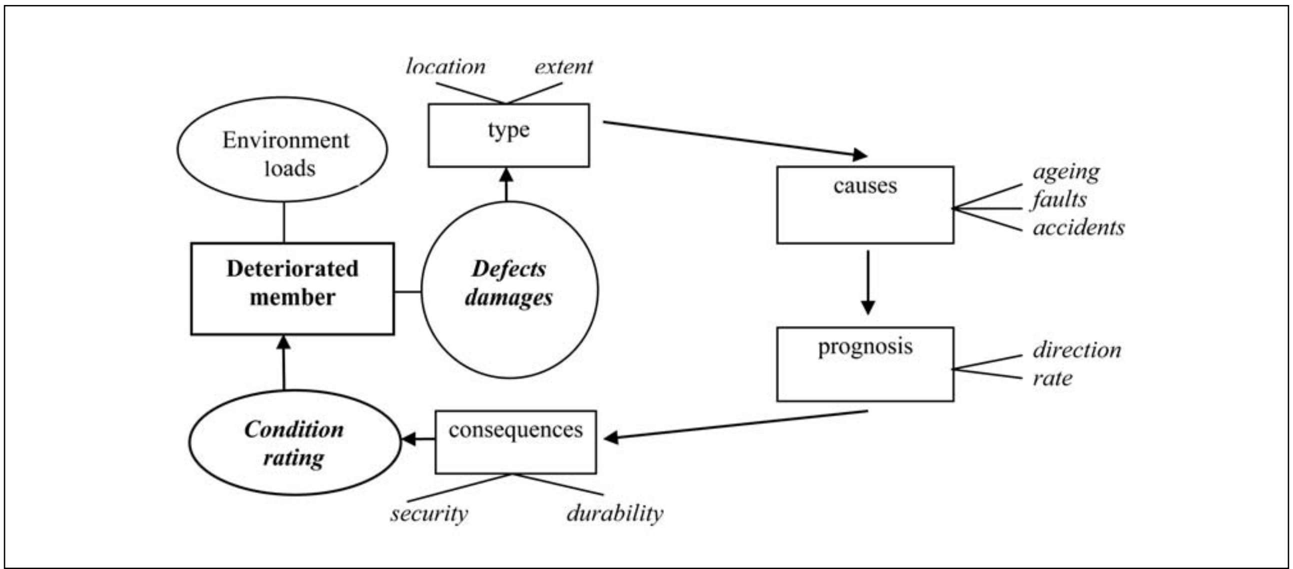

Fig 1. Sample decision tree for assessing bridge member's deficiencies

A rating system is always based on the quality and individual opinion of experts and is an approximate evaluation of existing structures. Therefore the rating system has to fulfill four main demands:

- to be simple and easy to use;
- to include only the most important factors;
- to include the time factor;
- to allow the establishment of priorities with regard to maintenance or repair works.

A member condition rating is simply the scale used to describe a set of discrete states (ie members' entire condition). In this paper all members are rated using the following scale:

CR*7 *excellent – new condition; no action required within the next 5–7 years (until the next detailed inspection);

CR*5 *good – minor deterioration, ie first signs of aging, but functioning as originally designed; action required within 3–5 years;

CR*3 *fair – serious deterioration or damage or not functioning as originally designed; action required within 1–3 years;

CR*1 *poor – potentially hazardous; action required within 1 year.

Totally deteriorated or in failed condition members are not included in condition rating as the immediate actions (eg limitation of use, repair or replacement) must be taken as soon as possible. Condition ratings 6, 4 and 2 can be used to shade between 5 and 7, 3 and 5, 1 and 3, respectively. Items 3 and lower require substantial rehabilitation. Items higher than 3 may be corrected with daily maintenance work. Maintaining members at least at a "good' level not only enhances safety for bridge owners and users, it is also a cost effective policy.

It can be seen that the serviceability rating includes an assessment of the actual condition of the member, as well as the prediction of future its behaviour, so that the required measures can be made in time. Prediction of a long-term behaviour should include the prognosis of deterioration rate and the environment in which the member resides. Evaluation can be carried out on the element level, whole bridge or a whole bridge population when only average performance level is needed.

The proposed rating system allows the systematisation of bridge deck serviceability diagnosis, which is easy to modify or to update. On the basis of the comprehensive members' serviceability rating, the most suitable improvement options can be selected.

2.2. Markovian process

Deterioration of deck members is transition process from an initial or a given condition state to a lower-grade state leading to a gradual decrease of members' performance (Fig 2). The transition of members' performance depends on a large number of random variables and is always treated as stochastic process.

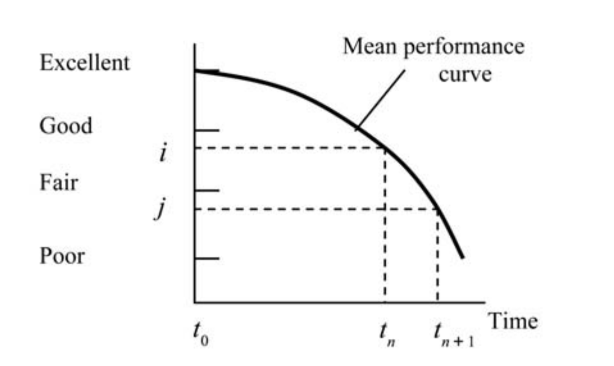

Fig 2. Relationship between deterioration of a bridge member and its condition rating

In this paper the time-dependent probabilistic modelling of the deck members' condition deterioration is carried out using Markov Chain model [eg 12–14]. The Markov chain approach is based on the concept that given just the present condition of a member and a known probability of the change in a member's condition over a given time interval, the future condition of the member can be reasonably predicted. The basis of the Markovian model is the condition state transition probability square matrix $\mathbf{M} = n \times n$ shown below:

$$\mathbf{M} = \begin{bmatrix} p_{11} & p_{12} \cdots p_{1n} \\ p_{21} & p_{22} \cdots p_{2n} \\ \multicolumn{2}{c}{\dots\dots\dots\dots\dots\dots} \\ p_{n1} & p_{n2} \cdots p_{nn} \end{bmatrix}, \quad (1)$$

where p_{ij} is the condition transition probability from state i at time t_n to state j at time t_{n+1} (Fig 2). For new as built structure $t_n = t_0$.

In deterioration modelling it is assumed that the members condition can stay in the same state or move to a state of greater degradation, ie $p_{ij} = 0$ for $i > j$. Another assumption is that the final state is a state that cannot be vacated if no repair is made, ie $p_{nn} = 1$. These assumptions lead to **M** being an upper triangular matrix of the following form:

$$\mathbf{M} = \begin{bmatrix} p_{11} & p_{12} \cdots p_{1n} \\ 0 & p_{22} \cdots p_{2n} \\ \multicolumn{2}{c}{\dots\dots\dots\dots\dots\dots} \\ 0 & 0 \dots\dots\dots 1 \end{bmatrix}. \quad (2)$$

The probability of being in state j at time t_{n+1} is determined as follows:

$$p_j(t_{n+1}) = p_i(t_n) \sum_{i=1}^{j} p_{ij}, \quad (3)$$

where $p_i(t_n)$ is the probability of being in state i at time t_n.

The M matrix used in this study is based on the four-state model (7-5-3-1) described above. Hence:

$$\mathbf{M} = \begin{bmatrix} p_{77} & p_{75} & p_{73} & p_{71} \\ 0 & p_{55} & p_{53} & p_{51} \\ 0 & 0 & p_{33} & p_{31} \\ 0 & 0 & 0 & 1 \end{bmatrix}. \qquad (4)$$

Markov models require only two successive cycles of inspection and rating of member's condition before model estimation becomes possible. If the time interval between two adjacent inspections is short enough that the condition state of member will change by only one state grade, we obtain the diagonal matrix in the form:

$$\mathbf{M} = \begin{bmatrix} p_{77} & 1-p_{77} & 0 & 0 \\ 0 & p_{55} & 1-p_{55} & 0 \\ 0 & 0 & p_{33} & 1-p_{33} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \qquad (5)$$

where p_{ii} and $1 - p_{ii}$ is the probability of remaining at the same condition rating and the probability of deteriorating by one condition rating, respectively.

Transition probability matrix **M** [Eq (5)] can be described by state vector **P**, containing the main diagonal of matrix **M**, i e, $\mathbf{P} = \{p_{77}, p_{55}, p_{33}, 1\}$.

The predicted condition state for a set of particular members in future years, $pS(t_m)$, is obtained by matrix multiplication between initial condition state matrix, $pS(t_0)$, and the one-step condition state transition probability matrix, $\mathbf{M}(\tau)$:

$$pS(t_m) = pS(t_0) \times \mathbf{M}^m(\tau), \qquad (6)$$

where m is a number of transitions; τ is the time interval between two adjacent assessments ($\tau = t_{n+1} - t_n$).

For a new member a condition state probability distribution is $pS(t_0) = \{1; 0; 0; 0\}$.

3. Practical application

3.1. Condition evaluation procedure

The approach presented in Section 2 of this paper was applied as an example for condition assessment of bridge roadway members in the city of Vilnius. Condition rating scales based on a set of numerical ratings between 7 and 1 as presented above and condition criteria with classification of member's deficiencies for 3 groups of deck members (asphalt surfacing, asphalt plug expansion joints, and concrete safety barriers) were summarised in our previous publication [1] and are not reported here due to limited space of paper. As shown in Fig 1, the information recorded for each type of member included distress type, its causes and consequences. This task was performed by a team of 3 inspectors.

Table 1. Resulting condition transition probability vectors

Member	Sample size	p_{77}	p_{55}	p_{33}	p_{11}	Age at CR3
Surfacing	26 600 m^2	0,654	0,378	0,878	1,0	26,0
Expansion joints	2 274 m	0,451	0,410	0,620	1,0	15,5
Safety barriers	1 533	0,653	0,637	0,708	1,0	25,2

The initial condition of deck members at time of inspection is presented in Fig 3. The total number of 56 city bridges with 26 600 m^2 of surface area, 2274 m of expansion joints, and 1533 precast concrete safety barriers were included in the analysis. The condition rating 3 and below indicates poor or worse conditions and results in structural deficiencies. Of all 31,5 % of surfacing, 4 % of expansion joints, and 12,1 % of parapets were classified as structural deficient.

The simulation of time-dependent deck member's deterioration was carried out using Markov chain model with a four-year transition probability matrix. The number of municipal bridges with an extensive deterioration increased during this interval (Fig 3). The four-year state probability matrixes for condition assessment of deck members are presented in Table 1.

Using Markovian stochastic model and the matrixes in Table 1, the deterioration of bridge deck members is predicted for the next 36 years. Fig 4 shows the average *CR* of deck members as a function of time. As shown in Fig 4, the gradual deterioration of deck member's condition is nonlinear. The deterioration of deck members takes the convex functional form, with deterioration rate slowing with age.

It was assumed in this investigation that the daily maintenance can slow deterioration, but it does not result in a condition state improvement. Based on this assumption, the bridges that had been repaired or rehabilitated were excluded from the analysis. It can be seen in Fig 4 that the worst performing deck component is the expansion joints. All deck members after 8 years in operation could have an average *CR* of 5. An unserviceable condition with *CR* of 3 is predicted for 15–26 years (Table 1) that can be denoted as average service life of the members. The probability of the members having *CR* more than 3 after this time of service is very small unless rehabilitation had been performed. It should be mentioned that no rehabilitation work had been carried out for expansion joints and parapets, while surfacing of bridges have seen some type of rehabilitation work (repair of small potholes and spalls near expansion joints) that can be reflected on the data of evaluation.

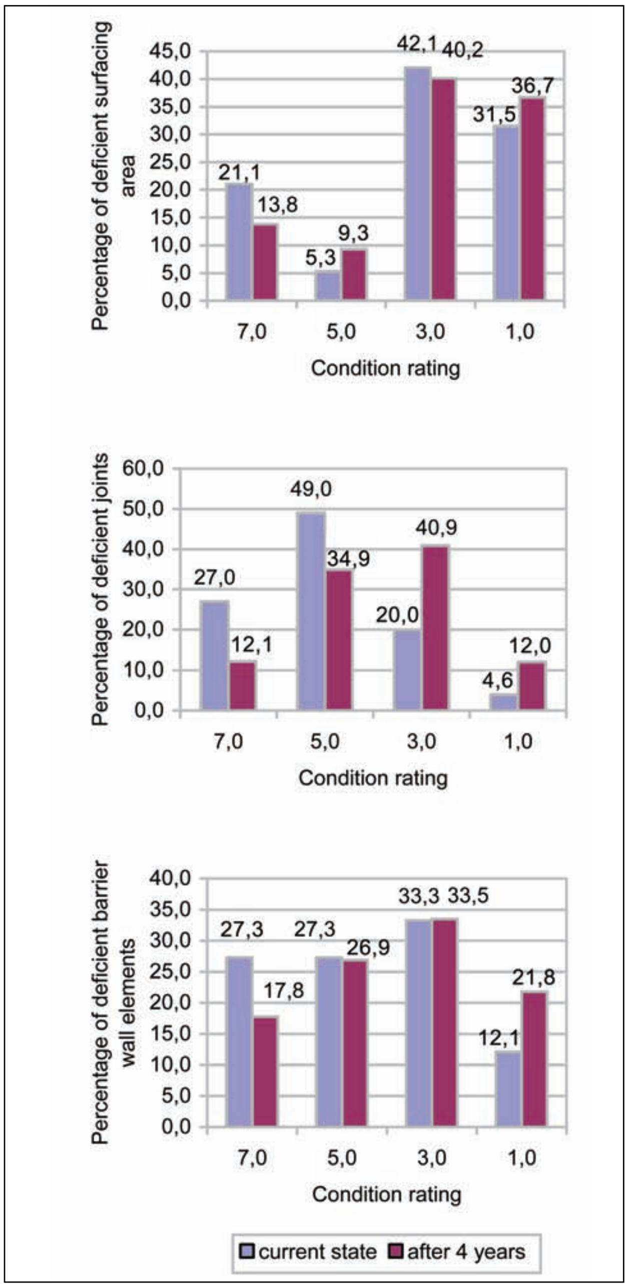

Fig 3. Condition rating of deck roadway members

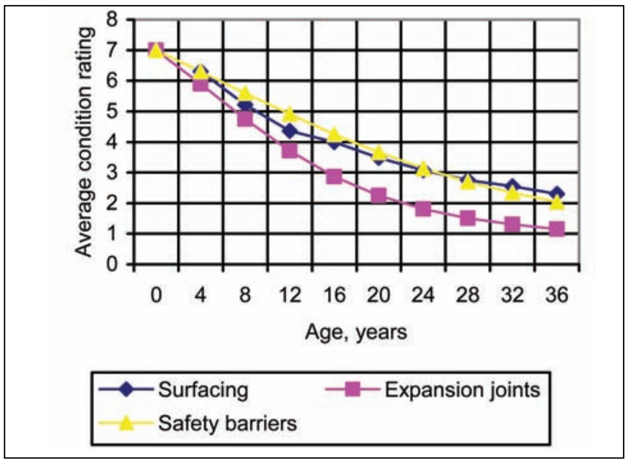

Fig 4. Average condition rating of deck roadway members versus age using Markov model

3.2. Model validation

A very important procedure is to verify that the Markov probability performance prediction models are consistent with observed actual condition states for each transition period. Deterioration functions have to be developed by means of statistical data obtained from successive regular inspection records. Unfortunately, a systematic condition assessment in the form of condition ratings of city bridges is lacking. Without a detailed information, it is not possible to compare discrete state deterioration indicators obtained in simulation and a statistical regression based models.

The author disposed some data from his own investigations of reinforced concrete precast safety barriers. A total of 669 safety barriers with similar characteristics and environmental conditions were inspected and rated from May to August, 2006. The safety barriers were selected based on their age (8, 22, 26, and 36 years old) and no rehabilitation was carried out during their service time. Typical examples of concrete barriers deterioration are shown in Fig 5. De-icing salts are considered to be likely the most serious cause of deterioration. Concrete parapets on bridges are exposed to splash and spray from traffic. A recent study showed that the quantity of chlorides into water of the snow accumulated on the sides of pavement in City Vilnius may receive over 2,5 mg/l.

In Fig 5, a it can be seen that concrete surface pitting and scaling are listed as the chief manifestations of concrete surface deterioration after 8 years in service. Surface degradation is observed approximately on up to 50 % of precast members leading to a decrease of average *CR* from 7 to 5. The signs of concrete cover deterioration are obvious, but they are frequently ignored. If the barriers are not repaired the deterioration progresses rapidly with the results shown in Fig 5, b and c. It is obvious that loss of protection properties of concrete cover leads to reinforcement corrosion. The mechanism of safety barriers corrosion is complex and depends on a number of factors, including the environment conditions as well as the depth and quality of concrete [15, 16].

The comparison between simulated and observed values for the average barrier condition is shown in Fig 6. The observed and simulated condition state distributions for 8, 22 and 36 years are shown in Fig 7. As it can be seen, the Markovian deterioration model yields a good agreement between the observed and simulated condition states distributions. Although this conclusion is based on a limited series of safety barriers observations, it appears that this method should be also valid for other roadway members. Hence, the proposed Markovian model for condition state transitions can be successfully applied for predicting of the performance of deteriorating members regardless of the subjective and arbitrary condition state definitions based on condition rating system presented in section 2.1 of this paper.

Fig 5. Typical deterioration of RC safety barriers after 8 (a), 26 (b), and 36 (c) years in service

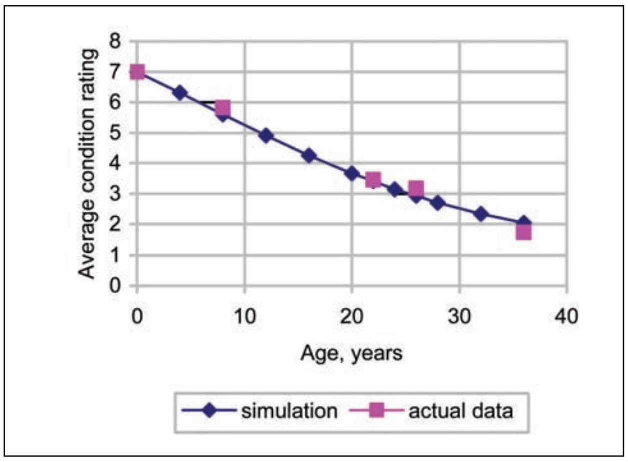

Fig 6. Comparison of Markov simulation and observed safety barriers condition

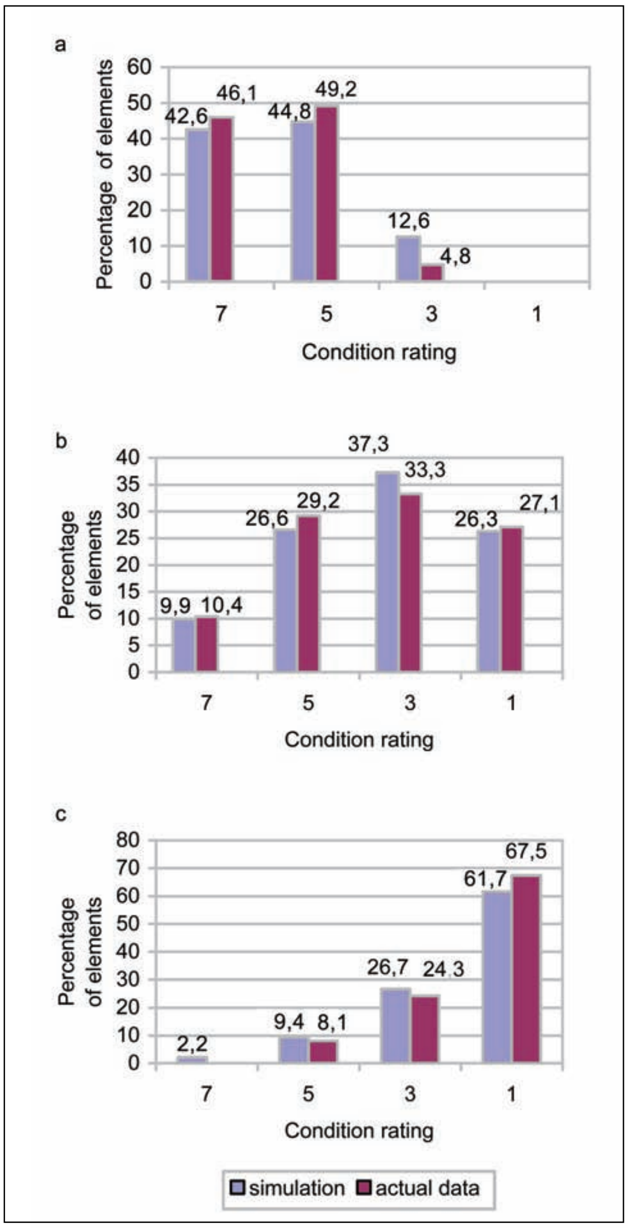

Fig 7. Comparison of observed and simulated condition state distributions of barrier wall elements after 8 (a), 22 (b), and 36 (c) years in service

4. Conclusions

Assessment of bridges and their members in service is one of the most important actions in bridge management policy. The quality of evaluation reflects in the effectiveness of maintenance, repair or replacement of members as well as investments planning.

A simple system for serviceability rating of bridge roadway members is presented. This research examines the condition assessment data for deck asphalt surfacing, asphalt plug expansion joints and precast concrete safety barriers in the bridges of City Vilnius. The condition states of these members are outlined in part I of this two-part paper. In this paper a rating system with a scale of 7 to 1 was developed to allow a numerical comparison between components and also to establish levels of tolerable deficiencies. The condition rating 3 and below indicates poor or worse conditions and results in structural deficiencies. Of all 31,5 % of surfacing, 4 % of expansion joints, and 12,1 % of safety barriers at the time of inspection were classified as structural deficient (Fig 3). The bridge deck members are inspected and values of rating system assigned according to visual observations.

The Markov transition probability matrices are used for prediction of the deterioration process. The four-year state probability matrixes for condition assessment of deck roadway members were determined (Table 1). Using Markovian stochastic model and the matrixes determined, the deterioration of bridge deck members is predicted for the next 36 years. An unserviceable condition with *CR* of 3 is predicted for 15–26 years (Table 1) that can be denoted as average service life of the members. The comparison of observed and computed using Markov chain model condition states of precast safety barriers shows a good agreement (Fig 5).

Any condition assessment in the form of condition ratings until now is carried out for Vilnius city bridges. The bridge members have to be inspected and assessed together with condition ratings. Condition ratings have to be assigned directly by the bridge inspectors by evaluating the type, the causes and the consequences of deterioration (Fig 1). Changes in condition ratings between inspection cycles can be determined. Based on condition ratings, a better estimation of maintenance or repair actions as well as cost savings can be achieved.

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