ANALYSIS OF PARAMETERS OF STRUCTURES DETERIORATION MODELS WITHIN MOSCOW BRIDGE MANAGEMENT SYSTEM

Abbreviated version of the title:
DETERIORATION ANALYSIS IN MOSCOW BMS

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ABSTRACT

Adequate description of deterioration of structures and their elements is very important for the effective use of the BMS. In the course of exploitation of Moscow BMS, deterioration processes have been studied using the results of standard inspections of 1,059 facilities containing over 500,000 standard elements (SE). The analysis shows that for structural SE, deterioration of strength properties virtually does not occur or is of accidental character. In most cases, deterioration is attributable primarily to the wear of materials, which depends to a large degree on the quality of their manufacturing and protection. Also, lifespan prediction for a set of SE should take into account their mutual effects on each other. The methodological sequence of adjustment of deterioration models for different SE, initially adopted on the basis of experts' judgments, is suggested.

KEYWORDS

Bridge management, deterioration model, standard element

The main objective of a bridge management system (BMS) is to ensure optimal planning of repair and rehabilitation activities and to establish a budget for it. Within most BMS, this objective is attained on the basis of deterioration models, which describe wear of structures and their elements in the course of time in quantitative terms, using both probabilistic (Thompson & Shepard, 1993) and deterministic (Kuznetsov et al., 2003) prediction methods. To plot a deterioration model, it is crucial to determine wear intensity for standard elements (SE) and, as a consequence, to predict durability of structures.

In the BMS of the city of Moscow, deterioration of each SE is described as an exponential relationship of wear in the course of time (Curve A, Fig. 1):

$$I = e^{\lambda * t} - 1 \tag{1}$$

where t is the time and λ is the rating coefficient determined for each SE on the basis of the boundary condition:

$$\lambda = (Ln2)/T_c \tag{2}$$

T_c is the average life of a given SE assigned using historical data of bridge management in Russia [3].

In order to ensure efficient inspection of bridges, it is reasonable to replace the continuous function by a step-like function (Curve B, Fig. 1), because the SE condition is assessed on the basis of a five-point scale. Three basic levels correspond to the main types of repair work, i.e., preventive, current and major repairs.

Figure 1

This approach allows the inspector to assess the degree of wear by the questionnaire principle: “Yes,” “No” or “May be” with minimal human error This is important since the most controversial assessments are related to intermediate levels, i.e., between good and bad conditions of an element. The uncertain condition is designated with a basic point of 2 or a fractional value of 1.5 or 2.5. The latter gradations refer to cases in which a structure has not deteriorated to a level corresponding to a basic category. From the viewpoint of repair planning, the category of 1.5 corresponds to the necessity for preventive work, while the category of 2.5 is the lowest permissible level of wear indicative of the need for inclusion of a given structure into the plan of top-priority repair work.

Chart 1 presents classification of condition categories on the basis of different criteria. The visual signs of wear corresponding to certain condition categories are given in the general BMS catalogue for each SE.

Once the condition of all SE is known, one can determine the technical condition index of the entire structure as follows (Shepard & Johnson, 1999):

$$H_{brg} = \Sigma(H_{ej} \times q_j \times C_j) / \Sigma(q_j \times C_j), \tag{3}$$
$$H_{ej} = \Sigma(k_s \times q_{js}) / \Sigma(q_{js}),$$
$$k_s = (5 - s) / 4,$$

where q_j is the number [units of measurement] of standard elements with a serial number “j” assigned for a bridge; C_j is the cost of complete restoration of a standard element with a serial number “j”; s is the index of the condition category; q_{sj} is the number [units of measurement] of standard elements with a serial number “j” having condition “s.”

With an equal distribution of the total number of elements between all condition categories $H_{ej} = 0.5$.

Chart 1

The BMS of the City of Moscow has been operated by the State Unitary Enterprise (GUP) “Gormost” since January 2002. During this period, this institution has taken the inventory and standard inspections of 1,059 facilities (bridges, tunnels, pedestrian bridges, embankments, etc.) containing in total over 500,000 different SE. Accumulation of such significant volume of experimental data allows for initiating verification of the adequacy of deterioration models, previously adopted as regulatory models on the basis of experts’ judgments.

At first, an analysis of inspection data has indicated that there is no significant correlation between the age of a given facility and its technical condition index (Fig. 2).

Figure 2

Zhang et al. (2003), who have also noted a similar effect, link this absence of correlation to the validity of presentation of a structures deterioration in the form of Markovian process, in which the wear intensity of an SE is dependent only on its current condition and independent of its past history (Ventzel & Ovcharov, 2000). We believe, however, that the results obtained should be attributed to the fact that selective repair activities compensate for different rates of bridge wear, which depends, to a substantial degree, on the following three main factors:

- Quality of manufacture of an element / bridge;
- Specific design features predetermining various mutual effects of SE on each other; and
- Degree of protection of a structure against external impacts.

Only the repair actions that change either the quality of elements (replacement of an old element with a new one) or the conditions of exploitation (such as the installment of waterproofing) have a corresponding effect on the wear intensity of the SE.

To verify this assumption, which leads to a significant modification of adaptation procedure for deterioration models, we carry out an analysis of variations of the condition states values for different SE in the course of time.

The law of condition changes has been determined as a trendline for a set of points on the graph of $COND_{med} = F(t)$, where $COND_{med}$ is the medium condition category of an SE under study at time t_i. It has been assumed that the baseline point is the year of construction or major rehabilitation of a bridge, if any.

The medium condition category was determined as follows:

$$COND_{med} = \Sigma(COND_i \times N_i) / \Sigma(N_i), \qquad (4)$$

where $COND_i$ is the condition category of the i-th SE; N_i is the number of SE.

A set of SE for each year of operation varies from 5,000 to 50,000 elements.

The actual values of λ_{real} have been determined in agreement with a procedure for adaptation of baseline data, by computing an actual residual service life to failure and a corresponding rating coefficient based on a specific inspection findings in the course of the BMS operation.

Calculated in this way, the projected wear of every SE is analyzed by the methods of mathematical statistics, through determining the means, classified intervals, variance coefficients etc., as well as analyzing the cases where the wear parameters went beyond these intervals.

The results obtained suggest a conclusion that strength deterioration (fatigue) of most bearing or frame structures does not become apparent even during periods compatible with or exceeding the service life prescribed by regulatory deterioration models (Fig. 3). It should be, however, taken into account that in order to identify any fatigue damage at its initial development stage, one should apply the investigation techniques and the means of access that are not traditionally used for standard inspections.

Figures 3a – 3d

Thus, in the coarse of standard inspection, it was found that in an overwhelming majority of cases, deterioration of bearing and frame structures has been caused by wear of material due to corrosion of reinforced concrete and steel, which led to decrease in their working cross-sectional area.

The reported scatter of condition categories is attributable mainly to variations in the properties of material and its protection (illustrated using an example of reinforced concrete slabs with damaged waterproofing, figures 3e, 3f and 3g). Another cause of the scatter can be traced to the occasional, infrequent and unpredictable emergency situations, such as collision of vehicles with bridge structures, errors in the design or imperfection of the design development norms and standards.

Figures 3e – 3g

For SE referring to construction materials, scatters of condition states are significantly more pronounced (Figs. 4a through 4e). This can be explained by variations of parameters of particular materials (in case of SE "Concrete"- different grades of strength, frost-resistance and impermeability), their initial properties dependent on both the manufacturing conditions and the quality of secondary protection under a given operational environment. The latter is especially true for SE "Steel." In general, with an irregular scatter of points, it becomes difficult to find any correlation between the degree of wear and the time parameter. Most likely, deterioration models for such elements should be specifically assigned to each particular bridge. Such detailed prediction should be based on post-construction tests or experimental data obtained on facilities with similar design structures and environmental conditions. The use of generalized deterioration models for similar SE is permissible only within a significant prediction error.

Figures 4a – 3e

For elements with a limited service life, e.g., for expansion joints, the regulatory deterioration models are very close to reality (Fig. 5).

Figure 5

An analysis of the obtained data suggests that experts' judgment referring to "rated durability" for most SE was excessively pessimistic and corresponded to minimal values within the given life span obtained on the basis of inspection findings (Chart 2). An assessment of the durability using the "lower limit" criterion affected the objectivity of the prediction in the process of the BMS operation. The error in durability predication of SE not accessible for examination had been especially significant. Their condition categories, determined with the aid of the BMS software, took into account parameters of deterioration models assigned by experts. They resulted in the appearance of unjustifiable expenses in the plans of scheduled repairs.

Chart 2

Summarizing the results obtained, we can subdivide all SE into 4 groups:

a. SE, the deterioration models of which can be assigned on the basis of mean values obtained in the process of bridge operation without taking into consideration specific design features or specific conditions of a region, like SE "Filled movement joint";
b. SE, the deterioration models of which can be assigned on the basis of mean values obtained in the process of bridge operation but should be adjusted taking into account specific design features of a bridge and/or specific conditions of a given region, as well as operating conditions, for example, SE "Reinforced concrete ledge";
c. SE, deterioration of which is caused only by accidental situations, and repairs of which should be predicted based on the probability of accidental failures, such as SE "Steel beam";
d. SE, deterioration of which is dependent on specific design features of a bridge or the structural environment to such an extent that their deterioration models should be selected in the process of development of an inspection scheme rather than assigned automatically, for example, SE "Butt-end of reinforced concrete beam," SE "Steel" and SE "Reinforced concrete."

Thus, in order to obtain a relatively reliable prediction, one should take into consideration the quality of a SE, as well as the mutual influence of its adjacent elements.

An estimate of quality of the entire package of SE together with the specific features of their structural environment appears to be a rather complex mathematical problem. Within the framework of a BMS, however, this problem can be solved relatively easily by applying specific individual deterioration models to each SE with a rating coefficient equal to

$$\lambda_i = k_{qi} \times k_{inf,j} \times \lambda_{0i} \tag{5}$$

where λ_i is the rating coefficient for the i-th SE,

k_{qi} is the quality coefficient for the i-th SE,

$k_{inf,j}$ is the coefficient of the effect of the j-th SE,

λ_{0i} is the rating coefficient (stored in the BMS catalogue) of a given SE. It is assigned according to average service time as prescribed by the procedure of refining initial data based on the inspection results.

The quality coefficient (k_{qi}) characterizes those individual properties of an element that affect its service lifespan. It is determined as a ratio of the actual residual lifespan, estimated on the basis of inspection findings, to the initially determined lifespan, stated in the catalogue of deterioration models:

$$k_{qi} = \lambda_{real} / \lambda_{0i} \text{ at } k_{inf,j}=1 \tag{6}$$

If the values of k_{qi} are beyond the range of the average statistical scatter, two possible alternatives are considered, i.e. an inspection error and the effect of the structural environment can be either positive (e.g., the effect of tiling on reinforced concrete elements) or negative (damaged waterproofing, failure of expansion joints, etc.).

If an inspection has been carried out with adequate quality, the element that has a none-zero effect should be identified and the effect coefficient for SE couple "**j-i**" should be introduced into the computational models. This coefficient can be calculated as follows:

$$k_{inf,j} = f(k_{qi} / k_{q\,med}; COND_j) \tag{7}$$

where k_{qi} is the quality coefficient of a given element; and

$k_{q\,med}$ is the average value of the quality coefficient of SE of the same type for a given bridge falling into the range of the average statistical scatter.

The quality coefficient may be used not only for considering specific properties of a given SE or objectivity of a given inspection but also as a criterion for prescribing certain repair actions, e.g., provision of protective coating or replacement of an element with a new one of better quality.

Let us consider as an example a fragment of a reinforced concrete slab on the bridge surface. The slab is described as a combination of the following standard elements: SE-6060 "Reinforced concrete slab," SE-1020 "Reinforced concrete" and SE-3020 "Waterproofing." An assessment of values of parameters of deterioration models based on inspection findings is given in Chart 3.

Chart 3

Typically, the given standard elements are exposed to more intensive wear than the average statistical wear due to the low quality of insulation ($k_{q3020} > 1$).

For "reinforced concrete and "concrete slab", the values of λ_i/λ_{0i} are also high ($\lambda_{1020}/\lambda_{0,1020} > 2$, $\lambda_{6060}/\lambda_{0,6060} > 1.6$), showing negative effects of malfunctioning of waterproofing (leakage of water and salts) and the consequent corrosive impairment (deterioration of concrete and corrosion of steel reinforcement), which in the long run lead to a decreasing of slab's load capacity. To evaluate this causality in the forecast, the quality of "reinforced concrete and "concrete slab" is taken to be their statistical mean ($k_{q1020} = 1$ и $k_{q6060}=1$), and the value of coefficients of influence was estimated by extrapolation, starting from $k_{inf,j}=1.0$ in the case of new $1 < k_{inf,j} < 3$ in case of actual condition state of waterproofing.

Figure 6 presents a graphic illustration of the deterioration models of structural components with and without accounting for their quality and their mutual effect on each other. As can be seen from Fig. 6, failure of the slab structure in case of no repair may occur during Year 74 of operation. At the same time, according to the average statistical prediction and without accounting for the condition of the reinforced concrete and insulation, a failure may be expected in Year 200.

Figure 6

If a "do nothing" repair strategy is adopted for the period of service, failure and the subsequent replacement of a slab structure, then the interval between repairs for the given slab will be 55 to 75 years depending on the quality of insulation and reinforced concrete (Fig.7).

Figure 7

Alternatively, if during Year 30, with the appearance of first sign of insulation failure (COND=2), the insulation is replaced, the slab repair (remediation of reinforced concrete) will be needed only during Year 115 (Fig.8). Thus, the life of the slab structure can be increased more than twice (145-175 years) if, while optimizing a repair strategy, one takes into account the mutual effects of standard elements on each other. In this case, the cost of bridge maintenance will decrease substantially (Fig.9).

Figures 8 – 9

Chart 4 gives the estimated costs for the first year of operation (planning period) calculated as:

$$Z_{\text{пр}} = Z \ \text{x} \ (1+f)^{n-k} \tag{8}$$

where Z is an absolute cost; f is the interest rate; n and k are the numbers of the last year of the planning period and the year, during which repairs are carried out.

Chart 4

Conclusions

The following conclusions can be drawn from the analysis of the results of standard inspection:

1. Usually, experts' judgment provides underestimated prediction of the condition corresponding to the lower limit of the average statistical scatter of service lifespan. For most standard elements such an approach is not justified and leads to substantially erroneous results, which necessitates adjustments of parameters of the deterioration models in conformity with inspection findings.

2. Deterioration of bearing and frame structures of bridge facilities is attributable primarily to the wear of materials. Deterioration of strength properties virtually does not occur or is of accidental character.

3. The intensity of wear of construction and protective materials depends to a large degree on their quality, specific effect of their structural environment and the extent of their protection against adverse impacts. Underestimation of these factors results in noticeable errors in prediction of the condition of bridge elements.

4. The applicability of the general principles adopted worldwide for describing deterioration of bridge facilities and their components (standard elements) by a fair monotonic curve has not been substantiated by the findings of standard inspections carried out in the process of the operation of Moscow BMS. It is, therefore, reasonable to describe deterioration of SE by taking into account their physical nature, quality of manufacture and mutual influence within a specific structural environment. For this purpose, an SE should be characterized, in addition to its metric parameters, by its quality indicators. Also, a set of SE should be characterized by indicators of their mutual effects on each other. These parameters should be determined in each particular case on the basis of inspection findings. The actual quality indicators can be applied to the

assessment of objectivity of an inspection and as a criterion for decision making with respect to types and volumes of repair activities.

5. Prediction of deterioration of structures with due account of their quality and mutual effect of components (SE) on each other can serve as a basis for selection of optimal repair strategies permitting a substantial reduction in the costs of bridge maintenance.

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Charts and Figures

Chart 1. Classification of condition categories

Condition category	Assessment of external appearance	Wear	Type of required repair
1	Good	Less than 20%	Cleaning, scheduled maintenance
1.5	Not very good	20-40%	Preventive maintenance
2	Poor	40-60%	Current (local) repair
2.5	Very poor	60-80%	Major repair
3	Unacceptable	80-100%	Replacement or restoration repair

Note: The degree of wear in this chart is indicated as a percentage of a permissible degree of wear for a given element. It ranges from 60% to 80% of the ultimate wear (i.e. hazardous from the viewpoint of the bridge operation).

Chart 2. **Service life of some standard elements**

Standard element	Age according to inspection findings, years		Age according to experts' judgment, years
	Average	Minimal	
Reinforced concrete parapet	121	27	20
Stone parapet	262	112	60
Reinforced concrete ledge	104	12	30
Reinforced concrete beam	219	100	80
Steel beam	306	182	100
Pre-stressed beam	180	123	100
Reinforced concrete slab	203	111	60
Pre-stressed slab	233	217	100
Reinforced concrete column	218	131	60
Reinforced concrete jack column	205	80	30
Butt-end of reinforced concrete beam	82	34	30
Reinforced concrete stair flight	96	39	30
Reinforced concrete	151	77	60
Steel	234	148	100
Waterproofing	79	30	30
Paint coating	18	9	10
Close movement joint	24	8	10
Filled movement joint	25	9	10

Chart 3. **Inspection Results**

№	Name	COND	Tre	Li/L0	Kqi	Kqi,med	Kinf,j	$Kinf\|_{CONDj=3}$
3020	Waterproofing	3	47	1,56	1,56	1	1	1
1020	Reinforced concrete	2,5	47	2,46	-	1	2,46	2,95
6060	Reinforced concrete slab	1,5	47	1,63	-	1	1,63	6,52

Chart 4. Cost of repair of reinforced concrete slab reduced to the first year of operation

f	Zero strategy		Optimal strategy	
	Absolute cost, RUR/m^2	Unit cost, RUR/(m^2·year)	Absolute cost, RUR/m^2	Unit cost, RUR/(m^2·year)
0.00%	825.00	4.85	351.50	2.06
3.00%	7125.06	41.91	841.87	4.95
5.00%	42370.88	249.24	4173.86	24.55

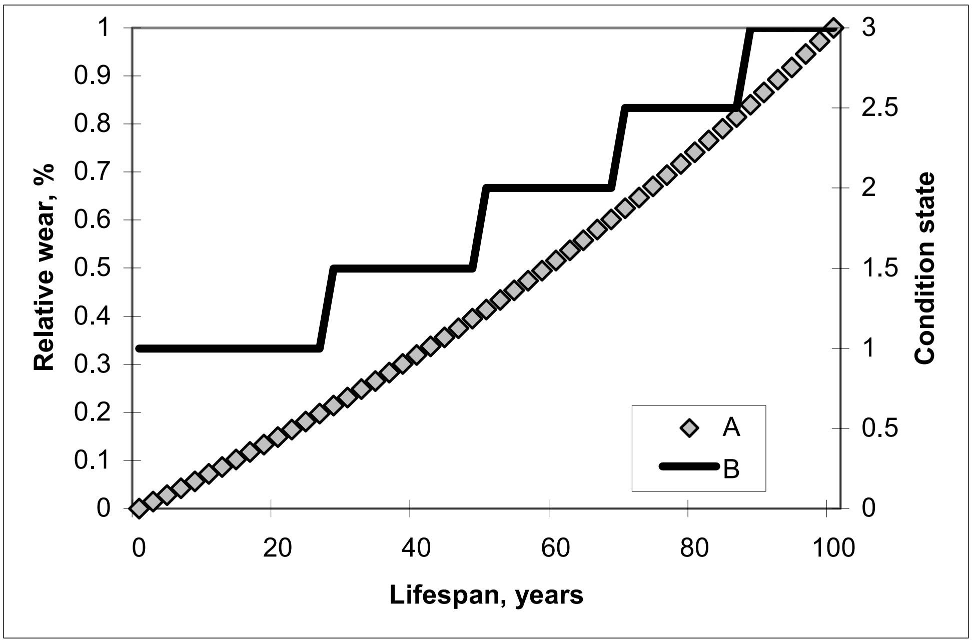

Fig. 1. Deterioration model for SE with a rated lifespan of 100 years

Fig. 2. Values of technical condition indicator for bridges of different ages (Data for 1,059 bridges in City of Moscow)

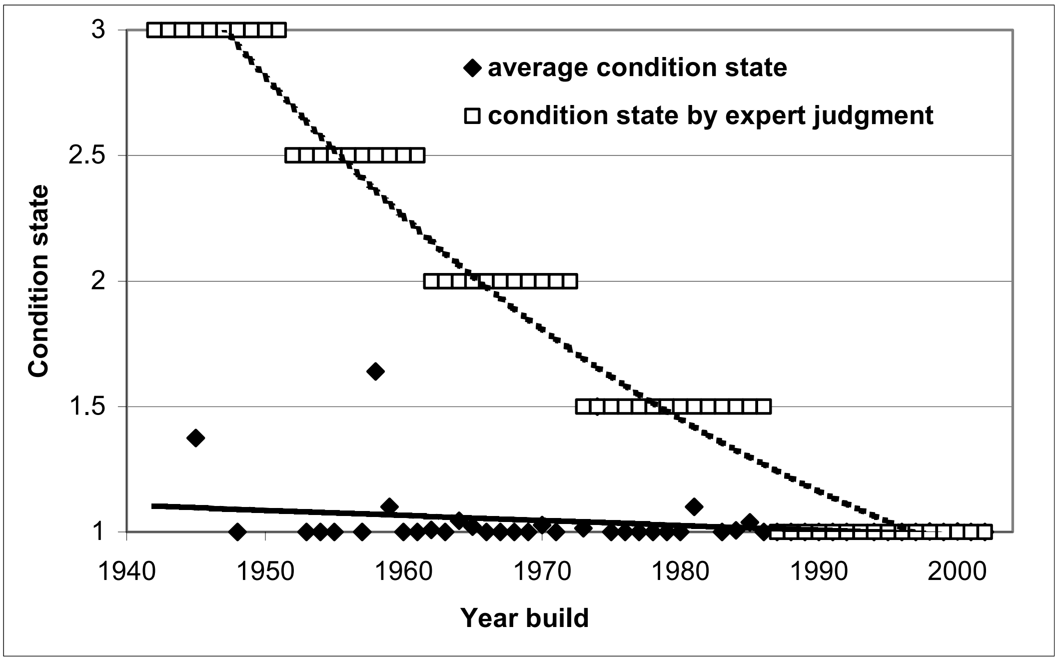

Fig. 3a. Deterioration of standard element 5020 “Reinforced concrete column”

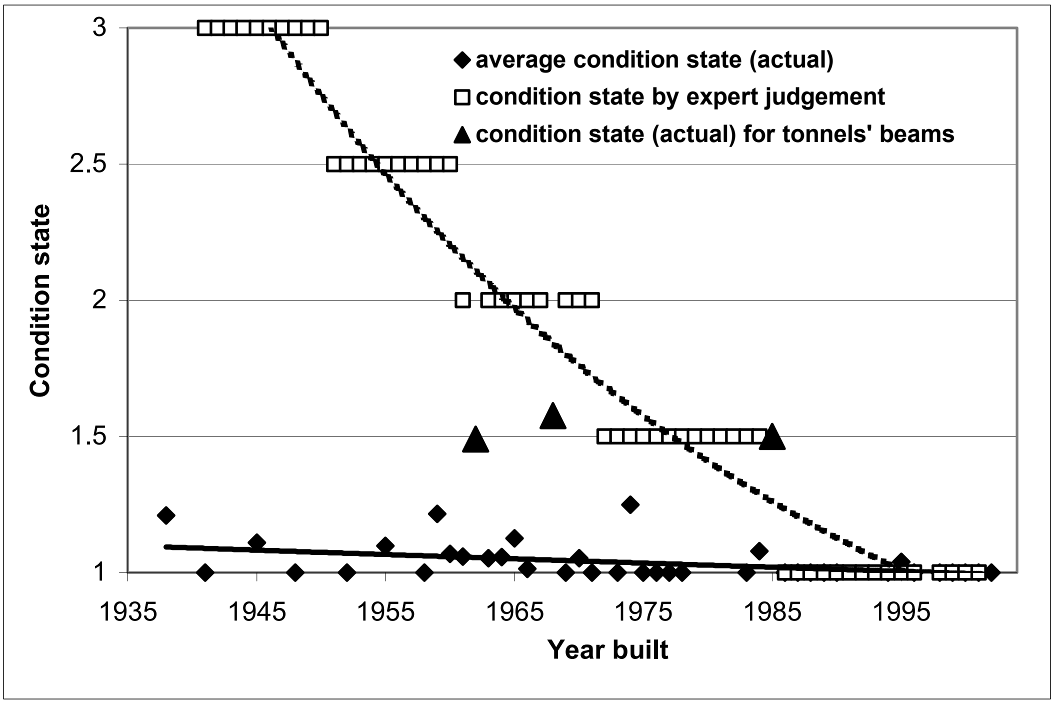

Fig. 3b. Deterioration of standard element 6000 "Reinforced concrete beam"

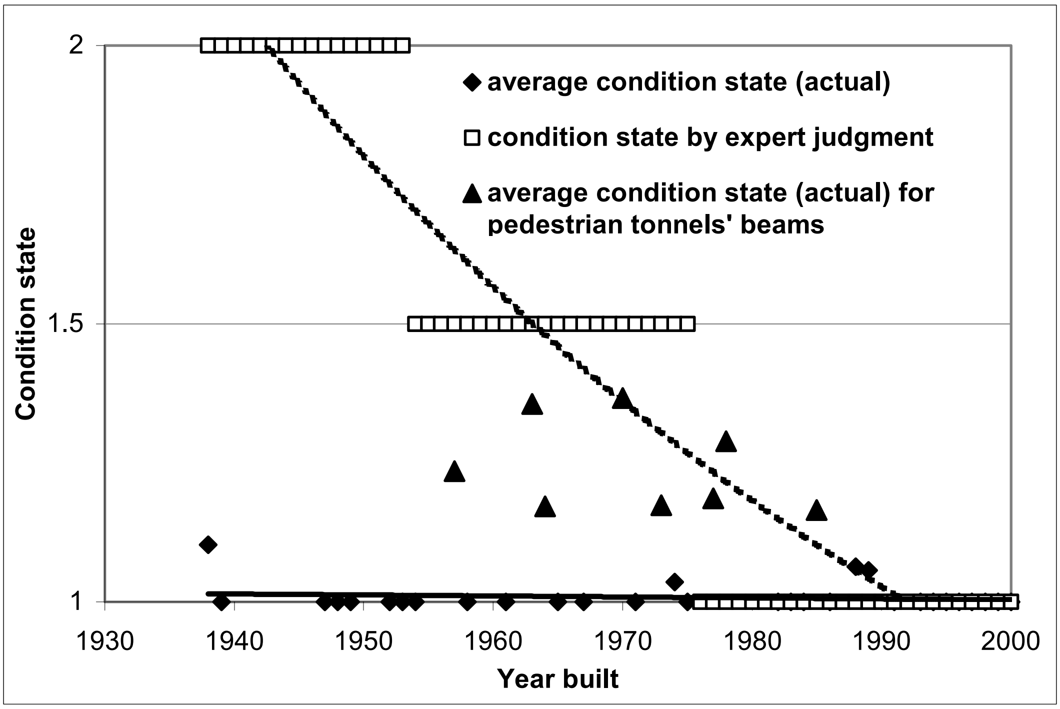

Fig. 3c. Deterioration of standard element 6020 “Steel beam”

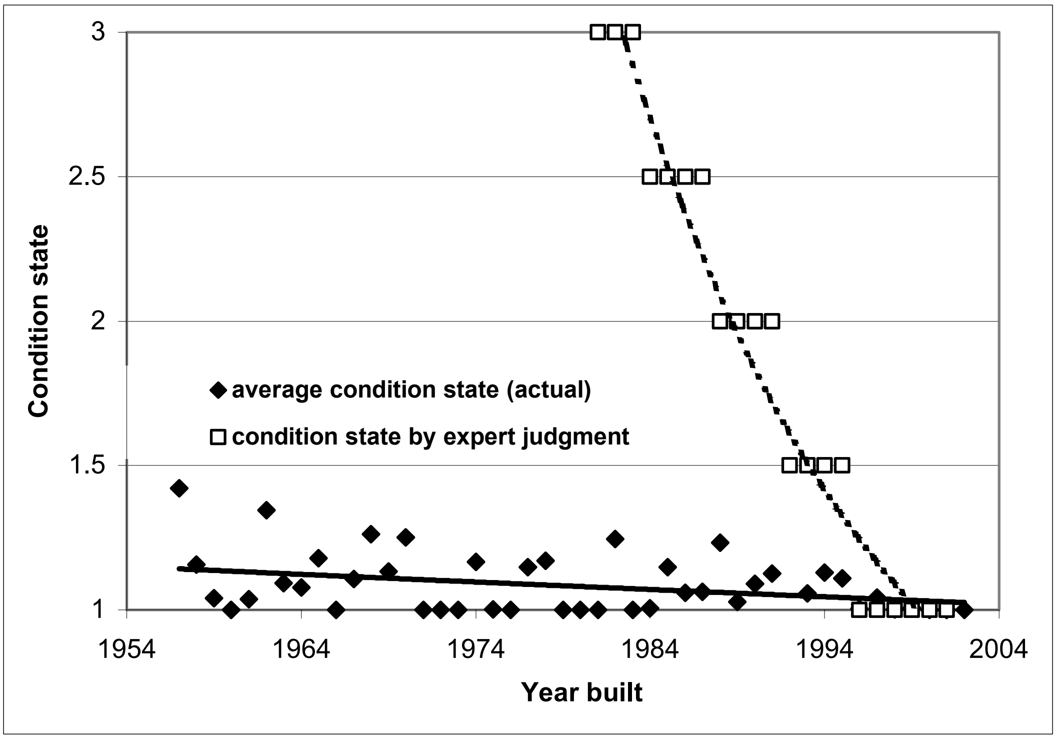

Fig. 3d. Deterioration of standard element 4041 “Reinforced concrete parapet”

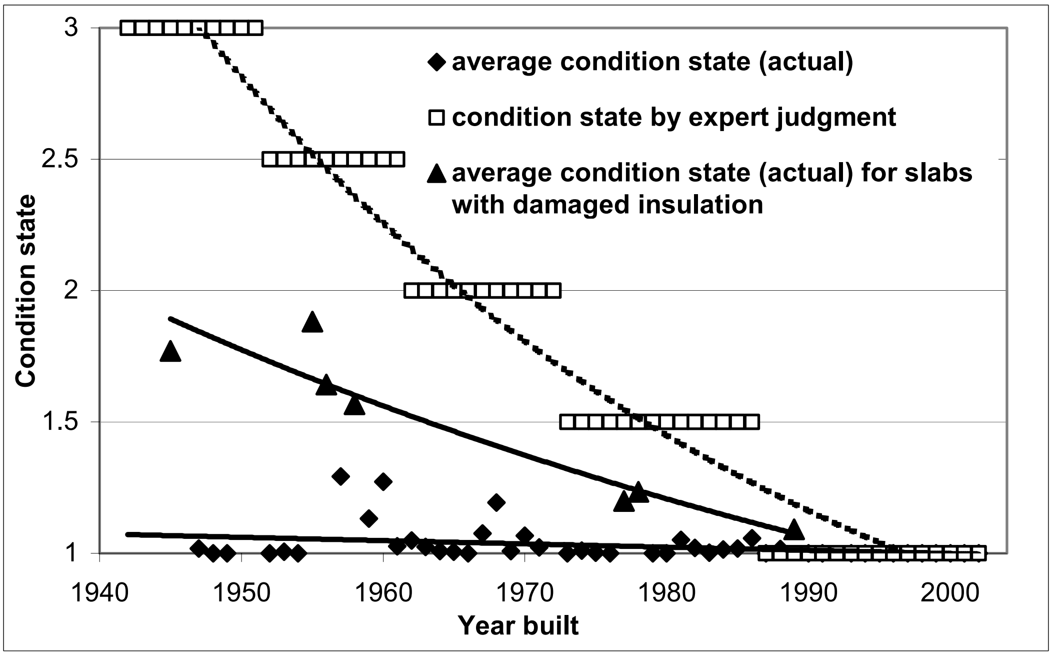

Fig. 3e. Deterioration of standard element 6060 “Reinforced concrete slab”

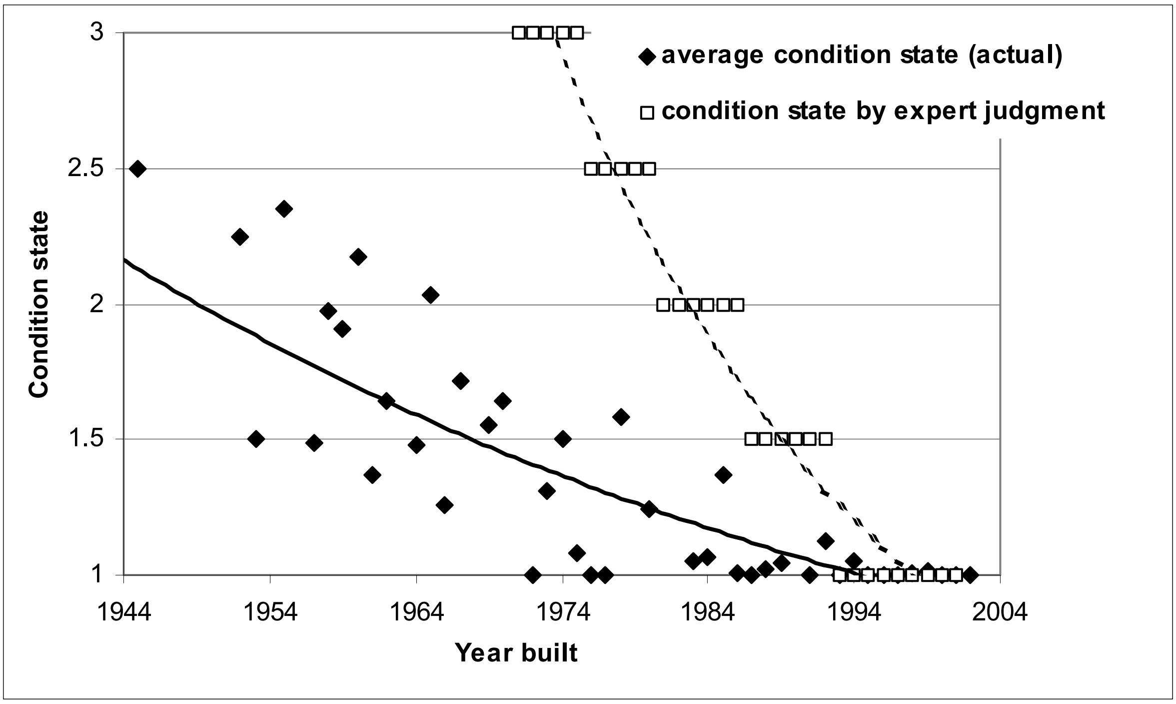

Fig. 3f. Deterioration of standard element 4240 “Reinforced concrete cornice”

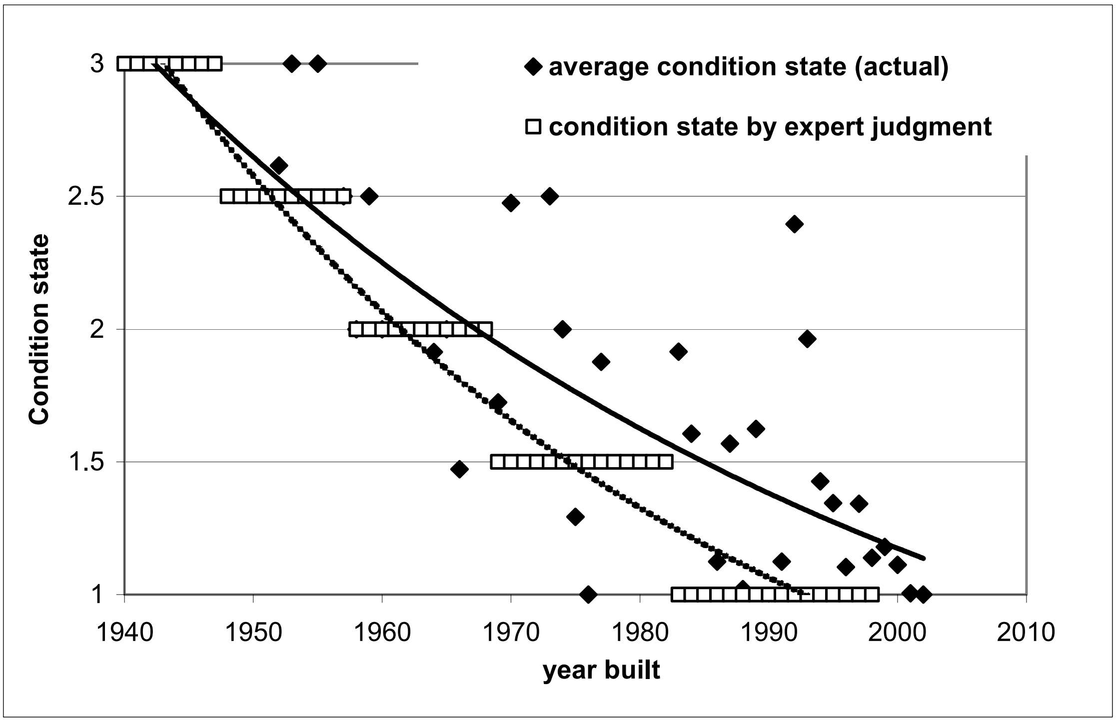

Fig. 3g. Deterioration of standard element 1020 “Reinforced concrete ” in the structure of standard element 4240 “Reinforced concrete cornice”

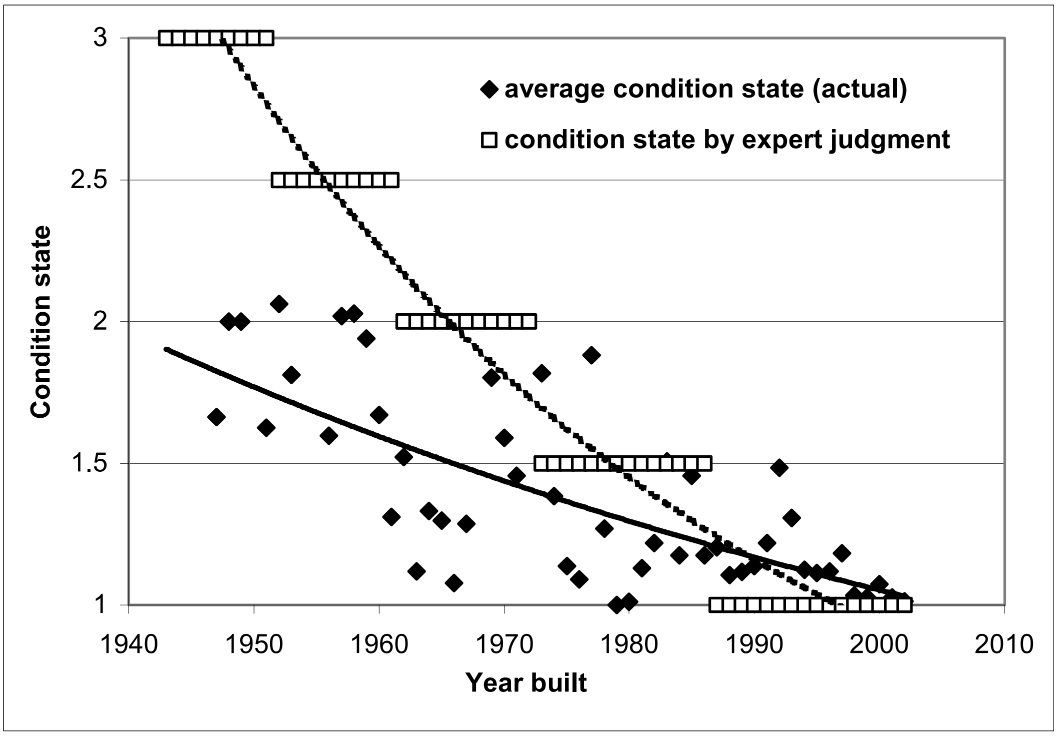

Fig. 4a. Deterioration of standard element 1020 "Reinforced concrete"

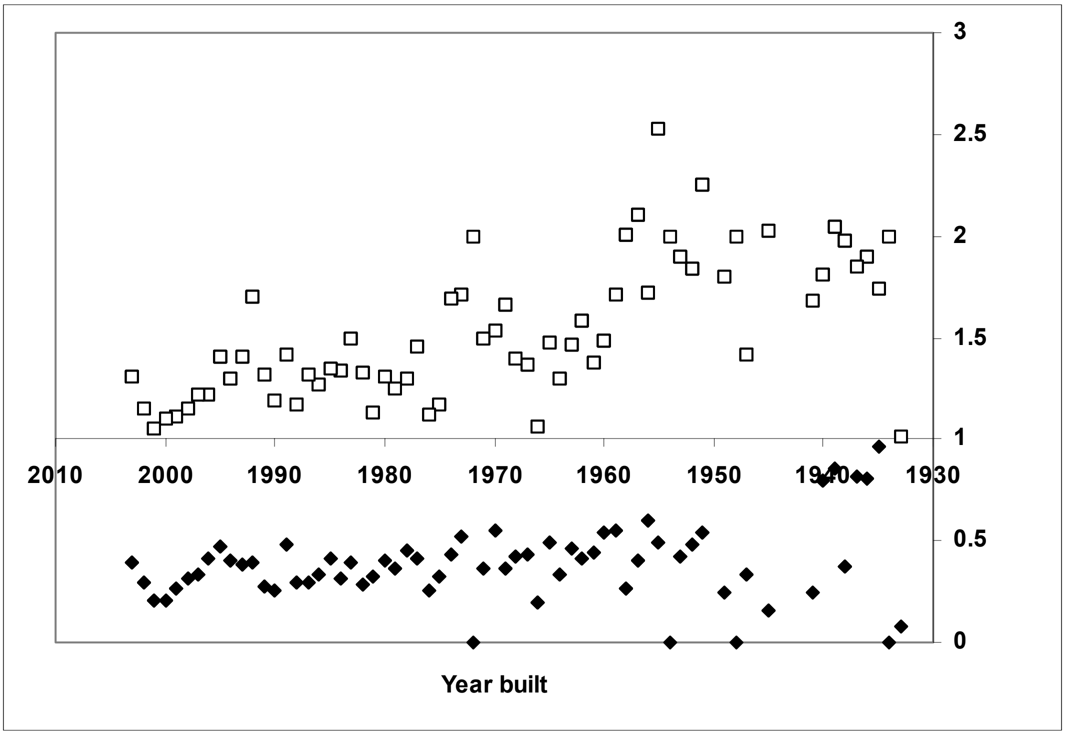

Fig. 4b. Scatter of experimental data when determining the degree of deterioration of standard element 1020 “Reinforced concrete” (above x-axis: average condition state, below x-axis: root-mean square deviation from average condition state)

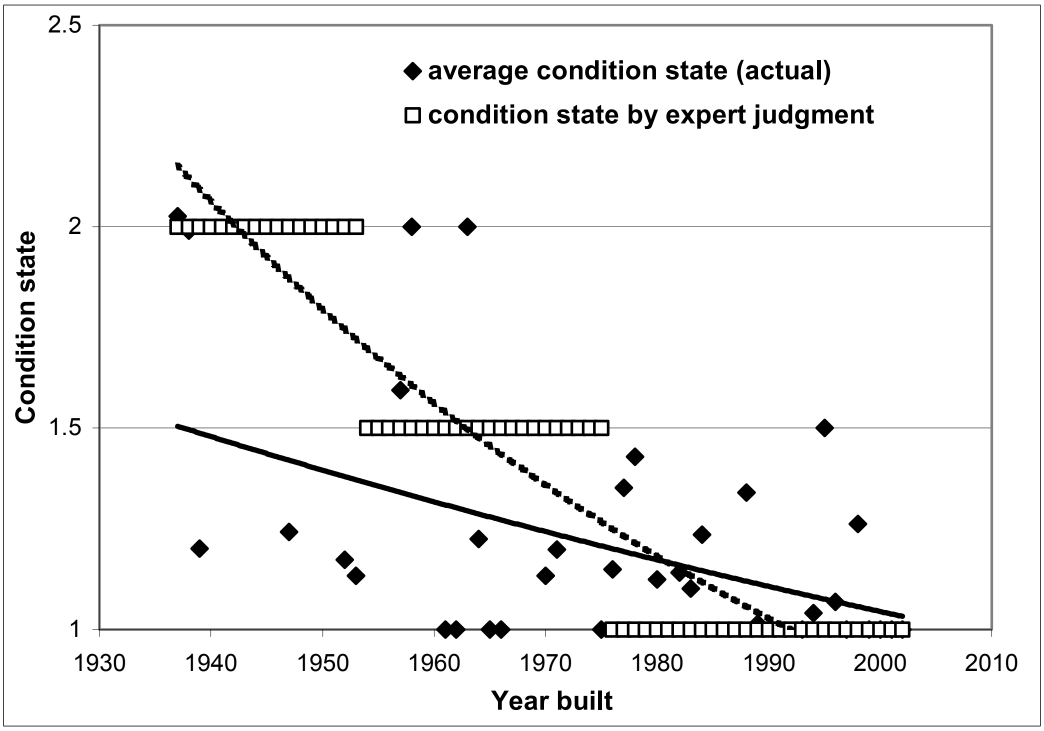

Fig. 4c. Deterioration of standard element 1060 “Steel”

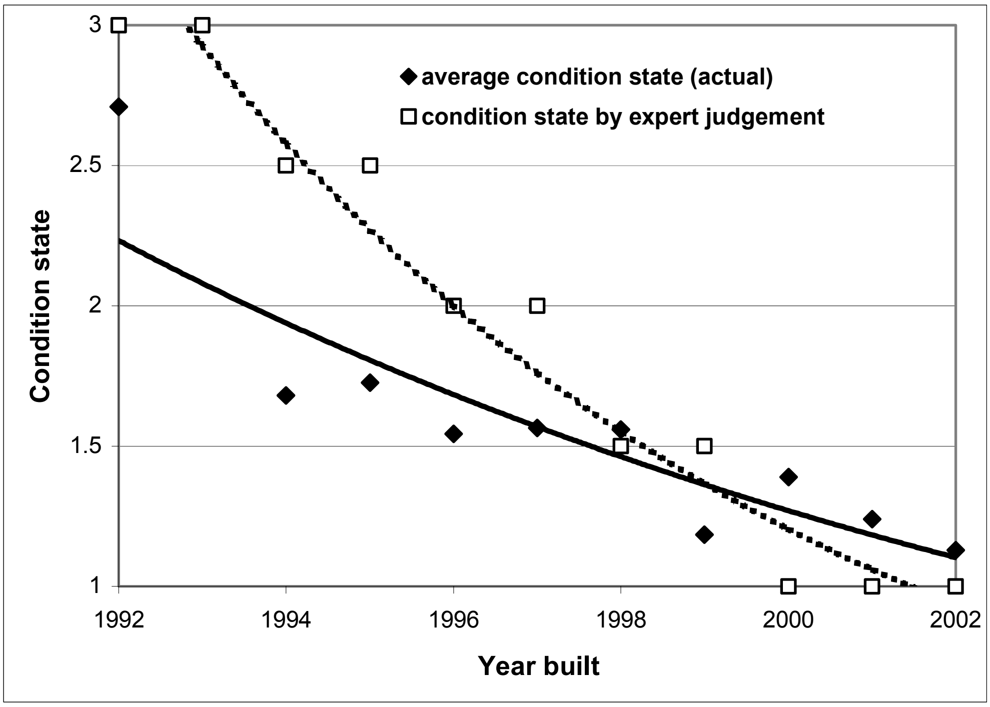

Fig. 4d. Deterioration of standard element 3010 "Paint coating"

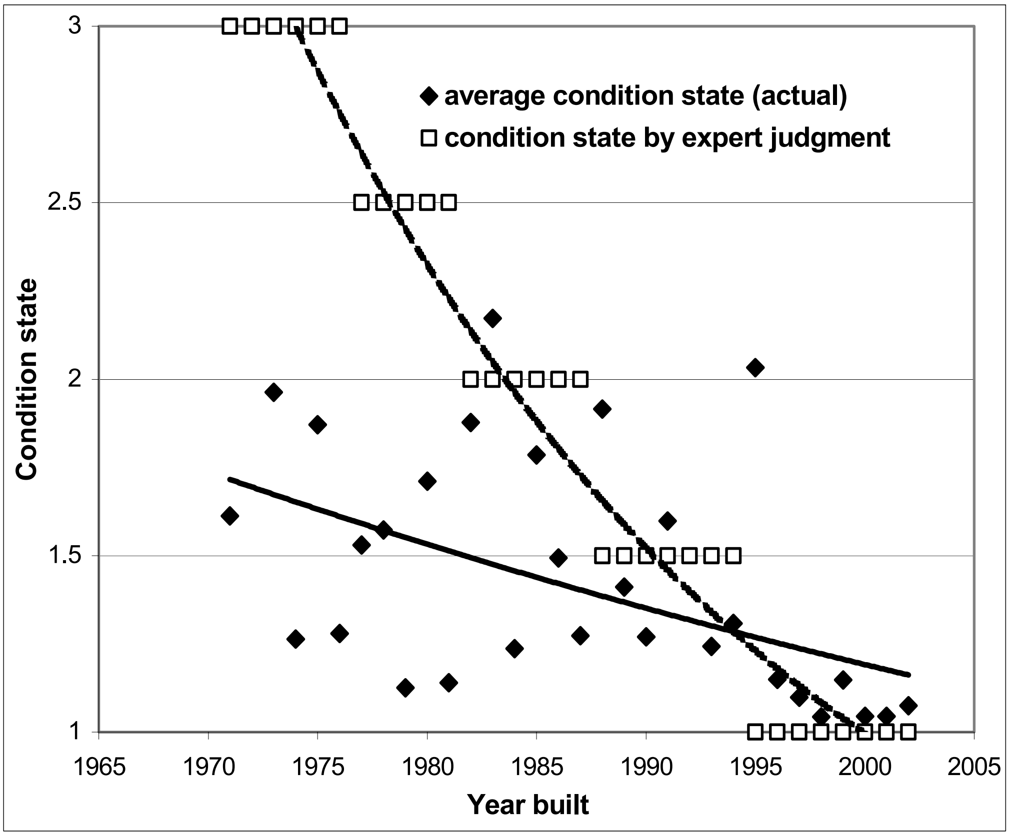

Fig. 4e. Deterioration of standard element 3020 "Hydraulic isolation"

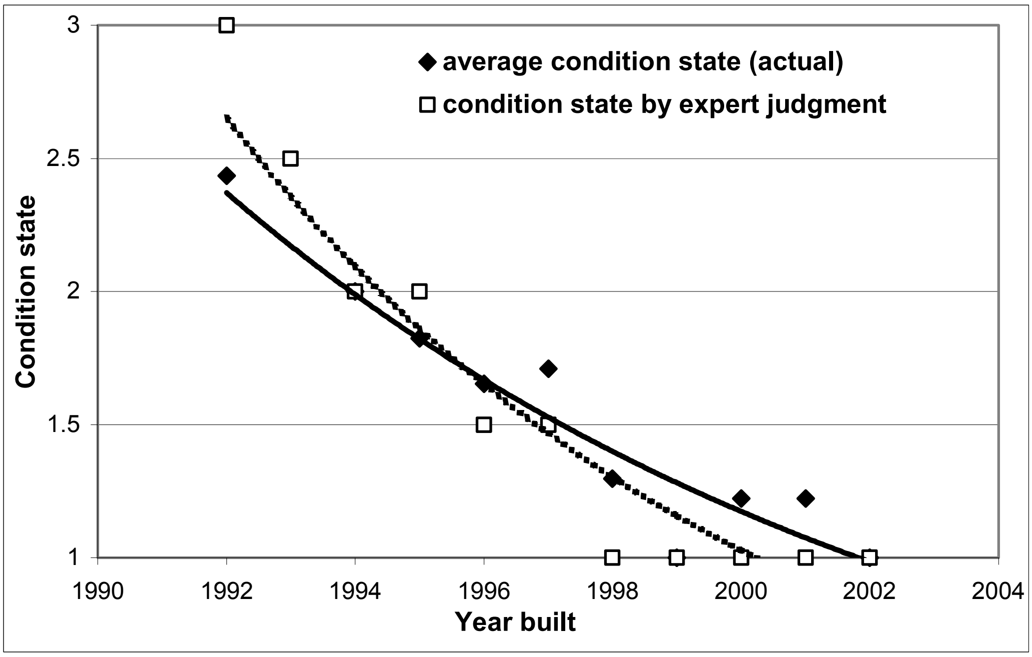

Fig. 5. Deterioration of standard element 4200 “Close movement joint”

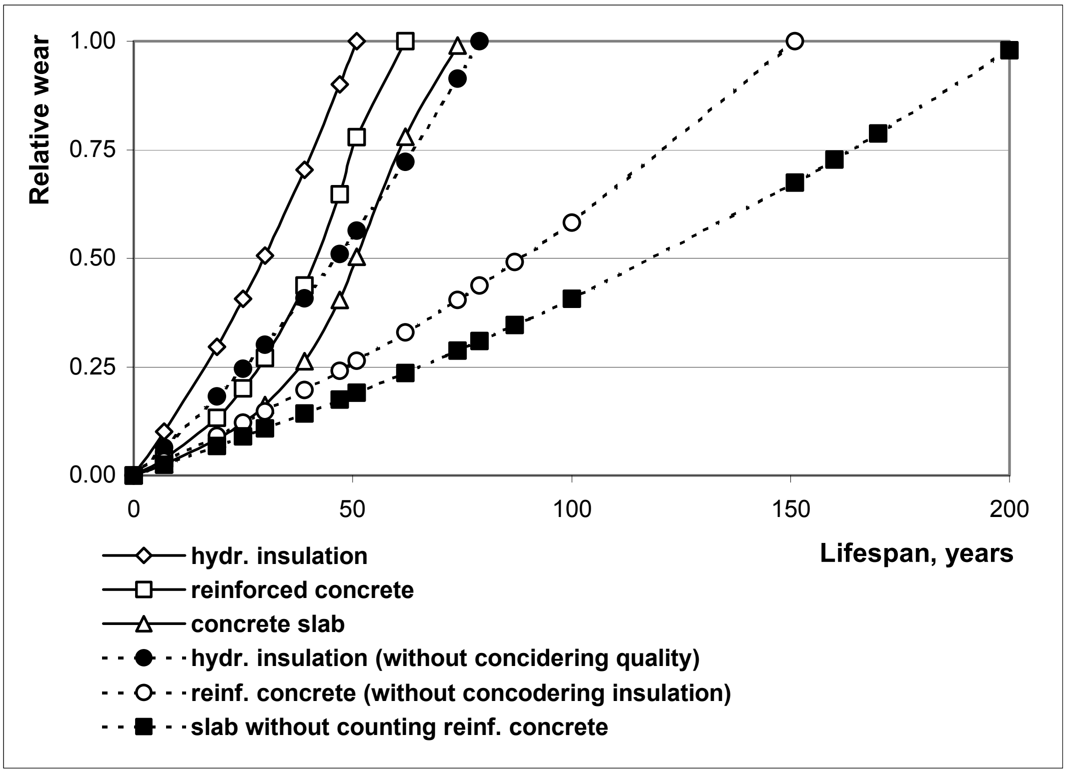

Fig. 6. Deterioration models for components of reinforced slab structure

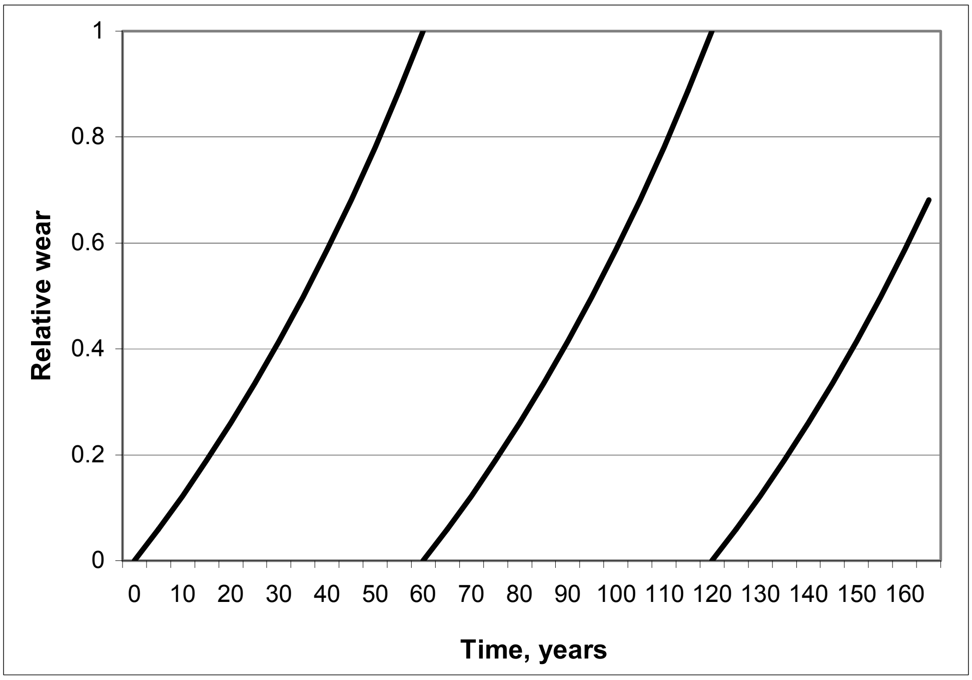

Fig. 7. “Do nothing” Strategy for reinforced concrete slab (no repairs until complete wear)

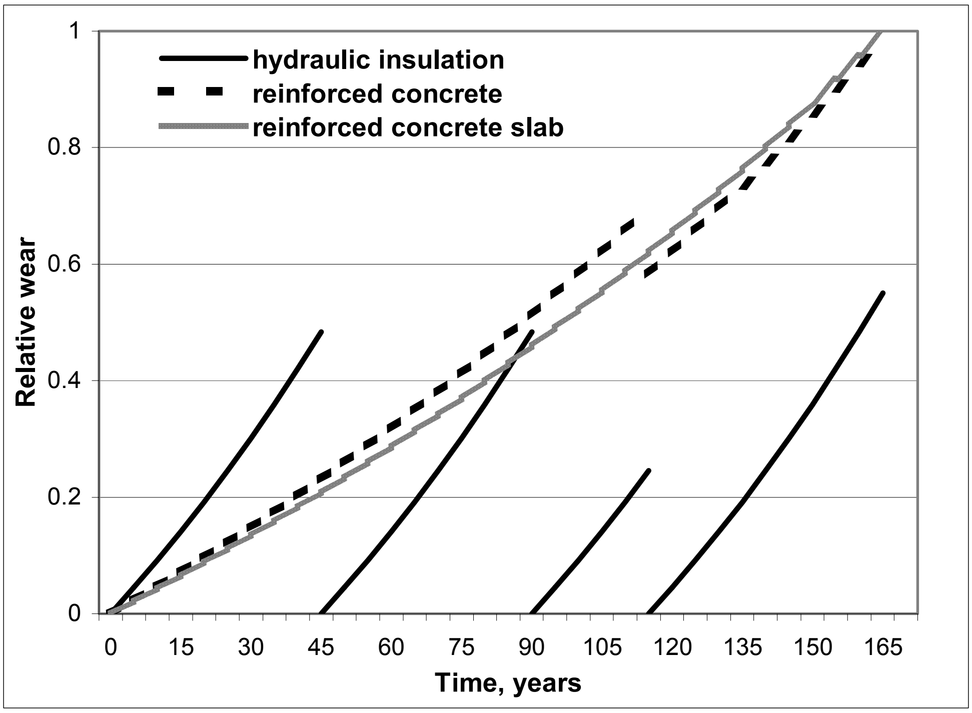

Fig. 8. Optimal repair strategy for reinforced concrete slab

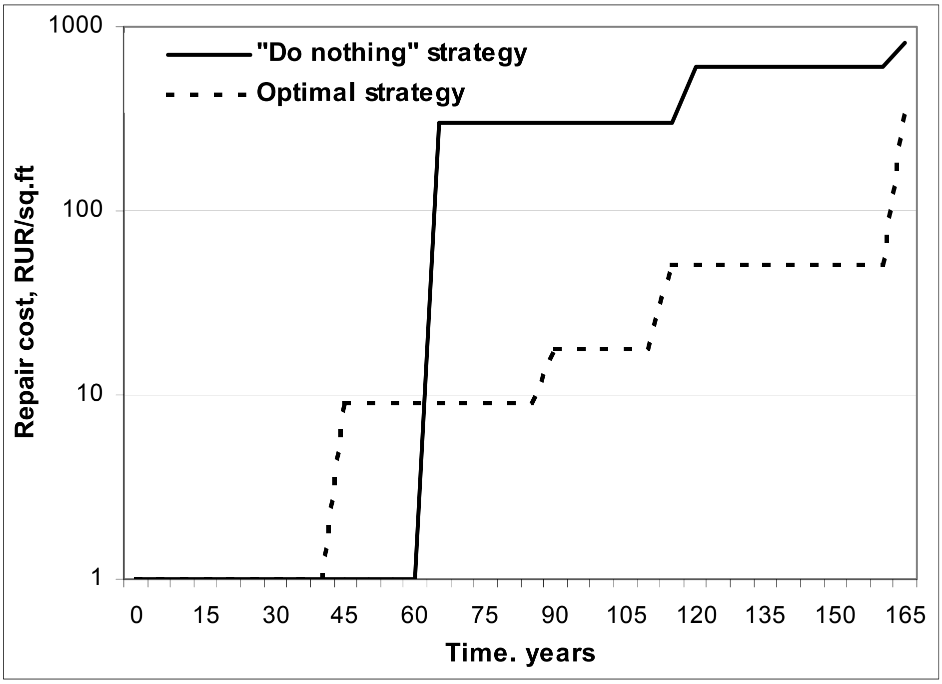

Fig. 9. Costs of reinforced concrete slab repair:

- **"Do nothing" strategy 825.00 RUR/m^2 or 4.85 RUR/(m^2·year)**
- **Optimal strategy 381.50 RUR/m^2 or 2.07 RUR/(m^2·year)**