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Technical diagnostics of reinforced concrete structures using intelligent systems

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Abstract. The results of the development of an effective intelligent system for technical diagnostics of reinforced concrete structures are presented. The category of technical condition is the main criterion in deciding on the degree of accident or the need to take measures to bring it to further safe operation of a building construction. For the purposes of this study, an expert system was developed based on the mathematical apparatus of the theory of fuzzy sets and fuzzy logic, which can take into account the scatter of individual opinions of experts, significantly reduce the examination time and improve the quality of the diagnostics. A hierarchical structure of the organization of expert knowledge is proposed for assessing the technical condition of building structures taking into account the universality of information and the possibility of its expansion based on ontological analysis. Moreover, a technique was developed for formalizing expert information using membership functions for input and output control parameters. To implement a fuzzy logical inference, an algorithm adapted to the given problem is developed. A computer program has been developed that implements the method of identification of the category of technical condition of building structures on the basis of fuzzy knowledge bases. The results of using this program in a survey of a real industrial building are given. The results of the technical state evaluation examined structure, obtained using the expert system, are confirmed by expert opinions of specialists who did not participate in the creation of the program and have extensive experience in examining the building structures. The present work is motivated by a need to transfer knowledge from the technical books and experienced experts in the domain field of diagnostics of building structures to make that knowledge and expertise available to practicing engineers.

1. Introduction

The main tasks of buildings and structures technical diagnostics are detection of defects and damage to building structures, identification of the causes of their occurrence, definition of operational suitability of the object at the time of the survey. The condition of existing structure needs to be evaluated for a variety of reasons. Such as: changes in use or increase of loads, new regulations with higher load requirements, effects of deterioration, and damage as result of extreme loading events, and concern about design and construction errors and about the quality of building material and workmanship [1–3]. The procedures used to evaluate the structural safety and condition of existing buildings may vary depending on the behavior of the structure and the reason for the evaluation.

There are numerous references describing methods for investigating the condition of a structure. These include methods presented by the International Standards Institutions e. g. Committee of the Russian Federation on Standardization and Metrology (GOST), American Concrete Institute (ACI), British Standards Institute (BSI), International Organization for Standardization (ISO), European Norm standards and others. All

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of these documents adopt a planned regime of investigation for existing structures with variable levels of complexity according to the situation and the structure importance.

There is large amount of methodological literature on the diagnosis of damage to buildings and engineering structures. [4–6]. Different approaches and methods for assessing the technical condition of reinforced concrete structures are presented in the publications: Z. Zhao, C. Chen, Y.M Kim, C.M. Kim, S.G. Hong (2006), S. Sasmal, K. Ramanjaneyulu (2008), F.M. Zain, M.N. Islam, I.H. Basri (2005), J. Sobhani, A.A. Ramezanianpour (2011), F. Pakdamar., K. Guler (2016), F. Moodi (2004), Khader M. Hamdia (2010), [7–13]; мethods for diagnosing damage to brickwork are described in publications by Van Balen (2001), S.D. Shtovba, O.D. Pankevich (2002, 2011, 2018) [13–17] and others.

The technical condition category (TCC), determined by engineering inspection of buildings and structures is the main criterion in deciding on the degree of accident or in deciding whether measures are necessary to bring the construction object to further safe operation. GOST (Russian state standard) scale that includes only 4 TCC – normative, operational, limited operational or emergency. The "transition" of a construction structure from one technical state to another actually does not take place "abruptly", but through a multitude of intermediate states, the boundaries between which are blurred. All this requires from the expert when appointing TCC designs to make strong-willed decisions, increasing the undesirable share of subjectivity in the technical conclusion.

The examiner conducting the examination should establish most significant characteristics from the selected set of parameters characterizing the state of the construction, and for this is needed experience that develops individual, personal knowledge from the specialist. This knowledge, called heuristic, allows experts to make reasonable assumptions, find approaches to problems and make effective decisions, which are based mainly on personal interpretations, intuitions and engineering judgments of experienced engineers. But humans are unable to retain large amounts of data in memory. Humans get tired from physical or mental workload, forget crucial details of a problem; They are inconsistent in their day-to-day decisions and unable to comprehend large amounts of data quickly.

It is advisable to strengthen and expand the professional capabilities of specialists through the application of intellectual technologies in the form expert systems (ES), built on generalized systematized expert knowledge. This will ensure the transition to a new, higher-quality and cost-effective technological level of inspection of construction sites, characterized by high efficiency in decision-making, reliability and validity of the results issued in problem situations.

Analysis of world experience shows that the technology of expert systems is used to solve various types of problems (management, interpretation, diagnostics, planning, design, control, etc.) in a wide variety of problem areas. Among them – the oil and gas industry, energy, transport, medicine, space, metallurgy, mining, chemistry, telecommunications and communications, ecology, etc. In Russia, research and development in the field of expert systems are included in a number of state and sectoral scientific and technical programs. The technology of expert systems is of interest and has great prospects to specialists in the construction industry, as evidenced by both Russian and foreign publications: V.A. Sokolov, (2010, 2016), T.N. Soldatenko (2011), A. Badiru A and J. Cheung (2002), Khader M. Hamdia (2010) and others [18–22].

Expert systems are intelligent computer programs that mimic the decision-making and reasoning process of human experts. They can provide advice, answer questions and justify their conclusions. In such a computer program, human expertise in the designated domain is well represented and saved in the form of a knowledge base. It uses a systematic approach for finding the answer to the problem.

The architecture of expert systems (Figure 1) is typical for most projects from the point of view program modules [24].

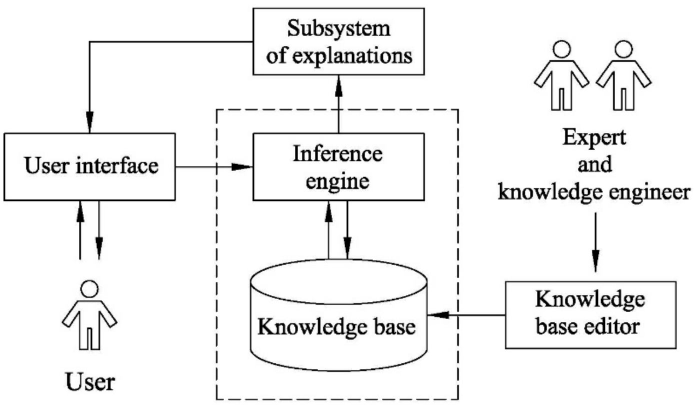

Figure 1. The architecture of the expert system.

Modules of ES can be differently implemented, but their composition and interaction have a clear purpose. When creating an expert system, the main efforts of developers are concentrated on creating a knowledge base, namely on the choice of knowledge representation models and a solver – decision-making methods expert knowledge is understood as a combination of theoretical understanding of the problem and empirical rules (heuristics) for solving it. The nature of knowledge has two sides. It's description of facts, signs, states, phenomena, (declarative knowledge) and description of manipulations with them (procedural knowledge) [24].

Collecting informal information in the knowledge base is a strategically important and most difficult task in the development of ES. This important function provided by only one person or a small group frequently. Two major sources exist for the knowledge: human expert(s) who have been identified as possessing the special skill or mastery and an extensive base of practical and theoretical research on the technical diagnostics of buildings and structures [4–6] (documents or text). The knowledge base can be developed gradually over an extended period of time, much of the knowledge can be changing and these knowledge units need to be updated.

When the knowledge is acquired, it is necessary to represent them into machine-readable form. That is, actually taking the knowledge and putting it into some computer code. For this purpose, it is advisable to use ontological analysis [26, 27], which is aimed at researching and interpreting systemic links in complex objects using methods and tools of computer modeling. The term "ontology" in the theory of artificial intelligence is knowledge formally presented in the form of a description of a set of objects, concepts and connections between them. The formal ontology of the organizational and functional structure of diagnostics of a construction object is the basis for developing a hierarchy of indicators that are used in the decision support system.

When diagnosing the state of a building object, experts often use approximate parameter estimates that have some degree of error and ambiguity. For example, in the process of measuring quantitative parameters, almost always there is an error that depends on the instrument base used and the qualifications of the specialist. The expert's answers on the questions about the preference of factors affecting the evaluation of the technical condition of the structure, their number and interconnection are largely subjective and fuzzy. This is due to the fuzzy of the criteria for assessing the structure, building or structure, formulated in regulatory documents, as well as a short scale GOST (Russian state standard), which includes only 4 categories [3].

There are several approaches used to uncertainty management for expert systems. The best-known and used methods in existence are; Bayesian inference, Certainty factors and Fuzzy set. Fuzzy set theory is one of the major approaches used to handle uncertainties and ambiguities and has important applications in the field of knowledge based expert systems [3, 23, 27, 28]. Professor Lofti Zadeh [29] first introduced fuzzy logic in 1960's. This theory provides a major paradigm in modeling and reasoning with uncertainty and provide decision support. Fuzzy logic theory is not a fuzzy theory but it is logic interpret the fuzziness. In other words, fuzzy theory itself is precise; and the "fuzziness" appears in the phenomena that the theory tries to study [30].

Fuzzy set theory allows one to formalize and process the most heterogeneous information contained in the description of the signs of the technical state of structures, to simulate loosely formalized reasoning such as: "many," "little," "often," "rarely," "about ...," "approximately ... "," not less than ... "," no more ... "," in the range from ... to ... ", etc. There is knowledge the reliability of which is expressed by some coefficient, for example 0.8 or 0.5.

The application of fuzzy sets theory and its applications makes it possible to construct formal schemes for solving problems with approximate quantitative or qualitative estimates of parameters, using linguistic variables [12]. The concept of a linguistic variable is the basis of approximate reasoning. Its meanings can be words or phrases (terms) in natural or formal language. At the same time, information from the subject area (technical diagnostics of buildings and structures) must be formalized in terms of fuzzy sets – as membership functions [24, 31] for both input and output parameters describing the current state structural damage and possible causes of these damage.

The membership function $\mu A\ \{x\}$ (Figure 2) quantitatively indicates the degree of belonging of an element x to a fuzzy set A of the argument space X. Value of 0 means that the element is not included in the fuzzy set, 1 describes the fully included element. Values between 0 and 1 characterize the fuzzy elements included.

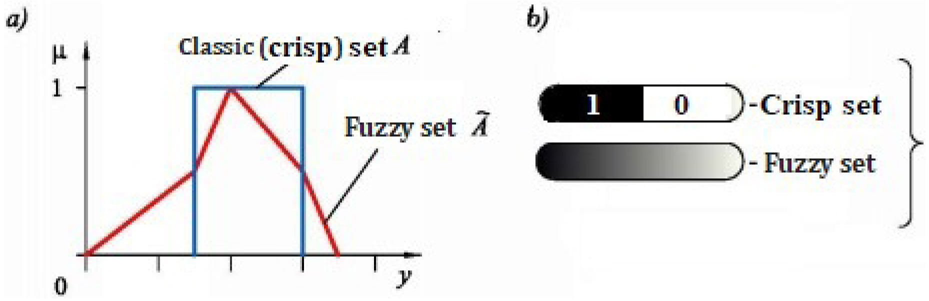

Figure 2. Graphs of the membership functions of the classical (crisp) and fuzzy set (*a*) and their semantic difference (*b*).

Finite fuzzy sets are usually written in the form

$$\overline{A} = \{<X, \mu A\ (x)>\} \text{ or } = \{<x / \mu A\ (x)>\}\}, x \in X\}. \quad (1)$$

The membership functions, in a sense, are a database that is necessary to convert for both input and output heterogeneous information into the format of the subsequent dialogue with the knowledge base. The quality of solutions issued by a fuzzy system is most dependent on the professional knowledge of experts and the adequacy of their reflection by membership functions.

Fuzzy logic output systems perform the transformation of the values of input variables into output variables. To do this, they must contain a procedural knowledge base of fuzzy inference based on rules compiled in natural language (embedded in the ES at its creation) of the form: "***IF*** <prerequisite>, ***THEN*** <conclusion>". Fuzzy logic allows to technically implement the linguistic links of the rules "IF-THEN", "and", "or" with the help of mathematical operations.

As a result of logical inference, a fuzzy value of the structure technical state category with the maximum degree of confidence is obtained. Crisp value of the category (both integer and fractional) can be determined using the defuzzification operation (for example, using the "center of gravity" method) [24].

Automated search for an expert solution, using intellectual expert systems, can help in the work not only for a beginner, but also an experienced expert. The present work is motivated by a need to transfer knowledge from the technical books and experienced experts in the domain field to make that knowledge and expertise available to practicing engineers.

2. Methods

When diagnosing real construction objects, it is necessary to identify all possible causes leading to change of technical condition category and suggest possible solutions for their elimination. The expert's tasks in technical inspection of various types of building structures include visual and instrumental assessment of structural damage (presence and parameters of defects, cracks), assessment of the condition of materials (wood, reinforced concrete, metal), carrying out the necessary calculations of the stress-strain state taking into account the existing damage, and also check of compliance of the characteristics of the structures established during the inspection with the current regulatory requirements.

Conceptual model of the knowledge base [24] was obtained in the form of a hierarchical 4-level structure of interrelated solution stages (Figure 3), as a result of the research. It implements the principle of decomposition of a set of controlled parameters of the technical condition and connections between them of any building structures. TCC of the structure or building (1 – normative, 2 – operational, 3 – limited operational, 4 – emergency) is determined at the target level as for a complex system as a whole

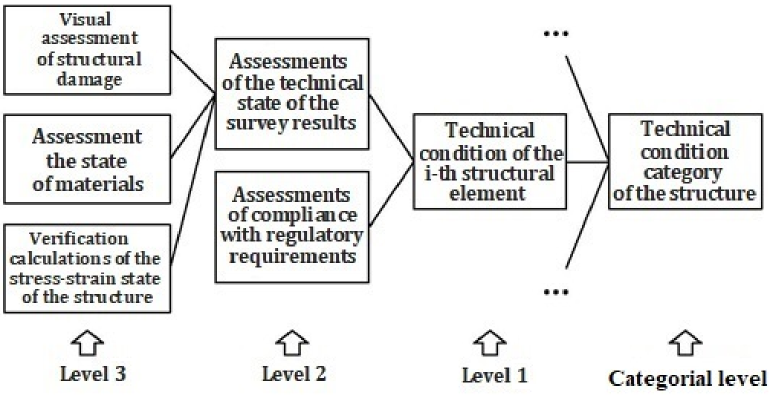

Figure 3. Conceptual model of the knowledge base "Definition of the category of technical condition of building structures".

For the automated search of an expert opinion on the TCC of a building object, it is necessary to provide all possible causes leading to a change in the category of technical condition. Sources of knowledge are an extensive base of practical and theoretical research on the technical diagnostics of buildings and structures, regulatory documentation, heuristic knowledge and reasoning of specialists.

It is proposed to formalize the declarative knowledge about the technical state of constructions by the method of computer ontologies (O), which allows establishing mathematical and logical connections between parameters. Ontological analysis begins with an analytical work on the allocation and consolidation of subject knowledge, i.e. an informal conceptual model of knowledge is constructed by defining a set of basic concepts and the relationships between them.

The formal expression of declarative knowledge or computer ontology (O) for the considered area, which provides the possibility of unified and repeated use on different computer platforms, can be represented [26]:

$$O = \langle K, R, F \rangle, \quad (2)$$

where $K = \{k_1, k_2, ..., k_i, ..., k_n\}$, $i = \overline{1, n}$, $n = Card\ K$ – finite set of concepts of the studied subject area (input, intermediate and output controlled parameters);

$R = \{r_1, r_2, ..., r_j, ..., r_m\}$, $R : k_1 \times k_2 \times ... \times k_m$, $j = \overline{1, m}$, $m = card\ R$ – a finite set of semantically meaningful relationships between concepts;

$F : K \times R$ – a finite set of interpretation functions defined on concepts and / or relationships.

Formal ontological models have good computational properties. They provide computer processing and automatic formal inference when solving specific problems.

The state and damage assessment of structures are inherently subject to vagueness, ambiguity and consequently to uncertainty, where subjective opinion and incomplete numeric data are unavoidable [12]. When diagnosing the state of a building object, experts often use approximate parameter estimates that cannot be interpreted as completely true or completely false. The expert's answers on the questions about the preference of factors affecting the evaluation of the technical condition of the structure, their number and interconnection are largely subjective.

Expert Systems are relatively new and can be attractive to structural engineers.The system has the advantage of enhancing the efficiency and reliability of assessment and flexibility concerning missing or inadequate criteria. The most effective solutions to problems containing blurring and inaccuracy can be obtained using the mathematical apparatus of the theory of fuzzy sets and fuzzy logic which makes it possible to take into account the scatter of individual opinions.

The process of the technical condition category determining is a set (*p*) of solutions of interrelated subtasks of a multilevel task. For fuzzy parameters X_p^{l+1}, Y_p^{l+1}, the parameter y_p^l is a fuzzy subset $\tilde{B}$:

$$\tilde{B} = \tilde{A} \circ \tilde{R}, \tag{3}$$

where $\tilde{A}$ is a fuzzy subset of the input variables sets (term-set),

$\tilde{B}$ is a fuzzy subset of the output variable sets y_p^l; (term-set);

l is the level of subtask p;

$\circ$ is the symbol of the maximin composition L. Zade;

$\tilde{R}$ is a fuzzy relation $PA \times PB$, represented by control rules of the form "*IF* <prerequisite>, *THEN* <conclusion>";

PA is the set of input values of the parameters X_p^{l+1}, Y_p^{l+1};

PB is the set of output values of the parameter y_p^l [32].

Monitored parameters of the diagnosed object state can be quantitative (actual and estimated values of deflections, crack opening width, strength of concrete, etc.) and qualitative (operating conditions, visible damage, etc.)

Information in the subject area of buildings and structures technical diagnostics containing fuzziness must be formalized in terms of fuzzy sets. For this, membership functions and linguistic variables are used. The concept of a linguistic variable is the basis of approximate reasoning. Its meanings can be words or phrases (terms) in a natural or formal language, for example, "high", "above average", "below average", "low" [24].

The person designing the ES creates from the rules in the verbal representation specific membership functions. Usually he defines their values by the method of questions and answers; instructs experts to perform operations and recreate the situation from time-stamped data; can correct the values of membership functions, getting the best results from experiments, previous experiences that simulate this situation.

Each membership function in this case indicates a degree of confidence in the value of the output variables for given values of the input parameters and the use of rules that determine the ratio of input and output variables.

Each controlled qualitative and quantitative parameter of the technical state (x_i, $i = 1{:}\ n$) of structures (inputs), as well as the result of the state estimation or category *y* (output) are represented by linguistic variables on the corresponding universal sets $X_i = [\underline{x_i}, \overline{x}_i]$, where $\underline{x_i}$ and $\overline{x}_i$ are the minimum and maximum values of the input variable, $\underline{y}$ and $\overline{y}$ – output variable, respectively.

For quality variables, rank measurements are used that reflect the preferences of experts. When constructing the functions of controlling parameters, it is convenient (but not necessary) to use 4 linguistic estimates: "high", "above average", "below average", "low", which are called "terms" and constitute a term-sets $\boldsymbol{T}$ for the variables $\boldsymbol{x}$. These term-sets of inputs can be described by analytic functions or be displayed graphically in the form of a triangular, trapezoidal, bell-shaped, singleton and other forms.

To describe concepts characterized by measurable properties, the optimal methods from the point of view of labor costs are direct methods of constructing membership functions. To describe concepts and attributes that are not measured (qualitative) properties, such as color of concrete or a description of the results of visual inspection of reinforcement damaged by corrosion, indirect methods are usually used. Studies have shown that the joint use of indirect methods of Saati [34], in combination with the method of P.J.M. Laarhoven and W.A. Pedrycz, [34], Chang [35], for the construction of membership functions, makes it possible to control distortions of information, inconsistencies in statements in order to obtain more adequate results in comparison with other known methods [31].

Technical state of any construction is represented by the Cartesian product of the input and exit spaces [32]:

$$C \subset X^* \times Y^*, \quad X_i^* = \left[\underline{x_i}, \overline{x_i}\right], \quad Y^* = \left[\underline{y}, \overline{y}\right]. \tag{4}$$

Expert opinion on the category of technical condition is determined by the expression:

$$X = \{x_1, x_2, ..., x_n\} \rightarrow y.$$

there x_i is set of input monitored parameters of the structure, taking the values X^*;

Y^* is set of output values of monitored parameters;

y is the category of the structure technical state (the output parameter takes the value Y^*).

The development and application of fuzzy inference systems include a number of steps (see Figure 4).

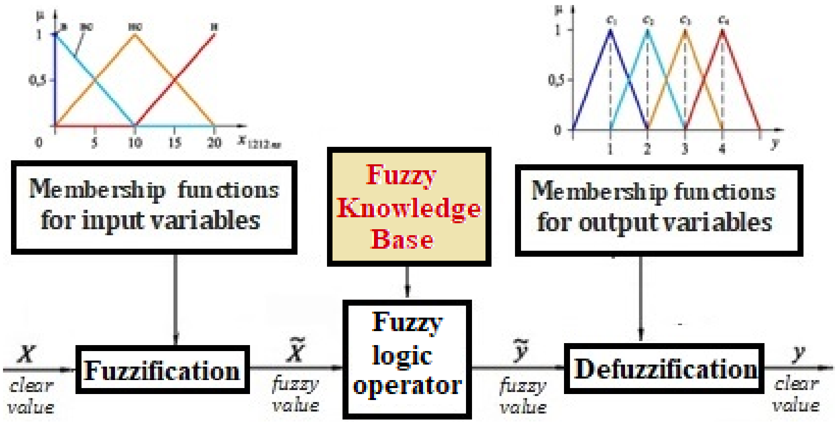

Figure 4. Fuzzy Inference Scheme.

Fuzzification is the process of taking actual real-world data and converting them into a fuzzy input. Defuzzification is the conversion of a fuzzy quantity to a precise quantity. Fuzzy logic operator includes procedures for aggregating and accumulating – determining the degree of truth conditions for each of the rules of fuzzy inference for each input and output linguistic variables. As a result of logical inference, an indistinct value of the output variable is obtained – the result of evaluating the category of the technical state of the construction as a class with the maximum degree of membership. A clear (numerical) value of the category Y (both integer and fractional) can be determined with the help defuzzification operation, for example, using the "center of gravity" method. The possibilities of using known algorithms for fuzzy inference are considered (Sugeno, Mamdani, Singleton and etc.). The choice is made in favor of the Mamdani algorithm, which is modified and adapted to the solution of this problem. Preference is due to the suitability of this algorithm for cases of complex sampling of experimental data (in the absence of an effective system for collecting information), as well as the inherent ability of the graphical interpretation of the resulting conclusion about the technical state of the design [24].

When assigning a TCC, the "space" of a technical state of any structure for the period of its existence is proposed to be divided into 4 parts with blurred boundaries (Figure 5) (similar to the number of categories corresponding to Russian State Standard GOST 31937–2011).

$$C_p = C = \{c_1, c_2, c_3, c_4\}, \tag{5}$$

where C are fuzzy terms corresponding to categories of technical states: normative is c_1, operational is c_2, limited operational is c_3, emergency is c_4 [32].

Then a fuzzy set characterizing the result of solving a subtask <*p*> – for a variable y_p^l takes the form:

$$\tilde{C}_p = \left\{ \frac{\mu_{c1}\left(X^{\langle P \rangle}\right)}{c_1}, \frac{\mu_{c2}\left(X^{\langle P \rangle}\right)}{c_2}, \frac{\mu_{c3}\left(X^{\langle P \rangle}\right)}{c_3}, \frac{\mu_{c4}\left(X^{\langle P \rangle}\right)}{c_4} \right\},$$

and a fuzzy set of variable *y* (the result of a comprehensive evaluation of the structure):

$$\tilde{C} = \left\{ \frac{\mu_{c1}(X)}{c_1}, \frac{\mu_{c2}(X)}{c_2}, \frac{\mu_{c3}(X)}{c_3}, \frac{\mu_{c4}(X)}{c_4} \right\}.$$

3. Results and Discussion

The technique of development of ES on definition of clear value of TCC is presented on through an example of the research module of estimation of a technical condition of bent reinforced concrete designs (plates, beams). As a result of the analysis of the subject area, an informal conceptual model of *declarative* knowledge is constructed. Categorical level 1 includes five groups of indicators: the state of supports, normal cross-sections, inclined cross-sections, fixed parts and connections, evaluation of rigidity (Figure 6).

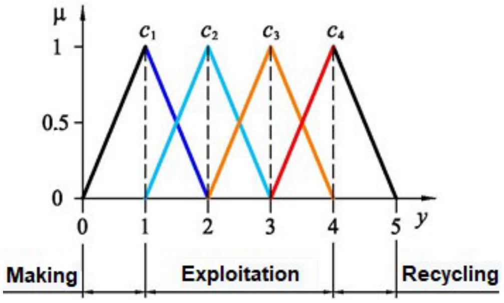

Figure 5. Fuzzy triangular numbers.

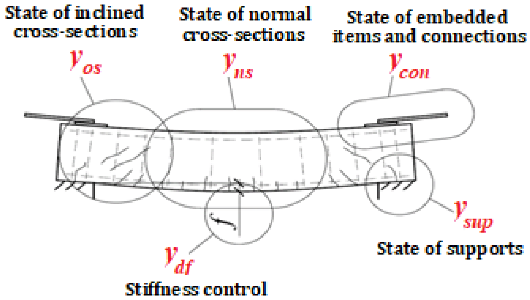

Figure 6. Indicators of the 1-level ontology "Technical condition of a bent reinforced concrete structure".

The formal representation of the ontology of the concepts used and the scheme of their relations is represented in the form of a graphical ontograph (Figure 7a), on which a system of notation and indexing is provided, which makes it possible to compress its visual representation. Figure 7b shows a fragment of this ontograph, which includes a part of the subsystem "State of normal cross-sections" with explanations of the concepts of the categorical level of ES [24]. Notation and indexing reflect that each concept characterizes: a class, a group of characteristics or a parameter, and also levels, sublevels and connections. The letter *x* denotes concepts that characterize the input monitored parameters, *y* is the output intermediate and final grades of the technical condition category. In the research module of the ES "Technical condition of the reinforced concrete bending structure" ~90 possible controllable parameters are included, for each of which the membership functions are constructed [24, 32].

The developed ES must contain knowledge that allows to search for the leading signs of damage to building structures among any number of defects (states), taking into account their degree of severity, subordination and mutual influence.

Let us explain the technology of constructing the membership functions by examining the corrosion index of the reinforcement of a reinforced concrete structure that is a part of the ontology "State of normal cross-sections" [25]. Linguistic variables: qualitative ($x_{1211\ ns}$) – "Result of certification of corrosion of reinforcement" and quantitative ($x_{1212\ ns}$) – "Result of measuring the residual cross-sectional area of the reinforcement" – are set by experts based on inspection of the surface of the reinforcement and measurement of the residual cross-section area of the reinforcement of reinforced concrete structures.

Universal set of the considered linguistic variable $x_{1211\ ns}$ is defined by a finite number of qualitative attributes (1 – surface net reinforcement (at dissection), 2 – local areas of reinforcement damage by surface corrosion (dots and spots of corrosion), 3 – solid surface corrosion of reinforcement; 4 – local areas of ulcered, lamellar corrosion of the reinforcement, cracking of the protective layer of concrete, 5 – lamellar corrosion of the reinforcement, cracking and extrusion of the protective layer of concrete by corrosion products). The set X_{1211ns}= {1, 2, 3, 4, 5} is discrete and exact. The linguistic variable $x_{1212\ ns}$ "Result of measuring the residual cross-sectional area of the reinforcement" must evidently take quantitative values from the universal continuous set $X_{1212\ ns}$ of the reduction in the cross-sectional area of the reinforcement in %.

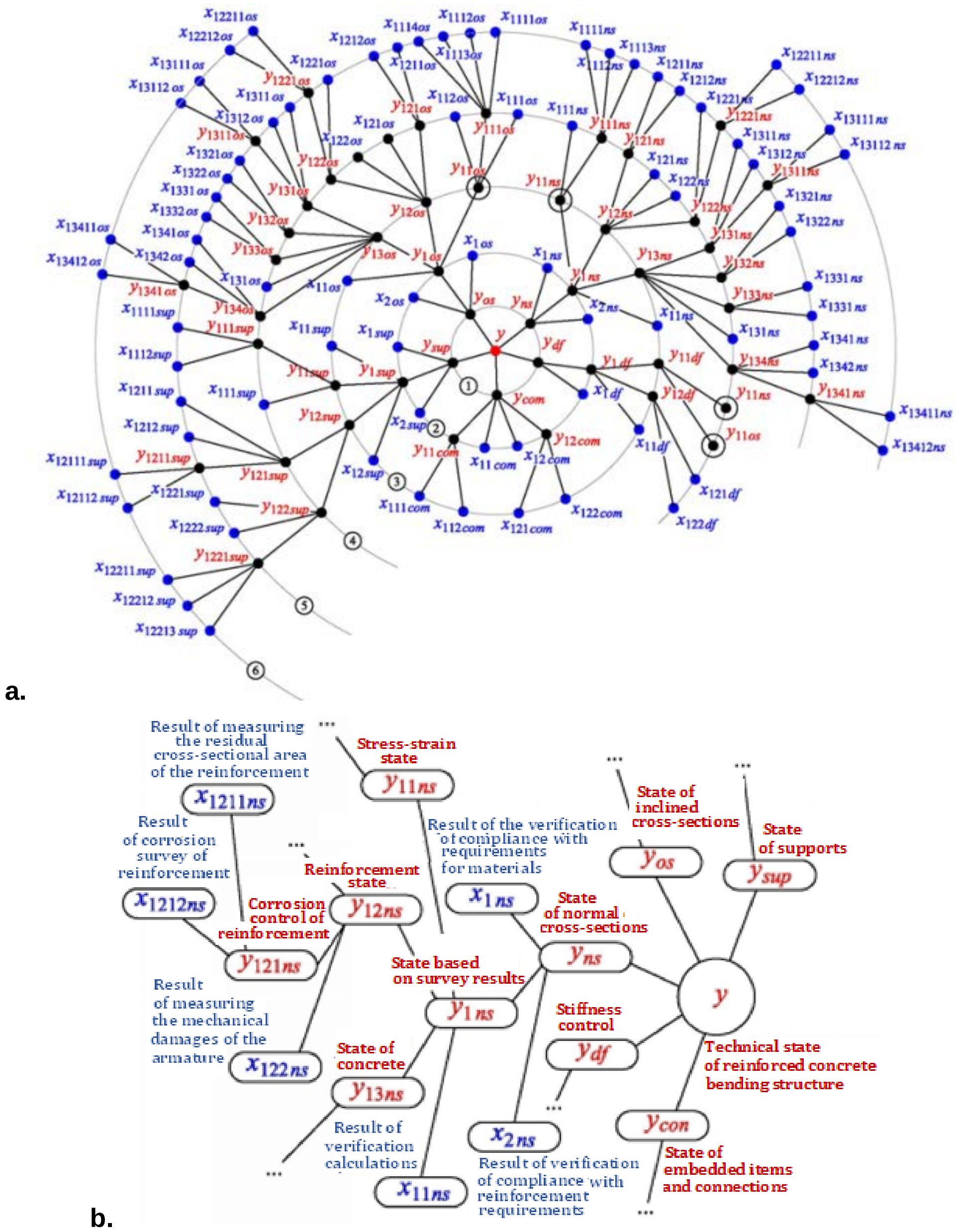

Figure 7. Indexed ontograph "Technical condition of the bent reinforced concrete structure".

As shown by our studies, in order to describe the parts of the membership functions between the characteristic points, the "classical" triangular function and its modified version is a triangular "broken line" are best suited. In Figure 8, for illustrative purposes, examples of graphs of the functions of the variables "

Result of the inspection of reinforcement corrosion "(a) and "Result of measurement of the residual cross-section area of the reinforcement "are shown (b) with the degree of belonging to terms (local areas of reinforcement damage and reduced cross-sectional area reinforcement by 2 %) [24, 32].

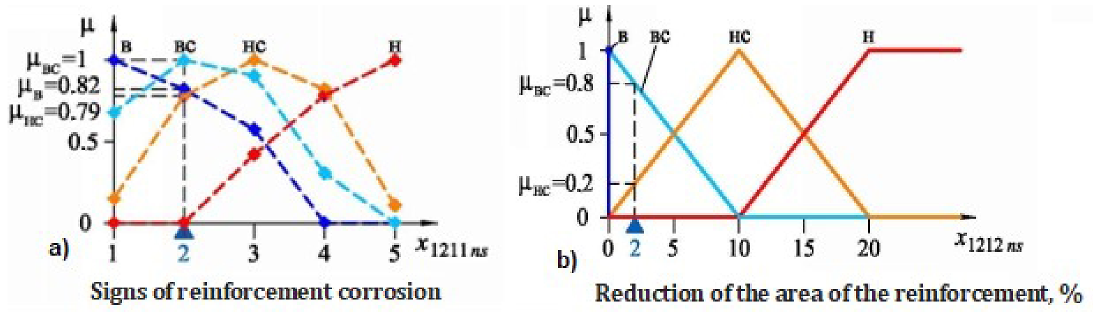

Figure 8. Examples of graphs of the membership functions of the terms of the variables $X_{1211\ ns}$ (*a*) and $X_{1212\ ns}$ (*b*) with the mapping of degrees of belonging to terms.

Fuzzy knowledge base for definition of the TCC of bent reinforced concrete elements is developed on the basis of experience (heuristic knowledge) of specialists in engineering survey of structures of buildings and structures. Rules are linked together by logical operations "or", and the premise of a rule can consist of fragments that are linked by the operations "and" or/and "or". The knowledge base fragment for the controlled output variable y_{121ns} – "Reinforcement corrosion control", which includes the first four (out of 16) rules has the following form:

If $x_{1211\ ns}$ = " *high* " *and* $x_{1212\ ns}$ = " *high* ",

then $y_{121\ ns}$ = " *high* ", *or*;

if $x_{1211\ ns}$ = " *high* " *and* $x_{1212\ ns}$ = " *above average* ",

then $y_{121\ ns}$ = " *above average* ", *or*;

if $x_{1211\ ns}$ = " *high* " *and* $x_{1212\ ns}$ = " *below average* "

then $y_{121\ ns}$ = " *below average,* " *or*;

if $x_{1211\ ns}$ = " *high* " *and* $x_{1212\ ns}$ = " *low* ",

then $y_{121\ ns}$ = " *below average,* " *or* ...

In total, the knowledge base of the ES research module contains more than 5000 rules.

A series of double-girder truss beams of an I-section was inspected at a manufacturing plant in the Perm Territory (Figure 9a). The results of the evaluation of their technical condition are shown on the example of one of the surveyed beams in the form of histograms with grouping of characteristics into categories (from 1 to 4), obtained using the developed expert system (Figure 9b). Visualization of the results significantly increases the "transparency" of decisions taken on the degree of accident rate, forms an understanding of the causes and risks of a possible change in the technical condition of structures, buildings or structures. Figure 9c shows the location of the monitored parameters. Parameters with detected anomalies are marked. Table 1 shows their meaning.

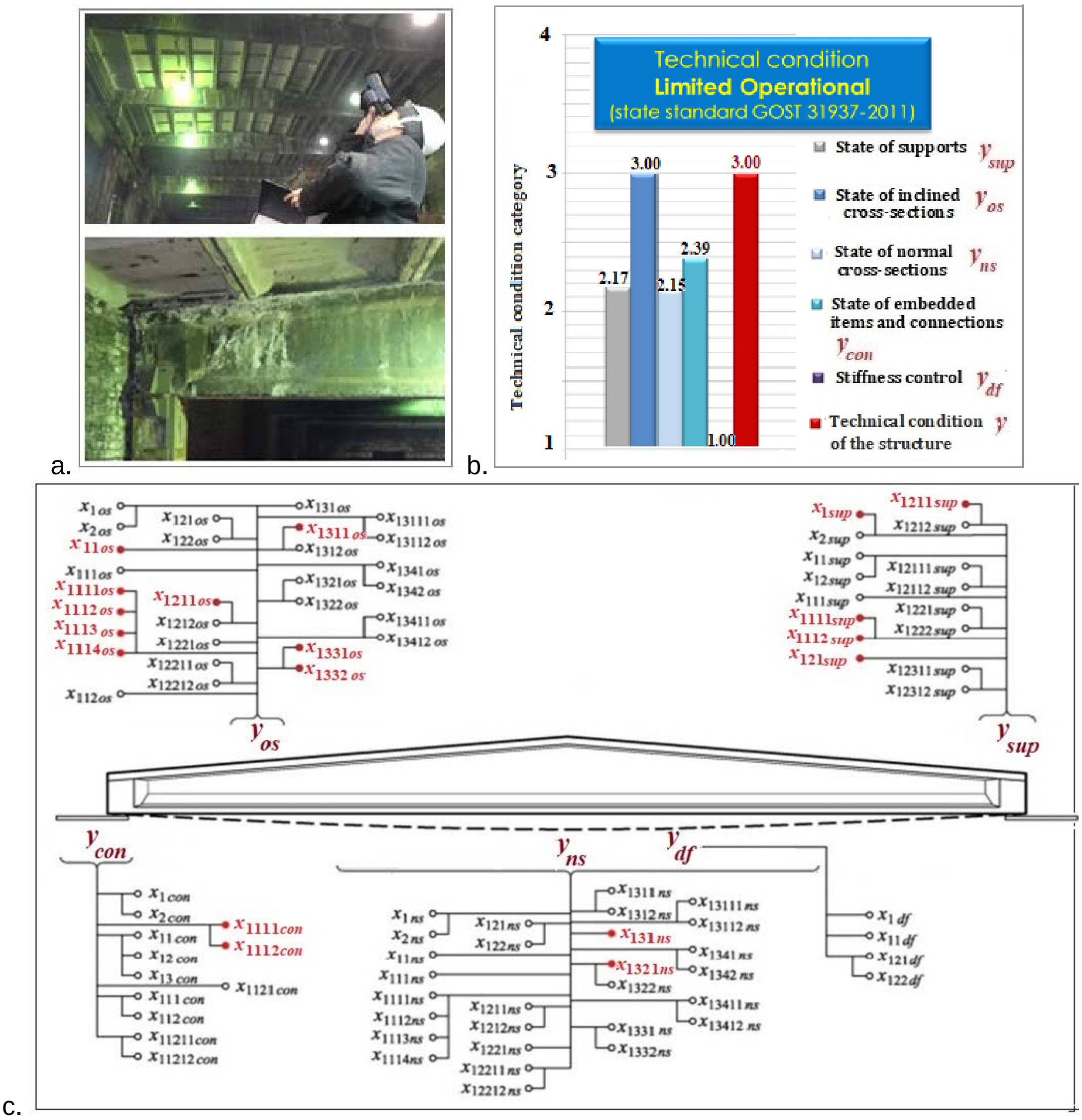

Figure 9. An example of displaying clear values of the technical condition category of a reinforced concrete beam at the stage of monitoring.

The results of the technical state evaluation examined structure, obtained using the expert system, are confirmed by expert opinions of specialists who did not participate in the creation of the program and have extensive experience in examining the building structures.

In the course of creating an expert system, Microsoft Excel was used in the spreadsheet, which is one of the most accessible software tools, providing the user with the opportunity to independently implement the mechanisms for solving mathematical problems. In a formalized form, the description of the navigation structure of the application is an XML file that allows processing, changing data in any other system regardless of the client platform or operating system [32].

Table 1. Parameters of the surveyed beam with anomalies that affect the category of the structure technical state.

Parameter designation x_i (index i)	Name of the controlled parameter	Expert's answer to the question of the system
	State of supports **(y_{sup})** – 18 *monitored parameters*	
1*sup*	The result of checking compliance with design requirements	No deviations detected
1111*sup*	The result of the inspection of corrosion of reinforcement	Pieces of continuous surface corrosion of reinforcement were found
1112*sup*	Result of measuring the residual cross-sectional area of reinforcement	The cross-sectional area of reinforcement is reduced by 3 % as a result of corrosion
1211*sup*	Measurement result of lime leaching from concrete	1 %
121*sup*	Measurement result of mechanical damage to concrete	The cross-sectional area on the support has not changed
	State of inclined cross-sections **(y_{os})** – *29 monitored parameters*	
11*os*	The result of calibration calculations	Strength is not provided, overvoltage – 4 %;
1111*os* 1112*os* 1114*os*	The result of the presence of inclined cracks on the support	Inclined crack opening width – 0.1 mm; distance between cracks – 910 mm; inclined crack angle – 48°
1211*os*	The result of the inspection of corrosion of reinforcement	Pieces of continuous surface corrosion of shear reinforcement were found
1311*os*	Measurement result of lime leaching from concrete	1 %
1331*os*	Result of measuring the neutralization depth of the protective layer	No more than 35 %
1332*os*	Measurement result of damage to the protective layer	Damage area – 14 %
	State of normal cross-sections **(y_{ns})** – *28 monitored parameters*	
131*ns*	Measurement result of mechanical damage to concrete	Cross- section area reduced by 3 %
1321*ns*	The result of the examination of concrete	When you knock, a rather sonorous sound is emitted, barely visible chips on the surface of the concrete remain
	State of embedded items and connections **(y_{con})** – *11 monitored parameters*	
1111*con*	The result of the inspection of corrosion of items	Pieces of continuous surface corrosion of items were found
1112*con*	Result of measuring the residual cross-sectional area of items	The cross-sectional area of item is reduced by 2 %

4. Conclusion

1. An expert opinion on the technical condition of building structures requires deep specialized knowledge and depends on the experience of the expert and the accuracy of the information. An expert system is a useful tool for solving ill-defined problems in which intuition and experience are necessary ingredients An automated search for an expert solution using intelligent expert systems can help in the work of not only a beginner, but also an experienced specialist.

2. The organization structure of expert knowledge for an intelligent expert system for assessing the building structures technical condition, taking into account the hierarchy of knowledge, information universality and the possibility of expansion, based on ontological analysis, is proposed.

3. A technique has been developed for formalizing expert information on the basis of the theory of fuzzy sets, expert estimation methods and analysis of hierarchy.

4. An expert system has been developed to assess the technical condition of reinforced concrete bent elements, which can significantly reduce the time and improve the quality of the expert opinion. The assessment of the adequacy of the decisions issued by the EC was carried out on the basis of modeling scenarios for various damage to flexible concrete structures, analyzing data from a number of technical reports on the examination of real structures and tested on real construction sites.

5. The present work is motivated by a need to transfer knowledge from the technical books and experienced experts in the domain field to make that knowledge and expertise available to practicing engineers.

6. An intelligent fuzzy expert system patented in the Federal Service for Intellectual Property (Certificate No. 2018615097 dated 24/04/2018) was implemented in the Perm Territory.

References

1. Rücker, W., Rohrmann, R.G., Hille, F. Guidelines for monitoring and assessment – A SAMCO initiative as a basis for the international standardization. Structural Health Monitoring and Intelligent Infrastructure – Proceedings of the 2nd International Conference on Structural Health Monitoring of Intelligent Infrastructure, SHMII. 2005. Vol. 2. Pp. 1671–1676.
2. Jeppsson, J. Reliability-Based Assessment Procedures for Existing Concrete Structures. Unpublished doctoral thesis. Lund University. Sweden. 2003. 199 p.
3. Tonkov, I.L., Tonkov, Yu.L. Aktual'nyye problemy otsenki tekhnicheskogo sostoyaniya stroitel'nykh konstruktsiy [Actual problems of assessing the technical condition of building structures]. Vestnik PNIPU, Prikladnaya ekologiya. Urbanistika. 2017. No. 3. Pp. 94–104. (rus)
4. Grozdov, V.T. Priznaki avariynogo sostoyaniya nesushchikh konstruktsiy zdaniy i sooruzheniy [Signs of an emergency condition of buildings and structures]. SPb.: Izdatel'skiy Dom KN+, 2000. 39 p. (rus)
5. Guchkin, I.S. Diagnostika povrezhdeniy i vosstanovleniye ekspluatatsionnykh kachestv konstruktsiy [Diagnosis of damage and restoration of performance of structures]. M.: Izdatel'stvo ASV, 2001. 171 p. (rus)
6. Dobromyslov, A.N. Diagnostika povrezhdeniy zdaniy i inzhenernykh sooruzheniy [Diagnostics of damage to buildings and engineering structures]. Moskva: MGSU, 2006. 256 p. (rus)
7. Kim, Y.M., Kim, C.M., Hong, S.G. Fuzzy based state assessment for reinforced concrete building structures. Engineering Structures. 2006. Vol. 28. Iss. 9. Pp. 1286–1297.
8. Sasmal, S., Ramanjaneyulu K. Condition evaluation of existing reinforced concrete bridges using fuzzy based analytic hierarchy approach. Expert Systems with Applications. 2008. Vol. 35. Pp. 1430–1443.
9. Pakdamar, F., Guler, K. Fuzzy logic approach in the performance evaluation of reinforced concrete structures (flexible performance). [Online]. System requirements: AdobeAcrobatReader. URL: http://www.iitk.ac.in/nicee/wcee/article/14_05-03-0100.PDF (date of the application: 11.08.2016).
10. Zain, F.M., Islam, M.N., Basri, I.H. An expert system for mix design of high performance concrete. Advances in Engineering Software. 2005. Vol. 36. No. 5. Pp. 325–337.
11. Moodi, F. Integration of knowledge management and Information Technology into the repair of concrete structures: an innovative approach. International Journal of IT in Architecture, Engineering and Construction. 2004. Vol. 2. Iss. 3. Pp. 173–190.
12. Khader, M. Hamdia. Expert System for Structural Evaluation of Reinforced Concrete Buildings in Gaza Strip Using Fuzzy Logic. A Thesis Submitted in Partial Fulfillment of the Requirement for the Degree of Master of Science in Civil Engineering Rehabilitation and Design of Structure. 2010. 92 p.
13. Sobhani, J., Ramezanianpour, A.A. Service life of the reinforced concrete bridge deck in corrosive environments: A soft computing system. Applied Soft Computing Journal. 2011. Vol. 11 (4). Pp. 3333–3346.
14. Balen, K. Learning from damage of masonry structures, expert systems can help . International Seminar on Historical Constructions. 2001. November. Pp. 15–27.
15. Pankevich, O.D., Shtovba, S.D. Application of fuzzy models for diagnostics of constructional structure. Bulletin of the Vinnytsia Polytechnic Institute. 2011. No. 4. Pp. 32–36.
16. Shtovba, S., Rotshtein, A., Pankevich, O. Fuzzy rule based system for diagnosis of stone construction cracks of buildings. Advances in Computational intelligence and learning, methods and applications. Dordrecht: Kluwer Academic Publisher. 2002. Pp. 401–412.
17. Shtovba, S.D., Pankevych. O.D. Fuzzy technology-based cause detection of structural cracks of stone buildings // Proceedings of the 14th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Kyiv, 2018. Vol. I: Main Conference. Pp. 209–218.
18. Sokolov, V.A. Ocenka tekhnicheskogo sostoyaniya stroitel'nyh konstrukcij zdanij na osnove mnogourovnevogo veroyatnostnogo analiza [Building systems technical condition assessment based on the multilevel probabilistic analysis]. Magazine of Civil Engineering. 2011. No. 7 (25). Pp. 45–51. (rus) DOI: 10.5862/MCE.25.7
19. Sokolov, V.A. Kategorii tekhnicheskogo sostoyaniya stroitel'nykh konstruktsiy zdaniy pri ikh diagnostike veroyatnostnymi metodami. [Technical condition categories of building structures in their diagnosis by probabilistic methods]. Fundamental'nyye issledovaniya. 2014. No. 6 (6). Pp. 1159–1164. (rus)
20. Soldatenko, T.N. Model of identification and prediction of building design defects on the basis of its inspection results. Magazin of Civil Egineering. 2011. No. 7. (25). Pp. 52–60. (rus).
21. Badiru, A., Cheung, J. Fuzzy engineering expert systems with neural network applications. John Wiley and Sons. USA. 2002. 289 p.
22. Sokolov, V.A. Veroyatnostnyj analiz tekhnicheskogo sostoyaniya (VATS) stroitel'nyh konstrukcij zdanij staroj gorodskoj zastrojki [Probabilistic analysis of the technical condition (VATS) of building structures of buildings of old urban buildings]. Monografiya. – Saarbrücken, Germany: Izd-vo LAP LAMBERT Academic Publishing is a trademark of: AV Akademikerverlag GmbH& Co. KG. HeinrichBöcking-Str. 6–8, 66121. 2013. 152 p. (rus)

23. Kkaetzel, L.J., Clifton, J.R. Expert Knowledge Based Systems for Materials in the Construction Industry. State-of-the-Art Report, Materials and Structures. 1995. Vol. 28. Pp. 160–174.
24. Kashevarova, G.G., Tonkov, Yu.L. Intellektual'nyye tekhnologii v obsledovanii stroitel'nykh konstruktsiy. [Intelligent technology in the survey of building structures]. Academia. Architecture and building. 2018. No. 1. Pp. 92–99. (rus) DOI: 10.22337/2077-9038-2018-1-92-99
25. Smirnov, S.V. Ontologicheskiy analiz v sistemakh komp'yuternogo modelirovaniya: dis. dokt. tekhn. nauk. [Ontological analysis in computer simulation systems]. Ros. akad. nauk., In-t probl. upr. slozh. sistemami. Samara, 2002. 348 p. (rus)
26. Palagin, A.V., Petrenko, N.G., Malakhov, K.S. Metodika proyektirovaniya ontologii PdO [Methods of designing ontology PdO]. Companions, systems and systems. 2011. No. 10. Pp. 5–12. (ukr)
27. Lu, X.; Simmonds, H. KBES for evaluating R.C. framed buildings using fuzzy sets. Automation in Construction. 1997. Vol. 6. Iss. 2. Pp. 121–137.
28. Pomykalski, J.J., Truszkowski, W.F., Brown, D.E. Expert System. Wiley Encyclopedia for Electrical and Electronics Engineering. February, 1999.
29. Zadeh, LA. Fuzzy sets as a basis for a theory of possibility. Fuzzy Sets and Systems. 1999. Vol. 100. Pp. 9–34.
30. Tararushkin, Ye.V. Primeneniye nechetkoy logiki dlya otsenki fizicheskogo iznosa nesushchikh konstruktsiy zdaniy. [The use of fuzzy logic to assess the physical deterioration of the supporting structures of buildings]. Vestnik BGTU im. V.G. Shukhova. 2016. No. 10. Pp. 77–82. (rus)
31. Tonkov, Yu.L. Vybor effektivnogo metoda postroyeniya funktsiy prinadlezhnosti dlya otsenki kachestvennykh priznakov tekhnicheskogo sostoyaniya stroitel'nykh konstruktsiy [The choice of an effective method of constructing membership functions for assessing the qualitative signs of the technical condition of building structures]. Vestnik PNIPU, Prikladnaya ekologiya. Urbanistika. 2016. No. 3(23). Pp. 126–146. (rus) DOI: 10.15593/2409;5125/2016.03.09
32. Tonkov, Yu.L. Matematicheskie modeli dlya identifikacii kategorii tekhnicheskogo sostoyaniya stroitel'nyh konstrukcij na osnove nechetkoj logiki [Mathematical models for identifying the category of technical condition of building structures based on fuzzy logic]: dis. … kand. tekhn. nauk. Perm. nac. issled. politekhn. un-t. Perm. 2018. 208 p. (rus)
33. Saaty, T.L. The Analytic Hierarchy Process. McGraw-Hill, New York. 1980. 287 p.
34. Laarhoven, P.J.M., Pedrycz, W.A. A fuzzy extension of Saaty's priority theory. Fuzzy sets and systems. 1983. Vol. 11. Pp. 229–241.
35. Chang, D.Y. Extent analysis and synthetic decision, optimization techniques and applications. World Scientific. 1992. Vol. 1. Pp. 352–355.

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Техническая диагностика железобетонных конструкций с применением интеллектуальных систем

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Ключевые слова: диагностика зданий и сооружений, железобетонные конструкции, категория технического состояния, экспертная система, нечеткая логика, онтологический анализ

Аннотация. Представлены результаты разработки эффективной интеллектуальной системы диагностики технического состояния железобетонных конструкций зданий и сооружений. Категория технического состояния является основным критерием при определении степени аварийности строительного объекта или необходимости принятия мер для его дальнейшей безопасной эксплуатации. Для того, чтобы решить эту проблему, разработана экспертная система, на основе математического аппарата теории нечетких множеств и нечеткой логики, которая может учесть разброс индивидуальных мнений экспертов, значительно сократить время обследования и повысить качество экспертного заключения. Предложена структура организации экспертных знаний для оценки технического состояния строительных конструкций с учетом иерархии знаний, универсальности информации и возможности ее расширения на основе онтологического анализа. Разработана методика формализации экспертной информации с помощью функций принадлежности для входных и выходных параметров управления. Для реализации нечеткого логического вывода разработан алгоритм, адаптированный к данной проблеме. Разработана компьютерная программа, которая реализует метод идентификации категории технического состояния строительных конструкций на основе нечетких баз знаний. Приведены результаты использования этой технологии при обследовании реального промышленного здания. Результаты оценки технического состояния исследуемой структуры, полученные с использованием экспертной системы, подтверждаются экспертными заключениями специалистов, которые не участвовали в создании программы и имеют большой опыт в обследовании строительных конструкций. Настоящая работа мотивирована необходимостью передачи знаний опытных экспертов, и технической книг в предметной области диагностики строительных конструкций, чтобы сделать эти знания и опыт доступными для практикующих инженеров.

Литература

1. Rücker W., Rohrmann R.G., Hille F. Guidelines for monitoring and assessment – A SAMCO initiative as a basis for the international standardization // Structural Health Monitoring and Intelligent Infrastructure – Proceedings of the 2nd International Conference on Structural Health Monitoring of Intelligent Infrastructure, SHMII. 2005. Vol. 2. Pp. 1671–1676.
2. Jeppsson J. Reliability-Based Assessment Procedures for Existing Concrete Structures. Unpublished doctoral thesis. Lund University. Sweden. 2003. 199 p.
3. Тонков И.Л., Тонков Ю.Л. Актуальные проблемы оценки технического состояния строительных конструкций // Вестник Пермского национального исследовательского политехнического университета. Прикладная экология. Урбанистика. 2017. № 3. С. 94–104.
4. Гроздов В.Т. Признаки аварийного состояния несущих конструкций зданий и сооружений. СПб: Издательский Дом КН+, 2000. 39 с.
5. Гучкин И.С. Диагностика повреждений и восстановление эксплуатационных качеств конструкций. М.: Издательство АСВ, 2001. 171 с.
6. Добромыслов А.Н. Диагностика повреждений зданий и инженерных сооружений. М.: МГСУ, 2006. 256 с.
7. Kim Y.M., Kim C.M., Hong S.G. Fuzzy based state assessment for reinforced concrete building structures // Engineering Structures. 2006. Vol. 28. Iss. 9. Pp. 1286–1297.
8. Sasmal S., Ramanjaneyulu K. Condition evaluation of existing reinforced concrete bridges using fuzzy based analytic hierarchy approach // Expert Systems with Applications. 2008. Vol. 35. Pp. 1430–1443.
9. Pakdamar F., Guler K. Fuzzy logic approach in the performance evaluation of reinforced concrete structures (flexible performance). [Электронный ресурс]. System requirements: AdobeAcrobatReader. URL: http://www.iitk.ac.in/nicee/wcee/article/14_05-03-0100.PDF (дата обращения: 11.08.2016).

10. Zain F.M., Islam M.N., Basri I.H. An expert system for mix design of high performance concrete // Advances in Engineering Software. 2005. Vol. 36. No. 5. Pp. 325–337.
11. Moodi F. Integration of knowledge management and Information Technology into the repair of concrete structures: an innovative approach // International Journal of IT in Architecture // Engineering and Construction. 2004. Vol. 2. Iss. 3. Pp. 173–190.
12. Khader M. Hamdia. Expert System for Structural Evaluation of Reinforced Concrete Buildings in Gaza Strip Using Fuzzy Logic. A Thesis Submitted in Partial Fulfillment of the Requirement for the Degree of Master of Science in Civil Engineering Rehabilitation and Design of Structure. 2010. 92 p.
13. Sobhani J., Ramezanianpour A.A. Service life of the reinforced concrete bridge deck in corrosive environments: A soft computing system // Applied Soft Computing Journal. 2011. Vol. 11 (4). Pp. 3333–3346.
14. Balen K. Learning from damage of masonry structures, expert systems can help // International Seminar on Historical Constructions. 2001. November. Pp. 15–27.
15. Pankevich O.D., Shtovba S.D. Application of fuzzy models for diagnostics of constructional structure // Bulletin of the Vinnytsia Polytechnic Institute. 2011. No. 4. Pp. 32–36.
16. Shtovba S., Rotshtein A., Pankevich O. Fuzzy rule based system for diagnosis of stone construction cracks of buildings // Advances in Computational intelligence and learning, methods and applications. Dordrecht: Kluwer Academic Publisher. 2002. Pp. 401–412.
17. Shtovba S.D., Pankevych O.D. Fuzzy technology-based cause detection of structural cracks of stone buildings // Proceedings of the 14th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Kyiv, 2018. Vol. I: Main Conference. Pp. 209–218.
18. Соколов В.А. Оценка технического состояния строительных конструкций зданий на основе многоуровневого вероятностного анализа // Инженерно-строительный журнал. 2011. № 7(25). С. 45–51. DOI: 10.5862/MCE.25.7
19. Соколов В.А. Категории технического состояния строительных конструкций зданий при их диагностике вероятностными методами // Фундаментальные исследования. 2014. № 6(6). С. 1159–1164.
20. Soldatenko T.N. Model of identification and prediction of building design defects on the basis of its inspection results // Magazin of Civil Egineering. 2011. No. 7. (25). Pp. 52–60.
21. Badiru A., Cheung J. Fuzzy engineering expert systems with neural network applications. John Wiley and Sons. USA. 2002. 289 p.
22. Соколов В.А. Вероятностный анализ технического состояния (ВАТС) строительных конструкций зданий старой городской застройки. Монография. Саарбрюкен, Германия: Издательство LAP LAMBERT. 2013. 152 с.
23. Kkaetzel L.J., Clifton J.R. Expert Knowledge Based Systems for Materials in the Construction Industry. State-of-the-Art Report // Materials and Structures. 1995. Vol. 28. Pp. 160–174.
24. Кашеварова Г.Г., Тонков Ю.Л. Интеллектуальные технологии в обследовании строительных конструкций // Academia. Архитектура и строительство. 2018. № 1. С. 92–99. DOI: 10.22337/2077-9038-2018-1-92-99
25. Смирнов С.В. Онтологический анализ в системах компьютерного моделирования: дис... д.т.н. Самара, 2002. 348 с.
26. Palagin A.V., Petrenko N.G., Malakhov K.S. Metodika proyektirovaniya ontologii PdO [Methods of designing ontology PdO] // Companions, systems and systems. 2011. No. 10. Pp. 5–12.
27. Lu X.; Simmonds H. KBES for evaluating R.C. framed buildings using fuzzy sets // Automation in Construction. 1997. Vol. 6. Iss. 2. Pp. 121–137.
28. Pomykalski J.J., Truszkowski W.F., Brown D.E. Expert System. Wiley Encyclopedia for Electrical and Electronics Engineering. February, 1999.
29. Zadeh LA. Fuzzy sets as a basis for a theory of possibility // Fuzzy Sets and Systems. 1999. Vol. 100. Pp. 9–34.
30. Тарарушкин Е.В. Применение нечеткой логики для оценки физического износа несущих конструкций зданий // Вестник БГТУ им. В.Г. Шухова. 2016. № 10. С. 77–82.
31. Тонков Ю.Л. Выбор эффективного метода построения функций принадлежности для оценки качественных признаков технического состояния строительных конструкций // Вестник ПНИПУ. Прикладная экология. Урбанистика. 2016. № 3(23). С. 126–146. DOI: 10.15593/2409;5125/2016.03.09
32. Тонков Ю.Л. Математические модели для идентификации категорий технического состояния строительных конструкций на основе нечеткой логикиЖ дисс… к.т.н. Пермский национальный исследовательский политехнический университет. Пермь, 2018. 208 с.
33. Saaty T.L. The Analytic Hierarchy Process. McGraw-Hill, New York. 1980. 287 p.
34. Laarhoven P.J.M., Pedrycz W.A. A fuzzy extension of Saaty's priority theory // Fuzzy sets and systems. 1983. Vol. 11. Pp. 229–241.
35. Chang D.Y. Extent analysis and synthetic decision, optimization techniques and applications // World Scientific. 1992. Vol. 1. Pp. 352–355.

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