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QUANTIFICATION ASSESSMENT OF THE EXISTING REINFORCED CONCRETE STRUCTURES BASED ON FUZZY LOGIC

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Abstract

Fuzzy logic is the useful tool when assessing the existing reinforced concrete structures. The introduction of the method for quantitative assessment of the technical condition of the existing structures built on the fuzzy logic represents a transition to a new and higher-quality level for survey of constructions sites. As a result, it is seen that the assessment of the existing building with usage of the proposed expert system is in compliance with the estimation of the qualified experts.

Keywords: quantification assessment, fuzzy logic, existing structures, technical condition.

КОЛИЧЕСТВЕННАЯ ОЦЕНКА СУЩЕСТВУЮЩИХ ЖЕЛЕЗОБЕТОННЫХ КОНСТРУКЦИЙ НА ОСНОВЕ НЕЧЕТКОЙ ЛОГИКИ

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Реферат

Нечеткая логика является полезным инструментом при оценке существующих железобетонных конструкций. Внедрение методики количественной оценки технического состояния существующих конструкций, построенной на инструментах нечеткой логики, представляет собой переход на новый и более качественный уровень обследования зданий и сооружений. В результате видно, что оценка существующего здания со сборными железобетонными элементами с использованием предложенной нечеткой системы имеет достаточно хорошее совпадение с результатами профессиональных экспертов.

Ключевые слова: количественная оценка, нечеткая логика, существующие конструкции, техническое состояние.

1 Introduction

Assessment of existing reinforced concrete structures is becoming a most important but complicated engineering task. General principles of sustainable development regularly lead to the need for an extension of a life of a structure, in most practical cases with severe economic constraints.

As it was shown in [1] visual inspection becomes the dominant practice in the management of maintenance, even when the importance of the structural elements are significant. Subjectivity heavily affects the process of assessment of degradation degree based on the results of visual inspection. Most of assessment approaches and methods are similar in principle, but vary in the details.

In order to use the visual inspection as a robust and reliable instrument to evaluate the safety level of an existing structural element, we decided to take advantage of the ability of Fuzzy Logic to treat uncertainty as expressed by linguistic judgements [2, 3].

In order to develop the multilevel expert system for existing structures assessment a Fuzzy Logic-based algorithm is proposed, which used the Fuzzy Logic Toolbox package of MatLab Software [1].

As it pointed in [1], «*a Fuzzy Logic is a versatile tool, particularly suitable for the management of decisional trees involving the processing of data endowed with «vague» nature (both numerical and qualitative one), and is naturally able to provide a linguistic, qualitative assessment of the health conditions of the building*».

In this context, the Fuzzy Logic appears the most qualified tool for the processing of numerical data and uncertain information in order to obtain a linguistic description of structural damage.

2 Rule-based Fuzzy model/Expert system development

The stages of development of the Fuzzy Logic System are presented in details in [4, 5]. For the development of the fuzzy production model for assessing of the existing structures performance it is necessary to formulate set, consisting the basic variables (see Table 1) which are characterized performance of element and set, characterizing (present) damage level (see Table 2).

Table 1 – Input linguistic basic variables

Designation linguistic variables	Description of the linguistic variables	Term-set
Phase A: Visual Inspection (A-1)		
x_1	Crack propagation (bending/shear)	T4 = {no «0»; single «S»; numerous «N»; massive «M»}
x_2	Positions of the cracks (bending/shear)	T4 = {no «0»; in the mid-span «1»; near support «2»; mid-span+ near support «3»}
x_3	The longitudinal corrosion cracks propagation	T4 = {no «0»; local «L»; partial «P»; solid «S»}
x_4	Corrosion damage (deteriorations)	T2 = {no «0»; yes «1»}
x_5	Surface degradation of concrete (deteriorations)	T2 = {no «0»; yes «1»}
x_6	Propagation of the longitudinal corrosion cracks in compression zone of the section	T2 = {no «0»; yes «1»}
Phase A: Basic Testing (A-2)		
x_7	Concrete cover to diameter ratio, $\frac{c}{\varnothing}$	T3 = {small «S»; mean «M»; large «L»}
x_8	Load-induced cracks width, w_k (bending/shear)	T4 = {small «S»; permissible «P»; exceeded «Ex»; excessive «E»}
x_9	Longitudinal corrosion cracks width, w_l	T3 = {small «S»; medium «M»; excessive «E»}
x_{10}	Level of the reinforcement corrosion	T3 = {small «S»; mean «M»; large «L»}
x_{11}	Deflection ratio, $\frac{\delta}{L}$	T4 = {small «S»; permissible «P»; exceeded «Ex»; excessive «E»}
Phase A: Damage Class		
x_{12}	Visual Inspection (A-1)	T3 = {critical «1»; significant «2»; minor «3»}
x_{13}	Basic Testing (A-2)	T3 = {critical «1»; significant «2»; minor «3»}
x_{14}	Documentation	T2 = {no «0»; yes «1»}

Table 2 – Output linguistic basic variables

Designation linguistic variables	Description of the linguistic variables	Term-set
y_1	Damage level	T3 = {critical «1»; significant «2»; minor «3»}
y_2	Damage level	T3 = {critical «1»; significant «2»; minor «3»}
y_3	Damage class	T3 = {small «1»; moderate «2»; severe «3»}

As it was shown above, in the damage assessment of an existing buildings (structures), several input data are required (crack width and propagation, residual strength of materials, amount and condition of the steel reinforcement, deflection, corrosion level et al.) that will all be treated, according to previous remarks, as fuzzy sets. The common structure deficiencies associated with the deterioration of the structural element are corrosion of steel reinforcement and the cracking, scaling and spalling concrete, deflections. The ranges for basic variables and correlation function were adopted based on the own numerical and experimental studies [4-6].

3 Realization of the Fuzzy production model for assessment of existing structures in MatLab Software

Step 1: Fuzzification – Input Fuzzy. At this stage, we adopted the membership function for term-sets of input and output linguistic variables, as shown in Table 3. The most commonly used membership functions are the trapezoidal and triangular ones. These membership functions will be indeed the functions adopted in the proposed algorithm.

Table 3 – Membership functions mathematical descriptions

Designation of the linguistic variables	Membership function type	Mathematical description (upper index designate the corresponding term)
x_1	Trapezoidal	μ_{Δ}^{0} (x; -1; -1; 0; 0), μ_{Δ}^{S} (x; 0.5; 0.5; 5; 15), μ_{Δ}^{N} (x; 5; 15; 35; 45), μ_{Δ}^{M} (x; 35; 45; 90; 100)
x_2	Triangular	μ_{Δ}^{0} (x; -0.5; 0; 0.5), μ_{Δ}^{1} (x; 0.5; 1; 1.5), μ_{Δ}^{2} (x; 1.5; 2; 2.5), μ_{Δ}^{3} (x; 2.5; 3; 3.5)
x_3	Trapezoidal	μ_{Δ}^{0} (x; -1; -1; 0; 0), μ_{Δ}^{L} (x; 0.5; 0.5; 5; 15), μ_{Δ}^{P} (x; 5; 15; 35; 45), μ_{Δ}^{D} (x; 35; 45; 90; 100)
x_4	Triangular	μ_{Δ}^{0} (x; -0.5; 0; 0.5), μ_{Δ}^{1} (x; 0.5; 1; 1.5)
x_5	Triangular	μ_{Δ}^{0} (x; -0.5; 0; 0.5), μ_{Δ}^{1} (x; 0.5; 1; 1.5)
x_6	Triangular	μ_{Δ}^{0} (x; -0.5; 0; 0.5), μ_{Δ}^{1} (x; 0.5; 1; 1.5)
x_7	Trapezoidal	μ_{Δ}^{M} (x; -1; 0; 0.5; 1.5), μ_{Δ}^{C} (x; 0.5; 1.5; 2.5; 3.5), $\mu_{\Delta}^{Б}$ (x; 2.5; 3.5; 8; 10)
x_8	Trapezoidal	μ_{Δ}^{M} (x; -0.1; 0; 0; 0.1), μ_{Δ}^{S} (x; 0; 0.1; 0.35; 0.45), μ_{Δ}^{P} (x; 0.35; 0.45; 0.95; 1.05), μ_{Δ}^{D} (x; 0.95; 1.05; 1.2; 2)
x_9	Trapezoidal	μ_{Δ}^{S} (x; -0.1; 0; 0; 0.1), μ_{Δ}^{M} (x; 0; 0.1; 0.95; 1.05), μ_{Δ}^{E} (x; 0.95; 1.05; 2; 3)
x_{10}	Trapezoidal	μ_{Δ}^{S} (x; -1.5; 0; 0.5; 1.5), μ_{Δ}^{M} (x; 0.5; 1.5; 2.5; 3.5), μ_{Δ}^{L} (x; 2.5; 3.5; 5; 8)
x_{11}	Trapezoidal	μ_{Δ}^{S} (x; -0.001; 0; 0,0005; 0.0015), μ_{Δ}^{P} (x; 0.0005; 0.0015; 0.0035; 0.0045), μ_{Δ}^{Ex} (x; 0.0035; 0.0045; 0.0195; 0.0205), μ_{Δ}^{E} (x; 0.0195; 0.0205; 0.025; 0.03)
x_{12}	Triangular	μ_{Δ}^{1} (x; 0.5; 1; 1.5), μ_{Δ}^{2} (x; 1.5; 2; 2.5), μ_{Δ}^{3} (x; 2.5; 3; 3.5)
x_{13}	Triangular	μ_{Δ}^{1} (x; 0.5; 1; 1.5), μ_{Δ}^{2} (x; 1.5; 2; 2.5), μ_{Δ}^{3} (x; 2.5; 3; 3.5).
x_{14}	Triangular	μ_{Δ}^{0} (x; -0.5; 0; 0.5), μ_{Δ}^{1} (x; 0.5; 1; 1.5)
y_1	Triangular	μ_{Δ}^{1} (x; 0.5; 1; 1.5), μ_{Δ}^{2} (x; 1.5; 2; 2.5), μ_{Δ}^{3} (x; 2.5; 3; 3.5)
y_2	Triangular	μ_{Δ}^{1} (x; 0.5; 1; 1.5), μ_{Δ}^{2} (x; 1.5; 2; 2.5), μ_{Δ}^{3} (x; 2.5; 3; 3.5)
y_3	Triangular	μ_{Δ}^{1} (x; 0.5; 1; 1.5), μ_{Δ}^{2} (x; 1.5; 2; 2.5), μ_{Δ}^{3} (x; 2.5; 3; 3.5)

Step 2: Setting Fuzzy Rules in accordance with Table 4. The base of the Rules of the Fuzzy production model is defined as a structure with an appropriate member of inputs x_i and one output y_i.

Table 4 – Example of the fuzzy rules of the production model

Rule number	Antecedent	Consequent
Base of the rules R1		
R1.1	$(x_1 = 0 \wedge x_2 = 0 \wedge x_3 = 0 \wedge x_4 = 0 \wedge x_5 = 1 \wedge x_6 = 0) \vee$ $(x_1 = 0 \wedge x_2 = 0 \wedge x_3 = 0 \wedge x_4 = 1 \wedge x_5 = 1 \wedge x_6 = 0) \vee$ $(x_1 = S \wedge x_2 = 1 \wedge x_3 = 0 \wedge x_4 = 0 \wedge x_5 = 0 \wedge x_6 = 0) \vee$ $(x_1 = S \wedge x_2 = 2 \wedge x_3 = 0 \wedge x_4 = 0 \wedge x_5 = 0 \wedge x_6 = 0) \vee$ $(x_1 = S \wedge x_2 = 1 \wedge x_3 = 0 \wedge x_4 = 0 \wedge x_5 = 1 \wedge x_6 = 0) \vee$ $(x_1 = S \wedge x_2 = 2 \wedge x_3 = 0 \wedge x_4 = 0 \wedge x_5 = 1 \wedge x_6 = 0) \vee$ $(x_1 = S \wedge x_2 = 3 \wedge x_3 = 0 \wedge x_4 = 0 \wedge x_5 = 0 \wedge x_6 = 0) \vee$ $(x_1 = S \wedge x_2 = 3 \wedge x_3 = 0 \wedge x_4 = 0 \wedge x_5 = 1 \wedge x_6 = 0)$	$y_1 = 3$
<…>		
R3.3	$(x_{12} = 2 \wedge x_{13} = 1 \wedge x_{14} = 0) \vee$ $(x_{12} = 1 \wedge x_{13} = 2 \wedge x_{14} = 0) \vee$ $(x_{12} = 1 \wedge x_{13} = 1 \wedge x_{14} = 1) \vee$ $(x_{12} = 1 \wedge x_{13} = 1 \wedge x_{14} = 0)$	$y_3 = 3$

Step 3: Aggregation is the process by which the fuzzy set that represent the outputs of each rule are combined into a single fuzzy set. A rule premise in general is a compound fuzzy proposition. Aggregation only occurs once for each output variable, which is before the final defuzzification step. According to the original proposal of Zadeh for aggregation of the confidence level of assumption min-conjuction is used:

$$\alpha_i = \min \{\mu_{A_{i1}}(x_1), \mu_{A_{i2}}(x_2), \mu_{A_{i3}}(x_3), \mu_{A_{i4}}(x_4)\}, i = 1, 2, ..., n \tag{1}$$

Step 4: Activation. A fuzzy «IF-THEN» rule is a connection of two (compound) fuzzy propositions. Hence, this connective has to be interpreted within the framework of set theoretic or logical operators. The simplest interpretation is that of the conjuction of premise and conclusion, such that the appropriate operation is the minimum:

$$\mu_{B'_i}(y) = \min\{\alpha_i, \mu_{B_i}(y)\}, i = 1, 2, ..., n \quad (2)$$

Step 5: Accumulation. Usually, a rule base is interpreted as a disjunction of rules, i.e. rules are seen as independent «experts». Accumulation has the task to combine the individual «expert statements», which actually are fuzzy sets of recommended output values. Consequently, an appropriate accumulation operation is the maximum:

$$\mu_{B'}(y) = \max\{\mu_{B'_1}(y), \mu_{B'_2}(y), ..., \mu_{B'_n}(y)\} \quad (3)$$

Step 6: Defuzzification – from a fuzzy decision to real decision. As inference results in a fuzzy set, the task of defuzzification is to find the numerical value which «best» comprehends the information contained in this fuzzy set. A frequently used method is the so-called Center-of-Gravity defuzzification (CoG, also called Center-of-Area defuzzification CoA):

$$y' = \frac{\int_{Y_{\min}}^{Y_{\max}} y \mu_{B'}(y) dy}{\int_{Y_{\min}}^{Y_{\max}} \mu_{B'}(y) dy} \quad (4)$$

which chooses the y' – coordinate of the center of gravity of the area below the graph μ(y). This defuzzification can be interpreted as a weighted mean, i.e. each value y weighted with μ(y) and integral in the denominator serves for normalization.

4 Implementation of the Assessment Algorithm of the Proposed Expert System

According to [1] the whole phase is managed by a nested fuzzy algorithm: starting from the assessment of the single structural elements, and progressively proceeding through the structural hierarchy (element/storey/building), input data are processed and collated in order to obtain the new Phase – assessment of the whole building. It is worth remarking that part of the results provided by the preliminary investigation could be used also at this stage.

The starting point, as it has pointed out in numerious publications [7-10], is the availability of an inventory of data and information derived from the investigation on the analyzed building, the collecting and organization of which is performed by using the survey diagnostic forms, as it shown in [5].

As an example of the implementation of the proposed expert system results of the assessment of the existing building with precast concrete elements is presented.

Structure description. Precast ribbed slabs with size in plane 1.5x6 m, with height of the rib 300 mm. Longitudinal tensile reinforcement is Ø16 B400, concrete cover 32 mm (ratio c/Ø=2).

Results of the Visual Inspection and Basic Testing are presented in Diagnostic Protocol Example (Table 5).

Table 5 – The diagnostic protocol example

Phase A: Visual Inspection (A-1)					
Structural Member	***Precast ribbed slabs***				
General Description	*Size in plane 1.5x6 m, with height of the rib 300 mm*				
Propagation of the flexural (bending)/shear cracks, x_1	Parameter: propagation length of the damaged linear size, [%] span length				
	no	**single**	**numerous**	**massive**	
	0	0.5-10	10-40	>40	
Inspection results				*45%*	
Position of the flexural (bending)/shear cracks, x_2	Parameter: position in span				
	no	**mid-span**	**not sure**	**near support**	**mid-span+near support**
	0	1	1.5	2	3
Inspection results					×
Propagation of the longitudinal corrosion cracks, x_3	Parameter: propagation length, [%] span length				
	no	**local**	**partial**	**solid**	
	0	0.5-10	10-40	>40	
Inspection results				*45%*	
Corrosion damage (deterioration), x_4	Parameter: damage appearance				
	no	**not sure**	**yes**		
	0	0.5	1		
Inspection results			×		
Surface degradation of concrete (deterioration), x_5	Parameter: damage appearance				
	no	**not sure**	**yes**		
	0	0.5	1		
Inspection results			×		
Propagation of the longitudinal corrosion cracks in compression zone of the section, x_6	Parameter: damage				
	no	**not sure**	**yes**		
	0	0.5	1		
Inspection results	×				
Damage Level	***1 (critical)***				

Phase A: Basic Testing (A-2)		
Characteristic of the Structure	Parameters	
	Length, l [mm]	*6000*
	Height, h [mm]	*300*
	Concrete cover, c [mm]	*32*
	Diameter of steel bar, Ø [mm]	*16*

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Concrete				
Ratio $\frac{c}{\varnothing}$ (concrete cover/diameter), x_7	Parameter: $\frac{c}{\varnothing}$			
	small	**mean**	**large**	
	<1	1-3	>3	
Inspection results		*2*		
Flexural (bending) cracks, x_8	Parameter: crack width, w_k			
	small	**permissible**	**exceeded**	**excessive**
	no more 0.05 mm	from 0.05 to 0.4 mm	from 0.4 to 1 mm	more 1 mm
Inspection results			*0.8*	
Longitudinal corrosion crack, x_9	Parameter: corrosion crack width, w_l			
	small	**medium**	**large**	
	no more 0.05 mm	from 0.05 to 1 mm	more 1 mm	
Inspection results			*1.2*	
Reinforcement (steel)				
Level of the corrosion damage, x_{10}	Parameter: loss of the mass			
	small	**mean**	**large**	
	no more 1 %	from 1 to 3 %	more 3%	
Inspection results		*2.5%*		
Deflections, deformations				
Deflections, x_{11}	Parameter: relative deflection			
	small	**permissible**	**exceeded**	**excessive**
	no more 1/900	from 1/900 to 1/250	from 1/250 to 1/50	more 1/50
Inspection results			*1/85*	
Damage Level	***1 (critical)***			
Phase A: Damage Class				
Documentation	**no**	**partially**	**yes**	
	0	from 0 to 1	1	
	×			
Damage Class	***3 (severe damage)***			

General view of the structural element are presented in Figure 1. Results of the assessment with usage of the proposed algorithm are listed in Table 6 and are in compliance with the estimation of the qualified experts.

Table 6 – Results of the assessment

The structural element	Results of the assessment with usage of the proposed algorithm	Results of the estimation of the qualified experts
Precast ribbed slabs	Severe damage	Severe damage

Figure 1 – General view of the evaluated ribed slabs

5 Conclusions

1. An effective structural assessment expert system for evaluation of the existing reinforced concrete structural systems using Fuzzy Logic MatLab Toolbox was developed and verified on the real objects in this study.
2. Although the presented expert system based on close visual inspections and simple measurements, it may provide substantial assistance to more complicated work (for example, evaluation of existing structures based on detailed investigations).

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