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APPLICATION OF QUANTITATIVE ASSESSMENT BASED ON FUZZY LOGIC RULES TO THE TECHNICAL CONDITION OF EXISTING STRUCTURES

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Abstract
Approaches based on the use of fuzzy logic concepts provide effective solutions to problems containing uncertainties present in the assessment of existing buildings. The article presents the principle of development and implementation of quantitative assessment of the technical condition of existing structures. The process is based on an algorithm in which the input data and information collected at each step are processed and interpreted to determine the next step of the procedure. The result shows that the evaluation of the existing precast concrete building using the proposed fuzzy system is consistent with the evaluation of qualified experts.

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

ПРИМЕНЕНИЕ КОЛИЧЕСТВЕННОЙ ОЦЕНКИ, ОСНОВАННОЙ НА ПРАВИЛАХ НЕЧЕТКОЙ ЛОГИКИ, К ТЕХНИЧЕСКОМУ СОСТОЯНИЮ СУЩЕСТВУЮЩИХ КОНСТРУКЦИЙ

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Реферат
Подходы, основанные на использовании концепции нечеткой логики, дают эффективные решения проблем, содержащих неопределенности, присутствующие при оценке существующих зданий. В статье представлен принцип разработки и внедрения количественной оценки технического состояния существующим сооружениям. Процесс основан на алгоритме, в котором входные данные и информация, собранная на каждом этапе, обрабатываются и интерпретируются для определения последующего шага процедуры. В результате видно, что оценка существующего здания из сборных железобетонных элементов с использованием предлагаемой нечеткой системы соответствует оценке квалифицированных экспертов.

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

1 Introduction

In recent years assessment of existing structures is becoming a more and more important engineering task. The process of assessment and structure management is a decision process which aims to remove any doubts regarding its current condition and future structural performance and/or to identify the most effective interventions required to fulfil the basic requirements. This process must be optimised considering the total service life costs of the structure. The standard ISO 13822, defines *«assessment of existing structures»* as the *«set of activities performed in order to verify the reliability of an existing structure for future use»*. It defines investigation as *«collection and evaluation of information through inspection, document search, load testing and other testing»*. Moreover, inspection is *«on-site non-destructive examination to establish the present condition of the structure»*.

According to ISO 13822, the assessment of the existing structure can be initiated under the following circumstances:

– an anticipated change in use or extension of design working life;
– a reliability check (e.g. earthquakes, increased traffic actions) as required by authorities, insurance companies, owners, etc.;
– structural deterioration due to time-dependent actions and influences (e.g. corrosion, fatigue);
– structural damage by accidental actions (ISO 2394).

General principles of sustainable development regularly lead to the need for extension of a life of a structure, in the majority of practical cases in conjunction with severe economic constraints. The purpose for which the concrete structure was designed and developed can change during the lifespan of the building. When this occurs, and concrete structure no longer fulfils its new requirements, a decision is made whether the building will be demolished or transformed. According to [1], *transformation* is different than *restoration* or *renovation* in that it not necessarily strive to maintain the social, political or cultural embodiment of the place. *Transformation* can lead to a switch in the function of the building. For example, a former industrial building can be transformed into social housing.

In general case the estimation procedure of the present conditions of the existing building consists of three main phases which can be singled out as follow:

Phase A: Preliminary analysis (visual inspection; basic *in-situ* testing) is aimed at obtaining a coarse estimation but general information of the real present state conditions of the existing structure and defining a rapid mapping of instabilities, damage and vulnerability. Based on the data obtained, it will be then decided if further and more detailed investigation needs.

Phase B: Extensive or detailed in-depth investigation, including a complete and systematic survey of the degradation scenery; experimental and laboratory tests, including both destructive and non-destructive *in-situ* methods.

Phase C: Interpretation and assessment of the obtained results; formulation of the judgment on the level of damage and reliability; specification of the repair and retrofitting interventions need in order to meet safety format requirements.

As was shown in [2] the diagnostic process for evaluation of the safety level and structural conditions of existing buildings is based on a decisional tree in which the data information collected at each phase are processed and interpreted in order to define the successive step of the procedure.

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The investigation, including updating of information, is one of the most important activities in the assessment process. It must take into consideration all available information and, in particular, the influences of present damage and deterioration mechanisms. The aim of a preliminary inspection (designed as Phase A) is to identify the structural system and possible damage of the structure by visual observation with simple tools. The information collected is related to aspects such as surface characteristics, visible deformations, cracks, spalling, corrosion, etc. The results of the preliminary inspection are expressed, traditionally, in terms of a qualitative grading of structural conditions (e.g. none, minor, moderate, severe, destructive, unknown) for possible damage. According to the Recommendation given by [3], the preliminary assessment (Phase A) is organized in three consecutive steps, each of which provides an intermediate judgment: (1) *Typological and structural description and existing original design documentation analysis;* (2) *Visual inspection,* which consists of visual evaluation of cracks (extension an amplitude), concrete condition (degradation , covering thickness), reinforcing bars conditions (corrosion); (3) *In-situ experimental testing* (non-destructive or destructive).

Thus, preliminary inspection (*visual inspection + in-situ testing*) becomes the ruling practice in the management of maintenance, even when the importance of the construction is significant. The process of evaluation of degradation based on the results of visual inspection is heavily affected by subjectivity. It is because most of the assessment approaches are similar in principle but varies in the details.

As was shown above, most practical cases the expert in charge of the inspection writes down on a safety assessment protocol a linguistic statement, which represents the subjective judgment for the degradation under examination. When relying only on visual inspection both the problems of dealing with different levels of expertise of the inspectors and the problems of handling subjective information on degradation raise this information, which needs to be turned into objective and reliable assessments.

To use the visual inspection as a robust and reliable instrument to evaluate the safety level of existing structures of the buildings, it was decided to take advantage of the ability of Fuzzy Logic to treat uncertainty as expressed by linguistic judgments [4, 5].

Following Aristotle's logic: *«It is impossible that the same thing can at the same time both belong and not belong to the same object and in the same respect» (Aristotle, Metaphysics, Principle of non-contradiction).* This law is very helpful if the problems are simple and linear, but the real-life and nature are not as easy as this [6].

The Fuzzy Logic was introduced in the 60's by Zadeh, who stated that the *«key elements of human thought cannot be represented by numbers, but rather are the labels of fuzzy sets, that is to say, linguistic values identifying fuzzy sets».* Fuzzy sets are classes of object characterized by a gradual transition from the membership conditions to the non-membership one, whereas crisp sets (that where the only one known before this new theory) only allow the drastic binary condition membership/non-membership.

Some common theoretical background of the Fuzzy Logic approach to the civil engineering problems described in detail in numerous international publications [2, 7–11].

As it pointed in [2], *«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 to obtain a linguistic description of structural damage.

In order to create the multilevel expert system for existing structures assessment based on the diagnostic process outlined above, a Fuzzy Logic-based algorithm is proposed, which exploits the Fuzzy Logic Toolbox package of *MatLab* Software.

Fuzzy Logic System: Some Background Information

Figure 1 presents a general view of a Fuzzy Logic system that is widely used for the assessment of the different technical problems. A fuzzy logic system maps crisp inputs into crisp outputs. It contains four basic components: (1) fuzzifier; (2) rules; (3) inference engine and (4) defuzzifier. Once the rules have been established, a fuzzy logic system can be viewed as a mapping from inputs to outputs [7, 12].

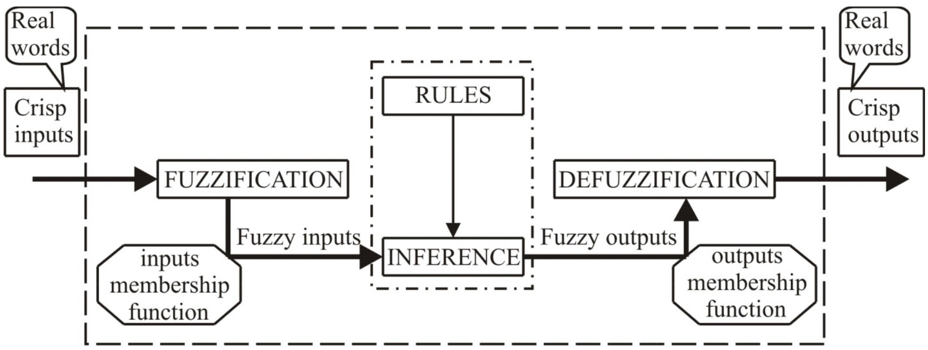


Figure 1 – Block diagram of Fuzzy Logic system, according to (Khader, 2010)

Fuzzification is the process of making of crisp quantity fuzzy. In other words, the fuzzification procedure consists in transforming the numerical value of the considered variable in its corresponding value of membership to the given fuzzy sets through the corresponding membership function. This is done by recognizing that many of quantities, which are considered crisp and deterministic, are not deterministic at all and they carry considerable uncertainty when the variable is probably fuzzy and can be represented by a membership function. Typically, the membership function overlaps so that the values of the variable can partially belong to multiple fuzzy sets. In general case, *the wider the area that overlaps, the more the uncertainty the system includes.*

The procedure of *inference* involves the application of the rules of combination of fuzzy sets. Usually, these are simple linguistic expressions, which are converted to mathematical formalism in the language of the «IF-THEN» logic. This is important because the information gathered through the examination of a given problem can be used without any translation into formulas, which are often of complex determination [13].

On the other hand, rules may be provided by experts or can be extracted from numerical data. In either case, engineering rules are expressed as a collection of «IF-THEN» statements. In general case, each rule contains one or clauses in the «IF» part of the rule, these clauses are known as the *antecedent*, and one (but potentially more than one) clause in the «THEN» part of rules, these clauses collectively are called the *consequent*.

The fuzzy inference engine combines rules into a mapping from fuzzy sets in the input space to fuzzy set in the output space based on fuzzy logic principles.

Defuzzification is the conversion of a fuzzy quantity to a precise quantity, just as fuzzification is the conversion of precise quantity to a fuzzy quantity. The output of a fuzzy process can be logical upon for two or more membership functions defined on the universe of discourse of the output variable. The output is also a fuzzy membership value that can be used either «raw» as qualitative assessment or defuzzified as a real number, compatible with nonfuzzy approaches [4, 5, 13–15].

2 Development Steps of the Expert System

The expert system should be designed and developed depending on the experience of experts. In this case, the procedure for developing the proposed expert system is divided into two main steps: Designing and Implementation. For each step, there is a list of procedures as shown in Table 1.

Table 1 – Scheme of damage assessment expert system [12]

Development of damage Assessment Expert System	Selecting Assessment Criteria (that indicate structural conditions)	The structural evaluation of building involves several criteria that should be considered. The criteria will be selected based on inspection results and previous records of regular inspections. They will be such basic items that can be inspected by close visual inspections and do not require special testing or long-term investigation.
	Estimating the Importance of Assessment Criteria	In the evaluation of any structure decisions must be made on the weighting to be given to the different observations and calculations relating to the strength and serviceability of individual members and to their effect on the overall structure.
	Designing of Damage Assessment Expert System	Development an expert system for condition evaluation that includes final state assessment of the building and recommended action. In this expert system, fuzzy sets used and knowledge representation tool.
Implementation State Assessment of Building	Collecting Information	Collection and evaluation of information through close visual inspection, document search, on-site non-destructive examination etc.
	Using Investigations and Inspection Records as Input data	Investigation and inspection records of the previous step used as input data of the expert system.
	Assessing the Structural State of the Building	State assessment of the building under consideration.

3 Selecting Assessment Criteria. Relations Between the Basic Variables

It should be noted that not always the excess of information results in a significant improvement of the input data obtained (additional uncertainty reduces the accuracy of estimation). Moreover, it can be uselessly time and finances consuming. As shown in [16] in the practical evaluation, one finds that the influence of the most basic variables is not as important as predicted. Therefore, a more rational approach which restricts the set of input data based on the criteria of simple availability and actual high relevance is suggested. For instance, one originally regards that the deflection increasing and resistance decreasing of each structural member will result in decreased safety in the existing structure as a whole. Resistance is generally satisfied by the specification requirements to materials in the design. Therefore, to simplify the evaluation process, some variables, such as the strength of materials and so on are neglected in the evaluation method. The basic variables utilized in the proposed expert system, are listed in Table 3. The inputs to the system are mostly linguistic variables and some numerical data concerning the selected categories for the assigned criterion. As rule, they extracted from reports of the building assessment. Traditionally, the state conditions for criteria constructed by extracting knowledge mainly from technical books and experts in the domain fields. In the case of the proposed model, the state conditions for criteria and the logic relationships between basis variables (the selected assessment criteria) have been obtained based on the results of the own investigations.

The relationship between the corrosion level of steel reinforcement and corrosion cracks width

As it was shown in the numerous publications [17–20] after corrosion initiation, hydrated rust accumulates around the bar, causing pressure and leading to cover cracking. To predict the damage caused by corroding reinforcing bars, knowledge of the state of stress in the surrounding concrete is required, and this can be determined to employ concrete ring or thick-wall cylinder, as it was proposed by most of the researchers, for example [21]. In the last decade, numerous models [18, 20, 22] for corrosion assessment was proposed. Based on the results of the own comparative study [23], the following expression for calculation of the corrosion crack width proposed by [22] has been adopted:

$$w_{cr(l)} = 0,05 + \beta \cdot \left(x - x_{cr}\right), \qquad (1)$$

where x is the penetration depth (µm);

x_{cr} is the critical penetration depth initiated longitudinal crack;

β is the empirical coefficient.

For calculation of the critical penetration depth the following empirical expression [17] has been chosen:

$$x_{cr} = 7,53 + 9,32\frac{c}{\varnothing}, \qquad (2)$$

where c is the concrete cover and $\varnothing$ is the bar diameter.

Figure 2 shows the results of the comparison of the theoretical crack width values $w_{cr(l)}$ obtained by the calculations with usage generalized model equation (3) and experimental data. Taking into account statistical uncertainties evaluated by EN 1990, Annex D (b = 0.34; V_δ = 50.9 %) expression equation (1) can be rewritten as:

$$w_{cr(l)} = k \cdot \left[0,05 + \beta \cdot \left(x - x_{cr}\right)\right]. \qquad (3)$$

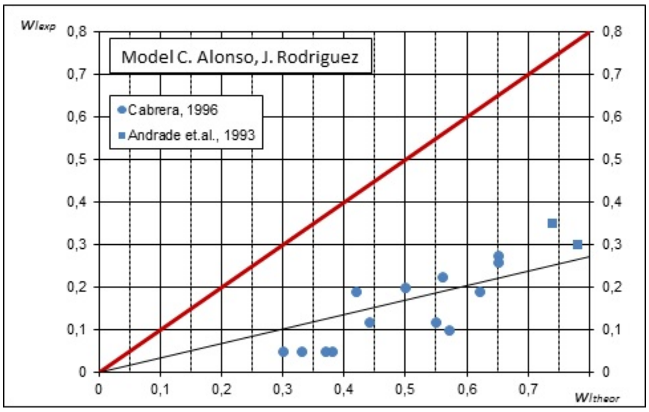


Figure 2 – Comparison of experimental and theoretical values of the corrosion longitudinal cracks width

The mass loss at a specified depth of corrosion damage propagation is calculated:

$$ML = \frac{r^2 - (r - x)^2}{r^2} \cdot 100\%, \qquad (4)$$

where r is the bar radius.

The relationships between corrosion level of steel, corrosion longitudinal crack width $w_{cr(l)}$ and flexural crack width w_k

The parametrical study of the concrete elements with corroded reinforcement for a wide range of combinations of the input variables (concrete compressive strength, ratio $c/\varnothing$, level of the corrosion damage of reinforcement) has been performed with the usage of the developed numerical resistance model and results of the parametrical study presented in detail [23].

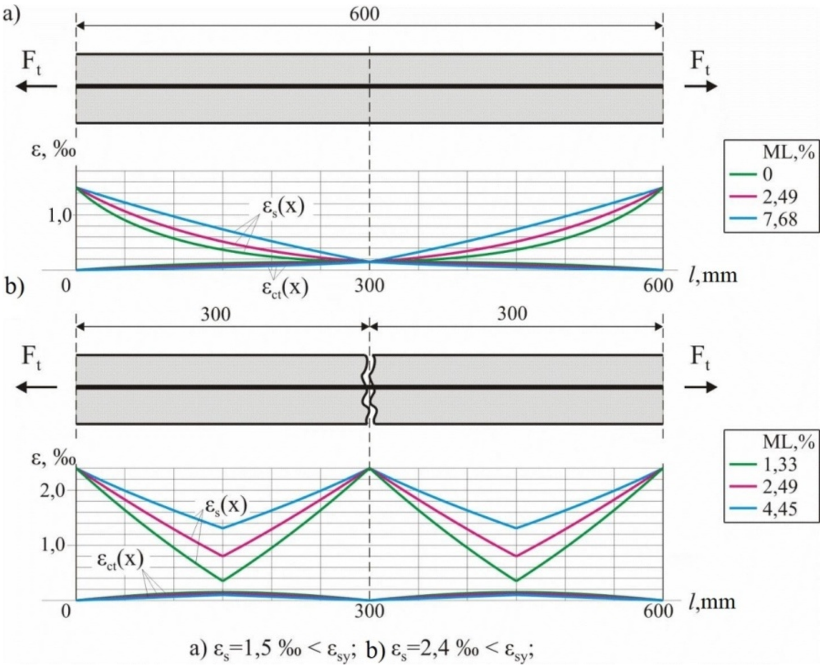


Figure 3 – The strain distributionsin concrete $\varepsilon_{ct}(x)$ and in reinforcement $\varepsilon_s(x)$ for the different level of corrosion damage and value $\varepsilon_s(0)$ = 1,5 ‰ in cracked section (exploitation stage) (in case f_{ck} = 20 MPa, $\varnothing$ 12 mm, $c/\varnothing = 3{,}5$)
(a) before cracking of the block; (b) stabilized cracking stage

Figure 3 shows an example of the characteristic strain distributions in concrete $\varepsilon_{ct}(x)$ and reinforcement $\varepsilon_s(x)$ for the different level of corrosion damage of the steel reinforcement (ML, %) and constant value of the steel strain in cracked section $\varepsilon_s(0)$ = 1,5 ‰ (for exploitation stage), which were obtained with the usage of developed resistance model [23]. Figure 4 shows the relationship between normal crack width (w_k) and level of corrosion damage (ML, %), and Figure 5 shows the relationship between flexural crack width (w_k) and longitudinal corrosion crack width (w_l) for different corrosion damage level (ML, %), what has been obtained in parametrical study [23] in case of listed input data. The red solid and dashed lines indicate the critical penetration depth which initiates a longitudinal crack.

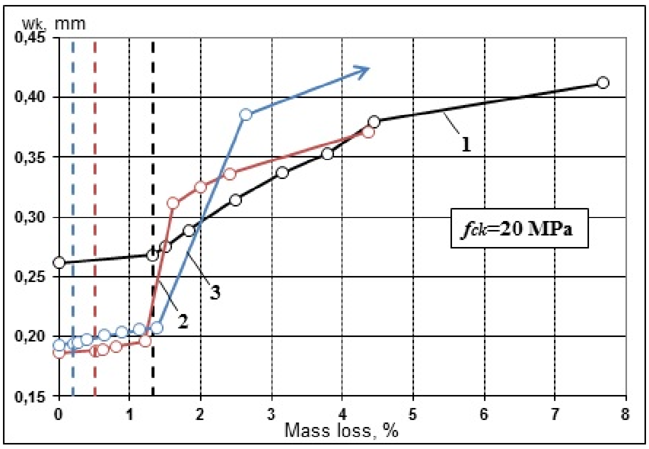


Figure 4 – The relationships between normal crack width (w_k) and corrosion damage level (ML, %) (in case f_{ck} = 20 MPa)
1 – $\varnothing$ 12 mm; 2 – $\varnothing$ 20 mm; 3 – $\varnothing$ 32 mm

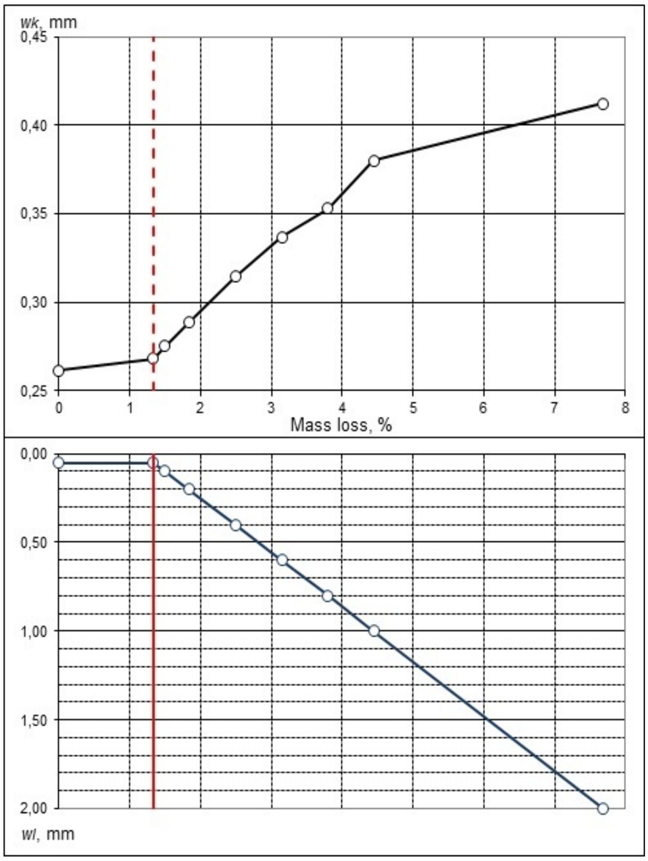


Figure 5 – The relationship between normal crack width (w_k) and longitudinal crack width (w_l) for different corrosion damage level (ML, %) (in case f_{ck} = 20 MPa, $\varnothing$ 12 mm, $c/\varnothing = 3{,}5$)

The relationship between deflection (a/L_0) and flexural crack width (w_k).

Based on results of the investigation [23] performed with the usage of the simplified numerical resistance model (as shown in Figure 6), the following relationship between relative deflection (a/L_0) and flexural crack width (w_k) has been developed:

$$\frac{a}{L_0} = \alpha_0 \cdot \frac{w_m}{(1-\beta_0)\cdot 300} \cdot \delta \,, \tag{5}$$

where β_0 is the coefficient calculated from expression:

$$\beta_0 = \alpha_e \rho_l \left(\sqrt{1 + \frac{2}{\alpha_e \rho_l}} - 1 \right), \tag{6}$$

α_0 is the coefficient accounting boarding (support) conditions;

L_0 is the effective span; wm is the average normal crack width [mm];

ρ_l is the reinforcement ratio $\rho_l = \frac{A_s}{b \cdot d}$;

α_e is the modular ratio $\alpha_e = \frac{E_s}{E_{cm}}$;

$\delta = \frac{L_0}{d}$ is the ratio effective span to the effective depth of the section.

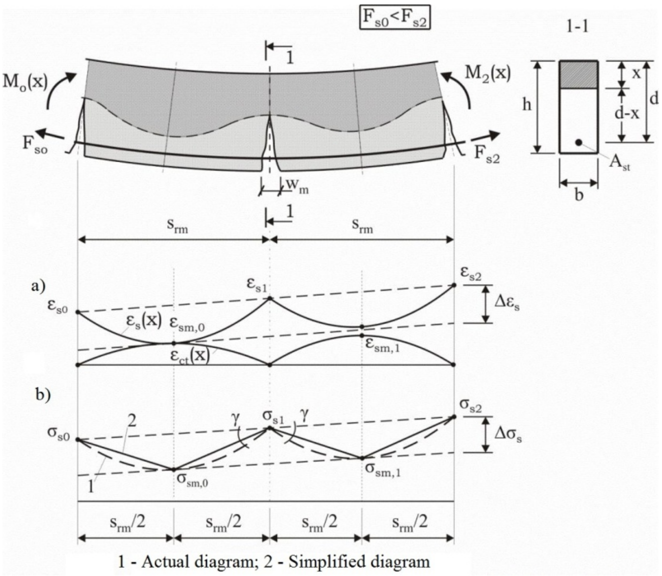


Figure 6 – The strain distributions in concrete and reinforcement (a) and stresses distribution in reinforcement (b) along the block between adjacent cracks

The proposed expression equation (5) was verified based on the experimental database [24] and compared with the calculation model proposed by [24]. The obtained comparison results are shown in Figure 7 and listed in Table 2. As can be seen from Figure 7 and Table 2 the calculation results obtained using the proposed relationship equation (5) have a good agreement with experimental data. Figure 8 shows the relationship between the relative deflection (a/L_0) and normal crack width (w_k) obtained based on the proposed expression equation (5) in the case study [23].

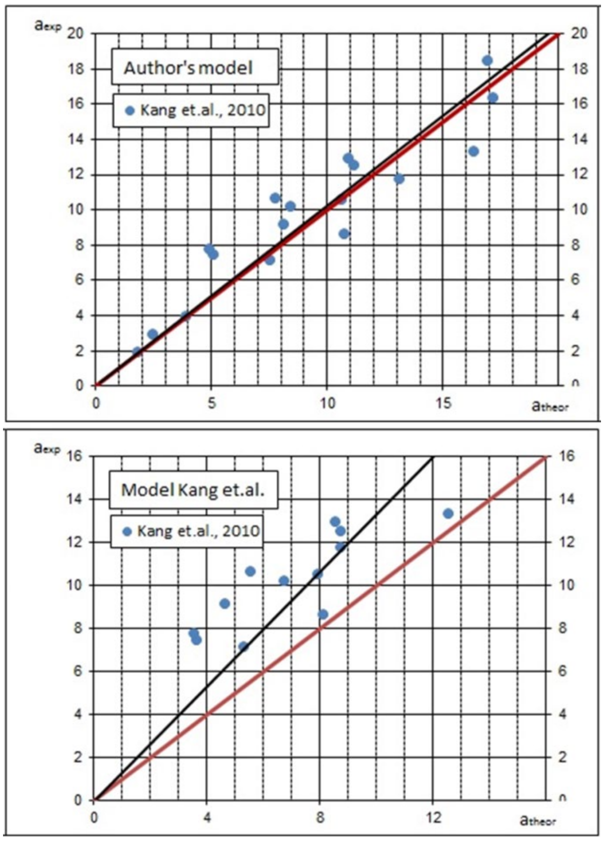


Figure 7 – Comparison of the experimental and theoretical values of the deflection

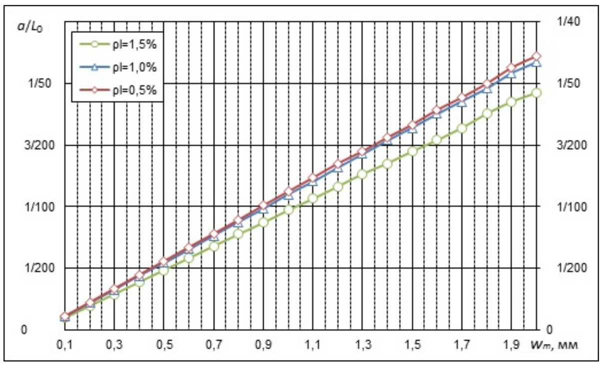
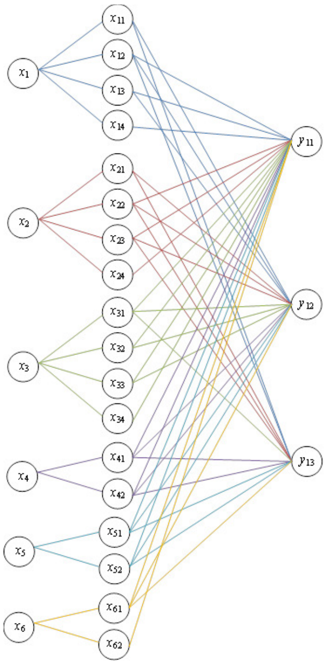


Figure 8 – The relationship between the relative deflection (a/L_0) and normal crack width (w_k) obtained based on the proposed expression (5)

Table 2 – Comparison of the statistical parameters

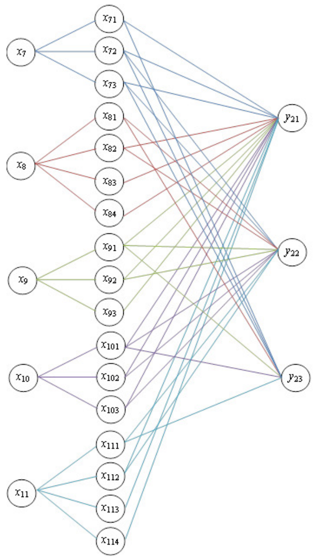
Model	The statistical evaluation of the model error	
	b	V_δ, %
Author's model	1.02	19.2
Model Kang et al. [24]	1.34	24.3

The relationships of the evaluation factors (basic variables) in existing structures, which was obtained based on the classification and established domains $x[0, x_u]$ for each basic variables stated above are shown in Figures 9–11.



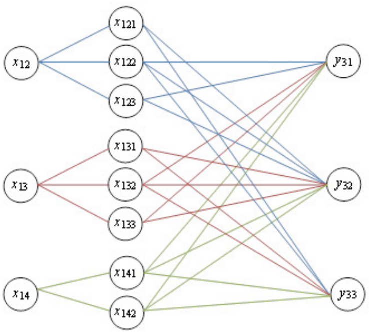
Basic variable	Level	Linguistic	Range
x_1	x_{11}	no	0
	x_{12}	single	0.5-10 %
	x_{13}	numerous	10-40 %
	x_{14}	massive	>40 %
x_2	x_{21}	no	
	x_{22}	mid-span	
	x_{23}	near support	
	x_{24}	mid-span+ near support	
x_3	x_{31}	no	0
	x_{32}	local	0.5-10 %
	x_{33}	partial	10-40 %
	x_{34}	solid	>40 %
x_4	x_{41}	no	
	x_{42}	yes	
x_5	x_{51}	no	
	x_{52}	yes	
x_6	x_{61}	no	
	x_{62}	yes	

Figure 9 – Relationship between basic variables: Phase A: Visual Inspection (A-1)



Basic variable	Level	Linguistic	Range
x_7	x_{71}	small	<1
	x_{72}	mean	1-3
	x_{73}	large	>3
x_8	x_{81}	small	no more 0.05 mm
	x_{82}	permissible	from 0.05 to 0.4 mm
	x_{83}	exceeded	from 0.4 to 1 mm
	x_{84}	excessive	more 1 mm
x_9	x_{91}	small	no more 0.05 mm
	x_{92}	medium	from 0.05 to 1 mm
	x_{93}	large	more 1 mm
x_{10}	x_{101}	small	no more 1 %
	x_{102}	mean	from 1 to 3 %
	x_{103}	large	more 3 %
x_{11}	x_{111}	small	no more 1/900
	x_{112}	permissible	from 1/900 to 1/250
	x_{113}	exceeded	from 1/250 to 1/50
	x_{114}	excessive	more 1/50

Figure 10 – Relationship between basic variables: Phase A: Basic Testing (A-2)



Variable	Level	Linguistic
x_{11}	x_{111}	critical
	x_{112}	significant
	x_{113}	minor
x_{12}	x_{121}	critical
	x_{122}	significant
	x_{123}	minor
x_{13}	x_{131}	no
	x_{132}	yes

Figure 11 – Relationship between basic variables: Phase A: Damage Class

4 Realization of the Fuzzy production algorithm in MatLab Software [25]

Step 1: Fuzzification – Input Fuzzy. At this stage, the membership functions for term-sets of input and output linguistic variables are adopted. The most commonly used membership functions are the trapezoidal and triangular one, that will be indeed the functions adopted in the proposed fuzzy algorithm.

Step 2: Setting Fuzzy Rules. This is now to need to combine these elements each with the other, to obtain the desired final diagnosis of the existing structures. This performed by introducing proper «fuzzy rules», relating the input data with the final output variable.

Step 3: Aggregation is the process by which the fuzzy set that represents the outputs of each rule are combined into a single fuzzy set.

Step 4: Activation. A fuzzy «IF-THEN» rule is a connection of two (compound) fuzzy propositions.

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 are fuzzy sets of recommended output values.

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.

5 Implementation of the Fuzzy Algorithm

The starting point, as it has pointed out in ISO 13822, ISO 2394, 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 protocol form.

As an example of the implementation of the proposed expert system results of the assessment of the existing building with load-bearing precast concrete elements and masonry walls is presented.

Structures description. A main load-bearing element is precast reinforced concrete beam with following geometrical parameters: T-section with height 450 mm, web width 120 mm, flange width 200 mm and length of the span 6 m. Longitudinal main reinforcement is 2$\varnothing$22 B400, concrete cover 22 mm (ratio $c/\varnothing = 1$). Precast ribbed slabs have the size in plane 1.5x6 m and height of the rib 300 mm. Longitudinal main reinforcement is $\varnothing$16 B400, concrete cover 32 mm (ratio $c/\varnothing = 2$). Figure 12 shows the characteristic defects and deterioration of the structural elements.

The evaluation factor scores obtained as results of the Visual Inspection and Basic Testing for reinforced structures are listed in the diagnostic protocol (Table 3).

Figure 12 – Characteristic defects of the evaluated precast beam and ribbed slabs

Table 3 – The input data collection (diagnostic protocol example)

Phase A: Visual Inspection (A–1)				
Structural Member	**Precast beam**			
General Description	T-section with height 450 mm, web width 120 mm, flange width 200 mm and with 6 m span			
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			*35 %*	
Position of the flexural (bending)/shear cracks, x_2	Parameter: position in span			
	no	**mid-span**	**near support**	**mid-span+near support**
	0	1	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	×			
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]	450		
	Concrete cover, *c* [mm]	22		
	Diameter of steel bar, Ø [mm]	22		
Concrete				
Ratio $c/\varnothing$ (concrete cover/diameter), x_7	Parameter: $c/\varnothing$			
	small	**mean**	**large**	
	<1	1–3	>3	
Inspection results		*1*		
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	*0*			
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	*0*			
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			*1/120*	
Damage Level	***1 (critical)***			

Table 4 presents the results of the assessment of building under examination using the proposed algorithm, which has been realized by Fuzzy Logic *MatLab* Toolbox. As can be seen from Table 4, obtained estimates comply with the estimation formulated by the highly qualified experts.

Table 4 – Results of the assessment

The structural element	Results of the assessment	
	proposed fuzzy algorithm	highly qualified experts report
Precast beams	Severe damage	Severe damage
Precast ribbed slabs	Severe damage	Severe damage

6 Conclusions

In this study, an effective structural assessment expert system for evaluation of the existing reinforced concrete buildings using Fuzzy Logic *MatLab* Toolbox was developed and verified on the existing buildings, to assess, in a more objective and reliable way, the real state conditions of the building under examination. It was shown that obtained estimates are in good agreement and compliance with the estimations formulated by the highly qualified experts.

Although the presented expert system based on close visual inspections and simple measurements (Phase an investigation), nevertheless, it may provide substantial assistance to more complicated assessment (for example, evaluation of existing structures based on detailed investigations Phase B).

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References

1. Hitchcock Becker, H. Transformative architecture for the shrinking city / H. Hitchcock Becker // ARCC Conference Repository. – 2014. – P. 49–55.
2. Mezzina, M. Decisional trees and fuzzy logic in the structural safety assessment of damaged R.C. buildings / M. Mezzina, G. Uva, R. Greco // 13th World Conference on Earthquake Engineering. – Vancouver, 2004. – P. 149–159.
3. New European Technical rules for the Assessment and Retrofitting of Existing Structures / P. Luechinger [et al.] ; ed.: S. Dimova [et al.] ; European Commission EUR 27128 EN. – Luxembourg : Publications Office of the European Union, 2015. – 125 p.
4. Carbone, V. I. Structural safety evaluation by means of fuzzy-probabilistic approach / V. I. Carbone, G. Mancini, F. Tondolo // Proceedings of the 29th Conference on Our World in Concrete & Structures. – Singapore, 2004. – P. 29–37.
5. Zadeh, L. A. Fuzzy sets / L. A. Zadeh // Information and Control. – 1965. – Vol. 8, iss. 3. – P. 338–353.
6. Pakdamar, F. Fuzzy logic approach in the performance evaluation of reinforced concrete structures (flexible performance) / F. Pakdamar, K. Güler // 14th World Conference on Earthquake Engineering. – Beijing, 2008. – 8 p.
7. Badiru, A. Fuzzy engineering expert systems with neural network applications. // A. Badiru, J. Cheung. – New York : John Wiley&Sons, 2002. – 291 p.
8. Serviceability analysis of concrete beams with different arrangements of GFRP bars in the tensile zone / R. Jakubovskis [et al.] // American Society of Civil Engineers. – 2014. – No. 18. – P. 1–10.
9. Mendel, J. M. Fuzzy logic systems for engineering: A tutorial / J. M. Mendel // Proceedings of the IEEE. – 1995. – Vol. 83, iss. 3. – 36 p.
10. Ross, T. J. Fuzzy logic with engineering applications / T. J. Ross. – New York : John Wiley&Sons, 2004. – 652 p.
11. Wang, L. A course in fuzzy systems and control / L. Wang. – New Jersy : Prentice Hall, 1997. – 220 p.
12. Khader, M. Hamdia Expert system for structural evaluation of reinforced concrete buildings in Gaza Strip using Fuzzy Logic : Master thesis / M. Khader ; Islamic University of Gaza. – Gaza Strip, 2010. – 92 p.
13. A reliable visual inspection method for vulnerability assessment of hyperstatic structures using fuzzy logic analysis / M. V. Piras [et al.] // Journal of Construction Engineering. – 2015. – 15 p.
14. Blockley, D. I. Predicting the likelihood of structural accidents / D. I. Blockley // Proceedings. Part 2. Research and Theory. – 1975. – Vol. 59, iss. 2. – P. 659–668.
15. Lefteri, H. T. Fuzzy and neural approaches in engineering / H. T. Lefteri, E. U. Robert. – New York : John Wiley&Sons, 1997. – 600 p.
16. Analytical model for the bond-slip behavior of corroded ribbed reinforcement / K. Lundgren [et al.] // Structure and Infrastructure Engineering. – 2012. – Vol. 8, iss. 2. – P. 157–169.
17. Factors controlling cracking of concrete affected by reinforcement corrosion / C. Alonso [et al.] // Materials and Structures. – 1998. – Vol. 31. – P. 435–441.
18. Coronelli, D. Corrosion cracking and bond strength modeling for corroded bars in reinforced concrete / D. Coronelli // ACI Structural Journal. – 2002. – Vol. 99, iss. 3. – P. 267–276.
19. Mak, M. W. T. Corrosion-induced cracking and bond strength in reinforced concrete / M. W. T. Mak, P. Desnerck, J. M. Lees // Construction and Building Materials. – 2019. – Vol. 208. – P. 228–241.
20. Webster, M. P. The assessment of corrosion-damaged concrete structures : PhD thesis / M. P. Webster ; University of Birmingham. – Birmingham, 2000. – 318 p.
21. Balafas, I. Modeling the structural effects of rust in concrete cover / I. Balafas, C. J. Burgoyne // Journal of Engineering Mechanics. – 2011. – Vol. 120, iss. 1. – P. 175–185.
22. Rodriguez, J. Corrosion of reinforcing bars and service life of reinforced concrete structures: Corrosion and bond deterioration / J. Rodriguez, L. M. Ortega, J. Casal // Int. Conf. on Concrete across Borders. – Odense, 1994. – Vol. II. – P. 315–326.
23. Tur, V. V. Influence of the reinforcing bar corrosion level on the flexural crack's width in the existing structure / V. V. Tur, Y. S. Dardziuk // Modern Engineering. – 2019. – Vol. 1. – P. 1–9.
24. Correlation between crack widths and deflection in reinforced concrete Beams / J. O. Kang [et al.] // Journal of the Korea institute for structural maintenance and inspection. – 2010. – Vol. 14. – P. 184–192.
25. Tur, V. V. Quantification procedure of the existing reinforced concrete structures based on fuzzy logic / V. V. Tur, Y. S. Dardziuk // Vestnik of Brest State Technical University. – 2022. – No. 3. – P. 16–19.

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