Fuzzy reasoning in condition assessment of side corridor structures

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Abstract—**The continuous maintenance of the old residential building stock and the completion of the necessary renovation works is a significant task from economic point of view, as many people still live in old residential buildings today. Therefore, it is strategically important to qualify the load bearing structures of residential buildings and apply decision support system based on various priority aspects. We have developed a method that evaluates the condition of side corridor structures based on the observed damages detected by building diagnostics (e.g. cracks, corrosion, humidity, abrasion). Value of side corridor condition is calculated by fuzzy signatures. In these signatures, Fuzzy Inference System-like Aggregation Operator (FISAO) and Weighted Relevance Aggregation Operator (WRAO) is used with State Dependent Dynamic Weighting (SDDW). The results of our study can be efficiently used during the renewal of side corridor structures.**

Keywords— decision support system; building diagnostics; side corridor structure; fuzzy signatures; fuzzy sets; condition assessment; aggregation operator

I. Introduction

Maintenance of the existing residential building stock and carrying out the necessary renovations is a worldwide important national strategy. In Hungary, the issue of keeping the old housing stock in good condition is particularly actual, as - especially in Budapest - there are still many residential properties built in the first half of the 20th century - or even earlier. It is significant to assess the condition of these buildings, which is a prerequisite for making the right decision about which buildings (and within that which load bearing structures) to renovate or strengthen.

The knowledge of the condition of the structures to be renovated and the choice of the optimal reinforcement method is very important from a safety point of view, but it also affects the economy, the aesthetics and the well-being of the people living in it. Therefore, it is important to have condition assessment and decision support methods that allow us to make a reliable and uniform decision about the future of buildings.

The ultimate goal of the research is to develop a condition assessment and decision support method that evaluates all important load-bearing structures of old (late 19th or early 20th century) residential buildings and, if necessary, suggests the extent and method of ideal renovation.

We have previously carried out research to determine the condition of the supporting structures of old residential buildings [1] [2] [3], and we will also use the results and conclusions in the development of the new decision support method. In the current phase of the research, we are developing a method to support the condition assessment of side corridor structures.

In this case the two-valued logic is unsuitable for modelling the given phenomenon because in most cases of the linguistic characteristics of this type there is a well noticeable joint element, which express a kind of inaccuracy or uncertainty. One good solution to this problem is to use fuzzy signatures, so we use this method to determine the condition of the side corridors. Successful applications like this can be found elsewhere in the literature [4].

II. Fuzzy logic, fuzzy signatures

Fuzzy logic (fuzzy set theory) as the generalization of multi-valued logical systems was introduced in 1965 by L. A. Zadeh [5]. Fuzzy sets are such classes of objects with continuous membership values from 0 to 1. Comparing to Boolean algebra of sets, 0 means that the object is not an element of the set and 1 means full membership (NO and YES in Boolean logical system). Fuzzy sets are given by their membership functions, according to the membership values (μ) of the elements.

As the membership value of an element in a fuzzy set can be infinitely many (in the range 0-1), also fuzzy set operations can be implemented by infinitely many functions. Certainly, these functions must fulfil the axiomatic needs for each operation. The most common ones were proposed by Zadeh, minimum for fuzzy intersection, maximum for fuzzy union and 1- μ for fuzzy complement (Fig. 1).

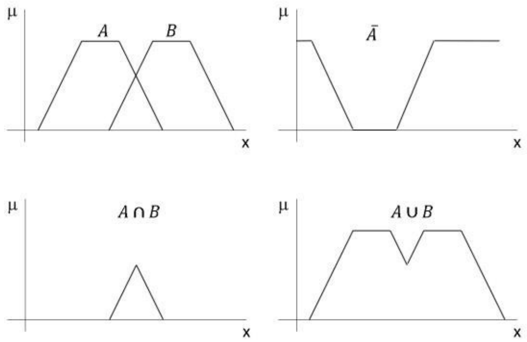

Fig. 1. Fuzzy set operations by Zadeh's operators.

The use of continuous membership values and fuzzy set operators make easy formalization of complex logical connections worded in human language possible. Using fuzzy logic, rule bases containing IF-THEN rules can be mathematically easily described. Besides logical connections, (AND, OR) these rules contain linguistic variables. Actual values of linguistic variables are calculated as the membership values of the input data in the relevant sets. According to applied fuzzy set operators, there are more different applications (called fuzzy inference systems). One of the most used is Mamdani's inference system, where logical operators are represented by Zadeh's set operators (min() for AND and max() for OR) [6]. As an example, (1) gives the mathematical formula of the two-dimensional rule base

R1: If A_1 and B_1 then C_1

R2: If A_2 and B_2 then C_2

$$C = \max\Big(\min\big(\mu_{A_1}(x_1), \mu_{B_1}(x_2)\big), \min\big(\mu_{A_2}(x_1), \mu_{B_2}(x_2)\big)\Big), \quad (1)$$

where A, B and C are fuzzy sets and x_1 and x_2 are the observed values of the input dimensions.

The result C is also a fuzzy set, for direct use it must be defuzzified. Defuzzification is a process to calculate crisp values that are characteristic to the corresponding fuzzy sets. Most known procedures are the mean of maxima and the centroid defuzzifications. Mean of maxima (MOM) gives the mean of the supremum of C while centroid returns the x coordinate of the gravitation center of C.

Fuzzy inference systems are successfully used in decision-making or evaluation applications, and are able to handle even complex, but logically described problems. However, in particular cases their use is not necessary. If the observed system is well-known, status checks can be performed by more simple fuzzy models, e.g., by fuzzy signatures.

Fuzzy signatures were introduced as the generalization of vector valued fuzzy sets by Kóczy et al. in 1999 [7]. Vector valued fuzzy sets are collection of fuzzy values (2).

$$\nu = \left[\mu_1, \mu_2, \mu_3, \ldots, \mu_n\right] \quad (2)$$

Fuzzy signatures are such nested fuzzy vectors, where the elements themselves may be further fuzzy vectors (3).

$$s = \left[\nu_1, \mu_2, \nu_3, \ldots, \mu_n\right] = \left[\left[\mu_{11}, \mu_{12}, \ldots, \mu_{1m}\right], \mu_2, \left[\mu_{31}, \mu_{32}, \ldots, \mu_{3o}\right], \ldots, \mu_n\right] \quad (3)$$

visual representations as tree structures are clearer (Fig. 2).

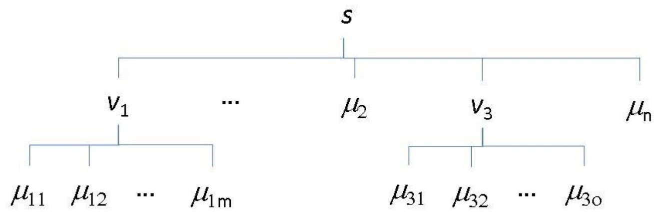

Fig. 2. Fuzzy signature as a tree structure. The root of the signature is denoted by s. As they have further sub-structures, ν_s are called branches, while μ_s, as lowest elements, are called leaves.

III. BASIC STRUCTURE OF FUZZY SIGNATURES

At this stage of the research, we are investigating the side corridors with stone plate and steel cantilever.

As the basic structure a three-level fuzzy signature was applied, because in the course of the inspection of the side corridors this depth was considered necessary to achieve appropriate accuracy in defining the condition.

The information available about the condition of the side corridor structure of the buildings, providing the basis for the database, was divided into three main groups (condition of steel cantilever, condition of stone plate, condition of balustrade). Further levels of the structure and the whole set-up of the fuzzy signature in tree-structure format are presented in Fig 3. The symbols in the figure are as follows: μ_0: condition of side corridor, μ_1: condition of steel cantilever, μ_2: condition of stone plate, μ_3: condition of balustrade, μ_{11}: corrosion inspection, μ_{12}: load bearing surplus, μ_{13}: cantilever anchoring, μ_{21}: load bearing surplus, μ_{22}: crack inspection, μ_{23}: strength test, μ_{24}: stability inspection, μ_{25}: damage inspection, μ_{26}: humidity inspection, μ_{27}: abrasion inspection, μ_{31}: surface protection inspection, μ_{32}: damage inspection, μ_{33}: anchorage inspection, μ_{34}: stability inspection, μ_{35}: corrosion inspection,

μ_{111}: corrosion at the fixed support, μ_{112}: corrosion away from fixed support, μ_{131}: fixed support depth, μ_{132}: wall structure inspection at the cantilever, μ_{133}: rotation inspection, μ_{221}: transverse crack, μ_{222}: longitudinal crack, μ_{223}: crack parallel to the slab of the plate, μ_{224}: cobweb-like surface crack, μ_{225}: crack around balustrade fastening, μ_{241}: eccentricity inspection, μ_{242}: support length inspection, μ_{251}: damage in the middle of the plate, μ_{252}: damage on the edge of the plate, μ_{261}: slope of the side corridor, μ_{262}: dripping edge, WRAO: Weighted Relevance Aggregation Operator, SDDW: State Dependent Dynamic Weighting, FISAO: Fuzzy Inference System-like Aggregation Operator.

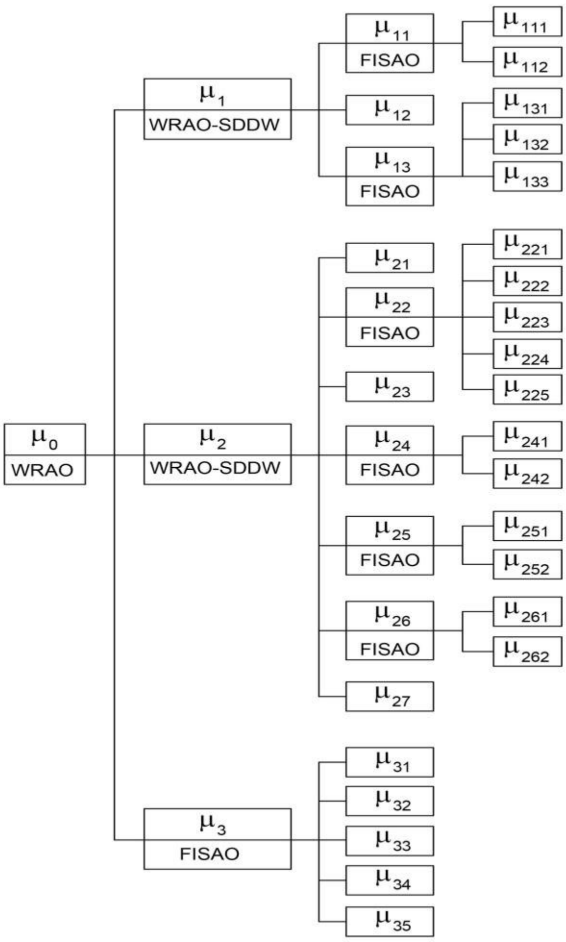

Fig. 3. Set of fuzzy signature structure in tree structure format.

IV. Applied Aggregation Operators

Leaves of the signatures are aggregated by Fuzzy Inference System-like Aggregation Operator (FISAO). FISAO operates on the basis of the logical relationships between the input properties of the sub-systems of the side corridor. In our work, Mamdani's method and centroid defuzzification are used for FISAO calculations, resulting the core of the output fuzzy set of that rule which fires the most. As the rule bases belonging to different branches are different, the FISAO calculations are different as well.

As an example, 3 rows of the rule base used to determine the degree of corrosion are shown, Cor(1) stands for the value of corrosion at the fixed support, cor(2) stands for the value of corrosion away from fixed support and cor stands for the value of corrosion.

Rc1: If cor(1) is no significant corrosion and cor(2) is no significant corrosion than cor is very good

Rc2: If cor(1) is no significant corrosion and cor(2) is moderately corrosion than cor is good

Rc6: If cor(1) is moderately corrosion and cor(2) is large scale corrosion than cor is bad

At higher nodes (branches) Weighted Relevance Aggregation Operator (WRAO) is used. Calculation of WRAO is performed by (4) [9]

$$@(x_1, x_2, \ldots, x_n; w_1, w_2, \ldots w_n) = \left(\frac{1}{n}\sum_{i=1}^{n}(x_i w_i)^p\right)^{\frac{1}{p}}, \quad (4)$$

where $x_1, \ldots, x_n$ are values of the nodes in the signature, $w_1, \ldots, w_n$ are weights of the nodes and p is the aggregation factor (in this work, p=1).

We use dynamically changing weights which depends on the input state (SDDW). In case of steel cantilever condition assessment (scl) (5) is used.

$$scl = \frac{\alpha_{cor} \cdot \kappa \cdot cor + \alpha_{cla} \cdot cla}{\alpha_{cor} \cdot \kappa + \alpha_{cla}}, \quad (5)$$

where α_{cor} is the base weight of the corrosion, κ is a modifying factor, cor stands for the value of corrosion and cla for the state of cantilever anchoring. κ is defined by the following rules

Rk1: If cor is medium or better and load bearing surplus (lbs) is moderately oversized than k=1.1

Rk2: If cor is medium or better and lbs is oversized to a large extend than k=1.2

Rk3: If cor is bad or worse and lbs is slightly oversized than k=0.9

Rk4: If lbs is undersized than scl=0

Rk5: Otherwise, k=1

V. Construction of the Fuzzy Sets

The condition of the three main structural units of the side corridor structure (steel cantilever, stone plate, balustrade) is also determined separately. For each structural unit, we examine the types of damage that may occur and the inspections that should be performed to determine these. We primarily use visual building diagnostic inspections, but in some cases instrumental tests are also possible. The results of each inspection are entered into the system using fuzzy sets.

As an example, the corrosion inspection of a steel cantilever and the determination of the load-bearing surplus of the steel cantilever and their fuzzy sets are presented. The reduction in the load-bearing capacity of the steel cantilever and thus its quality is influenced not only by the degree of corrosion, but also by the location of the corrosion damage within the cantilever beam. Because the cantilever has maximum stresses (bending moment, shear force) at the anchoring, corrosion damage at the cantilever anchoring is more dangerous than farther away. Therefore, in a fuzzy condition assessment system, the condition of the steel cantilever is affected not only by the degree of corrosion damage but also by the location of the damage. As an example, the fuzzy set describing the degree of corrosion in the environment of the steel cantilever anchoring is shown in Fig 4.

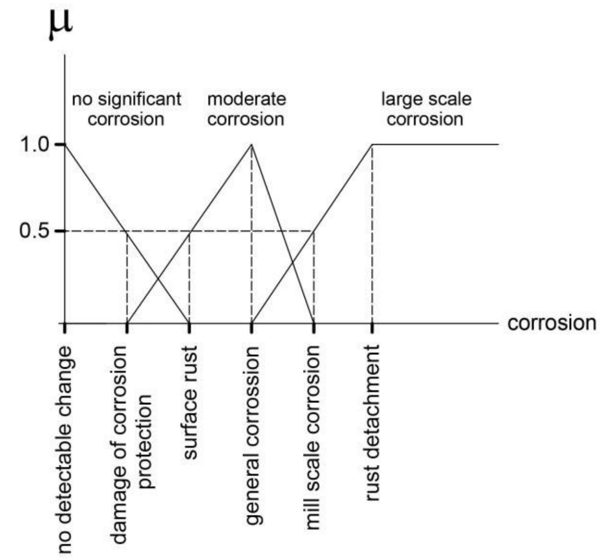

Fig. 4. Fuzzy sets of corrosion of cantilever

The extent of the reduction of load-bearing capacity of a steel cantilever depends not only on the magnitude and location of the corrosion, but also on the extent to which the steel cantilever was oversized during construction.

To do this, we need to know the load-bearing surplus of the steel cantilever. We need to identify the section of the steel cantilever, which is usually clearly identifiable based on the width of the lower flange of the I-section (this can be easily measured on site). We collected which other input data was needed to calculate the load-bearing surplus in the steel cantilever and found that based on some easily available data (e.g., width of side corridor, distance between cantilevers), the degree of oversizing can be calculated.

The degree of oversizing can be characterized by the fuzzy set shown in Fig 5. The amount of the load-bearing surplus affects the condition of the side corridor. It also affects the extent to which certain damages (e.g., corrosion) reduce the quality of the side corridor.

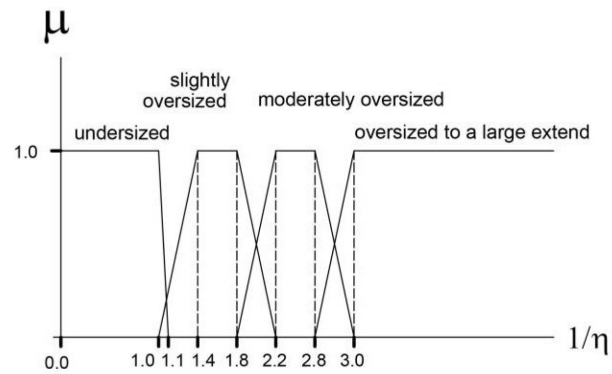

Fig. 5. Fuzzy sets of load bearing surplus

VI. Testing the Model

The condition of the side corridors of three residential buildings built in the early 20th century was examined, using the developed method.

The first examined side corridor is in good condition (numerical result of the condition assessment: 0.70). The second side corridor is in medium condition (0.62), while the third side corridor is also in medium condition (0.47). The side corridor of the 3 buildings was also examined by experts and the condition of the structures was assessed linguistically.

The expert evaluation and the evaluation of the fuzzy signature-based system were the same for all side corridors. Further tests will be conducted during the research.

VII. Summary

A new condition assessment and decision support method was developed in order to be able to compare the condition results of individual buildings on the basis of a unified set of criteria and to provide assistance in decision support for the renovation of building structures.

The fuzzy signature-based condition assessment system is well applicable for side corridors. The use of the Fuzzy Inference System-like Aggregation Operator (FISAO) and the Weighted Relevance Aggregation Operator (WRAO) used with State Dependent Dynamic Weighting (SDDW) allows a sophisticated assessment.

As the next step of the research, the model will be further developed so that it can be used for side corridors of different structural systems and materials. The ultimate goal is to create a complete system that evaluates the condition of the entire building and makes a proposal for the selection of optimal renovation methods.

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