Nominal Cover Thickness Design of RC Quantitatively Considering Environment Condition by Means of Fuzzy Inference System

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Abstract
This article involves designing the Nominal cover thickness by means of fuzzy inference system (FIS) for quantitatively representing the environment load coefficient to reinforced concrete in corrosive environment. In this work, several variables defining the quality of concrete and environment condition, viz. environment load coefficient (ELC), were treated as fuzzy variables. To qualify ELC the environment conditions of cycle degree of wet-dry, relative humidity, distance from coast and temperature were used as input variables. To determine the Nominal cover thickness a qualified ELC, concrete grade, and water-cement ratio were used. The membership functions of each fuzzy variable were generated from the engineering knowledge based on some references as well as some international codes of practice.

The restraining conditions of this work are as follows;
1. The knowledge bases for generating the rule base of fuzzy inference system are derived just from some references as well as BS 8110 and BS EN 206-1/BS 8500.
2. The procedure of this study is applicable only to the corrosive environments.
3. It is limited to the cover to reinforcement for normal building structures with an intended service life of at least 50 years.

Keywords: nominal cover thickness; fuzzy logic; durability design; fuzzy inference system; performance-based design

1. Introduction
The design of RC structure can be divided into strength-based structure design and durability-based performance design. The former is what is based on the structural and mechanical safety of all structure members and frames while the latter involves service life of the structure. Normally, the prediction of service life is closely involved in the corrosion rate of reinforcement steel bar embedded in concrete. Therefore, most of the durability-based designs of RC are carried out from the standpoint of economically ensuring as sufficient cover thickness as capable of compensating performance-reducing factor which stem from the boundary condition such as site condition, environment condition etc. within planned service life.

According to cement and concrete terminology reported by ACI Committee 116, two technical terminology of durability and durability factor are defined as the ability of concrete to resist weathering action, chemical attack, abrasion, and other conditions of service and as a measure of the change in a material property over a period of time as a response to environment and to an influence that can cause deterioration, usually expressed as percentage of the value of the property before environment, respectively.

Thus, as a definition of the terminology, among other factors, service life of a structural member regarding corrosion of reinforcement rely upon the environment condition and the type and quality of concrete used. In most of the international codes of practice, environment conditions tend to be exhibited in a general and qualitative manner. This gives rise to ambiguity in the selection of the type of environment condition for a structure member required in the durability-based design. Also, there are uncertainties in the actual values of grade of concrete, water-cement ratio, cover thickness used in the construction. These uncertainties and ambiguities stem from the use of linguistic terms for defining the environment conditions and quality of construction. While there are several techniques for treating the linguistic uncertainties arising from randomness, imprecision, vagueness, ambiguity etc., fuzzy sets are commonly used for handling uncertainties associated with linguistic concepts.

The limitation of this study is as follows;
(1) The procedure of this work is applicable only to the corrosive environments (such as coastal
(2) The knowledge bases for generating the rule base of fuzzy inference system (FIS) are derived just from some references as well as BS 8110 and BS EN 206-1/BS 8500.

(3) It is limited to the cover to reinforcement for normal building structures with an intended service life of at least 50 years as specified in BS EN 206-1/BS 8500.

The purpose of this work is to design nominal cover thickness quantitatively treating environment condition and construction grade by means of the proposed methodology of the fuzzy logic. User-friendly graphic interface design is the additive benefits from this work.

2. Simple overview of fuzzy logic
2.1 Fuzzy inference system (FIS)
Fuzzy logic is a method of rule-based making used for expert systems and process control that emulates the rule-of-thumb thought process used by human beings. The basis of fuzzy logic is fuzzy set theory which was developed by Lotfi Zadeh in the 1960s. Fuzzy set theory differs from traditional Boolean (or two-valued) set theory in that partial membership in a set is allowed. A linguistic term can be defined quantitatively by a type of fuzzy set known as a membership function. The membership function specifically defines degrees of membership functions defined for expert system inputs and outputs, you can formulate a rule base of IF-THEN type conditional rules. Such a rule base and the corresponding membership functions are employed to analyze inputs and determine outputs by the process of fuzzy logic inference.

2.2 Applications of linguistic variables
Fuzzy logic is primarily concerned with quantifying and reasoning about vague or fuzzy terms that appear in out natural language. In fuzzy logic, these fuzzy terms are referred to as linguistic variables. The concept of a fuzzy number plays a fundamental role in formulating quantitative fuzzy variables. These are variables whose states are fuzzy numbers. When, in addition, the fuzzy numbers represent linguistic concepts, such as very small, small, medium, and so on, as interpreted in a particular context, the resulting constructs are usually called linguistic variables.

Each linguistic variable the states of which are expressed by linguistic terms interpreted as specific fuzzy numbers is defined in terms of a base variable, the values of which are real numbers within a specific range. A base variable is a variable in the classical sense, exemplified by any physical variables (e.g., temperature, pressure, humidity, etc.) as well as any other numerical variable, (e.g., age, performance, probability, reliability, etc.). In a linguistic variable, linguistic terms representing approximate values of a base variable, pertinent to a particular application, are captured by appropriate fuzzy numbers.

3. Cover thickness design by FIS
3.1 Durability design concept in this work
In making durability design, as mentioned above, there is a need to take into consideration the actual environmental conditions to be experienced by the structure. Thus environmental load coefficient dependent on the environmental condition is first determined. Second, concrete grade and water-cement ratio is selected by the reference of BS EN 206-1/BS 8500. Finally, based on the ELC and the determined concrete grade and water-cement ratio, Nominal cover thickness is determined.

3.2 Definition of the problem and system structure
Corrosion durability of a reinforced concrete structural member depends on the environment in which the member is located and on the type and quality of concrete used. There are relative humidity, temperature, distance from coast, cycle degree of wet-dry etc. in environment load coefficient which is used as the term qualifying environment condition in this work. These parameters were selected through some references as well as BS
### Table 1. Fuzzy variables

| Variable Name | Term Names                              | Range             |
|---------------|-----------------------------------------|-------------------|
| CWD           | low, medium, high                       | 0 to 1 ratio      |
| Distance      | close, medium, fur                      | 0 to 1200 meter   |
| Grade         | low, medium Low, medium, high, high     | 20 to 60 MPa      |
| RH            | very low, low, medium, high, very high  | 30 to 100 percent |
| Temperature   | low, medium_low, medium, high, high     | 5 to 45 degrees   |
| WC            | low, medium_low, medium, high, high     | 30 to 65 percent  |
| ELC           | ELC1, ELC2, ELC3, ELC4, ELC5            | 0 to 6 index      |
| Thickness     | C20, C25, C30, C35, C40, C45, C50, C55, C60 | 15 to 65 mm      |

### Fig. 2. Membership functions of each fuzzy variable

- Membership functions of input variables
- Membership functions of output variables
- Rule base for inferring BLC
- Environment load coefficient
- Water flow load coefficient
- Material overlay thickness
- Minimal overlay thickness
- Deturization by load
- Deturization by coil
Table 2. Rule base for selecting environment load coefficient

| CWD | Distance | RH | Temperature | THEN(EQC) |
|-----|----------|----|-------------|-----------|
| low | close    | very_low | low | ELC2       |
| low | medium_low | medium_low | high | ELC3       |
| low | medium_high | high | ELC4       |
| low | high | ELC5       |
| medium | low | medium_low | medium_low | ELC3       |
| medium | medium_high | high | ELC4       |
| medium | high | ELC5       |
| high | close | very_low | low | ELC6       |
| high | medium_low | medium_low | high | ELC7       |
| high | medium_high | high | ELC8       |
| high | high | ELC9       |

3.3 Definition of fuzzy variables

This sub-chapter contains the definition of all linguistic variables and all fuzzy numbers. Linguistic variables and fuzzy numbers are used to translate real values into fuzzy value. Table 1 lists all linguistic variables and fuzzy numbers of this system and their term names. The universes of each fuzzy variable are listed in Table 1, which is equal to indicate the limitation of this study. The ranges of each input variable were set to be based on some references as well as BS 8110 and BS EN 206-1/BS 8500.

3.4 Definition of fuzzy sets

This phase involves defining the fuzzy set on each universe. Namely, the membership grades of each term to the linguistic variable was defined conforming to designer or expert’s intuition and engineering knowledge as well as some references in this work. More detailed information about the membership function of each linguistic variable was illustrated at Fig. 2.

3.5 Definition of fuzzy rule base

Table 2 and 3 list all fuzzy logic rule bases generated in this fuzzy system for determining ELC and the Nominal cover thickness, respectively. Generally, the fuzzy logic rule base is the main part of a fuzzy system and contains all the engineering knowledge necessary to control a system. The rule base supplies all the actions to be taken by the fuzzy inference in certain situations. In a sense, the rule base represents the system’s intelligence.
Table 3. Rule base for determining Nominal cover thickness

| IF(Antecedent) | THEN(Consequent) |
|----------------|------------------|
| ELC grade WC Thickness | ELC grade WC Thickness |
| low low C35 | medium_high ELC3 |
| medium_low ELC2 | medium_low ELC2 |
| medium_low ELC2 | medium_high ELC3 |
| medium_low ELC2 | high ELC3 |
| low low C40 | medium_high ELC3 |
| medium_low ELC2 | medium_high ELC3 |
| medium_low ELC2 | high ELC3 |
| low low C45 | medium_high ELC3 |
| medium_low ELC2 | medium_high ELC3 |
| medium_low ELC2 | high ELC3 |
| low low C50 | medium_high ELC3 |
| medium_low ELC2 | medium_high ELC3 |
| medium_low ELC2 | high ELC3 |
| low medium C30 | medium_low ELC3 |
| medium_low ELC3 | medium_high ELC3 |
| medium_low ELC3 | high ELC3 |
| low media medium_high ELC4 | medium_low ELC3 |
| medium_low ELC4 | medium_high ELC3 |
| medium_low ELC4 | high ELC3 |
| low medium C31 | medium_low ELC3 |
| medium_low ELC3 | medium_high ELC3 |
| medium_low ELC3 | high ELC3 |
| low low C32 | medium_low ELC3 |
| medium_low ELC3 | medium_high ELC3 |
| medium_low ELC3 | high ELC3 |
| low low C33 | medium_low ELC3 |
| medium_low ELC3 | medium_high ELC3 |
| medium_low ELC3 | high ELC3 |
| low low C34 | medium_low ELC3 |
| medium_low ELC3 | medium_high ELC3 |
| medium_low ELC3 | high ELC3 |
| low low C35 | medium_low ELC3 |
| medium_low ELC3 | medium_high ELC3 |
| medium_low ELC3 | high ELC3 |
| low medium C36 | medium_low ELC3 |
| medium_low ELC3 | medium_high ELC3 |
| medium_low ELC3 | high ELC3 |
| low medium C37 | medium_low ELC3 |
| medium_low ELC3 | medium_high ELC3 |
| medium_low ELC3 | high ELC3 |
| low medium C38 | medium_low ELC3 |
| medium_low ELC3 | medium_high ELC3 |
| medium_low ELC3 | high ELC3 |
3.6 Building system

This phase is to build the system and involves the coding of the fuzzy sets, and rules and procedures for performing fuzzy logic functions such as fuzzy inference by setting the operator, inference mechanism and defuzzification method related to the fuzzy system. To build fuzzy system this work relied on the fuzzy logic development shell of fuzzyTECH.

To accomplish this task the standard common operators for the AND-and the OR-operation was the Min-and Max-operators and the standard inference mechanism of the fuzzy inference mechanism was Max-Min method. Center-of-Maximum was used as the defuzzification method in order to derive a crisp output value that best represents the linguistic result obtained from the fuzzy inference.

3.7 Verification of built-fuzzy inference system(FIS)

(1) Environment load coefficient

As illustrated in Fig. 2, the linguistic variable of ELC is fuzzified on an arbitrary scale of 0-6 within the extent of the classification of environment conditions specified in BS 8110 and BS EN 206-1/BS 8500.

Figs. 3, 4, and 5 show that the values of ELC tend to be dependent on the different values of the cycle degree of wet-dry, relative humidity, temperature, and distance from coast. The dependence of the values of ELC on temperature and relative humidity for the cycle degree of wet-dry of 0.5 and RH for the cycle degree of wet-dry of 0.5 is shown in Fig.3 and 4. For the given distance and the cycle degree of wet-dry, the value of ELC increases as temperature and RH increases. This system represents well the actual tendency that the values of ELC for the close distance be much higher than those for the far distance. The increase of
The close distance from coast of about 200m

Fig. 5. ELC according to the relationship between temperature and cycle degree of wet-dry for relative humidity of 60% gives rise to the increase of the values of ELC for the given RH. It is in accordance with the actual tendency that the corrosion of reinforcement is positively affected by temperature and negatively by distance.

(2) Nominal cover thickness

Fig. 6 shows the variation of Nominal cover thickness dependent on water-cement ratio, concrete grade, and the value of ELC which is determined from the environmental condition. The tendency that Nominal cover thickness is significantly dependent on the values of ELC, water-cement ratio, and concrete grade is well represented as a similar form with the thing actual.

4. Example for checking the validation of this system

4.1 Environment condition

The reinforced structure is placed in the distance of
4.2 Nominal cover thickness required by the specification

The given environment (characterized by the distance from coast of about 850m, a temperature of around 28°C, RH of about 70%, and cyclic degree of wet-dry around 0.5) can be qualitatively included in exposure class Severe because of the RH and the frequent cyclic degree of wet-dry according to Table 4. Thus the minimum grade of concrete and maximum water-cement ratio for the exposure class of Severe is 40MPa and 55%, respectively, and minimum required cover thickness is 40mm.

4.3 Nominal cover thickness inferred by this system

In the given environment, distance of about 850m is a member of the fuzzy set medium with a grade of membership 1.0, RH of 70% is a member of both the fuzzy sets medium with a grade of membership 0.33 and high with a grade of membership 0.67, and temperature of 28°C is a member of both the fuzzy sets medium-low with a grade of 0.12 and medium-high with a grade of 0.88. First, the output of ECF is obtained through the given input value. The defuzzified value of ECF is 2.8209. Thus in the case of that the minimum grade of concrete and maximum water-cement ratio is 40MPa and 55%, respectively, the defuzzified output of the nominal cover thickness is obtained as 44.1070mm.

Table 5 lists the defuzzified nominal cover thickness according to the different concrete grade and water-cement ratio under above given environment. It is found that this system represents well the variation of the defuzzified nominal cover thickness with the different concrete grade and water-cement ratio whilst nominal cover thickness of concrete by the specification is very discrete.

5. Conclusion

A fuzzy approach to durability-based nominal cover thickness design of reinforced concrete structural member by quantitatively handling the environment condition qualitatively, uncertainly, ambiguously expressed is presented in this work.

Since this work is planed as a form of the prototype, as treated in this premise, the somewhat degree of error of the specification and this system cannot be prohibited. Anyway, the feasibility of fuzzy inference system to design cover to reinforcement was proved to be possible. In the following work, the study to predict the service life of RC structural member with cover thickness designed by this system will be carried out after more delicately tuning the grade of membership function of all terms in linguistic invariables, the rule-base, and operator etc.

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