

Fuzzy inference based cover thickness estimation of reinforced concrete structure quantitatively considering salty environment impact

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Abstract. This article involves architecting prototype-fuzzy expert system for designing the nominal cover thickness by means of fuzzy inference for quantitatively representing the environment affecting factor to reinforced concrete in chloride-induced corrosion environment. In this work, nominal cover thickness to reinforcement in concrete was determined by the sum of minimum cover thickness and tolerance to that defined from skill level, constructability and the significance of member. Several variables defining the quality of concrete and environment affecting factor (EAF) including relative humidity, temperature, cyclic wet and dry, and the distance from coast were treated as fuzzy variables. To qualify EAF 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 EAF, concrete grade, and water-cement ratio were used. The membership functions of each fuzzy variable were generated from the engineering knowledge and intuition based on some references as well as some international codes of practice.

Keywords: durability design; reinforced concrete; fuzzy inference system; expert system.

1. Introduction

1.1. Generals

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 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 (Somerville 1992, ACI 201.2R-01, Oh 2004, and CEB 1989).

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

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weathering action, chemical attack, abrasion, and other condition of service and as a measure of the change in a material property over a period of time as a response to environment to an influence that can cause deterioration, usually expressed as percentage of the value of the property before environment, respectively (ACI 116R-00). 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 (ENV13670-12000). 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 (Do 2004, George 1995, and Kim 2003).

1.2. Service life of concrete structure

The service life of the reinforced concrete (RC) structures used to be often endangered by aggressive environment, like carbonation and chloride effects. Both are an often cause of the deterioration of RC structures when they are in a contact with sea atmosphere. It is reported that a reduction in pH in concrete due to its carbonation will increase the severity of the attack in the presence of chlorides (Broomfield 1992). According to H. Roper and D. Bajewa, interactive effects of carbonation and chloride lead to much more rapid corrosion of reinforcement than where both phenomena are separately. The effect was more pronounced when the w/c ratio was increased. The intensifying effect of the carbonation is more pronounced when the carbonation of concrete foregoing the action of chloride solution (Živica 2003a).

The deterioration of RC structures and the economical damages are a driving motive for the development of the methods for service life prediction of RC structures. For prediction of service life of RC structures several mathematical models have been developed considering the various environment and material conditions. These models take into consideration the depassivation rate expressed by the penetration rate of aggressive substances through the concrete cover to the reinforcement bars surface, or by the amount of corrosion expressed as weight loss of reinforcement due its corrosion.

As an example of the first approach is the method reported by Papadakis, *et al.* (1991). The calculation is based on the physico-chemical processes of concrete carbonation modeled mathematically, considering the effects of various composition parameters, ambient relative humidity, and CO₂ concentration for given concrete cover. The model allows determination of the approximative time of depassivation of reinforcement. However, information about the actual state of the reinforcement and corrosion rate is missing.

More reliable and valuable information is able to give the approach based on the determination of the weight loss of reinforcement due to its corrosion. As the examples may be presented the methods reported by S. Morinaga (1991) and by Zivicac (1994a, 1994b, 1995, 1998).

2. Scope and limitation of this work

Most of the current approach to durability design is included in probabilistic method which is the concept that if harmful ion reaches the reinforcement and excess the chloride threshold, the corrosion of rebar occurs. Thus it needs to solve the differential equation representing the relation of diffusion of ion in concrete and depth of chloride ingress dependent on time. Additionally, this mathematical equation requires for the specific constant defining the influence of exposure condition, the quality of concrete and so on. The beginning of the methodology proposed in this work is to generalize several parameters (Do 2005).

The limitation of this study is as follows;

- 1) The procedure of this work is designed to be applicable only to the structure exposed to the corrosive environments.
- 2) 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 (Bentur 1997, BS 8119, 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 and to using the ordinary portland cement concrete.

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.

3. Simple overview of fuzzy logic

3.1. 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 (George 1995).

3.2. Applications of linguistic variables

Fuzzy logic is primarily concerned with quantifying and reasoning about vague or fuzzy terms that appear in our 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.

4. Item to be considered in design for durability

4.1. General environment action on concrete structure in chloride induced corrosion environment

The deterioration of concrete structures is governed by the interaction between the environment and the response from the concrete. The environment has a large influence on the durability and consequently also the service life of a concrete structure. The environmental action on a concrete structure can be modeled in three levels; (Somerville 1992 and CEB 1989)

Regional conditions (Macro level description): All parts of the structures are assumed to have the same environmental conditions.

Local conditions (Meso level description): The local climate follows from the regional but the large-scale geometry and orientation of the structure are also taken into account. A difference, e.g. surface orientation, is made between different parts of the structure.

Near surface and surface conditions (Micro-level description): The near surface and surface conditions follows from the local but the shape of the structure and the texture and material properties are also taken into account.

4.2. Primary factor influencing chloride ingress

The rate of chloride ingress through the cover to reinforcement depends primarily on the following material and environmental factors (Maher 2003).

- Chloride diffusivity of the concrete
- Sorptivity of the concrete
- Ability of concrete to bind chlorides
- Water/cement ratio
- Chloride diffusivity of the aggregate
- Degree of exposure to chloride source
- Temperature
- Hydrostatic head

In this work, the above primary factor affecting chloride induced corrosion of reinforced concrete in chloride rich environments will be identified by the exposure condition and factor related to concrete quality, respectively. Exposure condition is regarded as the specific climate environment where the target reinforced concrete are located, which is identified with relative humidity, temperature, initial chloride concentration, i.e., boundary condition, and degree of cyclic wet and dry (Yoshiki 2001 and Živica 2003b). Concrete quality is identified by minimum compressive strength, maximum water-cement ratio, and minimum cement content. The skill level of worker and supervisor and the properties of materials used defined as the quality of aggregate and the quantity

of C_3A in cement, the addition of dampproofer is a significant factor influencing the concrete quality (Bentur 1997, ENV 13670-1 2000 and pr EN 1992-1-1, 2002).

5. Determining nominal cover thickness

5.1. General

In this work, nominal cover to reinforcement is regarded as the sum of minimum cover defined by environment affecting factor and cover tolerance defined by the structural significance of substructure components, the quality of material used and the degree of constructability.

5.2. Cover thickness design by FIS

5.2.1. Durability design concept in this work

In making durability design, as mentioned above, there is a need to take into consideration of the actual environmental conditions to be experienced by the structure. Thus environmental affecting factor 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 EAF

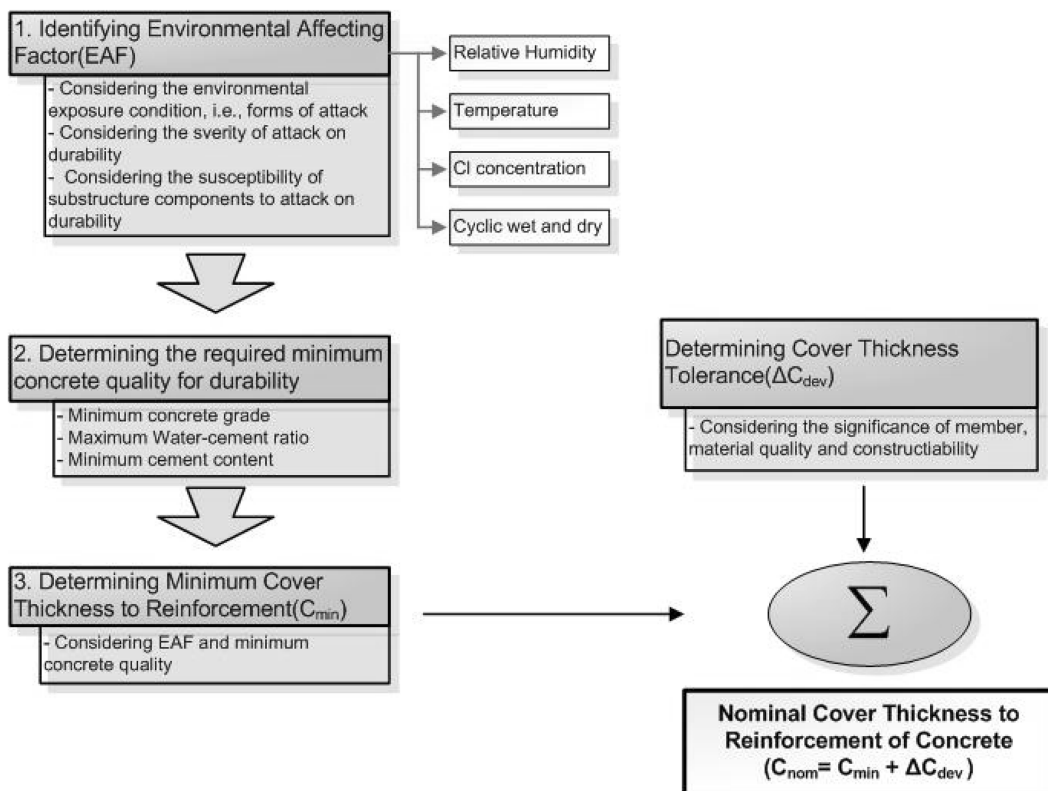


Fig. 1 Study procedure of this work

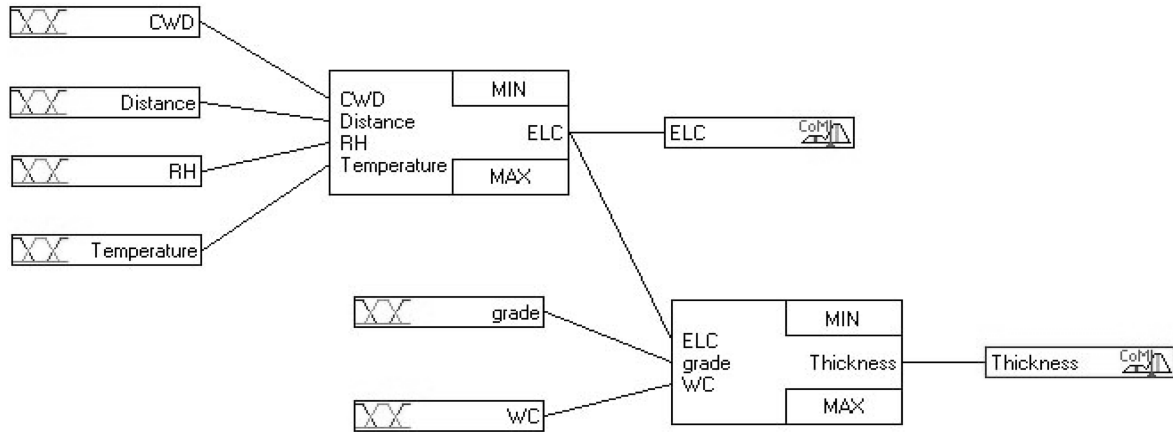


Fig. 2 Schematic diagram for determining minimum cover thickness by FIS

and the determined concrete grade and water-cement ratio, nominal cover thickness is determined as represented in Fig. 2.

5.2.2 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 is relative humidity, temperature, distance from coast, degree of cyclic wet-dry etc. in environment affecting factor which is used as the term qualifying environment condition in this work.

These parameters were selected through some references as well as BS 8110 and BS EN 206-1/BS 8500. The system structure identifies the fuzzy inference flow from the input variables (antecedences) to the output variables (consequents). The fuzzification in the input interfaces translates analog inputs into fuzzy values. The fuzzy inference takes place in rule blocks which contain the linguistic control rules. The outputs of these rule blocks are linguistic variables. The defuzzification in the output interfaces translates them into analog variables. Fig. 1 shows the whole structure of this fuzzy system including input interfaces, rule blocks and output interfaces. The connecting lines symbolize the data flow.

Table 1 Fuzzy variables

Variable Name	Description	Range	
CWD	Qualitative degree of cyclic wet and dry	0	to 1
Distance	Distance from the coast	0	to 1200 meter
RH	Average Relative Humidity in region climate	30	to 100 percent
Temperature	Average Temperature in region climate	5	to 45 degrees
EAF	Environmental affecting factor considering exposure condition	0	to 6 index
Grade	Designed concrete strength by characteristic cylinder strength	20	to 60MPa
WC	Water-cement ratio of concrete	30	to 65 percent
Thickness	Thickness inferred by EAF as well as grade and WC	15	to 65 mm

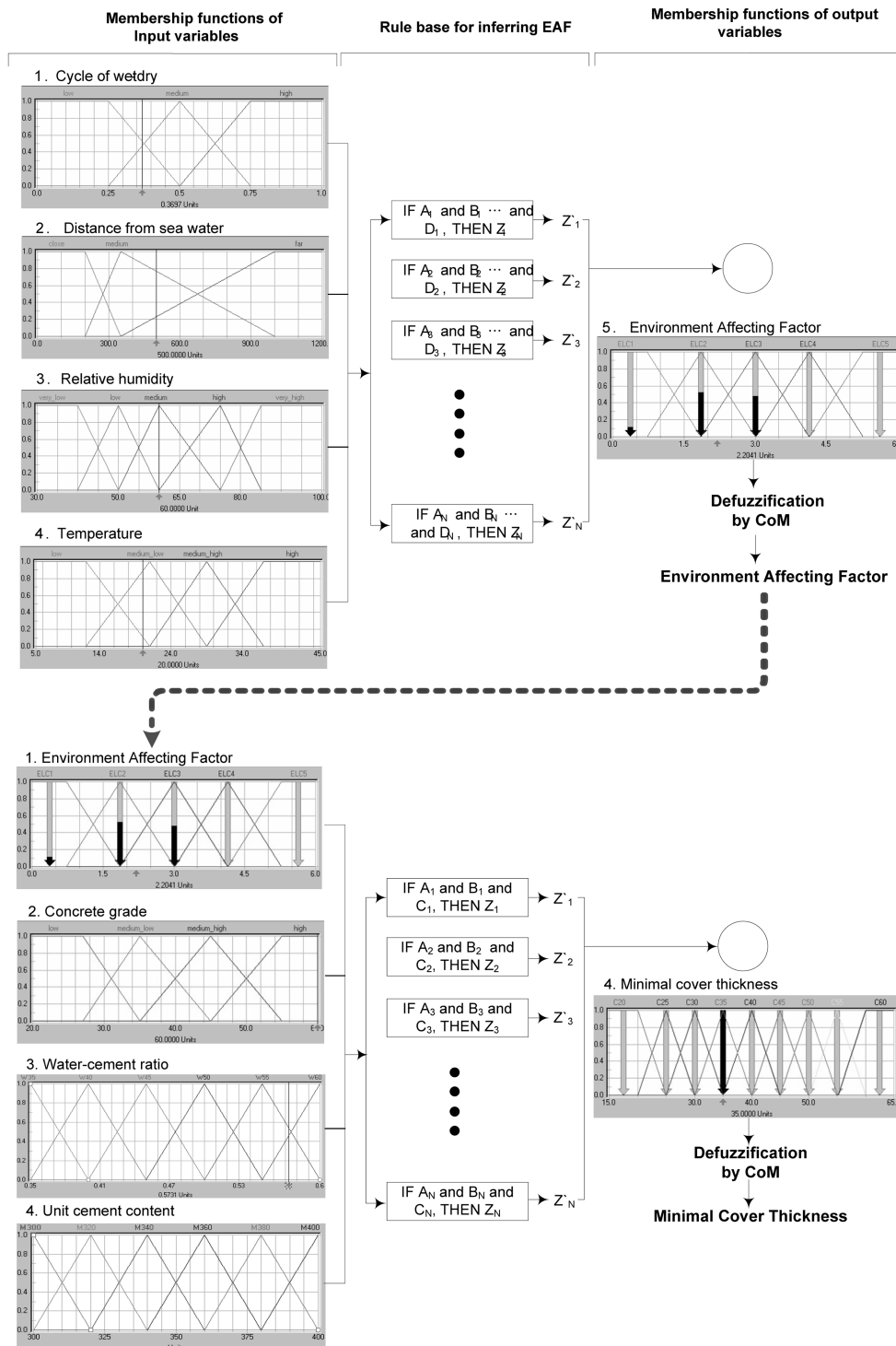


Fig. 3 Membership functions of each fuzzy variable

5.2.3. Definition of fuzzy variables

This section 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.

5.2.4. 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. 3.

5.2.5. Definition of fuzzy rule base

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. A part of fuzzy logic rule bases generated in this fuzzy system for determining the minimum cover thickness are summarized as follows.

1) Rule base for Minimum Cover thickness

- If **EAF** is **EAF1** AND **Grade** is low AND **WC** is low, Then **Thickness** is C25.
- If **EAF** is **EAF1** AND **Grade** is low AND **WC** is medium low, Then **Thickness** is C30.
- If **EAF** is **EAF1** OR **EAF2** AND **Grade** is high AND **WC** is medium low, Then **Thickness** is C20.
- If **EAF** is **EAF2** AND **Grade** is low AND **WC** is medium high, Then **Thickness** is C40
- If **EAF** is **EAF2** AND **Grade** is medium high AND **WC** is medium high, Then **Thickness** is C30

: Omitted

- If **EAF** is **EAF4** AND **Grade** is low Or medium low AND **WC** is low, Then **Thickness** is C40
- If **EAF** is **EAF4** **Grade** low AND **WC** is medium high, Then **Thickness** is C50
- If **EAF** is **EAF4** **Grade** is medium low AND **WC** is medium high, Then **Thickness** is C45
- If **EAF** is **EAF4** **Grade** is high AND **WC** is medium low, Then **Thickness** is C35
- If **EAF** is **EAF5** AND **Grade** is medium high AND **WC** is low, Then **Thickness** is C40
- If **EAF** is **EAF5** AND **Grade** is high AND **WC** is medium low, Then **Thickness** is C40
- If **EAF** is **EAF5** AND **Grade** is high AND **WC** is high, Then **Thickness** is C45.

5.2.6. Building sub-system

This 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 commercial fuzzy logic development shell. 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.

5.2.7. Verification of built sub-system

(1) Environment affecting factor

As illustrated in Fig. 3, the linguistic variable of EAF was 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.

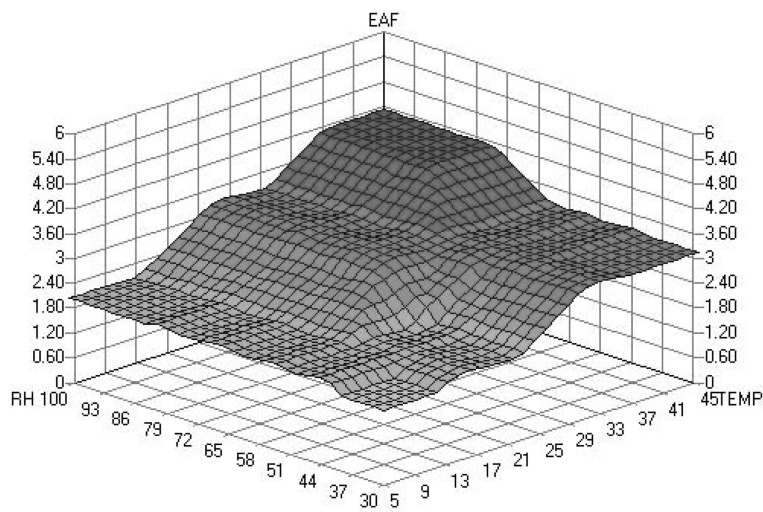


Fig. 4 EAF according to the combination between temperature and RH for the degree of cyclic wet-dry of about 0.75 and about 900m distance from coast

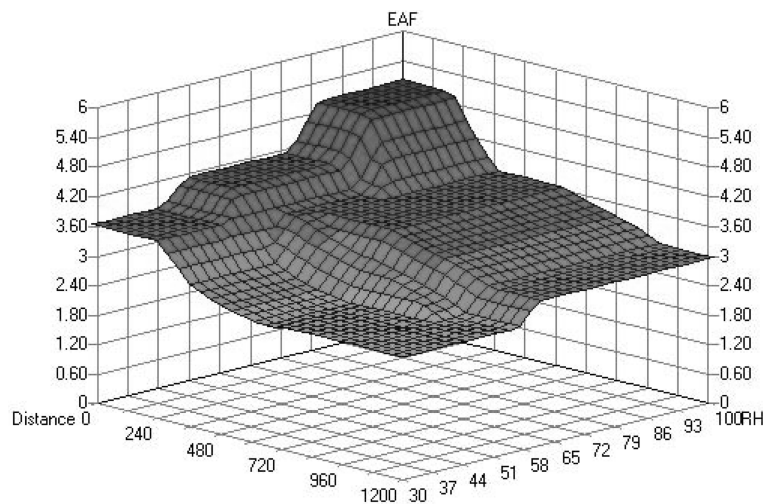


Fig. 5 EAF according to the combination between distance and RH for the degree of cyclic wet-dry of about 0.75 and temperature of about 25 degrees centigrade. nt ratio and EAF for concrete grade of about 40 MPa

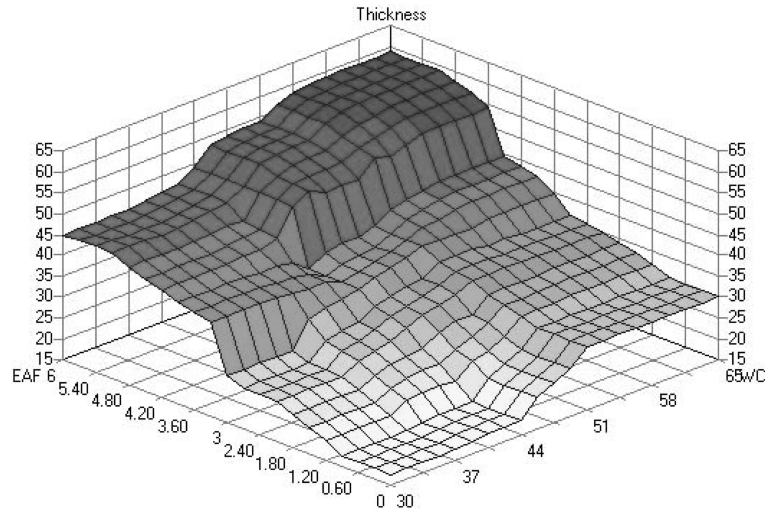


Fig. 6 Minimum cover thickness according to the combination between water-cement ratio and EAF for concrete grade of about 4 MPa

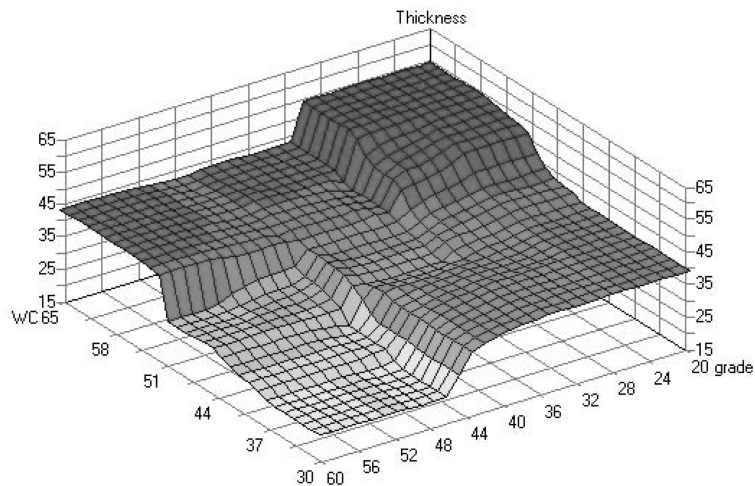


Fig. 7 Minimum cover thickness according to the combination between water-cement ratio and concrete grade for EAF of 3.5

Figs. 4 and 5 show that the values of EAF tend to be dependent on the different values of the degree of cyclic wet-dry, relative humidity, temperature, and distance from coast. The dependence of the values of EAF on temperature and relative humidity for the degree of cyclic wet-dry of 0.75 and distance from coast of about 900m is shown in Fig. 3. For the given distance and the degree of cyclic wet-dry, the value of EAF increases as temperature and RH increases. The increase of relative humidity, as shown in Fig. 5, gives rise to the increase of the values of EAF for the given temperature and this system represents well the actual tendency that the values of EAF for the close distance be much higher than those for the far distance. It is in accordance with the actual tendency that the corrosion of reinforcement is positively affected by temperature and negatively by distance.

(2) Minimum cover thickness

Figs. 6 and 7 show the variation of nominal cover thickness dependent on water-cement ratio, concrete grade, and the value of EAF which is determined from the environmental condition. The tendency that nominal cover thickness is significantly dependent on the values of EAF, water-cement ratio, and concrete grade is well represented as a similar form with the thing actual.

5.3. Determining cover thickness tolerance by FIS

5.3.1. Definition of fuzzy variables and fuzzy sets

Besides minimum cover to reinforcement in concrete, as mentioned above, there are a need to consider the effect of the quality of concrete materials itself, the skill level of manufacturer and construction condition and so forth on cover thickness, i.e., cover thickness tolerance. Fig. 8 represents schematic diagram for determining cover thickness tolerance by means of fuzzy inference system. A significant factor to tolerance was characterized into three types of the quality of

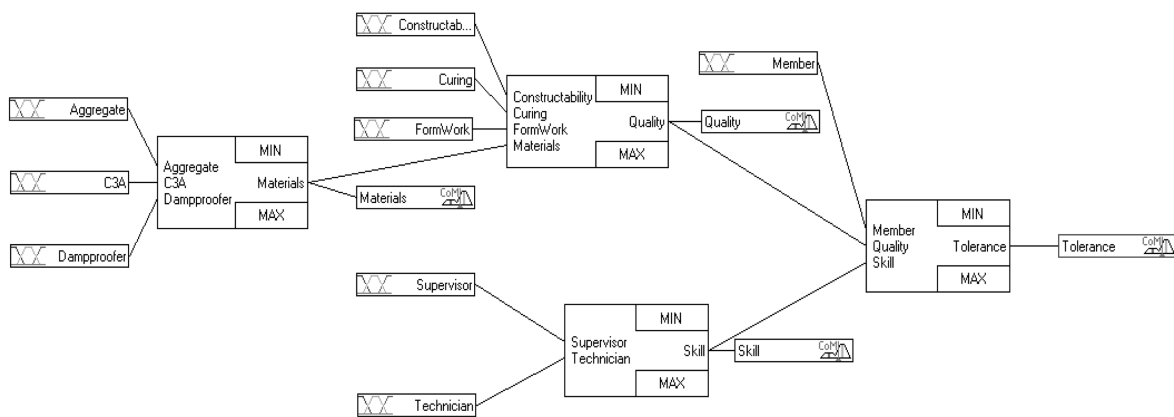


Fig. 8 Schematic diagram for determining cover thickness tolerance by FIS

Table 2 Description of item for determining cover thickness tolerance

Fuzzy variables for determining tolerance		Description	Range
Quality	Materials	Aggregate	The quality of aggregate
		C ₃ A	The quantity of C ₃ A
		Dampproofers	Chemical agent for water-repellency
Skill	Constructability	Constructability	0 to 6
	Curing	Curing Quality	0 to 6
	FormWork	Quality of Formwork and Form	0 to 6
Member	Supervisor	Level of Supervisor	0 to 1
	Technician	Level of technician	0 to 1
Tolerance		Tolerance for cover thickness	0 to 10

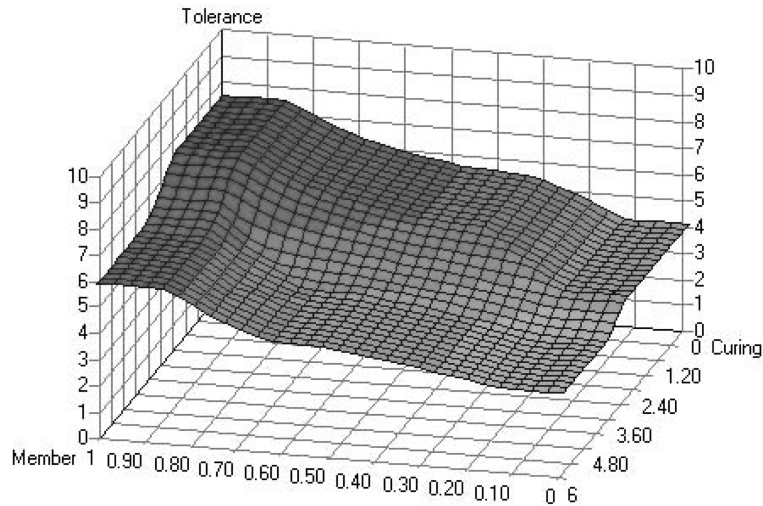


Fig. 9 Tolerance according to the combination between curing and member for the skill of moderate

construction, the skill level of manufacturer and the structural significance of member and the detailed subfactors are listed in Table 2. These subfactors were treated as fuzzy variables for building FIS. And also, each fuzzy variable was defined as the term of quantifier illustrated in Fig. 10, which represents membership functions of each fuzzy variable defined in fuzzy inference system for cover thickness tolerance, which the degrees of membership functions of each variable were defined in view of the intuition based on some references and the expertise. To infer cover thickness tolerance first is to assess the quality of material through the combination of aggregate, the quantity of C_3A and the usage of dampproofer in concrete mixture. The inferred quality of material, together with constructability, curing and formwork, is used to assess the construction quality. Finally, cover thickness tolerance is determined by means of the combination of the significance of member, construction quality and Skill level. Rule base for inferring cover thickness tolerance from member, quality and skill is as follows. Alike the operation of minimum cover thickness, a standard operator is used as operator for the AND-and the OR-operation to calculate the fuzzified variables.

Rule base for Tolerance

- If Member is negative AND Quality is low OR medium AND Skill is low, then Tolerance is medium
- If Member is negative AND Quality is low AND Skill is medium or high, then Tolerance is medium
- If Member is negative AND Quality is medium AND Skill is medium or high, then Tolerance is low
- If Member is negative AND Quality is high AND Skill is low, then Tolerance is low
- If Member is negative AND Quality is high AND Skill is medium or high, then Tolerance is very low
- If Member is positive AND Quality is low AND low or Skill is medium, then Tolerance is very high
- If Member is positive AND Quality is low AND Skill is high, then Tolerance is high

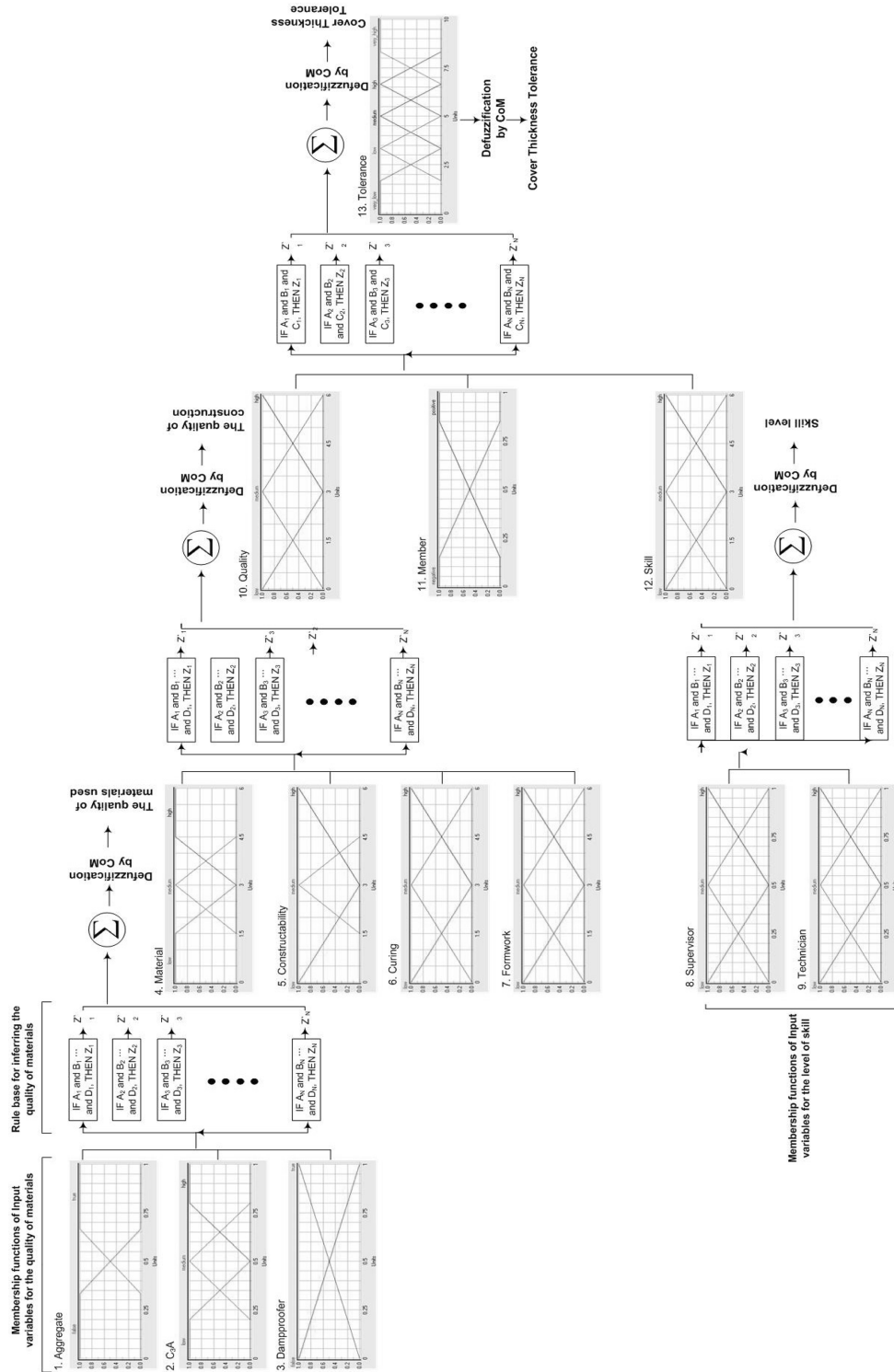


Fig. 10 Membership function of each fuzzy variable for inferring cover thickness tolerance

- If Member is positive AND Quality is medium AND Skill is low or medium, then Tolerance is high
- If Member is positive AND Quality is medium or high AND Skill is high, then Tolerance is medium
- If Member is positive AND Quality is high AND Skill is low or medium, then Tolerance is medium

5.3.2. Verification of sub-system

As stated earlier, cover thickness tolerance is to consider the deviation resulting from several factors to cover thickness including the quality and type of supplementary admixture, the level of supervisor or worker and the quality of curing and formwork, etc. Fig. 9 represents the influence the combination of material and curing to tolerance when the level of skill determined by the level of supervisor and technician is supposed to be medium. This sub-system reflects well quantitatively the tendency that tolerance should be dependent on the structural significance of member and the quality of curing from the qualitative view.

6. Example for checking the validation

6.1. Environmental condition

The reinforced structure is placed in the distance of about 900 m from coast. The structural member to be designed is exposed to the environment conditions characterized by: temperature of about 28, RH of about 70%, and cyclic degree of wet-dry about 0.6.

6.2. Construction condition

This structure is supposed to be constructed by the middle level of supervisor and worker. Concrete will be made up of good quality of aggregate and the proper usage of dampproofer. The structure member to be designed is moderate significant and tension area. Curing for concrete will be conducted with a proper method like moisture curing and the good form will be used.

6.3. Determining proper cover thickness to the given condition

6.3.1. Nominal cover thickness required by the specification

As listed in table 3, the given environment (characterized by the distance from coast of about 900 m, a temperature of around 28, RH of about 70%, and the degree of cyclic wet-dry around 0.6) can be qualitatively included in exposure class SEVERE because of the RH and the moderate frequent degree of cyclic wet-dry according to code of practice. Thus, the minimum grade of concrete and maximum water-cement ratio for the exposure class of SEVERE is 40 MPa and 55%, respectively, and nominal required cover thickness is required to 40 mm. According to EN 201-1, the given environment will be regarded as the middle of XD2 and XD3, and for 45 MPa and 35%, minimum cover thickness of 40mm is required and for 40 MPa and 40%, 45 mm is required.

Table 3 Comparison between the defuzzified nominal cover thickness and specification of BS 8110 and EN201-1 for the given environmental condition

Evaluation for the given environmental condition	BS 8110			EN201-1			Built system			
	Severe			Middle of XD2 and XD3			3.2021			
Selected concrete properties	C40	C45	C50	C45	C40	C35	C40	C50	C30	C35
	0.55	0.50	0.45	0.35	0.40	0.45	0.55	0.45	0.40	0.50
Mini. cover thickness, mm	40	30	25	40	45	50	37.28	23.27	34.45	34.04
Tolerance, mm	N/A	N/A	N/A	5	5	5	6.09	6.09	6.09	6.09
Nominal, mm	40	30	25	45	50	55	43.37	29.36	40.54	40.13

Notes,

- 1) BS 8110 gives nominal cover thickness and EN201-1 and this built system do minimum cover thickness.
- 2) Severe means the condition that concrete surface is exposed to severe rain, alternate wetting and drying.
- 3) XD2 means wet and rarely dry condition, and XD3 does cyclical wet and dry condition.
- 4) N/A means not applicable

6.3.2. 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 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 EAF is obtained through the given input value. The defuzzified value of EAF is 2.8209. Thus in the case of that the minimum grade of concrete and maximum water-cement ratio is 40 MPa and 55%, respectively, the defuzzified output of the minimum cover thickness is obtained as 37.28 mm. Considering the given construction condition, it is assessed by this system for determining tolerance into 6.09 as listed in Table 3.

Finally, table 3 lists the defuzzified nominal cover thickness considering tolerance of various different affecting factor 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.

7. Conclusions

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 planned 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.

8. Future research

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. Also, to optimize the grade of the membership function of the built system it is reviewed to use artificial neural network.

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