Fuzzy Inference Based Design for Durability of Reinforced Concrete Structure in Chloride-Induced Corrosion Environment

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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

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.[1-4]

According to cement and concrete terminology reported by ACI Committee 116, two technical terminology of dura-

bility and durability factor are defined as the ability of concrete to resist 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.[5]

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 con-

struction. 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.[6,7]

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.

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.[3,7-11]
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.
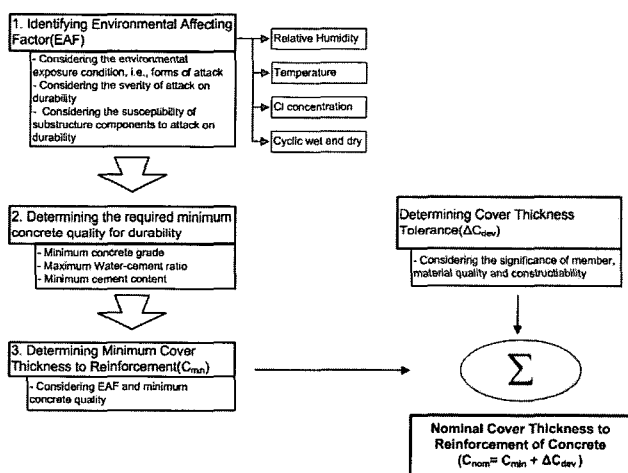

Fig. 1 Study procedure of this work

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.[6]

3.2 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.

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;[1]

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.[1]
- 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. Concrete quality is identified by minimum compressive strength, maximum water-cement ratio, and minimum cement content. Additionally, the susceptibility of substructure component to attack on durability should refer to the structural significance of the compression bar or tension bar. 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.

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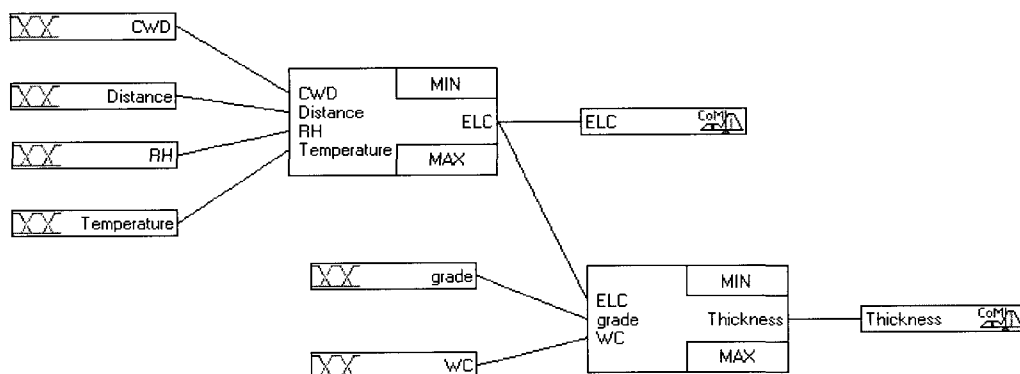

Fig. 2 Schematic diagram for determining minimum cover thickness by FIS

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.

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

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- 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 form 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.

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
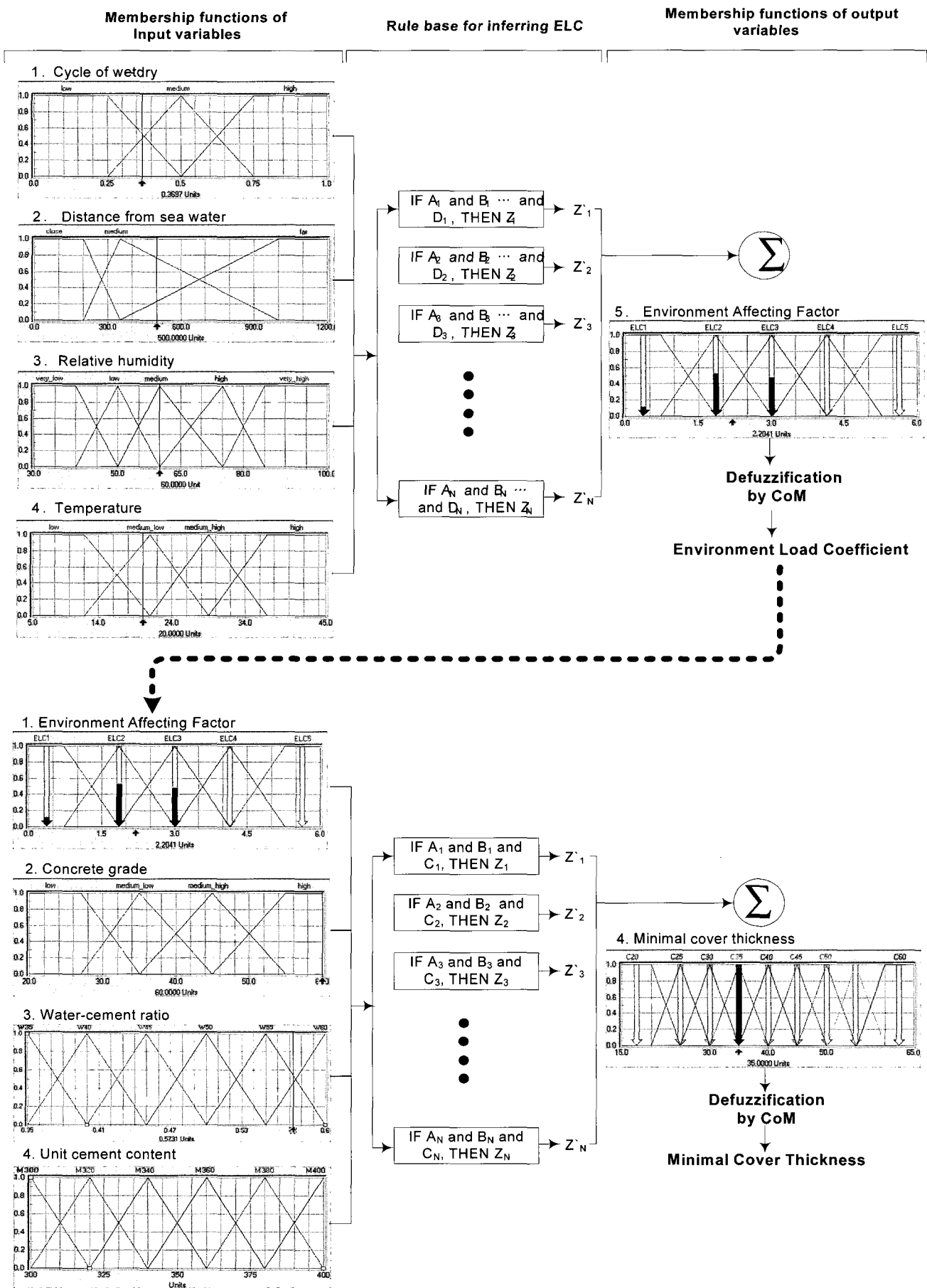
Membership functions of
Input variables

Rule base for inferring ELC

Membership functions of output
variables

1. Cycle of wetdry

low   medium   high

0.3697 Units

2. Distance from sea water

close   medium   far

500.0000 Units

3. Relative humidity

very_low   low   medium   high   very_high

60.0000 Unit

4. Temperature

low   medium_low   medium_high   high

20.0000 Units

IF A₁ and B₁ ··· and D₁, THEN Z₁ → Z'₁

IF A₂ and B₂ ··· and D₂, THEN Z₂ → Z'₂

IF A₃ and B₃ ··· and D₃, THEN Z₃ → Z'₃

IF Aₙ and Bₙ ··· and Dₙ, THEN Zₙ → Z'ₙ

Σ

5. Environment Affecting Factor

ELC1   ELC2   ELC3   ELC4   ELC5

2.2041 Units

**Defuzzification
by CoM**

Environment Load Coefficient

1. Environment Affecting Factor

ELC1   ELC2   ELC3   ELC4   ELC5

2.2041 Units

2. Concrete grade

low   medium_low   medium_high   high

60.0000 Units

3. Water-cement ratio

W35   W40   W45   W50   W55   W60

0.5731 Units

4. Unit cement content

M300   M320   M340   M360   M380   M400

Units

IF A₁ and B₁ and C₁, THEN Z₁ → Z'₁

IF A₂ and B₂ and C₂, THEN Z₂ → Z'₂

IF A₃ and B₃ and C₃, THEN Z₃ → Z'₃

IF Aₙ and Bₙ and Cₙ, THEN Zₙ → Z'ₙ

Σ

4. Minimal cover thickness

C20   C25   C30   C35   C40   C45   C50   C60

35.0000 Units

**Defuzzification
by CoM**

Minimal Cover Thickness

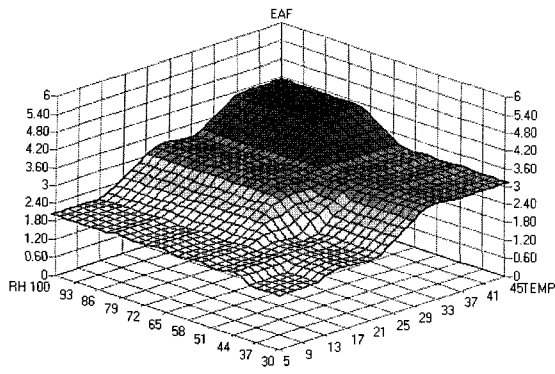**Fig. 3** Membership functions of each fuzzy variable

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 dis tance from coast
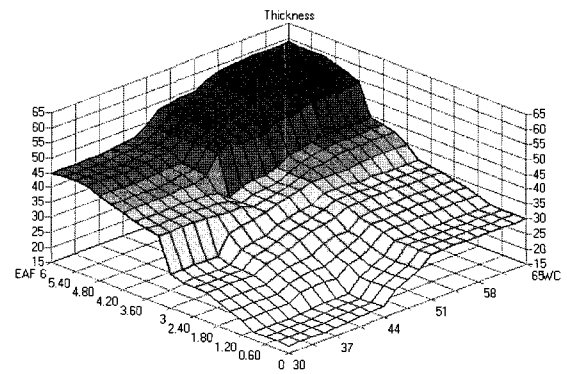

Fig. 6 Minimum cover thickness according to the combination between water-cement ratio and EAF for concrete grade of about 40MPa
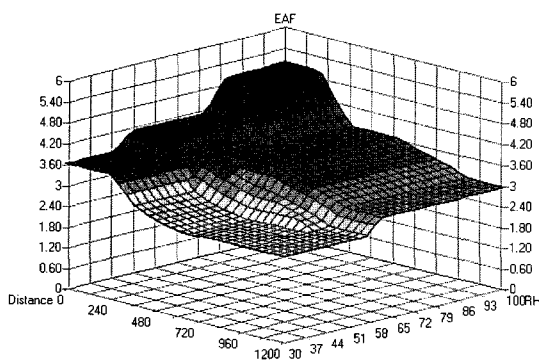

Fig. 5 EAF according to the combination between distance and RH for the degree of cyclic wet-dry of about 0.75 and temperature of about 25 degrees centigrade.
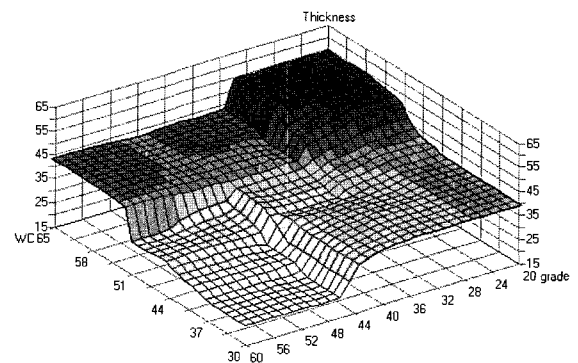

Fig. 7 Minimum cover thickness according to the combination between water-cement ratio and concrete grade for EAF of 3.5

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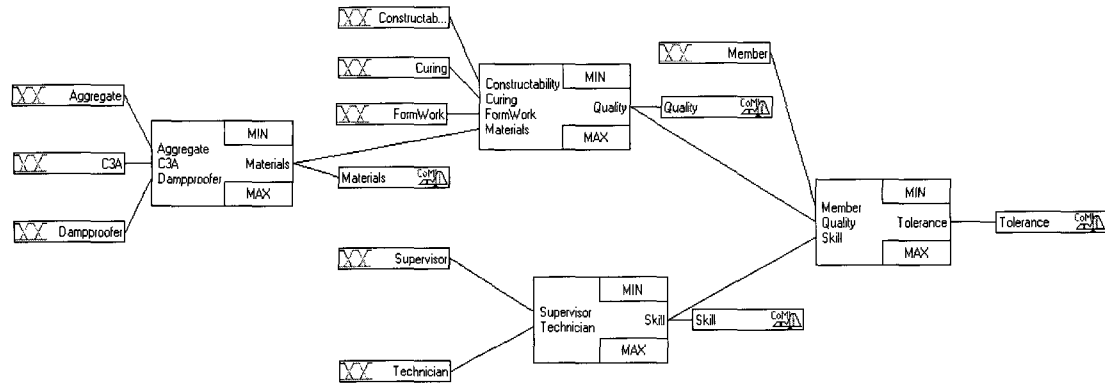
Fig. 8 Schematic diagram for determining cover thickness tolerance by FIS

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, quailtiy 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
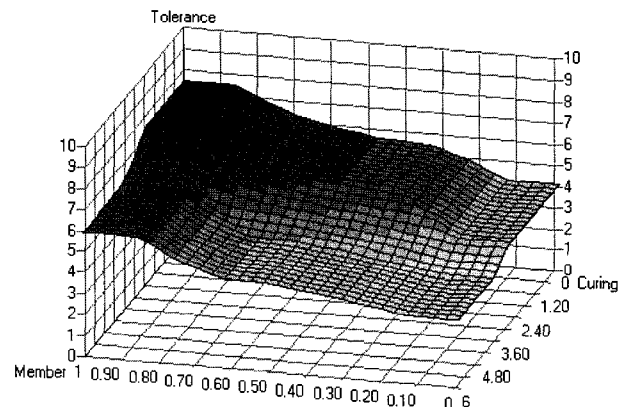- If Member is negative AND Quality is high AND Skill is low, then Tolerance is low

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

Table 2 Description of item for determining cover thickness tolerance

| Fuzzy variables for determining tolerance				Description	Range		
	Quality	Materials	Aggregate	The quality of aggregate	0	to	1
			C_3A	The quantity of C_3A	0	to	1
			Dampproofer	Chemical agent for water-repellency	0	to	1
		Constructability		Constructability	0	to	6
		Curing		Curing Quality	0	to	6
		FormWork		Quality of Formwork and Form	0	to	6
	Skill	Supervisor		Level of Supervisor	0	to	1
		Technician		Level of technician	0	to	1
	Member			Significance of each member	0	to	1
Tolerance				Tolerance for cover thickness	0	to	10
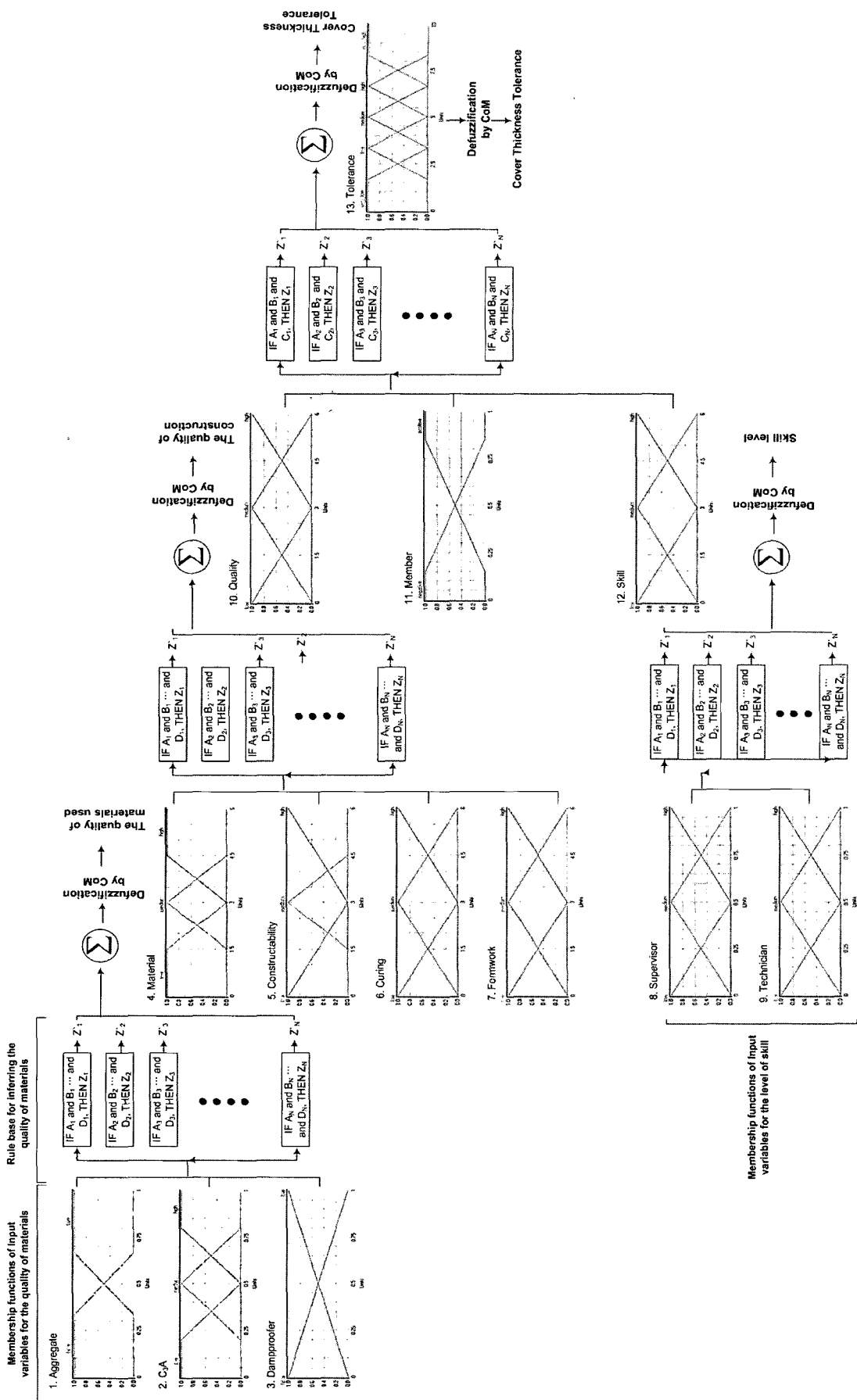
Fig. 10 Membership function of each fuzzy variable for inferring cover thickness tolerance

- 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
- 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 900m 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 conditon

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 900m, 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 40MPa and 55%, respectively, and nominal required cover thickness is required to 40mm. According to EN 201-1, the given environment will be regarded as the middle of XD2 and XD3, and for 45MPa and 35%, minimum cover thickness of 40mm is required and for 40MPa and 40%, 45mm is required.

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

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

	BS 8110			EN201-1			Built system			
Evaluation for the given environmental condition	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	40	30	25	40	45	50	37.28	23.27	34.45	34.04
Tolerance	N/A	N/A	N/A	5	5	5	6.09	6.09	6.09	6.09
Nominal	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

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 40MPa and 55%, respectively, the defuzzified output of the minimum cover thickness is obtained as 37.28mm. 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. Ii 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. 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.

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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