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Application of Multi-environmental time similarity theory based on relative information (RI-METS) theory in durability of concrete structures in marine chloride environment

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ABSTRCT

The Multi-environmental time similarity (METS) method is a testing method that establishes the similarity relationship between the indoor test environment and the on-site environment to evaluate the durability and predict service life of the proposed or under-constructed concrete structure. Based on the METS theory, a similarity ratio of chloride ion concentration and diffusion coefficient between the indoor accelerated environment and the on-site natural environment was established. Then the relative information entropy was introduced into the Multi-Environmental Time Similarity based on Relative Information (RI-METS) theory to consider the time variability of the diffusion coefficient and the surface chloride ion mass fraction. Then the service life of a component in a marine chloride environment by Monte-Carlo simulation method was predicted.

1. Introduction

In the coastal area of China, the damage caused by the corrosion of steel bars caused by the transport of chloride ions in the concrete structure with water level fluctuation or seawater infiltration is quite serious [1]. The economic losses caused by corrosion at home and abroad are very huge. Sitter,1983 [2] adopted the "five-fold law" to illustrate the importance of concrete durability. The durability of reinforced concrete structures is an urgent problem to be solved. Carrying out research on the durability of reinforced concrete structures has practical significance for the durability design of the proposed project and the durability evaluation and residual life prediction of the in-service structure.

For concrete structures, domestic and foreign scholars often adopts durability theory models [3] and accelerated durability tests [4] to study the durability of concrete structures. Although they can simulate the effect of the exposed environment on the spot, the field degradation data of the study object is very insufficient, and the degradation time relationship between the artificial simulation environment and the natural environment can not be established, so they can not be directly applied to the durability design and evaluation of the real structure. Jin et al., 2009 [5] proposed a Multi-environment time similarity theory by introducing the third-party reference objects in a similar environment, and established a similarity relationship between the indoor acceleration environment and the on-site natural environment. However, the traditional METS theory does not consider the randomness of the actual situation, the ambiguity and the incompleteness of the information, which leads to the dispersion of the service life prediction results [6,7]. In order to obtain more reliable results, probabilistic statistical methods are needed to compensate for the inaccuracy of the prediction results caused by the uncertainty of the parameters and the incompleteness of the information, so that the life prediction results can be more credible. This paper combines METS theory and relative information theory to establish the Multi-environmental time similarity theory based on relative information (RI-METS) theory, which introduces the concept of observer and METS path, obtains the statistical parameters of each degradation indicator, and calculates the failure probability and relative information entropy to predict service life of the components in the actual environment. Finally, the field exposure test data of the research object and the result calculated through RI-METS theory are compared to confirm the reliability of the method.

2. Multi-environmental time similarity (METS) theory

METS theory is based on the classical similarity principle. First the observer R selects a reference object (existing structural system S_{es}) that has a similar environment (natural environment E_n) and a certain service life compared with the research object (the proposed structural system S_{ns}). Then the accelerated durability test of the research object model (test system S_{ex}) and the reference object model (test system $S_{ex,1}$) are carried out in the laboratory (artificial simulated environment E_a). Finally the research object is predicted and evaluated in the design life through the similarity between the reference object and the reference object model in the natural environment and the artificial simulated environment [8,9]. The basic principle is shown in Figure 1.

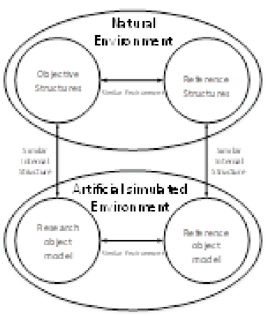


Figure 1. The basic schematic of METS theory

3. Multi-environmental time similarity theory based on relative information (RI-METS theory)

3.1 Relative information theory

Shannon, 1948 [10] proposed the concept of "information entropy", considering entropy as a measure of the degree of system uncertainty, but it only focused on the grammatical information entropy in the grammatical space and ignored the meaning in the semantic space. De Luca and Termini, 1972 [11] gave the calculation formula of fuzzy entropy of fuzzy sets based on Shannon information entropy formula, which provided a practical method for calculating semantic information entropy.

Since different observers have different observation abilities, different comprehension abilities, and different traits [12], different observers (cognitive subjects) can obtain different information from the same system (objects of things), which is called the relativity of information [**Error! Bookmark not defined.**,13]. In 1979, Jumarie, 1979 [14] proposed the theory of relative information. The grammatical information entropy and semantic information entropy were regarded as two dimensions in the Minkowski space, and the Lorentz transformation was used to describe the relativity of information. Jin and Luz,1994; Jin and Han,1996 [15,16] regarded structural reliability analysis as a process of information transmission. Based on METS theory, relative information entropy is used to consider the relative information in structural reliability, thus processing multiple reference objects, a variety of accelerated durability tests, and the randomness of similarity coefficients. As shown in Figure 2, both the observer R_l and the observer R_2 are observing the same system S, and the observation processes are respectively recorded as S/R_l and S/R_2.

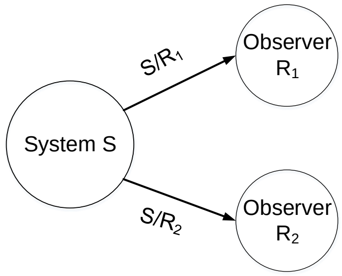


Figure 2. Relativity of information

3.2 METS path

Figure 3 shows that the observer R observes through i existing structural systems $S_{es,1}$ and $S_{es,2}$ and …$S_{es,i}$ and j artificial simulated environments $E_{a,1}$ and $E_{a,2}$ and…$E_{a,j}$ to construct the METS(i; j) type path of the proposed structural system S_{ns}.

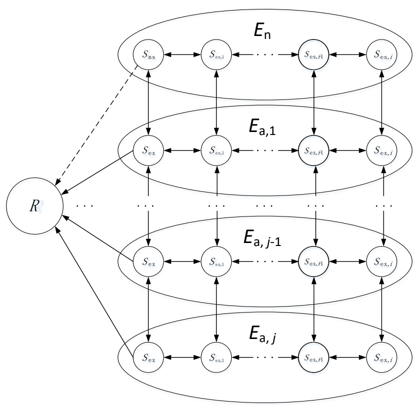


Figure 3. METS($S_{es,1\sim i}$; $E_{a,1\sim j}$) path

a) Entropy expression

3.3.1 Shannon information entropy

Assume that a continuous random variable X whose probability density function is described by $p(x)$, thus the expression of the information entropy of the

$$H(X) = -k \cdot \int_X p(x) \cdot \ln p(x) \cdot dx \qquad (1)$$

continuous random variable X is defined as:

Where the base of the logarithm is e, k is equal to1, the corresponding unit of entropy is nat.

3.3.2 Fuzzy entropy

In 1965, Zadeh, 1965 [17] proposed fuzzy set. Usually, the fuzzy set is represented by $\boldsymbol{A}$. The fuzzy set $\boldsymbol{A}$ is characterized by the membership function [18] and the membership function of $\boldsymbol{A}$ is described by $\mu_{\boldsymbol{A}}(\mu)$:

$$\mu_{\boldsymbol{A}} : U_s \rightarrow [0,1] \qquad (2)$$

For any u belonging to U_s, it corresponds to $\mu_{\boldsymbol{A}}(u)$, where the range of $\mu_{\boldsymbol{A}}(u)$ is [0,1]. The $\mu_{\boldsymbol{A}}(\mu)$ is referred to as the membership degree of the element u for the fuzzy set $\boldsymbol{A}$.

De Luca and Termini gave the calculation formula of fuzzy entropy of fuzzy sets based on Shannon infor mation entropy formula:

$$G(\boldsymbol{A}) = -K\sum_{i=1}^{n}\{\mu_{\boldsymbol{A}}(u_i)\cdot\ln\mu_{\boldsymbol{A}}(u_i) + [1-\mu_{\boldsymbol{A}}(u_i)]\cdot\ln[1-\mu_{\boldsymbol{A}}(u_i)]\} \qquad (3)$$

Where K is the logarithmic bottom parameter of the fuzzy entropy. For a binary fuzzy set, K=k/2 may be accepted.

According to Figure 2, the information obtained by the observer is relative due to the role of the observer. Considering the condition of having observer R, the grammatical information entropy and semantic information entropy of system S can be expressed as $H_i(S/R)$ and $H_o(S/R)$ respectively. Grammatical information entropy and semantic information entropy are two dimensions of the relative information entropy. For the proposed structural system S_{ns}, the functional function Z [19,20] is generally used to characterize the state of the engineering structure, which is $Z = \xi - \eta$, where ξ is the structural resistance and η is the effect. The system S_{ns} is output to the structural engineer R. The grammatical information entropy the system S_{ns} output to the structural engineer R is the Shannon information entropy of the function Z in the grammar space $\boldsymbol{\Psi'}$. The semantic information entropy the system S_{ns} output to the structural engineer R is the fuzzy entropy of the grammatical information entropy of the function Z mapping in the semantic space $\boldsymbol{\Psi}$. As are shown in Figure 4).

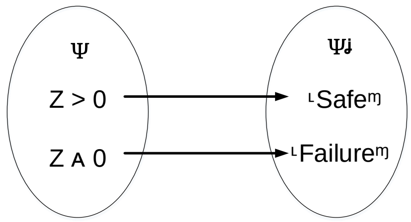


Figure 4. Syntax space and semantic space

3.4 Reliability calculation method based on relative information

The design service life T is divided into m equal time periods, and each time segment has a length of $\tau=T/m$. $P_s(S_{ns,0})$ is defined as the reliable probability when the proposed structural system S_{ns} is built. $P_s(S_{ns,i\tau})$ is defined as the reliable probability of the proposed structural system S_{ns} in the interval $(i\tau-\tau, i\tau]$. Thus, the reliable probability of the proposed structural system S_{ns} within the design service life T is:

$$\begin{aligned} P_s(S_{ns};T) &= P[Z(S_{ns,0})>0 \cap Z(S_{ns,\tau})>0 \\ &\cap Z(S_{ns,i\tau})>0 \cdots \cap Z(S_{ns,m\tau})>0] \\ &= \prod_{i=0}^{m} P[Z(S_{ns,i\tau})>0] = \prod_{i=0}^{m} P_s(S_{ns,i\tau}) \end{aligned} \quad (4)$$

For the proposed structural system S_{ns}, the failure probability within the design service life T is:

$$\begin{aligned} P_f(S_{ns};T) &= P[Z(S_{ns,0}) \le 0 \cup Z(S_{ns,\tau}) \le \\ & 0 \cup Z(S_{ns,i\tau}) \le 0 \cdots \cup Z(S_{ns,T}) \le 0] = \\ & P_f(S_{ns,0}) + \sum_{i=1}^{m} P_f(S_{ns,i\tau}) \cdot \prod_{i=1}^{m} P_s(S_{ns,i\tau-\tau}) \end{aligned} \quad (5)$$

The probability of "reliable" of the proposed structural system S_{ns} in the interval $(i\tau-\tau, i\tau]$ is:

$$P_{\tilde{A}}(S_{ns,i\tau}) = \int p[Z(S_{ns,i\tau})] \cdot \mu_A(Z) \cdot dZ$$

(6)

Where $p[Z(S_{ns,i\tau})]$ is the probability density function of the function function $Z(S_{ns,i\tau})$.

Similarly, the probability of "failure" in the interval $(i\tau-\tau, i\tau)$ of the proposed structural system S_{ns} is:

$$P_{\tilde{B}}(S_{ns,i\tau}) = \int p[Z(S_{ns,i\tau})] \cdot \mu_B(Z) \cdot dZ$$

(7)

Thus, the probability of "reliable" of the proposed structural system S_{ns} within the design service life T is:

$$P_{\tilde{A}}(S_{ns};T) = \prod_{i=0}^{m} P_{\tilde{A}}(S_{ns,i\tau}) \quad (8)$$

Similarly, the probability of "failure" of the proposed structural system S_{ns} within the design service life T is:

$$P_{\tilde{B}}(S_{ns};T) = P_{\tilde{B}}(S_{ns,0}) + \sum_{i=1}^{m} P_{\tilde{B}}(S_{ns,i\tau}) \cdot \prod_{i=1}^{m} P_{\tilde{A}}(S_{ns,i\tau-\tau})$$

(9)

The Shannon information entropy can be used to characterize the grammatical information entropy of the proposed structural system S_{ns} within the design service life T:

$$\begin{aligned} H_i(S_{ns};T) &= -P_s(S_{ns};T) \cdot \log_2 P_s(S_{ns};T) \\ & -P_f(S_{ns};T) \cdot \log_2 P_f(S_{ns};T) \end{aligned} \quad (10)$$

The fuzzy entropy can be used to characterize the semantic information entropy of the proposed structural system S_{ns} within the design service life T:

$$\begin{aligned} H_o(S_{ns};T) &= -\{P_{\tilde{A}}(S_{ns};T) \cdot \log_2 P_{\tilde{A}}(S_{ns};T) \\ & +[1-P_{\tilde{A}}(S_{ns};T)] \cdot \log_2[1-P_{\tilde{A}}(S_{ns};T)] + \\ & P_{\tilde{B}}(S_{ns};T) \cdot \log_2 P_{\tilde{B}}(S_{ns};T) + [1-P_{\tilde{B}}(S_{ns};T)] \cdot \\ & \log_2[1-P_{\tilde{B}}(S_{ns};T)]\}/2 \end{aligned} \quad (11)$$

The METS path can be represented by the observation process in which the observer R observes the proposed structural system S_{ns}.

4. Application of RI-METS theory in durability of structure in marine chloride environment

In the marine chloride environment, there are many factors affecting the durability of concrete structures, which is mainly the steel corrosion caused by chloride salts from seawater [21,22]. When the concentration of chloride ions in the concrete pore liquid on the surface of the steel bar exceeds a certain limit, the passivation film on the surface of the steel bar is destroyed, and the steel bar is rusted. Surface chloride ion concentration and diffusion coefficient are important parameters affecting transportation of chloride ion. The similarity of surface chloride ion concentration and diffusion coefficient are important for applying test results of

$$\kappa = \frac{x}{2\sqrt{D \cdot t}} \quad (18)$$

accelerating transportation of chloride ion for the durability design and evaluation of actual structure [23].

4.1 METS theory

There are generally four environment zones in marine chloride environment, including submerged zone, tidal zone, splash zone and atmospheric zone. The study object sea cap is in the tidal zone and is subjected to the dry and wet interaction of seawater. Therefore, the durability problem is mainly chloride ion erosion. In the pure diffusion region (i.e., $x \geq \Delta x$), the diffusion model of chloride ions in concrete is generally described according to Fick's second law [24], i.e.:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \cdot (D \cdot \frac{\partial C}{\partial x}) \quad (12)$$

Where,

$$D = D_{\text{app}} = \begin{cases} D_{28} \cdot (0.0767 / t)^n , & t < T_u \\ D_{28} \cdot (0.0767 / t)^n , & t \geq T_u \end{cases} \quad (13)$$

$$C_{\text{s}} = C_{\Delta x} = \begin{cases} a \cdot t^b, & t < t_{cr} \\ a \cdot t_{cr}^b, & t \geq t_{cr} \end{cases} \quad (14)$$

Select the moment chloride ion concentration on the

$$Z = C_{\text{cr}} - C(d_{\text{cover}}, t) \quad (15)$$

steel surface reach the critical chloride ion concentration [25,26,27,28] as the durability limit state in marine chloride environment:

$$\zeta = \frac{C - C_0}{C_{\text{s}} - C_0} \quad (16)$$

When $Z > 0$, the system is in a reliable state; When $Z \leq 0$, the system is in a failed state.

Introduce a dimensionless concentration variable:

The inverse residual error dimensionless concentration variable is defined as:

$$\kappa = \text{erfcinv}(\zeta) \quad (17)$$

Where erfinv() is the inverse residual error function.

Substitute equation (16) and (17) into equation (12) :

The function Z can be converted as followed:

$$\begin{aligned} Z &= (C_{\text{cr}} - C_0) - [C(d_{\text{cover}}, t) - C_0] \\ &= (C_{\text{s}} - C_0) \cdot [\frac{C_{\text{cr}} - C_0}{C_{\text{s}} - C_0} - \frac{C(d_{\text{cover}}, t) - C_0}{C_{\text{s}} - C_0}] \\ &= (C_{\text{s}} - C_0) \cdot (\zeta_{\text{cr}} - \zeta) \end{aligned} \quad (19)$$

Since erfinv() is the inverse complement error function which is decreasing, equation (15) is equivalent to:

$$Z = \kappa - \kappa_{\text{cr}} \quad (20)$$

Where κ_{cr} is the critical inverse residual error dimensionless concentration, which is equal to erfinv(ζ_{cr}).

For a proposed structural system in the marine chloride environment E_{n} , equation (18) is noted as:

$$\kappa_{\text{n}} = \text{erfc inv}(\zeta_{\text{n}}) = \frac{x_{\text{n}}}{2\sqrt{D_{\text{n}} \cdot t_{\text{n}}}} \quad (21)$$

Where the variable subscript n indicates the natural environment.

For the test system in the laboratory artificial simulated marine chloride environment E_{a} , equation (18) is noted as:

$$\kappa_{\text{a}} = \text{erfcinv}(\zeta_{\text{a}}) = \frac{x_{\text{a}}}{2\sqrt{D_{\text{a}} \cdot t_{\text{a}}}} \quad (22)$$

Where the variable subscript a indicates the laboratory artificial simulated environment.

Define the similarity rate of the inverse residual error dimensionless concentration variable κ, diffusion coefficient D, surface chloride ion concentration C_s, distance from concrete surface x and time t as:

$$\begin{cases} \lambda(\kappa) = \kappa_{\text{a}} / \kappa_{\text{n}} \\ \lambda(D) = D_{\text{a}} / D_{\text{n}} \\ \lambda(C_{\text{s}}) = C_{\text{s,a}} / C_{\text{s,n}} \\ \lambda(x) = x_{\text{a}} / x_{\text{n}} \\ \lambda(t) = t_{\text{a}} / t_{\text{n}} \end{cases} \quad (23)$$

Substitute equation (23) into equation (21):

$$\kappa_{n} = \frac{x_{n}}{2\sqrt{D_{a} \cdot t_{n}}} \cdot \sqrt{\lambda(D)} \tag{24}$$

4.2 Engineer overview

For a proposed structural system S_{ns}, the engineering category belongs to highway engineering, and the cross-sea bridge is designed for a service life of 100 years. The bridge structural system is mainly a continuous concrete beam bridge. The components include box girder, pier (set), wet joint, cap, pile. Marine concrete materials are used.The natural environment is the marine chloride environment E_{n}, where the chloride ion content in seawater is between 8.9 and 15.4 g/L, the annual average temperature is 15.6°C, the coldest month average temperature is 3.3°C, the annual average relative humidity is 82%, and the annual average precipitation is 1220mm, the average number of precipitation days is 140 days. The annual average tide level is 2.18m, the average high tide level is 4.40m, the average bottom tide level is -0.29m (the reference surface is WuSong zero point).

4.3 Test system

The sea cap in tidal zone were selected as the study object. The concrete strength grade was C40, 28-day cube compressive strength standard value 57.4MPa, water-to-binder ratio 0.33, mixed with fly ash and slag, cementitious material 405 kg/m^3, concrete cover thickness 90mm. Two kinds of laboratory artificial simulated environment $E_{a,1}$ (NTBuild-492[29]) and $E_{a,2}$ were constructed. The input parameters of test system (S_{ex}, $E_{a,1}$) are: NaCl solution concentration was 10%, laboratory temperature 20~25°C, initial voltage 30V; the output parameter was the color depth of $AgNO_3$ indicator. Input parameters of test system (S_{ex}, $E_{a,2}$) were: NaCl solution concentration was 5.74%, simulating the dry-wet cycle of the tidal zone every 48 h, the temperature of the air-drying phase 20 °C; the output parameter is the free chloride ion concentration.

4.4 METS path

Selected two reference objects (existing structural systems $S_{es,1}$ and $S_{es,2}$) in the same environment as the research object (the proposed structural system S_{ns}), and the laboratory artificial simulation environment $E_{a,1}$ and $E_{a,2}$ were constructed respectively as mentioned above. Concrete strength grade of $S_{es,1}$ and $S_{es,2}$ were C25 and C40 respectively; water-to-binder ratio of $S_{es,1}$ and $S_{es,2}$ were 0.45 and 0.40 respectively.

The test was carried out to obtain chloride ion concentration for existing structural systems ($S_{es,1}$, E_{n}) and ($S_{es,2}$, E_{n}) as well as test systems ($S_{ex,1}$, $E_{a,1}$) and ($S_{ex,2}$, $E_{a,2}$). Then the surface chloride ion concentration C_s and the diffusion coefficient D were calculated by the equation (23) and (24) respectively. There were four METS paths used to observe the proposed structural system S_{ns} in the marine chloride environment E_{n}, including METS($S_{es,1}$; $E_{a,1}$) and METS($S_{es,2}$; $E_{a,2}$) and METS($S_{es,1}$; $E_{a,2}$) and METS($S_{es,2}$; $E_{a,2}$). For the above four METS paths, they were numbered as $METS_1$, $METS_2$, $METS_3$, and $METS_4$ respectively. The statistical parameters of all METS paths are shown in Table 1.

Table 1. Statistical parameters of all the METS paths

METS paths	Variables	Unit	μ	σ	Distribution type
METS($S_{es,1}$; $E_{a,1}$) $METS_1$	C_s	%	0.62	0.16	Normal
	D	mm^2/d	0.071	0.022	Normal
	$\lambda(D)$	-	6.66	0.76	Normal
	d_{cover}	mm	90	9	Lognormal
	C_{cr}	%	0.05	0.01	Normal
METS($S_{es,2}$; $E_{a,1}$) $METS_2$	C_s	%	0.65	0.13	Normal
	D	mm^2/d	0.071	0.022	Normal
	$\lambda(D)$	-	4.40	1.15	Normal
	d_{cover}	mm	90	9	Lognormal
	C_{cr}	%	0.05	0.01	Normal
METS($S_{es,1}$; $E_{a,2}$) $METS_3$	C_s	%	0.472	0.076	Normal
	$\lambda(C_s)$	-	0.91	0.15	Normal
	D	mm^2/d	0.030	0.008	Normal
	$\lambda(D)$	-	3.21	1.21	Normal
	d_{cover}	mm	90	9	Lognormal

	C_{cr}	%	0.05	0.01	Normal
METS($S_{es,2}$; $E_{a,2}$) METS$_4$	C_s	%	0.472	0.076	Normal
	$\lambda(C_s)$	-	1.24	0.24	Normal
	D	mm^2/d	0.030	0.008	Normal
	$\lambda(D)$	-	2.53	0.69	Normal
	d_{cover}	mm	90	9	Lognormal
	C_{cr}	%	0.05	0.01	Normal

4.5 Relative information entropy

For the proposed structural system S_{ns} in the marine chloride environment E_n , the system S_{ns} outputs the function Z (i.e., equation (15)) to the observer R. The relative information entropy in the time period [0, t] when observer R observes the proposed structural system S_{ns} through METS($S_{es,1\sim i}$; $E_{a,1\sim j}$) path is as followed:

$$\begin{cases} H_i[S_{ns}(Z;t)/\mathrm{METS}(S_{es,1\sim i};E_{a,1\sim j})] = \\ -P_s(S_{ns};t)\cdot\log_2 P_s(S_{ns};t) - P_f(S_{ns};t)\cdot\log_2 P_f(S_{ns};t) \\ H_o[S_{ns}(Z;t)/\mathrm{METS}(S_{es,1\sim i};E_{a,1\sim j})] = \\ -\{P_{\tilde{A}}(S_{ns};t)\cdot\log_2 P_{\tilde{A}}(S_{ns};t) + [1-P_{\tilde{A}}(S_{ns};t)] \\ \quad \cdot\log_2[1-P_{\tilde{A}}(S_{ns};t)] + P_{\tilde{B}}(S_{ns};t)\cdot\log_2 P_{\tilde{B}}(S_{ns};t) \\ +[1-P_{\tilde{B}}(S_{ns};t)]\cdot\log_2[1-P_{\tilde{B}}(S_{ns};t)]\}/2 \end{cases} \tag{25}$$

The grammatical information entropy $H_i[S_{ns}(Z;\ t)/\mathrm{METS}(S_{es,1\sim i};\ E_{a,1\sim j})]$ is calculated first by calculating the $P_s(S_{ns};\ t)$ and $P_f(S_{ns};\ t)$ according to the durability limit state equation in marine chloride environment, then substitute $P_s(S_{ns};\ t)$ and $P_f(S_{ns};\ t)$ into equation (25).The semantic information entropy $H_o[S_{ns}(Z;\ t)/\mathrm{METS}(S_{es,1\sim i};\ E_{a,1\sim j})]$ reflects the ambiguity of the observer R on the semantics of the function Z. The ambiguity of the semantics of the function Z comes from that the understanding of the critical chloride ion concentration C_{cr} is ambiguous and can be expressed by total chloride ion concentration, free chloride ion concentration, chloride ion to hydroxide ratio, etc [30,31]. Even if the chloride ion concentration on the surface of the steel bar reaches the critical chloride ion concentration, it does not mean that the steel bar must be corroded, it only means that the steel bar has a high probability of depassivation [**Error! Bookmark not defined.**,32]. Then, there is a fuzzy interval [$C_{cr,min}$, $C_{cr,max}$] for the critical chloride ion concentration C_{cr}, and the minimum critical chloride ion concentration $C_{cr,min}$ means that the probability of steel bar corrosion is 0 when the concentration is not exceeding it, and the maximum critical chloride ion concentration $C_{cr,max}$ means that rust will must be produced when this concentration is reached.

Defined the membership function of the function Z belonging to the fuzzy set $\boldsymbol{A}$={"reliable"} as $\mu_{\boldsymbol{A}}(Z)$, the membership function of the function Z belonging to the fuzzy set $\boldsymbol{B}$={"failure"} as $\mu_{\boldsymbol{B}}(Z)$.The membership function $\mu_{\boldsymbol{A}}(Z)$ was constructed as followed:

$$\mu_A(Z) = \begin{cases} 0 & Z < C_{cr} - C_{cr,max} \\ \dfrac{Z}{C_{cr,max} - C_{cr,min}} & C_{cr} - C_{cr,max} \le Z \le C_{cr} - C_{cr,min} \\ 1 & Z > C_{cr} - C_{cr,min} \end{cases} \tag{26}$$

Construct the membership function $\mu_{\boldsymbol{B}}(Z)$ =1-$\mu_{\boldsymbol{A}}(Z)$. The curve of the membership function $\mu_{\boldsymbol{A}}(Z)$ and $\mu_{\boldsymbol{B}}(Z)$ of the function Z are shown in Figure 6. Substitute the formula $\mu_{\boldsymbol{A}}(Z)$ and the formula $\mu_{\boldsymbol{B}}(Z)$ into the equations (6) to (7) respectively to calculate the "reliable" possibility $P_{\tilde{A}}(S_{ns};\ t)$ and "failure" possibility $P_{\tilde{B}}(S_{ns};\ t)$, then substitute $P_{\tilde{A}}(S_{ns};t)$ and $P_{\tilde{B}}(S_{ns};\ t)$ into equation (25) to obtain semantic information entropy.

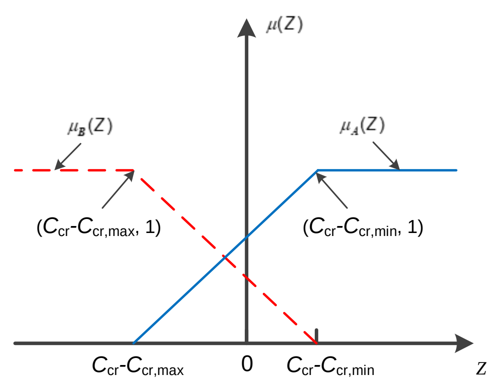
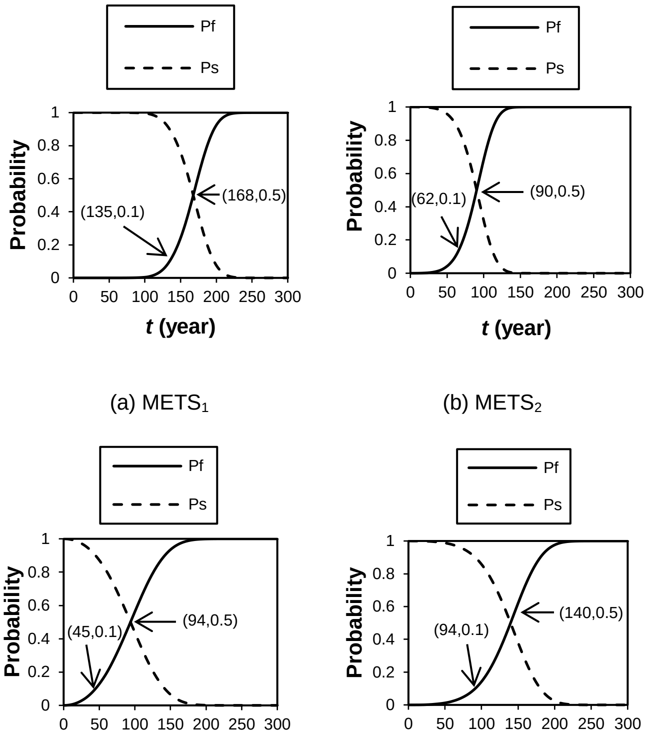


Figure. 6 Membership function of performance function Z

5 Calculation results

5.1 Observation result through METS path



(a) $METS_1$ (b) $METS_2$

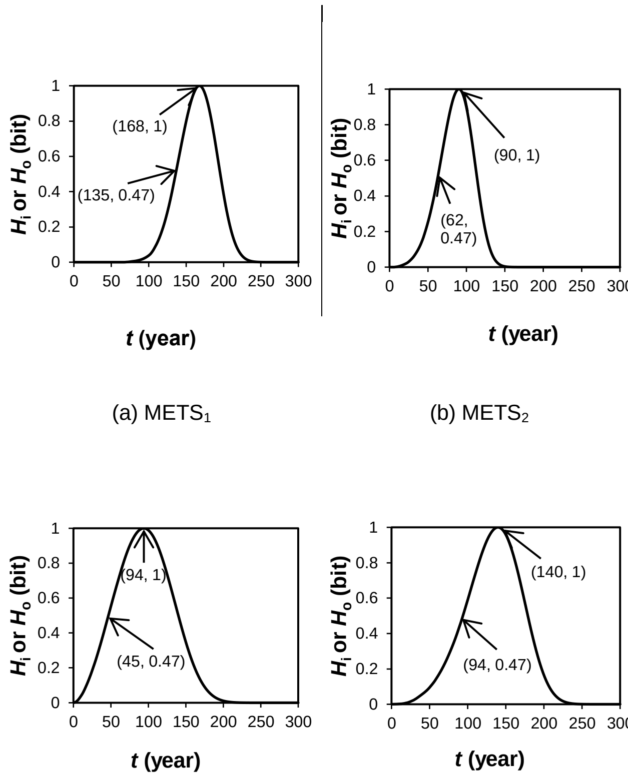
(c) $METS_3$ (d) $METS_4$

Figure. 7 Reliable probability and failure probability of all the METS paths

Through the four METS paths in Table 1, the reliable probability $P_s(S_{ns};t)$ and the failure probability $P_f(S_{ns};t)$ of the proposed structural system S_{ns} are calculated respectively. The calculation results are shown in Figure 7.

The reliable probability $P_s(S_{ns};t)$ is monotonically decreasing, and the failure probability $P_f(S_{ns};t)$ is monotonically increasing. It can be seen from Figure 7 that for the $METS_1$ path the failure probability $P_f(S_{ns};t)$ exceeds 0.1 in the 135th year (the corresponding β^* is 1.3); the reliable probability $P_s(S_{ns};t)$ and the failure probability $P_f(S_{ns};t)$ are both 0.5 at the 168th year (corresponding to β^* is 0). For the $METS_2$ path: the failure probability $P_f(S_{ns};t)$ exceeds 0.1 in the 62nd year; the reliable probability $P_s(S_{ns};t)$ and the failure probability $P_f(S_{ns};t)$ are both 0.5 at the 90th year. For the $METS_3$ path: the failure probability $P_f(S_{ns};t)$ exceeds 0.1 in the 45th year; the reliable probability $P_s(S_{ns};t)$ and the failure probability $P_f(S_{ns};t)$ are both 0.5 at the 94th year. For the $METS_4$ path: the failure probability $P_f(S_{ns};t)$ exceeds 0.1 in the 94th year; the reliable probability $P_s(S_{ns};t)$ and the failure probability $P_f(S_{ns};t)$ are both 0.5 at the 140th year.

The ambiguity of semantics of observer's function Z is not considered, which means that the grammatical information entropy or semantic information entropy are equal. The calculated results of relative information entropy of the proposed structural system S_{ns} are shown in Figure 8.



(a) $METS_1$ (b) $METS_2$

(c) $METS_3$ (d) $METS_4$

Figure 8. Relative information entropy of all the METS paths

The grammatical information entropy is equal to the semantic information entropy, which is monotonically increasing first, and then monotonically decreasing after reaching the extreme point.It can be seen from Figure 8 that for the $METS_1$ path the relative information entropy exceeds 0.47 bit in the 135th year (the corresponding failure probability $P_f(S_{ns};t)$ is 0.1, β^* is 1.3); the relative information entropy reaches the maximum value 1 bit in the 168th year(corresponding failure probability $P_f(S_{ns};t)$ is 0.5, β^* is 0). For the $METS_2$ path, the relative information entropy exceeds 0.47 bit in the 62nd year; the relative information entropy reaches the maximum value 1 bit in the 90th year. For the $METS_3$ path, the relative information entropy exceeds 0.47 bit in the 45th year; the relative information entropy reaches the maximum value 1 bit in the 94th year. For the $METS_4$ path, the relative information entropy exceeds 0.47 bit in the 94th year; the relative information entropy reaches the maximum value 1 bit in the 140th year.

5.2 Test results of the built system

After the proposed structural system S_{ns} was built, the chloride ion concentration of the tidal zone cap was tested, and the surface chloride ion concentration and diffusion coefficient were obtained according to equation (25). In the marine chloride environment E_n , the statistical parameters of the built structural system S_{ns} are shown in Table 3.

Table. 3 Statistical results of surface chloride ion content and diffusion coefficient from S_{ns}

System	Variables	Unit	μ	σ	Distribution type
METS($S_{es,1}$; $E_{a,1}$)	C_s	%	0.173	0.063	Normal
	D	mm^2/d	0.018	0.012	Normal

The reliable probability $P_s(S_{ns};t)$ and the failure probability $P_f(S_{ns};t)$ of the proposed structural system S_{ns} were calculated. The results are shown in Figure 9. The failure probability $P_f(S_{ns};t)$ exceeds 0.1 in the 101st year; the reliability probability $P_s(S_{ns};t)$ and the failure probability $P_f(S_{ns};t)$ are both 0.5 at the 147th year.The calculated results of relative information entropy of the built structure system S_{ns} are shown in Figure 10.

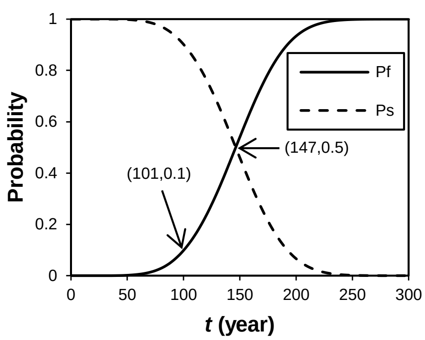


Figure. 9 Reliable probability and failure probability of S_{ns}

The relative information entropy exceeds 0.47 bit in the 101st year; the relative information entropy reaches the maximum value of 1 bit in the 147th year.

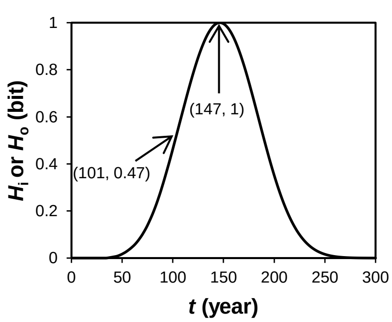


Figure 10: Relative information entropy of S_{ns}

The 90% guaranteed rate of steel bar depassivation time $T_{c,0.9}$ and the average depassivation time $T_{c,m}$ of each METS path and the proposed structural system S_{ns} are shown in Table 4.

Table 4. Steel bar depassivation time from all METS paths and S_{ns}

Observation path and system	$T_{c,0.9}$ /(year)	$T_{c,m}$ /(year)
$METS_1$	135	168
$METS_2$	62	90
$METS_3$	45	94
$METS_4$	94	140
S_{ns}	101	147

It can be seen from Table 4 that the predicted life of the proposed structural system S_{ns} through the $METS_1$ path is slightly higher than the calculated durability life of the post-built system, and the predicted life through the $METS_2$ ~ $METS_4$ path is smaller than that that of the post-built system, while the result of $METS_4$ path is closer. Therefore it is reasonable to observe the proposed structural system S_{ns} through the $METS_1$ path and the $METS_4$ path.

6 Conclusion

1) METS path may characterize the observation process in which the observer (structural engineer) observe the study subject (the proposed structural system). The observation process contains information of the third-party reference object (existing structural system) and accelerated durability test (test system).

2)RI-METS theory based on concrete damage in marine chloride environment is established, and the similarity formula of variables is given. Considering ambiguity of the semantic of function Z, the membership function is established, and the calculation formula of relative information entropy is given.

3)Taking the cap in the marine chloride environment as example, the application process of RI-METS theory in the durability of concrete structures in marine chloride environment is given. Four METS paths are used to observe the proposed structural system Sns. The METS1 path and METS4 path are found more closer to results obtained from the built structural system.

4)More METS paths and information should be considered to determine the most reasonable system observation path. The application of RI-METS theory in the durability of concrete structures in other chloride environments such as deicing salt, chemical corrosion environment, salt crystallization environment, and abrasive environment still needs further study.

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