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Bearing capacity reliability analysis of Service Bridge under rebar corrosion attack

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ABSTRACT

During all the service life, bridge structure subjected to environmental attack and repeatedly loads, which leads deformation wider, more surface carbonization and steel embedded corrosion seriously. Two corrosion models are introduced in this paper, the random variables are determined, the failure probability is calculated by Monte-Carlo method. The reliability factors, such as material variation, dead loads, live loads, corrosion rate are analyzed also. It shows the decreasing rate of cross section area is faster than that of local corrosion's, the failure probability is bigger too. The effective cross-section area of steel-bar, yield strength, and live loads is more sensitive on failure probability.

Key words: Bridge; damage; bearing capacity; reliability

INTRODUCTION

Reinforced concrete structure has been widely used in bridge engineering for its good performance and economic cost. However, the reinforced concrete bridge will gradually aging damage in the course of its operations, though the degradation process of resistance is gradual, the final result of structural damage is sudden and brittle, with high randomness and unpredictability, which often bring on considerably difficulties for safety precautions. The structural damage factors can be generally divided into the three aspects as following, 1) load effect; 2) environmental effect on steel and concrete, including concrete carbonation and steel corrosion ; 3) material performance degradation including shrinkage and creep etc.[1] The steel bar corrosion is one of the main factors causing component resistance deterioration.

Chloride, sulfate, and freeze-thaw cycles often lead to reinforcement bar corrosion. In early 1980s, based on summation of existing research results, Page etc. gave a detailed exposition of protective role with reinforced concrete, carbonation corrosion and corrosion mechanism of reinforcement bar. Gonzalez discussed the corrosion process, the influence and limit rate of steel corrosion. Roberto analyzed the effect mechanism of corrosion to reinforced concrete bending, shear, torsion bearing capacity qualitatively[2][3]. WangLei established the fuzzy random reliability time-varying probability model of existing bridges[4],which focused on concrete strength, steel bar cross-sectional area and strength. A number of scholars analyzed the failure probability of existing bridge by FOSM design point method, Monte-Carlo method, JC method etc.[5][6][7]. In this paper, based on the analysis of two different steel bar corrosion modes, the random variables on bridge capacity reliability are studied, which involve material variation, dead loads, live loads and steel bar corrosion rate.

INFLUENCE FACTORS OF STEEL BAR CORROSION

Steel corrosion in concrete structures is the important factor that affects the reliability, the harm is shown mainly in three aspects as following: Firstly, reducing the structural (or component) carrying capacity and safety reservation; secondly, lessening the structural (or component) stiffness, increasing the deformation, even leading to spalling of the concrete cover and can't use normally; thirdly, reducing the structure ductility, even changing their destructive patterns and resulting in destructive disaster. Steel bar corrosion results in engineering destroyed repeatedly, it has attracted the attention of engineers all over the world.

2.1 Electrochemical corrosion principle of reinforcement bar

The dissolve oxygen in water absorbs the anode electron, then generates hydroxide ions OH^- . The corrosion current generated because electrons from the anode flows to cathode continuously. The ferric hydroxide is formed on the surface of reinforce bar, i.e. rust. Since the rust is loose, porously, non-coherent structure, good gas and water permeability. It can't prevent the internal steel bar from corrosion no matter how thick it is.

2.2 Corrosion by carbonation

For reinforced concrete structures, once the carbonation reach to the steel bar surface, reinforced carbon film will be destroyed, resulting in decreased alkalinity. As long as it has appropriate temperature and oxygen on the steel surface, corrosion of steel bar in concrete will expand and result in concrete structure destruction.

2.3 Other key factors

In general, the rebar does not produce rust under the protection of the surrounding concrete. However, the carbon dioxide in the air may be penetrate into the concrete easily as insufficient compacting concrete, thin or destroyed concrete cover layer, the higher porosity, uneven composition. Then the alkalinity of the concrete is less, the protective effect of concrete is weakened. In addition, structural cracks accelerated steel corrosion due to other various reasons.

STRUCTURAL PERFORMANCE OF CORRODED REINFORCED CONCRETE

3.1 Nonuniformity of steel bar corrosion

Unevenness of concrete means a small area of protective membrane damaged firstly by the invasion of the hazardous substances. The local corrosion is deep with small area. When the harmful substances invade concrete comprehensively, the rebar protective film in large area will be destroyed. The rebar will rust widespread because of anodic electrochemical reaction. The corrosion thickness increases gradually.

For practical engineering, local corrosion and Uniform corrosion are often both exist, but the corrosion inhomogeneity is not same as different environment and concrete quality.

3.2 Stress - strain curve of corroded steel bar

In general, the hot-rolled steel made by normal production process and chemical composition has obvious yield point and yield plateau, the ratio of tensile strength with yield strength is generally 1.25 to 1.5. Some experimental studies show the hot rolled steel has a distinct yield point when the loss of cross-section area is less than 10%. However, the stress-strain curve of severe corrosion rebar changed considerably, with no apparent yield point, the yield strength and tensile strength are very close. It may lead to sudden destruction of the structure easily.

With the increasing of steel corrosion rate, the yield and tensile strength decrease, which was mainly due to the stress concentration at the outer edge of the rebar micro corrosion.

China Academy of Building Research studied the feature of steel bar d = 12 mm, got the relation of nominal ultimate tensile strength (tensile force divided by the nominal cross-sectional area) with λ as follows,

$$\sigma_b^* = (1 - 0.695\lambda)\sigma_b \tag{1}$$

Where, λ is local sectional loss rate of rebar.

② The following formula is given by Hui Yunling etc.

$$f_{ys} = \frac{0.985 - 1.028\eta_s}{1 - \eta_s} f_{yo} \tag{2}$$

$$f_{bs} = \frac{0.986 - 1.103\eta_s}{1 - \eta_s} f_{bo} \tag{3}$$

where f_{ys} 、 f_{bs} is the yield strength and tensile strength Respectively derived by the actual area after corrosion ; f_{yo} 、 f_{bo} is the yield strength and tensile strength before corrosion, η_s is the area loss rate at

Corroded Rebar minimum cross-section.

3.3 Bonding performance of corroded steel bars and concrete

The bond grappling between steel and concrete is a very complex interaction, which passes the stress and deformation, so good bond grappling is the co-work precondition of steel and concrete. Studies shows that steel corrosion will cause the bond performance degradation between steel and concrete, because:

- A loose rust layer will form after steel corrosion in concrete, which destroy the Chemical adhesive between rebar surface and cement gel. The interface contact conditions have been changed, the friction coefficient between the steel and concrete has reduced.

- The radial expansion force acting on concrete around rebar will generate while corrosion steel caused volume expansion. When the radial expansion force reaches tensile strength of concrete, the concrete protective layer will fall away or cracking, which result in reducing the constraints of concrete with the rebar.

- For deformed bar, the deformation rib will degrade gradually due to rust. When it has been rusted badly, the occlusion effect between deformation ribs and concrete lost. The co-work reduction factor k_b is given by

$$k_b=e^{-0.093w} \tag{4}$$

$$w = 2.132\left(1-\sqrt{1-0.01\eta_s}\right)d - 0.075 \tag{5}$$

Where, d is the bar diameter(mm),η_s is the loss rate of rebar section (%) .

3.4 Mechanism of performance degradation for corroded reinforced concrete structure

In summary, for corroded reinforced concrete structure, the degradation of mechanical properties is due to degradation of steel and the bond performance degradation.

The structural strength and ductility will change after Rebar corrosion, even severe structural damage occurs from plastic into sudden brittle failure.

MODEL OF STEEL CORROSION

Reinforcement corrosion is an electrochemical process. The amount of corrosion is a parameters related with time, which can be determined by non-destructive techniques. Steel corrosion rate is evaluated by current density i_{corr}, the steel weight loss is determined by corrosion current. Faraday's law shows the reduced cross-section of rebar is 11.6μm one year, when the corrosion current density i_{corr} is $1\mu A / cm^2$, correspondingly [8].

According to its different shape, steel corrosion can be divided into uniform corrosion and localized corrosion. The localized corrosion are often located at cracks or weaker position [9] . for general member, the local corrosion is more common.

4.1 Uniform Corrosion

For uniform corrosion, the corroded reinforced diameter D (t) after t_1 years can be expressed as follow [10]

$$D(t) = D_0 - 0.0232\int_{t_0}^{t_1} i_{corr}(t)dt \tag{6}$$

For a constant corrosion rate, above equation can be written as

$$D(t) = D0-0.0232(t-t0)\, i_{corr} \tag{7}$$

Where, D_0 is the initial diameter of the reinforcement (mm), t_0 is corrosion initiation time (year) .

4.2 Localized corrosion

For localized corrosion, the maximum pit depth on steel surface is 4 to 8 times than that of uniform corrosion. These pit shapes are different from each other and it is difficult to determine the area accurately. For simplicity, it is assumed that the local corrosion point is eroded as circumferentially shape, shown in Figure 1. The rust spot radius ρ(t) after t years can be calculated as

$$\rho(t) = 0.0116(t-t0)\, i_{corr}\omega \tag{8}$$

Where, ω = 4 ~ 8 is uniformity coefficient of rust, which can be considered as a deterministic parameter, i_{corr} is the variant following normally random distribution. A(t) is the remaining reinforcement area (shaded area) after t years, it can be expressed as

$$A(t)=\begin{cases}\dfrac{\pi D_0^2}{4}-C_1-C_2 & (\rho(t)\le\dfrac{\sqrt{2}}{2}D_0)\\ C_1-C_2 & (\dfrac{\sqrt{2}}{2}D_0<\rho(t)\le D_0)\\ 0 & (\rho(t)>D_0)\end{cases} \qquad (9)$$

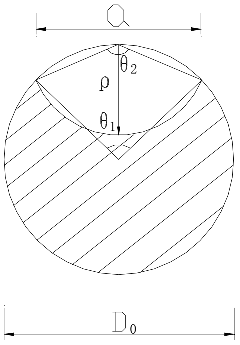

Fig. 1: Local corrosion of steel reinforced bar

$$C_1=\frac{1}{2}\left[\theta_1\left(\frac{D_c}{2}\right)^2-\frac{1}{2}\alpha\sqrt{D_c^2-\alpha^2}\right];$$

$$C_2=\frac{1}{2}\left[\theta_2\rho(t)^2-\alpha\frac{\rho(t)^2}{D_0}\right];$$

$$\theta_1=2\arcsin\left(\frac{\alpha}{D_0}\right);$$

$$\alpha=2\rho(t)\sqrt{1-\left[\frac{\rho(t)}{D_0}\right]^2};$$

For reinforced of localized corrosion, the average diameter is $D(t)=2\sqrt{A(t)/\pi}$. Not all bars rust at the same time. It is usually that the lateral reinforcement corrodes at first. So after elapsed time t, the total cross-sectional area of reinforcement is as follows:

$$A_s=\frac{\pi}{4}\sum_{j=1}^{n}\left[D_j(t)\right]^2 \qquad (10)$$

$$D_j(t)=\begin{cases}D_{0j} & t\le T_j\\ D_{0j}-r_c(t-T_j) & T_j<t<T_j+D_{0j}/r_c\\ 0 & t\ge T_j+D_{0j}/r_c\end{cases} \qquad (11)$$

Where, Dj (t) is the diameter of the bar j at time t, n is the number of steels, D_{0j} is the initial diameter of the rebar j, $r_c = 0.0232\times i_{corr}$ is the corrosion rate , t is the elapsed time, T_j is the initial corrosion time of rebar j.

After Reinforcement corroded, the carrying capacity of components reduced to a certain degree with different corrosion level. According to the test results, for the reinforcement corrosion flexural and compression members, when we calculate the component strength by normal method, the section loss, yield strength loss, strength degradation caused by bond loss should be considered, which based on the degree of corrosion cracking and damage.

DETERMINATION OF RANDOM VARIABLES

The variability of materials and load have been taken into account for calculation, the structural dimensions variability is ignored. According to *Highway Engineering uniform standards for reliability design* and statistics results, it can be considered that material strength and dead load follow normal distribution, the vehicle load follows distribution normal too[11][12]. The normal distribution function is expressed as following form:

$$S(x) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{+\infty} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2} \right] dx \tag{12}$$

$\mu = kG \qquad \sigma = \mu \cdot Cov$

Where, $S(x)$ is the probability distribution function, G is the design value of random variable, μ 、σ 、Cov is the variable mean, standard deviation and coefficient of variation respectively.

Under the live load of vehicles, the moment in middle span of concrete bridge can be expressed as

$$M_b = C_r(1+\mu)M_q \tag{13}$$

Where, M_b is the moment generated by live load in middle span, the dynamic impact factor and model uncertainty factor has been considered, C_r is uncertain variable in the calculation model which the mean value is 1.0980, the coefficient of variation is 0.071[13] ; $1+\mu$ is the coefficient of impact factor, the mean value is 1.15, the standard deviation is 0.1.

Reinforcement corrosion current density i_{corr} (steel corrosion rate) can be regarded as following normal distribution. Because lack of the measured data related to rust uniformity coefficient ω, the coefficient of variation(COV) for local corrosion i_{corr} is set to higher than that of overall corrosion. The types and distribution functions of the probability distribution with Some variables are given as following.[14]

Tab. 1 probability distribution type and parameters of Some variables

variable	Distribution Type	Mean	Coefficient of variation
variationC25 concrete compressive strength (MPa)	Normality	$1.5868M_k$	0.1928
Steel tensile strength (MPa)	Normality	$1.0849R_a$	0.0719
uncertainty coefficient of resistance calculation model (Moment)	nality	$1.0980R_g$	0.071
Uniform Corrosion of i_{corr} ($\mu A / cm^2$)	Normality	3	0.20
Local corrosion i_{corr} ($\mu A / cm^2$)	Normality	3	0.30
Constant loads	Normality	$1.0148\ W_k$	0.0431
Vehicle load (axle load)	Logarithmic normal	0.633925	0.922265
Automobile shock coefficient	Normality	1.15	0.10

EQUATIONS AT LIMIT STATE

For reinforced concrete T-beam, the limit state equation of normal section flexural can be expressed as following

$$R_g A_g (h_0 - y) - C_r (M_D + M_q) = 0 \tag{14}$$

(1) When $R_A bh_j \geq R_g A_g$, the neutral axis is located on the upper flange,
From $\Sigma N = 0$ it can be Obtained $N = R_g A_g = bxR_a$ (15)

From $\Sigma M = 0$ get

$$R_g A_g \left(h_0 - \frac{R_g A_g}{2bR_a} \right) - C_r (M_D + M_q) = 0 \tag{16}$$

Where, R_g- reinforced bar strength, A_g is area of main reinforcement, R_a is compressive strength of concrete, h_0 is effective height, b is width of flange plate, h_j is the height of upper flange plate, M_D is the moment by dead load, Mq is moment by vehicle live load.

(2) When $R_a bh_j < f_s A_s$, the neutral axis is within the web,
From $\Sigma N = 0$, the following is obtained $N = R_g A_g = [b \bullet h' + b'(x-h')] R_a$ (17)

From $\Sigma M = 0$, get $M = R_g A_g \left(h_0 - y\right)$ (18)

$$y = \frac{x}{2} \cdot \frac{b'x}{b'x + (b - b')h'} + \frac{h'}{2} \cdot \frac{(b - b')h'}{b'x + (b - b')h'}$$

$$x = \frac{f_s A_s - f_c (b - b')h'}{f_c b'}$$

Where y is the distance from weight center of compression areas to the top of the beam, x is the distance from the neutral axis to the top of beam, b' is the thickness of web.

EXAMPLES

7.1 Basic data

A simply supported beam bridge span is 20.0 m, the deck horizontal clearance is 9 +2 × 1.0m. Each span consists of five prefabricated reinforced concrete T-beams, the beam plate width 2.2m. Five diaphragms have been arranged along the main beam longitudinally. The pavement is used by asphalt concrete. The design vehicle load level is truck 20t and trailer 100t, crowd loading is 3.5KN / m.

The resistance is analyzed by the finite element method, each span is divided into 20 elements and 21 nodes, the piers is simplified mobile and fixed hinge bearing.

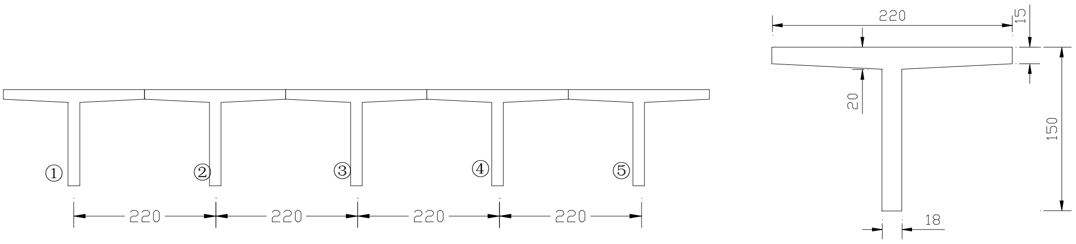

Fig. 2: Cross section of main girders (unit: cm)

7.2 Reliability Calculation

Monte-Carlo method is used to calculate the reliable indicator. Based on the load model and steel corrosion model, the reliability changes of reinforced concrete bridges during operations are analyzed. Under different modes of steel corrosion, some parameters are used to study the influence on the reliability, which include the strength of materials, live load, dead load and corrosion rate. In this paper, only the moment failure mode at middle span is discussed, other reliability analysis of failure modes can be calculated based on the same principle.

(1) Area changes of Rebar over time

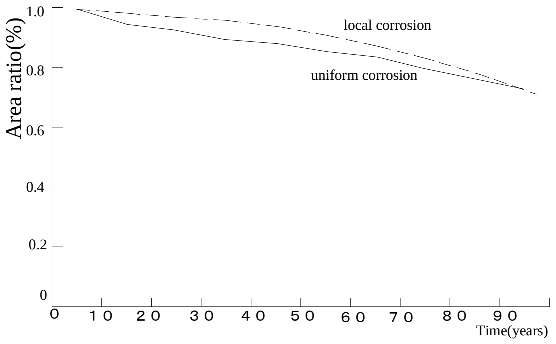

Fig. 3: Rebar area variation with the time

The carbonized model is used to calculate the initial time of steel corrosion, the rebar effective area variation with the time is obtained by reinforced rust model, which is shown in Figure 3. In local corrosion model, it is assumed that the rebar only close to the protective layer of reinforced concrete produces local corrosion. It is shown that the effective area of reinforcement always decreases during the service life of the bridge. In the earlier time, the area reduction of overall rust is faster than that of local corrosion, which is gradually approaching over time.

(2) Reliability analysis of the main girder

Since five main girders are symmetrical for bridge axis, so we study only the girders of 1-3 #. In both corrosion models, the changes of failure probability during the operation are shown in Figure 4-5.

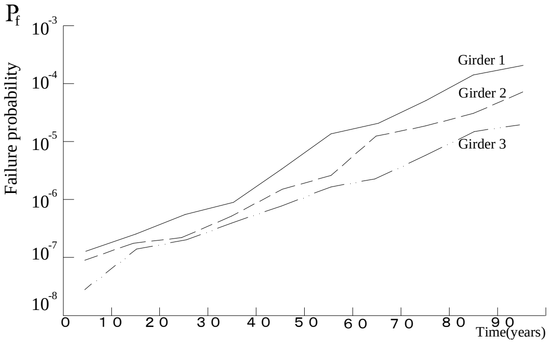

Fig. 4: Failure probability of main girder (uniform corrosion)

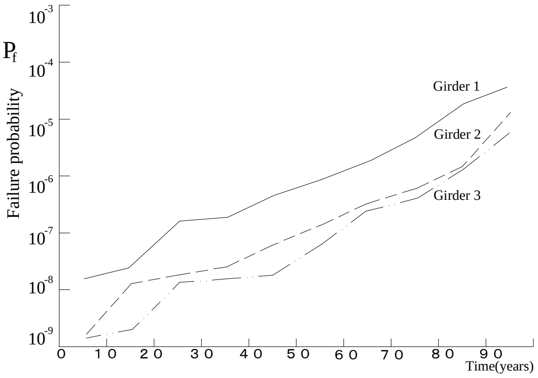

Fig. 5: Failure probability of main girder (local corrosion)

For both corrosion model, with the elapse time of the bridge, the reliability of all beams decrease with the time, i.e. the probability of failure increases. The comparison shows that the failure probability of uniform corrosion is greater than that of local corrosion at the same time, which is inconsistent with the area change of rebar. Because the transverse load distribution coefficient of beam No.1 is greater than others, the load effect is obviously, the failure probability is greater too.

(3) Reliability Analysis of Main Beam System

The bridge girders bear the load together, so a few several main beams may carry ultimate load by larger loads, external load will react by linear distribution. In particular, the influence of correlation between main beams on system reliability is considered. At present, the results on correlation beam system are seldom. In this paper, it is assumed that strengthen of each component follows the same distribution, the correlation coefficient is equal. The system reliability is analyzed for two beams and five beams respectively. It is shown in Figure 6.

The difference of failure probability for two beams and five beams shows the beam bridge has the nature of parallel system, this also explains the beam bridge has the remaining reliability.

The more the number of system components is, the smaller of correlation coefficient, and the greater of the system failure probability. In general, the components strength and load are not the same, the few individual components act on system reliability than other components significantly. The difference of initial strength between members is one reason. Besides, the strength degradation mechanism is different and the decay rate and the initial time are various. During different running times, the member effect the system reliability mostly is changeable also.

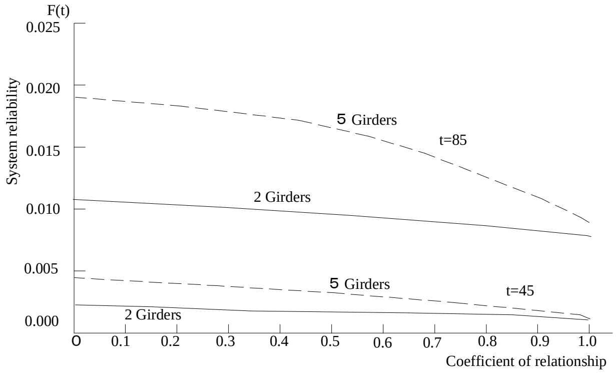

Fig. 6: Dependence of system failure probability on correlation coefficient

(4) Analysis of Parameter Sensitivity

Taking the beam No.1 as an example, some parameters on the component reliability are discussed, which are the material variation, dead loads, live loads, and corrosion rate.

1)Reinforced bar yield strength

The variation coefficient of steel yield strength is 0.0719, 0.1719 and 0.2719 respectively. The reliability changes of girder No.1 is shown in Figure 7 by uniform corrosion model. The variation coefficient of steel strength influence the girder reliability is greatly. With the service life increasing, the failure probability is faster.

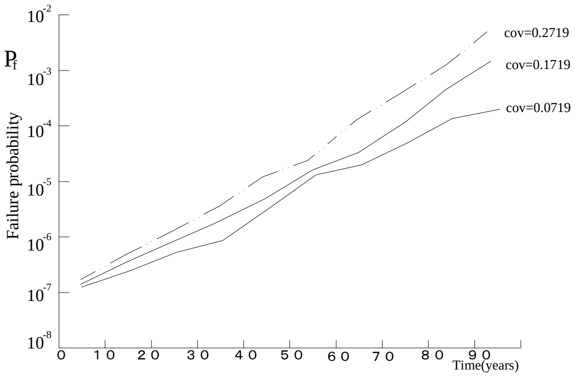

Fig. 7: Influence of reinforced bar yield strength

2) Compressive Strength of Concrete

The variation coefficient of concrete compressive strength is 0.19, 0.29 and 0.39 respectively. The reliability changes of girder No.1 is shown in Figure 8 by uniform corrosion model. The concrete compressive strength influences the girder reliability slightly. At last service years the variability influence the component reliability more remarkable.

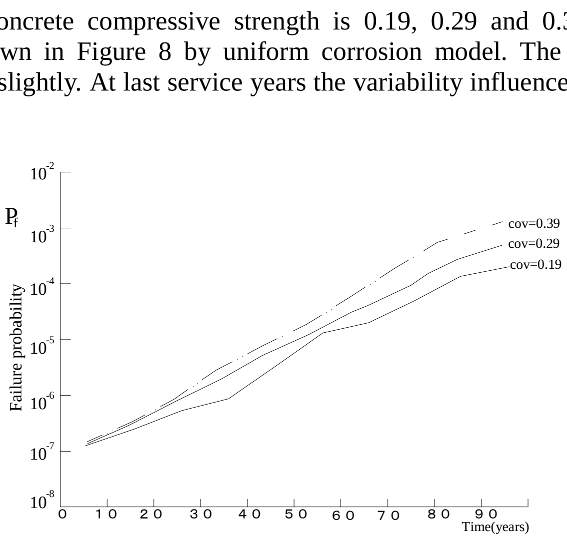

Fig. 8: Influence of concrete crush strength on failure probability

3) Steel corrosion rate

In uniform corrosion model, the variation coefficient of steel corrosion density icorr (steel corrosion rate) is 0.10, 0.20 and 0.30 respectively. In local corrosion model, the variation coefficient is 0.20, 0.40 respectively. The reliability changes of girder No.1 is shown in Figure 9 and Figure 10 for both model. It is shown that the steel corrosion rate affects little to the reliability of the component. For localized corrosion, the corrosion rate of steel influences on the component reliability bigger and bigger in last service years.

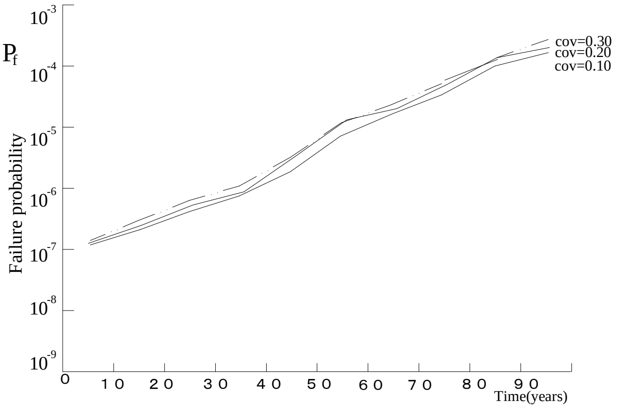

Fig. 9: Influence of rebar corrosion velocity (uniform corrosion)

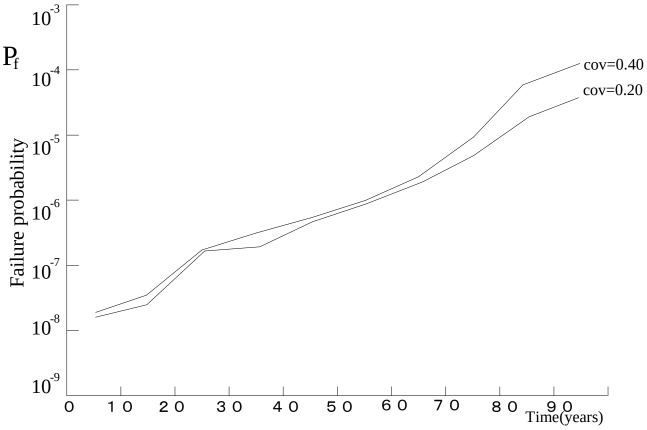

Fig. 10: Influence of rebar corrosion velocity (local corrosion)

4) Influence of dead load on the component failure probability

The variation coefficient of dead load (including the bridge deck and T-beam weight) is 0.043, 0.143 and 0.243 respectively. The reliability changes of girder No.1 is shown in Figure 11 and Figure 12 for both model. It is shown that the dead load affects little to the failure reliability of the T-beam. For local corrosion, the influence of dead load is greater slightly than that of the uniform corrosion in service years.

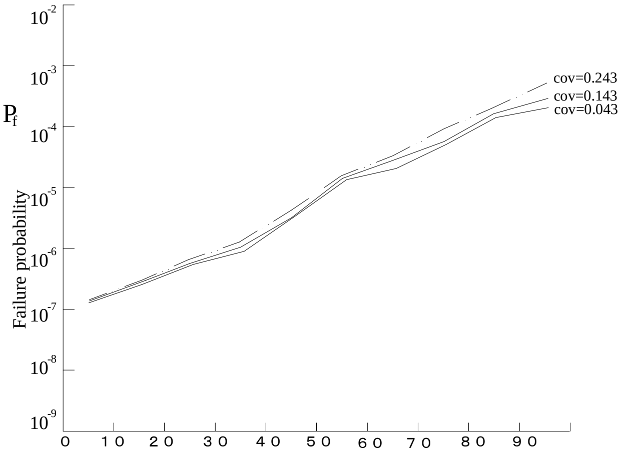

Fig. 11: Influence of dead load on main girder (uniform corrosion)

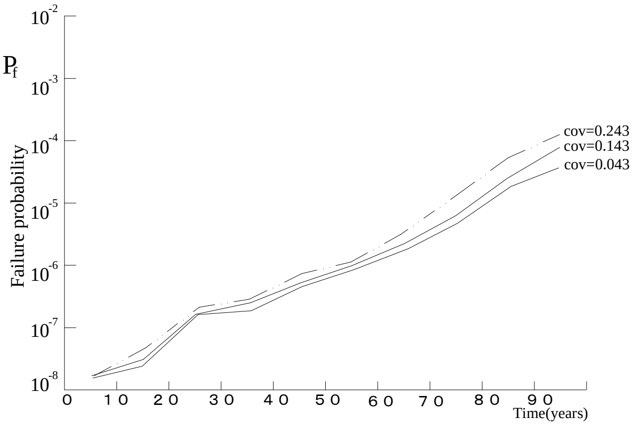

Fig. 12: Effect of dead load on main girder (local corrosion)

5) Influence of live load on the component failure probability
The variation coefficient of vehicle load (axle weight) is 0.922, 1.022 and 1.122 respectively. The reliability changes of girder No.1 is shown in Figure 13 and Figure 14 for both model.

It is shown that the live load affects obviously to the failure reliability of the component. The live load influence is significant in early years, but it is less and less in general with the running time.

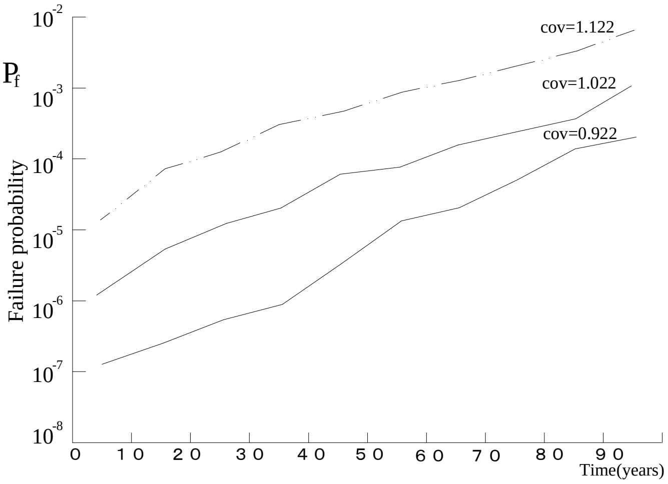

Fig. 13: Effect of vehicle load on failure probability (uniform corrosion)

From the above mentioned, the parameters of A_s, f_s, M_q influence the reliability greatly, but the concrete strength f_c, dead load M_d is not significant to the effect of the reliability index. The changes of random variable A_s (effective cross-sectional area of rebar) influences on the reliability index mostly.

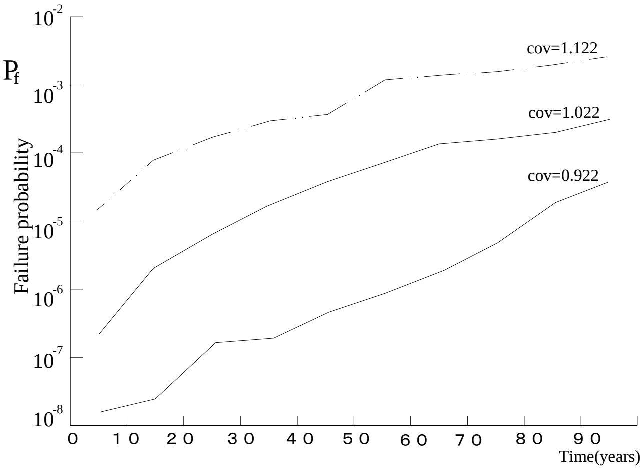

Fig. 14: Effect of vehicle load on failure probability (local corrosion)

CONCLUSION

Bridge damage and its diagnosis is a complex research subject which is attracted by many engineers. Under natural conditions, bridge structure suffers from the atmosphere, water spray and external load continuously. This causes concrete carbonation, steel corrosion, member surface flaking and section decreasing. At the same time, it brings about the performance of concrete structure or component deterioration, the mechanical properties degradation, and the bridges carrying capacity reduced, even significant loss of life and property seriously. The structural reliability will decrease as the service life, but the time of resistance and load effects is not considered in the reliability analysis usually. Therefore, it is very important and has more realistic significance for studying the reliability in the life of the bridge. This helps with repairing and reinforcing bridge to make use of funds reasonably. Based on a theoretical assessment of the reliability, a existing bridge structure load model and resistance model is built. The failure mode and its structural reliability are analyzed. The sensitivity of several parameters on bearing capacity decay is studied too.

A lot of factors affect the carrying capacity of existing bridge, which are non-deterministic and difficult to quantify. This study shows that rebar corrosion is the most obvious factors in all factors affecting the bearing reliability of concrete beams. As long as the steel corrosion has controlled, the service life of the bridge structure will be extended.

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