-Technical Paper-

A STUDY OF REPAIR ALTERNATIVES BASED ON LCC ESTIMATION FOR RC INFRASTRUCTURE

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ABSTRACT

Enormous amount of money is investing for the rehabilitation of infrastructure like bridges by the government. Efficiently manage the infrastructure system thus become critical issue to the engineers and decision makers. The amount of deterioration and maintenance strategies will affect extremely the life cycle cost of bridges. In this study, the variation of cover depth, permeability and degree of saturation are considered in probabilistic nature with log-normal distribution in service life prediction. 5 different types of repair methods and 2 different repair alternatives are taken as repair strategies. Finally the analysis results are compared to help the decision makers to select the appropriate strategy.

Keywords: cover concrete, permeability, LCC, repair strategy

1. INTRODUCTION

Transportation system is of major importance out of infrastructures that provides mobility of economy. Bridges play the key link in transportation system.

But it is very difficult to control the performance of bridge in severe aggressive environmental attack. Chloride induced steel corrosion is one of the major deterioration problem for steel reinforced concrete bridge in US caused by salty environment. The cost of highway bridge repair in US is estimated $70 billion. However cost effective maintenance plan and proper decision making can efficiently reduce the life cycle cost of infrastructure like bridges. To assist the decision makers for initiating better maintenance strategy the engineers and economists have to think for the better management system.

JSCE concrete committee TC335 found that air permeability does not give indications similar to strength characteristic indicates [1]. It suggests that durability of concrete is not best indicated by strength only. Most of the popular models gave preferences on cover size, diffusion coefficient and surface chloride. But it is very important to take consideration about cover quality such as permeability characteristics to design service life of structure.

Life cycle cost of the infrastructure is included here with the costs incorporate by aging of structure and repair when needs as direct cost and delay cost, by traffic, at the time of repair is considered as indirect cost.

Moreover 5 types of repair methods and 2 types of repair alternatives are compared to help the owner to choose the best. The prediction framework stated here will be useful to the engineers to design considering durability parameter and will help the owner to choose the required repair strategy that cost least.

2. DETERIORATION MODEL

2.1 Corrosion Initiation

The flow of chloride ion through pores in concrete is modeled here under both diffusion and convection same as solute transport shown as follows.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} \tag{1}$$

where C is chloride ion concentration (kg/m^3), D is the apparent diffusion coefficient (cm^2/sec), V is average linear rate of flow (cm/s) and follows Darcy's law when concrete pores are saturated.

$$V = \frac{k}{n}\frac{\partial h}{\partial x} \tag{2}$$

where k is the hydraulic permeability (cm/s), n is porosity (0.2) and $\frac{\partial h}{\partial x}$ is hydraulic gradient (0.02). The solution of Eq. 1 for semi infinite column of porous media is given in references [2][3] as follows.

$$\frac{C(x,t)}{C_o} = 0.5\left[erfc\left(\frac{x-Vt}{2\sqrt{Dt}}\right) + \exp\left(\frac{Vx}{D}\right)erfc\left(\frac{x+Vt}{2\sqrt{Dt}}\right)\right] \tag{3}$$

where $C(x,t)$ is chloride ion concentration at depth x (cm) after time t sec. (kg/m^3). C_o is the surface chloride concentration (kg/m^3), D is the apparent diffusion coefficient (cm^2/sec).

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$$D = D_o \times \phi \times S \times e^{\left[2285\left(\frac{1}{293} - \frac{1}{273+T}\right)\right]} \quad (3a)$$

D_o is the diffusion coefficient in pore water, φ is the porosity, S is the degree of saturation, T is the temperature in concrete. Time dependency of surface chloride (C_o) and apparent diffusion coefficient (D) are considered according to references [4][5].

2.2.Crack Formation

Corrosion product is formed and internal pressure is gradually increased after corrosion initiates. As internal pressure reaches to the tensile strength of concrete cracks are generated.

Based on the concept of fracture mechanics and thick-wall cylinder Li et al. (2003) [6] formulated the crack width generation model.

$$w_c = \frac{4\pi d_s(t)}{(1-v_c)\left(\frac{a}{b}\right)^{\sqrt{\alpha}} + (1+v_c)\left(\frac{b}{a}\right)^{\sqrt{\alpha}}} - \frac{2\pi b f_t}{E_{ef}} \quad (4)$$

where w_c is the crack width (mm), v_c is the poisson's ratio of concrete, α is the stiffness reduction factor which can be determined from Li et al (2006) [7], f_t is the tensile strength of concrete (MPa) taken as 10% of f_c', E_{ef} is effective modulus of concrete $\frac{E_c}{1+\phi_{cr}}$, E_c is the elastic modulus of concrete, a is equal to $\frac{D_b + 2d_o}{2}$, b is equal to $x + \frac{D_b + 2d_o}{2}$, D_b is the steel diameter (mm), d_o is thickness of pore band of steel-concrete interface (mm) which is dependent on thickness of corrosion product ring $d_s(t)$ and can be determined based on Liu and Weyers (1998) [8].

$$d_s(t) = \frac{W_{rust}(t)}{\pi(D_b + 2d_o)}\left(\frac{1}{\rho_{rust}} - \frac{\alpha_{rust}}{\rho_{st}}\right) \quad (4a)$$

Thickness of corrosion product is related to mass generation of rust product $W_{rust}(t)$ (mg/mm) and is stated in literature of Liu and Weyers (1998). α_{rust} is the coefficient for rust product, ρ_{rust} is the corrosion product density (3600 kg/m^3) and ρ_{st} is the steel density (7850 kg/m^3).

3. RELIABILITY BASED FAILURE

Bridge performance is defined in terms of reliability index (β) and the profile of reliability is the variation of reliability index with time β(t). Similar bridges designed and constructed to the same requirements, for various reasons, end up with different reliability levels [9]. This variation is influenced by different loading and degrading resistance conditions that can be usefully presented by random variables of durability parameters. The performance limit state for corrosion initiation of reinforcing steel and crack width are shown below.

$$z = C_{\lim} - C(x,t) \quad (5)$$

$$z = w_d - w_c \quad (6)$$

Eqs. 5 and 6 can be generalized as load –capacity model shown in Eq. 7.

$$Performance = Strength - Load = A - B \quad (7)$$

where C_{lim} and w_d are the threshold chloride concentration and maximum allowable crack width. Reliability index can be determined using load-capacity model.

$$\beta = \frac{1}{V_z} = \frac{\mu_z}{\sigma_z} = \frac{\mu_{\ln A} - \mu_{\ln B}}{\sqrt{\sigma_{\ln A}^2 + \sigma_{\ln B}^2}} \quad (8)$$

V_z is the coefficient of variation of performance function z. All random variables are taken as log-normal distribution. Thus μ_{lnA}, μ_{lnB}, σ_{lnA} and σ_{lnB} are the mean of strength, load and standard deviation of strength, load respectively.

It is assumed that corrosion will initiate when β(t)<0.8 using Eqs. 3 and 5 and similarly crack will exceed its allowable width when β(t)<0.8 using Eqs. 4 and 5.

The time to initiation of corrosion is referred as t_i and t_{cr} is named as time to reach allowable crack. Thus, the study reports the failure time as the summation of both the times indicated above.

$$t_f = t_i + t_{cr} \quad (9)$$

where t_f is the time to failure. The performance of deteriorating structure is characterized by probability of failure or damage over the interval [0, T] as shown in Eq. 10.

$$P_f(t) = \phi(-\beta) \quad (10)$$

where $P_f(t)$ is the probability of failure of structure which is fixed at 21.2% corresponds to β(t) value and ϕ is the standard normal cumulative distribution function.

4. RANDOM VARIABLES

Table 1 presents the cases used in this study. Cover depth, hydraulic permeability and degree of saturation are considered as the main durability

parameters varied according to Table 1. Variation of permeability is maintained according to previous literature [10]. The importance of curing time can be understood by varying the hydraulic permeability of cover concrete.

Table 1 Case Definition

Case	Mean	COV
Cover depth, x (cm)	4, 5, 6	0.1
Hydraulic Permeability, k (m/s)	$1e^{-9}$, $1e^{-11}$, $1e^{-12}$	0.1
Saturation Degree, S (%)	80, 90, 100	0.1

Table 2 Random Variables

Variables	Mean	COV	References
C_o (kg/m^3)	9	0.1	
C_{lim} (kg/m^3)	1.2	0.1	Enright and Frangopol, 1999
w_d (mm)	0.2	0.1	
f_c' (MPa)	35	0.2	Nowak et al. 1994
ϕ_{cr}	1.1	--	JSCE (2005-3)
v_c	0.18	--	Liu & Weyers, 1998
d_o (μm)	12.5	--	Liu & Weyers, 1998
D_b (mm)	12	0.2	
α_{rust}	0.57		Liu & Weyers, 1998

All the following calculations are based on the input random variables shown in Table 2.

5. LIFE CYCLE COST ESTIMATION

LCC plays key role in maintaining the infrastructure and provides necessary information to the manager or owner. In this study LCC is computed in the following way.

$$LCC = \sum_{t=0}^{T} (AgingCost + DelayCost + RepairCost)$$

The three terms in the right hand side were assumed as explained by the following sections.

5.1 Aging Cost

This is the cost carried by the owner due to regular maintenance operation. Aging cost is assumed to be proportional to the failure probability, as both of them increase with the increase of age of the infrastructure.

$$Aging\ Cost = Initial\ Cost \times 0.05 \times P(f)_{t_i} \quad .....u = 0 \qquad (11)$$

$$Aging\ Cost = Initial\ Cost \times 0.05 \times P(f)_{t-t} \quad .....u = 1 \qquad (12)$$

It is assumed that 5% of initial construction cost will be expended for maintenance. $P(f)_t$ is the probability of failure at yrs. t, number of repair is subscript i,t_i is the *ith* repair, u is the decision for repair, $u=0$ means no repair and $u=1$ represents do repair.

5.2 Delay Cost

This is the part of expenditure carried by the road user for extra fuel consumption and delay due to congestion at the time of repair for partial or full closure of traffic way. It is assumed to be proportional of age as traffic volume is increased with the age and capacity of the road if remains constant.

$$Delay\ Cost = 0 \qquad .....u = 0 \qquad (13)$$

$$Delay\ Cost = \%traffic\ delay \times (traffic\ volume)_t \times repair\ time \times average\ delay \times unit\ Cost \quad .....u = 1 \qquad (14)$$

where *% traffic delay* is the number of vehicle delayed at the repair time and is kept assumed here 10%, *traffic volume* is the function of time, *repair time* is the time taken by the repair in days, *average delay* is the % time delay due to repair by car or truck, *unit cost* is the time value of delay. Delay cost is calculated from literature stated in reference [11].

5.3 Repair Cost

This cost is provided by the owner due to repair when the performance goes down below the required. In this study the repair is taken to be happened at reliability or state of structure goes below 80% of initial. Repair cost is modeled in two different alternatives according to level of improvement of performance by repair.

5.3.1 Alternative 1

The schematic nature is shown below in Fig. 1.

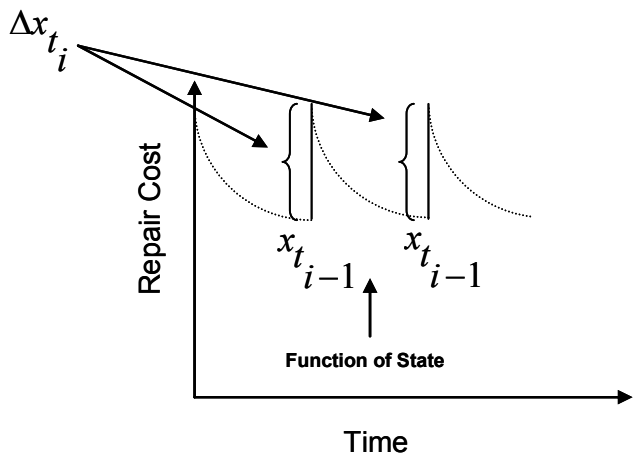

Fig. 1: Concept of Repairing cost for alternative 1

$$Repair\ Cost = 0 \qquad .....u = 0 \qquad (15)$$

$$Repair\ Cost = \left[Fixed\ Cost + \left(unit\ Cost \times area \times P(f)_{t_{i-1}} \times \Delta x_{t_i} \right) \right] \times \frac{t_{RSL}}{t_{Repair}} \quad .....u = 1 \qquad (16)$$

where *unit cost* is the cost of repair for unit area, $P(f)_{t_{i-1}}$ is the failure probability just before repair, Δx_{t_i} is the change of state done by repair *i* at time *t*, t_{RSL} is the residual service life in years, t_{Repair} is the life time of repair material.

It is assumed that the performance will be improved up to Δx_{t_i} that will meet initial level of performance.

5.3.2 Alternative 2

Repair cost is calculated with some difference based on the following equations.

$$Repair\ Cost = 0 \qquad .....u = 0 \tag{17}$$

$$Repair\ Cost = \left[Fixed\ Cost + \left(unit\ Cost \times area \times P(f)_{t_{i-1}} \times \Delta x_{t_i} \times k \right) \right] \times \frac{t_{RSL}}{t_{Repair}} \qquad .....u = 1 \tag{18}$$

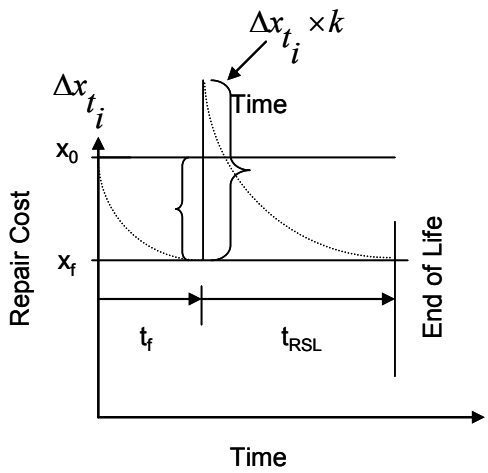

Fig. 2: Concept of Repairing cost for alternative 2

Above Fig. 2 is the schematic representation of the alternative. It is assumed here that the improvement done by repair will not always be up to initial level. Change of state Δx_{t_i} is multiplied by *k* named as improvement factor, which is equal to $\frac{t_{RSL}}{t_f}$, where t_{RSL} is the residual service life and t_f is the time to first failure. In this alternative the manager is strict to repair the structure once in whole service life.

5.4 Repair Methods

To investigate the effect of different repair methods on LCC, 5 types of repair methods from references [12] and [13] are included in the calculation as in Table 3.

6. EFFECT OF REPAIR METHODS ON LCC

The cost of repairing included in LCC computation is according to Table 3. For both alternatives lower bound of degrading state is 80% of initial but upper bound is same as initial for alternative 1 but depends on residual service life for alternative 2 strategies.

Figs. 3 and 4 show state dynamics and cumulative cost over entire service life for alternative 1. The repair takes place more than 1 time in this case and cost is compared among no repair and repair with different methods.

Table 3 Cost of Repairing

Category	Types	Fixed Cost ($)	Variable Cost ($/m^2)	Life time (yrs.)
RM1	Cathodic Protection (Mounted Conductive Polymer w/ concrete overlay)	6870	97	20
RM2	Cathodic Protection (Titanium mesh w/ shotcrete)	6870	150	35
RM3	Patching	1450	277	8
RM4	Overlay (Low slump dense concrete)	6000	43	24
RM5	Overlay (Hot mix asphaltic concrete with a membrane)	6000	11	12

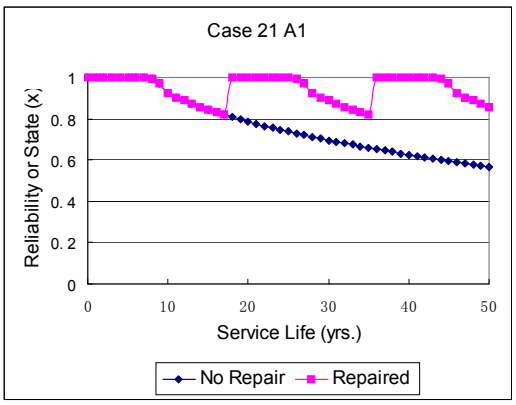

Fig. 3: Effect of repairing on State dynamics

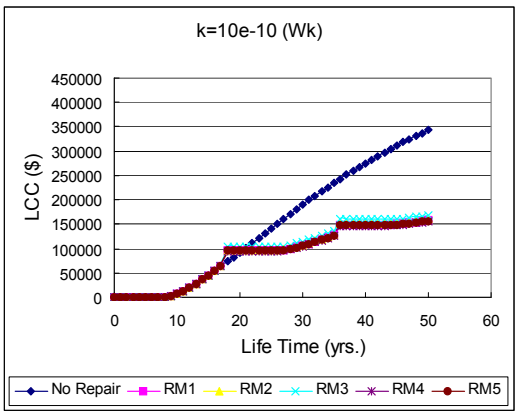

Fig. 4: Effect of repair methods on LCC

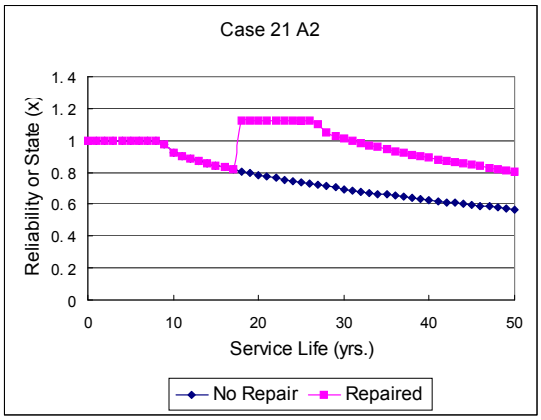

Fig. 5: Effect of repairing on State dynamics

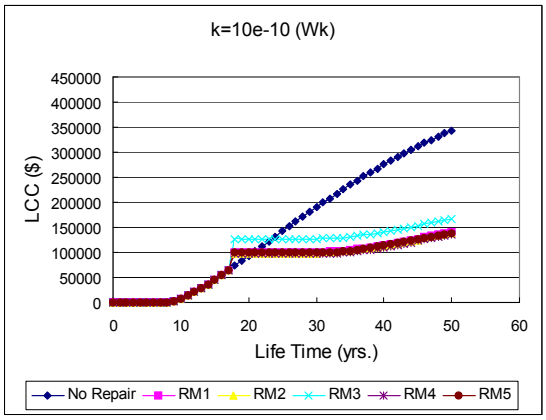

Fig. 6: Effect of repair methods on LCC

Figs. 5 and 6 show state dynamics and cumulative cost for alternative 2. The state is improved greater than that of initial by 1 time repairing in whole service life. Figs. 3 to 6 describe the case of best cover (6 cm.), Fully saturated (100%) and worst permeability (1e-9). All 5 types of repair methods and 2 repair alternatives are considered in calculating total cost that is shown in Figs. 7, 8 and 9.

These figures explain three extreme cases based on durability parameters. In all cases repair method 3 shows highest cost due to highest variable cost of repairing. Repair method 4 has lowest cost due to low variable cost and longer service life compared to method 5 having variable cost lower than method 4.

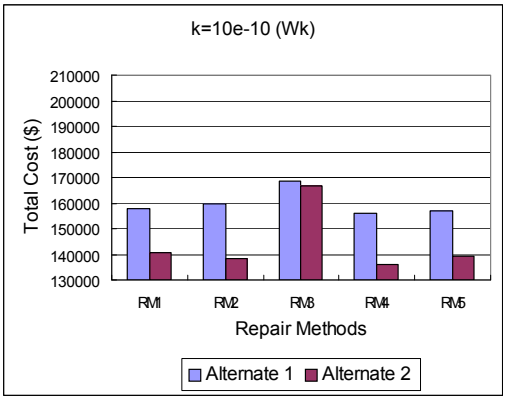

Fig. 7: Effect of repair strategies on total cost for maximum permeability

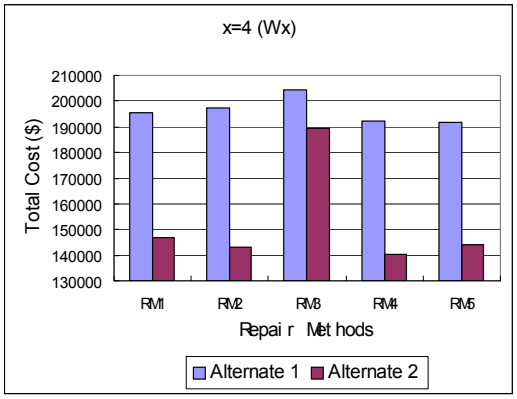

Fig. 8: Effect of repair strategies on total cost for minimum cover

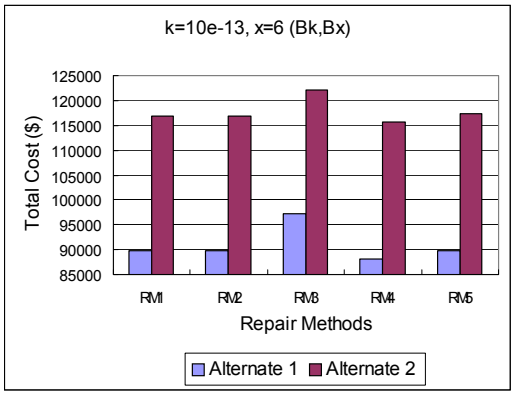

Fig. 9: Effect of repair strategies on total cost for minimum permeability, maximum cover

7. EFFECT OF REPAIR ALTERNATIVES ON LCC

Figs. 7 and 8 show that the cost is lower for alternative 2 than that of alternative1. but opposite scenario is found in Fig. 9. Due to change of durability parameters the time to failure and residual service life are changed. This is factor that affects the cost of alternatives.

Fig. 10 is plotted for total cost with 27 durability cases as in Table 1. For each case and alternative, total cost is taken as the average of 5 types of repair methods to exclude the effect of repair methods. It can be seen that for particular 6 durability cases the total cost is less for

alternative 1 than that of alternative 2. Alternative 2 has lower cost for rest of the cases.

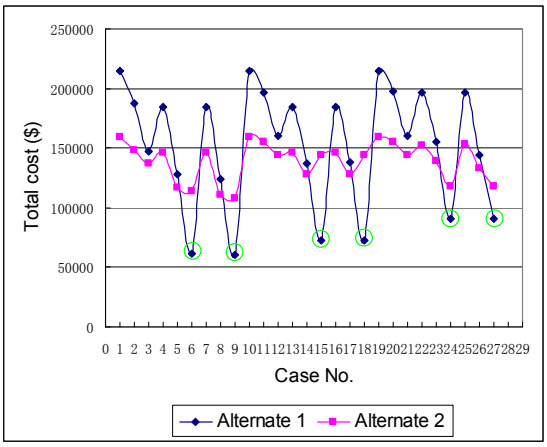

Fig. 10: Effect of repair alternatives on total cost

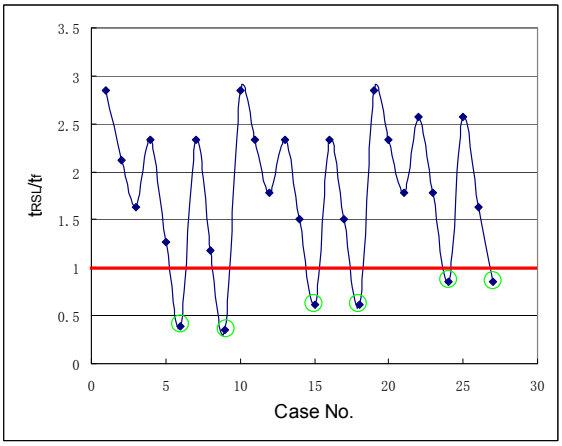

Fig. 11: Improvement factor (t_{RSL}/t_f) for different cases

The ratio between residual service life and failure time is plotted In Fig. 11 against each case. The 6 cases marked by green circle having larger cover depth and lower permeability where failure come later than mid of life span. This means if the failure comes after middle of service life of the structure, it is better to adopt alternative 1 as repair strategy else alternative 2 should be chosen.

8. CONCLUSIONS

The computation framework leads to the following conclusions.

(1) RM3 costs highest to the owner due to maximum variable cost of repairing.
(2) RM4 costs lowest due to low variable cost and greater life time of repairing as well.
(3) One time repairing with the improvement of performance greater than that of initial level is preferable when the failure comes before middle of age of service life.
(4) Repairing with the improvement up to initial level of performance is suitable when the failure comes after middle of age of service life.

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