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Life Cycle Cost GA Optimization of Repaired Reinforced Concrete Structures Located in a Marine Environment

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ABSTRACT

Life-Cycle-Cost (LCC) analysis of corroded structures located in corrosive marine environments considers the time-dependent resistance and loading affect, and repair and maintenance scenarios applied during life time of these structures. Finding the optimum repair and maintenance scenario for a corroded reinforced concrete (RC) structure is a significant process to select a repair and maintenance scenario with minimum LCC and maximum service lifetime. For this purpose, a finite element (FE) model is applied to assess the time-dependent capacity of corroded RC circular column using nonlinear analysis. In corrosion initiation phase, empirical chloride diffusion and surface chloride concentration models obtained for silica fume RC under long-term exposure in splash zone of Bandar-Abbas coasts, located in south side of Iran, and in corrosion propagation phase, empirical corrosion current density model for splash zone of a marine environment in literature is used for modeling of corrosion process. In this analysis, the influence of a number of repair or rehabilitation scenarios on the performance of a corroded circular RC column due to chloride-induced corrosion, including five different concrete surface coatings used on the external surface of concrete, four different increasing concrete cover thickness and using the new longitudinal and horizontal reinforcements after the initial cracking of concrete cover are investigated. These 11 different scenarios with considering a scenario without any repair are optimized by Genetic Algorithm (GA) based on minimum LCC cost and 40 years failure time in terms of corrosion.

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1. Introduction

Increasing concrete cover thickness repair, concrete overlay, externally bonded concrete, epoxy injection of cracks, external posttensioning, externally bonded steel or composite plates, penetrant sealers, wrapped carbon fibres, and the addition of supplemental or replacement members are a number of repair or rehabilitation methods for damaged RC structures [1]. Chloride induced corrosion into RC structures in marine environments have three main phases: Initiation, propagation and cracking [2–4]. The chloride ions penetrate into reinforced concrete from surface of cover concrete, gradually. When the chloride concentration on the surface of reinforcements equals to a critical value of chloride concentration, and until sufficient oxygen and moisture, the corrosion of reinforcements is initiated. The critical value of chloride concentration depends on several factors, including exposure conditions and the chloride ion value of the sea water [3]. After the corrosion initiation time, the chloride concentration, the iron rust as the productions of corrosion reaction increases on the reinforcement surface, and the percentage of corrosion timely increases from zero.

Empirical models are presented for predicting the chloride diffusion coefficient [5–7] and surface chloride concentration [8–10] in concrete in the initiation phase of corrosion. Moreover, empirical models are presented for predicting the corrosion rate using concrete resistance [11–14] in the propagation phase of corrosion.

Once corrosion initiates the rust product around the reinforcement starts expanding. Therefore, the stresses induced by this expansion will make tensile stress in concrete cover and cause concrete cover cracking, delamination and spalling. As a result, the ultimate strength and bond between steel and concrete decreases and this will ultimately result failure of the section.

Some researchers presented corrosion models in initiation, propagation and cracking phases for simulation of corrosion process. These models are summarized in Table A1, and their parameters are defined in Table A2, in Appendix section.

As a result, for improving the time-dependent structural performance of existing RC structures located in corrosive marine environments, selecting the best repair and maintenance method is critical to reduce the chloride diffusion into the concrete and corrosion rate of reinforcements.

One of the repair methods is increasing the concrete cover thickness of concrete after initiation of crack time due to rust expansion for delaying the failure time of RC structures and increasing their service life. The influence of increasing the concrete cover thickness on the corrosion of the reinforcement due to chloride penetration into concrete has been studied by Cho et al. [15]. They concluded that increasing the increment of concrete cover thickness reduces the corrosion rate. However, corrosion potential, electronic resistance and current intensity are not dependent on the concrete cover thickness. The effect of shotcrete repair has been investigated by Enright et al. [16]. The performance of 6 different surface coatings as repair layer on the surface of concrete including acrylic modified cementitious, type E (CPE), acrylic modified cementitious, type D (CPD), epoxy polyurethane (PU), aliphatic acrylic (AA), cementitious (CE), styrene acrylate (SA) is investigated by Khanzadeh et al. [17] in the real marine zone of BandarAbbas in southern Iran for five years.

Yanaka et al. [18] have investigated reliability based and LCC oriented design recommendations for prestressed concrete bridge girders. They have considered two methods to decide appropriate design recommendations to prevent corrosion of reinforcing steel in prestressed concrete bridge girders. The first one is based on the target probability of corrosion initiation and the initial cost. The other method is based on the life cycle cost that includes the initial cost, maintenance cost, and expected failure cost. Their study deals with the development of recommendations for durability design of structures in marine environments from the reliability point of view, taking into consideration the life cycle cost of a structure.

Genetic Algorithm (GA) [19,20] is the metaheuristic algorithm can be successfully applied to solve structural optimization problems.

In this study, for minimizing the LCC of a corroded RC circular column by considering 40 years service life, Genetic Algorithm (GA) is used.

2. Circular RC column FE model

To investigate the influence of every repair methods on structural performance of corroded circular RC columns, a series of time-dependent non-linear pushover analyses with various corrosion percentages are conducted in OpenSees software. Farahani et al. [21] have presented the nonlinear finite element modelling technique employed by using the fibre beam-column element in OpenSees software to simulate the flexural response of corroded columns and repaired corroded columns (Fig. 1). The modelling technique has been calibrated and validated for a rectangular RC column of bridge piers, for both uncorroded and corroded columns with no matter the discussion of the repair and maintenance against corrosion [22].

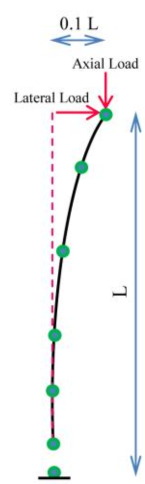

Fig. 1. Proposed nonlinear fibre beam-column model [21].

Repair and maintenance methods used in this research, including,

Using five different surface coatings (CPD, PU, AA, CPE, CE and SA):

The equivalent concrete cover thicknesses of concretes with five different surface coatings CPD, PU, AA, CPE and SA surface coatings are calculated equal to 14.4, 31.2, 38.9, 27.6 and 12.6 mm by Farahani et al. [21].

Four different increasing the concrete cover thickness (10 mm, 15 mm, 20 mm and 25 mm):

Each one of four different increasing concrete cover thicknesses, as repair scenarios, is added to the initial concrete cover thickness after destroying the initial concrete cover thickness at the crack initiation time.

Using the new longitudinal and horizontal reinforcements:

At the crack initiation time, after destroying the initial concrete cover thickness and pull out the corroded longitudinal and horizontal reinforcements, new longitudinal and horizontal reinforcements are replaced and new concrete cover equals to the initial concrete cover thickness is molded and replaced.

3. Optimization information

Different sections of an optimization problem are including,

3.1. Optimization objective function

In this study, the objective function is finding the best repair method with minimum life cycle cost for corroded RC circular column located in corrosive marine environments, such as Bandar-Abbas coasts, located in south side of Iran. The life cycle cost is including of initial construction cost and repair and maintenance cost by considering 40 years service life of RC members.

3.2. Optimization constants

The constant parameters are section diameter, number of longitudinal reinforcements, horizontal reinforcement diameter, horizontal reinforcement spacing, height of column and silica fume percentage as a replacement of Portland cement in mixture design that they equal to 350 mm, 8, 10 mm, 80 mm, 2000 mm and 7.5 %, respectively.

3.3. Optimization variables

The optimization variables are five parameters including 11 repair scenarios (including 5 surface coatings, 4 increasing concrete cover, 1 new reinforcements and 1 no-repair scenario), 4 water-to-binder ratios (including 0.35, 0.40, 0.45 and 0.50), 9 different initial concrete cover thicknesses (from 30 mm to 70 mm by distance 5 mm), 3 different initial diameters of longitudinal reinforcement (including 18 mm, 20 mm and 22 mm). As a result, optimization process is based on 11×4×9×3=1188 random selection.

3.4. Optimization limitations

The optimization limitations are defined as the core concrete crushing in compression, concrete cover cracking and bar fracture occur close to top column drift equal to 8% of column length [23] and the service life of corroded RC column equals to 40 years.

3.5. Optimization method

In this research, Genetic Optimization Algorithm (GA) as a metaheuristic algorithm is used for optimization of LCC of a circular RC column located in Bandar-Abbas coasts, south of Iran by considering different repair and maintenance scenarios. GA has main steps including (1)

Initiation: Individuals of population or chromosomes are selected randomly from search space, (2) Fitness based selection: Chromosomes with better finesses are selected as parents of the next population, (3) Crossover: Each pair of selected parents is replaced by a pair of new chromosomes (considered as children) in a way that each gene of children is gained from one of the parents, (4) Mutation: Some genes of a chromosome changes randomly, (5) Repeat steps 2 to 4 until convergence criterion is satisfied.

In this study, population number and iteration number are considered 10 and 9, respectively for GA optimization method.

4. Results and discussions

Details of life cycle costs are summarized in Table 1.

Table 1
LCC details.

Life Cycle Costs	Cost Value
Engineering Cost	\$1.32/ m^2
Initial Construction Cost:	
Concrete	\$184.21/ m^3
Steel	\$1.97/ kg
Destroy and Operation Costs	\$144.74/ m^3
Inspection Cost	\$10.00/ m^2
Repair and Maintenance Costs:	
Concrete	\$184.21/ m^3
Steel	\$1.97/ kg
Surface Coatings:	
SA	\$53.59/ m^2
CPD	\$84.79/ m^2
CPE	\$84.21/ m^2
AA	\$55.10/ m^2
PU	\$76.50/ m^2

The properties of repaired corroded RC circular column with optimized LCC by GA optimization algorithm are presented below:

- Section Diameter: 350 mm
- Length: 2000 mm
- Number of Longitudinal Bar: 8
- Initial Longitudinal Bar Diameter: 18 mm
- Initial Horizontal Bar Diameter: 10 mm
- Horizontal Bar Spacing: 80 mm
- Initial Concrete Cover: 70 mm
- Water-to-Binder Ratio: 0.35
- Silica Fume Percentage: 7.5 %
- Repair Method: 20 mm Increasing Cover Thickness
- Service Life: 40 years
- Optimized Life-Cycle-Cost: 101.3 $

The optimized LCC for every nine iterations optimized by GA optimization algorithm is indicated in Fig. 2. Optimized repair and maintenance method is select 20 mm increasing concrete cover thickness adding the initial concrete cover 70 mm; Because, repair cost by increasing concrete cover is cheaper rather than using new reinforcement as replacement of corroded reinforcements at concrete cover cracking time. Furthermore, concrete with minimum 0.35 water-to-binder ratio is selected in optimized RC column; because, the chloride penetration rate, corrosion current density and corrosion percentage of bars reduces with decreasing water-to-binder ratio.

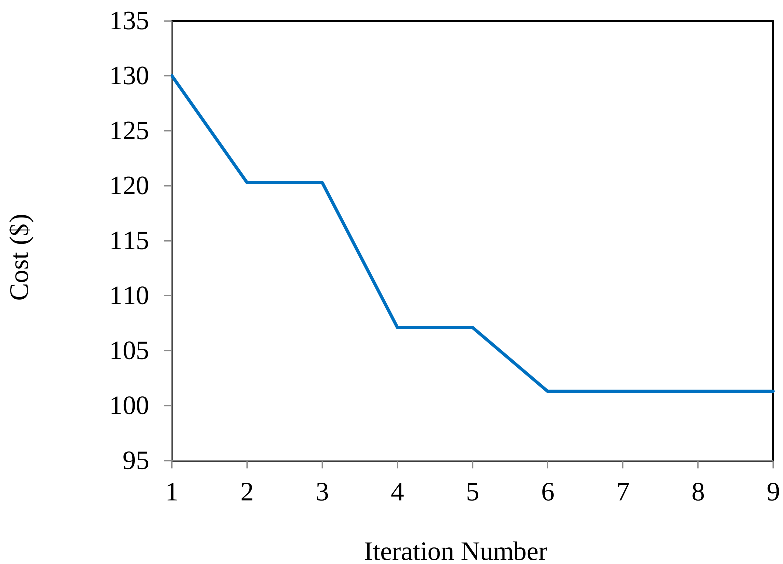

Fig. 2. Optimized cost of each iteration for GA algorithm.

5. Conclusions

This research investigates the time-dependent capacity of a corroded circular RC column by using nonlinear finite element analysis. A number of repair and maintenance methods have been developed for life cycle analysis of damaged RC structures due to chloride-induced corrosion; These 11 repair scenarios are included using five different concrete surface coatings on external surface of concrete, four different increasing the concrete cover thickness and using the new longitudinal and horizontal reinforcements after the initial cracking of concrete cover. GA algorithm is applied to find the optimized scenario by considering minimum life cycle cost and 40 years service life of a corroded RC circular column located in marine environments of Bandar-Abbas coasts, south of Iran. Optimized RC column with 40 years service life and 101.3 dollars life cycle cost, is selected with 20 mm increasing concrete cover thickness adding the initial concrete cover 70 mm repair scenario, 0.35 water-to-binder ratio, 7.5 % silica fume as a replacement for Portland cement in mixture design, initial longitudinal and horizontal reinforcements diameter equal to 18 mm and 10 mm, respectively.

Appendix

The corrosion models in initiation, propagation and cracking phases for simulation of corrosion process are summarized in Table A1, and their parameters are defined in Table A2.

Table A1
Used corrosion models in initiation, propagation and cracking phases.

Model	Formulation	Limitation and application
Farahani et al. [24]	$D = D_{ref}\, f(T)\, f(t)\, f(h)$	For silica fume concrete, Used in corrosion initiation phase
	$D_{ref} = 10^{(-12)} \times (-4.002 + 18.09 w/\mathrm{b} + 1.512 (w/\mathrm{b})^2 - 0.09937\mathrm{SF} + 0.01861\mathrm{SF}^2 - 0.8558 w/\mathrm{b} \times \mathrm{SF})$	
	$f(T) = \exp\left[U / R.(1/T_{ref} - 1/T)\right]$	
	$f(t) = \left(t_{ref} / t\right)^{0.24}$	
	$f(h) = \left[1 + \dfrac{(100-h)^4}{(100-h_c)^4}\right]^{-1}$	
Tadayon [25]	$C_s = k\,t + C_0$	For silica fume concrete, Used in corrosion initiation phase
	$w/b = 0.40\ ,\ SF = 7.5\% \Rightarrow k = 6.00e(-4),\ C_0 = 0.309$	
	$w/b = 0.50\ ,\ SF = 7.5\% \Rightarrow k = 9.00e(-4),\ C_0 = 0.151$	
Vu and Stewart [26]	$i_{corr}(t) = 0.85\, i_{corr0} (t - t_{corr})^{-0.29}$	For Portland cement concrete, Used in corrosion propagation phase
	$i_{corr0} = \dfrac{37.8(1-w/c)^{-1.64}}{x}$	
Vidal et al. [27]	$dt = d_0 - \alpha P_{avg}$	
	$dt_{tie} = d_{0tie} - \alpha P_{avg,tie}$	
	$P_{ave}(t) = \kappa \int_{T_{corr}}^{t} i_{corr}(t)\, dt$	
	$\psi = 100(1 - (dt/d_0)^2)$	
	$\psi_{tie} = 100(1 - (dt_{tie}/d_{0tie})^2)$	
Liu and Weyers [28]	$t_{cr} = \dfrac{W_{crit}^{\ 2}}{2k_p}$	Used in corrosion cracking phase
	$k_p = 9.8 \times 10^{-5} \dfrac{\pi d_0 i_{corr}(t)}{\beta}$	

Table A2
Definition of parameters used in corrosion models summarized in Table 1.

Parameter	Definition of parameter
D (in m^2/s)	Chloride diffusion coefficient
D_{ref} (in m^2/s)	Reference diffusion coefficient at reference time (3 months)
t (in s)	Current exposure time
t_{ref} (in s)	Reference time (3 months)
w/b	Water-to-binder ratio $(0.35 \leq w/b \leq 0.50)$
SF	Silica fume percentage (%)
U (in J.mol^{-1})	Activation energy of diffusion process
R (in J. mol^{-1}.K^{-1})	Gas constant (8.314 J. mol^{-1}.K^{-1})
T (in K)	Current temperature
T_{ref} (in K)	Reference temperature (306.5 K)
h (in percent)	Relative humidity of concrete specimen
h_c (in percent)	Critical humidity level
C_s (in % weight of concrete)	Surface chloride concentration
t_{corr} (in s)	Corrosion initiation time
C_{cr} (in % weight of concrete)	Critical value of chloride is considered to be equal 0.07% of concrete weight in the Persian Gulf region [8].
$i_{corr}(t)$ (in µA/cm^2)	Corrosion current density of reinforcements at time after the corrosion initiation time
i_{corr0} (in µA/cm^2)	Corrosion current density at corrosion initiation time
dt (in mm)	Reduced diameter of longitudinal bars
dt_{tie} (in mm)	Reduced diameter of horizontal bars
d_0 (in mm)	Initial diameters of longitudinal bars
d_{0tie} (in mm)	Initial diameters of horizontal bars
α	2 for uniform corrosion and varied from 4 to 8 for pitting corrosion [26]
$P_{ave}(t)$ (in mm)	Average corrosion penetration depth based on the uniform volumetric mass loss at time t after corrosion initiation
κ	Conversion factor from µA/cm^2 to mm/year that equals to 0.0116
ψ (in percent)	Corrosion percent of longitudinal bars
ψ_{tie} (in percent)	Corrosion percent of horizontal bars
W_{crit}	Total amount of critical rust products needed to fill the volumes of pores and rust expansion available in [28]
k_p	Rate of the production of corrosion products
β	Ratio between molecular weight of steel and molecular weight of corrosion products available in [28]

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