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Maintenance Planning of Multiple Prestressed Concrete Girders with Multiple Performance Criteria and Constraints

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Abstract

Recently, the maintenance planning of prestressed concrete (PC) structures has been a significant problem and needed to be concerned. An appropriated structural maintenance is defined in order to minimize life cycle cost and extend the lifetime of structures with satisfied performance. This paper proposes an optimization method for maintenance planning of multiple prestressed concrete girders with considering multiple performance criteria and constraints. The girders are varied in environmental conditions, covering depth, number of tendons, etc. The performed criteria are durability, serviceability and load carrying capacity. Moreover, the constraint is maintenance budget. Therefore, member prioritizing, shifting repairing time or changing repairing method must be considered in optimization. It is shown that the annual repairing cost depends on the number of repairing time, unit cost of repairing, amount of damage and number of girder. The result of this study can be used for the decision making tool for planning budget of repairing work and prioritizing repairing prestressed concrete girders. Based on example given in this study, maintenance budget can be reduced for almost 30% within 50 years of service life.

Keywords: Prestressed concrete, Failure probability, Maintenance planning, Life cycle cost, Monte Carlo simulation

1. INTRODUCTION

The deterioration of prestressed concrete structures has been a significant problem during the past decade. Bridge structures especially girders and decks have been deteriorated due to many factors such as environments, heavy loads and construction errors. There are many researchers and engineers have been tried to find the best solution to implement and develop maintenance management or planning in order to extend the lifetime of structures effectively. For instance, there are 27.1% of the 590,750 existing bridges in the United States have to be substituted and improved with the predictable annual investment cost around US$ 9.4 billion for the next 20 years.

Most of an existing solution for maintenance and planning of concrete structure is to minimize life cycle cost and maximize lifetime of structure. To develop the maintenance strategies, it is required to provide an effective methodology to deal with constraints. The constraints of this computation are the limit budget for maintenance and control the deteriorating over the time limitation. The repairing techniques also help improving maintenance planning and balancing the whole maintenance cost and lifetime structure performance [1].

The problem regarding the financial resources is not enough. The manager has to propose the solution in order to balance the annual repairing cost. Another problem relates to the criteria specified a requirement of repair. Three main criteria such as durability, serviceability and load carrying capacity are normally considered to justify performance of structures. As a result, the criteria that provide the lowest life cycle cost scenario is selected for maintenance planning.

The objective of this study is to propose method for optimizing the maintenance budget within required service life of structure by considering many criteria at the same time. Moreover, due to many presented constrains in actual situation, they must be considered in the optimization procedure as well.

2. LITERATURE REVIEW

There are various researchers who have studied in optimization techniques for maintenance planning and management of reinforced concrete (RC) structures. For example, Jung S. Kong [2] has evaluated about the expected life cycle maintenance cost of deteriorating structures. Jung S. Kong [2] estimated the maintenance cost of deteriorating structure by using the methodology of simple calculation. The main composition of maintenance that related to the repair cost is specified. Moreover, the additional part describes the method calculation by using software programming to analyze cost in the near future.

Frangopol and Liu [1] have reviewed the improvement of life cycle management and maintenance design for deteriorating RC structures and Highway Bridge. This reviewed paper has used optimization techniques and also examined and competed standard in relation to safety, condition and life cycle cost. This multi-objective procedure plays a significant role in solving maintenance and management to help decision making by selecting the best solution of structure performance and cost service life.

However, most of researchers focused on RC structure. Prestressed concrete girders are widely used in Thailand for expressway or elevated structures. So, it is significant to study causes of deterioration of prestressed concrete structures and determine failure probability due to random parameters by Monte Carlo simulation. Moreover, a numerical calculation to minimize total life cycle cost and maintenance planning of multiple prestressed concrete girders is emphasized. With the combination of all related costs, the net present value is performed. The estimated life cycle cost in different period and criteria is considered. Normally, structure must satisfy many performance criteria simultaneously such as durability, serviceability and load carrying capacity. Therefore, the maintenance planning of multiple prestressed concrete girders with multiple criteria and constraints is conducted in different conditions for 50 years of service life to represent the problem of real infrastructure.

3. METHODOLOGY

3.1 Overview

Fig.1 shows process of this study starting from selecting structures and getting the inspection results. Then the probability of failure is calculated with three main criteria as durability, serviceability and load carrying capacity. In addition, it is essential to optimize the lowest LCC, then make a decision planning to repair with considering constraints such as budget, time, etc.

3.2 Prediction of Probability of Failure

After inspection results were obtained from the study of Sukprasit, Sancharoen [3], the process of this study begin and the prediction of failure probability is conducted. The probability of failure is defined as a chance that structural performance is lower than the requirements. The probability of failure is calculated due to the performance criteria such as durability limit state, serviceability limit state and load carrying capacity based on Monte Carlo simulation technique. The Monte Carlo simulation was done by Microsoft Excel with the assigned distribution function and parameters of each variable. Random number is generated, and values of each variable are predicted. Then performance criteria will be checked for each step of random number and variable. The step was repeated for 1,000 times. Finally, probability of failure (P_f, %) for each performance criteria can be computed as shown in Equation (1).

$$P_f = \frac{No.of\ steps\ fail\ to\ performance\ crieria}{Total\ No.of\ repeated\ steps} \times 100 \qquad (1)$$

The considered deterioration in this study is mainly chloride migration [3]. In order to determine this probability of failure, the values of parameters and variables have been used as shown in Table 1. Distribution of parameters is assumed to be normal distribution. The selected 9 girders are examples of case studies only which represent the major variation of girder properties affecting performance of girder for example covering depth, environmental condition, concrete properties, etc.

3.2.1 Durability limit state

Durability limit state contains three main criteria as corrosion initiation, surface cracking due to rust and spalling. The condition used to check the initiation for corrosion is chloride content at steel surface versus critical chloride content [4]. Chloride diffusion prediction is shown in Equation (2). Crack is generated when the corrosion amount is more than 10mg/cm^2 [5]. Moreover, spalling is caused when corrosion amount is more than 20mg/cm^2 [5]. Time to crack or spalling are predicted corrosion mass loss is predicted based on Equation (3).

$$C_{d,t} = (C_s - C_0)\left[1 - erf\left(\frac{0.1c}{2\sqrt{D_{cl}\cdot t}}\right)\right] + C_0 \qquad (2)$$

Where, $C_{d,t}$ is chloride content at depth d and time t (% by weight of binder), C_s is surface chloride content (% by weight of binder), C_0 is initial chloride content(% by weight of binder), c is covering depth (mm), D_{cl} is chloride diffusion coefficient (cm^2/year), t is service life (year).

$$t_{cr} = \frac{W'_{steel,cr}}{0.009113\ i_{corr}} \qquad (3)$$

Where $W'_{steel,cr}$ is the critical mass loss of steel equal to 0.01 g/cm^2 and 0.02 g/cm^2 for cracking and spalling, respectively i_{corr} is corrosion rate (μA/cm^2).

3.2.2 Serviceability limit state

Serviceability limit state has three main criteria such as deflection, allowable flexural and shear stress. The limitation of deflection is span length (L)/800 [3, 6]. The allowable flexural and shear stress in serviceability performance criteria consider the service load is analyzed according to AASHTO, 2007. Allowable stress of material as shown in Equation (4) [3, 6] is considered as performance criteria:

$$\left|\bar{\sigma}_{ts}\right|_{allowable} \geq \left|\sigma_{ts}\right|_{actual} \qquad (4)$$

where $\bar{\sigma}_{ts}$ is allowable stress (MPa), σ_{ts} is actual stress at service load (MPa).

3.2.3 Load Carrying Capacity Criteria

In the load carrying capacity, the two main criteria are flexural and shear capacity. Factored load is used in the prediction. It will be failed due to moment or shear when the flexural or shear capacity is less than required flexural or shear stress. The analysis of moment and shear capacity of structure is followed [3, 6].

Load carrying capacity uses factored load and full strength of material as shown in Eq. (5) and (6) and considered as performance criteria:

$$\phi M_n \geq M_u \qquad (5)$$

$$\phi V_n \geq V_u \qquad (6)$$

where M_n is capacity of designed moment (N.m), M_u is required moment (N.m), V_n is capacity of designed shear (kg), V_u is required shear (kg) and ϕ is safety factor.

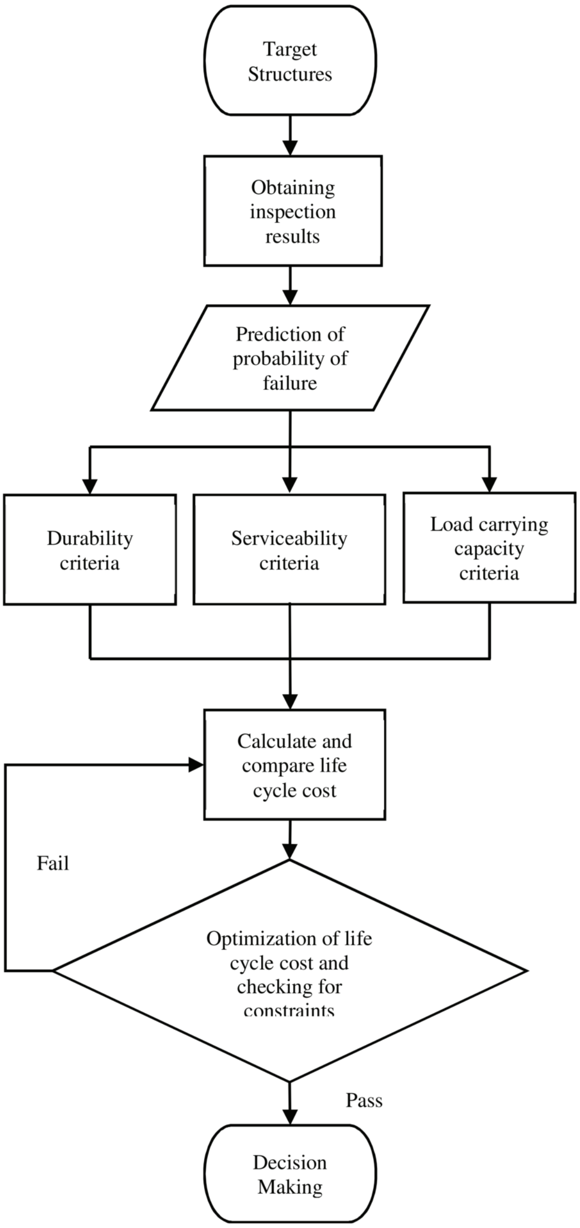

Figure 1 Flow chart of the study

3.3 Life Cycle Cost Analysis

There are two main costs of life cycle cost such as direct and indirect cost. The direct cost includes all related costs incurred directly over the lifetime of project such as the initial construction cost, inspection and repairing cost. The indirect cost consists of user cost and failure cost. Life cycle cost is a method of assessment the financial performance of investment project by determining the total costs of possession over the lifetime of project [7]. In term of normal construction, there are many costs related not only the initial construction cost but also other costs associated with inspection, maintenance and failure [8-15].

The main objective function of optimizing life cycle cost (LCC) in this study is to define the repairing-time which provide the lowest life cycle cost of structural maintenance. The expected life cycle cost is determined by Equation (7) [9, 16]:

$$LCC = C^{init} + \sum_{t=1}^{n} \frac{1}{(1+r/100)^t} \left(C^{ins} + C^{rep} + C^{fail} \right) \qquad (7)$$

where LCC is the total life cycle cost (THB), C^{init} is the initial construction cost (THB), C^{ins} is the inspection cost (THB), C^{rep} is the repairing cost (THB), C^{fail} is the failure cost (THB), r is the interest rate (%) and t is the number of year in life cycle. In this study, the initial construction cost and inspection cost are neglected.

To calculate the life cycle cost, it is significant to follow Equation (7) and know some parameters such as failure cost coefficient, unit cost, amount of damage and fixed cost. Table 2 shows associated cost due to different performance criteria. The failure cost coefficient of corrosion initiation criteria is assumed be zero because no significant change of structural performance due to corrosion initiation. In this study, the interest rate is 3% [17].

Table 1 Parameters of different properties of girders

Parameters	Girders									References
	G1	G2	G3	G4	G5	G6	G7	G8	G9	
1. Covering Depth of PC										
- Average (mm)	50	50	50	50	50	50	**40**	**45**	**50**	[18]
- Coefficient of variation (%)	16	16	16	16	16	16	16	16	16	
2. Covering Depth of Stirrup										
- Average (mm)	25	25	25	25	25	25	**15**	**20**	**25**	[18]
- Coefficient of variation (%)	16	16	16	16	16	16	16	16	16	
3. Corrosion rate										
- Average (μA/cm^2)	**1**	**2**	**3**	1	1	1	1	1	1	[19]
- Coefficient of variation (%)	20	20	20	20	20	20	20	20	20	
4. Chloride Diffusion Coefficient										
- Average (cm^2/year)	**0.3**	**0.4**	**0.5**	0.3	0.3	0.3	0.3	0.3	0.3	[4]
- Coefficient of variation (%)	20	20	20	20	20	20	20	20	20	[19]

3.3.1 Repairing Cost

Repairing cost are the costs include labor, materials, and equipment cost. The expected repairing cost is calculated using total area of structure, unit cost of maintenance method and probability of failure. The expected repairing cost is determined by Equation (8) [20]:

$$C^{rep} = \sum_{t=1}^{n} \frac{C^{fix} + (A * UC_i * Pf)}{(1 + r/100)^t} \quad (8)$$

where C^{rep} is the repairing cost or maintenance cost (THB), C^{fix} is the fixed cost of repair (THB), A is the total area of structure (m^2), UC_i is the unit cost of maintenance method i^{th} based on damage condition (THB/m^2), Pf is the probability of failure (%), r is the interest rate (%) and t is the year from 1 to n.

For the repairing cost, totally five time repairs of the 50 year of service life are conducted in order to compare life cycle cost between no or multi-repair. It is certainty that the structure cannot become to original state because repairing is not conducted to all structure area. It means that damaged area is initially renovated.

3.3.2 Failure Cost

Failure cost includes the loss of structure, loss of human life, cost of injuries, driver delay cost driver delay cost, etc. The difference of failure alternatives may occur at different time, so failure cost related to time and discounted rate [16]. Expected failure cost is determined with probability of failure as shown in Equation (9) [16]:

$$C^{fail} = \sum_{i=1}^{n} \frac{A * C^{f} * Pf}{(1 + r/100)^t} \quad (9)$$

where C^{fail} is the failure cost at decision time (THB), A is the total area of structure (m^2), C^f is the failure cost coefficient (THB/m^2), Pf is the probability of failure (%), t is the time of failure and r is the discount rate (%).

3.4 Optimization

Optimization is a decision of choosing the best way or method to get a maximum or minimum output. The maximum or minimum values depend on objective function. In this study, the main optimization objective is to minimize the maintenance life cycle cost with required service life of structure. In order to find the best solution, it is significant to vary conditions. The variations are repairing time, repairing cost, repairing method and other constraints such as limit budget and timing as shown in Equation (10) [21]: Matlab is used to calculate LCC of all combination cases between repairing method, repairing cost and repairing time. Then the lowest LCC from all combinations is determined.

$$\min LCC(t) \ \text{subject to} \begin{cases} t < 50\,years \\ budget < 1.5\,million(THB) \end{cases} \quad (10)$$

- Objective functions: Minimize life cycle cost (min LCC)
- Variables: Time of repair (t)
- Constraints: Annual budget (1.5 million THB), Service life (50 years)

3.5 Case Studies

The case study is considered as 9 girders to present the real problem of infrastructure stock. Three criteria (cracking, spalling and flexural moment criteria) were selected. These selection criteria are due to the most common failure.

To determine the probability of failure due to durability, serviceability and load carrying capacity, different variables and parameters are considered due to constructional error or effects of local environment. Monte Carlo simulation is used to generate random parameters with probability density function as normal distribution as shown in the Table 1. The example of the section of girders that are used for this study is I shape with 0.18 m effective slab thickness, span length of 25m, 1.975m of effective width. Dimension of girder is shown in [3]. The girder was designed according to the AASHTO LRFD Bridge Design Specifications [22] . There are some fixed values such as the size of reinforcing steel and dimension of girders. Varied parameters include covering depth of prestressed, covering depth of stirrup, corrosion rate and chloride diffusion coefficient as shown in Table 1. Table 2 shows the cost parameters to calculate the repairing and failure cost in different criteria.

Table 2 Cost of repair and failure cost

Parameters	**Damage Conditions**					**References**
	Corrosion	Cracking	Spalling	Flexural	Shear	
Unit cost of repair (UC) (THB/m^2)	7,100	7,200	13,420	35,500	32,940	[20, 23]
Fixed cost of repair (F_c) (THB)	17,800	53,200	53,400	231,400	303,400	[20, 24]
Failure cost coefficient (C_f) (THB/m^2)	zero	1,780	3,550	7,000	17,800	[24, 25]

4. Results and Discussion

4.1 Probability of Failure

Due to the different parameters of nine girders, there are different failure probabilities of these three criteria. Fig.2 shows the probability of failure based on cracking criteria of all nine girders. In Fig.2, G7 is cracked fastest because the covering depth is lowest. The second severe girder is G3 because it has very high corrosion rate and chloride diffusion. Therefore, the corrosion is very fast and the girder is deteriorated quickly. It is assumed that the major factors controlling cracking criteria are covering depth of PC, corrosion rate, covering depth of stirrup, chloride diffusion. Fig.3 shows the probability of failure base on spalling criteria of all nine girders. The graph shows that girder G3, G7 are the severest spalled girders because its failure probability increased firstly. These two girders are low durability girders. The major factors controlling spalling criteria are the same as cracking.

Due to the result of failure probability in Fig.4 which is in ultimate limited state (flexural moment criteria), the G3 is the most severe among all girders because its failure probability also increased fastest. Therefore, in the future it is possible to reduce the failure by improving the quality control of covering depth and the corrosion rate. Fig.5 shows probability of failure of G4 after repairing three times based on cracking performance criteria. As shown in Fig.5, after repairing probability of failure is reduced but does not reach to zero because all structural area has not been repaired.

4.2 Life Cycle Cost

Due to calculation and comparison of the minimum LCC, the result of the lowest LCC has shown in Table 3. This table provides results of the different girders and different criteria. Results of G3, G4 and G7 were selected due to the large different of their properties such as covering depth, corrosion rate, and concrete properties as shown in Table 1. Therefore, the effects of different girder properties can be shown in LCC result clearly. To maintain cracking performance criteria, PC girders needed to be repaired many times because cracking criteria is reached very fast. In contrast, for very severe criteria such as flexural capacity criteria required only one time repairing. However, it is important to consider all of criteria cracking, spalling and flexural moment simultaneously for maintenance planning. Then, the results of Table 4 are shown.

However, the structure will be repaired all damages when repairing work is conducted. Therefore, considering LCC based on individual criteria is not so practical. Table 4 shows the sample of how to consider the life cycle cost of repairing when considering various performance criteria at the same time. Girder No. 3 in 50 years of service life is given as an example. Repairing cost of all damages from every performance criteria is calculated. Repairing time is considered based on each criterion. For example, C^{rep} of C, S and F of cracking are repairing cost of all cracking, spalling and flexural criteria when repairing time is as of cracking criteria (4 times repair at year 9th, 17th, 26th, and 43rd). Or C^{rep} of C, S and F of flexural are repairing cost of all cracking, spalling and flexural criteria when repairing time is as of flexural criteria (only one time repair at year 40th). By comparing the three maintenance criteria, the result of Table 4 shows that among the three criteria, four time repairs (at year 9th , 17th , 26th and 43th) based on cracking criteria of G3 provides the lowest combining LCC of all criteria. Repairing and failure cost of other criteria are needed to include in total LCC because failure cost can be considered not only cracking criteria but also spalling and flexural criteria. The total LCC base on cracking criteria is (6.533 million baht) lower than that of spalling and flexural. Thus, it is decided to repair according to schedule of cracking criteria for G3.

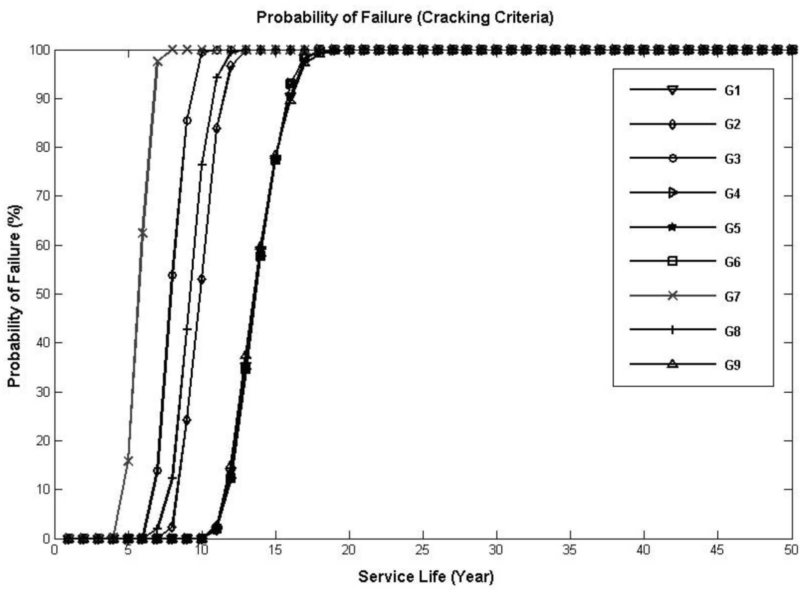

Figure 2 Probability of failure based on cracking criteria of all nine girders

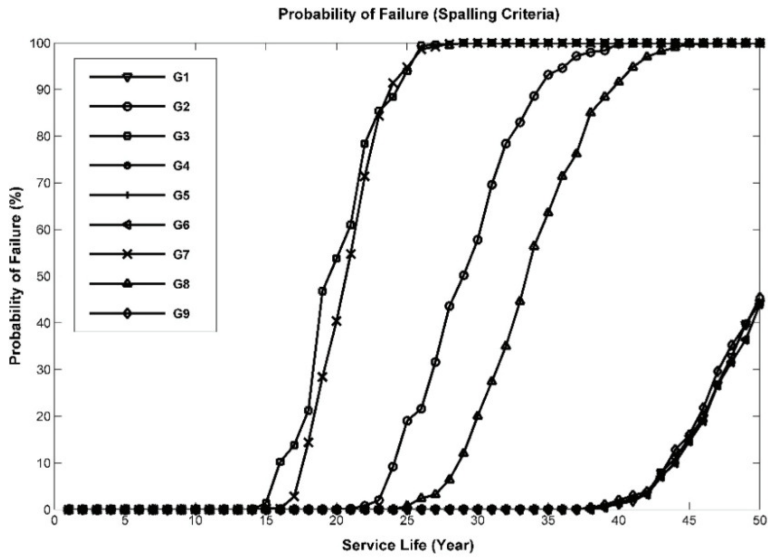

Figure 3 Probability of failure based on spalling criteria of all nine girders

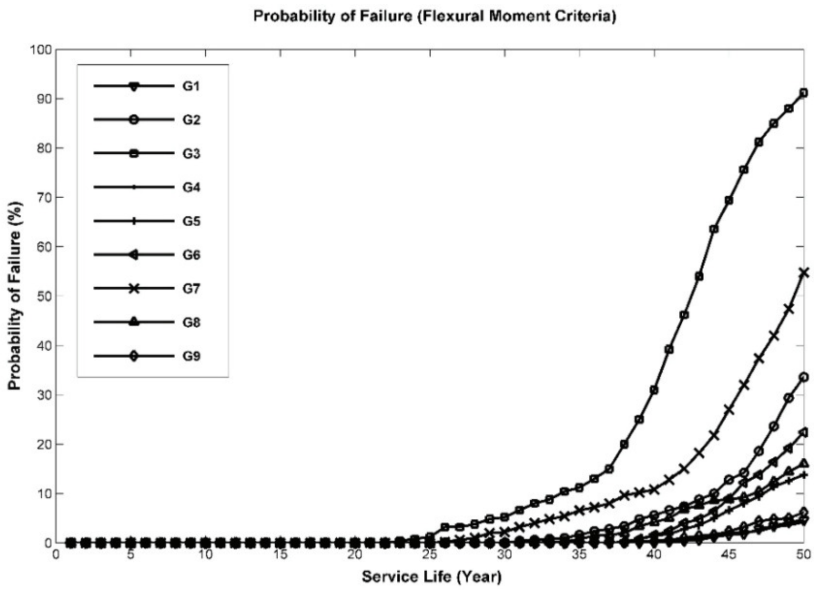

Figure 4 Probability of failure based on flexural moment criteria of all nine girders

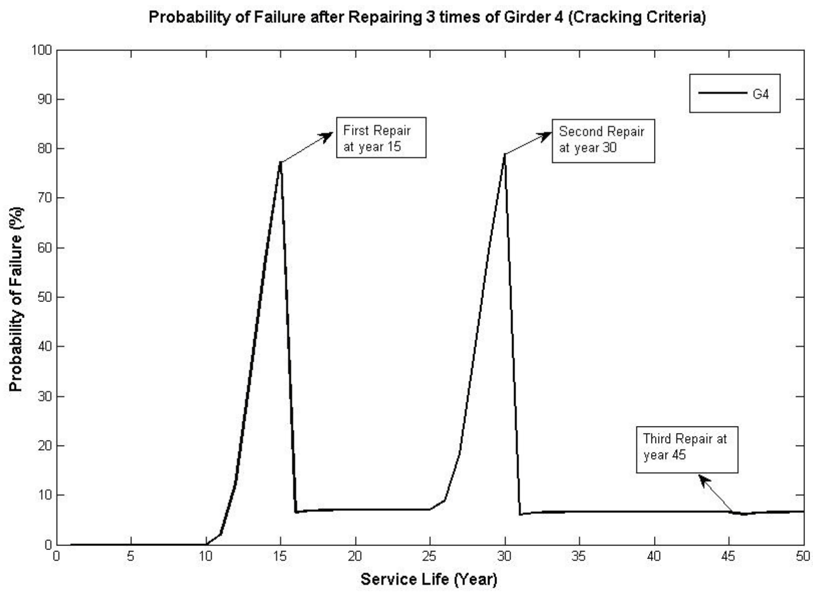

Figure 5 Probability of failure after repairing 3 times of G4 based on cracking criteria

Table 3 The comparison of total life cycle cost in 50 years of service life considering one criterion at a time for 3 girders

Girders	Repairing Criteria	Optimum Repairing Times (Year)					C^{rep} (THB)*10^6	C^{fail} (THB)*10^6	LCC (THB)*10^6
		T1	T2	T3	T4	T5			
G3	Cracking	9	17	26	43	-	0.954	0.511	**1.465**
	Spalling	21	39	-	-	-	0.715	1.525	2.240
	Flexural	40	-	-	-	-	0.446	1.309	1.755
G4	Cracking	15	30	45	-	-	0.742	0.567	1.310
	Spalling	39	-	-	-	-	0.018	0.188	**0.206**
	Flexural	41	-	-	-	-	0.325	0.039	0.364
G7	Cracking	6	12	18	30	48	0.724	0.594	1.318
	Spalling	23	43	-	-	-	0.871	1.212	2.083
	Flexural	34	-	-	-	-	0.087	0.229	**0.316**

Table 4 The total life cycle cost in 50 years of service life considering all criteria at a time for girder 3.

Girders	Repairing Criteria Base	Optimum Repairing Times (Year)				C^{rep} (THB)*10^6			C^{fail} (THB)*10^6			Total LCC (THB) *10^6
		T1	T2	T3	T4	C	S	F	C	S	F	
G3	Cracking	9	17	26	43	0.954	0.915	0.960	0.511	1.793	1.399	**6.533**
	Spalling	21	39	-	-	0.728	0.715	0.509	2.673	1.525	1.399	7.551
	Flexural	40	-	-	-	0.261	0.474	0.446	3.387	3.394	1.309	9.272

* C is cracking performance criteria
* S is spalling performance criteria
* F is flexural moment performance criteria

From results as shown in Table 4, Fig.6 is plotted to show annual maintenance cost based on cracking spalling and flexural criteria of all nine girders.

4.3 Limit Budget Constraints

In case repairing budget is limited to 1.5m THB per year. As shown in Fig.6, budget is not enough to repair in year 15^{th} and 30^{th}. So solution is proposed:

4.3.1 Cumulative maintenance cost

The first solution is to accumulate the remaining budget from the previous repaired year. For example, the company has the amount of maintenance cost only 1.5 million per repairing year and the required maintenance budget in year 15 is 2.17 million baht, then the basic solution is to accumulate the cost at year 6 until year14. Then, the summation cost is 11.45 million baht and it is enough to repair at year 15 as shown in Fig.7.

4.3.2 Shifting Time of Repairing

However, if the accumulate cost is not enough, it is essential to find the way out. Consequently, the second solution is presented by shifting some girders which is less damaged. As shown in Fig.2, G1, G4, G5, G6 and G9 can be shifted because its failure probabilities are very low. When these girders were shifted, the failure cost is not increased too much. In Fig.6, the maintenance cost is very high at year 15 because there are five girders needed to be repaired at the same year. In Fig.8, the maintenance cost lower than limit budget because some girders (G1 and G9) are shifted to repair in year 17. Therefore, the maintenance cost in year 17 increases but it is still lower than the limit budget. Therefore, it is possible to prioritize some girders to repair later to solve budget problem.

4.3.3 Changing Repairing Method

The third solution is to use another method and repairing material. For example, if it is required to repair by using coating and patching method, then it should do patching only or use cheaper repairing material. In this study, using lower unit cost represent using the cheaper repairing material (unit cost of repairing for cracking criteria is reduced to 4,570 THB/m^2 from 7200 THB/m^2 as shown in Table 2). It is cheaper, but it shortens the service life a little bit. Fig.9 shows the annual repairing cost base on cracking, spalling and flexural moment criteria of all nine girders during 50 years of service by reducing repairing material cost. When repairing material is changed the failure probability will be changed because of low performance material. The result shows that this method reduces the high maintenance cost in year 15. Therefore, this solution can be used to solve the limit budget constraints too.

5. CONCLUSIONS

The result of this study is based on probability and variation of inspection results to predict the deterioration degree of prestressed concrete structures and the prediction result is used to optimize life cycle cost. Due to the results, it can be concluded that:

- The failure probability can be calculated, and the repairing cost can be also estimated.
- The optimal life cycle cost can be determined, and maintenance planning of multiple girders can be decided by considering different criteria and constraints.
- Multiple repairing times will reduce life cycle cost due to minimize failure cost.
- The solution of limit budget is proposed with best maintenance planning.

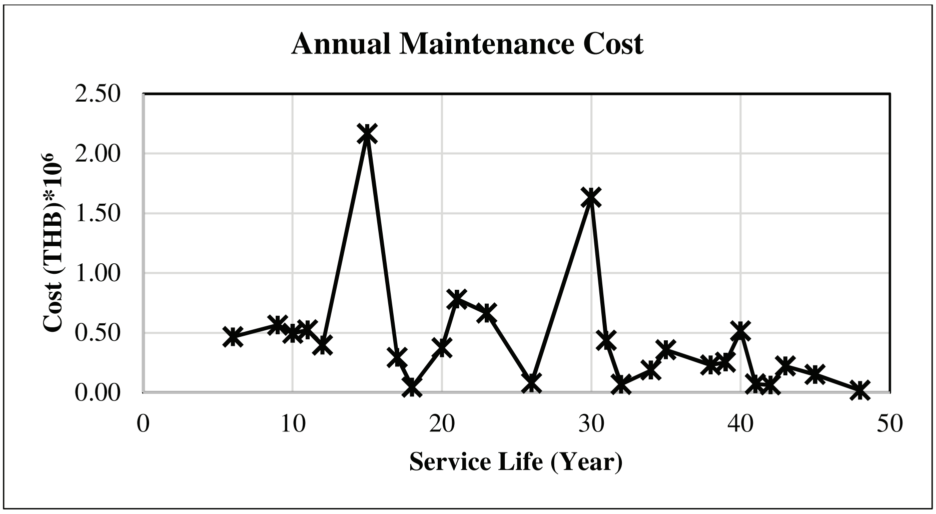

Figure 6 Annual repairing cost based on cracking, spalling and flexural moment criteria of all nine girders during 50 years of service

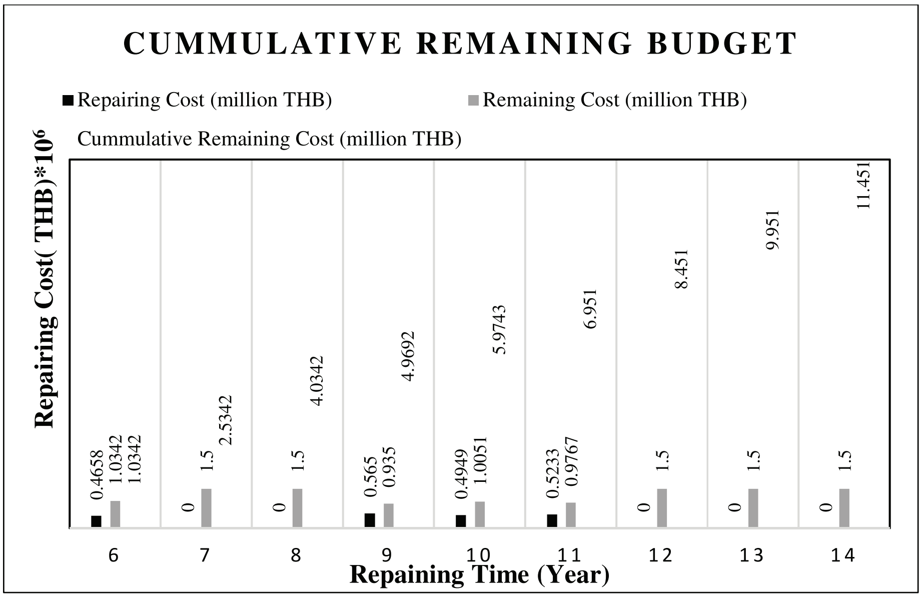

Figure 7 The cumulative maintenance cost to solve limit budget

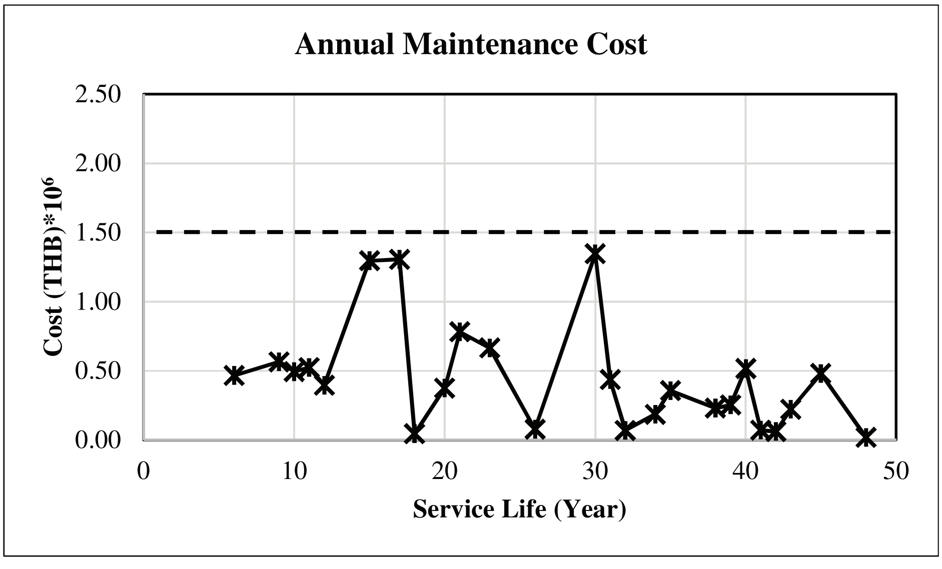

Figure 8 Annual repairing cost based on cracking, spalling and flexural moment criteria of all nine girders during 50 years of service by shifting girders

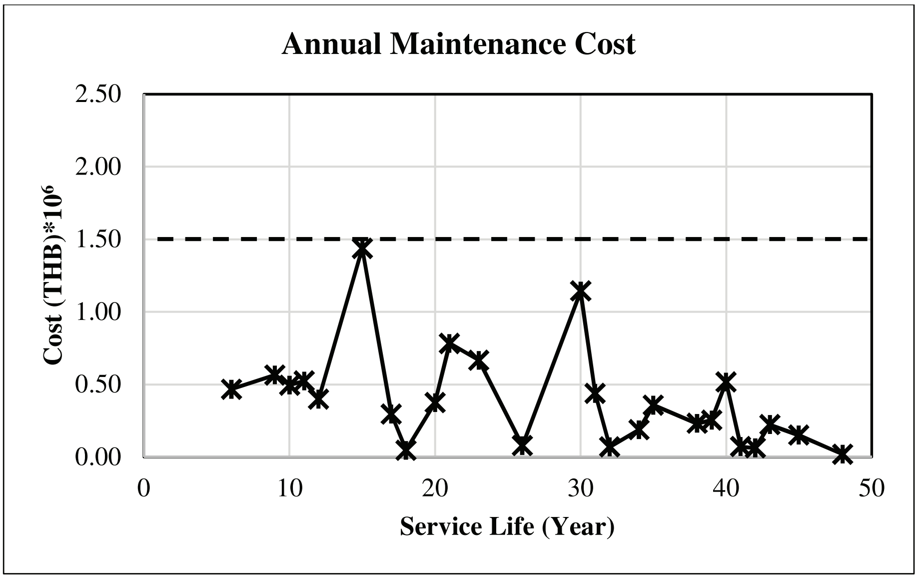

Figure 9 Annual repairing cost based on cracking, spalling and flexural moment criteria of all nine girders during 50 years of service by reducing repairing material cost

This study can be used as a guide for estimating the LCC over the whole service life. This can be used as a guideline for planning the repairing budget of prestressed concrete structures.

6. ACKNOWLEDGMENT

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