

Life-cycle framework based on non-destructive evaluation for optimal inspection/repair plan

Bouchra Kouddane^{1,2}

¹I2M, University of Bordeaux; Talence, France

²EMI, Mohammed V University; Rabat, Morocco

Abstract

Au cours de leur durée de vie, les infrastructures en béton comme les ponts ou les plates-formes offshore deviennent moins fiables et nécessitent des procédures d'inspection et de maintenance appropriées. Afin d'évaluer la performance des infrastructures tout au long de leur cycle de vie dans un contexte incertain, il est crucial d'étudier les mécanismes de détérioration structurelle. Dans cet article, l'intensité des dommages définit le degré des dommages existants en raison de la diminution du module d'Young au fil du temps. Cet article développe un cadre d'inspection/réparation optimal, basée sur la minimisation du coût total attendu du cycle de vie, tout en maintenant la fiabilité de la structure pendant toute sa durée de vie. Le coût global à minimiser comprend le coût initial, le coût d'inspection, le coût de réparation et le coût de défaillance. Par conséquent, le plan d'inspection/réparation est la solution d'un problème d'optimisation sous incertitude. Les variables de décision dans l'optimisation sont les moments auxquels les inspections/réparations sont effectuées et le nombre d'inspections, pendant la durée de vie de la structure. De plus, l'impact de plusieurs facteurs est mis en évidence pour voir comment ils influencent la stratégie optimale, comme la qualité de l'inspection par les techniques de contrôle Non Destructif, le coût attendu de la défaillance structurelle, ainsi que les effets des intervalles de temps d'inspection uniformes et non uniformes. Les résultats indiquent que le nombre optimal d'inspections est sensible à chacun des paramètres impliqués.

Key words: optimisation, coût total, minimisation, CND, fiabilité.

I. INTRODUCTION

Making quantitative estimations of the service life of structures and components constructed of concrete is becoming possible because of our growing understanding of the mechanics and kinetics of several events that lead to concrete degradation. The degradation in strength of a concrete structure exposed to an aggressive environment can be evaluated from a damage growth model, (Baji et al., 2017; Mori and Ellingwood, 1994). Understanding the structural degradation mechanisms is essential to quantify the life-cycle performance of structural systems under uncertainty (Kim et al., 2013). Some studies have been done to determine optimal inspection/maintenance strategies for metallic structures subjected to fatigue, assuming that a component is replaced if the intensity of detected damage exceeds a critical value (Thoft-Christensen and Sørensen, 1987). For the early time detecting of concrete degradation, many

studies proposed the implementation of Non Destructive Evaluation “NDE” techniques as (ultrasonic, Ground Penetrating Radar (GPR), Impact Echo (IE), and Infrared Thermography (IT), etc.) (Farhangdoust and Mehrabi, 2019; Robles et al., 2022; Shah and Ribakov, 2009). For instance, (Kashif Ur Rehman et al., 2016) provided an interesting overview of current NDTs used for defect detection in reinforced concrete bridges. To highlight the benefits and shortcomings of alternative NDTs, several comparative studies were done (Yehia et al., 2007), (Pushpakumara et al., 2017), (Gucunski et al., 2012).

The optimization strategy is applicable for any type of damage whose evolution can be modelled over time. Every design strategy or assessment of service life involves a number of essential elements: a deterioration model, acceptance criteria defining satisfactory performance, relevant characteristic material properties, and factors or margins of safety that take into account uncertainties in the overall system (Somerville, 1992), (Bismut and Straub, 2019).

This paper proposes a new methodology to optimize the lifetime inspection/repair strategy by minimizing the total life-cycle cost while satisfying different constraints, by introducing NDE inspection methods. The decision variables in the optimization are the times at which inspections/repairs are carried out and the number of inspections, during the service life of the structure. The influence of the number of inspections can be taken into account by solving the optimization problem for a number of different values (from 1 to 10) to identify that value for which the total cost is minimum.

A python program was developed to compute the minimisation problem and associated expected costs. The formulations derived in the coming sections are embedded in this program. An optimal inspection plan involves several aspects such as cost and quality of inspection by NDE, cost of repair, failure cost, net discount rate, uniform or nonuniform inspections, etc. The fundamental problem consists in calculating the number of optimal inspections in the lifetime of the component considering the indicated aspects, but also maintaining a certain level of reliability.

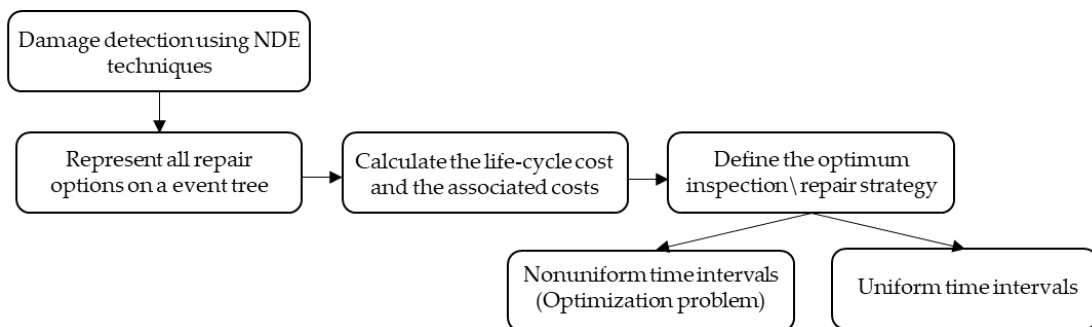


FIGURE 1. Optimization framework for an inspection\repair plan

II. Probabilistic modelling of structural damage

Several models have been developed to predict the service life of concrete subjected to degradation processes (Clifton, 1991). A variety of NDT methods, each with different costs and quality, can be used to assess the condition of a structure over its lifetime (Onoufriou and Frangopol, 2002). In this paper, the damage intensity η , which defines the degree of existing damage due to Young’s modulus decreasing over time, is defined as the ratio :

$$\eta(t) = \frac{E0 - E(t)}{E0} \quad (1)$$

Where $E0$ = concrete initial Young's modulus, $E(t)$ = Young's modulus at time t , and t = time in years.

The damage intensity can have a value between zero and one, meaning no damage and no residual strength, respectively. Young's modulus represents the elasticity, and the measure of the ability of a material to resist variations in length when undergoing longitudinal tension or compression in only one direction. In some special cases, it can also be used for investigation and indirect measurement of porosity, crack's creation, hardness, compressive strength and so on. Ultrasonic pulse velocity method is investigated to be a competent technique for accurately determine Young's modulus (Lin, 2018). Young's modulus $E(t)$ decreasing in function of time can be calculated as:

$$E(t) = E0 - k * Ti \quad (2)$$

Where k is the damage growth rate. Therefore, after repair, Young's modulus $E(t)$ is calculated as:

$$E(t) = E_r - k * Ti \quad (3)$$

Where E_r is Young's modulus of the repaired concrete that can be estimated by NDE.

When considering the intensity of damage η , the detectability function is modelled in this study as a cumulative normal distribution function for each NDE method. For a structure under a damage intensity η at time T_i inspected by an NDE method, the probability of damage detection is approximated as:

$$PoD = \begin{cases} 0, & \eta \leq \eta_{min} \\ \Phi\left(\frac{\eta - \eta_{0.5}}{0.1 \eta_{0.5}}\right), & \eta_{min} < \eta \leq \eta_{max} \\ 1, & \eta > \eta_{max} \end{cases} \quad (4)$$

Where $\eta_{0.5}$ is the damage intensity at which the NDE method has a 50% probability of detection. η_{min} and η_{max} are given, knowing that $\sigma = 0.1 \eta_{0.5}$:

$$\eta_{min} = \eta_{0.5} - 3\sigma = 0.7 \eta_{0.5} \quad (5)$$

$$\eta_{max} = \eta_{0.5} + 3\sigma = 1.3 \eta_{0.5} \quad (6)$$

III. Lifetime costs

A. Inspection Cost

In general, the effectiveness of the NDE methods affects the cost of the inspection. The cost associated with a real inspection method, C_{insp} can be estimated based on the quality of detectability, where C_{init} is the initial cost (Mori and Ellingwood, 1994). In order to define the quality of the inspection method, the median detectability of the inspection method $\eta_{0.5}$ is needed. It is used in the relation bellow to show the imperfect nature of the NDT method.

$$C_{insp} = 0,07C_{init}(1 - 0,7\eta_{0,5})^{20} \tag{7}$$

Thus, the overall expected inspection cost for a plan involving N_{insp} lifetime inspections is:

$$C_{INSP} = \sum_{i=1}^{N_{insp}} \frac{C_{insp}}{(1 + r)^{T_{insp,i}}} \tag{8}$$

For discounting, a discount rate r of 0,02 is used.

B. Repair Cost

The structure will not be repaired if the damage intensity is less than η_{min} . If a repair is performed after an inspection with a median detectability of $\eta_{0,5}$ at time T_i , the damage intensity will go from η_i to η_{rep} . When $\eta_i > \eta_{max}$ the damage of the repaired structure will be reduced to $\eta_{0,5}$.

$$\eta_{rep} = \begin{cases} \eta_i, & \eta_i \leq \eta_{min} \\ \frac{\eta_{min} + \eta_i}{2}, & \eta_{min} < \eta \leq \eta_{max} \\ \eta_{0,5}, & \eta_i > \eta_{max} \end{cases} \tag{9}$$

In this case, the repair cost can be expressed in terms of the repair effect e_{rep} as follows:

$$C_{rep} = m * C_{init} * e_{rep}^\gamma \tag{10}$$

Where γ is a model parameter assumed 0.5 and $m = 5$. The effect of a repair activity e_{rep} can be quantified as:

$$e_{rep} = \frac{|\eta_i - \eta_{rep}|}{\eta_{0,5}} \tag{11}$$

Then the expected total repair cost is:

$$C_{REP} = \sum_{j=1}^n (P(E_j) * \sum_{i=1}^{N_{insp}} \frac{C_{rep\ i,j}}{(1 + r)^{T_{insp,i}}}) \tag{12}$$

Where i ranges from 1 to the number of inspections and j ranges from 1 to the number of branches in the event tree. $P(E_j)$ is the probability of occurrence for each branch in the event tree. $C_{rep\ i,j}$ is the repair cost in each branch.

C. Failure Cost

Using the Weibull cumulative distribution function, the probability of failure P_f is determined as follow:

$$P_f = \begin{cases} 0, & \eta_i \leq \eta_{min} \\ 1 - [\exp - \left(\frac{\eta_i - \eta_{min}}{\eta_{0,5}}\right)^\alpha], & \eta_i > \eta_{min} \end{cases} \tag{13}$$

The expected failure cost C_{FAIL} can be expressed as:

$$C_{FAIL} = C_{fail} * P_{fail} \tag{14}$$

Where C_{fail} is the failure cost and P_{fail} is the lifetime probability of failure of the structure which is computed in equation 18.

D. Expected total cost

The annual total cost of the structure is used to determine the optimum maintenance management plan. The expected total cost C_T can be expressed as follow:

$$C_T = C_{init} + C_{INSP} + C_{REP} + C_{FAIL} \tag{15}$$

IV. Event Tree Analysis

To represent all the possible events associated with repair and non-repair actions, an event tree analysis is performed. The number of branches in the event tree depends on the number of inspections $n = 2^{N_{insp}}$. The probabilities associated with the events repair/no repair are computed as follow:

$$P(R) = \Phi\left(\frac{\eta - \eta_{0.5}}{0.1 \eta_{0.5}}\right) \tag{16}$$

$$P(NR) = 1 - P(R) \tag{17}$$

The probability that a reparation will occur at a specific time $P(E_j)$ can be obtained from the event tree by selecting all paths ending at time t and by adding all probabilities associated with these paths. Moreover, the probability of failure for each branch P_{fj} is used to compute the lifetime failure probability of the structure P_{fail} .

$$P_{fail} = \sum_{j=1}^n P_{fj} * P(E_j) \tag{18}$$

V. Uniform and Nonuniform interval inspection strategy

Although regular inspection intervals are more practical and manageable, taking into account nonuniform time intervals may result in lower costs and improved efficiency. The lifetime optimization procedure for nonuniform inspection intervals involves determining the ideal number of inspections N_{insp} and the ideal times for conducting inspections and repairs.

Minimum $C_T = C_{init} + C_{INSP} + C_{REP} + C_{FAIL} \tag{19}$

Subject to $t_{min} \leq t_i \leq t_{max}$
 $\sum_{i=1}^{N_{insp}} t_i \leq T$

Where T = life-cycle of the structure, $t_i = T_i - T_{i-1}$ time interval between the inspections $i - 1$ and i . t_{min} and t_{max} are minimum and maximum inspection time intervals. In this study, it is

assumed that the lifetime of the structure is 100 years. Initially, the inspection strategy is restricted to uniform time intervals, considering the number of inspections N_{insp} to be given. The optimization problem is solved for all values of N_{insp} and then the value that produces the smallest expected total cost is considered as the optimal number of inspections. Figure 2 shows the results of the cost analysis for different numbers of inspections with uniform intervals. For the same parameters considered in the uniform inspection interval strategy, figures 3 presents the expected total lifetime costs for different numbers of lifetime inspections associated with nonuniform time intervals. The cost of inspection is influenced by both the equipment's quality and the inspection method employed. Since the inspection is relatively inexpensive, the inspection cost has little effect on the total cost. On the other hand, repair cost is determined by the maintenance plan. However, the total expected cost is dominated by the expected losses due to structural failure. When expected cost of failure is included in the analysis, it is possible to find the optimal balance between safety and economy. Enhancing the overall safety level leads to an increase in most cost terms, but the expected costs of failure decrease. Figure 2 indicates that the optimum number of lifetime inspections is 6 for the case of uniform interval inspections with a minimum expected total cost of 1146.6. While the optimum nonuniform inspection interval strategy produces a cheaper solution with just 3 inspections at 61, 75, and 84 years of service life and a minimum expected total cost of 1061.3.

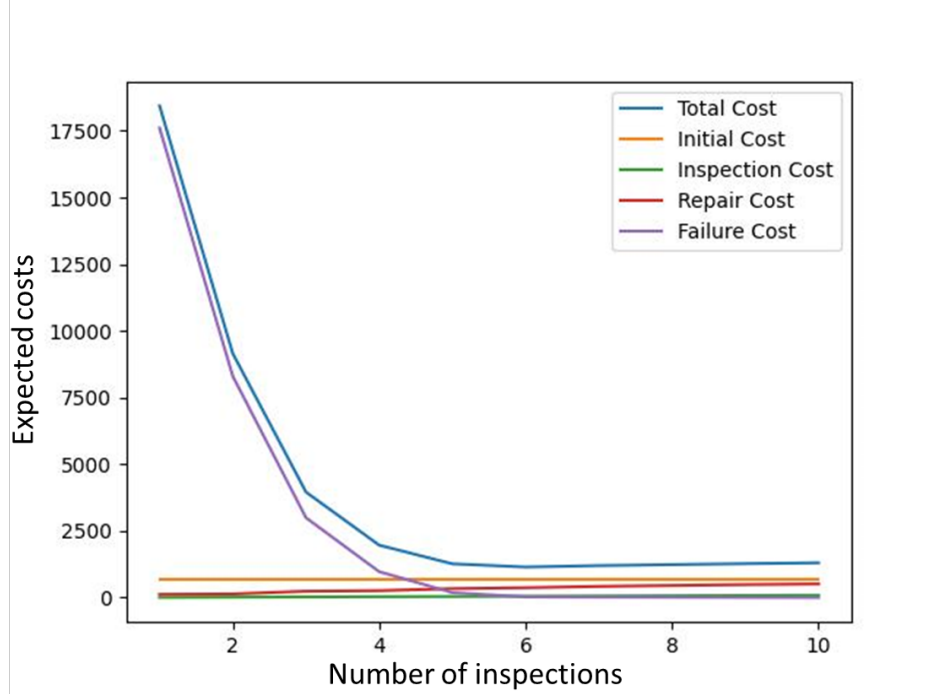


FIGURE 2. The different expected costs in euros as function of the number of uniform interval inspections

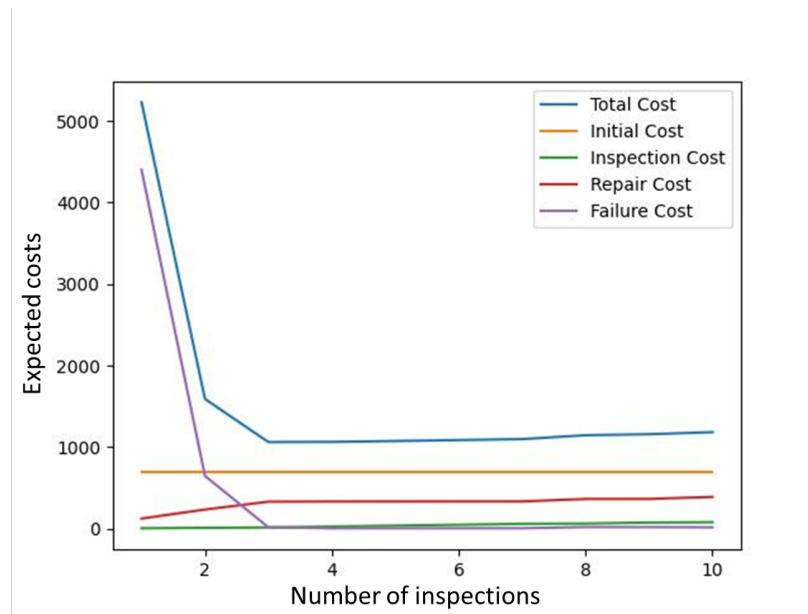


FIGURE 3. The different expected costs in euros as function of the number of nonuniform interval inspections

VI. Parametric study on the optimisation variables

In the case of uniform inspection intervals, a parametric analysis is introduced in order to evaluate the influence that each variable has in the determination of the optimal number of inspections. The variables analysed are: damage rate, quality of NDE, the annual discount rate and failure cost. The influence of damage rate is presented in figure 4 (a), it can be observed that the greater k is, greater is the number of optimal inspections in the life time cycle of the component. In addition, as the damage rate increases, the first inspection appears sooner in the life of the structure and the time intervals between successive inspections are smaller. In addition, quality of NDE technique has an effect on the optimum inspection/repair strategy. This effect is illustrated in figure 4 (b) using 5 different damage intensity. When using a good quality (low damage intensity), the optimum number of lifetime inspections decrease from 9 to 4 inspections. Figure 4 (c) presents the optimal number of inspections as function of the annual discount rate (r). The annual discount rate seems to be an important factor in the optimization study, as it also influences the determination of the optimal number of inspections in the life cycle of the component. The costs of failure also have a great influence in the determination of the optimal number of inspections. Figure 4 (d) shows that if the cost of failure increases, then the number of inspections increases. The optimum number of lifetime inspections is 5 when cost of failure is 10000. Under the same conditions when the cost of failure is 50000 the optimum number of inspections is 6. Consequently, a higher failure cost leads to an optimum solution requiring more inspections.

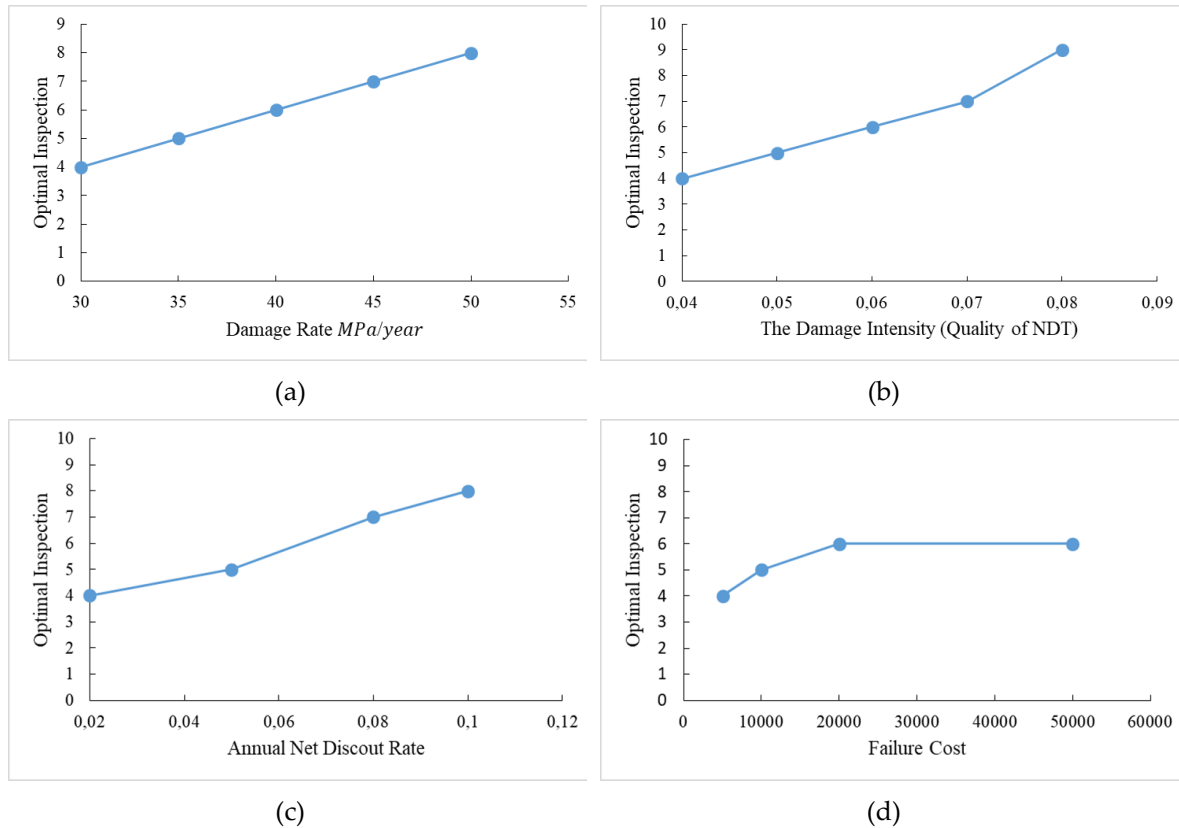


FIGURE 4. The influence of a) damage rate, b) quality of NDT, c) annual net discount rate and d) failure cost on the optimal number of inspection (Uniform intervals)

VII. Conclusion

This work shows the efficiency of minimizing the expected total life-cycle cost in order to find the optimal inspection\repair strategy of structures that deteriorate over time. The event tree model offers a systematic way to arrange and evaluate the repair possibilities. Regarding the optimisation strategy, the optimal nonuniform interval inspection/repair strategy is more cost-effective and requires fewer lifetime inspections/repairs than that based on uniform intervals. As stated previously, the effects of varying: the damage rate, quality of inspection techniques, the annual net discount rate and failure cost cannot be neglected. The findings show that each of the parameters involved can be considered when determining the best number of inspections to perform throughout the component's life. Therefore, the methodology presented here has the genuine potential for combining economic and safety considerations in structural design, using accurate input data. Future efforts are needed to consistently deal with another optimisation problem, by minimising the expected total cost and maximizing reliability index.

REFERENCES

- Baji, H., Li, C.-Q., Scicluna, S., Dauth, J., 2017. Risk-cost optimised maintenance strategy for tunnel structures. *Tunn. Undergr. Space Technol.* 69, 72–84. <https://doi.org/10.1016/j.tust.2017.06.008>
- Bismut, E., Straub, D., 2019. Optimal Adaptive Inspection and Maintenance Planning for Deteriorating Structural Systems. <https://doi.org/10.13140/RG.2.2.20252.85129>
- Clifton, J.F., 1991. Predicting the remaining service life of concrete (No. NISTIR-4712). National Inst. of Standards and Technology (NML), Gaithersburg, MD (United States). Center for Atomic, Molecular and Optical Physics. <https://doi.org/10.2172/469656>
- Farhangdoust, S., Mehrabi, A., 2019. Health Monitoring of Closure Joints in Accelerated Bridge Construction: A Review of Non-Destructive Testing Application. *J. Adv. Concr. Technol.* 17, 381–404. <https://doi.org/10.3151/jact.17.381>
- Gucunski, N., Maher, A., Ghasemi, H., Ibrahim, F., 2012. Segmentation and condition rating of concrete bridge decks using NDE for more objective inspection and rehabilitation planning. pp. 617–624. <https://doi.org/10.1201/b12352-83>
- Kashif Ur Rehman, S., Ibrahim, Z., Memon, S.A., Jameel, M., 2016. Nondestructive test methods for concrete bridges: A review. *Constr. Build. Mater.* 107, 58–86. <https://doi.org/10.1016/j.conbuildmat.2015.12.011>
- Kim, S., Frangopol, D.M., Soliman, M., 2013. Generalized Probabilistic Framework for Optimum Inspection and Maintenance Planning. *J. Struct. Eng.* 139, 435–447. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0000676](https://doi.org/10.1061/(ASCE)ST.1943-541X.0000676)
- Lin, K., 2018. Non-destructive measurement for Young's modulus using a self-mixing laser diode.
- Mori, Y., Ellingwood, B.R., 1994. Maintaining Reliability of Concrete Structures. II: Optimum Inspection/Repair. *J. Struct. Eng.* 120, 846–862. [https://doi.org/10.1061/\(ASCE\)0733-9445\(1994\)120:3\(846\)](https://doi.org/10.1061/(ASCE)0733-9445(1994)120:3(846))
- Onoufriou, T., Frangopol, D.M., 2002. Reliability-based inspection optimization of complex structures: a brief retrospective. *Comput. Struct.* 80, 1133–1144. [https://doi.org/10.1016/S0045-7949\(02\)00071-8](https://doi.org/10.1016/S0045-7949(02)00071-8)
- Pushpakumara, B.H.J., Silva, S.D., Silva, G.H.M.J.S.D., 2017. Visual inspection and non-destructive tests-based rating method for concrete bridges. *Int. J. Struct. Eng.* 8, 74–91. <https://doi.org/10.1504/IJSTRUCTE.2017.081672>
- Robles, K.P.V., Yee, J.-J., Kee, S.-H., 2022. Electrical Resistivity Measurements for Nondestructive Evaluation of Chloride-Induced Deterioration of Reinforced Concrete—A Review. *Materials* 15, 2725. <https://doi.org/10.3390/ma15082725>
- Shah, A.A., Ribakov, Y., 2009. Non-linear ultrasonic evaluation of damaged concrete based on higher order harmonic generation. *Mater. Des.* 30, 4095–4102. <https://doi.org/10.1016/j.matdes.2009.05.009>
- Somerville, G., 1992. Service Life Prediction--An Overview. *Concr. Int.* 14, 45–49.
- Thoft-Christensen, P., Sørensen, J.D., 1987. Reliability analysis of tubular joints in offshore structures. *Reliab. Eng.* 19, 171–184. [https://doi.org/10.1016/0143-8174\(87\)90002-3](https://doi.org/10.1016/0143-8174(87)90002-3)
- Yehia, S., Abudayyeh, O., Nabulsi, S., Abdelqader, I., 2007. Detection of Common Defects in Concrete Bridge Decks Using Nondestructive Evaluation Techniques. *J. Bridge Eng.* 12, 215–225. [https://doi.org/10.1061/\(ASCE\)1084-0702\(2007\)12:2\(215\)](https://doi.org/10.1061/(ASCE)1084-0702(2007)12:2(215))