Life-Cycle Reliability of Concrete Bridges in an Earthquake Prone Region and Aggressive Environment

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ABSTRACT

Over the last two decades, the probabilistic assessment of reinforced concrete (RC) structures under seismic hazard has been developed rapidly. However, little attention has been devoted to the assessment of the seismic reliability of corroded structures. This paper presents a framework for computing the time-dependent seismic reliability of concrete bridges in an earthquake prone region and a marine environment. It includes: (a) estimate of seismic capacity of corroded RC components; (b) seismic and airborne chloride hazard assessment; and (c) seismic reliability of bridges with corrosion damage. The effects of seismic hazard, hazard associated with airborne chloride, and spatial distribution of steel corrosion on the time-dependent seismic reliability are investigated in this paper. The findings show that the time-dependent reliability of concrete bridge depends on both the seismic and airborne chloride hazards, and that the spatial distribution of steel corrosion has to be taken into consideration in the seismic reliability analysis.

Keywords. Concrete Structures, Reliability, Seismic Hazard, Airborne Chloride, Spatial Distribution of Corrosion

INTRODUCTION

For structures located in a moderately or highly aggressive environment, multiple environmental and mechanical stressors lead to deterioration of structural performance. Such deterioration will reduce the service life of structures and increase the life-cycle cost of maintenance actions. Various environmental stressors affect the degradation mechanisms of structures. However, the effects of these stressors are difficult to predict, as these effects vary in time and space. Because of the presence of such uncertainties, long-term structural performance must be predicted based on probabilistic concepts and methods.

Since corrosion accelerates the vulnerability of concrete bridges subjected to seismic hazard, it is important to consider the effect of corrosion on life-cycle seismic reliability of bridges in earthquake prone regions and aggressive environments. Even though, Simon et al. (2010)

presented the effects of corrosion on the seismic response of a typical RC bridge based on realistic lifetime deterioration in strength due to the reduction in cross-sectional area of the reber. However, performing the structural analysis using the reduced rebar cross-section is an oversimplification for evaluating the relationship between load and displacement of deteriorating RC components. Ghosh and Padgett (2010) developed time-dependent seismic fragility curves of multi-span continuous steel girder bridges accounting for variation in ground motion and corrosion parameters. They illustrated the impact of aging on not only component but system reliability. However, their model associated with the corrosion deterioration of RC columns due to reber area loss needs to be improved.

Probabilistic methods for the evaluation of deterioration of RC structures due to chloride attacks have been reported and a probabilistic framework for life-cycle analysis of RC structures has been established. However, this framework did not include the reliability estimation of structures subjected to seismic hazard. These reliability analyses have included examination of chloride threshold concentration, cracking and spalling of cover concrete, and/or deterioration of flexural and shear strength of concrete components. These prior studies have not taken into consideration the probabilistic assessment of the effects of de-icing salt and/or airborne chlorides. Unlike the case associated with actions that are usually considered in structural design (e.g., probabilistic seismic hazard analysis (Kameda and Nojima, 1988)), there is a lack of research on marine environmental hazard assessment. This is because the data on coastal atmospheric exposure is very limited. It should be noted that whereas the seismic demand depends on the results of seismic hazard assessment, the deterioration of seismic capacity depends on the environmental hazard assessment. Akiyama et al. (2012) established a methodology for the probabilistic hazard assessment associated with airborne chloride and proposed the criterion for designing RC structures that satisfy a target durability level. The procedure to integrate the hazard associated with airborne chloride into life-cycle seismic reliability estimation of concrete bridge is provided herein.

COMPUTATINAL PROCEDURE TO ESTIMATE THE SEISMIC FAILURE PROBABILITY OF CONCRETE BRIDGE IN A MARINE ENVIRONMENT

The term 'seismic probabilistic risk assessment' is usually reserved for the comparison of criteria of risk acceptability to estimated structural risk, caused by potential earthquakes which could occur in the future, taking into account the variability and uncertainty in earthquake occurrence, in seismic ground motions and in structural response. In the seismic probabilistic risk assessment, the annual probability of exceedance of seismic capacity is

$$p_{fa} = \int_0^{\infty} -\frac{dp_0(\gamma)}{d\gamma} \cdot P\left[D_e \geq C_a \middle| \Gamma = \gamma\right] d\gamma \tag{1}$$

where p_0 (γ) = the annual probability that the seismic intensity, Γ, at a specific site would exceed a value γ; and $P[D_e \geq C_a \mid \Gamma = \gamma]$ = fragility, which is the conditional probability of the seismic demand D_e exceeding the seismic capacity C_a given the seismic intensity γ.

In the calculation of the conditional probability $P[D_e \geq C_a \mid \Gamma = \gamma]$ of concrete bridges in a marine environment, the effect of corrosion has to be taken into consideration. Using the total probability theorem, the annual probability of exceedance of seismic capacity C_a under earthquake excitation at t years after construction can be expressed as

$$p_{fa}(t) = \int_0^{100} \int_0^{\infty} -\frac{dp_0(\gamma)}{d\gamma} \cdot P\left[D_e \geq C_a \middle| \Gamma = \gamma, C_w = c_w(t)\right] \cdot f\left(c_w(t)\right) d\gamma \, dc_w \tag{2}$$

where $P[D_e \geq C_a \mid \Gamma = \gamma,\ C_w = c_w(t)]$ = conditional probability of the seismic demand D_e exceeding the seismic capacity C_a conditioned upon the seismic intensity γ and steel weight loss $c_w(t)$; and $f(c_w(t))$ = probabilistic density function, PDF of $c_w(t)$.

During a given time interval T, the cumulative-time failure probability p_f of concrete bridge subjected to both seismic hazard and hazard associated with airborne chlorides is

$$p_f = 1 - \left(1 - p_{fa}(1)\right) \cdot \left(1 - p_{fa}(2)\right) \cdots \left(1 - p_{fa}(t = T)\right) \tag{3}$$

It is assumed in Equation (3) that the events associated with the failure probabilities at different times t are statistically independent. However, technically, they are dependent through the strength. There have been studies published giving seismic hazard estimates based on non-Poissonian seismicity (Bommer, 2002). Since the lifetime of the structure is much shorter than the return period of earthquake, the assumption of using the same seismic hazard curve $p_0(\gamma)$ for time interval T could be acceptable.

The life-cycle reliability under earthquake excitations of corroded concrete structures is given by Equations (2) and (3). Figure 1 shows the flow chart for estimating $p_{fa}(t)$ in Equation (2). $P[D_e \geq C_a \mid \Gamma = \gamma,\ C_w = c_w(t)]$ is calculated by Monte Carlo Simulation (MCS) and it can be expressed as:

$$P\left[D_e \geq C_a \middle| \Gamma = \gamma, C_w = c_w(t)\right] = P\left[\frac{D_e(\Gamma = \gamma, C_w = c_w(t))}{C_a(C_w = c_w(t))} \geq 1.0\right] \tag{4}$$

where $D_e(\Gamma = \gamma,\ C_w = c_w(t))$ = seismic displacement ductility demand obtained by nonlinear dynamic analysis for concrete bridge at seismic intensity $\Gamma = \gamma$ and steel weight loss $C_w = c_w(t)$; and $C_a(C_w = c_w(t))$ = seismic capacity at $C_w = c_w(t)$.

The fragility provided by Equation (4) is estimated from the ratio p_γ of the number of times $D_e(\Gamma = \gamma,\ C_w = c_w(t))$ exceeds $C_a(C_w = c_w(t))$ to the total number of MCSs. $D_e(\Gamma = \gamma,\ C_w = c_w(t))$ is calculated by nonlinear dynamic analysis using a number of artificial ground motions.

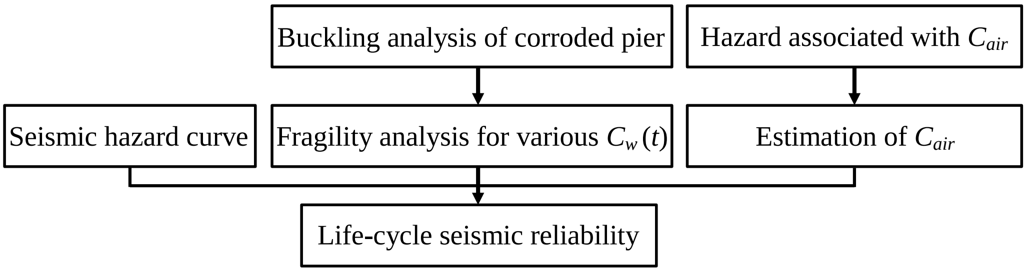


Figure 1. Flow chart to estimate the seismic reliability of concrete bridge in a marine environment

DESCRIPTION OF CONCRETE BRIDGE AND HAZARD CURVES

The typical rigid frame concrete bridge consisting of three PC box girders and two RC bridge piers is shown in Figure 2. This bridge was originally designed according to the Design Specifications for Highway Bridges (DSHB) by the Japan Road Association. Seismic design force was given based on the 1995 Hyogoken-Nanbu earthquake, independent of the bridge locations. Ground type was classified as Ground Type I in terms of natural period of soil (Japan Road Association 2002). Figure 2 shows the cross-section of RC bridge piers. Assuming that PC box girders remain the elastic behavior over the all seismic intensities in the fragility analysis and RC bridge piers have sufficient ties to prevent the shear failure, the limit state associated with the flexure for the RC bridge piers is considered to estimate the failure probability of concrete bridges. Figure 3 shows the two-dimensional nonlinear analytical model of the concrete bridge. The effect of the steel corrosion on the deteriorations of horizontal strength, stiffness, and ultimate ductility capacity are considered in the relationship between moment and rotation of plastic hinge of RC bridge pier, as shown in Figure 4. The model errors associated with the estimation of horizontal strength, stiffness, and ultimate ductility capacity of corroded RC bridge pier are used for calculating D_e ($\Gamma = \gamma$, $C_w = c_w(t)$) in the fragility analysis. These random variables are reported by Akiyama et al. (2011).

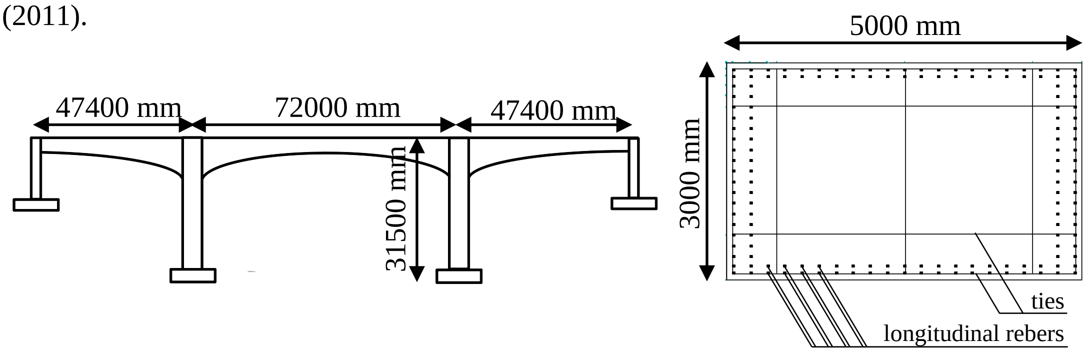
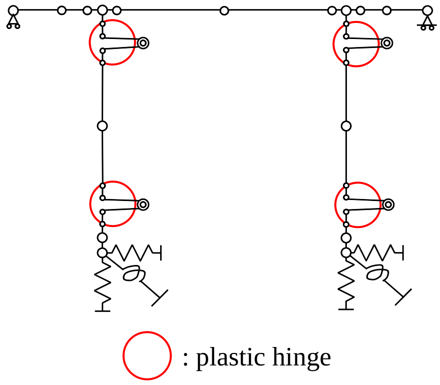


Figure 2. Rigid-frame concrete bridge and cross-section of the RC bridge pier



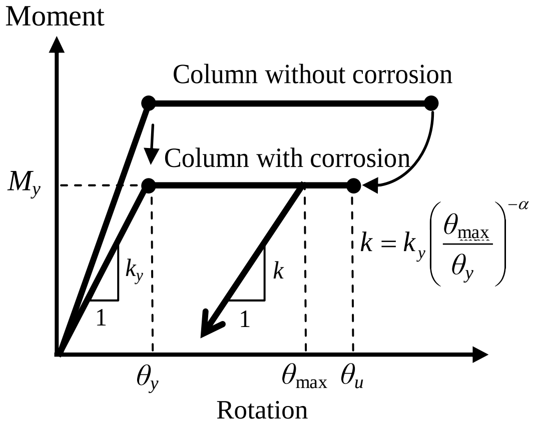


Figure 3. Multi degree of freedom model (MDOF)

Figure 4. Effect of corrosion on the bending moment and rotation relation

It is assumed that the concrete bridges are located in Niigata City (d = 0.1 km), Ishinomaki City (d = 0.5 km), and Uwajima City (d = 1.0 km) in Japan. Seismic hazard curves as shown in Figure 5 (a) are used to estimate the seismic demand of bridge. The horizontal axis of seismic hazard curves used in this study is the maximum velocity of the ground motion at the bedrock. This is also used as seismic intensity. Hazard curves associated with airborne chloride as shown in Figure 5 (b) are used in the estimation of steel weight loss of rebars C_w (t). Hazard curves associated with airborne chloride are established using the distance from coastline, speed of wind, and the ratio of sea wind (defined as the percentage of time during one day when the wind is blowing from sea toward land). The statistics of wind speed and the ratio of sea wind were obtained from meteorological data (Akiyama et al., 2012). These data shows that wind speed and the ratio of sea wind can be assumed to be statistically independent. By applying the concept of seismic probabilistic hazard assessment (Kameda and Nojima, 1988) to the probabilistic hazard assessment associated with airborne chlorides, the effect of a marine environment can be quantified. The procedure to estimate $C_w(t)$ includes nine random variables. The detailed methods to calculate $C_w(t)$ and all statistics of these variables are presented by Akiyama et al. (2010).

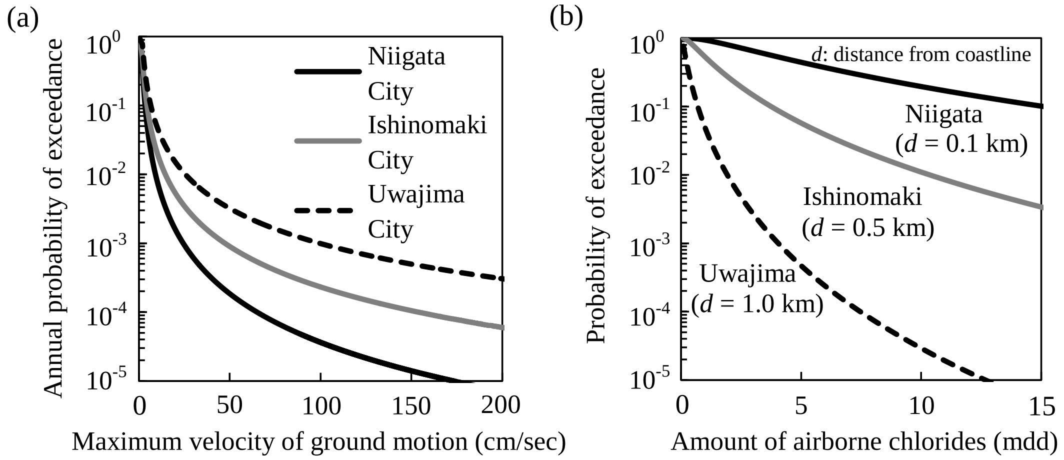


Figure 5. Hazard curves [(a) seismic hazard curves; and (b) hazard curves associated airborne chloride]

LIFE-CYCLE SEISMIC RELIABILITY OF RC BRIDGE

Figure 6 (a) shows the fragility associated with the maximum velocity of ground motion at bedrock, assuming that all the plastic hinges of the bridge piers have steel weight loss of 0 %, 5 %, 20 % and 40 %, respectively. The failure probability $P[D_e \geq C_a \mid \Gamma=\gamma, C_w = c_w(t)]$ is estimated under the condition that the seismic demand D_e (i.e., response rotation) exceeds the seismic capacity C_a (i.e., ultimate rotation θ_u in Figure 4) in even one of four plastic hinges given $\Gamma=\gamma$, $C_w = c_w(t)$. Since C_a ($C_w = c_w(t)$) decreases with the corrosion amount and D_e ($\Gamma=\gamma$, $C_w = c_w(t)$) increases with the corrosion amount and seismic intensity, the fragilities are different among the bridges with various steel weight losses as shown in Figure 6 (a).

Figure 6 (b) shows the fragility taking into consideration the spatial distribution of steel

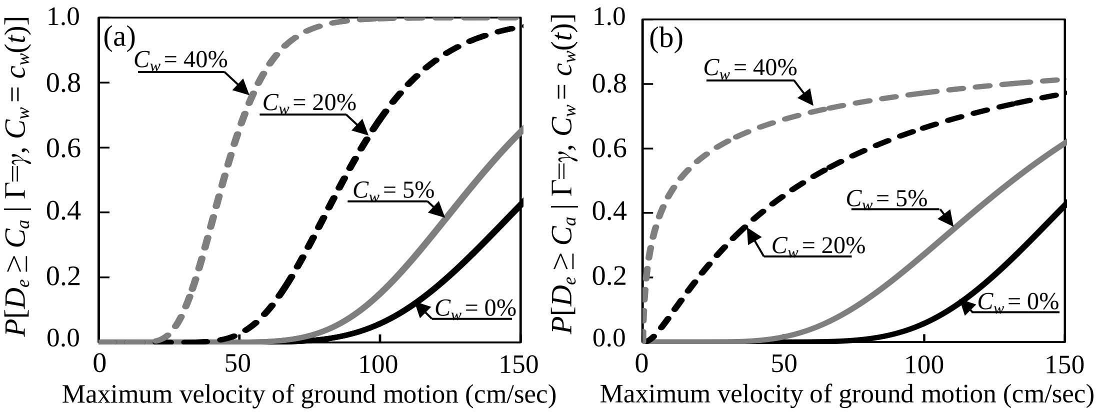


Figure 6. Comparison of fragility estimates with different amounts of steel weight loss ((a) without considering the spatial distribution of steel corrosion; (b) with considering the spatial distribution of steel corrosion)

corrosion in the concrete bridge. In the MCS to estimate the $P[D_e \geq C_a \mid \Gamma=\gamma, C_w = c_w(t)]$, it is assumed that each plastic hinge has the steel weight loss with the mean of c_w (t) and coefficient of variation of δ_s, and steel weight losses of different plastic hinges are statistically independent. δ_s is assumed to be 230% based on the measurements of steel weight losses of rebers in the existing marine concrete structures with the ages of larder than 30 years (Kato et al., 2006).

When considering the probability $\Gamma= \gamma$ and $C_w = c_w$ (t) shown in Figures 5 (a) and (b), respectively, life-cycle reliability of RC bridge accounting for seismic hazard and hazard associated with airborne chlorides can be obtained. Figure 7 shows the relationship between cumulative-time failure probability and time after construction of bridge using the fragility curves as shown in Figure 6 (a). To examine the effect of corrosion on the failure probability, cumulative-time failure probabilities without deterioration (i.e. annual failure probability $p_{fa}(t)$ in Equation (2) does not depend on time after construction) are also shown in Figure 7. Since the DSHB specifies the seismic design force without considering the differences of seismic hazards in Figure 5 (a), the geometry and structural details of bridge located in three cities are the same. Therefore, at the beginning, the failure probability of the bridge only depends on the seismic hazard, and the bridge located in Uwajima has the highest failure probability. However, as shown in Figure 5 (b), the probability of exceedance of a prescribed

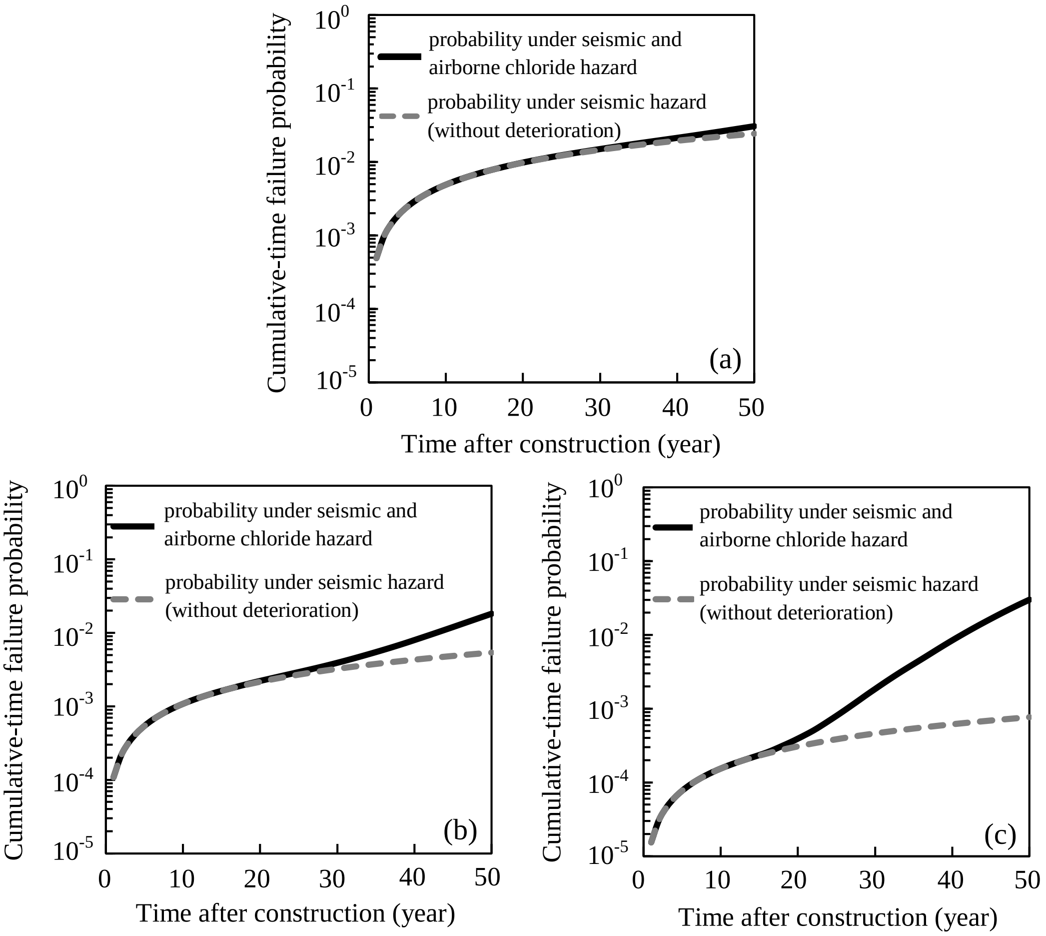


Figure 7. Relationship between time and cumulative-time failure probability ((a) Uwajima City; (b) Ishinomaki City; and (c) Niigata City)

amount of airborne chloride in Niigata City is much higher. The cumulative-time failure probability of concrete bridge pier in Niigata City increases with time due to chloride attack. The difference between the cumulative-time failure probability associated with both seismic and airborne chloride hazards and that associated with seismic hazard alone is the largest for Niigata City. Finally, at 50 years after construction, the cumulative-time failure probability of concrete bridge in Niigata City is the highest, even though the seismicity in Niigata City is the lowest among three cities. Therefore, to ensure the prescribed seismic reliability during the entire lifetime of concrete bridge in a marine environment, it is extremely important to consider the effect of corrosion on seismic capacity and demand.

Figure 8 shows the effect of spatial distribution of steel corrosion on cumulative-time failure probability of concrete bridge. The cumulative failure probabilities in Figure 8 are estimated using the fragility curves shown in Figure 6 (b). When considering the spatial distribution of steel corrosion, variability of steel weight loss in the plastic hinge becomes larger. As a result, the cumulative failure probability of bridge with spatial distribution of steel corrosion increases at an earlier time, comparing that without spatial distribution of steel corrosion. Especially, it is important in the seismic reliability estimation to consider the spatial distribution of steel corrosion if the concrete bridge is located in an aggressive environment like Niigata City, as shown in Figure 8 (c).

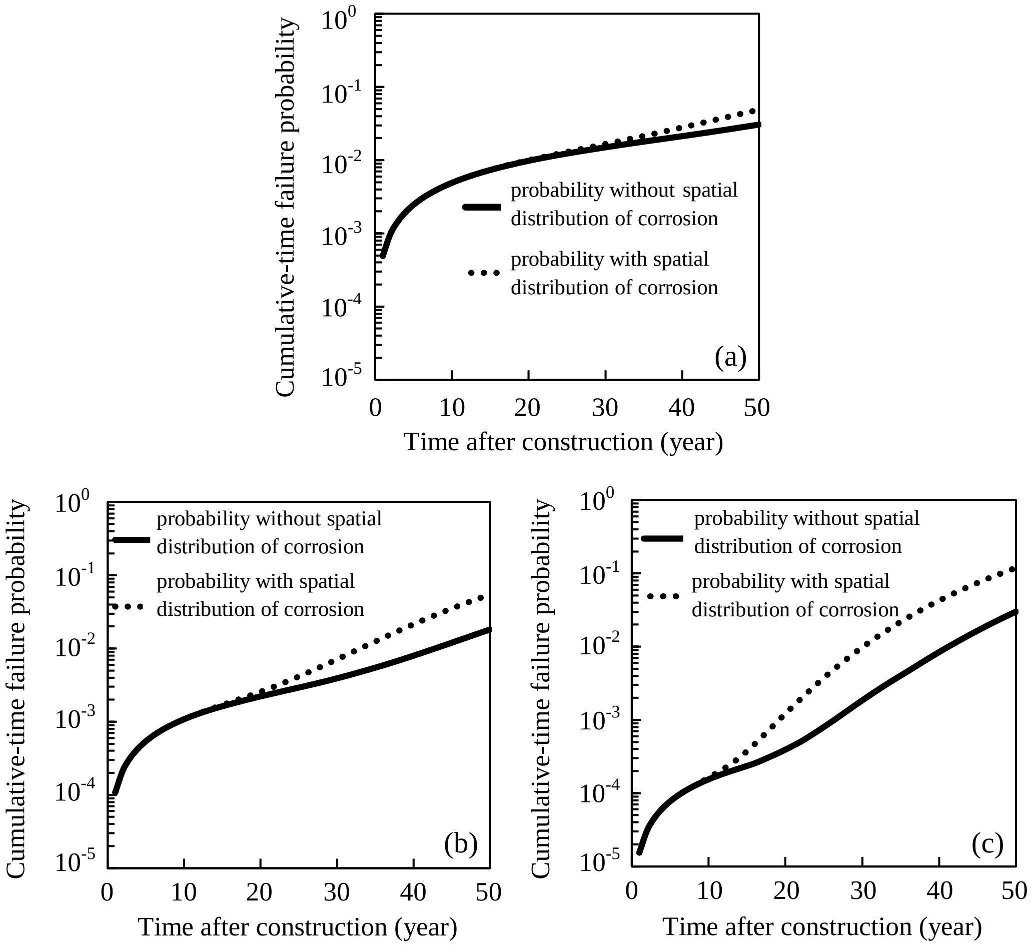


Figure 8. Effect of spatial distribution of steel corrosion on cumulative-time failure probability ((a) Uwajima City; (b) Ishinomaki City; and (c) Niigata City)

CONCLUSIONS

This paper presented a computational procedure to integrate the probabilistic hazard associated with airborne chlorides into life-cycle seismic reliability assessment of concrete bridge. Whereas the seismic demand depends on the results of seismic hazard assessment, the deterioration of seismic capacity depends on the airborne chloride hazard. In seismic reliability estimation of concrete bridge in a marine environment, it is important to take into consideration the effect of material corrosion on seismic performance.

The effects of seismic hazard and hazard associated with airborne chloride on life-cycle reliability were investigated. It should be noted that even if the failure probability is lower at the beginning of time after construction, it will increase with time due to the marine environment. These effects have to be used in decision-making considering reliability-based acceptance criteria and/or risk-cost benefit analyses.

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