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Probabilistic Life-Cycle Cost-Benefit Analysis of Portfolios of Buildings under Flood Hazard

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Abstract:

Nowadays, due to the extension of urbanization, the number of residential buildings in flood prone zones is increasing significantly. Therefore, for these buildings, it is of vital importance to conduct hazard risk mitigation strategies. In this paper, the probabilistic cost-benefit analysis of flood risk mitigation strategies for portfolios of residential buildings is investigated in a life-cycle context. Additionally, a methodology is proposed to aid decision-makers on whether or not to retrofit portfolios of structures considering both expected and standard deviation of life-cycle cost. The vulnerability model of buildings under flood hazard is introduced considering serviceability and ultimate limit states. Probabilistic cost-benefit analysis is performed by comparing the effectiveness of different retrofit actions. Additionally, uncertainty and correlation effects are considered in the probabilistic loss and cost-benefit analysis procedures. The proposed approach is applied to a portfolio of residential buildings located in Florida.

Key words: Flood; Portfolio of buildings; Regional risk; Probabilistic cost-benefit analysis; Uncertainty; Correlation; Life-cycle

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Introduction

Typically, flood causes include long-lasting rainfall, snowmelt, dam break, and temporary sea-level rise (FEMA 2014a). Flood accounts for almost 30% of the global losses associated with natural hazards (Dutta 2003; Douben 2006). Due to the catastrophic losses to the people and assets, flood is considered one of the major natural hazards for the society and economy in the United States and many other countries. Due to the effects of global warming and climate change, the frequency, intensity, and magnitude of the flood are increasing. Buildings play an important role in the economy and their damages resulting from a flood event contribute significantly to the total community loss. Furthermore, due to the rapid rate of extension of urbanization, buildings have an increasing exposure to flood in the urban areas. Thus, an effective probabilistic assessment and hazard mitigation approach of building portfolios is needed to estimate and optimize the performance of buildings under floods at a large scale in a life-cycle context.

Performance-based engineering (PBE) is a method to investigate infrastructure system performance under hazard effects (Cornell and Krawinkler 2000; Van de Lindt 2009; Barbato et al. 2013; Dong and Frangopol 2015). In this paper, the PBE approach is adopted within performance assessment and mitigation of building portfolios under hazard effects. Generally, the performance-based assessment can be divided into three parts: (a) hazard scenarios analysis, (b) structural performance and damage assessment, and (c) consequence and loss evaluation associated with decision variables (e.g., repair loss, downtime, and fatality). In this paper, PBE is adopted to investigate the performance of portfolios of buildings under flood effects.

The performance of a building under a flood event depends on many parameters, such as wall thickness, height of the building, presence of barriers, dimension of and configuration of doors and windows, and height of the raised foundation (Kreibich et al. 2005). The damage mechanisms of buildings under flood effects include physical and chemical deterioration, structural failure of walls or windows, and scour of foundation. The building performance also depends on the flood characteristics. Most vulnerability analyses under a flood event consider the flood depth as the main factor (Merz et al. 2004; Scawthorn et al. 2006). Although flood depth is the most common factor considered in the damage assessment, the flood velocity also has a significant effect on the structural failure (Kreibich et al. 2009). In this paper, both flood depth and velocity are considered in the structural vulnerability analysis. Roos (2003) investigated structural performance under flooding effects using a 2-dimensional (2D) structural analysis approach; Kelman (2002) presented an approach for the vulnerability assessment of residential buildings at a component level (e.g., wall and window) considering both flood rise and water infiltration processes; Mazzorana et al. (2014) developed an approach considering buildings' detail and system characteristics; and Custer and Nishijima (2015) proposed an approach for the flood vulnerability model considering relevant hazard and building characteristics at both component and system levels. These studies focused on the single building performance under flood effects; therefore, research associated with the performance of portfolios of buildings is needed.

There are uncertainties associated with hazard intensity, structural performance, and consequences of structural systems under flood effects. Accordingly, a probabilistic approach is needed to account for different kinds of uncertainties. Under a given flood event, there are uncertainties with respect to the hazard intensity in terms of depth and velocity at the locations of buildings. In this paper, a probabilistic risk assessment and mitigation approach is developed to compute the loss of a portfolios of buildings in a life-cycle context. Additionally, there exist similarities and correlations of the hazard intensities and structural properties among the buildings within a portfolio. Probabilistic loss of portfolios of buildings under flood effects at a large scale considering uncertainties and correlation effects has not been considered in previous studies. Herein, in order to quantify the probabilistic regional loss of portfolios of buildings, the uncertainties and correlation effects are incorporated within the evaluation procedure. Both mean and standard deviation are computed in the assessment process considering uncertainty and correlation effects.

Cost-benefit analysis should be incorporated into the hazard mitigation process in a probabilistic manner. Most of the previous studies emphasized the expected value of benefit and did not capture the uncertainty related to benefit analysis, which may lead to inappropriate decisions. The benefit associated with a specific retrofit plan depends on the intensity and frequency of the investigated hazard, time interval considered, and the structural performance under retrofit actions. In this paper, the uncertainties associated with benefit are considered in the hazard risk mitigation procedure. Furthermore, the life-cycle concept is adopted herein to investigate the building performance and benefit-cost ratio of retrofit actions.

In this paper, the performance and probabilistic cost-benefit analysis of flood risk mitigation strategies of portfolios of residential buildings are investigated. Probabilities of reaching different performance levels are assessed considering failure modes. The probabilistic cost-benefit analysis is conducted by comparing the effectiveness of different retrofit actions. Unreinforced masonry buildings, as one of the most common residential building types, are emphasized herein. The proposed probabilistic framework can be applied to other types of buildings. The approach presented in this paper could aid the decision-making process associated with residential building portfolios under flood effects in a life-cycle context.

Building Damage Assessment under Flood

In order to assess the structural performance of buildings under flood effects, a framework that considers hazard intensity and occurrence frequency, structural vulnerability under hazard, and consequence evaluation should be established. The flowchart regarding the performance-based hazard loss assessment is shown in Figure 1.

Flood Scenarios

The first step is to identify the magnitude and intensity of the flood. The PBE assessment of buildings under a flood event involves many parameters. The most critical parameters are the flood factors (e.g., depth and velocity) and the building properties. Thus, in order to compute the structural performance, the flood depth and velocity should be identified first. The flood characteristics, such as depth and velocity, can be obtained by using hydrodynamic flood simulation. This information, together with the detailed cartography of the investigated area and a digital elevation model is used as input into the hydraulic model. Then, the characteristics of the flood can be used for the flood load and structural performance analysis. In this paper, the load effects of the flood on residential buildings are related with flood depth, velocity, and debris considering different limit states.

Load Effects

The flood effects on buildings include hydrostatic forces, hydrodynamic forces, and forces generated by the impact of debris. The lateral hydrostatic pressure P_s and hydrostatic force per unit of length F_s could be computed as (Kelman 2002; FEMA 2012)

$$P_s = \rho_w g h \tag{1}$$

$$F_s = \frac{1}{2} P_s h \tag{2}$$

where g is gravity acceleration (m/s^2); ρ_w is mass density of water (kg/m^3); and h is the flood depth difference between the inside and outside water (m). The hydrostatic force could be computed as an equivalent point force at the height of $h/3$ from the ground.

The hydrodynamic load is related to the moving water and is assessed considering the velocity of flood water. The hydrodynamic pressure P_d and hydrodynamic force per unit of length F_d are

$$P_d = C_{drag} \rho_w \frac{V^2}{2} \tag{3}$$

$$F_d = P_d h \tag{4}$$

where C_{drag} is drag coefficient and V is average velocity of flood water (m/s).

The debris effect on the building is also considered in the loading effect evaluation procedure. The debris is carried along the flood and cause damage by crashing into the buildings. The debris sources could be identified based on the observation of the building site and urban planning documents. The structural damage subjected to debris usually depends on the weight of the debris and the flow velocity. The debris force can be computed as (Roos 2003)

$$F_{de} = V_{de} \sqrt{m_{de} k_s} \tag{5}$$

$$\frac{1}{k_s} = \frac{1}{k_{wa}} + \frac{1}{k_{de}} \tag{6}$$

where m_{de} is the debris mass (kg); V_{de} is the velocity of the debris (m/s); k_s is the spring stiffness; k_{wa} is the spring stiffness of wall; and k_{de} is the spring stiffness of debris.

Damage Analysis

The mechanical failure of the building under a flood event is emphasized in this section. Walls, acting as both structural and envelop components in the building, have significant importance and their failure can potentially result in the partial or total collapse of the building. Based on Roos (2003), the failure mechanism associated with wall failure is the most significant failure model for the masonry and concrete buildings. Thus, the wall failure is of most concern regarding building performance under flood and is emphasized in this section. The vulnerability analysis of masonry wall can be assessed using different methods, such as finite element analysis (De Risi et al. 2013; Xiao and Li 2013), yielding line analysis (Nadal 2007; Kelman and Spence 2003), and structural analysis (Roos 2003). The structural performance analysis represents the structural vulnerability under the given limit state. In this paper, the failure of walls under a flood event is investigated by considering the applied bending moments.

The wall can crack and collapse under the hydrostatic, hydrodynamic, and debris effects. For example, if the bending moment capacity associated with cracking of the wall is smaller than the applied loading bending moment, the cracks would appear and serviceability limit state will be reached. The four damage states associated with the wall failure considered in this paper are none, cracking, partial collapse, and collapse. The bending moment associated with cracking and ultimate capacity could be computed, respectively, as (Roos 2003; Custer and Nishijima 2015)

$$M_c = \frac{(f_t + \sigma_c)}{6} w \cdot t_w^{\,2} \tag{7}$$

$$M_u = \frac{(f_c - \sigma_c)}{6} w \cdot t_w^{\,2} \tag{8}$$

where σ_c is the compression stress (N/m^2); w is the width (m); t_w is the thickness of the wall (m); f_c is the compression strength (N/m^2); and f_t is the tensile strength (N/m^2). Given the loading moment M_f induced by the flood, the performance functions associate with cracking, partial, and total collapse can be expressed, respectively, as (Custer and Nishijima 2015)

$$g_{cra} = M_c - M_f \tag{9}$$

$$g_{pc} = M_u - M_f \tag{10}$$

$$g_{col} = 1.2 M_u - M_f \tag{11}$$

Given the performance functions and flood scenario, the probabilities associated with different limit states could be estimated. The probability of failure under flood could be computed using Monte Carlo simulation and/or first/second order reliability methods. The reliability and vulnerability analyses incorporate uncertainties associated with structural capacity and load effects associated with flood.

Loss and Life-Cycle Cost Assessment

Single Building Loss

The damage loss in monetary terms is investigated in this section. Given the limit states of the building under flood, the probability of the building being in different damage states including failure could be computed. Based on the theorem of total probability, the hazard loss is the sum of consequences weighted with the probabilities of having these consequences. The expected annual loss of the building *i* under the occurrence of the given hazard can be computed as (Dong et al. 2014)

$$l_i = \sum_{DS} C_{bi} \cdot r_{cr|DS} \cdot P_{DS|H} \tag{12}$$

where C_{bi} is the investigated building cost; $r_{cr|DS}$ is the repair cost ratio associated with a damage state DS; and $P_{DS|H}$ is the conditional probability of a damage state given a flood event. Given the flood intensity (e.g., depth and velocity) associated with different flood intervals, the performance of the building (e.g., probability of being in different damage states) could be computed. The repair loss, related to the flood induced structural damage, is emphasized herein. The repair cost of a building can be calculated as a function of the percentage of total cost, which depends on local labor cost, availability of materials, and local construction practices. Indirect cost could also be incorporated within the consequence evaluation procedure. Loss data from insurance companies can be used to derive an appropriate description of losses.

Assuming the occurrence of the flood as a Poisson process, the total life-cycle flood loss of the building i during the time interval [0, t_{int}] can be computed (Dong and Frangopol 2016)

$$Lt_i(t_{\text{int}}) = \sum_{i=1}^{N(t_{\text{int}})} l_i(t_k) \cdot e^{-\gamma t_k} \tag{13}$$

where t_{int} is investigated time interval; $N(t_{int})$ is the number of hazard events that occur during the time interval; $l_i(t_k)$ is the expected annual hazard loss at time t_k; and γ is the monetary discount rate. Based on Yeo and Cornell (2005), given the Poisson model with mean rate equal to λ_f, the time t_k has a uniform distribution in [0, t_{int}]. Given $N(t_{int}) = \lambda_f \times t_{int}$, the total expected life-cycle loss and variance can be computed (Ross 2000; Yeo and Cornell 2005)

$$E[Lt_i(t_{\text{int}})] = \frac{\lambda_f \cdot E(l_i)}{\gamma} \cdot (1 - e^{-\gamma \cdot t_{\text{int}}}) \tag{14}$$

$$Var[Lt_i(t_{\text{int}})] = \frac{\lambda_f \cdot E(l_i^2)}{2\gamma} \cdot (1 - e^{-2\gamma \cdot t_{\text{int}}}) \tag{15}$$

$$E(l_i^2) = (E(l_i))^2 + (\sigma(l_i))^2 \tag{16}$$

where $E(l_i)$ and $\sigma(l_i)$ is the expected value and standard deviation of annual loss l_i of building i given a flood event.

Building Portfolio Loss

The portfolio of structures considered herein is a group of residential buildings, which have similar characteristics, such as numbers of floors, material types, and geometrical pattern. The portfolio of the buildings located in the same neighborhood can be classified as one type of buildings (e.g., masonry building). The flowchart of building portfolio loss assessment under flood considering uncertainties and correlation is shown in Figure 2. The annual total loss associated with a spatially-distributed building portfolio under a given flood event is:

$$RL = \sum_{i=i}^{n_{bu}} l_i \tag{17}$$

where n_{bu} is the number of buildings within the investigated portfolio.

As indicated in Eq. (17), the expected loss of the investigated building portfolio is the sum of the expected losses for each building. Buildings within a portfolio are similar and correlated considering their basic characteristics. Additionally, affected by the same flooding, the flood intensities at the location of the buildings are also correlated. Consequently, the losses associated with the buildings within the portfolio are correlated. Overall, the correlations among the performances of spatially distributed buildings are stronger due to the shared effects from the flood event and similarities in structural performance.

The variance of the sum of the loss of the portfolio of buildings depends not only on the expected value of total loss but also on the variance and the correlation among the losses. Considering the correlation effects, the variance of the annual loss of the building portfolio under the flood event is expressed as

$$Var(RL) = \sum_{i=i}^{n_{bu}} Var(l_i) + 2 \cdot \sum_{i=1, i<j}^{n_{bu}} \sum_{j}^{n_{bu}} \rho(l_i, l_j) \cdot \sqrt{Var(l_i) \cdot Var(l_j)}) \tag{18}$$

where $\rho(l_i, l_j)$ is the correlation coefficient between the annual flood loss of buildings *i* and *j* under the given flood event, and $Var(l_i)$ and $Var(l_j)$ are the variances of the annual loss of the building *i* and *j*, respectively. By using Eq. (18), the variance of the total annual loss can be computed. With incomplete information on building configuration within a portfolio, the uncertainty may change.

Similarly, given the annual loss of the portfolio of buildings under a given flood event, the mean and variance life-cycle cost of a building portfolio can be calculated as

$$E[LCC_{BP}(t_{\text{int}})] = \frac{\lambda_f \cdot E(RL)}{\gamma} \cdot (1 - e^{-\gamma \cdot t_{\text{int}}}) \tag{19}$$

$$Var[LCC_{BP}(t_{\text{int}})] = \frac{\lambda_f \cdot E(RL^2)}{2\gamma} \cdot (1 - e^{-2\gamma \cdot t_{\text{int}}}) \quad (20)$$

Considering the uncertainties within the life-cycle cost analysis, the probability of exceedance of life-cycle cost during a certain time interval can be estimated. This information can aid the decision making process with respect to the hazard mitigation strategy.

Probabilistic Cost-Benefit Analysis

Cost-benefit analysis is a commonly used method to compare the cost and benefit of different hazard mitigation strategies over an investigated time interval. Herein, cost-benefit analysis is adopted to support the flood hazard mitigation procedure of portfolios of buildings under different retrofit actions in a life-cycle context. The Federal Emergency Management Agency (FEMA 2014b) proposed the retrofit guide for homeowners to protect the damage of buildings from flood. Retrofit actions can be adopted to make changes to the existing buildings and protect them from the flooding effects. The common retrofit methods for the buildings under flood are elevation, relocation, and demolition (FEMA 2014b). Among these retrofit methods, elevation is the most common used to lift the structure by building a new foundation or extending the existing foundation. Elevation actions are as follows: (a) separating the building from the foundation, (b) constructing a new and higher foundation, and (c) reattaching the building to the new foundation (FEMA 2014b). Heavy-duty jacks are used to lift the building and cribbing is used to support the building. By elevation, the flood depth would be reduced and the structural performance under the given reduced flood depth associated with the retrofit action (e.g., elevation) can be assessed.

Quantifying the relationship between the retrofit actions and the retrofit cost can help the decision regarding the hazard mitigation procedure. The investigated hazard scenarios, time interval, and structural performance under retrofit actions are considered within the cost-benefit analysis process. The flowchart of the cost-benefit analysis of flood mitigation strategy of a single building is indicated in Figure 3(a). In order to perform cost-benefit analysis, the probabilistic benefit should be computed firstly. The benefits are related to uncertainties because they depend on the occurrence of a natural disaster and consequences of structural failure. The cumulative life-cycle cost associated with flood loss of an investigated single building with and without retrofit action can be computed using Eqs. (14) and (15). Then, the economic benefit of hazard mitigation actions of the investigated building *i* can be expressed as

$$B_{sbi} = Lt_{sbi,\,NR} - Lt_{sbi,\,R} \tag{21}$$

where $Lt_{sbi,NR}$ and $Lt_{sbi,R}$ are the life-cycle cost without and with retrofit actions of the investigated single building *i*, respectively.

Similarly, the benefit associated with the retrofit plan of a portfolio of buildings can be computed. In this paper, the probabilistic benefit-cost ratio is introduced to directly compare the benefit and cost of a retrofit action and aid the decision making associated with flood hazard mitigation. The benefit-cost ratio can be calculated as

$$CB_{BP} = (LCC_{BP,NR} - LCC_{BP,WR}) / C_{r,BP} \tag{22}$$

$$C_{r,BP} = \sum_{i=0}^{n_{bu}} c_{r,bi} \tag{23}$$

where $LCC_{BP,NR}$ and $LCC_{BP,WR}$ are the life-cycle cost of building portfolio under flood effects without and with retrofit, respectively; $C_{r,BP}$ is the total retrofit cost of the building portfolio; and $c_{r,bi}$ is the retrofit cost associated with building *i*. The benefit-cost ratio essentially quantifies the effectiveness of a retrofit plan. Values less than 1 indicate that retrofit is not cost-effective while values greater than 1 denote that it is beneficial to perform retrofit.

The expected value and standard deviation of life-cycle cost of the portfolio of buildings under flood can be computed using Eqs. (19) and (20). Given the mean value, the standard deviation of the life-cycle cost, and correlation among the cases with and without retrofit actions, the expected value and standard deviation of the benefit-cost ratio can be computed. Furthermore, given the random variables associated with the benefit-cost ratio, the probability of exceedance of this ratio can be obtained. The probabilistic cost-benefit analysis of the retrofit actions associated with portfolios of buildings is qualitatively illustrated in Figure 3(b) considering probability density functions (PDFs) of various costs.

Illustrative Example

The proposed approach is illustrated on a portfolio of residential buildings located in Pinellas County, Florida, as indicated in Figure 4(a). The portfolio of structures considered herein is a group of masonry residential buildings, which have similar characteristics, such as the number of floors, material types, and geometrical pattern. The unreinforced single story masonry building is the most common residential building type. Herein, the portfolio of the residential buildings located in the same neighborhood is classified as one class of buildings. The annual loss of the single building and building portfolio under a given flood event is investigated. Additionally, the probabilistic life-cycle cost and cost-benefit analysis in a life-cycle context are investigated to aid the decision making process on the hazard mitigation strategy.

Building Damage Assessment

Floods generally originate from overflowing water or streams. Coastal floods occur on the shores of lakes and seas due to heavy rainfall and/or an atmospheric low-pressure system. Herein, the occurrence model of the flood is assumed a Poisson process, with an annual flood occurrence rate 0.01. In order to compute the building performance under flood, the flood characteristics (i.e., depth and velocity) should be identified. Based on the location of the building, the flood depth associated with a given flood event can be derived from existing data by fitting a PDF. Then, Monte Carlo simulation can be used to generate the probabilistic parameters. In this paper, the yearly maximum flood depth associated with the investigated flood is assumed to follow a lognormal distribution, with a mean of 2 *m* and a standard deviation of 0.4 *m*. Given the flood depth (*m*), the velocity of the flood (*m*/*s*) is computed using the following equation (FEMA 2014a)

$$V = 0.3048 \cdot (105.6 \cdot h)^{0.5} \tag{21}$$

The flooding actions on a single building considered herein are: hydrostatic pressure, hydrodynamic pressure, and debris impacts as indicated in Eqs. (1) to (6). The parameters used are shown in Table 1. The structural performance under flood effects is conducted using a 2D structural analysis model (Roos 2003). Accordingly, the maximum load effect bending moment is computed. The PDF of this moment is indicated in Figure 5(a), with a mean of 2.05×10^4 $N{\cdot}m$ and a standard deviation of 1.13×10^4 $N{\cdot}m$.

In order to compute the probability of structural failure under flood, the bending capacity has to be computed. The bending moment capacity associated with cracking and ultimate failure are emphasized in this paper by using Eqs. (7) and (8). The relevant parameters are indicated in Table 1. The PDF associated with the ultimate bending moment is shown in Figure 5 (b). Then given the input with respect to the load effects and capacity, the probability of failure of the investigated single building under the investigated flooding effects is obtained. Similarly, based on Eqs. (9) to (11), the probabilities of the investigated building being in none, cracking, partial collapse, and collapse are computed.

Loss Assessment of Single Building

Based on the building's performance, the consequence and loss in the monetary term are computed. Given the probabilities of the building being in different performance levels under a given flood, the annual repair loss is computed using Eq. (12). The cost of the investigated target single-family house is taken as C_b = 200,000 US$ and it is assumed that buildings within the portfolio all have the same cost. The repair cost ratio associated with cracking, partial, and total collapse is 0.33, 067, and 1.0, respectively (Custer and Nishijima 2015). The load effect considering the debris effects is computed by using Eqs. (5) and (6). Then, based on Eq. (12), the expected annual repair loss with and without considering debris effects is 7.07×10^4 and 6.03×10^4 US$, respectively. As indicated, the debris has a great effect on the building performance under flooding effects and affects the annual loss.

The life-cycle cost of the investigated building under the flood effects is also investigated. The expected and variance of the life-cycle cost are computed using Eqs. (14) – (16). In this paper, the monetary discount rate γ assumed is 2%. The expected value and standard deviation of total life-cycle loss of the investigated building under different time intervals are indicated in Figure 6. As indicated, the investigated service life has a large effect on both the expected and standard deviation of the life-cycle cost of the investigated building under flood. Additionally, the effect of monetary discount rate on the expected life-cycle cost is investigated in this paper. As shown in Figure 7, the monetary discount rate can affect the expected value of the life-cycle cost significantly.

Loss of Portfolio of Buildings

The regional loss of the portfolio of buildings under the given flood event considering uncertainty and correlation effects is computed in this section. The residential buildings located in the same neighborhood have similar characteristics (e.g., material types and geometrical pattern). The portfolio of the buildings investigated is classified as one class of buildings. There are 90 single buildings located in the investigated area indicated in Figure 4 (a). The expected value of the regional loss is the sum of the loss associated with all the buildings located in the investigated region and is computed using Eq. (17). The variance of annual regional loss of the portfolio under the investigated flood scenario considering different correlation coefficients is computed using Eq. (18). The relevant results are shown in Figure 8(a). Given γ = 2% and t_{int} = 75 years, increase associated with the standard deviation of the annual regional loss is consistent with the correlation coefficient. Additionally, the effects of uncertainty associated with building cost are also investigated. Herein, the coefficient of variation of the building cost C_{bi} is assumed 0.3 as a lognormal random variable. As indicated in Figure 8(a), the uncertainty associated with building cost has a larger effect on the standard deviation of the annual building portfolio. Overall, neglecting correlations can lead to underestimation of the standard deviation of losses.

Given the annual loss of the portfolio of buildings and occurrence model of the flood, the life-cycle cost of the portfolio is computed using Eqs. (19) and (20). The standard deviation of the life-cycle cost of the building portfolio is also investigated in this paper and shown in Figure 8(b). As indicated, this standard deviation increases with the correlation coefficient.

Probabilistic Life-Cycle Cost-Benefit Analysis

The cost-benefit analysis is adopted to investigate and compare the cost-effectiveness associated with different retrofit actions applied to buildings. Generally, the retrofit cost is related to the material and installation cost. Given the specific retrofit action, the cost and benefit associated with a given retrofit action are obtained. The flood mitigation technique investigated herein is elevation of buildings. The two elevation heights h_{ele} considered are 0.5 m and 0.25 m. By elevation, the height of the flood is reduced by h_{ele} and the flood effects on the building are reduced. Then, the probabilities of the building being in different performance levels are obtained. The benefit associated with the elevation retrofit action on a single building is computed by using Eq. (21). The benefit associated with hazard mitigation strategy on the investigated building considering different mitigation actions is shown in Figure 9.

The effects of retrofit actions on the life-cycle cost of building portfolio are also investigated. Herein, different retrofit plans associated with the portfolio of buildings are considered. The five cases considered are associated with the number of the buildings N_{ret} that are retrofitted. Herein, N_{ret} equals to 0, 23, 45, 68, and 90 among the portfolio of 90 buildings. Given t_{int} = 75 years and γ = 0.02, the effects of correlation coefficient on the standard deviation of the life-cycle cost of the building portfolio under these five different retrofit plans are shown in Figure 10(a). As indicated, given an increase in the number of retrofitted buildings, the standard deviation of the life-cycle cost of the investigated portfolio decreases. Additionally, the standard deviations of the life-cycle cost under different service lifetimes are shown in Figure 10(b).

Given the cost of retrofit actions, the benefit-cost ratio associated with different retrofit plans of the building portfolio is investigated using Eq. (22). Herein, the retrofit cost is assumed 5% of the cost of the building; it is also assumed that the life-cycle cost of portfolio follows lognormal distribution with the mean value and dispersion identified in Eqs. (19) and (20). Given the mean value and standard deviation of the life-cycle cost of building portfolio with and without retrofit and the retrofit cost, the benefit-cost ratio is computed using Eq. (22). Then, the probability of exceedance of benefit-cost ratio of the portfolio for different service lives is shown in Figure 11(a). As indicated, the benefit-cost ratio is increasing with the service life. Thus, the service life has a significant effect on the decision making regarding the flood retrofit plans of the portfolio of buildings. The probability of exceedance of benefit-cost ratio considering different number of buildings and service life is shown in Figure 11(b). Additionally, the effects of monetary discount ratio and cost of retrofit plans on the benefit-cost ratio are also investigated as indicated in Figure 12(a) and (b). As shown, the retrofit cost has a large effect on the probability of exceedance of the benefit-cost ratio.

The effects of the number of buildings within a portfolio on the benefit-cost ratio is also investigated. With incomplete information of building configuration within a portfolio, the uncertainty may change. As more buildings are considered in the assessment procedure, the uncertainties will increase. Herein, the coefficient of variation of the life-cycle cost of the investigated building portfolio is assumed to increase with the number of the buildings under investigation. The amplification factor af_u is introduced. It is assumed that the standard deviation of the life-cycle cost of the portfolio of buildings is amplified by the factor af_u, while the expected value remains the same. Relevant results are indicated in Figure 12(c). As shown, the probability of exceedance of benefit-cost ratio when the number of buildings increases can be smaller or larger depending on the amplification factor. Thus, the number of buildings within a portfolio and the uncertainty associated with life-cycle cost of this portfolio affect the decision making regarding the hazard mitigation plans.

Conclusions

In this paper, the regional loss assessment of building portfolios is investigated in a life-cycle context considering uncertainties and correlation effects. The probabilistic cost-benefit analysis associated with retrofit actions is also investigated. The probability of exceedance of the life-cycle loss and benefit-cost ratio under a given flood scenario is calculated. The presented approach is illustrated on a portfolio of residential buildings located in Pinellas County, Florida.

The following conclusions are obtained:

1. The mean and standard deviation of the life-cycle cost of buildings under flood effects are sensitive to the investigated time interval and monetary discount rate. These parameters should be carefully evaluated within the life-cycle performance assessment process.
2. The benefit associated with retrofit actions increases with the reduction of the flood depth and with the increase of the investigated time interval.
3. Correlation effects associated with the life-cycle cost of regional losses of building portfolios have a substantial effect on the variance of the life-cycle cost. Furthermore, the uncertainty associated with building cost can affect significantly the standard deviation of the annual loss of building portfolios. The variance of the life-cycle cost of the investigated portfolio decreases with the increase in the number of retrofitted buildings in the portfolio.
4. It is of vital importance to consider both the mean and standard deviation of the life-cycle cost of building portfolio within the decision making process with respect to hazard mitigation.
5. The uncertainty associated with the benefit analysis is considered in the hazard mitigation process. As the uncertainty increases with the number of the buildings under investigation, different decisions regarding retrofit plans are obtained by considering the probabilistic benefit-cost ratio.
6. Debris has a significant effect on the building performance under flood effects. Given the investigated flood scenario, the annual expected loss of the investigated building taking into account debris effect is about 20% larger than that without considering this effect.
7. Within the context of performance-based engineering, probabilistic hazard loss and cost-benefit analysis can provide the decision maker important information necessary for

assessment and mitigation of structural systems after disasters. This information can be used in design, maintenance, and retrofit optimization processes of civil infrastructure systems under extreme events. The life-cycle concept should also be incorporated within the hazard mitigation procedure.

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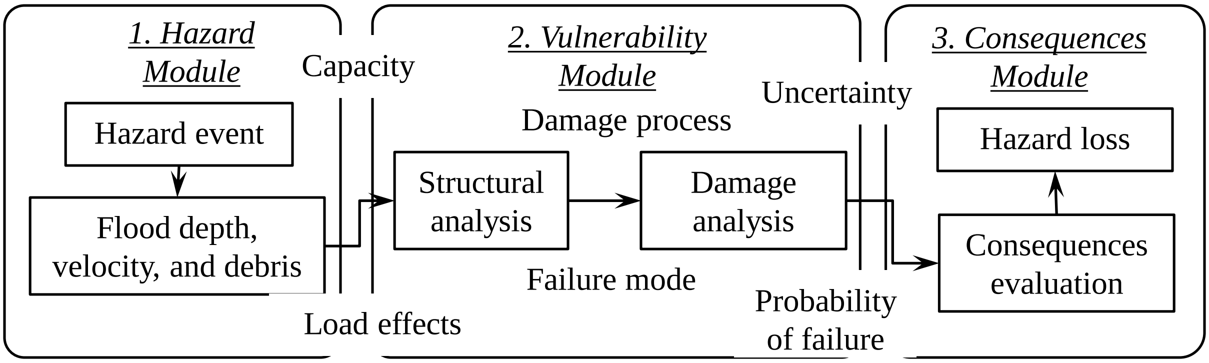
List of Tables

Table 1. Parameters of the random variables associated with the structural reliability and vulnerability analyses

Parameters	Mean	COV	Distribution type
Gravity acceleration, g	9.8 m/s^2	DNA	DNA
Drag coefficient, C_{drag} [a]	1	DNA	DNA
Mass density of water, ρ_w	1000 kg/m^3	0.2	LN
Debris mass, m_{de} [c]	25 kg	0.3	LN
Young's modules of debris [a]	9×10^9 Pa	0.2	LN
Length of the debris [c]	1.5 m	0.2	LN
Width, w	1 m	0.2	LN
Building height	3 m	0.2	LN
Thickness of wall, t_w	0.23 m	0.2	LN
Compression strength, f_c [b]	8 MPa	0.17	LN
Tensile strength, f_t [b]	0.9 MPa	0.3	LN

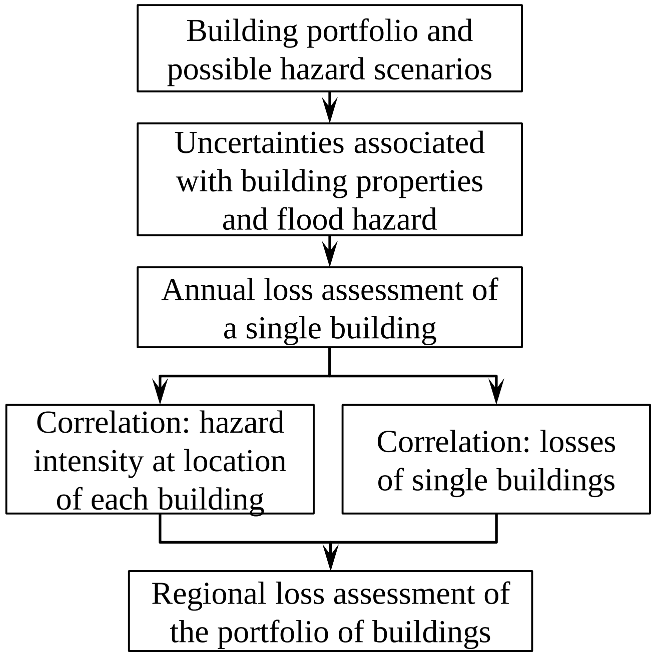
DNA: does not apply; LN: lognormal distribution; COV = coefficient of variation;
[a]: based on Roos (2003); [b]: based on Custer and Nishijima (2015); [c]: assumed.

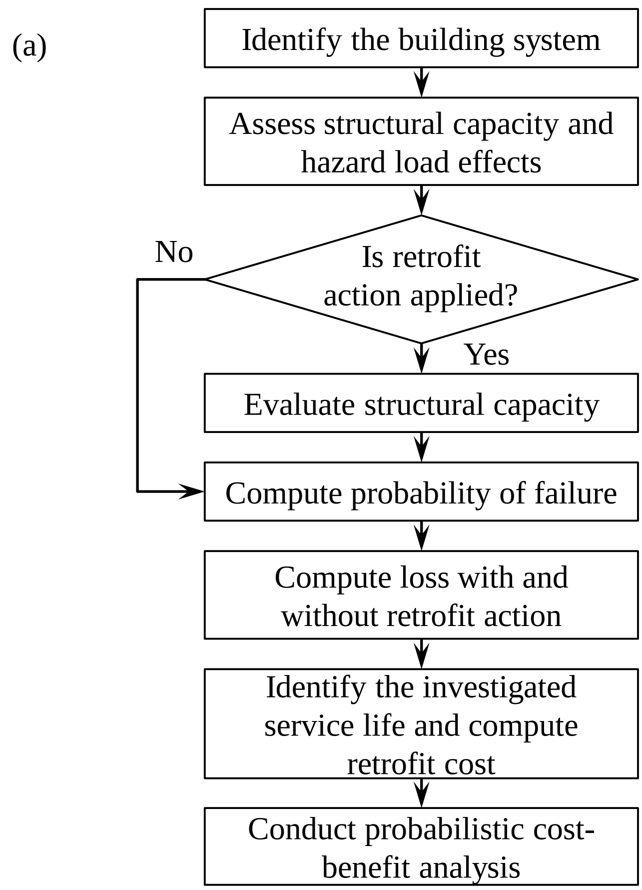
Figure 1



1. Hazard Module
Hazard event
Flood depth, velocity, and debris
Capacity
Load effects
2. Vulnerability Module
Damage process
Structural analysis
Damage analysis
Failure mode
Uncertainty
Probability of failure
3. Consequences Module
Hazard loss
Consequences evaluation

Figure 2 Click here to download Figure Figure 2.pdf




(a)
Identify the building system
Assess structural capacity and hazard load effects
Is retrofit action applied?
No
Yes
Evaluate structural capacity
Compute probability of failure
Compute loss with and without retrofit action
Identify the investigated service life and compute retrofit cost
Conduct probabilistic cost-benefit analysis

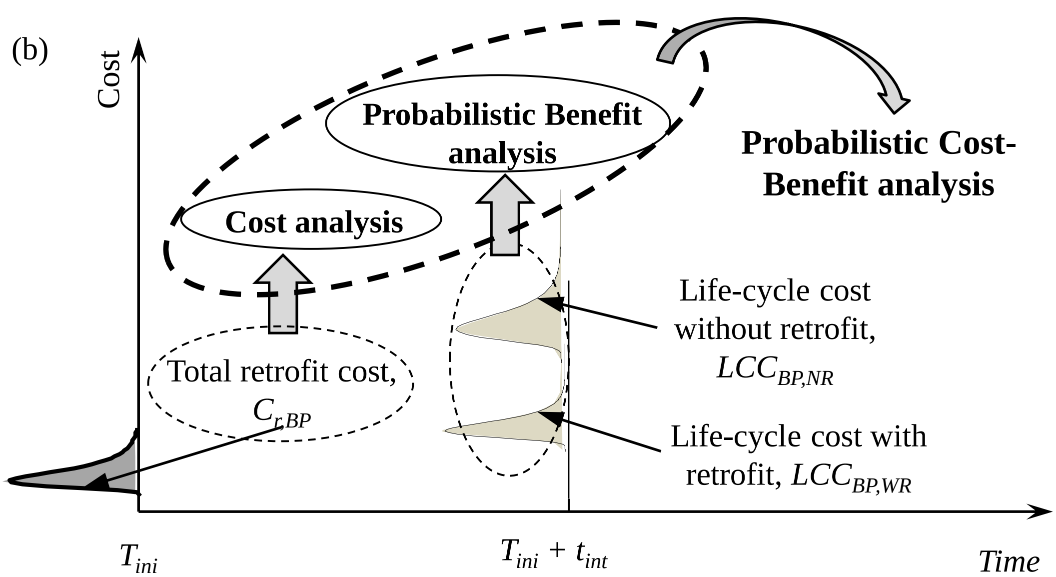
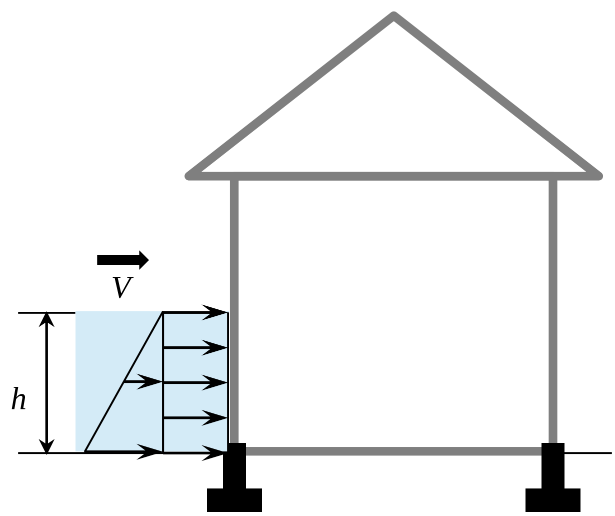

(b)
Cost
Probabilistic Benefit analysis
Cost analysis
Probabilistic Cost-Benefit analysis
Total retrofit cost, $C_{r,BP}$
Life-cycle cost without retrofit, $LCC_{BP,NR}$
Life-cycle cost with retrofit, $LCC_{BP,WR}$
T_{ini}
$T_{ini} + t_{int}$
Time

Figure 4 Click here to download Figure Figure 4.pdf

(a)

(b)



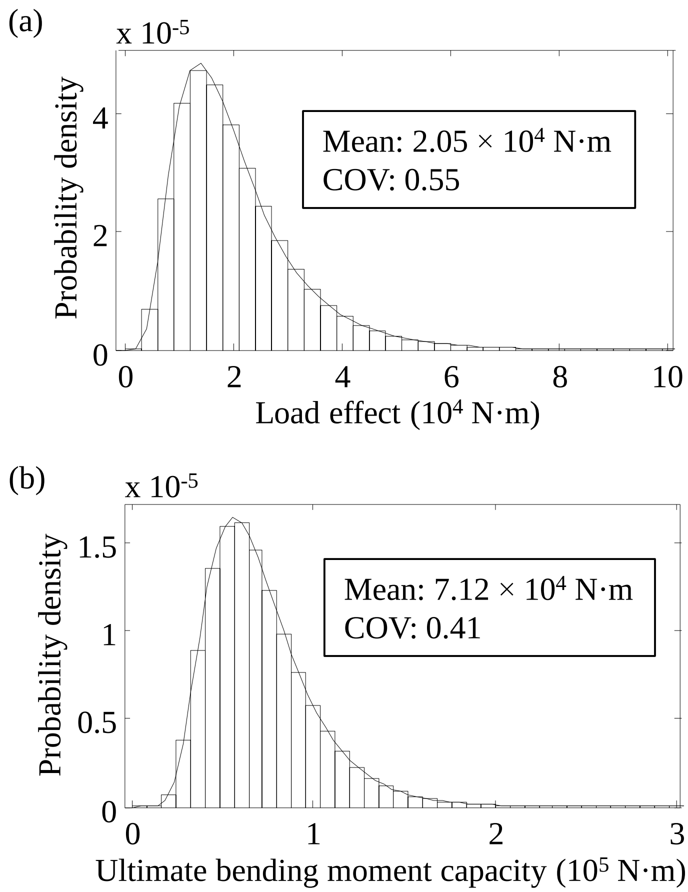

(a)
x 10-5
Probability density
Mean: 2.05 × 10^4 N·m
COV: 0.55
0
2
4
0
2
4
6
8
10
Load effect (10^4 N·m)
(b)
x 10-5
Probability density
Mean: 7.12 × 10^4 N·m
COV: 0.41
0
0.5
1
1.5
0
1
2
3
Ultimate bending moment capacity (10^5 N·m)

Figure 6

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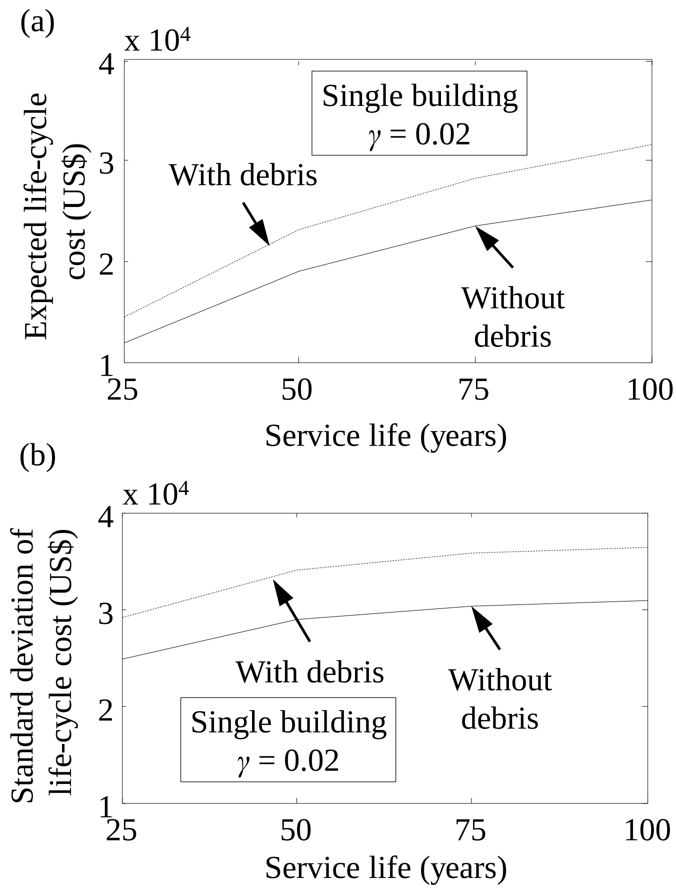

Figure 7

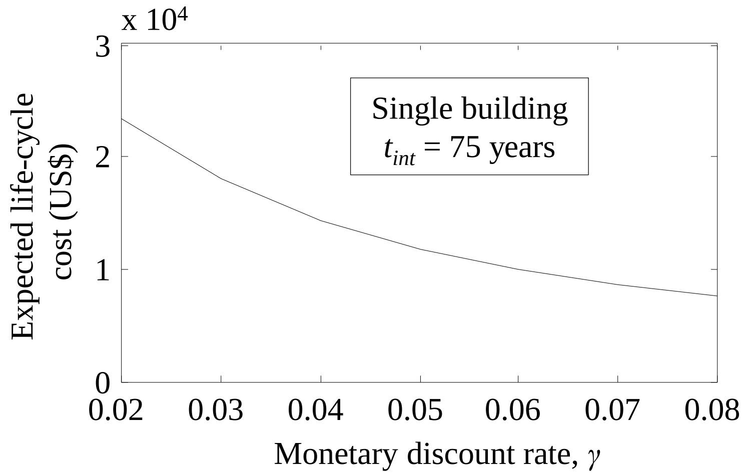
x 10^4
3
2
1
0
Expected life-cycle cost (US$)
Single building
t_int = 75 years
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Monetary discount rate, γ

Figure 8

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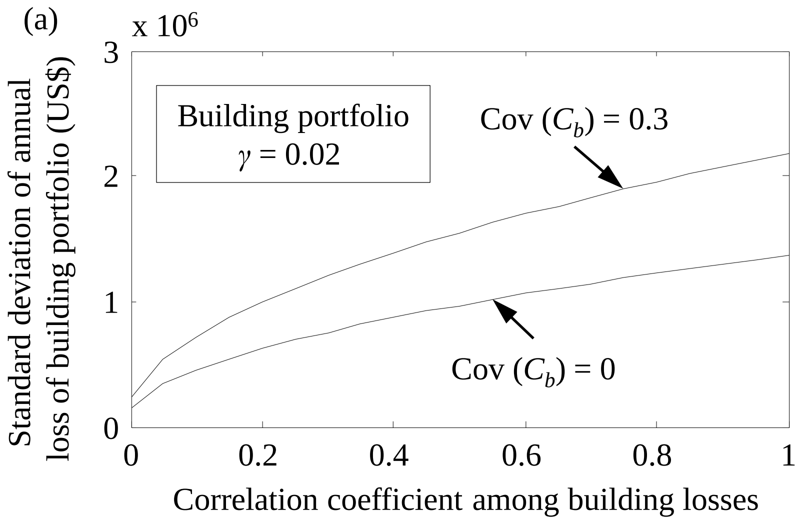


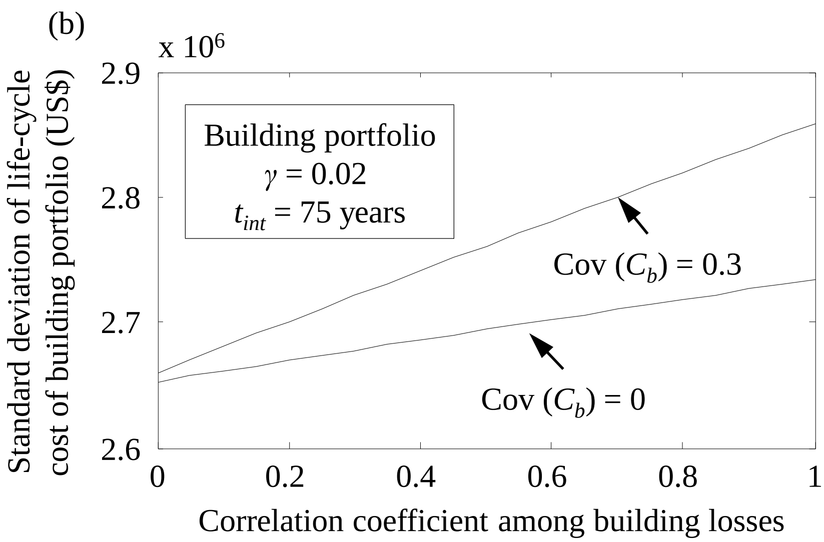
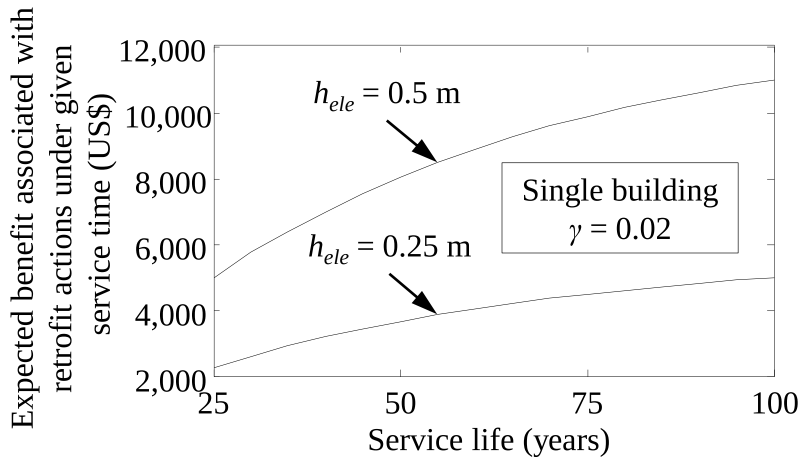


Figure 9



Expected benefit associated with retrofit actions under given service time (US$)
12,000
10,000
8,000
6,000
4,000
2,000
25
50
75
100
Service life (years)
h_{ele} = 0.5 m
h_{ele} = 0.25 m
Single building
γ = 0.02

Figure 10

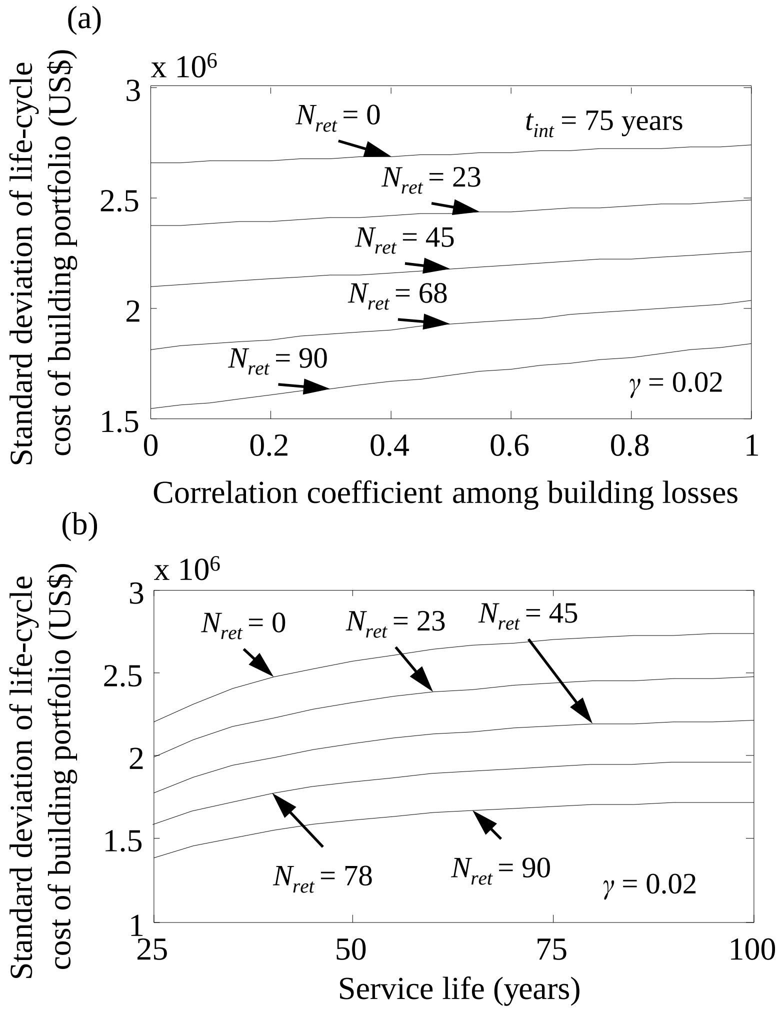
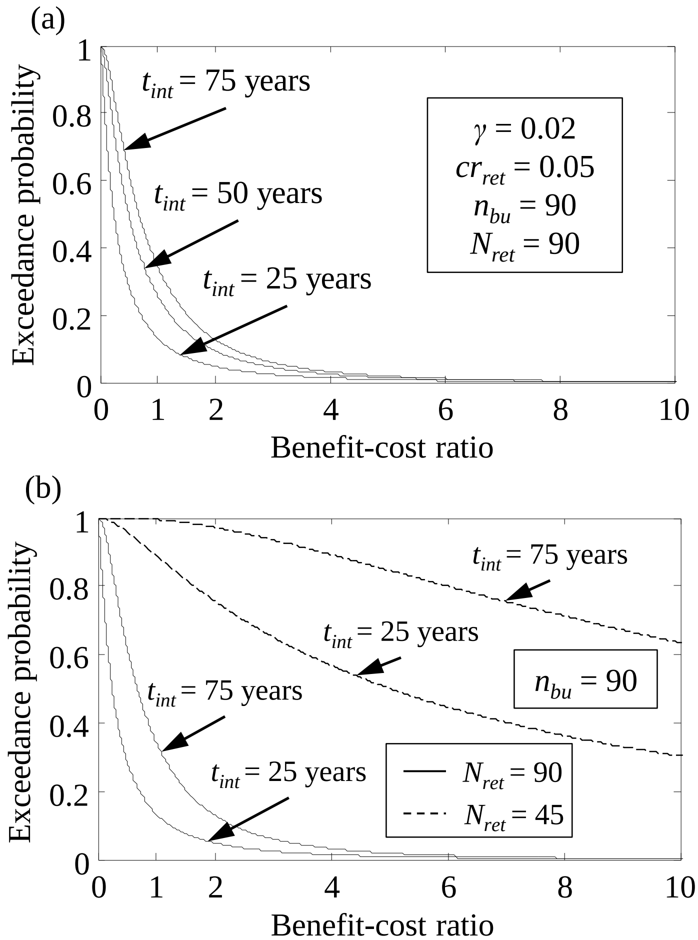
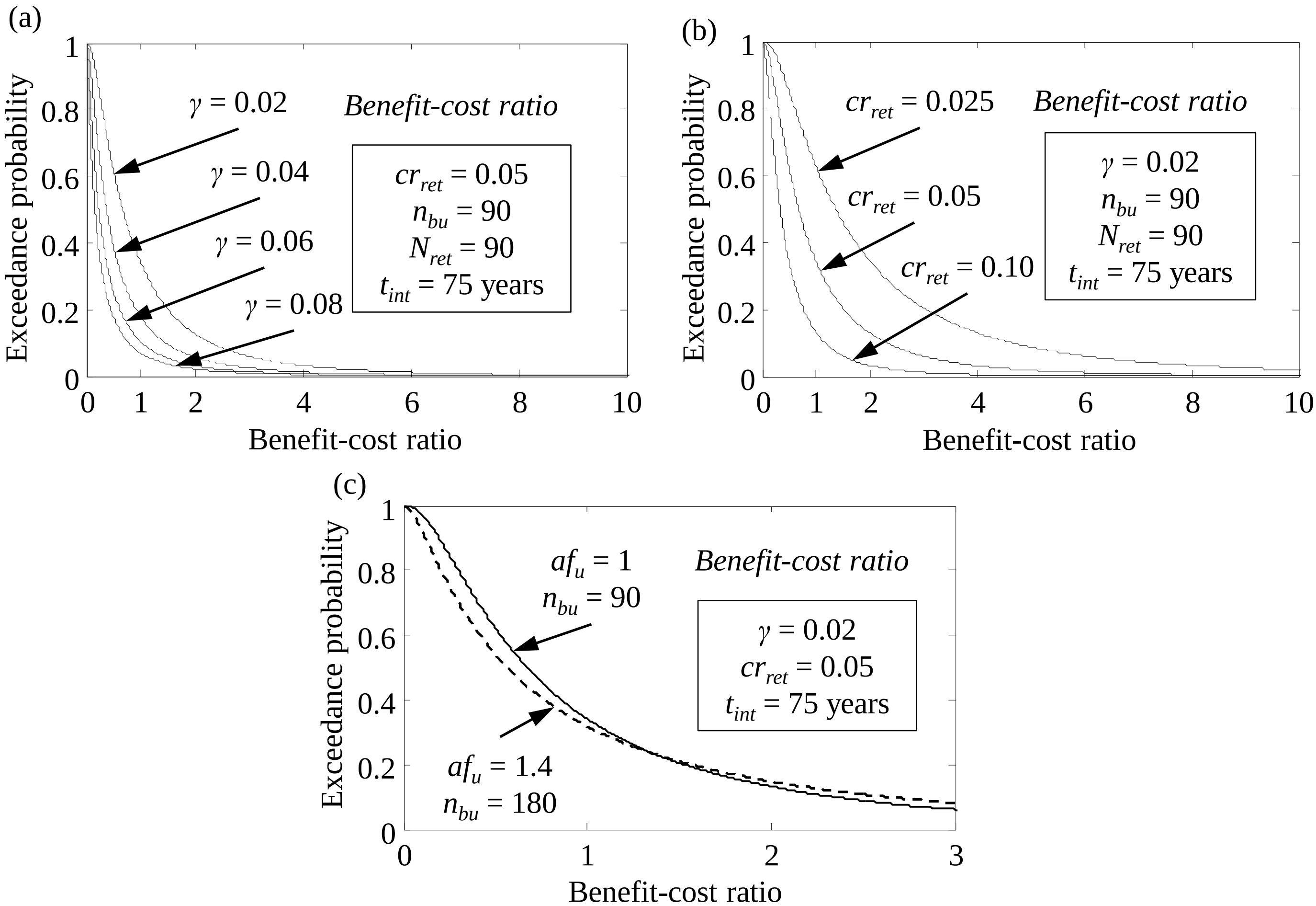

(a)
x 10^6
Standard deviation of life-cycle cost of building portfolio (US$)
N_{ret} = 0
t_{int} = 75 years
N_{ret} = 23
N_{ret} = 45
N_{ret} = 68
N_{ret} = 90
γ = 0.02
3
2.5
2
1.5
0
0.2
0.4
0.6
0.8
1
Correlation coefficient among building losses
(b)
x 10^6
Standard deviation of life-cycle cost of building portfolio (US$)
N_{ret} = 0
N_{ret} = 23
N_{ret} = 45
N_{ret} = 78
N_{ret} = 90
γ = 0.02
3
2.5
2
1.5
1
25
50
75
100
Service life (years)

Figure 11



(a)
Exceedance probability
Benefit-cost ratio
t_{int} = 75 years
t_{int} = 50 years
t_{int} = 25 years
γ = 0.02
cr_{ret} = 0.05
n_{bu} = 90
N_{ret} = 90
(b)
Exceedance probability
Benefit-cost ratio
t_{int} = 75 years
t_{int} = 25 years
t_{int} = 75 years
t_{int} = 25 years
n_{bu} = 90
N_{ret} = 90
N_{ret} = 45

Figure 12


(a)
Exceedance probability
Benefit-cost ratio
γ = 0.02
γ = 0.04
γ = 0.06
γ = 0.08
Benefit-cost ratio
cr_ret = 0.05
n_bu = 90
N_ret = 90
t_int = 75 years
(b)
cr_ret = 0.025
cr_ret = 0.05
cr_ret = 0.10
γ = 0.02
(c)
af_u = 1
n_bu = 90
af_u = 1.4
n_bu = 180

List of Figures

Figure 1. Flowchart for the performance-based assessment of residential buildings under flood

Figure 2. Building portfolio loss assessment under flood considering uncertainties and correlation effects

Figure 3. (a) Flowchart for cost-benefit analysis associated with retrofit actions and (b) probabilistic cost-benefit analysis at portfolio levels including probability density functions of various costs

Figure 4. (a) Plan view of 90 residential buildings located in St. Petersburg, Pinellas County, FL based on the data provided in Google Inc. (2016) and (b) building model under flood effects

Figure 5. Probability density function of (a) bending moment and (b) ultimate bending moment capacity

Figure 6. (a) Expected value and (b) standard deviation of the life-cycle cost of the building under flood with and without considering debris effects

Figure 7. Effect of monetary discount rate on the expected life-cycle cost of the investigated building

Figure 8. Standard deviation of (a) annual loss and (b) life-cycle cost of building portfolio under different correlation coefficients among the building losses with and without considering the uncertainty associated with repair cost

Figure 9. Expected benefit associated with different retrofit actions of single building in a life-cycle context

Figure 10. Standard deviation of life-cycle cost of building portfolio under different levels of retrofit actions considering (a) different correlation coefficients and (b) service life

Figure 11. Probability of exceedance of benefit-cost ratio of building portfolio under different (a) time intervals and (b) retrofit plans

Figure 12. Effects of (a) monetary discount rate γ, (b) retrofit cost cr_{ret}, and (c) number of the buildings n_{bu} on the probability of exceedance of benefit-cost ratio