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Modelling correlated damages of residential building portfolios under tropical cyclone wind loads

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ABSTRACT: Performing probabilistic damage assessment for a community under a tropical cyclone event needs to consider the collective damage of individual structures within the community, which involves modeling the spatial correlations of hazard demands and structural capacities between individual structures. However, how to model these two kinds of spatial correlations and how they influence the damage assessment remain unclear. In this paper, focus is given to the roof sheathing damage of a residential building portfolio consisting of multiple wooden residential buildings under the wind loads of a tropical cyclone event. Two methods are used to predict the damage of individual buildings based on their hazard demands: one is using a direct Monte Carlo Simulation in which structural (capacity) parameters of different buildings are treated as correlated. This method provides accurate results but needs a lot of information. Another approach is to probabilistically predict the damage state of each building based on its hazard demand using its fragility functions. The relative importance of the correlations of hazard demands and structural capacities is investigated. It is demonstrated that the correlations of damage states are strongly dependent on hazard demands. Finally, a method is developed to simulate correlated damage states of a building portfolio given hazard demands, through incorporating the hazard-dependent correlations with fragility functions using Gaussian Copula.

The dramatic economic losses and social disruptions caused by large-scale natural hazards, such as tropical cyclones and earthquakes, have raised great concerns among civil infrastructure owners and managers as well as the engineering community. The aftermath of recent disasters, such as Cyclones Larry and Yasi in Australia, has revealed the importance of disaster mitigation strategies that focus on the collective performance of all civil infrastructure facilities in a community. To support the development of the mitigation strategies, it is of significance to quantify collective hazard damage and losses of spatially distributed civil infrastructure facilities in a community.

Hazard damage of infrastructure is highly uncertain since hazard demands and structural capacities have considerable variations which need to be considered using probabilistic methods. In addition, under a large-scale natural hazard, spatial correlations exist between the damage of individual structures in a community, which needs to be treated carefully (Lee and Kiremidjian, 2007a; Goda and Hong, 2008). The spatial correlations include the correlations of hazard demands caused by a common hazard footprint (Wang and Takada, 2005; Jayaram and Baker, 2009) and the correlations of structural capacities resulting from the similarities in materials, design and construction practices in a common area (Vitoontus and Ellingwood, 2013). A number of studies have investigated the roles of these two kinds of spatial correlations in the seismic damage of multiple structures (Lee and Kiremidjian, 2007a; Vitoontus and Ellingwood, 2013). However, no effort has been made to study the relative importance of these two correlations in damage assessment under a tropical cyclone event whose uncertainty is considerably smaller than that of an earthquake event.

In probabilistic damage assessment of infrastructure, the hazard vulnerability of structures is usually represented by fragility functions which provide the marginal probabilities of structural damage states conditional on hazard demands (Li and Ellingwood, 2006; Lee and Rosowsky, 2005). Because of the existence of the correlations of structural capacities, the conditional damage states need to be modelled as correlated through assigning the correlations of the conditional damage states to each pair of structures. However, no data available can be used to quantify the correlations of structural capacities. Previous work (Lee and Kiremidjian, 2007b,a; Vitoontus and Ellingwood, 2013; Lin et al., 2016) simply assigned a constant correlation to the damage states of each pair of structures conditional on hazard demands, assuming that the correlation is independent of hazard demands. Nevertheless, the correlation is expected to be dependent on hazard demands since it is actually propagated from the correlation of structural capacity parameters such as component resistances given different hazard demands.

This study focus on the damage of a spatially distributed building portfolio under the wind loads of a tropical cyclone event, considering the uncertainty and correlations of both hazard demands and structural capacities. A direct Monte Carlo Simulation (MCS) is employed to calculate structural damage states based on hazard demands, in which structural (capacity) parameters of different buildings are treated as correlated. The relative importance of the correlations of hazard demands and structural capacities is investigated and the correlations of damage states conditional on hazard demands are developed. A method using fragility functions to predict structural damage states is developed to simulated correlated damage states. In this method, Gaussian Copula is used to incorporate the hazard-dependent correlation of conditional damage states with fragility functions.

1. METHODOLOGIES

1.1. Loss of spatially distributed building portfolios

To probabilistically assess the damage of a spatially distributed building portfolio under a tropical cyclone event, both hazard demands and damage states conditional on the hazard demands need to be treated as random fields which take into consideration the correlations of hazard demands and structural capacities and they are mathematically formulated as (Lin and Wang, 2016):

$$F_{Z|S}(z|s) = \int\int F_{Z|\boldsymbol{DS}}(z|\boldsymbol{v}) f_{\boldsymbol{DS}|\boldsymbol{U}}(\boldsymbol{v}|\boldsymbol{u}) f_{\boldsymbol{U}|S}(\boldsymbol{u}|s)\mathrm{d}\boldsymbol{v}\mathrm{d}\boldsymbol{u}, \tag{1}$$

where $f_{\boldsymbol{U}|S}(\boldsymbol{u}|s)$ is the joint probability density function (PDF) of hazard demands $\boldsymbol{U}$ at the sites of individual buildings conditional on a given scenario S of tropical cyclone. $\boldsymbol{U}$ is the set of surface-level wind speeds; $f_{\boldsymbol{DS}|\boldsymbol{U}}(\boldsymbol{v}|\boldsymbol{u})$ is the joint PDF of damage states $\boldsymbol{DS}$ of individual buildings conditional on $\boldsymbol{U}$; $F_{Z|\boldsymbol{DS}}(z|\boldsymbol{v})$ is the Cumulative Distribution Function (CDF) of the loss Z of the building portfolio conditional on $\boldsymbol{DS}$.

In this paper, the ratio of severe damage is considered as the loss metric of a building portfolio (Lin et al., 2016):

$$Z = \sum_{i=1}^{N} \mathrm{I}\left(DS_i >= 3\right), \tag{2}$$

where for each building, DS_i=1 (no or minor damage), 2 (moderate damage), 3 (severe damage) or 4 (destruction); N is the number of the individual buildings in the building portfolio; $\mathrm{I}(\cdot)$ is an indicator function which returns 1 if event "·" is true and returns 0 otherwise.

1.2. Stochastic model of correlated surface-level wind speeds

In Eq. (1), $f_{\boldsymbol{U}|S}(\boldsymbol{u}|s)$ captures the uncertainties in the simulation of a tropical cyclone scenario given cyclone key parameters. The uncertainties exist mainly because cyclone wind field models (Vickery et al., 2000, 2009; Georgiou, 1986) cannot fully capture the variations of cyclone surface winds.

The surface wind speed at site i can be formulated as:

$$U_i = U_{0i} \cdot \varepsilon_i, \tag{3}$$

where U_{0i} denotes the product of the long-lasting (10-minute to 1-hour) mean wind speed at 10 m above ground in open terrain calculated by cyclone wind field models and a factor converting the mean speed into 3-s gust wind speed; ε_i is a random residual modelling the wind field uncertainties. It is assumed ε_i yields to a lognormal distribution whose mean is one. So the mean of U_i, denoted by μ_U, equals U_{0i}. Coefficient of Variation (CoV) of ε_i, denoted by V_U, is assumed ranging from 0.1 to 0.2 (Vickery et al., 2000). In addition, spatial correlations exist between ε_i and ε_j (Pang et al., 2012), which is denoted by ρ_U. Since no mathematical model has been developed to calculate ρ_U, 3 cases are considered in this study: ρ_U =1 (perfectly correlated), 0.7 (partially correlated) and 0 (uncorrelated).

1.3. Method 1: model correlated damage by direct Monte Carlo Simulation

Given $\boldsymbol{U}$, $f_{\boldsymbol{DS}|\boldsymbol{U}}(\boldsymbol{v}|\boldsymbol{u})$ in Eq. (1) can be calculated through a direct Monte Carlo Simulation (MCS). To perform the direct MCS, the probability distributions of all basic variables of each building need to be known, such as the resistances of the structural components of each buildings denoted by $\boldsymbol{R}_i$. $\boldsymbol{R}_i$ and $\boldsymbol{R}_j$ of each pair of buildings are modelled as correlated with correlation coefficient ρ_R so as to consider the correlation of structural capacities. In each run of MCS, $\boldsymbol{U}$ is transformed into wind loads based on the wind load model in ASCE 7-16 (ASCE, 2016) and structural analysis is performed for individual buildings to calculate $\boldsymbol{DS}$.

Although the direct MCS can provide accurate results, it is inconvenient for applications since it needs a lot of information and computational efforts. In this paper, this method is used to verify the accuracy of method 2 which is described in the next section.

1.4. Method 2: model correlated damage by fragility functions

To model $f_{\boldsymbol{DS}|\boldsymbol{U}}(\boldsymbol{v}|\boldsymbol{u})$ in Eq. (1), a more common way is to use fragility functions to represent the vulnerability of a class of structure under hazard demands. Fragility functions provide the exceedance probabilities of damage states conditional on hazard demands, and the probability of the conditional damage state of ith building is given by

$$\begin{aligned} &P(DS_i = v|U_i = u) \\ &= P(DS_i \geq v|U_i = u) \\ &- P(DS_i \geq v+1|U_i = u), \end{aligned} \tag{4}$$

where $P(\cdot)$ represents the probability of event "$\cdot$". Therefore, to use fragility functions to probabilistically predict structural damage states, only structural types and hazard demands are needed, unlike the direct MCS which needs the information about the probability distributions of all basic variables such as the resistances of structural components. To model the conditional damage states of multiple structures as correlated, the correlation coefficient of the conditional damage states of each two structures, denoted by $\rho_{DS_{ij}}$, is needed. Once $\rho_{DS_{ij}}$ has been known, Gaussian Copula is employed to determine the joint probabilities of conditional damage states using fragility functions and $\rho_{DS_{ij}}$. However, in previous works (Lee and Kiremidjian, 2007b,a; Vitoontus and Ellingwood, 2013; Lin et al., 2016), simulated $\rho_{DS_{ij}}$ was inconsistent with given $\rho_{DS_{ij}}$ because the correlations of Gaussian Copula were considered same as $\rho_{DS_{ij}}$, and this will be explained in detail later. Furthermore, these studies simply assumed that $\rho_{DS_{ij}}$ is constant regardless of hazard demands ($\boldsymbol{U}$). Actually, $\rho_{DS_{ij}}$ is the function of U_i and U_j, which will be demonstrated in this paper.

In this section, in order to simulate correlated $\boldsymbol{DS}$ conditional on $\boldsymbol{U}$, a method is proposed to incorporate fragility functions with given $\rho_{DS_{ij}}$ using Gaussian Copula. This method can maintain the consistency of simulated and given $\rho_{DS_{ij}}$. Furthermore, an approach is developed to derive U-dependent $\rho_{DS_{ij}}$ and incorporate it with fragility functions.

Gaussian Copula is the Cumulative Density Function (CDF) of multiple standard uniform variables $X_k, k = 1, 2, ...N$, (Nelsen, 2007):

$$F_{X_1,...,X_N}(x_1,...,x_N) = \Phi_m\left(\Phi^{-1}(x_1),...,\Phi^{-1}(x_N)\right), \tag{5}$$

where Φ_m means multivariate standard Gaussian CDF and the correlation coefficient of the ith and

jth normal variables is denoted by $\rho_{G_{ij}}$; Φ^{-1} is the inversive function of standard Gaussian CDF. Since the probabilities of damage states mentioned in this section are all conditional on hazard demands, for the simplification of notation, $P(DS_i \leq v|U_i = u)$ is simplified as $G_i(v)$. Similarly, $P(DS_j \leq v|U_j = u)$ is simplified as $G_j(v)$. $P(DS_i = v_i, DS_j = v_j|U_i = u_i, U_j = u_j)$ is simplified as $g_{ij}(v_i, v_j)$. A deterministic relation which maps DS_i from X_i is established:

$$DS_i = v, \text{if } G_i(v-1) < X_i \leq G_i(v). \tag{6}$$

Then based on Eq. (6), the joint probabilities of DS_i and DS_j are formulated as:

$$\begin{aligned}
& g_{ij}(v_i, v_j) \\
& = F_{X_i,X_j}\left(G_i(v_i), G_j(v_j)\right) \\
& - F_{X_i,X_j}\left(G_i(v_i - 1), G_j(v_j)\right) \\
& - F_{X_i,X_j}\left(G_i(v_i), G_j(v_j - 1)\right) \\
& + F_{X_i,X_j}\left(G_i(v_i - 1), G_j(v_j - 1)\right).
\end{aligned} \tag{7}$$

Then through substituting Eq. (5) into Eq. (7), the analytical formula of the joint PMF of conditional DS_i and DS_j is given:

$$\begin{aligned}
& g_{ij}(v_i, v_j) \\
& = \Phi_m\left(\Phi^{-1}\left(G_i(v_i)\right), \Phi^{-1}\left(G_j(v_j)\right)\right) \\
& - \Phi_m\left(\Phi^{-1}\left(G_i(v_i - 1)\right), \Phi^{-1}\left(G_j(v_j)\right)\right) \\
& - \Phi_m\left(\Phi^{-1}\left(G_i(v_i)\right), \Phi^{-1}\left(G_j(v_j - 1)\right)\right) \\
& + \Phi_m\left(\Phi^{-1}\left(G_i(v_i - 1)\right), \Phi^{-1}\left(G_j(v_j - 1)\right)\right).
\end{aligned} \tag{8}$$

Given $\rho_{DS_{ij}}$, the correlation coefficient of Gaussian Copulas ($\rho_{G_{ij}}$) can be calculated through solving an optimization problem:

$$\min\left(\frac{\sum_{k,l} k \cdot l \cdot g_{ij}(k,l)}{\sigma_i \sigma_j} - \frac{\mu_i \mu_j}{\sigma_i \sigma_j} - \rho_{DS_{ij}}\right)^2, \tag{9}$$

where σ_i is the standard deviation of DS_i conditional on U_i; μ_i is the mean of DS_i conditional on U_i. The first two terms in Eq. (9) is the definition of correlation coefficients where $g_{ij}(k,l)$ is related to $\rho_{G_{ij}}$. Eq. (8) provides the analytical expression of $g_{ij}(v_i, v_j)$. However, it is impractical to extend this expression into the joint PMF of N individual buildings ($N \gg 2$). Therefore, MCS is used to simulate the conditional $\boldsymbol{DS}$ of a building portfolio using Gaussian Copula, once $\rho_{G_{ij}}$ of each 2 normal variables in Gaussian Copula has been known (Lin et al., 2016).

In summary, to simulate the conditional $\boldsymbol{DS}$ given $\boldsymbol{U}$ and $\rho_{DS_{ij}}$, the procedures are given:

Step 1: Calculate $\rho_{G_{ij}}$ of each two structures based on Eq.(9).

Step 2: Generate the realizations of correlated standard normal variables, s_1,...,s_N, using $\rho_{G_{ij}}$.

Step 3: Transform s_1,... s_N into the realizations of uniform variables, x_1,...x_N, by $x_i = \Phi(s_i)$.

Step 4: Map the realizations of DS_1,...DS_N from x_1,...x_N by: if $G_i(v-1) < x_i \leq G_i(v), DS_i = v$;

In previous works (Lee and Kiremidjian, 2007b,a; Vitoontus and Ellingwood, 2013; Lin et al., 2016), $\rho_{DS_{ij}}$ was simply considered same as $\rho_{G_{ij}}$, which is why simulated $\rho_{DS_{ij}}$ is inconsistent with given $\rho_{DS_{ij}}$.

In this paper, $\rho_{DS_{ij}}$ is found dependent on U_i and U_j. In order to incorporate the U-dependent $\rho_{DS_{ij}}$ with fragility functions to simulate the $\boldsymbol{DS}$, the function describing how $\rho_{DS_{ij}}$ depends on U_i and U_j needs to be known. Given different realizations of U_i and U_j, $\rho_{DS_{ij}}$ is calculated. Then the step 1 to 4 above are followed to simulate the $\boldsymbol{DS}$. However, this method is inconvenient to use. As shown in the following section, the U-dependent $\rho_{DS_{ij}}$ needs to be developed using the direct MCS when the correlation of structural capacities (ρ_R) is known, and there is no explicit formula of $\rho_{DS_{ij}}$'s relation to U_i and U_j. In addition, it is time-consuming to perform the optimization in Eq. (9) for each pair of structures in each MCS run. To simplify this method, an approximate method is proposed. It is found $\rho_{G_{ij}}$ (solved in Step 1 above) is nearly constant regardless of U_i and U_j, and is mainly decided by ρ_R. So in the applications of the approximate method, only $\rho_{DS_{ij}}$ at any U_i and U_j ($U_i = U_j = \mu_U$ is used in this paper) given ρ_R is needed. Then $\rho_{G_{ij}}$ is calculated and remains constant regardless of the realizations of U_i and U_j in MCS run. Afterward, the step 2 to 4 above are followed to simulate the $\boldsymbol{DS}$. It is unnecessary to know the function of $\rho_{DS_{ij}}$'s relation to U_i and U_j.

2. EXAMPLE: CORRELATED ROOF SHEATHING DAMAGE OF A RESIDENTIAL PORTFOLIO

An example is presented in this section. The purposes are to investigate the relative importance of hazard demand correlations (ρ_U) and structural capacity correlations (ρ_R), and demonstrate the dependence of $\rho_{DS_{ij}}$ on U_i and U_j as well as how to incorporate this U-dependent $\rho_{DS_{ij}}$ with fragility functions to simulate the correlated $\boldsymbol{DS}$ of a building portfolio. A residential portfolio consisting of 30 wooden residential buildings is considered and only roof sheathing damage is analyzed. The used baseline house is provided by Rosowsky and Cheng (1999a). It is a typical single-family wooden house with a gable roof in Southeast United States. The portfolio is considered as a typical homogenous residential block with a size of around 3 km $\times$ 3 km. In addition, it is assumed this portfolio was constructed at approximately the same time. If the portfolio is built by the same builder following similar design guidelines and using the construction materials from the similar sources, ρ_R is assumed considerably high, such as 0.8. For simplification, the wind speeds and structural capacities at different buildings are treated as stationary random fields with equal ρ_U and ρ_R between each two buildings.

2.1. *Fragility analysis of roof sheathing*

Once hazard demands have been known, they are transformed into wind loads based on the wind load model in ASCE (2016). The wind load of the ith building is formulated as

$$W_i = 0.613 K_z K_{zt} K_d K_e U_i^2 (GC_p - GC_{p0}) (\mathrm{N/m^2}), \tag{10}$$

where GC_p is the product of gust factor and external pressure coefficient and GC_{p0} is the product of gust factor and internal pressure coefficient; U_i is the hazard demand of the ith building; K_e is ground elevation factor; K_d is wind directionality factor; K_{zt} is topographic factor; K_z is velocity pressure exposure coefficient. Both K_{zt} and K_e are considered as 1. The nominal values of K_z, K_d, GC_p and GC_{p0} for roof sheathing are provided by ASCE (2016) and the ratios of nominal and mean values, as well as CoV, are given by Ellingwood and Tekie (1999).

The roof of the house consists of 32 roof panels and the limit state function for one roof panel is

$$g = R - (W - D \cdot \cos\theta), \tag{11}$$

where θ is the slope angle of the roof; D, W and R are dead load, wind load and panel resistance respectively. The statistics of D and R are given by Rosowsky and Cheng (1999b). If $g < 0$, the panel is considered as failure. The damage state of the roof is defined by the number of panel failures (FEMA, 2014). Specifically, $DS_i \geq 1$ if there is no panel failure; $DS_i \geq 2$ if there are panel failures; $DS_i \geq 3$ if there are more than three panel failures; $DS_i = 4$ if there are more than 25 percent of panels in failure. K_z, K_d, GC_p and GC_{pi} of different panels are considered independent (Li and Ellingwood, 2006; Lee and Rosowsky, 2005). However, the resistances of different panels on a roof, can be very correlated and it is assumed the correlation is constantly 0.8. To assess the damage state of a roof, the limit states of all panels are checked first when the house is regarded as enclosed. If there is any panel failure, GC_{pi} of each roof panel is resampled when the building is considered as partially enclosed and then the limit states of the undamaged panels are checked again.

The fragility function of the ith roof is calculated and then fitted by the lognormal functions in Eq. (12). And the logarithmic mean and standard deviation of the lognormal functions, λ_v and ξ_v, are given in Table 1.

$$P(DS_i \geq v | U_i = u) = \Phi\left[\frac{\ln(u) - \lambda_v}{\xi_v}\right]. \tag{12}$$

2.2. *Relative importance of the correlations of hazard demands and structural capacities*

To investigate the relative importance of hazard demand correlations (ρ_U) and structural capacity correlations (ρ_R), the damage of the roof sheathing of the 30-building portfolio is analyzed by the direct

Table 1: The parameters of the lognormal fragility functions of a roof.

$v, (DS_i \geq v)$	λ_v	ξ_v
2	3.815	0.1163
3	3.893	0.0979
4	3.985	0.0941

MCS when all roof panels in the portfolio are modelled as correlated.

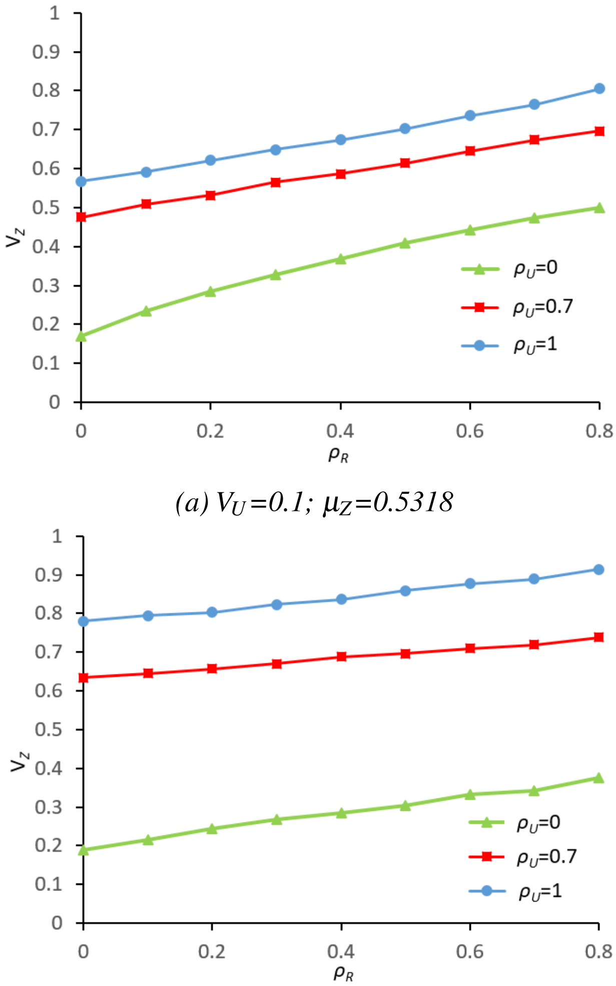
Figure 1 illustrates how V_Z depends on ρ_R and ρ_U, given several cases of V_U, and μ_Z is also provided which is not affected by ρ_U and ρ_R. Overall, the impacts of ρ_U and ρ_R on V_Z are related to V_U. Larger V_U is, weaker the influence of ρ_R on V_Z is. In contrast, the decrease of V_U makes the impact of ρ_U on V_Z less obvious. If V_U is as small as 0.1, ρ_R is nearly as important as ρ_U.

2.3. *Correlated damage based on fragility functions and Gaussian Copulas*

In the applications of fragility functions, because of the existence of ρ_R, conditional $\boldsymbol{DS}$ needs to be modelled as correlated. Firstly, when $\rho_{DS_{ij}}$ is directly given, Step 1 to 4 in section 1.4 are used to simulated correlated $\boldsymbol{DS}$. It is compared with the method where in Step 1 $\rho_{G_{ij}}$ is not calculated by solving the optimization in Eq. (9) but simply considered same as $\rho_{DS_{ij}}$ (Lee and Kiremidjian, 2007b,a; Vitoontus and Ellingwood, 2013; Lin et al., 2016). V_Z calculated by these two methods are given in Figure 2. It is shown the result solved by the previous method underestimate Z's uncertainty.

Afterward, the U-dependent property of $\rho_{DS_{ij}}$ and how to incorporate this $\rho_{DS_{ij}}$ with fragility functions to simulate correlated $\boldsymbol{DS}$ are demonstrated.

$\rho_{DS_{ij}}$ of a pair of buildings is calculated using the direct MCS method when their roof panel resistances are correlated. Figure 3 shows the results when the buildings have same hazard demands ($U_i = U_j = U$). Obviously, $\rho_{DS_{ij}}$ is highly dependent on U and it has a high value when U is around 50 m/s. Then the correlation of Gaussian Copula ($\rho_{G_{ij}}$) is solved, as shown in Fig.4. Unlike $\rho_{DS_{ij}}$, $\rho_{G_{ij}}$ is nearly unchanged regardless of U and can be



(a) V_U=0.1; μ_Z=0.5318

(b) V_U=0.2; μ_Z=0.4978

Figure 1: Impacts of ρ_U and ρ_R on V_Z; $\mu_U = 50$ m/s.

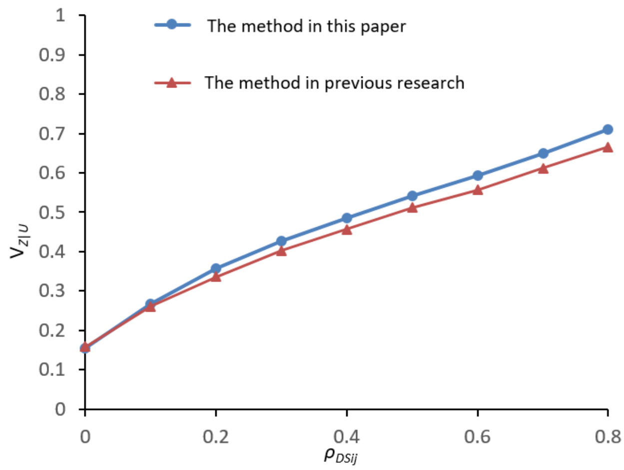


Figure 2: $V_{Z|U}$ solved using fragility functions and Gaussian Copulas;$U = 50$ m/s.

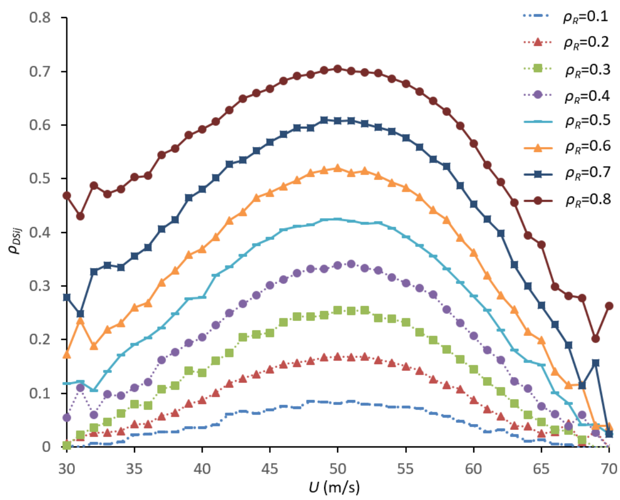


Figure 3: Relation between $\rho_{DS_{ij}}$ and U; U_i=U_j=U.

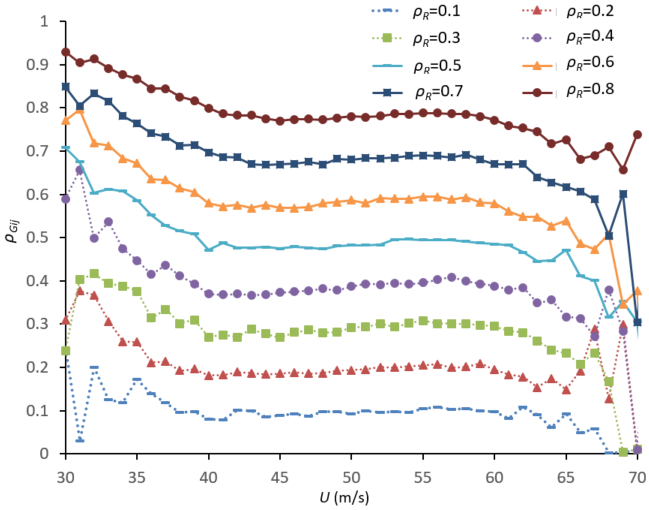


Figure 4: Relation between $\rho_{G_{ij}}$ and U; U_i=U_i=U.

considered constant. Although Figure 3 and 4 only provide the case where $U_i = U_j = U$, $\rho_{G_{ij}}$ is nearly constant no matter U_i and U_j are different or not. In this example, to incorporate U-dependent $\rho_{DS_{ij}}$ with fragility functions to simulate correlated $\boldsymbol{DS}$, $\rho_{G_{ij}}$ where $U_i = U_j = \mu_U$ is used and maintained unchanged regardless of U_i and U_j. Then the accuracy of this method is verified through comparing with the direct MCS method. Figure 5 provides V_Z solved by these two methods and obviously, their results are very close to each other.

3. CONCLUSION

Modeling the correlation of hazard demands (ρ_U) and that of structural capacities (ρ_R) plays a significant role in quantifying the risk of a spatially distributed building portfolio under a tropical cyclone event. In this paper, the roof sheathing damage of a residential building portfolio under a tropical cyclone was analyzed through two methods. One method is a direct Monte Carlo Simulation (MCS) in which structural (capacity) parameters of different buildings are treated as correlated. Another method is using fragility functions to probabilistically map buildings' damage states ($\boldsymbol{DS}$) from $\boldsymbol{U}$. Through these two method, the relative importance of ρ_U and ρ_R was discussed. In addition, how the correlation of the conditional $\boldsymbol{DS}$ ($\rho_{DS_{ij}}$) depends on hazard demands was also demonstrated. Furthermore, a method was proposed to incorporate the hazard-dependent $\rho_{DS_{ij}}$ with fragility functions to simulated correlated $\boldsymbol{DS}$.

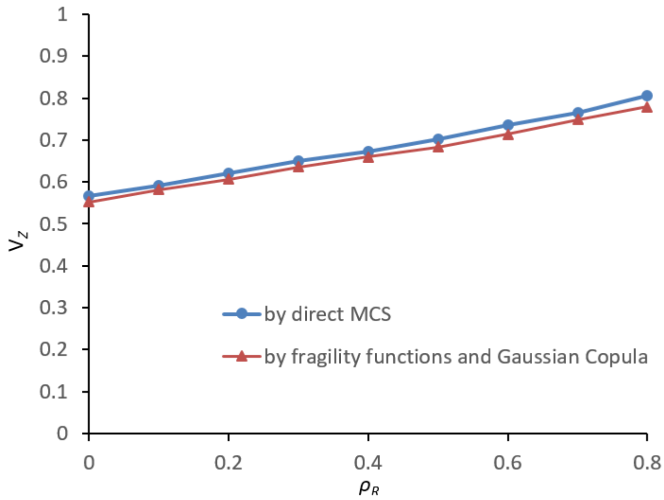


Figure 5: V_Z solved by 2 methods; $\mu_U = 50$ m/s; $\sigma_U =$ 0.1; $\rho_U = 1$.

A case study of a 30-building residential portfolio is presented. It is found that the importance of ρ_R compared with that of ρ_U is dependent on the uncertainty of $\boldsymbol{U}$. If the uncertainty is low (with a $\boldsymbol{U}$'s CoV of 0.1), ρ_R can be as significant as ρ_U. Nevertheless, when the uncertainty is high (with a $\boldsymbol{U}$'s CoV of 0.2), ρ_R can be negligible.

When fragility functions are used to probabilistically predict $\boldsymbol{DS}$ based on $\boldsymbol{U}$, Gaussian Copula can be used to incorporate U-dependent $\rho_{DS_{ij}}$ with fragility functions to simulate correlated $\boldsymbol{DS}$. The main reason is that although $\rho_{DS_{ij}}$ is strongly dependent on U_i and U_j, the correlation of Gaussian Copula ($\rho_{G_{ij}}$) is nearly constant regardless of U_i and U_j and can remain unchanged when the correlated ***DS*** of a building portfolio is simulated given different values of $\boldsymbol{U}$. Through the comparison with the direct MCS, the method of fragility functions and Gaussian Copula was found accurate.

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