Development of Flood Vulnerability Functions for General Buildings in Japan using a Component-Based Approach

Jaskanwal P.S. Chhabra
Staff Seismic Data Scientist, One Concern Inc., Menlo Park, California, USA.

Junichi Sakai
Data Science Manager, One Concern KK., Tokyo, Japan.

Youngsuk Kim
Senior Data Science Manager, One Concern Inc., Menlo Park, California, USA.

Shabaz Patel
VP of Data Science, One Concern Inc., Menlo Park, California, USA.

ABSTRACT: It is well known that Japan has historically faced many significant catastrophic (CAT) events, including floods, earthquakes, windstorms, among others. Evaluating the impact of CAT events on buildings is important to estimate direct damage and plan for future events. Since there are no publicly available functions to estimate the flood impacts on buildings at scale, in this study, a series of Japan-specific flood vulnerability and fragility functions are developed for general buildings. A component-based approach is employed to develop flood vulnerability and fragility functions. For this approach, component damage curves and component value ratios are essential. They are developed based on published literature by considering different building attributes, for example, the number of stories, construction material, occupancy, etc. Then, flood fragility functions were developed from Monte Carlo Simulation with consideration of different sources of uncertainty. This paper describes the framework developed to generate the Japan-specific building flood fragility curves and shows illustrative fragility curves for select building attributes.

Keywords: catastrophe risk; Japan flood model; flood fragility; component-based approach; resilience

1. INTRODUCTION

From the flood events of the 2015 Kanto flood, the 2018 West Japan heavy rain, and 2019 Typhoon Hagibis, among others, it was realized that a severe flood event has a significant impact on life and the economy. A series of vulnerability functions is one of the essential components in catastrophe risk modeling to evaluate the repair and reconstruction cost and the probability of damage states. FEMA (2022); Nofal and van de Lindt (2020) introduces flood fragility functions for the U.S.; however, there are no publicly available flood vulnerability models for general buildings in Japan. Currently, the functions used to estimate flood damage to general buildings in Japan tend to be empirical and/or do not allow to differentiate between the key building features to be readily applicable at scale (MLIT, 2005). Hence, it is necessary to develop flood vulnerability and fragility functions by considering Japanese building structures and configurations and regional construction practices, which is the subject of this study.

A component-based approach is developed where the building damage is calculated based on simulation of damage to the different key building components given flood inundation depth. In developing the framework, uncertainties in different

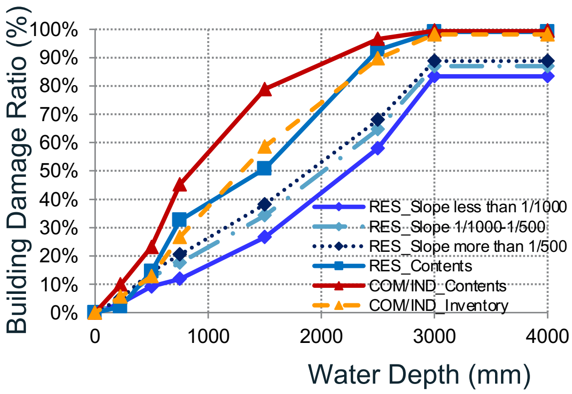


Figure 1: Vulnerability functions in Manual of Flood Impact Analysis by MLIT (2005)

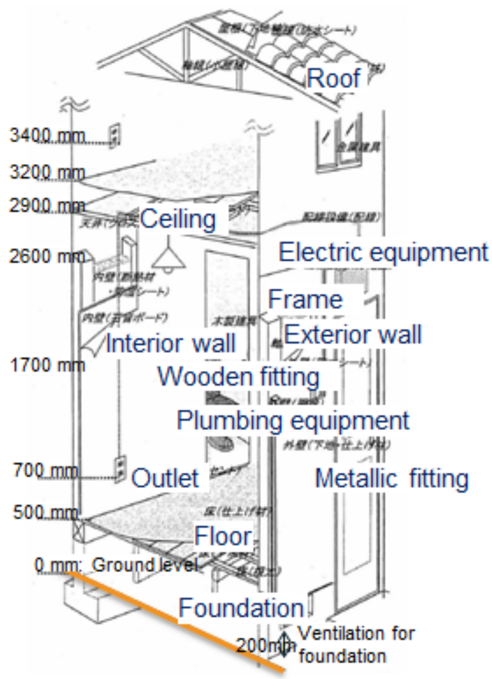


Figure 2: Vertical exposure distribution of a typical Japanese 2-story wooden SFD (Tada et al., 2013)

estimations are duly considered to arrive at a probabilistic estimation of building damage ratio (DR) and compute building fragility curves. Here, the damage ratio is defined as the monetary loss divided by the reconstruction cost value of the building, and fragility curves are defined as the probability of exceeding damage beyond a certain threshold. The JP flood building vulnerability model is developed to make predictions considering the following building features: 1) building occupancy 2) construction material 3) number of stories 4) basement 5) ground elevation, and 6) flood defense. Due to the space constraints, this paper primarily focuses on model development considering building occupancy, construction material, and the number of stories. Details of the model methodology and prediction trends are provided in the rest of this paper.

2. VULNERABILITY MODEL DEVELOPMENT

This section highlights the key methodology details behind the developed vulnerability model.

2.1. *Literature review*

This section highlights the important studies in the literature relevant to the development of flood vulnerability model for JP buildings. Figure 1 shows the flood vulnerability functions based on a study by River Bureau of the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) (MLIT, 2005). The maximum DR is relatively high (at least 80%) and occurs at a water depth of 3m, which is approximately the height of the 1st-story roof. These functions were developed based on the statistical analysis of damaged residential buildings due to flood events during 1993-1996, but the underlying data/research report is not publicly available.

Since 2011, the River Bureau of MLIT has conducted research to further improve flood vulnerability functions (MLIT, 2011). Some of the findings and conclusions from this study were summarized in Tada et al. (2013). This paper provides the vertical exposure distribution of building components and the inundation-depth-to-component-replacement relationship of a typical Japanese 2-story wood single-family dwelling (SFD), as shown in Figure 2. Different components are damaged to an extent when the flood water reaches the indicated height thresholds, and this information is later used in the model development described in this study.

2.2. *Component-based approach*

A component-based approach is developed where the building damage is calculated based on simulation of damage to the different key building components given flood inundation depth. In contrast to the empirical functions typically available in literature, such a component-based approach pro-

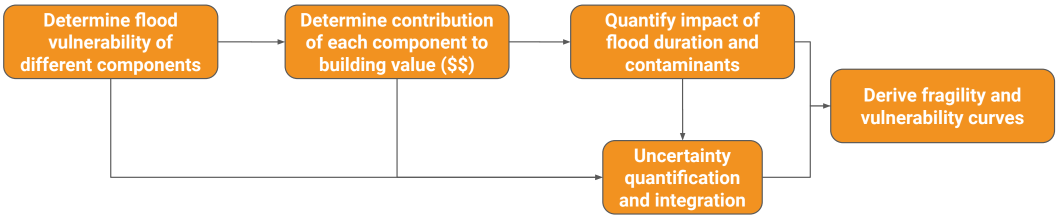


Figure 3: Different steps in calculating building flood vulnerability

vides flexibility to explicitly account for the damage to key building components when calculating the total building damage. This approach enables accounting for the different building features by changing the component characteristics, accordingly. The damage to building components is modeled using component-level vulnerability curves, which estimates the component DR as a function of inundation depth. Using the component value ratio (VR)—defined as the value of each component in proportion to the value of the building—the component DRs are translated into the building DR.

Figure 3 presents an overview of the key steps in the component-based approach to developing the building flood vulnerability curves. The key steps include: 1) calculating component vulnerability curves, 2) estimating component VRs, and 3) quantifying the impact of unknowns like flood duration, contaminants, and flood velocity on building flood vulnerability. The building vulnerability function is obtained from the equation below:

$$\text{Building Damage Ratio} = \sum_i DR_i \times CVR_i \quad (1)$$

where DR_i is the DR of the i-th component and CVR_i is the component VR of the i-th component.

Each of the steps described above considers a component of uncertainty that needs to be appropriately considered in the vulnerability simulation. The following are the key considerations:

Component DR : Given limited information about building-specific exposure, the damage to building components can be best described in a probabilistic manner because of the different possible construction materials, layouts, etc.

Component VR : The contribution of each component to the value of the total building can also be uncertain due to unique layout of each building. Figure 4 presents component VRs for different components of a 2-story wood SFD building as reported by multiple sources (MLIT, 2011; Cabinet Office, 2013) and the uncertainty in the component VRs is evident.

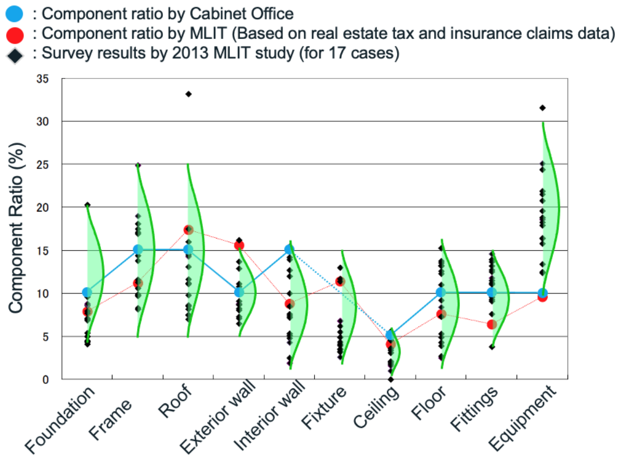


Figure 4: Component VRs for 2 story wood SFDs

Duration, velocity and contamination : The duration of the flooding, water velocity, and contaminants in the flood water (e.g., oil or sediment) have been shown to significantly affect the building DRs (Thieken et al., 2005; Büchele et al., 2006). Since the exact contribution of these factors at the building location remains unknown, the variance in the DR estimation due to these factors is considered by applying modification factors to the building DR computed based on Eq. 1. The modification factors are assumed to have normal distributions with a mean of one.

Story height : The component DRs are quantified based on the story height of the surveyed buildings in literature. However, there is typically variability in story heights in the stock of buildings in the exposure, which needs to be accounted for in their damage assessment.

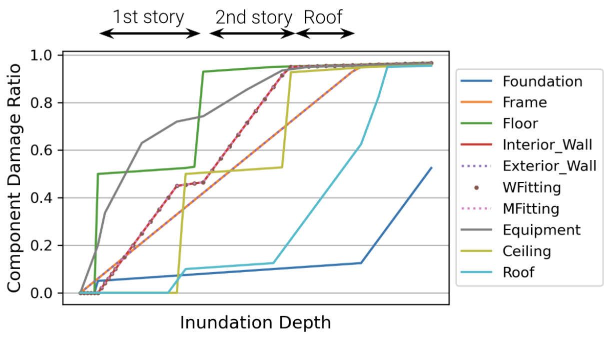


Figure 5: Mean vulnerability functions of each building component in 2-story wood SFDs

Every building and flood scenario is unique, and many factors which can be difficult to predict at the building level can influence the DR calculation. Hence the key consideration for the vulnerability model developed here is to account for different sources of uncertainty and produce probabilistic predictions for the building DR by performing Monte Carlo (MC) simulations.

2.3. Development for 2-story wood SFDs

This section highlights the key details for vulnerability function developments for 2-story wood SFDs. The component vulnerabilities are based on findings from the MLIT study (Tada et al., 2013) described in Section 2.1. Figure 5 shows the mean component vulnerabilities considering the vertical distribution of each component as shown in Figure 2. Since "Frame", "Foundation", "Floor", "Ceiling", and "Roof" are commonly understood building components, examples of the remaining building components are provided below:

- Interior Wall - Interior walls with gypsum board are commonly used as the base material.
- Exterior Wall - Walls in the exterior of a building, typically made of mortar, wood, or plaster.
- Fitting ("Tategu" in Japanese) - A general term for doors, sliding doors, windows, etc.
- Equipment - Electrical/water equipment, e.g., water heater, kitchen equipment, wiring, plumbing, bathtub.

The floor heights are considered based on the recommendations in the MLIT study. In order to interpret the component DR plots, consider the example of the "Floor" component shown in Figure 5.

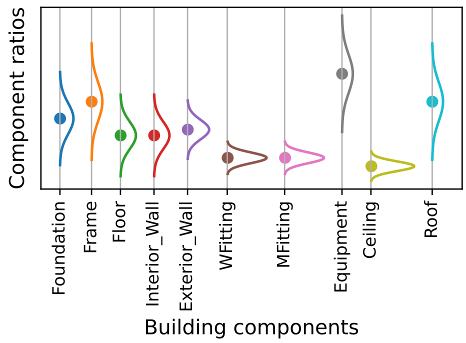


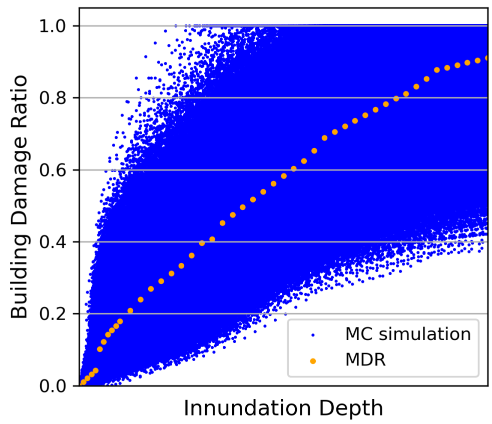
Figure 6: Component VR distribution of each building component in 2-story wood SFDs

As the water depth starts increasing, the first (i.e., ground) floor of the building is inundated, resulting in losses to the flooring system at the bottom of the first story. Damage to the "Floor" component does not increase significantly until the inundation depth reaches the second-floor level (i.e., the bottom of the second story). At this point, the floor system of the second story is also impacted, resulting in increased damage.

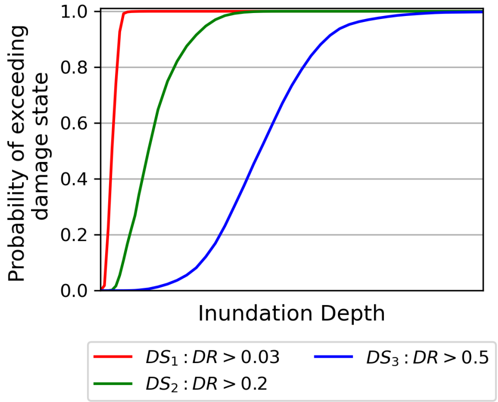
The means and standard deviations of component VRs were determined based on the information from sources shown in Figure 4. Figure 6 shows the distribution of component VRs for the different components in 2-story wood SFDs considered in the model development.

With the distributions of component DRs and component VRs determined, MC simulation is performed to determine the building DR for a given inundation depth by repeating the following steps:

1. Generate a DR sample for each building component (considering the beta distribution of component DR as described above).
2. Generate a VR sample for each building component (based on distributions shown in Figure 6), and normalize so that the sum of all component VRs equals 1.
3. Calculate the building DR using Eq. 1.
4. Apply modification factors to account for velocity, duration, and contamination effects.
5. Apply adjustment for variability in story height.



(a) Simulated DRs and mean DR (MDR)



(b) Fragility functions for exceeding different DRs

Figure 7: 2-story wood SFD building.

In order to generate robust estimates of the building DR distribution, 50,000 MC simulations are performed to calculate DR for each inundation depth. The results are shown in Figure 7a. These DR samples are used to compute the following: 1) mean DR, 2) standard deviation of DR, 3) empirical DR distribution and 4) probability of exceeding different damage states (DSs) (see Figure 7b). The fragility curves are calculated for DSs 1, 2, and 3 based on DR thresholds of 3%, 20%, and 50%, respectively. For each of the DSs, the probability of exceeding the DS is calculated at each inundation depth as the proportion of samples exceeding the corresponding DR threshold.

2.4. *Extension to different number of stories for wood SFD buildings*

Wood SFD buildings in Japan typically have 1 or 2 stories, and 3-story wood SFD buildings are rarely encountered in the Japanese building stock. Hence, a component-based approach similar to that described in the previous section is used to develop the building vulnerabilities for 1-story and 3-story wood SFD buildings.

Inundation depths and replacement triggers of building components for 1-story and 3-story wood SFDs were developed based on those for 2-story wood SFDs, and component vulnerability functions were developed accordingly. For 2-story buildings, steep increments of DRs for floors and ceilings occur at the first floor and second floor because once the water depth reaches those limits, the percentage of the components associated with those floor levels is damaged. But for 1-story buildings, once floor/ceiling is inundated, component DRs sharply increase to almost 100% because the total value of the component is associated to that single level. For 3-story buildings, the DRs of floors and ceilings were distributed to first, second, and third floors, respectively. The DRs of most of the other components are developed in a similar way.

Component VRs for 3-story buildings were derived from the VRs of 2-story buildings considering the distribution of component values to each floor. It can be expected that as the number of stories increases, the values of some components like frame and floor will increase proportionally; however, the values of other components like foundation and roof will not increase in the same proportion. This logic was used to determine the component VRs for 1-story and 3-story buildings.

For buildings with more than 3 stories, the building DR is calculated by scaling the DR of a 3-story building by a factor proportional to the inverse of number of stories to account for relatively low DR with increase in stories. Although an approach similar to that used for 3-story buildings could be used for taller buildings, given the uncertainty in estimation, and their relatively low representation in the building exposure, this simplified approach is considered sufficient.

2.5. *Development for different occupancies and construction types*

The goal of this section is to provide relevant details for the development of functions for non-wood buildings and to extend the methodology for Multi-Family Dwellings (MFDs), Commercial buildings (COM) and Industrial buildings (IND).

2.5.1. Non-wood SFDs

The component vulnerability functions for the non-wood SFDs are derived based on the recommendations in Tada et al. (2013) after making adjustments for non-wood buildings instead of the wood buildings considered in the study. DRs of the exterior wall and frame components were adjusted because these components are assumed to be non-wood (RC/Steel) and should therefore be less vulnerable to flood damage. The DR of the floor component was adjusted to reflect the different structural materials supporting the floor system even though the floor coverings (e.g., tile/carpet) can be the same in wood and non-wood buildings. The vulnerability of other components did not change significantly with the exception of roof and foundation, where the vulnerability functions were adjusted to account for non-wood materials. The mean component VRs are determined based on MLIT recommendations in Cabinet Office (2013).

2.5.2. Multi-family dwellings

The component-based approach described for SFDs is used to develop the flood functions for MFDs with 1-4 stories, and building height factors are used to scale the functions for a greater number of stories. Since 1-story MFDs are structurally very similar to 1-story SFDs, the same functions are used to estimate their flood vulnerability and fragility. A key distinction between SFD and MFD is the distribution of equipment over the height of the building. In the MFD development, the equipment component is subdivided into central equipment and distributed equipment. The central equipment is assumed to be present on the first floor in the absence of the basement and is otherwise assumed to be present in the basement, and its vulnerability function is adjusted accordingly. The distributed equipment is assumed to be uniformly distributed over the building height. Hence, as the number of stories increases, the vulnerability of the central equipment does not change, but the vulnerability of the distributed equipment reduces. Minor updates have been made to the roof vulnerability to reflect typical roof layouts in MFDs in contrast to SFDs, e.g., MFDs typically have all roof elements at the top story, whereas SFDs may have roof elements distributed across multiple stories.

The mean component VRs for the MFDs are developed based on the cost breakdown of the mid-rise MFDs studied in JFCC (2016) and by maintaining relativity with SFDs. It was found the equipment has a much higher component VR in MFDs compared to SFDs and drives differences in the relativity of these occupancies.

2.5.3. Commercial and industrial buildings

A similar approach as described for MFD buildings is followed for COM and IND buildings. A key difference in the development of COM building component vulnerability functions in contrast to MFDs is accounting for the difference in typical story heights of COM versus MFD buildings. The component vulnerability functions are adjusted for COM buildings assuming that the story height in COM buildings is typically $1m$ greater than in MFD buildings. The component VRs of the COM buildings are assumed to be the same as the component VRs of MFD buildings.

IND buildings are a complex system, and the content/industry-specific equipment damage can impact their vulnerability and fragility functions. Instead of generating industry-specific functions, a simplified procedure is used to derive the damage functions of general IND buildings. For non-wood IND buildings, a component-based approach is used to derive functions for 1-, 2- and 3-story buildings. The component vulnerability is assumed to be the same as the component vulnerability of non-wood COM buildings. The component VR of 2-story non-wood IND buildings is derived based on 2-story non-wood COM buildings by making adjustments for equipment and assuming negligible component VRs for interior walls and fittings in IND buildings. For 1- and 3-story non-wood IND buildings, the component VRs are determined to maintain relativity with the 2-story buildings.

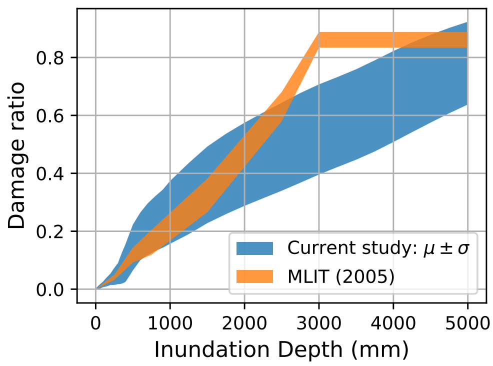


Figure 8: Comparison of vulnerability predictions for 1-story wood SFD buildings with the MLIT function

3. MODEL TREND VALIDATION AND TESTING

The previous section described the methodology for developing the flood vulnerability and fragility functions for different occupancies, numbers of stories and construction types. This section presents the impact of different building features on the fragility functions and compares the model predictions with functions found in the literature.

3.1. Comparison with published functions

Figure 8 compares the developed vulnerability function for 1-story wood SFD buildings with the function in MLIT (2005) described in Section 2.1. For MLIT functions, the interval of the DR is shown considering the different slope conditions described in Figure 1. From Figure 8 a good agreement can be seen for low inundation depths. However, the MLIT function saturates at 3m and has a higher DR than the model predictions for intermediate inundation depths. Since the MLIT functions are developed based on observations of buildings damaged by flooding from 1993-1996, it is possible that the number of data points for high inundations is relatively low. Also, since the MLIT functions are used to evaluate the effectiveness of river improvement projects, MLIT likely wanted to be conservative in estimating the building DR where data was unavailable, resulting in relatively high DRs.

3.2. Model trend validation

Figures 9 through 11 compare the building flood fragility functions for different construction types,

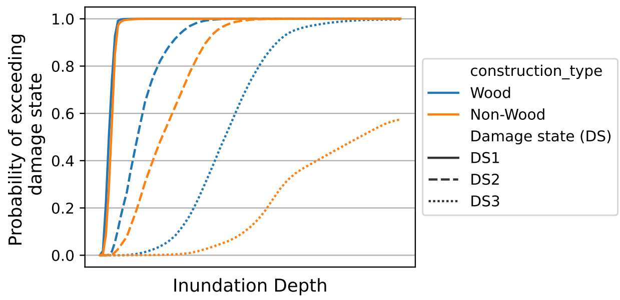


Figure 9: Fragility comparison by construction type for 2-story SFD buildings

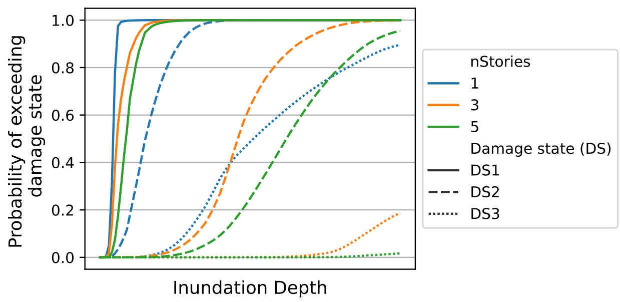


Figure 10: Fragility comparison by a number of stories for non-wood COM buildings

numbers of stories, and occupancies in order to study the sensitivity of the model with changes in building features. Figure 9 shows that wood buildings are typically more fragile than non-wood buildings. This follows from the discussion in Section 2.5.1 where components like "Frame", "Exterior wall" and "Floor" in non-wood buildings are considered less vulnerable than those components in wood buildings.

Figure 10 shows the impact of the number of stories on fragility functions for non-wood COM buildings. It can be seen that as the number of stories increases, the building flood fragility reduces. This follows from the discussion in Section 2.4 where, given constant inundation depth, as the number of stories increases, a smaller percentage of the building value is impacted.

Finally, Figure 11 shows the impact of building occupancy for 3-story non-wood buildings. These trends result from the relativity of component vulnerabilities and VRs as discussed in the previous sections. For example, COM buildings are considered to have higher story heights than MFDs, which contributes to the lower fragility of COM compared

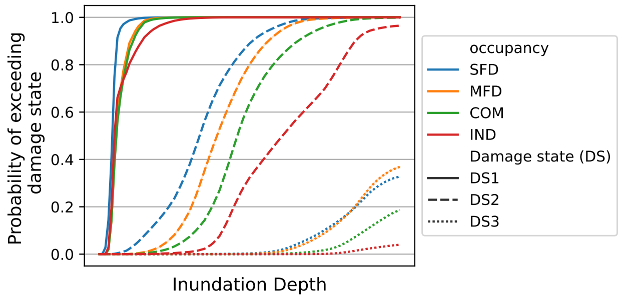


Figure 11: Fragility comparison by occupancy for 3-story non-wood buildings

to MFD. Also, IND buildings are less fragile than COM buildings because of the negligible contribution of relatively high-vulnerability components, like interior walls and fittings, to the value of IND buildings in comparison to COM buildings.

4. SUMMARY AND CONCLUSIONS

This study is focused on developing models for estimating the flood damage of buildings in Japan. A simulation-based framework is developed for estimating the building flood vulnerability and fragility considering different building features, e.g., occupancy, number of stories, construction type, etc. The proposed model explicitly considers the value of key building components and models their vulnerability based on Japan-specific published literature in order to estimate total flood damage to the building. The impacts of different building features on the building-level fragility functions are evaluated, and predictions of building-level vulnerability are compared to the vulnerability functions from MLIT (2005).

The outputs of the damage model are the building flood vulnerability and fragility functions, given inundation depth. Building damage prediction due to flooding can be highly uncertain due to various factors related to unique building features and hazard characteristics. The different sources of uncertainty are explicitly considered and integrated by performing a MC simulation. Hence, instead of producing point estimates of building damage, which can be highly variable and unrealistic, the model produces a distribution of building DRs, which could be very helpful in understanding the range of damage expected under flood inundation.

Some of the key limitations of the current model version are described next: 1. Model testing is primarily performed by explaining trends in the relativity of building-level fragility functions for different building features and by comparing the model vulnerability predictions with the MLIT vulnerability function. The model calibration and validation with respect to ground truth could not be performed due to the unavailability of any historical ground truth data to support such analyses; however, such a calibration will be considered in the future once the supporting data sets are available, 2. The current model includes the key structural and non-structural building components and does not account for content damage, and 3. A simplified general model is developed for industrial buildings, and it is noted that there could be specialized equipment and/or flood-prevention measures in industrial buildings that could impact their vulnerability, which is one of our ongoing research.

REFERENCES

Büchele, B., Kreibich, H., Kron, A., Thieken, A., Ihringer, J., Oberle, P., Merz, B., and Nestmann, F. (2006). "Flood-risk mapping: contributions towards an enhanced assessment of extreme events and associated risks." *Natural Hazards and Earth System Sciences*, 6(4), 485–503.

Cabinet Office (2013). "Manual of damage evaluation of residential buildings due to natural disasters".

FEMA (2022). "Hazus Flood Technical Manual".

JFCC (2016). "Manual for approximate cost estimation for architectural engineers".

MLIT (2005). "Manual for flood impact analysis".

MLIT (2011). "Committee on evaluation method of river construction/protection project".

Nofal, O. M. and van de Lindt, J. W. (2020). "Minimal building flood fragility and loss function portfolio for resilience analysis at the community level." *Water*, 12(8), 2277.

Tada, N., Ikeuchi, K., Hirose, M., Kuribayashi, T., Saruwatari, H., Ito, H., Kubota, K., OOnami, H., Odagiri, A., and Asami, Y. (2013). "Development of evaluation method of house damage due to flood." *Procs. of Advances in River Engineering Vol. 19*, 271–2761.

Thieken, A. H., Müller, M., Kreibich, H., and Merz, B. (2005). "Flood damage and influencing factors: New insights from the august 2002 flood in germany." *Water resources research*, 41(12).