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Reliability-based modeling of typhoon induced wind vulnerability for residential buildings in Japan

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ABSTRACT

The present paper presents an approach to developing a reliability-based vulnerability model for the assessment of typhoon induced wind risk of residential buildings in Japan. Following the approach, a provisional version of vulnerability model is developed with information available. By examining the model, it is found that the resistance of roof tile and the correlation of trajectories of flying debris play a significant role on the vulnerability. Critical assumptions made in the modeling, which requires further investigation and thus concerns the updating of the vulnerability model, are discussed and identified. Thereby, further research directions toward a more precise vulnerability model are addressed.

1. Introduction

Japan has experienced severe typhoon events that caused significant damages to buildings. Among the most disastrous typhoon events that challenged modern buildings in Japan is Typhoon Vera in 1959. With lessons learnt from these events efforts have been made to advance construction technology toward more wind-resistant structures. In parallel, the Japanese building design code has been revised several times. At earlier years these efforts and the revisions have been concerned with structural performance of buildings. More recently, attentions have been extended to non-structural elements of buildings such as roof elements, windows and claddings. By 2007 the building design code in Japan has included the requirement on the safety of relevant non-structural elements as well as structural elements. Reflecting them statistics over the last half century clearly show a decrease in the number of the damages to buildings, see e.g. Uyeda (2008). However, it is observed that a substantial number of buildings still suffer from minor damages that are accounted for by non-structural element failures.

In the context of risk assessment, e.g. portfolio loss assessment in the insurance industry, a precise assessment of small losses that are often associated with non-structural element failures is important, since these are usually more frequent than larger losses and thus account for a large fraction of risk when aggregated. Vulnerability models are often developed based on the statistical analysis using data from post-disaster investigations. These models generally suffer from large scatter of data points, which implies large modeling uncertainty. The validity of the models is sometimes questionable especially for smaller losses. These observations have led academia to an alternative but also complementary approach to developing vulnerability models; approach considering physical processes leading to non-structural element failures.

Necessity of such an approach and vulnerability models therewith has been recently reinforced by the emerging climate change. Several climate change research works reveal that the track, intensity and frequency of typhoons are likely to change under the future climate; see e.g. for general circulation model Murakami et al. (2011), for statistical interpretation Yasuda et al. (2010) and Nishijima et al. (2012). In order to quantify the impact of the climate change on typhoon induced wind risk of residential buildings in Japan, Nishijima et al. (2012) conduct a preliminary impact assessment. In their study, the typhoon induced wind risk is assessed using an ad-hoc fragility model that is developed based on post-disaster statistical loss data, which is hereafter called empirical fragility model. One of the conclusions in the study is that a more credible fragility model, which together with a cost model constitutes a vulnerability model, is required to perform a more precise assessment of climate change risk. A fundamental

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drawback of the empirical fragility/vulnerability model, however, is the lack of capability to examine the efficiency of adaptation of buildings to the climate change. A model with this capability is currently not available for residential buildings in Japan. Therefore, Nishijima et al. (2012) address the development of such a model as a future task.

A model that is capable of considering upgrades/downgrade of various parts of buildings is reliability-based fragility model. Here, a reliability-based fragility model refers to a model, in which failures are defined in terms of limit state functions with basic random variables and thereby the probabilities of failures are assessed within the framework of the structural reliability theory (see e.g. Madsen et al. (2006)). It explicitly accounts for different failures by modeling the resistance capacities of individual elements and the wind loads affecting to the elements. It thus allows for examining the effect of upgrading/downgrading on the increase/decrease of resistance capacity in a quantitative way. As a consequence, changes in the probability of failure can be assessed; which in turn the efficiency can be assessed in terms of risk change. Furthermore, such a model is facilitated not only for the impact assessment and risk management for climate change but also for the optimization of the current design practice.

There are several reliability/probability-based vulnerability models developed for buildings in the USA; e.g. the Florida Public Hurricane Loss Projection (FPHLP) model, see Pinelli et al. (2004, 2008, 2011), Gurley et al. (2005), and Hamid et al. (2010, 2011), the FEMA HAZUS-MH Hurricane model, see Vickery et al. (2006a, 2006b), hereafter called FEMA model, the model developed by Lin and Vanmarcke, see Lin and Vanmarcke (2010) and Lin et al. (2010), hereafter called Lin–Vanmarcke model. These three models are dedicated to the modeling of vulnerability of buildings during hurricane events in the USA. Among non-structural element failures, all of them account for the pressure damage, i.e. damage directly caused by gusty wind pressure, and debris damage, i.e. the damage caused by the impact of flying debris. Nonetheless, the models differ in several aspects such as the building and the damage types examined, the ways of calculating the wind loads and the fragility as well as in the modeling of interdependency of pressure and debris damage.

In what concerns the types of considered buildings and failures, the FPHLP model was initially developed to analyze the fragility of single-family buildings located in Florida, the USA, including typical one- or two-storey concrete block and wood frame buildings with gable and hip roof. More recently, it has been extended to analyze the fragility of commercial residential Middle High rise Buildings (MHB) comprised condominiums and multi-storey apartment buildings. Lin–Vanmarcke model takes basis in the model building in the FPHLP model; i.e. one storey concrete and wood-frame residential buildings with gable and hip roof in Florida, the USA. The FEMA model enables the analysis of fragility for typical residential and commercial buildings over the Atlantic and Gulf coasts of the USA, including one- or two-storey single family buildings, up to four storeys of multifamily buildings, manufactured houses, pre-engineered metal buildings, industrial and high rise buildings.

In the FPHLP model, for the analysis of fragility for single-family buildings, structural and non-structural failures are modeled including failures of roof cover, roof sheathing, roof-wall connections, walls and openings such as doors, garage doors and windows. For the analysis of fragility for MHB only non-structural failures are considered including the failure of cladding and openings. The damage type considered in the Lin–Vanmarcke model is the same as the damage types considered in the FPHLP model for single-family buildings. The FEMA model also models structural and non-structural failures similar to the FPHLP model.

In regard to the conversion from wind speed to wind load, the FPHLP model utilizes a modified version of the provision in ASCE 7-98 (ASCE, 1998). This modification disregards the so called importance factor, the directionality factor and the topographic effect factor. The pressure coefficients are specified for eight wind directions. Moreover, buildings are assumed to be isolated sufficiently from neighboring buildings and located in an open country terrain corresponding to the exposure category C. In the conversion, the maximum 3-s gust wind speed at roof height is employed as the reference wind speed. In contrast, the FEMA model converts the wind load based on a one-hour sustained wind speed. For the estimation of directionally dependent wind pressure coefficients an empirical modeling approach has been developed. These coefficients are drawn from a large number of boundary wind tunnel tests measuring wind induced pressures on model buildings together with the reference to the counterparts of the British and Australian design codes. The extreme values of the local pressure coefficients resulting from empirical modeling are set equal to agree with those given in the ASCE 7-02 provision (ASCE, 2002) on wind loads. Furthermore, the shielding and interference effects of surrounding buildings are accounted for by modifying the baseline pressures produced for isolated building, following the works by Ho (1992) and Case (1996). The Lin–Vanmarcke model takes basis in the methodology used in the FPHLP model.

For the estimation of fragility, two distinct approaches are employed. In the FPHLP model, the probabilities of structural and non-structural failures are estimated as a function of the maximum wind speed during an event. The effect of change of wind direction during an event is not accounted for. In the FEMA model those probabilities are estimated at individual time steps during an event. The cumulative damage over the event is obtained by integrating instantaneous failures over time. Hence, a detailed analysis of the effect of different wind environments on the damage is facilitated, e.g. in terms of the change of wind direction and speed over subsequent time steps. The Lin–Vanmarcke model is also capable of estimating the probabilities of non-structural failures at instantaneous time steps of an event.

In regard to the modeling of the interdependency between debris and pressure damage both the FPHLP and FEMA models consider the effect of pressure damage that follows debris damage by increasing the internal pressure of the building depending on the state (failure/no-failure) of its openings due to the impact of flying debris. Note that the increase in the internal pressure changes the probabilities of the failures of several building elements. The mechanism for objects to start flying when they fail due to the gusty wind pressures is not explicitly accounted for parameters such as the amount of debris of specific types are given as exogenous parameters. To summarize, in these two models only the effect of debris damage on the pressure damage is modeled. In contrast, the effect of pressure damage on debris damage is also modeled in the Lin–Vanmarcke model by feeding back the output from the pressure damage model as input to the debris damage model. It thus iteratively utilizes the pressure and the debris damage models in the fragility analysis.

In addition to these three suits of vulnerability models, several fragility/vulnerability models for (components of) buildings in the USA are developed based on the concept of structural reliability theory, such as roof sheathing (Lee and Rosowsky, 2005; Li and Ellingwood, 2006; Lindt and Dao, 2009; Rocha et al., 2010) and building (Unanwa et al., 2000; Unanwa and McDonald, 2000; Rosowsky and Ellingwood, 2002).

Although the methodologies behind these models provide a guidance on the development of vulnerability models in general, the models developed for buildings in the USA are not directly applicable to the case of residential buildings in Japan. This is due to the difference of residential buildings between Japan and the USA in several aspects: e.g. geometry of typical residential buildings, characteristics of non-structural elements such as roof shape