A Step Towards the Next Generation of Seismic Risk Models: A Comprehensive Case Study of a Highly Populated Building

BEHNAM BEHESHTIAN, RISK FRONTIERS

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DECLARATION:

Some parts of this briefing are based on the writer's PhD study, which focused on "Risk Analysis of the Built Environment in the Face of Extreme Events" at Swinburne University of Technology, Melbourne. The research was conducted under the guidance of Professor Hing-Ho Tsang and Professor Javad Hashemi.

ABSTRACT:

Earthquakes, although infrequent, hold a significant position in the risk portfolio of reinsurers. This significance is highlighted in the recent Insurance Council of Australia (ICA) insurance catastrophe resilience report, which places the 1989 Newcastle CBD earthquake, with a normalised loss of $6.54 billion, as Australia's third most devastating natural hazard [1]. This event, with its substantial single-event loss, underscores the necessity for the development of more sophisticated and precise risk models to more accurately assess the human and financial impacts of such hazards. Presently, the vulnerability component of the earthquake catastrophe models used within the global reinsurance sector predominantly relies on claims data and historical damage records. This reliance overlooks the myriad advantages that could be gained from the direct integration of buildings' structural properties into loss models. This research, by taking the AsiaWorld-Expo building in Hong Kong as a case study, aims to shed light on the benefits of leveraging the current state-of-the-art knowledge of earthquake and structural engineering to include buildings' structural properties in seismic risk models. Furthermore, the selection of the AsiaWorld-Expo, a densely populated facility with a capacity to accommodate over 30,000 individuals, underscores the often overlooked susceptibility of densely populated structures. These buildings, encompassing venues like entertainment arenas, stadiums, religious edifices, and community centres, have received limited attention from research communities and are particularly prone to substantial casualties and economic losses in the event of an earthquake. This study, as the first of its kind, provides a framework for the direct incorporation of buildings' structural models into the earthquake catastrophe models and signifies the particular importance of highly populated buildings and their potential risks of mortalities.

MODELLING OF THE CASE STUDY STRUCTURE:

The development of the numerical structural model for this study began with a meticulous reverse engineering process, where over 1500 sheets of structural drawings were carefully examined. This way, by focusing on the Typical Hall Building (THB) of the AsiaWorld-Expo in Hong Kong, as shown in Figure 1, the detailed numerical model of the structure was created on the OpenSees software. The modelled building encompasses an area of about 70,000 m2 (equivalent to 268 tennis courts), measuring 360 meters in length and 192 meters in width, and adheres to the Hong Kong Building (Construction) Regulations 1990 and the British Standards. The THB is characterised by its regular and symmetric structure, featuring columns spaced at 8.3 m along its length and two main bays, each 77 m wide. Additionally, The structure was loaded based on the available instructions of the drawings, considering for each floor the self-weight, live load and dead load of 15.7 kN/m2, 5 kN/m2 and 2.2 kN/m2, respectively [2].

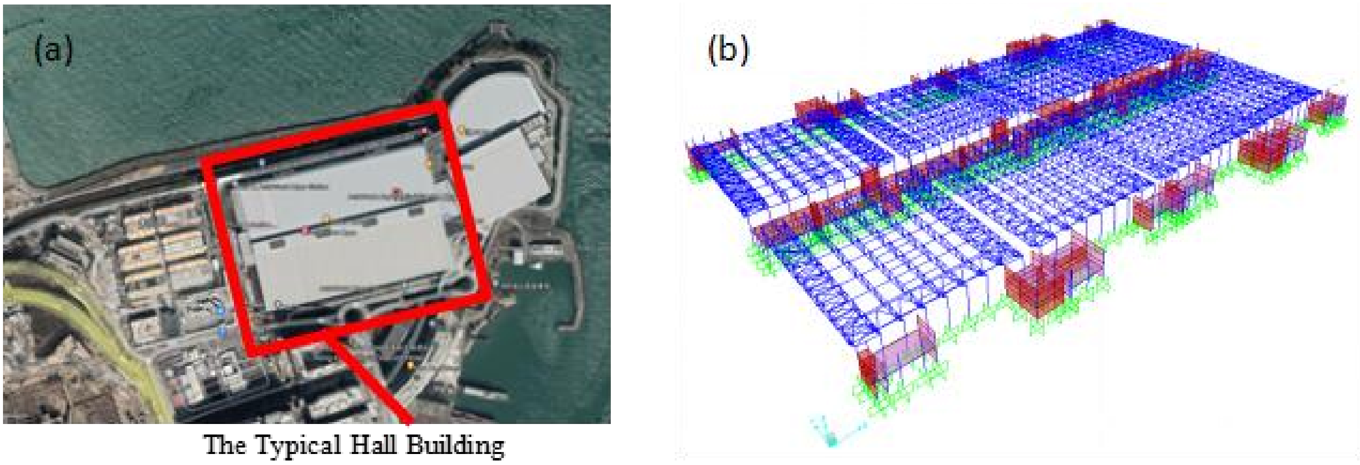

Figure 1: *(a) The satellite view and (b) a 3D view of the modeled structure*

FRAGILITY ANALYSIS:

The calculation of the fragility curves is an essential component of structural risk estimation. Fragility curves display the conditional probability of structural demand caused by varying levels of ground shaking. In earthquake and structural engineering, fragility curves are estimated through incremental dynamic analysis (IDA), a method in which structures are subjected to incrementally intensifying earthquake ground motions, and their structural response is constantly monitored against some performance limit states.

Building-specific global performance limit states of this structure are obtained from pushover analysis, with definitions of the damage states and their detailed descriptions being indicated in Menegon et al. [3] and restated in other seismic guidelines and design codes such as SEAOC (1995) and ATC [4]. This structure is evaluated for four damage states, which are Slight, Moderate, Extensive and Complete damage. As a result, for the X and Y directions of the structure, drift limits of 0.56, 1.2, 2.5, 4 and 0.5, 1.3, 2.8, 4 per cent are respectively set for the considered limit states.

For seismic analysis and achieving fragility curves, a suite of 300 intensifying ground motions was utilised. This suite was generated based on Atkinson and Boore [5] intraplate source model. The ground motions were chosen based on the magnitude-distance (M-R) pairs from a study conducted on the relationship of the peak ground velocity (PGV), magnitude, and distance parameters. Major faults in the region were also included when the earthquake scenarios were identified [3]. This way, by having the 300 intensifying ground motions, the numerical model of the structure is analysed, and the fragility curves of the building are achieved, as illustrated in Figure 2.

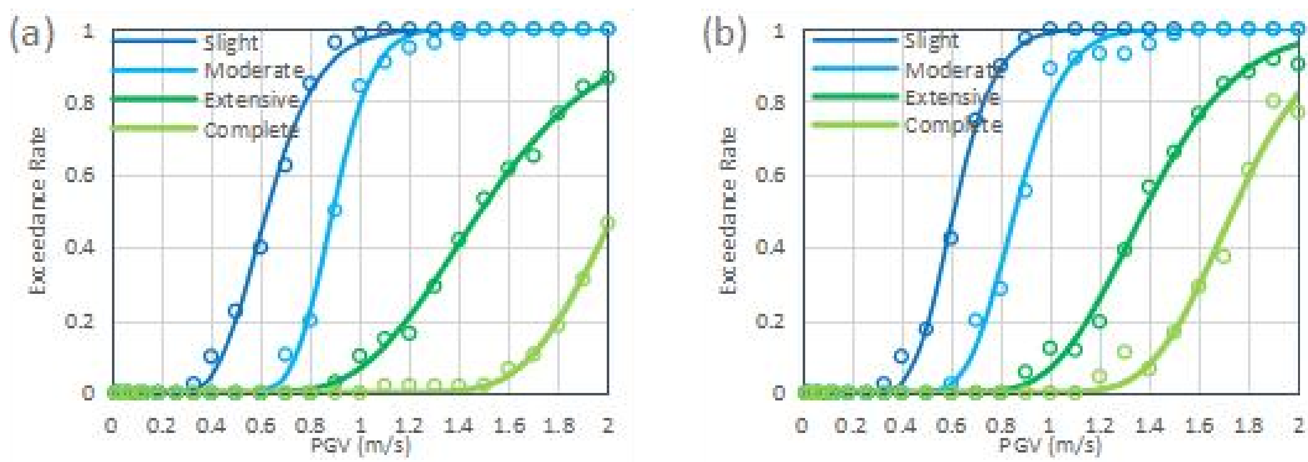

Figure 2: *Seismic fragility curves based on ground motions with various magnitude-distance (M-R) combinations, (a) and (b) are respectively for X and Y directions.*

RESULTS:

In this research, the AsiaWorld-Expo building in Hong Kong was used as a case study. A 3D numerical model was created using OpenSees software, and the fragility curves of the structure for various limit states were generated. As shown in Figure 2, the Y direction exceedance rates are generally higher than the X direction. For instance, the complete collapse rate for the Y direction at the PGV of 1.6 m/s is 0.3, while for the X direction is around 0.05. This means the structure is more vulnerable in the Y direction than the X, primarily due to the presence of fewer shear walls in the Y direction. Such a difference in strengths is quite common in structures. However, the current earthquake catastrophe models are incapable of capturing them. This shortcoming is one of the drawbacks that can be addressed by the direct incorporation of the buildings' structural properties into the risk models. Among other advantages, it could be the consideration of buildings' vertical irregularities, plan irregularities, and, most importantly, soft story formations, which are among the leading causes of structural damage in earthquakes.

The direct calculation of the expected number of casualties is another advantage of this method, which can highly benefit the reinsurance industry. To this end, as described in other studies [6,7], the concept of individual risk should be taken into account. Drawing on the work of Tanner and Hingorani [8], the number of casualties (N) should be defined as a function of the area of collapsed columns (Acol). Consequently, by following their method and performing the calculations, the predicted casualty count for this building losing one column would be approximately 14 individuals. Subsequently, referring to the fragility curves enables the realisation of collapse probabilities for any desired PGV. For instance, in an earthquake with a PGV of 1.4 m/s, the collapse probability would be 10%. Therefore, multiplying the estimated 14 casualties by the 10% collapse probability indicates a median casualty probability of 1.4 persons for an earthquake with a PGV of 1.4 m/s [9].

APPLICATIONS AND IMPLICAIONS:

As discussed above, this research provides a framework for developing the next generation of seismic risk models to be used within the reinsurance industry. By incorporating the building's structural details, a missed property of current models, the loss estimation accuracy of the earthquake catastrophe models can be improved. Although applying this method to a large portfolio presents its own set of difficulties, challenges should not deter us from pursuing the correct path. Currently, all the essential elements for taking this path are available: I) the structural drawings and models of all constructions exist within the engineering firms, II) the mathematical and engineering methods for assessing risk at the individual-building level are available, and III) some simplified, yet well-established alternative methods are available within the earthquake and structural engineering disciplines, which rather than the state-of-the-art method presented here, can help in managing the complexities of large portfolios and facilitate the initial implementation steps.

Realistically, remodelling existing structures and creating a digital twin can be extremely expensive. Costs can be lowered if structural drawings are available and further reduced with access to a building's digital structural model. However, extracting necessary parameters from even an already existing digital model remains expensive, often requiring extensive work by skilled engineers. Despite these challenges, the rapid advancement of artificial intelligence (AI) is likely to make the extraction of information from digital models and drawings more practical and cost-effective soon.

In the interim, a viable strategy is to concentrate on buildings at the end of their design phase, the buildings which have not yet been constructed. By developing specialised software that interacts with structural design programs, it's possible to analyse and extract critical parameters at the end of the design process. Implementing such software at the end of the modelling pipeline enables a cost-effective gathering of building characteristics crucial for estimating earthquake losses within the insurance sector. This way, the proposed approach can effectively improve the overall accuracy of seismic loss analyses, leading to a more accurate assessment of the seismic risks of large and high-value buildings.

Furthermore, as a futuristic and cutting-edge concept, streamlining the process of structural risk analysis can help in the incorporation of risk considerations into the fundamental stages of structural design. This integration, which falls under the concept of risk-based structural design, enables architects and engineers to create designs that are more attuned to potential risks. In this context, buildings designed with seismic risks in mind may have slightly higher initial costs; however, the additional expenses can later be compensated with lower insurance premiums due to enhanced safety. Consequently, as a byproduct of such integration, it can be expected that the built environment gradually becomes safer, a shift that can empower communities and their inhabitants over time.

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ABOUT THE AUTHOR/S

BEHNAM BEHESHTIAN
Risk Engineer

Behnam is a Risk Engineer at Risk Frontiers, responsible for developing and maintaining the QuakeAUS and QuakeNZ models, in addition to contributing to the development of other models within the group. He is passionate about researching the risk and resilience of the built environment in the face of natural hazards, including earthquakes, tsunamis, and bushfires.