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Vulnerability of industrial buildings to wind and storm surge

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ABSTRACT

Steel portal framed industrial buildings have been widely used as warehouses, supermarkets, manufacturing workshops and storage facilities, which make up a large portion of the building stock in a community or city. There is a lack of physics-based fragility and vulnerability assessments for this type of building under combined wind and storm surge loads. This study developed simulation-based fragility models that account for the physical damage mechanisms, probabilistic load effects and resistances of building components in both structural and non-structural subassemblies of a steel portal framed industrial building subjected to tropical cyclone-induced wind and storm surge loads. The physical damages of building components from the fragility assessment in conjunction with an empirical model for water inundating damage to building interior are then employed in an assembly-based building vulnerability assessment. The obtained building vulnerability express the expected building loss ratio as a function of various influencing variables including wind speed, surge inundation depth, surge flow velocity and flow direction. The analysis results suggest that the complex interactions between wind and surge loads, inundation level, fenestration damage and internal pressures have substantial impacts on the building vulnerability.

1. Introduction

Tropical cyclones are associated with multiple hazards such as wind, surge, wave and rainfall that cause billions of dollars in damage annually to civil structures and infrastructure systems in coastal regions. Physics-based models for fragility and vulnerability assessments provide a transparent damage prediction for individual buildings and building components/subassemblies with explicit physical meanings of multi-hazard effects and damage mechanisms, which better supports for many subsequent tasks for cyclone risk management and building resilience enhancement such as risk estimation, quantitative resilience assessment and cost-benefit evaluation of risk reduction measures (e.g., design enhancement, building retrofit and protective measures). So far, physics-based models for fragility, vulnerability and loss assessments have mostly been developed for low-rise timber framed residential buildings subjected to tropical cyclone-induced multiple hazards (e.g., Masoomi et al. 2019; Do et al. 2020). However, for cyclone risk management of building portfolios in a community or city scale, physics-based multi-hazard fragilities/vulnerabilities for different types of buildings (in terms of occupancy, structural type and construction practice, etc.) are further required. Low-rise industrial buildings have been widely used as warehouses, supermarkets, manufacturing workshops and storage facilities, which make up a large portion of the building stock in a typical community or city. Compared to residential buildings, industrial buildings have different load effects, building component resistances and damage mechanisms under cyclone-induced multi-hazard effects that require a new physics-based fragility/vulnerability model for this type of structure.

This study develops a physics-based fragility/vulnerability model for steel portal framed industrial buildings subjected to tropical cyclone-induced wind and storm surge. A damage (fragility) assessment is conducted for a prototype industrial building subjected to combined wind and surge loads by using Monte Carlo simulation considering critical failure modes of building components. It accounts for wind and surge damages to major building subassemblies including the building envelope (roof cladding, wall siding and fenestration) and structural framing (steel portal frames and end wall frames), and the water damage to building interior from storm surge. The physical building damages are then converted into monetary losses via an assembly-based vulnerability assessment. The obtained vulnerabilities express the expected building loss ratios as a function of hazard intensities (wind speed, surge inundation depth and water velocity), which can be used to support many subsequent tasks (e.g., risk estimation, resilience assessment and risk mitigation) of cyclone risk management and resilience enhancement for industrial buildings.

2. Prototype Industrial Building

The fragility/vulnerability model is developed for a prototype industrial building in Australia exposed to tropical cyclone-induced strong wind and coastal flood (storm surge). A plan view of the portal framed industrial building and the structural framing of the prototype industrial building is depicted in Fig. 1. The prototype industrial building is designed according to relevant Australian design standards considering dead load, live load, wind load and the corresponding load combinations. It is assumed that the building is on a flat site within suburban terrain, and that there are no nearby buildings providing direct shielding of the prototype building.

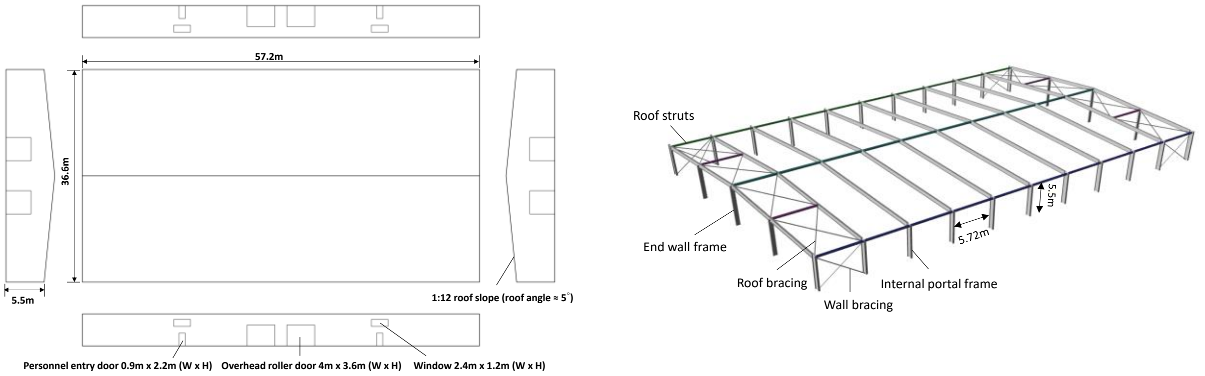


Figure 1. Plan view, Steel frame and bracing of the prototype industrial building.

3. Damage Assessment

3.1. Fragility modelling

The multi-hazard fragility assessment in this study considers physical damage from combined wind and surge loads to both the building envelope and structural framing including metal roof cladding, metal wall siding, fenestration (windows, personnel entry doors, overhead roller doors), steel portal frames and end wall frames. In this study, the fragility for a building subassembly (e.g., roof cladding, wall siding or fenestration in the building envelope, or structural framing) is defined as the cumulative probability of its damage ratio conditional on cyclone intensity measures:

$$FR_B(IM) = \Pr\left[DR \mid IM\right] \tag{1}$$

where the intensity measures herein, *IM*, include gust wind speed W_V, surge inundation depth *H* and water flow velocity F_V; FR_B (*IM*) is the fragility of the subassembly as a function of the intensity measures, and *DR* is the physical damage ratio of the building subassembly (e.g., the damage ratio of wall siding is the ratio between the number of damaged wall panels to the total number of wall panels). Given the evaluated damage ratio as a random variable, the fragility is often expressed as the exceedance probability of discrete damage states if these damage states are predefined. Alternatively, the fragility may be expressed in terms of the expected damage ratio (or any quantiles) in practice (e.g., Qin & Stewart 2019). The failure of either a single structural or non-structural component (e.g., a metal wall siding panel or a steel portal frame member) in the corresponding building subassembly is assessed by comparing corresponding demands (load effects) and capacities.

3.2. Wind and surge loads

Figure 2 illustrates the combined wind and surge loads acting on the building (assuming no floodwater inside) considering that the wind and surge flow approach in a transverse direction (i.e., direction perpendicular to the longitudinal axis of the prototype industrial building). Here it is assumed that wind and surge flows are in the same direction. The wind pressures directly act on the unsubmerged wall and roof areas, while the lateral hydrostatic and hydrodynamic pressures from storm surge affect the submerged wall areas. The buoyancy force (hydrostatic load in vertical direction) acts on the concrete slab and footings. The wind loads were probabilistically modelled based on wind tunnel test data (Ho et al. 2005), see details in Qin et al. (2023). The lateral hydrostatic and hydrodynamic loads from storm surge were modelled based on the code-based load equations given by ASCE 7-16 (2017). The change of internal pressure due to fenestration damage and the cancelation of hydrostatic loads due to quickly entered floodwater through damaged building envelope are also considered. It is noted that for the considered building height, it is reasonable to assume that the wind profile is approximately uniform along the building height.

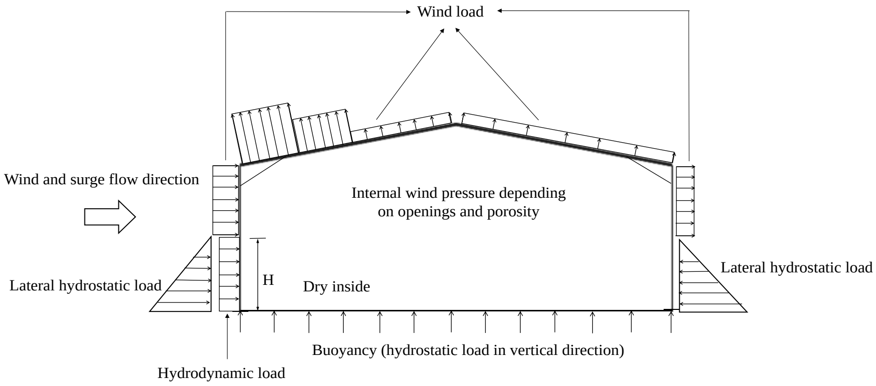


Figure 2. Combined wind and surge loads on the prototype industrial building (dry inside).

3.3. Failure modes, demands and capacities

The damage assessment considers wind and surge damages to the building envelope (roof cladding, wall siding and fenestration) and structural framing (portal frame and end wall frame). The demands on roof cladding, wall siding and fenestration are the wind and storm surge loads derived from the load modelling using a tributary area approach. The demands on framing members, column base connections and end wall cross-bracing systems are assessed using analytical structural analysis in conjunction with influence coefficients obtained from finite element analysis.

Metal roof cladding panels and unsubmerged wall siding panels fail by wind suction pressures due to fastener pull-over or pull-out. The uplift or outward capacity of a single roof or wall panel is probabilistically modelled with the statistics estimated using information provided manufacture’s manual and FEMA (2014). For roof and unsubmerged wall areas, any failure of purlins or girts due to wind suctions will also cause damage to metal roof and wall panels attached to them. The probability distributions and statistical parameters for the uplift or outward capacity of purlins and girts are derived based on manufacture’s manual. These capacities for purlins and girts consider both buckling failure and failure of the connections to supporting frames under uplift/outward loads. Fully submerged wall siding panels are subjected to inward pressures from hydrostatic and/or hydrodynamic surge actions. This study considers the damage of a submerged metal wall panel caused by the failure of any girt supporting the panel under inward surge loads. The probability distributions and statistical parameters for the inward capacity of girts (kN/m) are estimated based on manufacture's manual. For partially submerged wall siding panels, it is assumed that a panel fails if either the submerged part is damaged by inward surge loads or the unsubmerged part is damaged by wind suctions. In this study, fenestration (windows, entry doors and overhead roller doors) failures caused by high pressures from wind and/or storm surge are considered. Either positive or negative wind pressure can cause damage to unsubmerged fenestration, while inward surge pressure cause failures to fully submerged fenestration. For partially submerged fenestration, damage is due to combined wind and surge pressures. The fenestration capacities are assumed to follow a normal distribution with statistics estimated from AS2047 (Standards Australia 2014), AS/NZS4505 (Standards Australia 2012) and FEMA (2014).

The portal frame damage is considered to occur due to failures of frame members and column base connections. The failure modes for frame members are flexural failure, in-plane and out-out-plane buckling, while shear failures for column base connections. The frame members are treated as beam-columns and statistics of the capacities are estimated based on AS4100 (Standards Australia 2020) and Pham et al. (1986). The probabilistic capacity model and statistical information for column base connections are built and estimated based on AS4100 (Standards Australia 2020) and Pham & Hogan (1986). The end wall frame damage is caused by failures of wind columns (member failure or column base connection failure), roof struts, roof and wall bracing. The probabilistic capacity models for these elements are built based on relevant standards (e.g., AS4100) and statistics from the literature (e.g., Pham et al. 1986; Pham 1987).

3.4. Monte Carlo simulation

The fragility/damage assessment is conducted probabilistically using Monte Carlo simulation (MCS) considering a wide range of wind speeds, surge inundation depths, surge flow velocities and flow directions. The simulation-based fragility/damage assessment accounts for the probabilistic models of wind and surge loads, demands and structural capacities. The change of wind loads due to internal pressure change resulting from fenestration damage, and the change of surge loads due to water intrusion are also considered. Then the fragility can be assessed for each building subassembly in the building envelope and structural framing.

4. Building Vulnerability

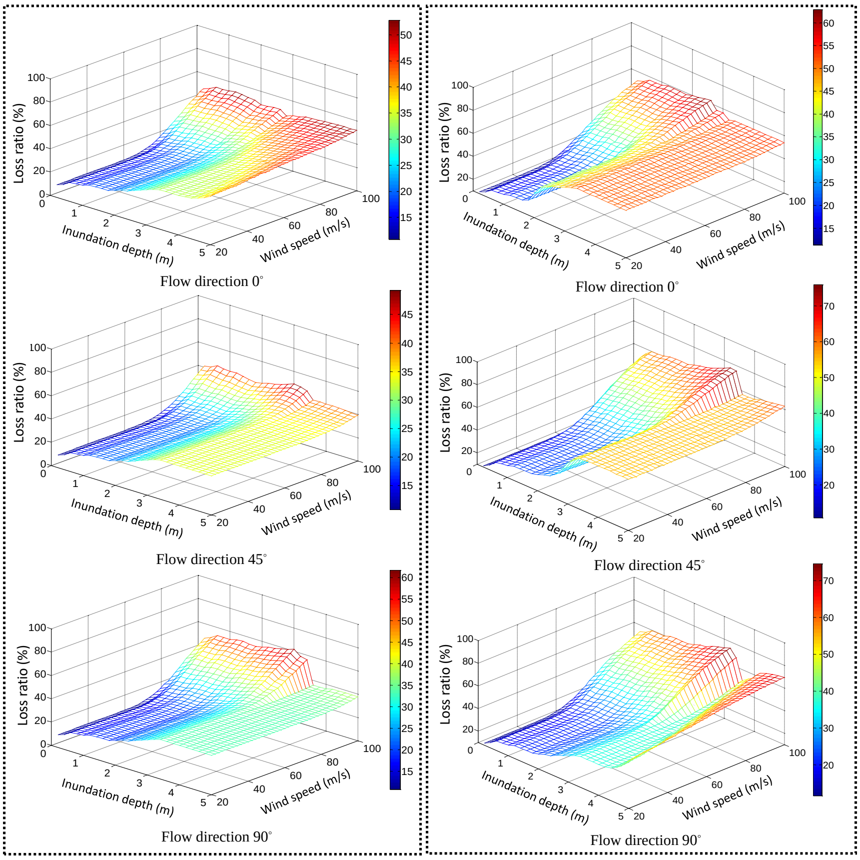
A vulnerability assessment links the physical building damages obtained from the fragility analysis to monetary building losses. An assembly-based approach (e.g., FEMA 2014) is adopted here for the vulnerability assessment by integrating losses from different building subassemblies. In this study, building vulnerability is expressed as the expected building loss ratio (ratio of the damage repair or replacement cost to the building value) conditional on cyclone intensity measures *IM* (i.e., wind speed, surge inundation depth and water velocity), which is given by

$$VN(IM) = \sum_{i=1}^{N_b} CR_i \times E(LS_i \mid IM) \tag{2}$$

where VN (IM) is the building vulnerability, N_b is the number of building subassemblies, CR_i is the cost ratio of the i^{th} subassembly defined as the ratio of the repair or replacement cost for the entire i^{th} subassembly to the building value, E (LS_i | IM) is the expected loss ratio (LS_i) of the i^{th} subassembly (ratio of the damage repair or replacement cost for the i^{th} subassembly to the cost for repairing or replacing the entire subassembly) conditional on cyclone intensities, which can be evaluated based on damage ratios obtained from the damage/fragility assessment. Five building subassemblies (N_b = 5) are considered in the vulnerability assessment including roof cladding (i = 1), wall siding (i = 2), fenestrations (i = 3), structural framing (i = 4) and building interior (i = 5). Table 1 shows the cost ratios for these subassemblies and the building components within each subassembly which are estimated from Australian construction cost guide (Rawlinsons 2021). The summation of these cost ratios is greater than 100% of the building value because of the extra costs induced by repair, removal and replacement works for an existing building. The expected loss ratios for building subassemblies considered in the fragility assessment (i =1, 2, 3, 4) can then be obtained based on their damage ratios. Considering that the building is not dry-proofed, it is not unreasonable to assume that the water depth inside the building will eventually equal to the outside inundation depth for a surge event. The expected loss ratio of the building interior for a given surge inundation depth is derived based on the loss estimates in USACE (2006).

Table 1. Subassembly cost ratios.

Subassembly		**Description**	**Cost ratio**	**Total**
Foundation		Concrete footings and slab	28%	125%
Building envelope	Roof cladding (i = 1)	Metal roof panels and purlins	9%	
	Wall siding (i = 2)	Metal wall panels and girts	7%	
	Fenestration (i = 3)	Windows, entry doors and overhead roller doors	4%	
Structural framing (i = 4)		Steel portal frames, end wall frames and bracing systems	37%	
Building Interior (i = 5)	Internal construction and finishes	Wall lining and flooring with finishes	6%	
	Mechanical	HAVC, plumbing and fire safety system	25%	
	Electrical	Lighting and power systems	9%	



(a) Flow velocity 2 m/s

(b) Flow velocity 5 m/s

Figure 3. Expected loss ratios (building vulnerability) for various flow directions, wind speeds, and inundation depths (flow velocity 2 and 5 m/s).

Figure 3 shows the building vulnerability for various wind speeds, inundation depths and flow directions considering surge flow velocities of 2 and 5 m/s. It suggests that the building vulnerability is generally increasing or non-decreasing with the wind speed, but not necessarily increasing monotonically with surge inundation depth due to the interdependencies between wind and surge loads, inundation level, fenestration damage and internal pressures.

5. Conclusions

Building vulnerability model was developed for steel portal framed industrial buildings under wind and storm surge hazards, which links building losses to wind speed, surge inundation depth, surge flow velocity and flow direction. The analysis results suggest that the complex interactions between wind and surge loads, inundation level, fenestration damage and internal pressures have significant impacts on building losses.

References

ASCE, 2017, "ASCE/SEI 7-16 Minimum design loads for buildings and other structures", American Society of Civil Engineer, Reston, VA, USA.

Do, T. Q., van de Lindt, J. W., & Cox, D. T. 2020. Hurricane surge-wave building fragility methodology for use in damage, loss, and resilience analysis. *Journal of Structural Engineering*, 146(1), 04019177.

FEMA, 2014, "Hazus Hurricane Model Technical Manual. Federal Emergency Management Agency", Mitigation Division, Washington DC, USA.

Ho, T. C. E., Surry, D., Morrish, D., & Kopp, G. A., 2005. The UWO contribution to the NIST aerodynamic database for wind loads on low buildings: Part 1. Archiving format and basic aerodynamic data. *Journal of Wind Engineering and Industrial Aerodynamics*, 93(1), 1-30.

Masoomi, H., van de Lindt, J. W., Ameri, M. R., Do, T. Q., & Webb, B. M., 2019. Combined wind-wave-surge hurricane-induced damage prediction for buildings. *Journal of Structural Engineering*, 145(1), 04018227.

Pham, L., 1987. Safety index analyses of tension members. *Civil Engineering Transactions*, Institution of Engineers Australia, CE29(2), 128-130.

Pham, L., & Hogan, T. J., 1986. Calibration of the proposed limit states design rules for bolted connections. *Civil Engineering Transactions*, Institution of Engineers Australia, CE28(4), 292-297.

Pham, L., Bridge, R. Q., & Bradford, M. A., 1986. Calibration of the proposed limit states design rules for steel beams and columns. *Civil Engineering Transactions*, Institution of Engineers Australia, CE28(3): 268-274.

Qin, H., & Stewart, M. G., 2019. System fragility analysis of roof cladding and trusses for Australian contemporary housing subjected to wind uplift. *Structural Safety*, 79, 80-93.

Qin, H., Mason, M., & Stewart, M. G. 2023. Fragility assessment for new and deteriorated portal framed industrial buildings subjected to tropical cyclone winds. *Structural Safety*, 100, 102287.

Rawlinsons, 2021, "Rawlinsons Construction Cost Guide 2021", Rawlinsons Publishing, Perth, Australia.

Standards Australia, 2012, "Garage doors and other large access doors", AS/NZS4505, Standards Australia.

Standards Australia, 2014, "Windows and external glazed doors in buildings", AS2047, Standards Australia.

Standards Australia, 2020, "Steel structures", AS4100, Standards Australia.

USACE, 2006, "Depth-Damage Relationships for Structures, Contents, and Vehicles and Content-to-Structure Value Ratios (CSVR) in Support of the Donaldsonville to the Gulf, Louisiana, Feasibility Study", US Army Corps of Engineers, LA, USA.