



Quantitative Method For Post-Windstorm Function of Community Shelters Considering The Impact of Urban Road Network

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Abstract

During strong windstorms in coastal cities, community shelters play a crucial role in reducing injuries and ensuring the basic living needs of citizens. However, previous studies mainly focus on the function assessment of healthcare systems during earthquakes, few studies discuss the post-windstorm functionality of community shelters. Thus, this study proposes a quantitative method for the post-windstorm function of community shelters considering the impact of urban road networks. In which, the refugee traveling time (RTT) and refugee admitted ratio (RAR) are introduced to quantify the post-windstorm functionality of community shelters. Both the networks of urban roads and community shelters are established using graph theory, and the wind-induced fragilities of urban road facilities are included to quantify the physical damages during windstorms, including tree/pole blow-down, damages on building envelopes, etc. Then, the population distribution and refugee generation models are also introduced. To determine accurate RTT and RAR, an efficient traffic flow allocation algorithm based on stochastic non-equilibrium assignment model are proposed to calculate the post-windstorm flows on urban roads. The proposed method can accurately and effectively quantify the post-windstorm functionality of community shelters, which can be applied on different cities and help improving urban resilience under wind hazards.

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Keywords

Windstorm; Community shelters; Refugee; Wind-induced fragility; Urban road network; Post-windstorm functionality

1. Introduction

In recent years, the economic losses and population injuries caused by strong windstorms have increased considerably and frequently in coastal cities. Such as the Hurricane Michael landing at the western Atlantic coast in 2018 and the Typhoon Lekima landing at the western Pacific coast in 2019, which caused transportation disruptions, water and power outages, and unsuitable living buildings in multiple regions of the United States and China, forcing tens of thousands of people to seek refuge in emergency shelters, ranging from a few days to several months (Roueche and Prevatt 2013; Huang and Wang 2024). Due to the capacity of the city shelter systems (CSS) after strong wind disasters is closely related to the ability to evacuate and transport people to shelters after strong wind disasters. Thus, it is necessary to carry out the capacity assessment of CSS after strong storm disasters to help quickly organize personnel to shelters, and minimize wind disaster losses and casualties as much as possible for the government.

A large number of previous studies focused on the function assessment of urban systems after extreme disaster events, including earthquakes, typhoons, tornadoes, floods, etc. (Nofal et al., 2023; Dong et al., 2022; Pei et al., 2023; Huang and Wang 2024; Anwar et al., 2022; Zhang et al., 2024). Among them, most studies are related to the function assessment of urban systems after earthquake disasters, and several scholars have conducted functional evaluation on network systems such as water supply, power supply, hospitals, and transportations after earthquake disasters (Amin and Padgett 2023; Nie et al., 2023; Liu et al., 2020; Yu et al., 2019). Several studies focus on evacuation plans through transportation systems under risks, but their consideration of physical damages to transportation systems is limited (Russo and Rindone 2024). The studies on windstorm disasters mainly focus on power supply and transportation systems, and most of them investigated on independent systems (Pei et al., 2023; Huang and Wang 2024). The CSS function under strong windstorms depends on urban road networks and shelters at the same time. After windstorms, refugees need to be transferred to shelters through the road network, and the space provided by shelters for refugees is generally limited. If a shelter is crowded with refugees, new refugees have to change their destination to another shelter and the overflow of refugees would be transferred once through the road network. The studies on function assessment of CSS considering the influences of coupled shelters and road networks after strong storm disasters are very limited.

The function assessment of CSS is similar to the post-disaster hospital capacity assessment, but compared to earthquake disasters, the main losses are living function loss of buildings during strong windstorms, and the function of CSS after strong windstorms will be affected by normal traffic flows. Given the lack of studies on the function assessment of CSS that considers the interdependence between urban shelters and road networks after strong windstorms. Thus, this study proposes a framework for the function assessment of CSS after strong windstorms. The proposed method can be applied to evaluate CSS function of any cities under strong windstorms, which can help the government make more reasonable decisions during post- and pre-windstorms to reduce wind-induced personnel and economic losses in coastal areas.

2. Quantitative Method For Post-Windstorm Function of Community Shelters

Given that previous studies usually neglect the interdependence between shelters and road networks, and there is no function assessment method for CSS after strong windstorms. Thus, this study establishes an assessment framework for CSS function considering the interdependence between shelters and road networks under strong windstorms by introducing graph theory and engineering fragilities, as shown in Figure 1. The key steps involved are as follows: (1) CSS topology model. Identify shelters and road networks through the GIS method, and simplify key facilities and road networks into nodes and links using graph theory. (2) Wind-induced engineering fragilities. Based on, conduct fragility analysis on the key infrastructures of the identified urban shelters and road networks. (3) CSS function indicators and assessment. Construct function indicators of CSS including the shelter efficiency and capacity under wind disasters, and conduct the function evaluation of CSS. The detailed contents are described from section 3 to section 5.

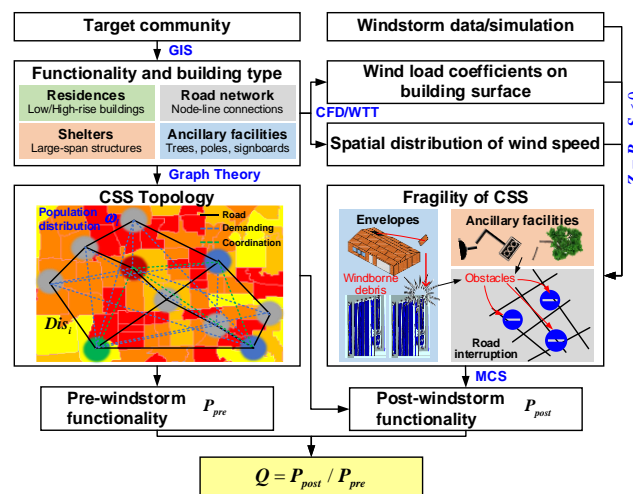


Figure 1 Framework of the post-windstorm function of community shelter system (CSS) (from authors)

3. Modeling The Interdependent Network Between Shelters and Urban Roads

To carry out the function assessment of CSS, the primary step is constructing a dual system network of shelters and road networks. Graph theory is often used to simplify the actual engineering systems into a topological structure model composed of nodes and links(Sharma and Gardoni, 2022; Bocchini and Frangopol, 2011), as shown in Figure 2. The required information for establishing a topology model includes the types of key infrastructures, the distribution of road networks, and the relationships between each key facility, such as road networks, sports venues, medical facilities, schools, etc. These data can be extracted through open-resource satellite maps.

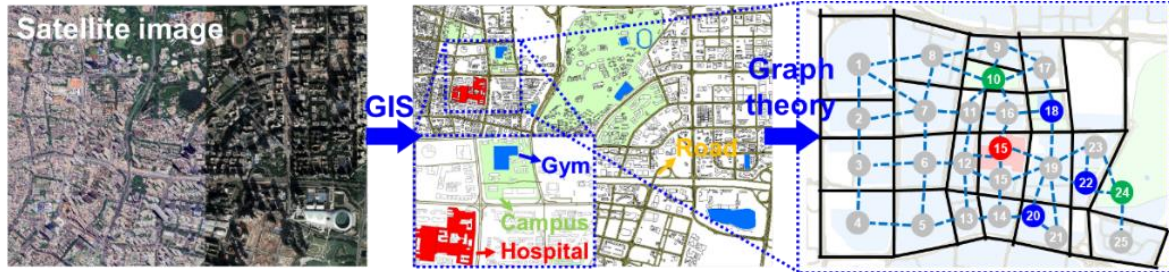


Figure 2 Topology network of CSS (from authors)

Based on the collected information from GIS, the topology model can be established by several matrixes using graph theory(Sharma and Gardoni, 2022), as shown in Figure 3. (1) Connection matrix, describing the matrix of key facility connection relationships; (2) Demand matrix, reflecting the evacuation needs of each node after a disaster; (3) Capacity matrix, reflecting the proportion of people that can be accommodated in shelters; (4) Traffic efficiency matrix, reflecting the traffic efficiency between different nodes. Normalized values are used for each matrix.

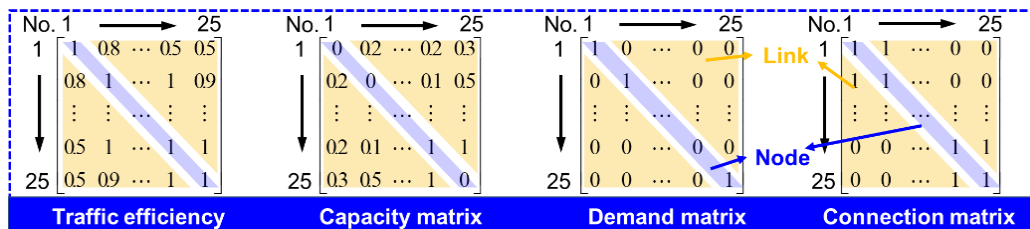


Figure 3 Topology matrixes (from authors)

4. Wind Hazards

To evaluate the emergency shelter function of cities after strong storms, it is necessary to determine the distribution of strong storm disaster fields in the city, and then determine the damage status of key facilities based on the vulnerability results of various key facilities in the network system, and then evaluate the network function status.

Wind Hazard Map

The distribution characteristics of wind speed fields at the urban community scale can be determined through wind tunnel tests(Chen et al., 2018) and computational fluid dynamics simulations(Wang and Wang, 2024). Considering the high cost of wind tunnel tests, this study uses CFD methods to determine the wind speed field distribution in the study area under different wind directions.

Wind-Induced Physical Damages

The variety of critical urban facilities means that conducting fragility analyses for each one can be time-consuming and computationally intensive. Therefore, this study categorizes common wind-induced fragilities into two main categories, as illustrated in Figure 4. (1) Wind-induced fragility of envelopes. Consider wind-induced damage to low rise building roof panels and damage to roof windows caused by wind-induced debris on the roof(Gu et al., 2023). (2) Wind induced fragility of ancillary facilities of road network(Gu et al., 2021; Wen and Xie, 2020; Panteli et al., 2017). The ancillary facilities of the road network only consider wind-induced damage to poles, billboards, and

roadside trees, and the damage mode only considers bottom bending failure. The state equations of wind-induced damage for each key facility are shown in Figure 4.

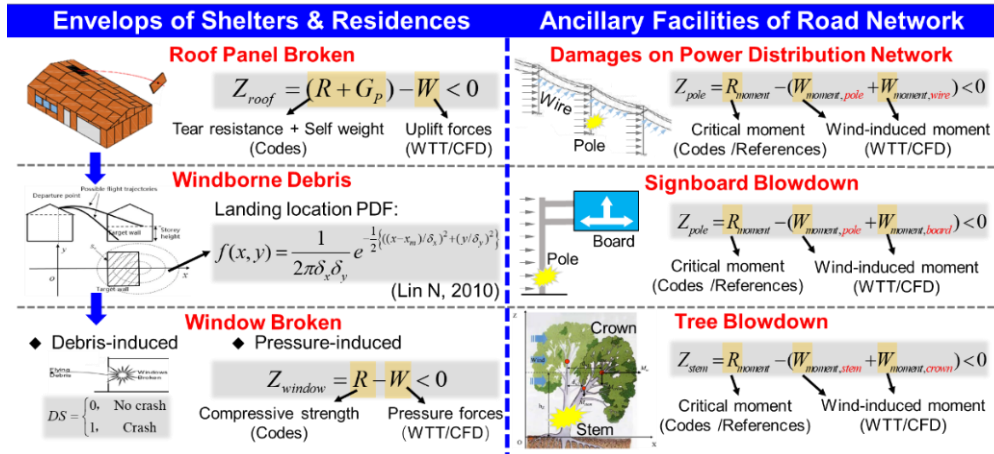


Figure 4 Wind-induced fragility models (from authors)

5. Functionality Loss of Community Shelter System

Evaluating the CSS function requires comprehensive consideration of various indicators. This study intends to use two types of indicators, namely shelter efficiency and venue capacity, to evaluate the emergency shelter function. By comparing the post disaster values of the two indicators with the initial state values, the final shelter system function indicator value Q is obtained, as shown in Figure 1.

5.1. Refugee Travelling Time (RTT)

Using the total travel time as the efficiency indicator for evacuees, as shown in equation (1). Where i represents the starting node of the i th group of refugees, j represents the j th shelter, S_{ij} represents the number of refugees from node i to node j , d_{ij} represents the shortest path length from node i to node j , and V_{ij} represents the travel speed from node i to node j . Actually, the majority of buildings are concrete and steel structures in China cities, and they are rarely damaged by windstorms. After a windstorm, only some nodes and routes may be interrupted due to physical damage of road ancillary facilities, the transportation system usually continues to operate with the reduced function. Which means that the normal transportation needs, such as the flow to work or to study, are still exist with the flow of refugees at same time after the windstorm, and the shelter needs account for a small proportion of total transportation needs. Based on above, the stochastic non-equilibrium assignment is used to calculate the traffic flow and speed of each line, and the Logit probability function is used in this paper. To evaluate the CSS function, the V_{ij} and d_{ij} of the shortest path from node i to node j (j is the shelter node) to define the Refugee travelling time indicator as shown in equation (1). In which, V_{ij} is determined by the stochastic non-equilibrium assignment.

$$P_{initial/post}^{RTT} = \sum_{i=1}^N \sum_{\substack{j=1 \\ j \neq i}}^M S_{ij} \frac{d_{ij}}{V_{ij}} \quad (1)$$

5.2. Refugee Admitted Ratio (RAR)

Using the ratio of the number of refugees to the capacity of the venue as another evaluation indicator, as shown in equation (2). Where j represents the j th shelter, S_j represents the total number of refugees arriving at node j , and R_j represents the capacity of the shelter at node j . To consider the impact of strong storm disasters, the capacity of emergency shelters and the number of refugees generated after the windstorms are continuously updated to update the capacity of refugees.

$$P_{initial/post}^{RAR} = \sum_{j=1}^M \frac{S_j}{R_j} \quad (2)$$

6. Conclusions

Considering the significant economic and human losses often experienced in coastal cities during severe storm events, it is necessary to evacuate large numbers of people to emergency shelters to minimize these losses. However, there is a paucity of research evaluating the effectiveness of urban emergency shelter functions specifically in the context of wind disasters. Thus, this study proposes a quantitative method for post-windstorm function of community shelters considering the impact of urban road network. In which, the refugee travelling time (RTT) and refugee admitted ratio (RAR) are introduced to quantify the post-windstorm functionality of community shelters. Both the networks of urban roads and community shelters are established using graph theory, and the wind-induced fragilities of urban road facilities are included to quantify the physical damages during windstorms, including tree/pole blow-down, damages on building envelopes, etc. Then, the population distribution and refugee generation models are also introduced. To determine accurate RTT and RAR, an efficient traffic flow allocation algorithm based on stochastic non-equilibrium assignment model are proposed to calculate the post-windstorm flows on urban roads. The proposed method can accurately and effectively quantify the post-windstorm functionality of community shelters, which can be applied on different cities and help improving urban resilience under wind hazards.

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The authors declare that there is no competing interest.

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