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Component-based Vulnerability of Large Facilities

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SUMMARY:
Large facilities have many components. Unlike many residential or commercial structures, different components have highly variable damageability, may be located outside, inside or mixed location and the value of the machinery, mechanical and electrical equipment may far exceed the value of the structure itself. For these types of facilities, considering the more traditional aspects of damageability (e.g., roof covering, cladding, main structural system, etc.) will not accurately capture the overall vulnerability of the facility. In order to accurately assess the overall vulnerability of different types of large industrial facilities, a component-based methodology was used. This methodology considers the unique vulnerability, interaction between components and the proportion of overall loss (value) for each component by combining component-level vulnerabilities to an overall facility level vulnerability to extreme winds.

Keywords: Wind Damage, Vulnerability, Industrial Facilities

1. LARGE FACILITIES

Large, high value facilities such as oil refineries and airports represent large potential losses for wind damage. The value and extent of these facilities can drive the loss for an entire event. For example, consider the facility in Lake Charles Louisiana which ignited after Hurricane Laura in 2020, or the oil, gas and port facilities at Port Fourchon, Louisiana, directly in the path of Hurricane Ida in 2021. Physical damage, lack of accessibility and safety shutdowns at these facilities causes widespread effects, often felt nationwide as gas prices rise.

Most residential and commercial structures are definable as buildings by relatively conventional means, such as having a roof and walls. While the office, warehouse and other structures at a given large industrial facility follow the same convention, many parts of these facilities, such as conveyors and storage tanks, have more nuanced components and different failure modes.

Large industrial facilities are also not usually defined by one primary structure and associated appurtenant structures. These facilities are comprised of many different types of structures. When considering the vulnerability of the facility as a whole, the vulnerability of each individual component must be considered as a part of the whole. This represents a different way of considering catastrophe modelling than modelling of other residential or commercial structures. A component-based methodology was developed, considering the vulnerability and damageability of key components of various large industrial facility types.

2. COMPONENT-BASED METHODOLOGY

In order to correctly identify the components of various facility types, detailed research was conducted into these facilities. For each component a value weight relative to the reset of the facility was also determined. This is important because it can significantly govern the performance of that facility overall for wind or other perils. As a case study, consider a large airport, which can be simplified to the components listed in the table below. Runways, which do not expect significant wind damage, constitute a significant portion of the total value of the airport, which would reduce the maximum expected airport-wide damage ratio. However, other natural hazards can significantly damage components with little to no vulnerability to wind and impact facility operation. For example, at the Oakland airport after the Loma Prieta earthquake in 1989, significant liquefaction damage to one runway caused flight delays and excess repair costs.

Table 1. Value weights for airport components

Component	Value Weight
Apron + Tarmac	15%
Airport Access Roads	1%
Air Traffic Control Tower	17.5%
Tank	5%
Hangers	2%
Airport Lighting - Runway & Taxiway	2.5%
Airport Lighting - Above Ground	5%
Parking	2%
Airport Runways	45%
Building - Airport Terminal	5%

The component-based methodology used considered the vulnerability of each individual component of these large facilities separately, using analytical damage-mechanism modelling. The component level damage was then aggregated to a facility level considering the types of damage expected and the value of that component within the facility.

3. ANALYTICAL MODELING OF DAMAGE MECHANISMS

Vulnerability of each component was developed by considering up to 18 damage mechanisms for each component, including collapse, yield, water damage, debris damage, and different aspects of structural damage: cladding, roof cover, interior, etc. Damage due to various mechanisms was developed by building analytical damage models as well as considering existing analytical models such as the wind-borne debris model from Stedman and Vojjala (2017).

One example of an analytical damage model directly applicable to an airport is for the buckling or yielding of fuel tanks. Many airports, particularly larger airports, have fuel reserves stored in onsite tanks. These tanks are not always guaranteed to be in the same state at any given time, and the amount of fuel in the tank has a direct effect on the probability of buckling or collapse. While similar, tanks at different airports or even different tanks within the same airport have different designs. Some tanks may have reinforcement rings on the inside. Other tanks may be designed with floating roofs instead of fixed roofs. These design differences can have large effects on the damageability. For example, floating roof tanks are more likely to have a roof failure where differential roof pressures cause the roof to start tipping, which causes any accumulated precipitation to move to the lower side, compounding differential loading and potentially leading to complete failure of the tank. To capture the large possible range of damage and construction expected, the analytical modelling considers different possible configurations and then assigns a probability of a tank having that type of construction. While resulting in an overall mean expected damage by wind speed, it also provides a range of possible damage at a given wind speed.

4. FACILITY-LEVEL DAMAGE

Analytical-based vulnerability curves were developed for more than 100 different components commonly found at large facilities. However, the weights of each component – as presented in Table 1, cannot directly be used with each component. At each facility type, the installation or type of that component will be different than the baseline developed in the analytical model. Sticking with the airport example, even at different sized airports, the construction of a control tower is expected to be different, as shown in Figure 2.

Figure 1. Comparison of air traffic control towers at large and small airports, Miami, USA (LEFT) and Marsh Harbor, Bahamas (RIGHT)

Similarly, fabrication equipment at a manufacturing facility will vary quite significantly in damageability. Even if the equipment is generally the same, different facilities and facility types have different tolerances for acceptable damage as well as requirements for repair vs replacement. In Puerto Rico, there are many large pharmaceutical facilities. If the products or indoor equipment are damaged by precipitation, the probability of replacement is high due to high cleanliness standards and medical regulatory requirements. While this is similar across all the plants, the actual construction, assembly and protection from envelope breach is variable between such facilities on the island.

A challenge of a component-based methodology for large facilities is the number of unique components that are susceptible and contribute to losses from wind damage compounded by the fact that even the same components can have significant variations between different facilities (e.g., using the same component vulnerability does not work across multiple facilities). To account for this variation, an additional adjustment factor was included, such as machine technology level or structure quality. Developed using the same analytical models and framework as the component vulnerability, these adjustment factors are used to adjust the vulnerability of the same component at different facility types, allowing for enhanced vulnerability differentiation while controlling the size of the component list. Considering each component type and weight at each individual facility, an overall vulnerability by facility type can be assembled.

5. VALIDATION

Detailed validation studies were performed to confirm that the resulting large facility vulnerability is reasonable. Due to a lack of extensive and detailed claim loss data, as is commonly used for validation in catastrophe modelling, a different approach was taken. For many of these facilities, overall locations and facility types are known. This is particularly true for airport locations. The wind speed at each of these locations was determined for several large, recent events such as: Charley, Frances, Harvey, Irma and Ida. Knowing the wind speeds at each facility, targeted research was done looking for damage reports for specific facilities subjected to higher wind speeds. When available, verifiable published data on expected damage was also used as a validation.

Expected tank farm damage is compared with damage reports as well as U.S. Department of Energy published guidelines (2014) in Figure 2. The D.O.E. guidelines are presented with error bars as they only provide an overall damage state, which could be a range of overall damage levels. It is important to note for this figure that the damage reports are estimated site-specific damage ratios, which have significant uncertainty and represent a single location. The facility-based vulnerability curve represents a mean across all such facilities subjected to the same wind speed. As there were many facilities with no damage or no damage report, the initial damage estimates recorded were adjusted by a frequency factor, based on the number of facilities/tanks affected by that wind speed vs the number of reports of damage found, making the comparison between the two more accurate.

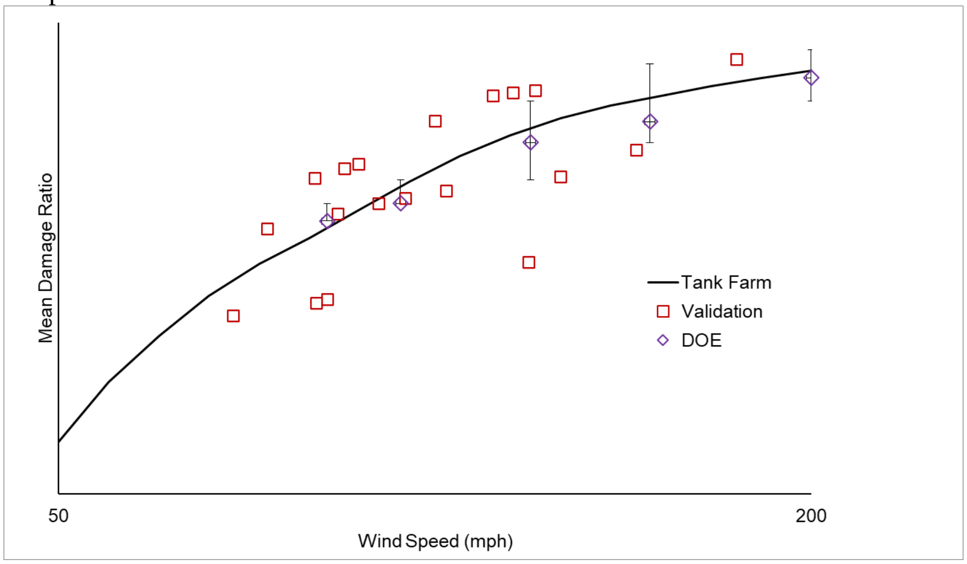

Figure 1. Component-based vulnerability for a Tank Farm facility compared with available validation points.

6. CONCLUSION

A detailed methodology was developed to build and validate vulnerability functions for large, high value facilities. The methodology considers detailed analytical modelling of the damage mechanisms expected to affect the components of each facility. Each component is then considered as a part of the whole facility. Validation of the resulting facility vulnerability showed a reasonable fit to available data. It is important to accurately quantify the vulnerability of these high-value facilities as damage can cause significant losses to all stakeholders, and for facilities like oil refineries or power generating facilities, cause rippling effects across entire regions/countries.

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