August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering
ICWE 16

Fragility-based sensitivity analysis framework for load paths subjected to wind hazards

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SUMMARY: A framework is presented for evaluating the sensitivity behavior of parameters in a structural load path with respect to wind hazard analytical fragilities. A preliminary analysis applies the framework to a vertical light wood-frame load path. A variance-based sensitivity analysis method is employed to compute first-order sensitivity indices of all input parameters on the basis of load path system resistance, fragility median, and fragility standard deviation. The results indicate that a sensitivity analysis predicated on fragility median provides a reasonable description of load path parameter influence and may serve as a useful complementary tool alongside traditional load path fragility approaches. The framework can be useful for identifying which fragility model parameters are most essential out of a broader suite of possible parameters, and for offering guidance to reconnaissance efforts for focusing on the most influential perishable data to capture following extreme hazard events.

Keywords: fragility analysis, sensitivity analysis, wind load path

1. INTRODUCTION

Development of analytical fragility curves from probabilistic load and resistance models is a common practice in performance-based wind engineering (Ellingwood et al., 2004; Amini and van de Lindt, 2014). Fragility assessment results have been applied in a number of ways, but to this point no study has interpreted fragilities through the lens of global sensitivity analysis, which offers a way to characterize the relative influence of input parameters in a model with respect to a model output quantity. The purpose of this study is to demonstrate a general framework for conducting a sensitivity analysis of structural load path parameters that is based on analytical fragility curves obtained for the load path. In this analysis, fragilities are developed for a detailed analytical model of the vertical load path wind resistance in a light wood-frame structure, but the framework can be similarly applied to other types of structures subjected to other hazards.

2. METHODS

The analysis consists of the following three stages. (1) Load path system-level resistance is computed as the minimum resistance in an equivalent load chain of series components. (2) Fragilities are developed from the load path resistance model output and a suitable wind load model. (3) A variance-based sensitivity method is applied to the set of fragilities to characterize the relative impact of each load path property on system fragility.

2.1. Load path resistance model

The resistance model is developed by transforming the vertical load path into an equivalent load chain composed only of connections in series. A more detailed description of this modeling approach is provided in Rittelmeyer and Roueche (2022). The procedure involves the following steps. (1) The uplift resistance of each connection is taken as the sum of connection ultimate capacity and cumulative dead load, where ultimate capacities are computed either from LRFD-based strength equations given in applicable design specifications or from a comparable mechanics-based model. Resistances are expressed in terms of force per unit length of wall. (2) Capacities of parallel connections, such as stud-plate and overlapping wall sheathing connections, are summed to form a chain of series connections. (3) After consolidating parallel connections, the system-level uplift resistance of the load path is taken as the resistance of the weakest connection in series. The input parameter set includes all structural and material properties needed to compute connection resistances; distributions may be continuous or discrete and numerical or categorical.

2.2. Fragility analysis

The fragility analysis considers the limit state function g expressed by Eq. (1) for a wind uplift pressure W and system-level wind uplift resistance R_s.

$$g = R_s - W \tag{1}$$

where the resistance term R_s in Eq. (1) is computed using the procedure outlined above and normalized by the along-slope length of the roof tributary area. The wind load model is based on ASCE 7-22 design provisions, with wind pressures W [N/m^2] computed as a function of wind speed V [m/s] according to Eq. (2).

$$W = 0.613 K_z K_d V^2 (GC_p - GC_{p_i}) \tag{2}$$

where the exposure coefficient K_z, directionality factor K_d, gust-effect factor G, external pressure coefficient C_p, and internal pressure coefficient GC_{pi} are normally distributed variables with means adjusted from nominal design values in accord with previous studies (Ellingwood and Tekie, 1999). Each fragility curve is developed for a deterministic value of R_s, corresponding to one load path realization; this approach produces a set of n fragility curves with a composite mean and variance comparable to those of a single fragility curve generated using n samples of resistance (Shinozuka et al., 2000) but which conveys the variation in performance of different realizations. The logarithmic median λ and standard deviation ξ of each curve are computed with Eqs. (3)-(4).

$$\lambda = \ln V_{50} \tag{3}$$

$$\xi = \ln V_{84} - \ln V_{50} \tag{4}$$

where V_{50} and V_{84} are the wind speeds corresponding to 50% and 84% probabilities of failure.

2.3. Sensitivity analysis

Variance-based sensitivity methods, or Sobol' methods, decompose the variance in a model output quantity and apportion it to the model input parameters according to their relative influence (Saltelli et al., 2008). In a variance-based framework, the first-order effect or main effect of input

x_i on output y is represented by the first-order sensitivity index S_i, defined according to Eq. (5).

$$S_i = \frac{V(E(y \mid x_i))}{V(y)} \tag{5}$$

The numerator in Eq. (5) is the variance of the conditional expectation of y with respect to x_i, which represents how the expected value of y changes as a function of x_i. The denominator is the unconditioned variance of y, so that S_i takes a value between 0 and 1, indicating what fraction of the output variance is contributed by input x_i, not including interaction effects with other inputs. The method applied in this analysis is a random balance design (Tarantola et al., 2006), which estimates first-order indices from Fourier spectra computed on n model evaluations.

3. RESULTS

Illustrative results for a light wood-frame structure on a masonry pier foundation are presented in Fig. 1. Sensitivity indices S_i for a subset of the load path attributes that comprise the input parameter set are calculated with respect to system resistance R_s and fragility curve parameters λ and ξ for 5,000 load path realizations. Fig. 1(*b*) depicts lognormal-fitted fragility curves for ten realizations generated at random, a representative sample of the full set of fragilities. Distributions of λ and ξ for all realizations are plotted in Fig. 1(*c*) and (*d*).

S_i computed for R_s and λ agree in their identification of the most influential inputs, with some variation in the precise rankings. In this case, attributes like roof-to-wall connection type, wall framing wood species, roof member spacing, and wall sheathing overlap substantially affect the capacities of the characteristic weak links in the load path, primarily the roof-to-wall and double top plate connections. In terms of the histogram of λ in Fig. 1(*c*), the influential inputs are those which contribute the most variability to the distribution. The sum of S_i for the six most influential attributes in the input set is 0.54 when computed for λ; the analysis thus estimates that, for this load path archetype, more than half the variability in fragility median is contributed by these six attributes alone. For all attributes that are either deterministic or otherwise expected to be non-influential, S_i is negligible. By contrast, S_i computed relative to ξ are not meaningfully different from one another. This signals that all inputs contribute similar levels of variability to ξ at the first order and are thus similarly non-influential with respect to fragility variance.

4. CONCLUSIONS

The results presented here demonstrate how an analytical fragility approach can be joined with a global sensitivity analysis method to evaluate input parameter influence on system fragilities. Variance-based sensitivity indices computed with respect to median failure wind speed provide a reasonable characterization of the most influential attributes for wind uplift performance in a light wood-frame load path. The same sensitivity measure is negligible for all attributes when computed with respect to fragility variance, indicating that the distribution of variance in a set of fragilities is not strongly affected by one input over another. The framework offers a new perspective on traditional fragility modeling and holds promise as a useful tool for failure risk analyses of all manner of wind-impacted structures.

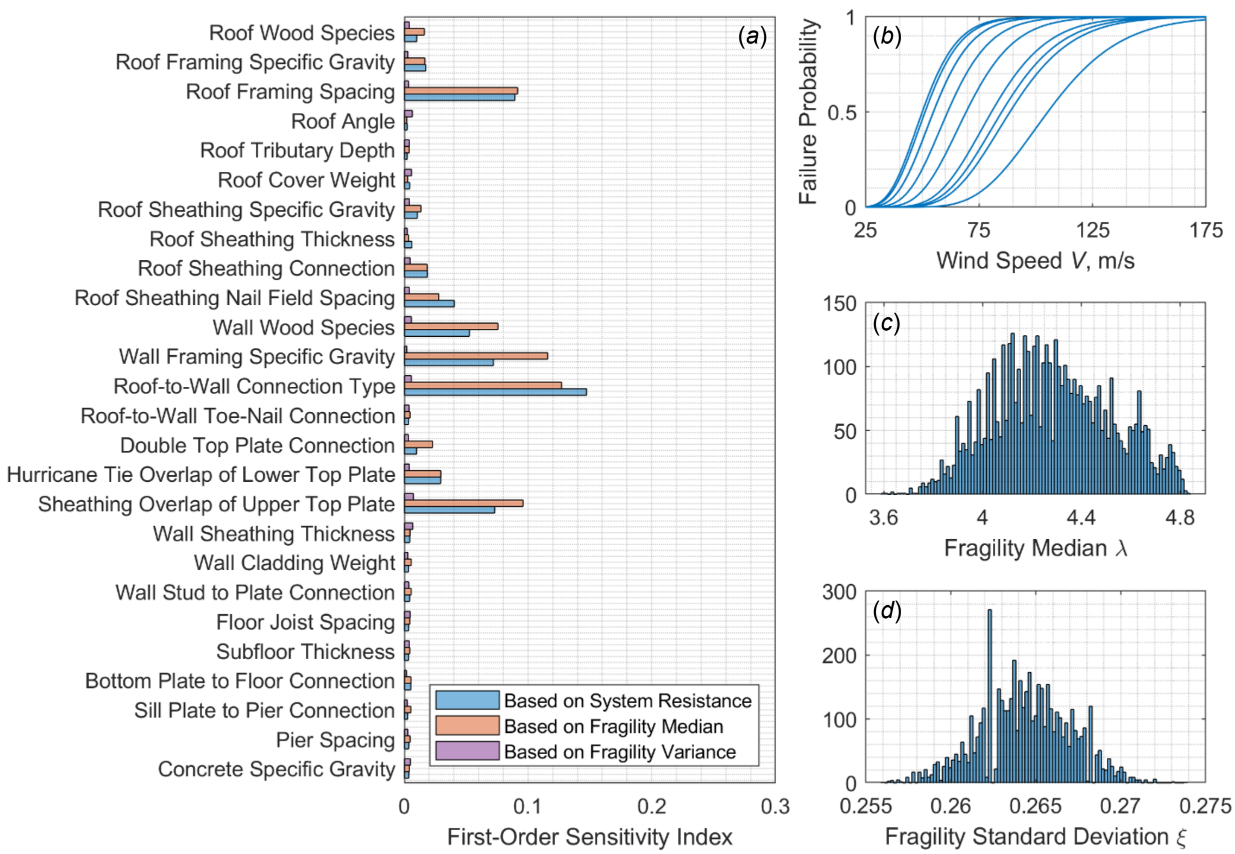

Figure 1. Analysis results for a light wood-frame structure on a pier foundation: (*a*) sensitivity indices S_i computed with respect to system resistance R_s, fragility median λ, and fragility standard deviation ξ for 5,000 realizations; (*b*) a random subset of system fragility curves generated; and distributions of (*c*) λ and (*d*) ξ for all fragilities.

ACKNOWLEDGEMENTS

This work is supported by the National Science Foundation under Grant No. CMMI-1944149. Any opinions, findings, and conclusions expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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