14th Americas Conference on Wind Engineering
May 17-19, 2022 – Lubbock, TX
National Wind Institute – Texas Tech University

Global Sensitivity Analysis Framework for Vertical Load Path Resistance in Wood-Frame Residential Structures

Brandon M. Rittelmeyer [a], David B. Roueche [b]

[a] *Auburn University, Auburn, Alabama, United States, bmr0036@auburn.edu*
[b] *Auburn University, Auburn, Alabama, United States, dbr0011@auburn.edu*

ABSTRACT: This study presents a framework for global sensitivity analysis of wind uplift resistance in wood-frame residential structures. The vertical load path is modeled probabilistically as an assemblage of connections, with resistance distributions based on connection design capacity and cumulative dead load. An established sensitivity analysis approach is applied to the load path resistance model to evaluate the influence of the input parameter set on the system resistance, which is taken as the resistance of the weakest connection in series. A preliminary analysis illustrates the potential of the framework as a useful tool for assessing the relative importance of structural attributes for wind resistance, adaptable to any arbitrary vertical load path and parameter set. The framework also facilitates the evaluation of the relative vulnerability of different load path configurations from structure to structure.

KEYWORDS: Field Reconnaissance, Light Wood-Frame, Sensitivity Analysis, Wind Load Path

1 INTRODUCTION

The essential task of post-storm field reconnaissance is to document structural damage levels for the purpose of understanding how and why wind-related structural failures occur and how damage can be mitigated in future events (Henderson et al., 2021). Within this scope of work, reconnaissance efforts have an interest in establishing the wind resistance of representative structures through detailed structural assessments. Because reconnaissance teams are afforded limited time to conduct door-to-door assessments, data collection must be prioritized to ensure that the most important structural attributes for characterizing wind resistance are recorded. Probabilistic modeling of load path resistance offers one avenue for analysis of attribute influence. Past studies have applied probabilistic models of wind resistance in the context of reliability assessments, analyzing both component-level performance, such as for roof sheathing and roof-to-wall connections (Lee and Rosowsky, 2005; Rosowsky and Cheng, 1999), as well as system-level performance of roof structures (Ellingwood et al., 2004; van de Lindt and Dao, 2009; Amini and van de Lindt, 2014; Masoomi et al., 2018) and vertical load paths composed of roof system connections and wall-to-foundation connections (Standohar-Alfano et al., 2017). However, such studies rely on relatively simple models of the vertical load path that do not explicitly account for the many different individual connections of which it is composed. Further, while failure risk analyses like these take into account models of both load and resistance, a methodology that considers only models of resistance in a sensitivity analysis context can provide a means of highlighting the model variables that most impact overall wind resistance, and better segregate the causal factors the relative wind performance of low-rise buildings.

The objective of this study is to demonstrate a sensitivity analysis framework for identifying the most influential parameters for vertical load path resistance in wood-frame residential structures. The proposed framework is intended for use as an adaptable analysis tool, applicable to any vertical load path that may be encountered in field reconnaissance. The framework thus provides a way to assess the importance of each attribute in an arbitrary vertical load path and thereby offer guidance for setting priorities in field data collection, as well as establish a method for identifying disproportionate capacities along the load path.

2 METHODS

The framework presented in this study consists of a probabilistic model of vertical load path resistance set within a Monte Carlo-based sensitivity analysis method. The sensitivity method (Saltelli, 2002) characterizes the relative influence of a set of k parameters on a model output quantity y by evaluating the model for an n by k set of parameter values. The load path resistance model, developed by the authors, provides the model on which the Saltelli sensitivity method operates.

2.1 *Vertical Load Path Resistance Model*

The vertical load path in a typical residential structure may be illustrated as in Figure 1, which depicts the exterior wall framing in a single-story structure on two foundation types. The load path is made up of an assemblage of connections through which wind uplift forces are transmitted from the roof to the foundation. The load path may be modeled as a chain, the overall strength of which is limited by the weakest link in series.

On this view, the following resistance modeling approach is adopted in this study. (1) Uplift resistance of individual connections is taken as the sum of design capacity and cumulative dead load. Design capacities are computed from LRFD-based strength equations provided in applicable design specifications, such as the withdrawal capacity and lateral capacity formulas prescribed in the AWC *National Design Specification* for nailed timber connections. For additivity, resistances are expressed in terms of force per unit length of wall. (2) To form a load chain of connections in series, capacities of parallel connections are summed. As an example, the nailed connection between the wall stud and the wall bottom plate is a relatively weak link intrinsically, limited by withdrawal capacity in wood end-grain, but the capacity of the local wall sheathing connection substantially improves the uplift resistance at this point. Accordingly, the uplift capacity of the composite connection is computed approximately as the sum of the withdrawal capacity of the stud-plate connection and the lateral capacity of the local sheathing connection. (3) After consolidating all parallel connections, the overall uplift resistance of the load path is taken as the resistance of the weakest connection in series. The input parameters needed to compute connection resistances are represented by a combination of continuous and discrete distributions, at present defined to encompass the range of options used in common residential construction practice encountered in the Southeastern United States, but the approach is scalable elsewhere. A representative parameter set is summarized in Tables 1-3, which contain parameter distributions for the roof system, wall system, and floor and foundation system of the load path illustrated in Figure 1. Some input parameters, such as roof cover weight, are modeled by continuous distributions. Most parameters are assigned discrete distributions, either numerical, as in roof structure spacing, or categorical, as in roof structure type. Certain parameters are coupled; the mean specific gravity of the roof system, for example, is tied to the categorical value selected for the roof wood species, such that if "Douglas Fir-Larch" is selected as the species, the specific gravity is drawn from a normal distribution with a mean of 0.50.

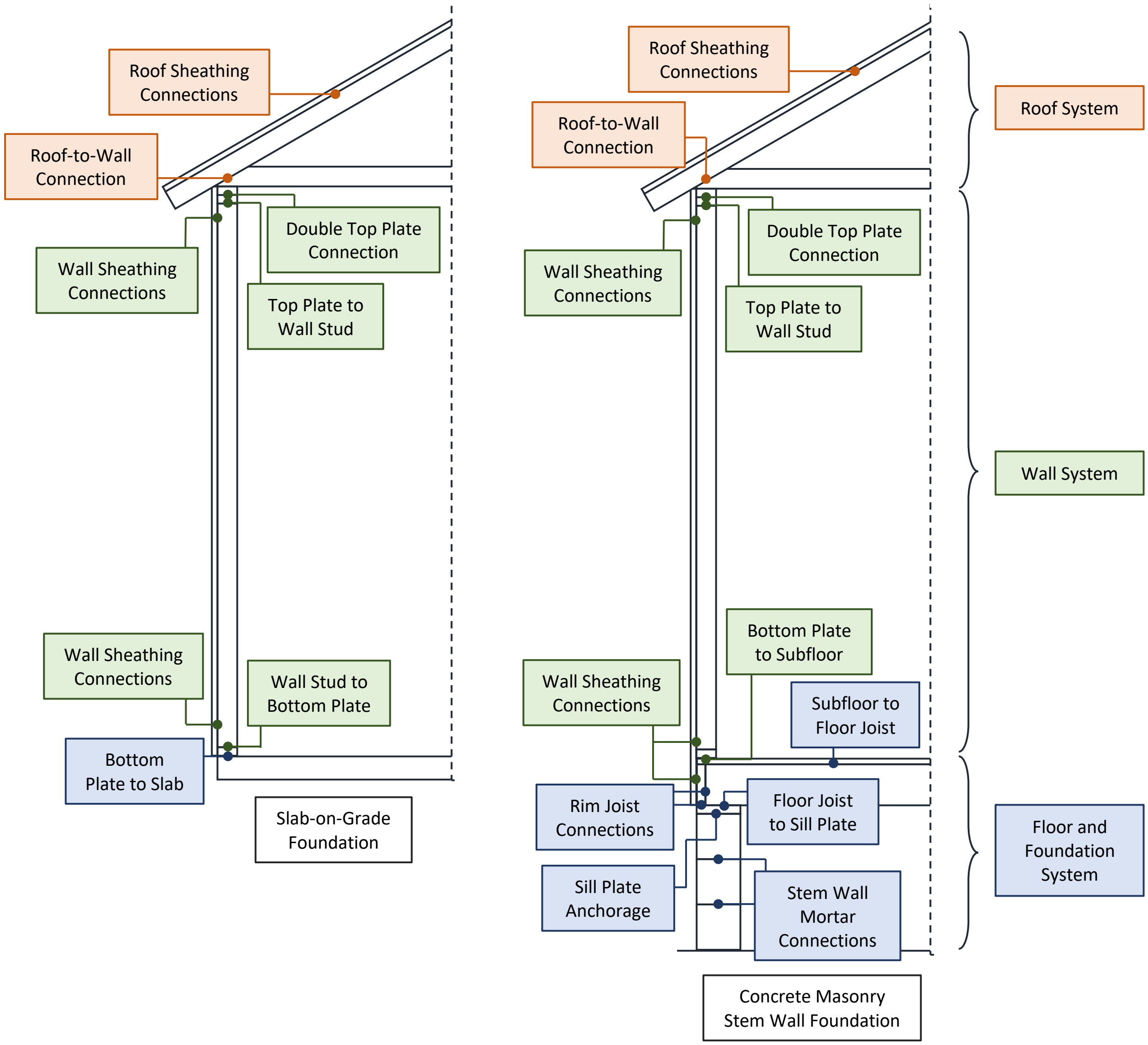

Figure 1. Exterior wall framing for a typical residential structure built on (a) a slab-on-grade foundation and (b) a stem wall foundation, illustrating the connections composing the vertical load path.

Of the categorical parameters, some serve as system-level decision variables, such as the foundation system type, which controls which foundation type is present in the load path. The value taken by a decision variable nullifies all incompatible downstream parameters; if the foundation system type is chosen as “Slab-on-Grade”, for example, all parameters that assume a stem wall foundation are disregarded in that simulation. Connection parameters are another special class of categorical variable that determine fastener configurations from a list of possible options; the illustrative distributions listed in Tables 1-3 differentiate connection options by fastener size, but other fastener attributes can be encoded within connection parameters as well, including number of fasteners and nail shank texture. The nailed connection options included in Tables 1-3 represent fastener schedules prescribed in the *International Residential Code* for different framing connections.

All discrete distributions are assumed uniform by default. For cases where the possible values in a distribution are not all equally likely to occur in ordinary construction practice, the input file system developed for use in this modeling framework allows for weights to be assigned to values in each distribution. In the wall stud spacing distribution, for instance, the typical spacing of 16 in. [0.41 m] is assigned a weight of 95%, with the remaining 5% divided between the less common spacings of 12 in. [0.30 m] and 24 in. [0.61 m]. For brevity, distribution weights assumed in this preliminary analysis are not listed in Tables 1-3.

Table 1. Vertical load path parameters: roof system

Parameter	Distribution	Units	Value Range
Roof Wood Species	Discrete		"Douglas Fir-Larch", "Hem-Fir", "Southern Pine", "Spruce-Pine-Fir"
Roof Specific Gravity	Normal		Mean: 0.50, 0.43, 0.55, 0.42 Coefficient of Variation: 0.12
Sheathing Specific Gravity	Normal		Mean: 0.42, 0.50 Coefficient of Variation: 0.10
Roof Angle	Discrete	deg.	18, 19, …, 44, 45
Roof Structure Spacing	Discrete	in. [m]	12, 16, 20, 24 [0.30, 0.41, 0.51, 0.61]
Roof Structure Type	Discrete		"Ceiling Joists and Roof Rafters", "Roof Trusses"
Roof Sheathing Thickness	Discrete	in. [mm]	7/16, 1/2, 9/16, 5/8 [11, 13, 14, 16]
Roof Tributary Depth	Discrete	ft. [m]	6.0, 6.1, …, 17.9, 18.0 [1.83, …, 5.49]
Roof Cover Weight	Normal	lb/ft.^{2} [kPa]	Mean: 5.00 [0.24] Coefficient of Variation: 0.10
Roof Sheathing Connection	Discrete		"8d Common", "10d Common", "8d Box", "10d Box"
Roof-to-Wall Connection Type	Discrete		"Toe-Nails", "Hurricane Tie"
Ceiling Joist to Rafter Connection	Discrete		"8d Common", "10d Common", "8d Box", "10d Box"
Roof-to-Wall Toe-Nail Connection	Discrete		"10d Common", "16d Box"

Table 2. Vertical load path parameters: wall system

Parameter	Distribution	Units	Value Range
Wall and Floor Wood Species	Discrete		"Douglas Fir-Larch", "Hem-Fir", "Southern Pine", "Spruce-Pine-Fir"
Wall Specific Gravity	Normal		Mean: 0.50, 0.43, 0.55, 0.42 Coefficient of Variation: 0.12
Wall Timber Shear Strength	Normal	lb/in.^{2} [MPa]	Mean: 180, 150, 175, 135 [1.24, 1.03, 1.21, 0.93] Coefficient of Variation: 0.10
Wall Stud Height	Discrete	in. [m]	96, 108 [2.44, 2.74]
Wall Stud Spacing	Discrete	in. [m]	12, 16, 24 [0.30, 0.41, 0.61]
Wall Sheathing Thickness	Discrete	in. [mm]	7/16, 1/2, 9/16, 5/8 [11, 13, 14, 16]
Wall Cladding Weight	Normal	lb/ft.^{2} [kPa]	Mean: 5.00 [0.24] Coefficient of Variation: 0.10
Sheathing Overlap [Upper Top Plate]	Discrete		"True", "False"
Wall Stud to Top Plate Connection	Discrete		"16d Common", "16d Box"
Wall Stud to Bottom Plate Connection	Discrete		"16d Common", "16d Box"

Table 3. Vertical load path parameters: floor and foundation system

Parameter	Distribution	Units	Value Range
Foundation System Type	Discrete		"Concrete Masonry Stem Wall", "Slab-on-Grade"
Bottom Plate to Slab Connection	Discrete	in. [mm]	Bolt Diameter: 3/8, 1/2, 5/8 [9.5, 12.7, 15.9]
Slab Bolt Spacing	Discrete	ft. [m]	3, 4, …, 7, 8 [0.91, 1.22, …, 2.13, 2.44]
Floor Joist Spacing	Discrete	in. [m]	12, 16, 20 [0.30, 0.41, 0.51]
Subfloor Thickness	Discrete	in. [mm]	7/16, 1/2, 9/16, 5/8 [11, 13, 14, 16]
Bottom Plate to Subfloor Connection	Discrete		"16d Common", "16d Box"
Wall Sheathing Overlap [Rim Joist]	Discrete		"True", "False"
Rim Joist to Sill Plate Connection	Discrete		"8d Common", "8d Box", "10d Box"
Sill Plate to Stem Wall Connection	Discrete	in. [mm]	Bolt Diameter: 3/8, 1/2, 5/8 [9.5, 12.7, 15.9]
Concrete Masonry Specific Gravity	Normal		Mean: 2.00 Coefficient of Variation: 0.05
Stem Wall Grouting Index	Discrete		"Ungrouted Cells", "Fully Grouted Cells"
Stem Wall Mortar Type	Discrete		"Masonry-Cement Mortar", "Cement-Lime or Mortar-Cement Mortar"

2.2 *Sensitivity Analysis*

The general objective of sensitivity analysis is to characterize the relative importance of the input parameters in a model, distinguishing the parameters that are strongly influential with respect to the model output from those that have little influence. Within the domain of sensitivity analysis, global sensitivity methods (Saltelli et al., 2004; Saltelli et al., 2008) involve exploration of the entire parameter space, as opposed to local sensitivity methods that return information useful only within a localized region of the parameter space. Several classes of global sensitivity analysis methods have been developed in recent decades, among which are variance-based methods. This class of methods, built on the concept of variance decomposition (Saltelli et al., 2008), evaluates the relative contribution of each input parameter to the variance in the model output, where more influential parameters have a greater effect on output variability.

Sensitivity measures can be defined in a number of ways within a variance-based framework. Two such measures are the first-order sensitivity index S_i and the total-effects index S_{Ti}, which Saltelli et al. (2008) define according to Equations 1 and 2:

$$S_i = \frac{V(E(y \mid x_i))}{V(y)} \tag{1}$$

$$S_{T_i} = 1 - \frac{V(E(y \mid \mathbf{x}_{\sim i}))}{V(y)} \tag{2}$$

The numerator in Equation 1 represents the change in the variance of output y as parameter x_i is held constant while the set of remaining parameters $\mathbf{x}_{\sim i}$ is free to vary. The numerator in Equation 2 is similarly the variance of output y conditioned on all parameters except x_i. In concise terms, S_i reflects the direct influence of input x_i on output y, while S_{Ti} reflects the influence of x_i through its interactions with other parameters. As ratios of variance, S_i and S_{Ti} always take a value between 0 and 1. Saltelli et al. (2008) have argued that the set of $2k$ indices containing the S_i and S_{Ti} terms for a model involving k parameters provides an adequate and informative picture of the sensitivity behavior of the model.

Saltelli has developed a Monte Carlo-based method for generating sensitivity indices for an arbitrary numerical model composed of k parameters and yielding a single output quantity y. The steps involved in the method can be found in Saltelli, 2002. Briefly, the method begins with an n by $2k$ sample set of random numbers, in which the numbers are commonly taken from quasi-random sequences, such as the Sobol' sequence, because of the established numerical advantage of using more orderly sampling strategies in sensitivity applications (Saltelli, 2008). The model is evaluated for a set of $k + 2$ matrices formed from the sample set, and the sensitivity indices are computed in terms of dot products of the model output vectors.

3 RESULTS

In this preliminary analysis, the Saltelli sensitivity method is applied to the vertical load path resistance model visualized in Figure 1 and composed of the parameters defined in Tables 1-3. The number of simulations n is $1 \cdot 10^4$, and the sample set is based on quasi-random numbers from the Sobol' sequence. The first-order and total-effects indices S_i and S_{Ti} are plotted in Figure 2 for two cases. In the left-hand plot, all parameters are allowed to vary over their respective ranges of uncertainty. In this case, the decision variable that determines whether the wall sheathing overlaps the wall upper top plate stands alone as the most influential parameter, followed by the decision variable for the foundation system type as arguably the second-most significant parameter. These are followed at some distance by the roof-to-wall connection type, the roof structure type, and the specific gravity of the wall framing. The sensitivity measures are negligible for the remaining parameters. These results can be understood in light of which connections in the load path tend to be the weakest link. Since the analysis considers the resistance of the weakest series connection as the output quantity of interest, the influential parameters must be those that have the greatest potential to change the location of the weakest link. For this load path configuration, the connection between the upper and lower top plates in the wall system tends to be the weakest point, but only when the wall sheathing does not overlap the upper top plate, forming a composite connection with improved uplift capacity. When the sheathing overlap is in effect, the weakest point typically relocates to the wall-to-subfloor connection, though this can only be true when a stem wall foundation is present. After these two connections, the other characteristic weak link is a toe-nailed roof-to-wall connection, for which the roof-to-wall connection type, roof structure type, and wall framing specific gravity parameters are controlling variables.

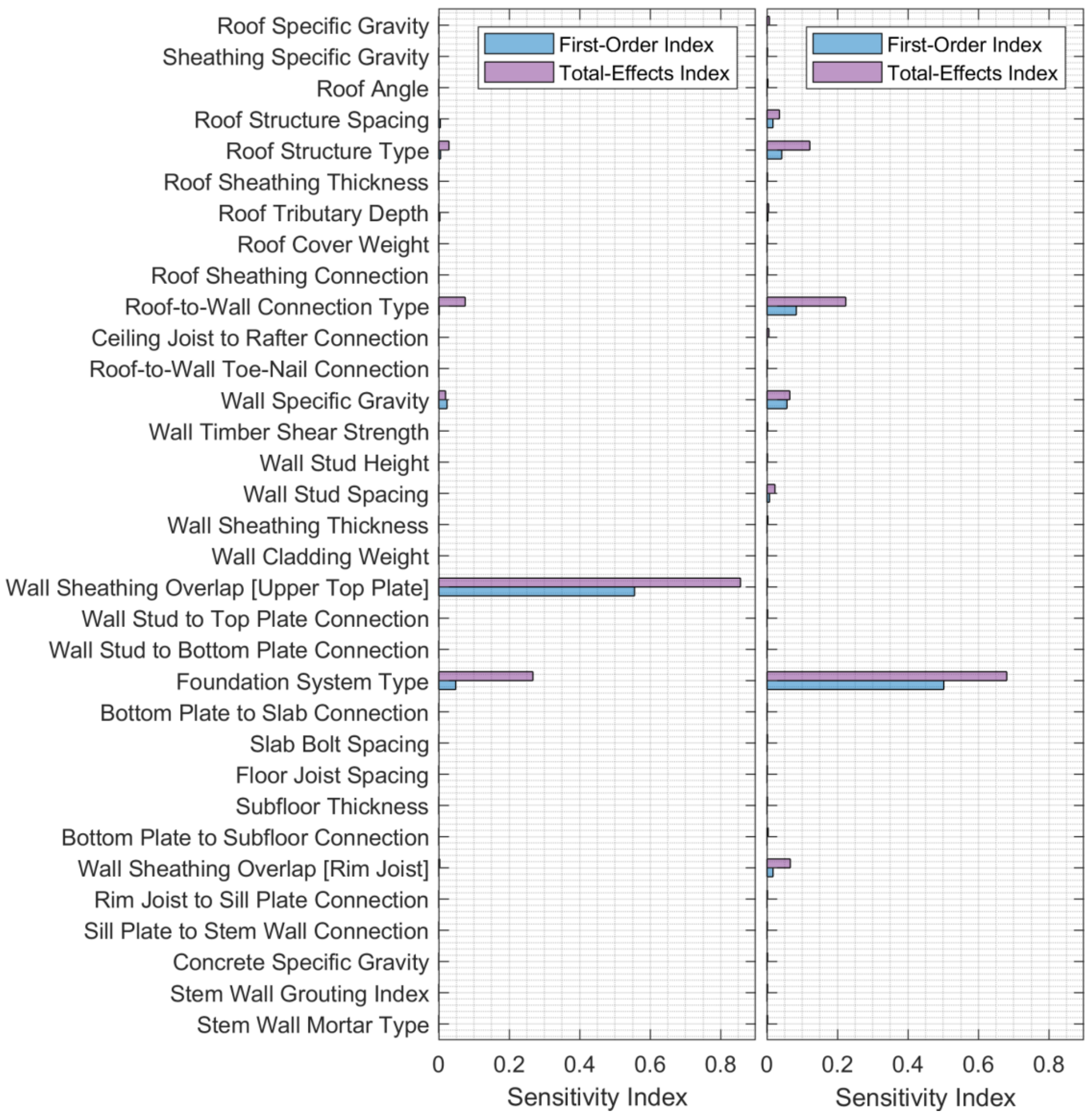

Figure 2. Sensitivity analysis results for the generalized vertical load path considered in this study. In the left plot, all parameters are free to vary over their ranges of uncertainty; in the right plot, the wall sheathing overlap at the upper top plate is restricted to “true”, redistributing influence to parameters that control other weak links in the load path.

If one of the characteristic weak links is eliminated from the system, influence is expected to redistribute to the parameters that most impact the remaining weak connections. In the right-hand plot of Figure 2, the decision parameter for the upper top plate wall sheathing overlap has been constrained to take a value of "true" in every simulation. Since this variable has only one possible state, its sensitivity measures become zero, and since the double top plate connection is no longer a characteristic weak point, the wall-to-subfloor connection becomes the most probable weakest link. The foundation system decision variable rises in influence accordingly, and two other contributing parameters take on at least marginal influence: (1) the decision variable that controls the wall sheathing overlap of the rim joist, which imparts additional capacity to the wall-to-subfloor connection, and (2) the wall stud spacing, which affects the nail spacing of the rim joist sheathing overlap. The toe-nailed roof-to-wall connection also becomes a more frequent weakest link, and the associated parameters increase in influence as a result.

This illustrative analysis is intended to point to the potential usefulness of the load path sensitivity framework as an analytical tool, capable of providing insight into the relative importance of structural attributes for wind resistance. The modular format of the framework allows for the definition of arbitrary vertical load paths and custom parameter lists, making it possible to evaluate sensitivity behavior for different configurations of a single load path or for different load paths.

4 LIMITATIONS

The sensitivity results are useful only as far as the resistance estimates produced by the load path model are accurate. One limitation of the framework at this stage of development is that the resistance model does not account for effects of load sharing among connections, which likely contributes to underestimation of resistances. Another simplifying assumption in the model is the use of the weakest-link resistance as the limiting resistance of the system and the adoption of this resistance as the output quantity on which the sensitivity analysis is based. As with the previous point, equating system failure with the exceedance of the weakest connection resistance in series likely underestimates system resistance, particularly the further down the load path the connection occurs at. Defining system failure in another way and setting this new quantity as the model output could materially affect the observed sensitivity pattern. The sensitivity results also depend on the completeness of the parameter space, which requires (1) including all potentially influential variables in the parameter set and (2) defining parameter distributions to cover the whole range of expected variability. The primary concern at this point is the possibility of missing an important parameter, or understating its importance by abbreviating its distribution. Notwithstanding, with further calibration the framework shows promise as a way to assign relative rankings to various wind load paths encountered in the field, with accompanying benefits to the optimization of new designs and construction and education of relevant stakeholders.

5 ACKNOWLEDGMENTS

This work was sponsored in part by the National Science Foundation under CAREER research grant CMMI-1944149. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

6 REFERENCES

M. Amini and J. van de Lindt, Quantitative insight into rational tornado design wind speeds for residential wood-frame structures using fragility approach, Journal of Structural Engineering, 140 (2014) 04014033.

B. Ellingwood, D. Rosowsky, Y. Li, and J. Kim, Fragility assessment of light-frame wood construction subjected to wind and earthquake hazards, Journal of Structural Engineering, 130 (2004) 1921-1930.

C. Henderson, T. Huff, and G. Bouton, Structural observations and tornado damage mitigation concepts: March 2020 Tennessee tornadoes, Practice Periodical on Structural Design and Construction, 26 (2021) 05021001.

K. Lee and D. Rosowsky, Fragility assessment for roof sheathing failure in high wind regions, Engineering Structures, 27 (2005) 857-868.

H. Masoomi, M. Ameri, and J. van de Lindt, Wind performance enhancement strategies for residential wood-frame buildings, Journal of Performance of Constructed Facilities, 32 (2018) 04018024.

D. Rosowsky and N. Cheng, Reliability of light-frame roofs in high-wind regions, II: Reliability analysis, Journal of Structural Engineering, 125 (1999) 734-739.

A. Saltelli, Making best use of model valuations to compute sensitivity indices, Computer Physics Communications, 145 (2002) 280-297.

A. Saltelli, S. Tarantola, F. Campolongo, M. Ratto, Sensitivity Analysis in Practice: A Guide to Assessing Scientific Models, Wiley, Chichester, UK, 2004.

A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, and S. Tarantola, Global Sensitivity Analysis: The Primer, Wiley, Chichester, UK, 2008.

C. Standohar-Alfano, J. van de Lindt, and B. Ellingwood, Vertical load path failure risk analysis of residential wood-frame construction in tornadoes, Journal of Structural Engineering, 143 (2017) 04017045.

J. van de Lindt and T. Dao, Performance-based wind engineering for wood-frame buildings, Journal of Structural Engineering, 135 (2009) 169-177.