

Flood Performance and Dislocation Assessment for Lumberton Homes after Hurricane Matthew

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ABSTRACT: In order to better understand community resilience following a disaster, a multi-disciplinary research team from the Center of Excellence (CoE) for Risk-Based Community Resilience Planning and the National Institute of Standards and Technology (NIST) jointly conducted a series of longitudinal field studies in the U.S. city of Lumberton, North Carolina following major flooding from Hurricane Matthew (2016). Damage surveys on structures and interviews with households were conducted during the first field study to explore physical, economic, and social impacts of major riverine flooding on this small, tri-racial community. This paper is focused on damage to housing and subsequent household dislocation. Empirical damage fragilities were developed for residential buildings using a comprehensive set of engineering damage inspection data collected by the team. Multi-variate models were developed to assess the consequences of physical damage to housing units

for household dislocation, including socio-demographic factors. The goal was not to develop the definitive model of household dislocation, but rather to show how engineering and social science data can be combined to better understand the broader social impacts of disasters – in this case, household dislocation. This study may help inform assessments of flood damage and dislocation patterns for other U.S. communities as a function of construction, social, and economic makeup.

Performance-based engineering (PBE), especially as it relates to recovery of buildings and infrastructure functions, is a promising tool for enhancing a community's resilience following a disaster. Community-level resilience goals, such as *no more than 5% of households dislocate following a specific hazard event with a specified probability of nonexceedance*, can be used to define performance objectives in a PBE framework. However, in order to better achieve resilience goals, PBE frameworks need to capture the relationship between physical damage and social impacts during the response and recovery phases of a disaster (van de Lindt et al., 2018; Koliou et al., 2018).

This paper summarizes research that is part of a longitudinal study documenting the impacts of Hurricane Matthew on Lumberton, North Carolina in an effort to better understand that relationship. Two sequential field studies for Lumberton were jointly conducted by interdisciplinary teams of researchers from the Center of Excellence for Risk-Based Community Resilience Planning (Center) and the National Institute of Standards and Technology (NIST). The field studies were performed approximately 2 months (in 2017) and 15 months (in 2018) after the 2016 Hurricane Matthew caused catastrophic flooding in Lumberton. Engineering damage evaluations and structured household interviews were performed during the 2017 field study to collect data on physical damage, utility service disruption, household dislocation, work and school disruption, and household socio-economic and demographic characteristics.

Multi-variate models were developed to link physical damage of housing units to household dislocation (i.e., a household vacating their housing unit), controlling for socio-demographic characteristics and tenure. In addition, household

demographics were combined with damage assessments to better understand the distributional consequences of flood damage among Lumberton's racial/ethnic groups. The outcomes from this study provide new insight in understanding and quantifying the consequences of housing damage for diverse racial/ethnic households in Lumberton, the impact of damage on the dislocation of households from their residences, and the effect of social factors such as race/ethnicity and tenure status on this dislocation. Findings are used to support recommendations on establishing community-level performance goals grounded in stronger measurements that link physical damage to social impacts.

1. HURRICANE MATTHEW'S IMPACT ON LUMBERTON

Lumberton is a small, racially and ethnically diverse in-land community in Robeson County, North Carolina with a population size of 21,542 residents (U.S. Census, 2010). Lumberton's racial/ethnic composition consists of 39% non-Hispanic White, 36.7% non-Hispanic Black, and 12.7% American Indian, 4.8% Hispanic, and 6.7% non-Hispanic other (U.S. Census, 2010). Lumberton also has a substantial portion of its community, 34.8%, living at or below poverty levels (U.S. Census, 2010).

In October 2016, the Lumber River, which runs through the middle of Lumberton, experienced historic flooding due to Hurricane Matthew. Stream gage data show a large rain event in early October, prior to Hurricane Matthew, which led to increased flooding and extremely saturated soils. The Lumber River crested at nearly 6.7 m (22 ft) above the gage datum, which is 2.74 m (9 ft) higher than the

National Weather Service flood threshold (USGS, 2017).

A two-staged random, non-proportional stratified cluster sample was pulled for housing units in Lumberton, consisting of 568 housing units. Census blocks were selected to identify a set of housing units through a two-stage process. During the first stage, a set of census blocks were randomly selected in flooded areas with a probability proportion to size based on the number of housing units per block. Census blocks were selected non-proportionally in high probability flooded areas at a ratio of 3:1 compared to blocks located in low probability flooded areas. The second stage consisted of randomly selecting a fixed number of housing units in each block.

Standardized engineering damage surveys were performed on the housing units, and standardized social science surveys were conducted with households occupying these housing units (or with neighbors, landlords, or managers in cases that the housing unit was not occupied) about potential household dislocation, utility disruption and socio-demographic characteristics. The damage surveys documented information regarding the building type, dimensions, structural system, and flood and damage information, such as the high-water mark location and evidence of damaged interior items (see Figure 1). The household dislocation survey documented information about the occupancy status of the housing unit, and when available, asked households about the duration and reason for their dislocation, as well as information on utility outage and household socio-demographics. Since the goal was to understand the consequences of direct damage and utility disruption for household dislocation along with other forms of social impacts, housing units in areas with a low probability of flooding were included in the sample. In total, 568 housing units were visited as part of our surveys; 402 sampled units completed damage assessments (no assessments were made in areas clearly not suffering from flooding); complete household

data was collected for approximately 300 households, with additional data about households gathered from neighbors or apartment managers. The following sections describe the data and subsequent findings. The full report with a detailed summary of the city, the impact of Hurricane Matthew, the field study and findings is provided in van de Lindt et al. (2018).

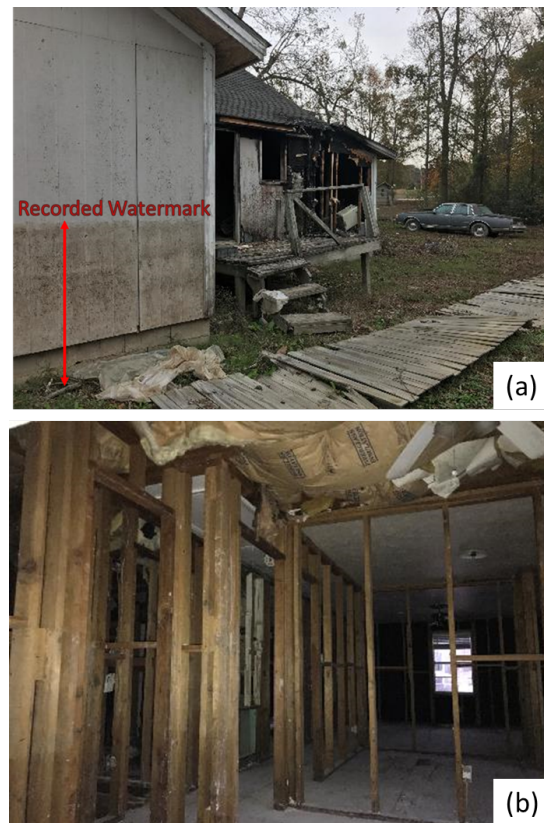


Figure 1: Assessing damage to residential buildings in Lumberton: (a) measured high water mark and (b) gutted interior.

2. EMPIRICAL FLOOD DAMAGE MODELS
Using results from the damage surveys, this section presents a flood performance assessment of Lumberton homes using empirical damage fragility curves. Table 1 summarizes the key characteristics of the 402 buildings in the dataset. Most of these homes, single- and multi-family, were light-frame wood structures (many with brick veneer), of typical maintenance for their age, and typically one to two stories in height. Almost two-thirds had crawlspaces, while the

remaining homes were built with slab-on-grade foundations. The field data showed that flood levels reached up to around 122 cm [48 in] above the first floor elevation (i.e., the threshold of the front or back door of the home), corresponding to approximately 195 cm [77 in] and 127 cm [50 in] above the grade level for buildings with crawlspaces and for buildings with slabs on grade, respectively. The damaged structures were classified into five discrete damage states, ranging from *DS0* (no damage) to *DS4* (complete damage), to identify their overall damage level based on the physical condition of the building (see Table 2). Most homes were classified as *DS0* to *DS2* (see Figure 2) indicating ‘slight’ to ‘major’ damage, particularly to the contents of these structures, but no substantial internal or structural impacts to the residence. The flood depths corresponding to the damage state for a given foundation type are highly variable (i.e. have a large value of standard deviation, ranging from 13 cm [5 in] to 43 cm [17 in]).

Significant variability in flood depth was observed in flood damage state estimates for the residential buildings. Therefore, a fragility model was used to characterize the uncertainty in the damage evaluations. This approach estimates the probability of being in or exceeding a given damage state as a function of flood depth. In engineering applications, a lognormal distribution is often used to allow values to remain positive, eliminating the need for statistical manipulation (Ellingwood, 2001; Li and Ellingwood, 2006; Porter et al., 2007; Deniz et al., 2017a; Deniz et al. 2017b). Lognormal distributions were considered to be appropriate for characterizing exceedance probabilities of damage of flooded homes in this study after performing goodness-of-fit tests for the empirical fragility curves. Several variables—including flood depth, flood source, occupancy-type, foundation type, and floor area—were considered in the development of these curves. However, foundation type and flood depth were found to be the most critical factors in the development of the damage fragilities.

Table 1: Summary of empirical dataset, including breakdown by foundation type, building type, number of stories, and construction type.

Foundation Type (with Number of Buildings)		Crawlspace (272)		Slab (116)	
Distribution of Occupancy Type (Single or Multi Family)		Single	Multi	Single	Multi
		96.7%	1.8%	33.6%	64.7%
Distribution of Number of Stories	One	95.4%	80%	97.4%	80.0%
	Two	2.7%	0%	0%	20.0%
	Other	1.9%	20%	2.6%	0%
Distribution of Construction Type	Wood	64.6%	78.9%	46.1%	34.7%
	Masonry	22.0%	0%	28.3%	24.0%
	Wood/Masonry	12.2%	21.0%	17.8%	41.3%
	Other	1.2%	0%	7.8%	0%

Table 2: Overall damage description for homes.

DS	Description
0	No damage: water may enter crawlspace or touch foundation (crawlspace or slab on grade) but water has no contact to electrical or plumbing, etc. in crawlspace, and no or limited contact with floor joists. No sewer backup into living area.
1	Minor water enters house; damage to carpets, pads, baseboards, flooring. Approximately 25.4 mm (1 in), but no drywall damage. Touches joists. Could have some mold on subfloor above crawlspace. Could have minor sewer backup and/or minor mold issues.
2	Drywall damage up to approximately 0.3 m (2 ft) and electrical damage, heater and furnace and other major equipment on floor damaged. Lower bathroom and kitchen cabinets damaged. Doors or windows need replacement. Could have major sewer backup and /or major mold issues.
3	Substantial drywall damage, electrical panel destroyed, bathroom/kitchen cabinets and appliances damaged; lighting fixtures on walls destroyed; ceiling lighting may be ok. Studs reusable; some may be damaged. Could have major sewer backup and/or major mold issues.
4	Significant structural damage present; all drywall, appliances, cabinets etc. destroyed. Could be floated off foundation. Building must be demolished or potentially replaced.

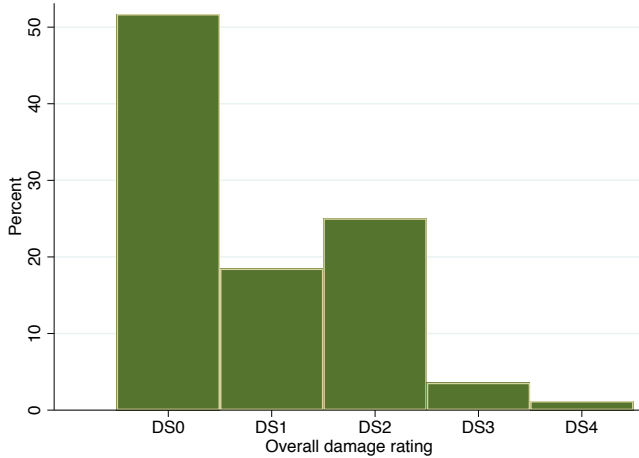


Figure 2: Overall damage state classification for surveyed housing units (van de Lindt et al., 2018).

The empirical lognormal fragility curves, of each damage state (e.g., *DS0*, *DS1*, and *DS2*), conditioned on the uncertain flood depth (*d*) measured from the grade level next to the building. It should be noted that no *DS4* observations were reported for the inspected buildings with slabs, while only five cases of homes reaching damage state *DS4* were reported for buildings with crawlspaces. Given the small sample and potential bias during data collection for buildings with crawlspaces, *DS4* data were merged into the *DS3+* damage state. For the curves shown in Figure 3, all damage state models passed the Kolmogorov-Smirnov (K-S) test for a significance level of 5%.

The empirical distribution functions of the raw data, plotted as step functions in Figure 3, show that the underlying data used to develop the fitted fragility curves (solid lines in Figure 3) have significant variability in the damage evaluation, building properties, flood characteristics, and data collection variability (human error). This points to the importance of considering variability in predictive damage models for reliable damage assessments and subsequent applications to community resilience studies.

Since the damage states considered in this study are sequential (i.e., *DS1* must be surpassed before reaching *DS2*), the total probability of reaching or exceeding all damage states, from *DS0* to *DS3* sum to 1. These probabilities of exceedance are shown in the shaded regions between the fragility curves in Figure 3. The median flood depths for exceeding the damage states are approximately 7.6 cm [3 in] to 38.1 cm [15 in] higher for homes with crawlspaces than for homes with slabs-on-grade. Homes with slabs on grade had higher flood depths inside the home because they do not have the advantage of the being slightly raised by the height of a crawl space, and as expected, are more vulnerable to flood events. As an example, buildings with crawlspace foundations that experience a flood depth of 127cm [50 in] with respect to the grade level have the 43%, 42%, 13%, and 2%

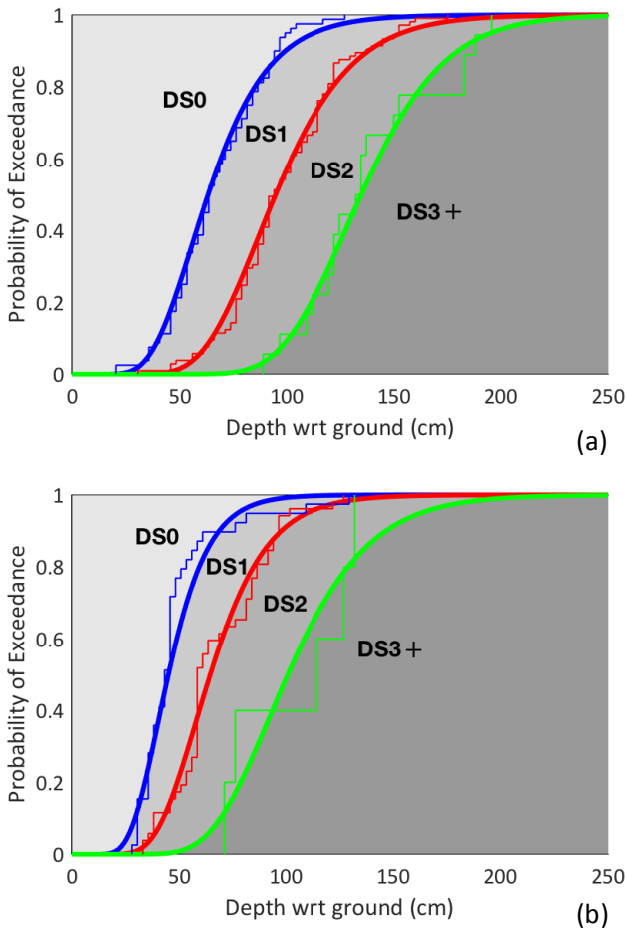


Figure 3: Fragility curves as a function of flood depth with respect to grade level for homes with: (a) crawlspace and (b) slab-on-grade (van de Lindt et al., 2018).

probability of being in or exceeding *DS3*, *DS2*, *DS1*, and *DS0*, respectively. At the same depth, buildings with slab-on-grade foundations have 80%, 17%, 3%, and 0% of being in or exceeding *DS3*, *DS2*, *DS1*, and *DS0*, respectively. While there is a high likelihood for buildings with slabs to exceed *DS3* when water reaches the mid-height of first story (127cm [50 in] above the grade level), the homes with crawlspaces have damage limited to floor joists, flooring, and insulation materials at the same depth above the grade. The parameters of the fragility curves and details on the analyses procedures can be found in van de Lindt et al., 2018.

3. INTEGRATED DAMAGE AND DISLOCATION MODELS

One goal of the study was to develop integrated housing damage and dislocation models to better capture population dislocation patterns of a community after flooding events based on flood damage levels. This section presents preliminary findings (this data continues to be collected by our team and the the 2018 field data collection is presented in Sutley et al., 2018) on the data from the damage assessments with relevant social science data from the household surveys to better understand dislocation for Lumberton households.

As noted above, Lumberton is a diverse community with relatively large proportions of its population classified as non-Hispanic White, non-Hispanic Black, and American Indian. Given the historical development patterns that result in higher proportions of minority populations (non-Hispanic Black and American Indian) being located in areas more susceptible to flooding, it was not surprising to find statistically significant variations in housing damage across these racial/ethnic groups. Specifically, over 80% of non-Hispanic White housing units were classified as *DS0*, while only 52% of non-Hispanic Black and 34.5% of American Indian housing units were *DS0*. Conversely, only 20% of White households were located in housing units with damage ratings from *DS1-DS3*, while 48% of non-Hispanic Black and 65.5% of American

Indian households were living in housing units rated *DS1-DS3*.

Based on the data collected by the field survey teams, the total dislocation rate for the sample was 75.6% ($\pm 3.6\%$). In other words, the survey results suggest that just approximately 75% of households dislocated from their homes for at least some period of time following the flooding due to damage to their housing unit, utility disruption, or some other factors. The length of dislocation ranged between 0 to 61 days as the interview team completed its survey work 61 days after the flood; the maximum dislocation time may be longer (this data continues to be collected by our team and the 2018 field data collection is presented in Sutley et al., 2018). Based on the survey from the 2017 data collection presented in this paper, the average number of days of dislocation is 34.4 (± 2.4) days.

The literature on household dislocation or displacement is still emerging in the broader disaster and hazards research community and ranges from qualitative observational research through more quantitative research (Esnard and Sapat, 2014). This literature has generally found that direct damage to the housing unit is a major determinant of dislocation, but that other factors can also shape dislocation as well. Similarly, other factors, such as tenure, can have consequences. Renters, for example, are generally found to dislocate at higher levels because the owners of damage properties are more likely to require residents to vacate due to safety and liability issues, while homeowners are more likely to stay (Girard and Peacock, 1997). The literature has also found other factors, such as race/ethnic, income, insurance, etc., can also have consequences for dislocation.

As part of this research, logistic regression analysis was used to develop a series of models utilizing the damage assessment data and household data to develop a more comprehensive model predicting household dislocation (see van de Lindt et al. (2018) for the details on the model parameters). The goal was not to develop the definitive model of household dislocation, but

rather to show how engineering and social science data can be combined to better understand the broader social impacts of disasters – in this case, household dislocation. This analysis employed logistic regression to predict the logged odds of household dislocation based on damage state, tenure, and race/ethnicity. Damage was entered into the model using three damage states, $DS0$, $DS1$ and $DS2+$. The damage states $DS2$, $DS3$ and $DS4$ were combined into $DS2+$ because there were so few observations in the $DS3$ and $DS4$ categories. Race/ethnicity was based on the self-identification of the household's key respondent, and classified as non-Hispanic White, non-Hispanic Black, and American Indian for the purposes of this analysis. Finally, since data on a household's tenure status was not available for all households, the percentage of renter occupied housing units in the census block was utilized as a surrogate measure for proportion tenure.

Three models were developed, with the first one only including damage state data, the second one adding household race/ethnic categories, and the final model also including proportion tenure. All models were statistically significant with 25.3%, 28.8%, and 31.1% of the variance respectively. Not surprisingly, the results suggested that higher levels of damage resulted in higher probabilities for dislocation. However, even after controlling for damage, dislocation was significantly higher for non-Hispanic Black and American Indian households, when compared to non-Hispanic White households. Furthermore, after controlling for both damage and race/ethnicity, the probabilities of dislocation were higher for housing located in blocks with higher proportion of renter households.

The finding for the final model are presented in Figure 4, which displays the predicted dislocation probabilities for each ethnic category (blue lines for non-Hispanic Whites, red lines for non-Hispanic Blacks, and green lines for American Indian households), at each damage state (circles are for $DS0$, triangles for $DS1$, and crosses for $DS2+$), for housing units located in

blocks varying in the proportion of rental units, from 0 to 100%, on the block (see x-axis). As Figure 4 shows, White households (blue lines) always have lower dislocation rates than Black (red lines) and American Indian (green lines) within each damage state $DS0$, $DS1$, and $DS2+$ (circles, triangles, and crosses respectively). Furthermore, all lines reflect higher dislocation probabilities as the percentage of renter households increase across blocks.

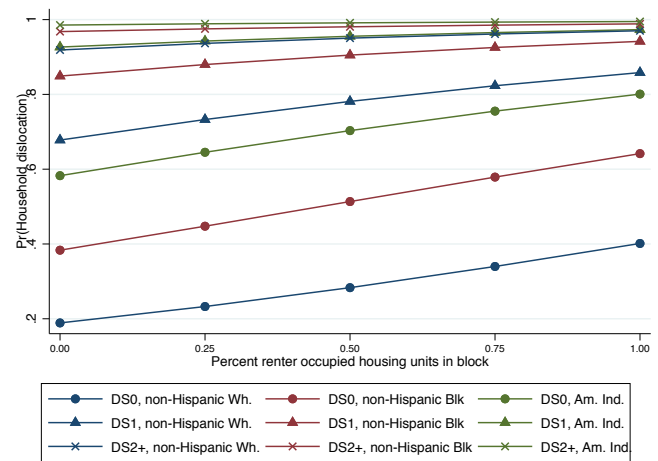


Figure 4: Probability of household dislocation by damage state, race/ethnicity, and tenure (van de Lindt et al., 2018).

The relative importance of damage is also reflected in Figure 4. Specifically, as damage state increases, higher probabilities of dislocation across race and tenure are observed. Indeed, there is a general convergence in dislocation probabilities at the highest damage state in those blocks with a higher proportion of renters, regardless of racial/ethnic status. Nevertheless, combining both engineering data on housing damage with social science data on race/ethnicity and tenure status improves the ability for models to capture complex social impacts, such as dislocation.

4. CONCLUSIONS, RECOMMENDATIONS, AND NEXT STEPS

The flood performance and dislocation models present a methodology for predicting damage and dislocation probabilities for residential homes

subject to flood events. They can also be integrated with flood hazard models to perform life-cycle performance and dislocation assessments for residential structures. Moreover, they can be used as predictive tools for other U.S. communities, which show similar residential construction practice across the country for implementation in community resilience studies.

When adopting performance-based engineering for community resilience as a design goal, design teams will need to think outside of a typical structural engineer's scope to include considerations of dislocation and the reasons occupants dislocate. Dislocation has important implications for community resilience and recovery due to socio-technical interdependencies. If residents leave the community because their home is damaged, then communities lose their tax base; businesses lack employees and customers to resume their normal operation; similarly, schools and hospitals have lose their employees as well.

Next steps for the Lumberton longitudinal study include evaluating community interdependencies to understand whether the closure of schools and businesses played a role in household dislocation time. This information becomes critical for prioritizing the distribution of resources across critical infrastructure sectors in a community during times of crisis, and can be used to develop new community-level performance goals for performance based engineering.

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