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Final Report: Damage Assessment of Residential Infrastructure Impacted by Hurricanes Harvey and Irma

Submitted to: National Association of Home Builders (NAHB) – Project sponsor

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1. EXECUTIVE SUMMARY

This report is submitted to the National Association of Home Builders (NAHB) as part of the NAHB-funded project to evaluate the performance of wood residential infrastructure in Texas and Florida after the 2017 Harvey and Irma Hurricanes, respectively. This report outlines the work performed by Drs. Koliou (project Principal Investigator) and Paal (project co - Principal Investigator) and their students, including description of the considered building stock datasets, analyses associated with their performance and damage state description, analyses to identify the most contributing damaging components, review of significant code changes in both states, and analyses of effective building code update years to associated damage. Major findings and concluding remarks are also provided at the end of this report.

2. DESCRIPTION OF BUILDING STOCK AND AVAILABLE DATA

2.1. Texas Impacted by Hurricane Harvey

A set of buildings were inspected following Hurricane Harvey as part of NSF-funded projects (StEER 2018) to identify the level of damage associated with their structural and non-structural components. The distribution of the building stock inspected and considered in this study for the State of Texas is shown in Figure 1, while the frequency distribution for the various counties is presented in Figure 2. It is observed that the majority of the buildings inspected are located at the Rockport, Port Aransas and Portland counties located along the Texas coastline.

Figure 1: Distribution of available dataset of building stock inspected after Hurricane Harvey

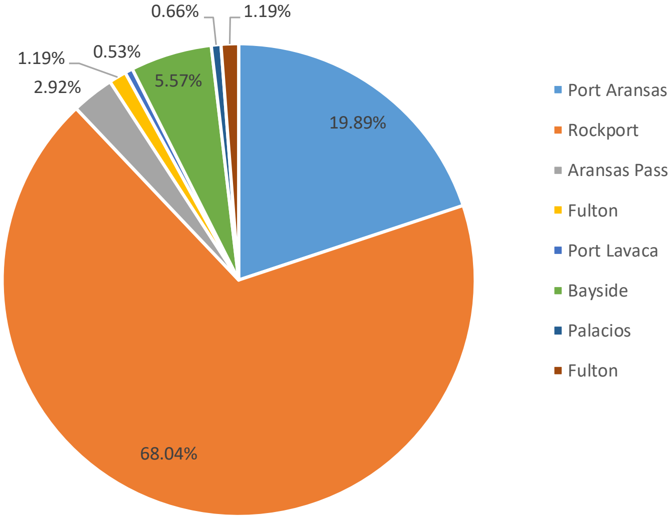

Figure 2: Distribution of counties for the building stock inspected after Hurricane Harvey and considered in this study

The dataset considered in this study included descriptive information regarding the roof shape, roof cover material, roof cover format, number of stories, wall cover cladding, as well as whether or not the structure was elevated. Note that only wood frame buildings were considered in this study, and the data associated with other types of construction was not considered in the analyses. The distributions in percentage of the construction component details (as identified above) are provided in the following figures.

The largest trend among the collected data regarding roof shape was that of a gable roof. Gable roofs are among the most popular types of roof construction in the United States. This type of roofing is commonly seen in the shape of a side gable which has two sides that peak at the top in the shape of a triangle which allows it to easily shed water and snow. Other types of gable roofing include crossed gables, front gables, and Dutch gables which offer many of the same structural advantages but different aesthetic appeals. The simple design of a gable roof makes it less expensive to construct and manufacture. Gable roofs can be an issue in high wind or hurricane-prone areas because, without the proper support, the roof can collapse inward due to wind loads. Strong winds can cause the roof cover to peel away or lift the roof completely away from the sides of the house. Commonly used roofing materials include asphalt shingles and metal, clay, or concrete tiles. For the building stock considered in this study, asphalt shingles were identified as the most common roof cover material used.

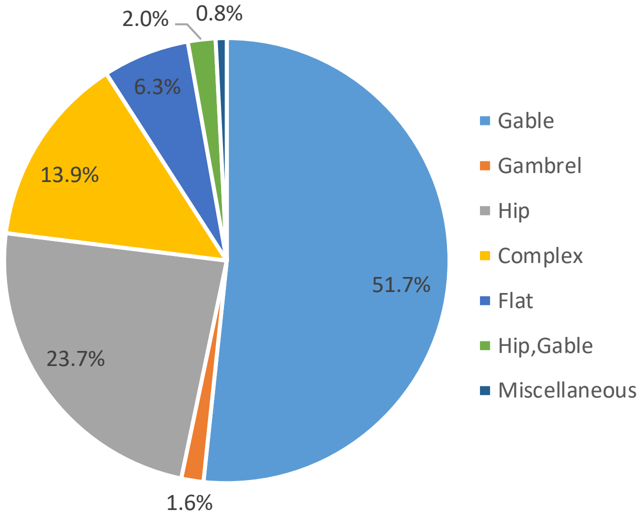

Figure 3: Distribution of roof shape type for the Texas building stock considered in this study

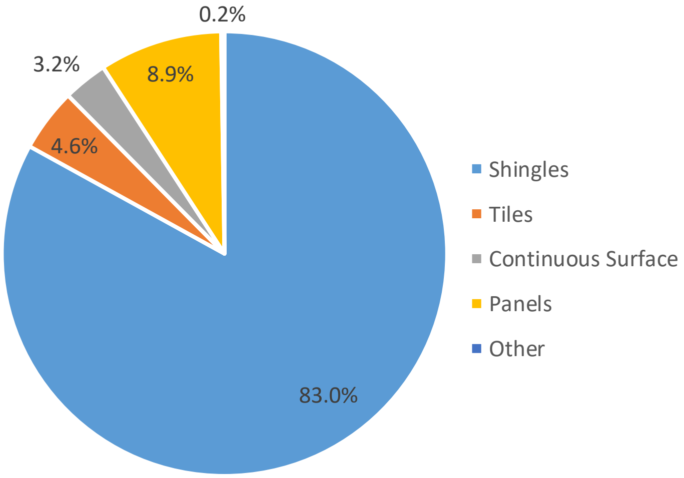

Figure 4: Distribution of roof cover type for the Texas building stock considered in this study

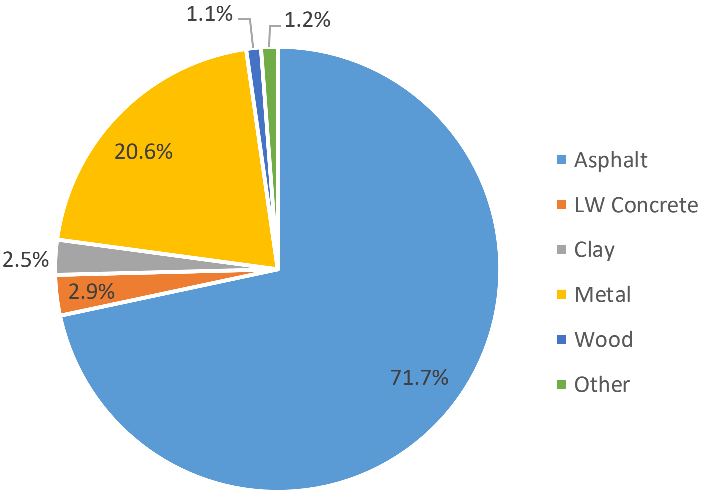

Figure 5: Distribution of roof cover material for the Texas building stock considered in this study

The most common type of cladding among the buildings considered in this study for the TX building stock was wood siding. This type of siding is very common in the south and southwest of the US because of how versatile and readily available wood is. Wood siding is also easy to install, which makes it desirable for homeowners. Wood siding is very susceptible to water rot and water damage, and wood that lacks proper circulation with 20% moisture or more will rot.

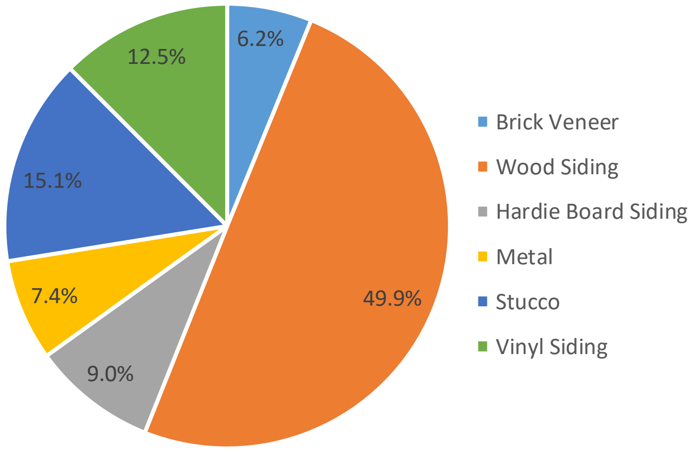

Figure 6: Distribution of wall cover cladding type for the building Texas stock considered in this study

The majority of the buildings considered in this study are one and two story buildings, and approximately 60% of those buildings are elevated structures.

2.1.1. Damage Evaluation and Analysis

The distribution of the observed overall damage in Texas after Hurricane Harvey is presented in Figure 7. This figure shows that the dataset has a good portion of each damage state. In addition, this figure indicates that a large percentage of the buildings within the community experienced overall damage over damage state 1 (associated with no damage). Furthermore, a considerable portion of the buildings (15%) have experienced the highest level of damage, damage state 5 (total-complete collapse). Hence, this figure implies a high level of overall damage throughout the community.

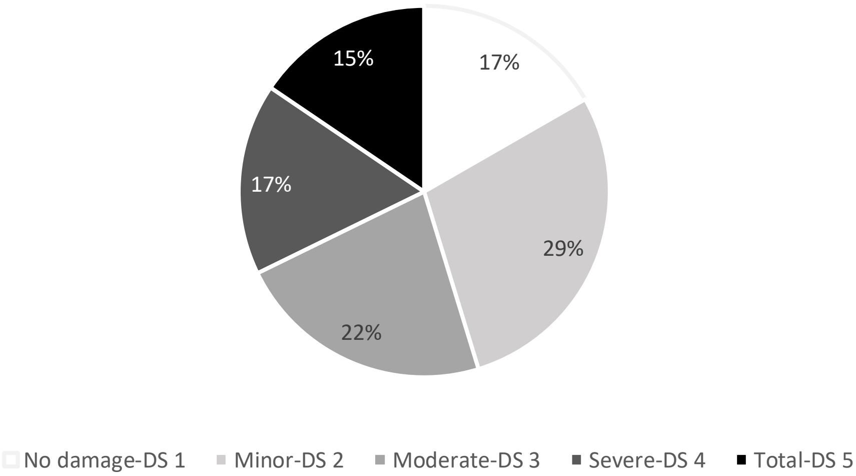

Figure 7: Distribution of overall damage in the Texas dataset after Hurricane Harvey.

The frequency of damage observed in the inspected buildings is shown in the histogram plot of Figure 8. Damage levels are defined based on the percentage of damage observed at each component. Five component damage levels are defined based on the damage percentage in increments of 20% from 0% to 100% damage. This figure shows that in the most severe damage level, damage level 5, the highest frequency is for roof cover damage. In addition, based on the associated frequencies in damage level 1, it can be observed that wall structure damage, roof framing damage, window damage, and wall sheathing damage are rarely observed or are minor.

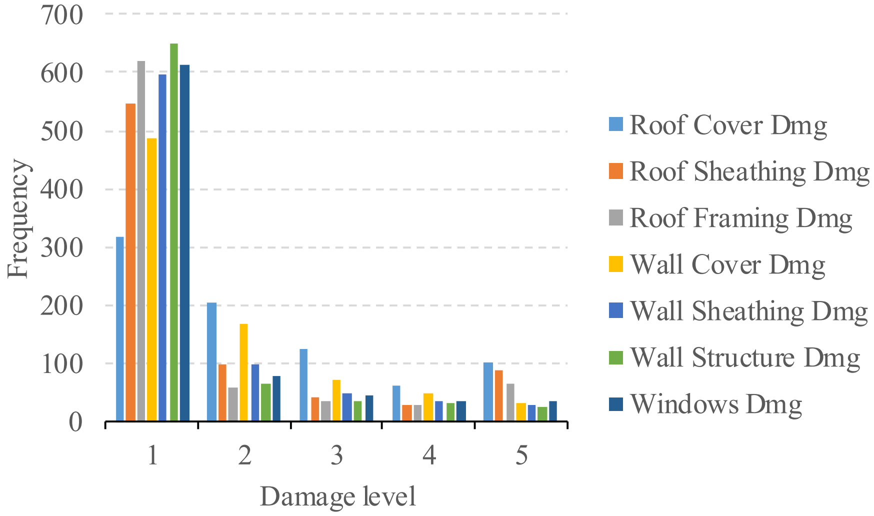

Figure 8: Histogram of damage in building components in the damage dataset of Texas after Hurricane Harvey.

In order to identify the damaged components which have the most significant effect on the overall damage of the buildings, a Bayesian linear regression analysis is conducted between the building overall estimated damage and the percentage of damage of the separate components of the building. The regression analysis is based on the following equation to associate the overall damage to the most contributing damaged components.

$$\delta_{Overall} = \theta_1 \cdot \delta_{Roof,C} + \theta_2 \cdot \delta_{Roof,S} + \theta_3 \cdot \delta_{Roof,F} + \theta_4 \cdot \delta_{Wall,C} + \theta_5 \cdot \delta_{Wall,Sh} + \theta_6 \cdot \delta_{Wall,St} + \theta_7 \cdot \delta_{Window} + \varepsilon$$

The posterior statistics of the Bayesian Linear regression analysis are presented in Table 1. As this table indicates, since Coefficient of Variations (CoV) of θ_2 and θ_6 are very large, they are not significant and hence not informative in this equation. This indicates that the components associated with these parameters are not significant in the overall damage status of the building. These components are roof sheathing and wall structure. The mean values for the model parameters are illustrated in Figure 9. This figure shows that three components which are directly related to the overall damage of the building are roof cover, wall cover, and windows, respectively based on their importance. Since, the values for these parameters in the regression are all in percentages, they are in the same order and there is no need to standardize them, and hence, the values shown in Figure 9 directly compare the influence of each component to the overall damage. The values for the other four components are negative which does not have a physical meaning. As mentioned previously, two of them, roof sheathing and wall structure, are insignificant due to high CoV of model parameters, and hence their mean value is out of value to interpret. In addition, θ_2 and θ_3 and also θ_5 and θ_6 are highly negatively correlated which means that they cancel the effect of one another on the overall damage. This indicates that the main contributing source of high damage to the buildings impacted by Hurricane Harvey in the TX building stock evaluated in this study is damage to the envelope of the building, including the wall and roof covers as well as windows. It does not mean that damage to the structure of the walls or roofs is not important. Rather, it means that damage to the envelope of the building causes high overall damage even if the structure is not damaged at all.

Table 1: Posterior statistics of the equation of overall damage versus components damages.

Parameter	Mean	CoV	Correlation Coefficient						
			θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7
θ_1	3.7135	0.035	1						
θ_2	−0.0957	2.630	−0.53	1					
θ_3	−0.6665	0.378	0.08	−0.72	1				
θ_4	2.4080	0.089	−0.26	0.04	−0.04	1			
θ_5	−0.7288	0.438	0.05	−0.20	0.19	−0.48	1		
θ_6	−0.2171	1.406	0.09	0.16	−0.38	−0.07	−0.62	1	
θ_7	0.3489	0.045	−0.08	−0.06	−0.03	−0.08	−0.15	−0.09	1
σ	0.8052	0.025							

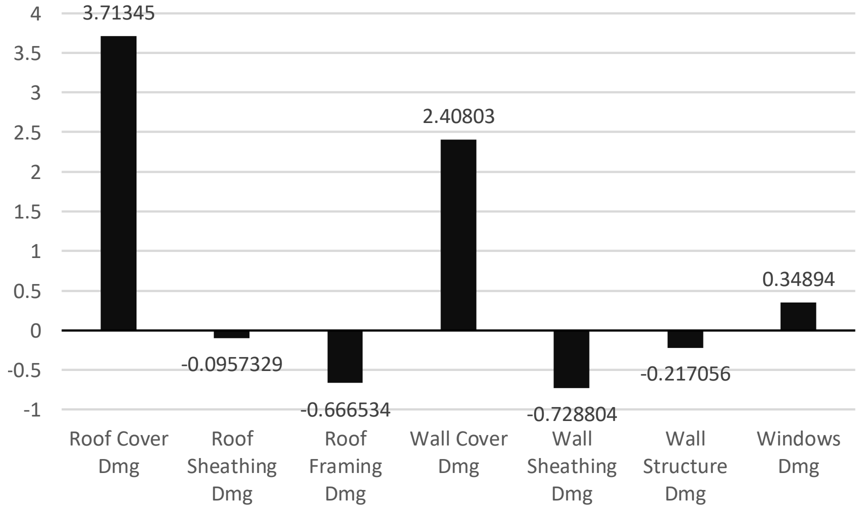

Figure 9: mean values of the model parameters.

2.2. Florida Impacted by Hurricane Irma

Similarly to the considered building stock for the State of Texas, the databased from NSF-funded reconnaissance studies was considered for inspected building stock impacted by Hurricane Irma. The distribution of the inspected building stock in the various locations across Florida is shown in Figure 10 and Figure 11.

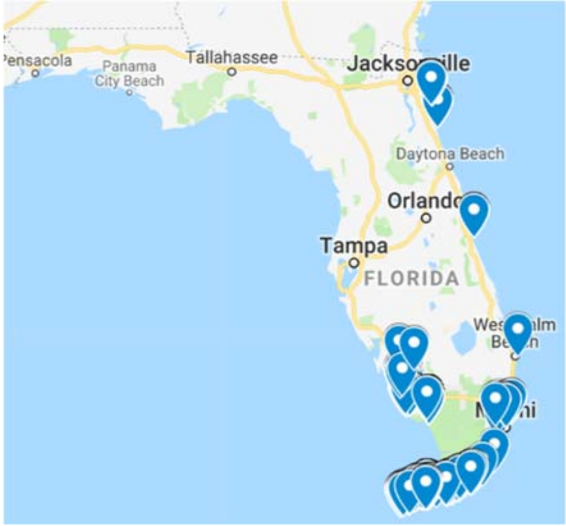

Figure 10: Distribution of available dataset of building stock inspected in Florida after Hurricane Irma

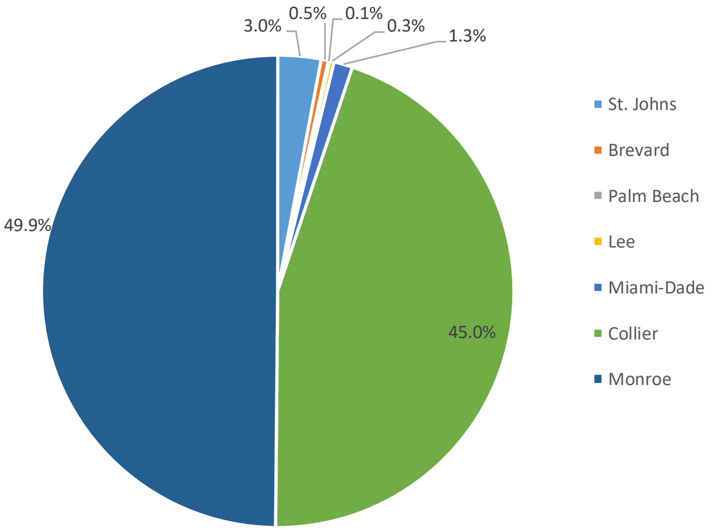

Figure 11: Distribution of counties for the building stock inspected in Florida after Hurricane Irma

Similarly to the dataset for Texas, descriptive components of the roof shape, roof cover material, roof cover format, number of stories, wall cover cladding, as well as if the structure was elevated are identified and their distributions in percentage of the construction component details are provided the following figures.

Similarly to the data compiled from Hurricane Harvey, Figure 12 the frequency and variety of roof shapes has a gable roof shape with the highest frequency, followed by hip roof shape with the second highest frequency, while asphalt shingles dominate the roof type and material for the majority of the building stock inspected in Florida as well.

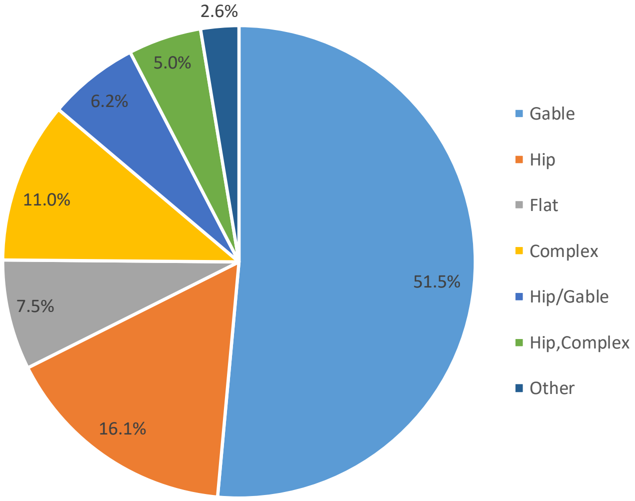

Figure 12: Distribution of roof shape type for the Florida building stock considered in this study

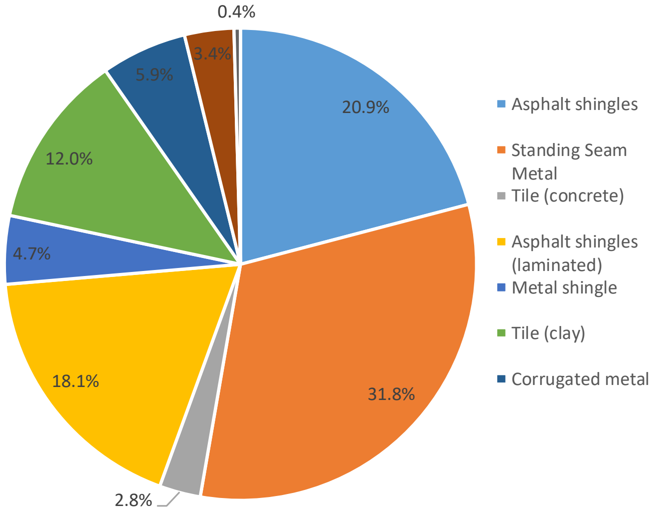

Figure 13: Distribution of roof cover type and material for the building Florida stock considered in this study

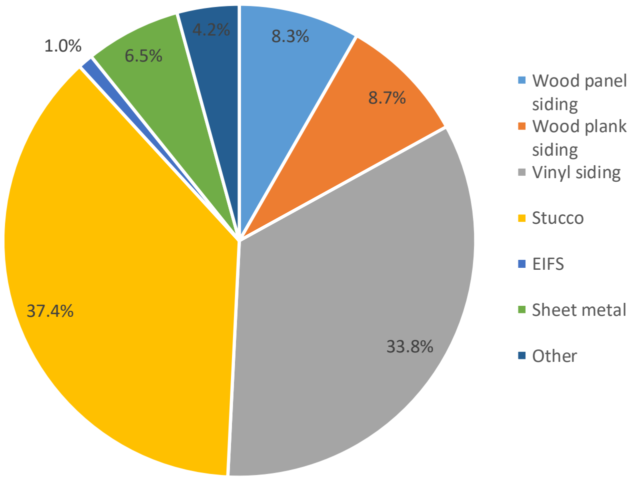

Figure 14: Distribution of wall cover cladding type for the building Florida stock considered in this study

2.2.1. Damage Evaluation and Analysis

The distribution of the state of the observed overall damage in Florida after Hurricane Irma is presented in Figure 15. This figure indicates that a large percentage of the buildings within the community experienced overall damage over damage state 1 (associated with no damage). A large portion of the buildings have experienced damage state 2, which is not very severe (minor damage). However, it is still very important in terms of restoration and recovery, and the socio-economic impacts of long duration of recovery.

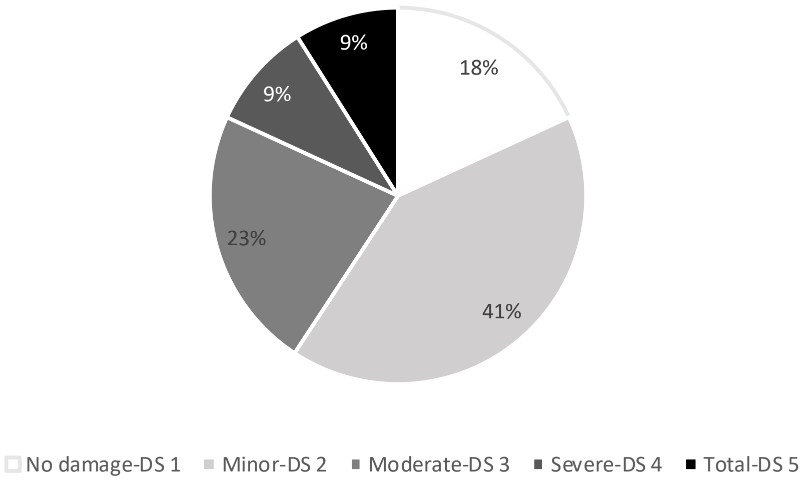

Figure 15: Distribution of overall damage in the Florida dataset after Hurricane Irma.

The frequency of damage observed in the inspected buildings is shown in the histogram plot of Figure 16. Damage levels are defined based on the percentage of damage observed at each component. Five damage levels are defined based on the damage percentage in increments of 20% from 0% to 100% damage. This figure shows that in the most severe damage level (damage level 5), the highest frequency is for roof cover damage. In addition, based on the associated frequencies in damage level 1, it can be observed that door damage, wall structure damage, window damage, wall sheathing damage, and roof framing damage are rarely observed or are minor.

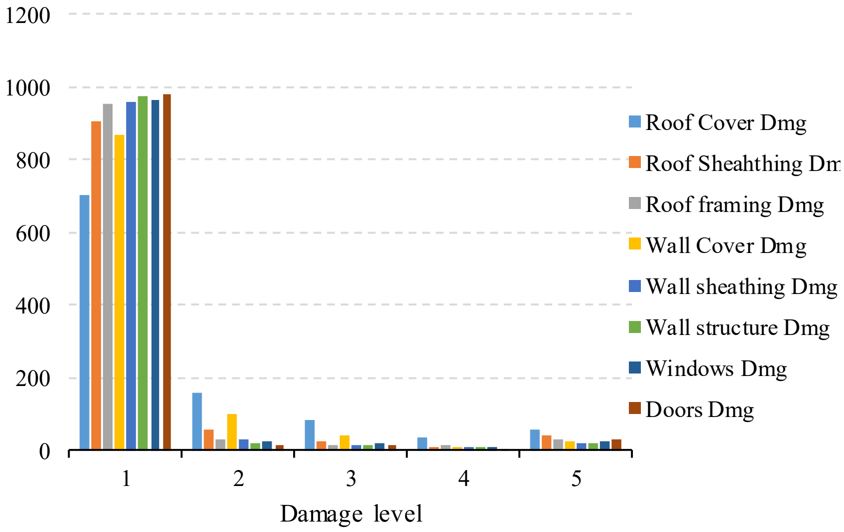

Figure 16: Histogram of damage in building components in the damage dataset of Florida after Hurricane Irma.

Similarly to the analysis of the TX inspected building stock, in order to identify the damaged components which have the most significant effect on the overall damage of the building, a regression analysis is conducted between the estimated overall building damage and the percentage of damage of the separate components of the building. This regression analysis is based on the following equation:

$$\delta_{Overall} = \theta_1 \cdot \delta_{Roof,C} + \theta_2 \cdot \delta_{Roof,S} + \theta_3 \cdot \delta_{Roof,F} + \theta_4 \cdot \delta_{Wall,C} + \theta_5 \cdot \delta_{Wall,Sh} + \theta_6 \cdot \delta_{Wall,St} + \theta_7 \cdot \delta_{Window} + \theta_8 \cdot \delta_{Door} + \varepsilon$$

The posterior statistics are as presented in Table 2. As this table indicates, since CoV of θ_2, θ_3, θ_6, θ_7, and θ_8 are very large, they are not significant and hence not informative in this equation.

This indicates that the components associated with these parameters are not significant in the overall damage status of the building. These components are roof sheathing, roof framing, wall structure, windows, and doors. The mean values for the model parameters are illustrated in Figure 17. Among the remaining informative parameters, θ_1, θ_4, and θ_5, the mean value of θ_5 is negative meaning that the overall damage decreases as the wall sheathing damage increases, which does not have a physical meaning, hence, there is no direct conclusion drawn out of this parameter. In contrast, this figure shows that two components which are directly related to the overall damage of the building are roof cover and wall cover, respectively based on their importance. Since the values for these parameters in the regression are all percentages, they are in the same order and there is no need to standardize them, and hence the values shown in Figure 17 directly compare the influence of each component to the overall damage. In summary, the results indicate that the main reason for high damage to the buildings in the inspected building stock in Florida impacted by Hurricane Irma is damage to the covering of the roof and walls. It does not mean that damage to the structure of the walls or roofs is not important. Rather, it means that damage to the envelope of the building causes high overall damage even if the structure is not damaged at all.

Table 2: Posterior statistics of the equation of overall damage versus components damages.

Parameter	**Mean**	**CoV**	**Correlation Coefficient**							
			θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8
θ_1	4.7533	0.044	1							
θ_2	−0.5020	0.928	−0.56	1						
θ_3	−0.8466	0.644	0.11	−0.69	1					
θ_4	3.8601	0.093	−0.34	0.07	0.03	1				
θ_5	−2.6705	0.267	0.11	−0.05	−0.15	−0.43	1			
θ_6	0.1642	3.768	0.04	0.09	−0.27	0.03	−0.58	1		
θ_7	−0.0152	29.475	−0.02	0.00	−0.02	−0.14	−0.15	−0.10	1	
θ_8	0.2033	1.796	0.07	−0.10	0.09	0.02	−0.11	−0.05	−0.55	1
σ	1.0747	0.022								

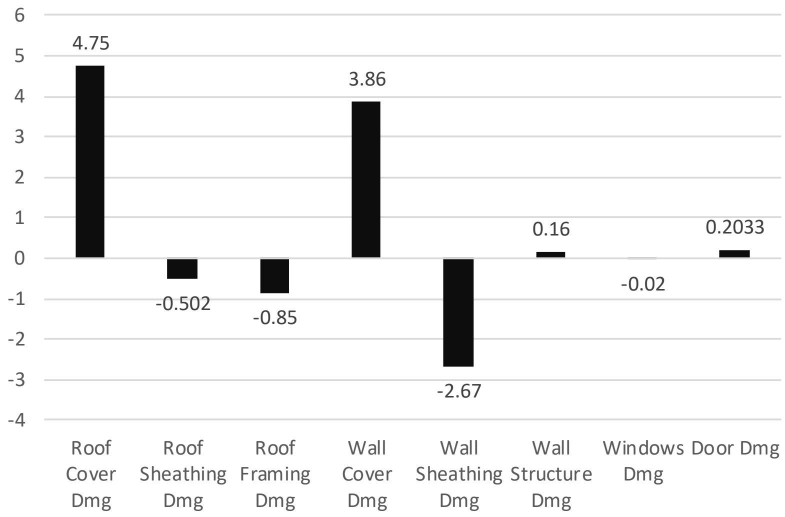

Figure 17: mean values of the model parameters.

3. BUILDING CODE UPDATES AND PROGRESSION

3.1. State of Texas

The first building code established in Texas was the Southern Standard Building Code (SSBC), published in 1946. Portions of Texas used the SSBC, and its subsequent revisions, until the International Code Council (ICC) published the first International Building Code (IBC) and International Residential Code (IRC) in 2000. Since its first edition, the IBC and IRC have been updated on a triennial basis. Only the 1957 and 1973 editions of the SSBC were found available for examination. For the IBC, the 2000-2012 editions are examined. For the IRC, the 2000-2015 editions are examined. Due to the large gap between available SSBC editions, an in-depth examination of changes was not entirely feasible. As the data primarily consists of one- and two-family residential structures, the progression of code requirements for wood structures in the IBC and wind provisions in the IRC are described below.

3.1.1. IBC Wood Structure Provisions

In the 2003 IBC, several changes were enacted as noted herein. Section 2305.7.2 was added to address perforated shear walls. Definitions, limitations, wall resistance, anchorage, load path, uplift anchorage at wall ends, anchorage for in-place shear, uplift anchorage between wall ends, and deflections of shear walls with openings are discussed in this section. In Section 2305.3.8 (summing shear capacities), the quantifier changed from material thickness to material capacity. This section details when shear capacities for shear panels of different capacities may be summed. Terminology changed from "*Detached Group R-3 dwellings*" to "*Detached one- and two-family dwellings*" for exceptions to Section 2308.2.2 (Buildings in Seismic Design Category B, C, D or E). This section provides references to additional requirements for conventional light-frame buildings in Seismic Design Category B, C, D or E.

In the 2006 IBC, the following additional changes were enacted. Two tables were added to Section 2305.2.2 (Deflection) which detail calculations for deflection in the design of wood diaphragms. Table 2305.2.2(1) provides nail or staple deformation for use in calculating diaphragm deflection due to fastener slip. Table 2305.2.2(2) provides panel rigidity values for use in calculating the deflection of wood structural panel shear walls and diaphragms. Previously these values were not included in the code. Equation 23-2, used to calculate deflections in wood shear walls, was changed to include the aspect ratio of the wall when considering elongation of anchorage details. Section 2305.3.3 (Construction) was added to Section 2305.3 (Design of wood shear walls). This section details minimum dimensions and supports for typical wood shear walls. Section 2305.3.5 (Shear wall height definition) was added which defines the height of a shear wall. Previously only shear wall width was explicitly defined. Terminology in Section 2306.2.1 (Wall stud bending stress increase) was modified. This section details the allowable increase to the AF&PA NDS fiber stress in bending design values. Wording changed from "*Wind loads*" to "*Out of plane wind loads*".

In 2009, the IBC was updated in the following ways. Section 2306 (Allowable Stress Design for wood structures) was changed to reference AF&PA SDPWS for most design and construction criteria. Previously values were provided directly in the International Building Code. Section 2308.9.1 (Size, Height, and Spacing) was added to Section 2308.9 (Wall Framing). This section states that studs shall be continuous from a support at the sole plate to a support at the top plate to resist loads perpendicular to the wall. Acceptable supports are detailed in this section.

In 2012, no relevant, notable changes were made to the IBC.

3.1.2. IRC Wind Provisions

The 2000 IRC was the first edition of the IRC. Prescriptive wind provisions were limited to basic wind speeds of less than 110 mph. Design for wind loads outside that limit was required to be in accordance with the SSTD-10 Standard for Hurricane-Resistant Residential Construction, AWC Wood Frame Construction Manual, or ASCE 7-98. Wind-borne debris protection or design for a partially-enclosed condition (higher internal pressure) was required for windows and doors of dwellings located within a mile of the coast, where the design wind speed was greater than or equal to 110 mph, or located anywhere the design wind speed was greater than 120 mph. Minimum roof sheathing nail size changed from 6d to 8d common nail based on findings from Hurricane Andrew and wood industry research, and the continuous wood structural panel sheathing method was added to wall bracing provisions.

In 2003, the IRC was updated with the following provisions. The AISI Standard for Cold-Formed Steel Framing-Prescriptive Method for One- and Two-Family Dwellings was added to the list of alternative standards for design in high-wind areas. A minimum 175-pound connector (hurricane clip or strap) was required for all roof truss-to-wall connections. The roof uplift load table was added for roof assemblies subject to uplift pressures exceeding 20 pounds per square foot. Asphalt shingles in high-wind areas (V > 110 mph) were required to be tested and classified per ASTM D3161 and to have fastening methods tested in accordance with ASTM D3161.

The following updates were made in the 2006 IRC. The limit on use of IRC prescriptive wind provisions was reduced from 110 mph to 100 mph for hurricane-prone areas. The option to design for a partially-enclosed condition (increased internal pressure) instead of providing hurricane shutters or impact-resistant glazing in wind-borne debris regions was removed. A prescriptive table was added for fastening of wood structural panels used as wind-borne debris protection. The table requires #6 or #8 screws long enough to penetrate into wood framing, block or concrete a minimum of 1-1/4”. Options for a portal frame with hold-downs at large openings in any braced wall line and a portal frame without hold-downs for continuously-sheathed walls were added. Garage doors were required to be tested for wind resistance per ASTM E330 or DASMA 108. Asphalt shingles in high-wind areas were specifically required to be ASTM D3161, Class F.

In 2009, the IRC was modified in the following ways. The ICC 600 Standard for Residential Construction in High Wind Areas replaced SSTD-10 in the list of alternative standards required in high-wind areas. Glazing in garage doors in wind-borne debris regions allowed to be tested to DASMA 115. Wood structural panels used as wind-borne debris protection were required to be pre-cut as required to cover the opening, pre-drilled as needed for the required fastening, and the attachment hardware must be corrosion-resistant and permanently installed on the dwelling. Screw sizes increased to #8 or #10 screws, or ¼" lag screws. Anchor bolts into foundation walls or monolithic slab foundations were required for sill and sole plates at all exterior walls around the perimeter of a dwelling and at sole plates of braced wall panels on the interior of the dwelling. The remaining portions of braced wall lines on the interior of the dwelling must be positively anchored to the slab or foundation. A new wind bracing table was added to Section R602.10. The table requires more bracing for 3-story houses or houses in high wind areas (100 and 110 mph wind speeds). Blocking or a blocking panel between deep rafters or high-heel trusses, or between all rafters and trusses in high-wind areas, was required at braced wall panel locations. Asphalt shingles were required to be tested and classified per ASTM D7158, except those not covered by D7158 were required to be tested and classified per ASTM D3161. Shingles in hurricane-prone regions must be Class G or H per D7158 (and Class H only for 130 mph wind speeds or greater), or Class F per D3161.

In 2012, the IRC changes were the following. New wind maps were added based on the ASCE 7-10 standard but converted to allowable stress design-level wind speeds. There was a slight reduction (5-10 mph) in wind speeds near the Gulf Coast due to updated simulation of wind hazards and new research showing hurricanes decay faster over land than previously thought. A new figure was added showing where wind design per the alternative standards (e.g., ICC 600, AWC WFCM) is required. Prescriptive IRC wind provisions were limited based on 130 mph ultimate wind speed (~103 mph ASD) along the Gulf Coast and from Florida to the Carolinas, 140 mph (~110 mph) elsewhere. With the change in wind speed contours, the "*wind design required*" region largely parallels the areas in the 2000 and 2003 IRC where the old allowable stress design-level wind speed was equal to or greater than 110 mph. Provisions for roof uplift connections were revised with a new table of roof-to-wall connection loads added and 200-pound maximum capacity defined for toe-nailed connections. Where loads from the new table exceed 200 pounds, hurricane clips or straps are required. #30 asphalt felt, self-adhered underlayment or equivalent products were required in high-wind areas where the nominal design wind speed is equal to or greater than 120 mph.

The following changes were enacted in the 2014 IRC. Wind provisions were fully correlated with ASCE 7-10 and ultimate wind speed basis. Extensive revisions were made to prescriptive tables to reference ultimate design wind speeds but incorporate 0.6 allowable stress design factor directly in calculations. Thus, little to no change in actual design occurred. The limit on use of wood structural panels for wind-borne debris protection changed from 2 stories maximum to 33-foot mean roof height. Wood structural panel sheathing was permitted to be used as lateral support for deep rafters and high-heel trusses in lieu of blocking or blocking panels. A prescriptive limit of 30 psf wall pressure was imposed on the standard table of siding and cladding attachments; beyond 30 psf an engineered design is required for attachment of siding and cladding.

3.2. State of Florida

After Hurricane Andrew landed in Florida in 1992, an effort was made in southern Florida to revise the current building codes. In 1994, the first post-Andrew version of the South Florida Building Code (SFBC) was published. In 2002, Florida became unified under the Florida Building Code: Building (FBCB). Notable sections and changes to the wind provisions of the 1994 and 1999 editions of the SFBC and the 2002-2017 editions of the FBCB are described below.

3.2.1. SFBC Wind Provisions

The following are notable sections from the 1994 SFBC. Section 2309.1 (a)(3) states that "*Buildings and structures in the coastal building zone and eastward of the Coastal Construction Control line shall be designed in accordance with exposure D of ASCE 7*." Section 2309.1 (a)(4) states that "*All other buildings in Broward County shall be designed in accordance with exposure C of ASCE 7*." Section 2309.1 (a)(5) states that "*All buildings and structures shall only utilize an importance factor "At Hurricane Coastline" in Table 5 of ASCE 7*." Section 2309.1 (i) states the "*The provisions for wind loads shall be as shown in 6. of ASCE 7 With Commentary*."

In 1999, Section 2309.8 (Air Permeable Cladding) was added to the SFBC. This section specifies the allowable methods for calculating design wind loads for air permeable cladding and rigid roof tile coverings.

3.2.2. FBCB Wind Provisions

In 2002, the first edition of the Florida Building Code: Building was created. Section 1609 (Wind Loads) was written to include full design specifications and calculations in the code. Previously the SFBC primarily referred to ASCE 7 for specifications and calculations. This code saw the first implementation of High Velocity Hurricane Zones. These zones were defined as Broward and Miami-Dade counties—three-second gust wind velocities were specified for both counties. All buildings were to be considered to be in Exposure Category C and designed based on a 50-year mean recurrence interval.

The 2004 FBCB included the 2007 amendments. In this version, contents of Table 1609.1.4 (Wind-Borne Debris Protection Fastening Schedule for Wood Structural Panels) was changed. Previously, fastener spacing was provided for 2 1/2 #6 wood screws, 2 1/2 #8 wood screws, and double-headed nails. The updated table provided fastener spacing for #8 wood screw-based anchor with 2-inch embedment length, #10 wood screw-based anchor with 2-inch embedment length, and 1/4 lag screw-based anchor with 2-inch embedment length. FBCB 2002 Section 1621 (High Velocity Hurricane Zones Allowable Stress Increase) was removed from the new edition.

The 2008 FBCB included the 2009 supplement and was revised to include a statement in Section 1609.1 (Applications) noting that all exterior wall coverings and soffits shall be able to resist the same pressures specified for wall for components and cladding loads. FBCB 2004 Section 1609.6 (Simplified Wind Load Method) was removed from this edition, and Section 1622 (High-Velocity Hurricane Zones – Screen Enclosures) was added. This section specifies how wind loads are to be calculated for screen enclosures, windbreakers, and permanent frames.

In the 2017 FBCB, all sections were updated to correlate with ultimate wind speed basis used in ASCE 7-10. FBCB 2008 Figure 1609 (State of Florida Debris Region & Basic Wind Speed) was converted to FBCB 2017 Figure 1609 (Ultimate design Wind Speeds). The new figure includes multiple subfigures corresponding to different risk categories. FBCB 2008 Table 1609.1.2

(Wind-Borne Debris Protection Fastening Schedule for Wood Structural Panels) was removed from the new edition. Section 1615.2 (Concentrated loads) was removed from Section 1615 (High-Velocity Hurricane Zones – Minimum Loads). Section 1617 (High-Velocity Hurricane Zones – Roof Drainage) and Section 1619 (High-Velocity Hurricane Zones – Live Load Reductions) were removed from the new edition. Section 1620 (High-Velocity Hurricane Zones – Wind Loads) was updated to reflect inclusion of multiple risk categories. All risk categories reflect an increase in three-second gust wind velocities for Broward and Miami-Dade Counties.

4. ANALYSES CONSIDERING BUILDING CODE MODIFICATIONS/UPDATES

4.1. State of Texas

In order to investigate the effect of code updates on the damage buildings experienced during these disasters, the dataset is divided into eight subsets according to year of construction: 1957 and before, 1957 to 1973, 1973 to 2000, 2000 to 2003, 2003 to 2006, 2006 to 2009, 2009 to 2012, and 2012 and after. These subsets are selected based on available code updates for wood structures which are followed in Texas (Section 3.1). Here, in accordance with the results of Section 2.1.1, the effect of code updates is studied for three components of the building, namely, roof cover, wall cover, and windows. Each component is further discussed in the following subsections.

4.1.1. Roof Cover

The histogram plots of damage to roof covering of buildings in the eight aforementioned subsets of years are presented at the same time in Figure 18. This figure indicates that the damage of the roof cover in most of the buildings which are built recently (for instance, consider 2012 and after) is classified as level 1. In contrast, the roof cover of the older buildings (consider 1957 and before) experienced a wide range of damage levels, and only a few of them (around 20% for the pre-1957 built buildings) were classified as damage level 1 (associated with no significant damage). In addition, according to the frequency percentages of the buildings classified as damage level 5, this figure indicates that more aged buildings are classified as damage level 5 compared to the less aged buildings. It should be noted that the buildings constructed between 2003 and 2006 have experienced considerably less damage to their roof cover in comparison to the two subsets of buildings constructed in previous years (2006-2009 and 2009-2012), which might be because of the code updates.

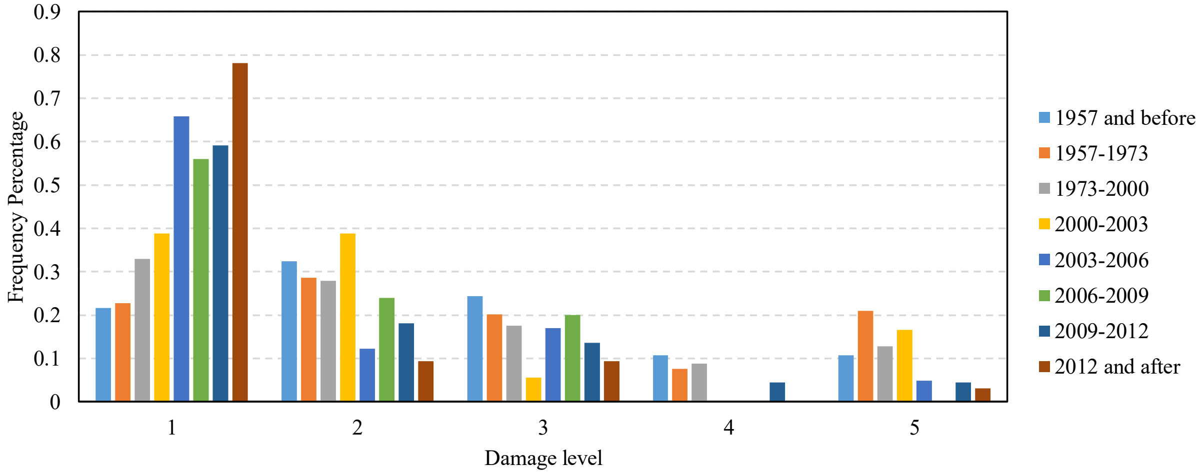

Figure 18: Histogram of damage to roof cover for different year subsets.

In addition, the average damage level of each built year subset is computed and shown in Figure 19. This figure shows that the average damage in the roof cover decreased significantly for subsets after 2003.

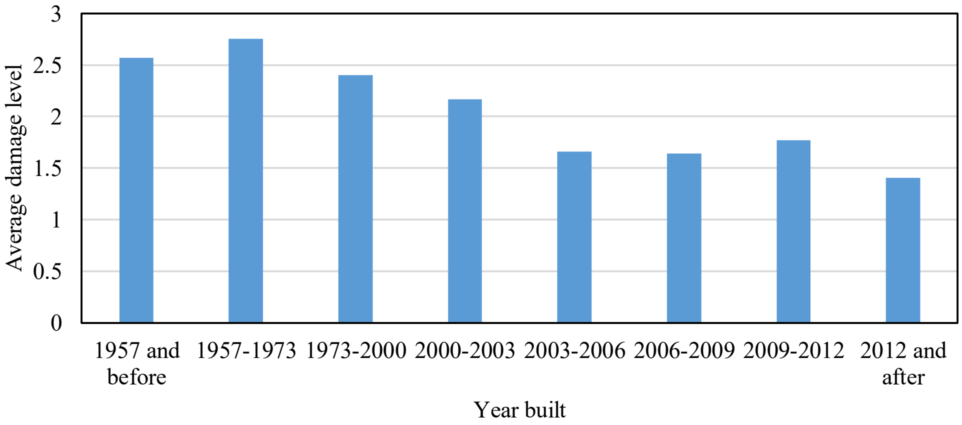

Figure 19: The average damage level of roof cover for each year bracket.

4.1.2. Wall Cover

The damage level vs. frequency for the various time frames associated with code updates for the wall cover is presented in Figure 20. The results regarding the relationship between damage and the year of construction are similar to the roof cover with one exception. The buildings constructed between 2009 and 2012 surprisingly experienced more damage to wall cover compared to a number of the subsets of years before it. The reason for this phenomena should be investigated through the code update. It should be mentioned that it may be due to some bias in the dataset, since the data points for this subset might be not be large enough to be reliable.

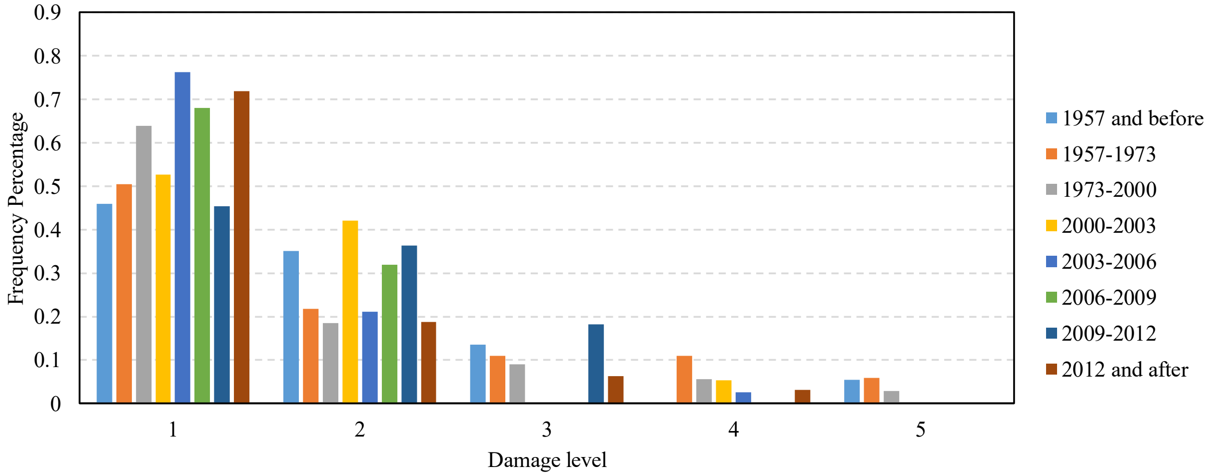

Figure 20: Histogram of damage to wall cover for different year subsets.

In addition, the average damage level of each construction year subset is computed and shown in Figure 21. This figure shows that the average damage in wall cover decreased significantly for subsets after 2003, with the exception of 2009-2012.

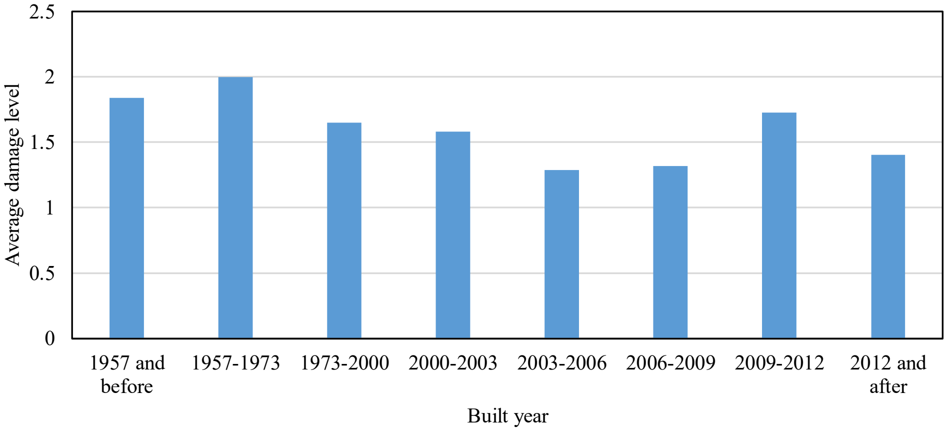

Figure 21: The average damage level of wall cover for each year bracket.

4.1.3. Windows

The damage level vs. frequency for the various time frames associated with code updates for window damage is presented in Figure 22. The results regarding the relationship between damage and the year of construction are similar to those presented for roof cover. This figure shows that in the thresholds of years 1957 and 2000 the damage levels changed more significantly. For instance, by observation of damage level 1, the frequency increases with a bigger step in these two year thresholds compared to the years before these thresholds. Considering damage level 1 is the least damage of windows, this figure shows that the windows in buildings constructed after 2000 experienced the least level of damage in comparison to those ones constructed prior to 2000.

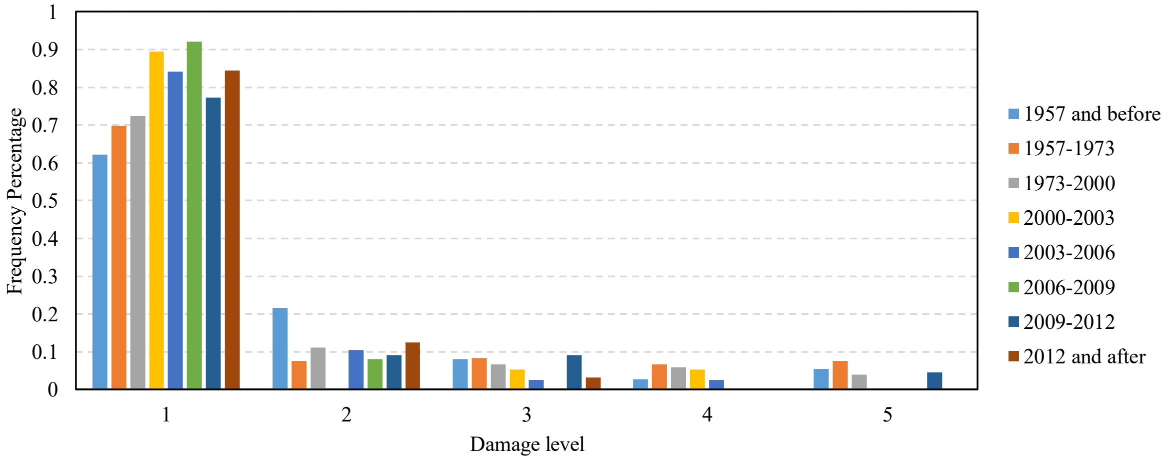

Figure 22: Histogram of damage to windows for different year subsets.

In addition, the average damage level of each construction year subset is computed and shown in Figure 23. This figure shows that the average damage in wall cover decreased significantly for subsets after 2000, with the exception of 2009-2012.

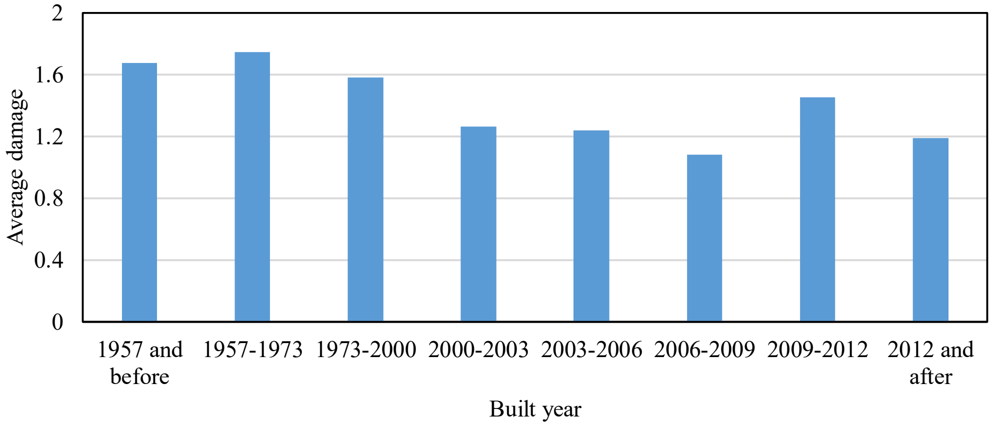

Figure 23: The average damage level of windows for each year bracket.

4.2. State of Florida

In order to investigate the effect of code updates on the damage buildings experienced during these disasters, the Florida dataset is similarly divided into seven subsets based on year of construction: 1994 and before, 1994 to 1999, 1999 to 2002, 2002 to 2004, 2004 to 2008, 2008 to 2017, and 2017 and after. These subsets are selected based on available code updates for wood structures which are followed in Florida (Section 3.2). However, since Irma happened in 2017, the last subset is not necessary and is eliminated. Here, in accordance with the results of Section 2.2.1, the effect of code updates is studied for two components of the building, namely, roof cover and wall cover. Each component is further discussed in the following subsections.

4.2.1. Roof Cover

The histogram plots of damage to roof cover of buildings in the six aforementioned subsets of years are presented at the same time in Figure 24. This figure indicates that less than 10% of buildings constructed between 2008 and 2017 have experienced damage greater than level 1 (associated with no significant damage). A surprising observation in this diagram is that roof cover of buildings constructed between 2004 and 2008 experienced a wide range of damage compared to other year brackets. Approximately 63% of the buildings constructed in this period experienced damage level 1 and below. This is even worse than the oldest buildings constructed prior to 1994.

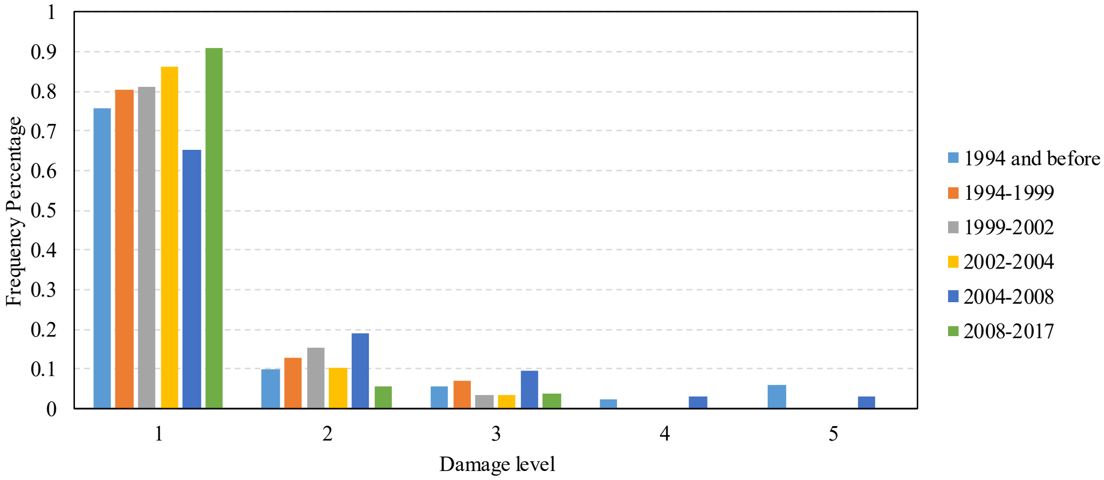

Figure 24: Histogram of damage to roof cover for different year subsets.

In addition, the average damage level of each construction year subset is computed and shown in Figure 25. This figure shows that the average damage in the roof cover decreased significantly after 1994, when the first state-wide code/standard was introduced. In addition, the results of this plot confirm the previous claim on the 2004-2008 year bracket. A sudden increase is present in the average damage level for this bracket compared to the others.

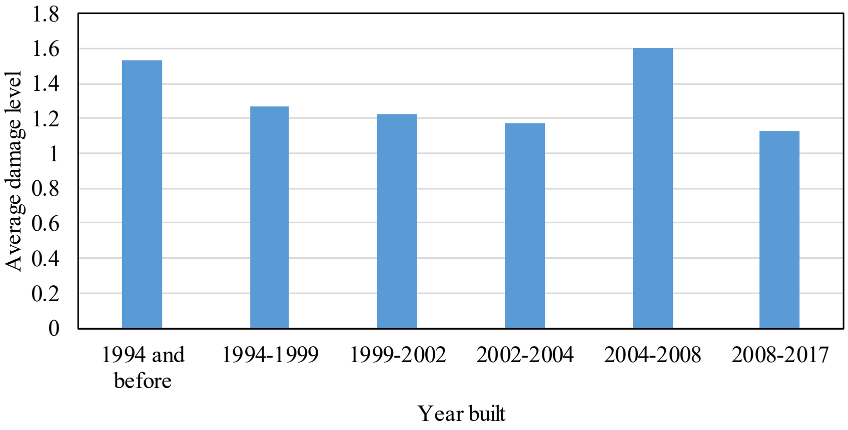

Figure 25: The average damage level of roof cover for each year bracket.

4.2.2. Wall Cover

The damage level vs. frequency for the various time frames associated with code updates for wall cover is presented in Figure 26. The highest frequency in damage level 1 is observed for the 2008-2017 bracket and the lowest is for those buildings constructed before 1994. In addition, the only bracket with damage level 5 is the bracket associated with construction before 1994.

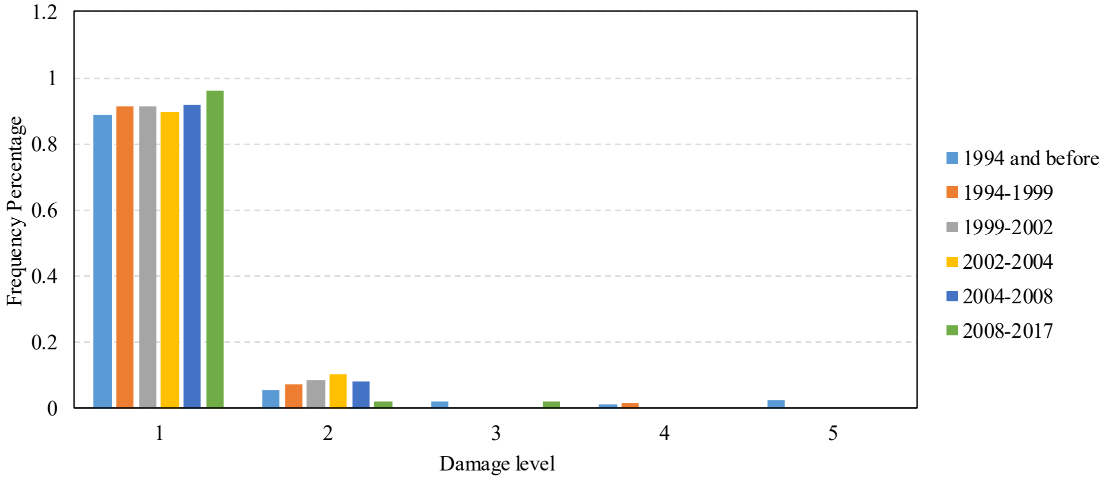

Figure 26: Histogram of damage to wall cover for different year subsets.

In addition, the average damage level of each construction year subset is computed and shown in Figure 27. This figure shows that the average damage in the wall cover decreased significantly for the subsets after 1994. There is a slight increase in the average damage of 2002-2004 compared to its previous bracket. However, since it is a slight (not significant) increase, it can be due to the nature of the dataset.

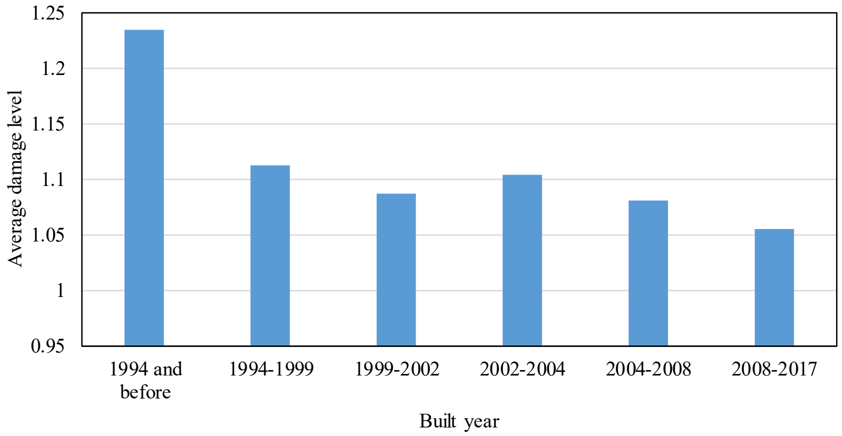

Figure 27: The average damage level of wall cover for each year bracket.

5. DISCUSSION – MAIN FINDINGS

Based on the analyses and results presented earlier in this document, it can be concluded that the overall damage in Texas after Hurricane Harvey was more significant to the residential building infrastructure when compared to the effect of Hurricane Irma in Florida. This may be due to the intensity of the events in these two states, and also differences between their building characteristics and designs (and associated building codes/standards in effect). Furthermore, Figure 7 and Figure 15 suggest that the damage to the building components is concentrated mainly in damage state 1 for the surveyed buildings in Florida but not for Texas. For both states, according to the results, roof cover and wall cover were the most important contributors to the overall damage of the buildings. However, in contrast to Texas, window damage was not a significant contributor for buildings located in Florida after Hurricane Irma. This might be due to the hurricane loads and also the differences between the typical windows in both states and associated design requirements.

Damage to the envelope of the buildings (roof and wall cover, and also windows for Texas) causes high overall damage. It may be attributed to the fact that when the envelope is damaged, the hurricane loads, including surge and rain water, can easily penetrate inside the building and destroy the vast majority of interior contents and nonstructural components even though the structure might be undamaged (structural damage). Hence, more attention should be devoted to the envelope of the building to decrease damage in future events.

In order to investigate the effect of code updates on the damage experienced by buildings in both states, the effect of such changes were also studied on the component damage level of the buildings.

For the Texas dataset, it is concluded that after the code update in 2003, a significant decrease in the *roof cover damage* of the buildings is observed. For the Florida dataset, it was found that the buildings constructed after 1994, when the first state-wide code was adopted in Florida, experienced less damage in their roof cover due to Hurricane Irma. In addition, surprisingly, the buildings constructed between 2004 and 2008 experienced more severe damage to their roof cover compared to the other brackets (years of construction), which might be attributed to either code updates or construction crew training and education on the newly updated codes and their implementation.

For the Texas dataset, it was found that that *damage to the wall cover* is lower for buildings constructed after 2003. Furthermore, surprisingly, damage to the wall cover is more severe for the buildings constructed between 2009 and 2012. Hence, the code updates in 2003 helped decrease damage to wall cover; however, the increased damage for buildings between 2009-2012 may be attributed to code updates or construction crew training and education on the newly updated codes and their implementation.

For the Florida dataset, the *damage to the windows* was not a significant contributor to the overall damage which might be due to the hurricane load characteristics. For instance, if there is less debris during the hurricane, the damage to the windows is less. On the other hand, it could be due to the design characteristics. For instance, the windows in Florida might have had a hurricane protector. For the Texas dataset, in contrast, the damage to the windows was one of the important contributors to the overall damage. It is observed that the window damage in buildings constructed after 2000 was less severe, which might be due to a better window design and characteristics, or due to more strict code requirements.

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7. REFERENCES

[1.] NSF StEER, https://web.fulcrumapp.com/communities/nsf-rapid?_ga=2.265489231.1163068473.1522345955-845539745.1519831616, 2018

[2.] C. C., 2000 International Building Code. Washington, DC: International Code Council, 2000.

[3.] C. C., 2003 International Building Code. Washington, DC: International Code Council, 2000.

[4.] C. C., 2006 International Building Code. Washington, DC: International Code Council, 2000.

[5.] C. C., 2009 International Building Code. Washington, DC: International Code Council, 2000.

[6.] C. C., 2012 International Building Code. Washington, DC: International Code Council, 2000.

[7.] C. C., 2000 International Residential Code. Washington, DC: International Code Council, 2000.

[8.] C. C., 2003 International Residential Code. Washington, DC: International Code Council, 2003.

[9.] C. C., 2006 International Residential Code. Washington, DC: International Code Council, 2006.

[10.] C. C., 2009 International Residential Code. Washington, DC: International Code Council, 2009.

[11.] C. C., 2012 International Residential Code. Washington, DC: International Code Council, 2012.

[12.] C. C., 2014 International Residential Code. Washington, DC: International Code Council, 2014.

[13.] Southern Building Code Congress, Southern Standard Building Code: 1957-58 Revision. Birmingham, AL: Southern Building Code Congress, 1945.

[14.] Southern Building Code Congress, Southern Standard Building Code: 1973 Edition. Birmingham, AL: Southern Building Code Congress, 1973.

[15.] State of Florida, 2001 Florida Building Code, Building. Florida: State of Florida, 2001.

[16.] State of Florida, 2004 Florida Building Code, Building. Florida: State of Florida, 2004.

[17.] State of Florida, 2007 Florida Building Code, Building. Florida: State of Florida, 2008.

[18.] State of Florida, 2017 Florida Building Code, Building. Florida: State of Florida, 2017.