Advancing Parcel-Level Hurricane Regional Loss Assessments Using Open Data and the Regional Resilience Determination Tool

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Abstract

Hurricanes are a major driver of losses in the United States and thus are the focus of risk assessment capacity building efforts in the public and private sectors, as well as in the scholarly community. Capabilities for loss modeling have been particularly advanced through the development of open-source scientific workflows that conduct site-specific, building-specific, and even component-level loss assessments across entire regions. Notable among these is the Natural Hazards Engineering Research Infrastructure's Computational Modeling and Simulation Center's (NHERI SimCenter) Regional Resilience Determination (R2D) tool. However, the modular architecture of R2D's computational scaffolding has only been described and illustrated through testbed applications thus far. This study presents the first replication and extension of the R2D tool to conduct parcel-level and component-level hurricane performance assessments outside of the SimCenter's testbed locations. The study first details how building inventories that capture time-evolving building characteristics and regional construction practices can be generated using updated heuristic rulesets that guide the integration of tax assessor data with other open data sources. These rulesets and supporting data are then utilized to generate building inventory information for a set of single family homes located in Florida's Bay County, the landfall site of Hurricane Michael in 2018. HAZUS-compatible, parcel-level damage and loss assessments are then conducted, considering Hurricane Michael's peak gust wind speeds. Finally, a set of custom fragilities, empirically-derived from multiple regional post-disaster datasets, are incorporated into R2D to conduct the first component-level damage assessment of buildings under hurricanes using the SimCenter's

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regional loss modeling workflows. In total, this represents an important first step in operationalizing replicable regional risk assessments down to the parcel level to provide more granular risk information to key stakeholders.

Keywords: hurricane, Florida, wind, open data, regional loss assessment

1. Introduction and Motivation

Large-scale disasters such as earthquakes, tsunamis, hurricanes, and other windstorms reveal how vulnerabilities in the built environment manifest as severe economic, environmental, and societal impacts, which threaten the lives and livelihoods of communities worldwide. The effective reduction of these disaster-related losses requires the driving mitigation at the scale of individual buildings [1], through policies informed by faithful regional loss assessments under realistic hazard scenarios [2]. Unfortunately prevailing loss assessment tools are far too generalized to guide parcel-level decisions: they adopt an aggregated approach that does not represent each building and its characteristics, as well as how they evolve over time, nor can these tools predict the anticipated levels of loss based on regional construction practices. Such capabilities are currently being advanced by investments in a new generation of open-source, data-enabled scientific workflows that evaluate hazard impacts on specific buildings considering site-specific features (e.g., [3-5]). In particular, the open-source software initiatives of the Natural Hazards Engineering Research Infrastructure Computational Modeling and Simulation Center (NHERI SimCenter) provide a modular and extensible application framework and access to high-performance computing necessary to further advance parcel-level regional loss assessments for entire building portfolios [6]. This offers an open-source computational scaffolding upon which researchers can architect their preferred data and analysis techniques along each step of the end-to-end loss assessment process. The development of such open-source loss modeling workflows is an important first step towards delivering tools that more faithfully predict an individual building's losses. This in turn gives building owners more actionable risk information for their property and responds to policy makers' desire for more realistic representation of potential losses to inform policy actions that incentivize mitigation [7].

To date, the modular architecture of the NHERI SimCenter's computational workflows has been described and illustrated through testbed applications that evaluate regional performance of buildings and lifelines under earthquake and/or hurricane scenarios [8]. While promising, these workflows enabled by the Regional Resilience Determination (R2D) tool [3], a research application for running regional simulations, must now be (1) replicated beyond these testbed sites and (2) extended to enhance their fidelity and/or granularity. This study responds by presenting the first replication of the NHERI SimCenter's R2D tool to conduct parcel-level performance assessments of buildings outside of the existing testbed regions and the first extension of R2D for component-level assessments under hurricane winds. These two contributions in turn demonstrate the robustness of the R2D tool's current capabilities as well as opportunities for the research community to further extend R2D for this and other hazard scenarios. Ultimately, the ability to contribute data and models within a common, open-source workflow such as R2D is imperative to advancing the research community's ability to support regional loss assessments capable of capturing each parcel's unique risk to hurricanes and associated vulnerabilities.

The following section presents a brief overview of the R2D tool's current methodology for conducting hurricane regional loss assessments. Given this additional context, Section 3 then discusses this study's first contribution: the replication of R2D's hurricane regional loss workflow for common building archetypes in Florida's Bay County, the landfall site of Hurricane Michael in 2018. Accordingly, Section 3.1 details this study's development of heuristic rulesets that guide the integration of parcel tax assessor data with other open data sources to automatically generate building inventories that capture time-varying regional construction practices in their asset descriptions. In Section 3.2, these rulesets and supporting data are then utilized to generate building inventory information for a set of wood-frame single family homes located in the Bay County municipalities of Mexico Beach and Panama City Beach. Parcel-level damage and loss assessments are executed for these homes, considering hindcasts of Hurricane Michael's peak gust wind speeds. This study's second contribution is next detailed in Section 4, wherein the R2D tool is further extended to enable component-level damage assessments for select homes in this inventory. Specifically, this implementation evaluates damage to asphalt shingle roofs under Hurricane

Michael's peak gust wind speeds, utilizing a set of empirically-derived fragilities informed by multiple post-disaster datasets from the region. The paper closes with a summary of this study's contributions and overview of key insights from the two extensions presented herein. Given the large number of acronyms used in the manuscript, a glossary is provided in the Supplementary Materials.

2. Background

The R2D tool currently adapts the Federal Emergency Management Agency (FEMA) Hazards United States Multi-Hazard (HAZUS-MH) damage and loss assessment methodology [9] to a parcel-level quantification of hurricane-related losses for entire building portfolios. Figure 1 summarizes the corresponding end-to-end workflow needed to execute such regional loss assessments, with emphasis herein on exposure to hurricane winds. Following the HAZUS-MH methodology, the building inventory is modeled using a set of pre-defined building classes. These classes consider the primary building material/construction mode (e.g., wood, masonry, concrete, steel, manufactured home) and occupancy (e.g., single family home). Each HAZUS-MH building class is then associated with specific attributes that characterize its load path and component vulnerabilities (e.g., roof shape, roof-to-wall connection, shutters) and the surrounding exposure (terrain roughness). Within such a framework, building (i.e., asset) descriptions are ultimately focused on providing the information necessary to map individual buildings in the inventory to their corresponding HAZUS-MH building archetype (i.e., building class and associated attributes). As noted in the development of R2D's current hurricane testbeds in Atlantic City, New Jersey [10] and Lake Charles, Louisiana [11], the generation of building descriptions often requires consideration of the region's specific regulatory environment and construction practices. Often, various data sources are interrogated using heuristic rulesets to populate the requisite information. For example, critical building characteristics needed for vulnerability descriptions not reported in parcel tax assessor data are often addressed by code-informed rulesets, human subject data, and classifications from machine learning algorithms [3,12,13]. Given each building's corresponding HAZUS-MH building archetype, hazard intensity measures (i.e., peak gust wind speed) can then be directly related to respective probabilities of damage and loss using each archetype's corresponding HAZUS-MH fragility and loss curves. The resulting damage and loss assessments are reported by R2D at the building level.

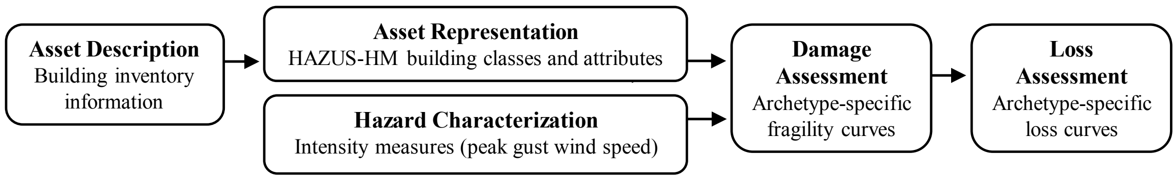

Figure 1: Schematic overview of HAZUS-MH's end-to-end loss assessment workflow currently implemented in R2D.

3. R2D Replication: HAZUS-Compatible Assessments for Parcels in Florida's Bay County

Extending R2D's damage and loss assessment workflow to regions outside of the SimCenter's current hurricane testbed regions ultimately requires a scalable means to generate and map building-specific attributes to HAZUS-MH representations. The first such extension of the R2D workflow herein focuses on common building archetypes in Florida's Bay County, the landfall site of Hurricane Michael in 2018. Section 3.1 details the identification and generation of building-specific attributes informing designations of HAZUS-MH representations for the building classes listed in Table 1. It should be noted that all the rulesets formalized in this section are openly available in DesignSafe through a set of Python scripts that allow for automated population of building-specific attributes [14]. In Section 3.2, the methodology is then applied to generate building inventories, which are also published in DesignSafe [15] and used to conduct damage and loss assessments of a set of single-family homes located in Mexico Beach, FL and Panama City Beach, FL subject to Hurricane Michael's peak gust wind speeds.

Table 1: HAZUS-MH building classes and descriptions replicated herein for Florida's Bay County

Building Class Descriptions	**HAZUS-MH Building Class (HAZUSClass)**
Wood, Single-Family Homes: 1 story, 2+ stories	WSF1, WSF2
Wood, Multi-Unit/Hotel/Motel 1 story, 2 story, 3 story	WMUH1, WMUH2, WMUH3
Masonry, Engineered Commercial Building: Low-Rise (1-2 stories), Mid-Rise (3-5 stories), High-Rise (6+ stories)	MECBL, MECBM, MECBH
Masonry, Low-Rise Industrial/Warehouse/Factory Building	MLRI
Steel, Engineered Commercial Building: Low-Rise (1-2 stories), Mid-Rise (3-5 stories), High-Rise (6+ stories)	SECBL, SECBM, SECBH
Steel, Pre-Engineered Metal Building: Small, Medium, Large	SPMBS, SPMBM, SPMBL

3.1 Building Descriptions and Representations

Table 2 lists all of the information needed to automatically identify a building's respective HAZUS-MH building class and populate the corresponding class-specific attributes. Similar to the methodologies enacted in the development of R2D's current hurricane testbeds [11,16], this study also leverages the use of parcel tax assessor data, along with other open data sources, to generate building inventory information; these data sources are also listed in Table 2, along with the format of the resulting description. The following information is available for most parcels containing buildings in Bay County: parcel identification number, year of construction, address, occupancy, number of stories, total floor area, frame type, exterior wall type, interior wall type, floor cover, and permit information (i.e., permit number, issue date, and description) [17]. Note that the range of data classes exposed by the Bay County tax assessor exceeds that available for the typical locality, which would normally expose the following subset of fields: year of construction, address, parcel identification number, occupancy, number of stories, and total floor area. Herein, further details are provided regarding the development of rulesets that guide the integration of parcel tax assessor data with other open data sources to populate building descriptions over this inventory.

Table 2: Bay County building inventory data model utilized in first replication of R2D

Attribute	Description	Format	Source
BldgID	Unique identifier for the building	Integer	User specified
ParcelID	Unique identifier for the parcel	String	Parcel tax data
Address	Assessor-reported property location: number, street, city, state, zip code	String (alphanumeric)	Parcel tax data
Occupancy	Assessor-reported property occupancy class	String (alphanumeric)	Parcel tax data
TotalFloorArea	Total floor area of building, reported in square feet	Integer	Parcel tax data
NumberOfStories	Assessor-reported number of stories or estimated	Integer	Parcel tax data
BldgYearBuilt	Assessor-reported building year of construction	Integer	Parcel tax data
RoofCover	Assessor-reported roof cover	String	Parcel tax data
FrameType	Assessor-reported frame type	String	Parcel tax data
PermitNumber	Assessor-reported permit numbers associated with this parcel	String (alphanumeric)	Parcel tax data
PermitType	Assessor-reported permit type, categorizing nature of requested action	String	Parcel tax data
PermitIssueDate	Issue dates of assessor-reported permits for parcel	String (alphanumeric)	Parcel tax data
PermitDescription	Description of permit-related action (e.g., repair, retrofit, demolition)	String	Parcel tax data
Latitude	Latitude of building footprint's centroid	Floating point number	Microsoft Building Footprints [18]
Longitude	Longitude of building footprint's centroid	Floating point number	Microsoft Building Footprints [18]
RoofShape	Classification of roof shape as either hip, gable, or flat	String	Rulesets (codes and standards) and post-disaster datasets
RoofSlope	Slope of roof covering majority of building	Floating point number	Rulesets (codes/standards)
TerrainRoughness	HAZUS-MH-defined terrain classifications based on Land Use Land Cover (LULC) data	String	LULC data [19]
DWSII	Ultimate design wind speed (DWS) in miles per hour, category II buildings, determined using BldgYearBuilt	Floating point number	ATC API [20] or Florida Building Code wind speed maps
County	Florida county building resides in	String	Parcel tax data
FloodZone	FEMA flood zone designation as defined by Flood Insurance Rate Maps	String	Bay County FEMA Flood Zones [21]
Garage	Garage presence (single-family homes)	Boolean	National survey data
AvgJanTemp	Average temperature in January below or above critical value of 25F	String	User specified
City	City building resides in	String	Parcel tax data
State	State building resides in (FL)	String	Parcel tax data
WBDRegion	Whether or not building is in a	Boolean	Rulesets

	windborne debris (WBD) region		(codes/standards)
HPR	Whether or not building is in a hurricane prone region (HPR)	Boolean	Rulesets (codes/standards)
HVHZ	Whether or not building is in the high velocity hurricane zone (HVHZ)	Boolean	Rulesets (codes/standards)
RoofReplaceYear	The year of the last reported roof replacement for the building	Integer	Building permit data

In this study, data from national surveys is utilized to statistically describe the presence of garages in single family homes (Garage attribute in Table 2). The authors have previously demonstrated how, given a building's occupancy, year of construction, location, and total floor area, a set of sample buildings can be selected from national surveys such as the Residential or Commercial Buildings Energy Consumption surveys [22,23] to inform weighted sampling of building attributes [24]. Note that this strategy is adopted herein as a proxy for the SimCenter's computer vision approaches [13] in situations where model retraining is not feasible due to time constraints and/or lack of surface imagery.

Codes and standards serve as another important data source in the generation of building inventory information. Given a building's location, occupancy, and year of construction, the corresponding code regulations governing at the time of construction can be utilized to infer the likely presence of specific building features or minimum clearances/component sizings [11,12,24]. It is important to note, however, that the utilization of building codes for attribute assignments is advisable only when local authorities have a demonstrated history of adopting and properly enforcing model codes, as is the case in the State of Florida [25]. Table 3 provides an overview of each edition of the Florida Building Code (FBC) and effective dates [26] for construction preceding Hurricane Michael in 2018. It should be noted that before the enactment of the FBC, Dade and Broward counties typically followed South Florida Building Code (SFBC) regulations, while the rest of the state adopted other minimum building codes such as the Standard Building Code (SBC) and the Council of American Building Officials (CABO) One and Two Family Dwelling Code [9,27].

Table 3: Legacy of FBC adoption in the State of Florida

	Effective Date			
Code Edition	**Original**	**Supplement 1**	**Supplement 2**	**Supplement 3**
2001 FBC	03/01/02	06/20/03	--	--
2004 FBC	10/01/05	12/16/05	12/08/06	07/01/07
2007 FBC	03/01/09	03/01/09	10/01/09	--
2010 FBC	03/15/12	04/15/12	--	--
2014 FBC	06/30/15	07/01/16	10/08/16	--
2017 FBC	12/31/17	--	--	--

Informed by the chronology in Table *3*, the population of time-varying, region-specific building attributes in Table 2 are accordingly facilitated through the formalization of heuristic rulesets whose time-evolving logic is tied to the effective dates of specific code editions. This is illustrated by Figures 2 and 3 which respectively provide schematic representations of rulesets informing whether a building is/is not located in a windborne debris (WBD) region (WBDRegion attribute), considering 2001 versus 2010 FBC regulations. Importantly, the ruleset visually depicted in Figure 2 provides one example of how code-informed rulesets can be utilized to capture critical, region-specific construction practices -- in this case, the infamous Panhandle exemption for windborne debris regions. It should be noted that designations of the Design Wind Speed (DWS) (DWSII attribute) herein consider each building's reported year of construction; such an implementation sometimes requires conversion of allowable stress design wind speeds to quantify the appropriate DWS. Figures 4 and 5 provide schematic representations of other rulesets developed in this study to generate attributes of the building site's association with a hurricane prone region (HPR) or a high velocity hurricane zone (HVHZ) using the 2010 FBC. It should be noted that descriptions of WBD, HPR, and HVHZ-related attributes are considered important meta-variables for subsequent population of specific attributes associated with common building classes in HAZUS-MH.

R2D's extension is ultimately facilitated by the formalization of heuristic rulesets using Bay County's governing codes and standards. These rulesets allow R2D to automatically populate various building descriptions, e.g., assigning flat roof shapes to all buildings with assessor-reported (low-slope) roof covers, including built-up, single-ply, and thermoplastic polyolefin roofing. Note that this approach also reduces reliance on computer vision to process satellite imagery using convolutional neural networks to populate descriptions of RoofShape. Unfortunately, for pitched roofs, such machine-learning-based approaches will often be necessary [13] since this feature is not reported in most assessor databases, unless another dataset is available to assign roof shapes in the region (e.g., post-disaster datasets, tax assessor data, exposure databases). Fortunately for this extension, such pitched roof shape descriptions are available for single family homes thanks to post-disaster field surveys following Hurricane Michael [28]. Codes and standards are also utilized to populate minimum roof slope descriptions (RoofSlope attribute) for each building's assessor-reported roof cover. This implementation is offered herein as an intermediary to the SimCenter's computer vision-based approach [10]. Note that the RoofSlope attribute only affects subsequent descriptions of secondary water resistance (SWR) for HAZUS-MH wood single family (WSF) and wood multi-unit housing (WMUH) building classes, considering roof construction between the years 1979-2001.

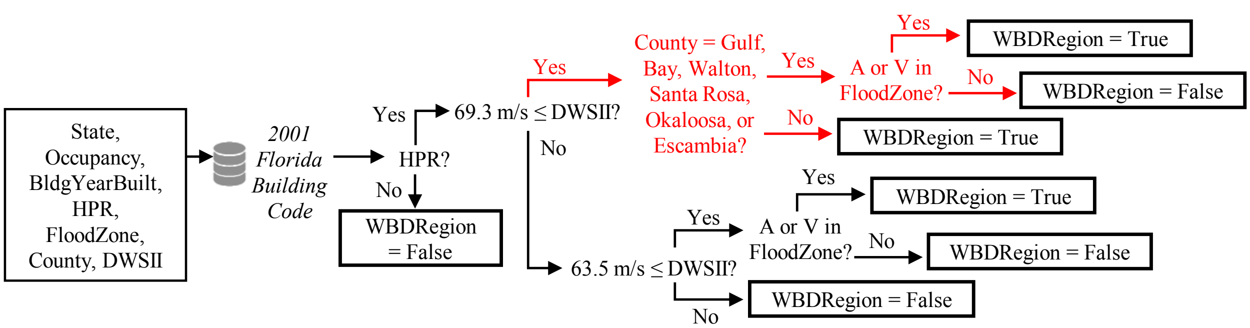

Figure 2: Schematic representation of code-informed ruleset used to determine if a building governed by the 2001 FBC is/is not in a windborne debris region (WBDRegion attribute). Ruleset includes Panhandle Exemption (see red).

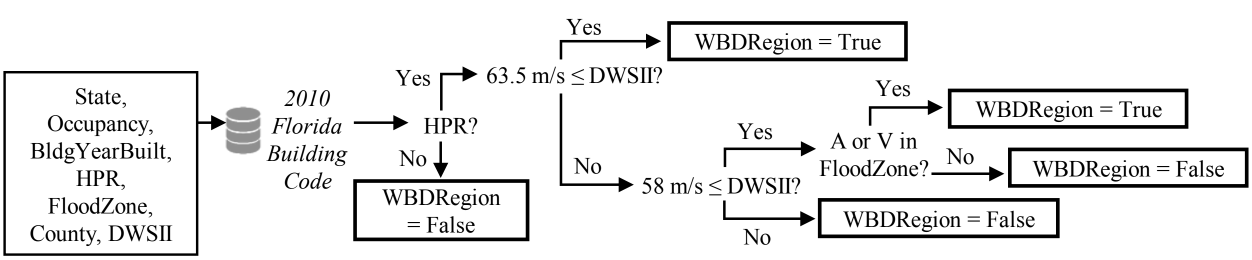

Figure 3: Schematic representation of code-informed rulesets used to determine if a building governed by the 2010 FBC is/is not in a windborne debris region (WBDRegion attribute).

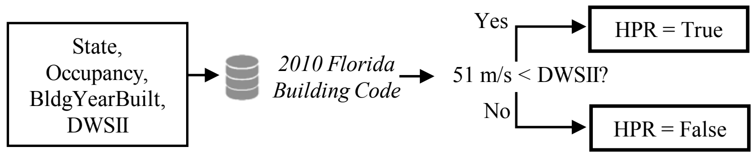

Figure 4: Schematic representation of code-informed rulesets used to determine if a building governed by the 2010 FBC is/is not in a hurricane-prone region (HPR attribute).

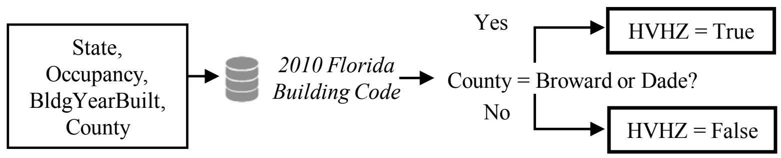

Figure 5: Schematic representation of code-informed rulesets used to determine if a building governed by the 2010 FBC is/is not in the High-Velocity Hurricane Zone (HVHZ attribute).

Importantly, the 2009 supplement to the 2007 FBC introduced new requirements for roof replacements on single-family homes. These requirements include the installation of a secondary water barrier, re-nailing of the roof deck, and retrofitting of roof-to-wall connections. It should be noted that all three of these attributes are used in HAZUS-MH representations of single-family homes. As previously stated, the Bay County Property Appraiser openly reports parcel-specific building permit information, which can be queried to refine the age of construction used by the rulesets when assigning roof-related attributes for homes that have been re-roofed. Figure 6 shows a schematic overview of the corresponding workflow that string processes the PermitType attribute to automatically identify the presence of roof-related permits. Upon verifying the presence of a roof permit, the corresponding permit description (PermitDescription) is queried for standard expressions (e.g., 'replace', 'replacement', 'new') to identify occurrences of re-roofing. Strings describing permit issue dates (PermitIssueDate) are then segmented to extract the year of the last reported roof replacement for each building (i.e., RoofReplaceYear). The resulting RoofReplaceYear attributes are later utilized when populating roof-related attributes for HAZUS-MH's WSF building class. Note that permits had not previously been used in SimCenter workflows to establish the age of specific building components, demonstrating a new use of open data for more faithful representations of building inventories.

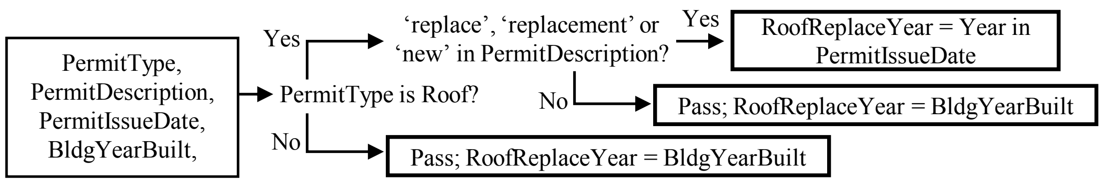

Figure 6: Schematic overview of workflow employed to identify RoofReplaceYear through queries of building permit information.

These HAZUS-MH classes are designated using the Occupancy and FrameType attributes listed in Table *2*. Once assigned, a unique combination of attributes associated with that building class must be assigned in order to specify the appropriate damage and/or loss curves. Table 4 provides an example of the rulesets used in this process for the HAZUS-MH WMUH building class. The various occupancies listed in Table 4 respectively categorize a building as either a multi-family residential building, a housing cooperative, or a hotel/motel. Using each building's assessor-reported number of stories and frame type, the corresponding HAZUS-MH building class is designated. As noted at the bottom of Table 4, default attributes are provided to facilitate assignments when tax assessor entries are incomplete, e.g., frame type defaults to wood. Rulesets developed in this study for all building classes listed in Table *1* are available on DesignSafe [14]. It is important to note that, while many of the rulesets developed in this study are immediately extensible for applications in other Floridian counties, rulesets used to automatically designate each building's respective HAZUS-MH building class will often require some modification to accommodate differences in the local reporting of building occupancies and/or frame types across counties.

Considering each parcel's corresponding HAZUS-MH building class, additional attributes are populated using the building inventory information listed in Table *2* and heuristic rulesets. These attributes are accordingly summarized in Table 5 for all HAZUS-MH building classes considered in this study. It should be noted that codes and standards provide the basis for most of the heuristic rulesets assigning these attribute descriptions. For example, the Shutters attribute is common amongst many of the HAZUS-MH building classes considered in this study. Figure 7 provides a schematic representation of a ruleset developed to identify likely presence of shutters for construction complying with the 2001 FBC. In the process of assigning attributes to buildings within an inventory, there may be multiple open data sources providing relevant information, requiring some hierarchy of information processing. This study prioritizes assessor-reported descriptions, e.g., rulesets used to populate descriptions of HAZUS-MH roof cover types (i.e., RoofCoverH) for various commercial building classes will first query the assessor-reported roof cover. After populating each building's corresponding HAZUS-MH building class and respective attributes, R2D utilizes a Python script supplied by the end-user to automatically identify each building archetype's unique HAZUS-MH identifier, which ultimately streamlines queries of appropriate HAZUS-MH damage and/or loss curves.

Table 4: Rulesets used to designate HAZUS-MH classifications of wood, multi-family residential or hotel/motel buildings using parcel tax assessor data extracted from the Bay County Property Appraiser's website

Building Class Description	**HAZUS Class**	**Frame Type***	**Occupancy Description****	**NumberOf Stories**	**Ruleset**
Wood, Multi-Unit/Hotel/Motel 1 story	WMUH1	Wood	Multi-fami (000300); Cooperativ (000500); or Hotels and (003900)	1	HAZUSClass=WMUH1, IF Occupancy = (Multi-fami (000300) or Cooperativ (000500) or Hotels and (003900)) & NumberOfStories = 1 & FrameType = Wood
Wood, Multi-Unit/Hotel/Motel 2 stories	WMUH2	Wood	Multi-fami (000300); Cooperativ (000500); or Hotels and (003900)	2	HAZUSClass=WMUH2, IF Occupancy = (Multi-fami (000300) or Cooperativ (000500) or Hotels and (003900)) & NumberOfStories = 2 & FrameType = Wood
Wood, Multi-Unit/Hotel/Motel 3 stories	WMUH3	Wood	Multi-fami (000300); Cooperativ (000500); or Hotels and (003900)	3	HAZUSClass=WMUH3, IF Occupancy = (Multi-fami (000300) or Cooperativ (000500) or Hotels and (003900)) & NumberOfStories = 3 & FrameType = Wood

*Assume primary building material is Wood when Frame Type is not reported.
** Verbatim terminology used by tax assessor website. Multi-fami = multi-family residential building, Cooperativ= housing cooperative; Hotels and = hotel or motel.

Table 5: Overview of attributes for each HAZUS-MH building class considered in this study, including relevant input information

HAZUSClass	**Representation Attribute**	**Description**	**Input Attributes**	**Representation Choices**
WSF, WMUH	SWR	HAZUS-MH	RoofShape,	Yes, no

		Secondary Water Resistance (SWR)	BldgYearBuilt, RoofSlope, AvgJanTemp, HVHZ, RoofReplaceYear (WSF only)	
WSF, WMUH	RDAw	HAZUS-MH roof Deck Attachment (RDA) for wood frame structures	BldgYearBuilt, DWSII, HVHZ	A, B, C, D
WSF, WMUH	RWCw	HAZUS-MH roof-to-wall connection (RWC) for wood frame structures	BldgYearBuilt, HPR, DWSII, County	Toe-nail, strap
WSF, WMUH, MECBL, SECBL, SPMBS	Shutters	Presence of opening protection	BldgYearBuilt, WBDRegion	Yes, no
WSF	Augmented Garage	HAZUS-MH garage door strength	BldgYearBuilt, Garage, Shutters	None, SFBC 1994, standard, weak
WMUH, MECBL, MLRI, SECBL	RoofCoverH	Defines roof cover type for wind vulnerability assessments in HAZUS-MH	BldgYearBuilt, RoofShape, RoofCover	BUR, SPM
WMUH, MLRI	RoofQual	Defines roof quality for wind vulnerability assessments in HAZUS-MH	BldgYearBuilt, RoofShape, RoofCoverH	Poor, good
MECBL, MLRI, SECBL, SPMBS	RDAm	Metal roof Deck Attachment (RDA) as defined in HAZUS-MH	BldgYearBuilt, DWSII	Standard, superior
MECBL, SECBL	WindDebris	Wind debris exposure	BldgYearBuilt, Occupancy	Res/Comm, Residential, None
MECBL, SECBL	WWR	Window to wall ratio	BldgYearBuilt, WindowArea	Low, medium, high
MLRI	Mreinf	Presence of reinforcement in masonry walls	BldgYearBuilt	Yes, no
SPMBS	RDage	Roof deck (RD) age	BldgYearBuilt	New/avg, old

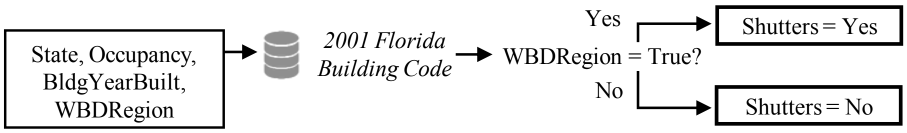

Figure 7: Schematic representation of code-informed rulesets used to determine likely presence of opening protection (Shutters attribute), considering compliance with 2001 FBC.

3.2 Regional Loss Assessment of Single Family Homes in Florida's Bay County

To demonstrate the extension of the SimCenter's workflows for hurricane impacts using region-specific rulesets and open data sources, this section utilizes the R2D tool to conduct regional loss assessments of 2244 wood-frame single family homes located in Florida's Bay County. Figure 8 depicts the locations of these single-family homes, which reside in the Mexico Beach, FL and Panama City Beach, FL municipalities, along with corresponding Hurricane Michael wind speed contours for the region [29]. For context, Bay County has 108,675 housing units with a majority of the county's households (59.9%) residing in single-family detached homes [30]. Impacts of Hurricane Michael were most significant in this building class, especially along the coastal zones adjacent to the landfall site (i.e., within 1 mile or 1.6 km from the coast), which encompassed 5912 single-family homes in Bay County. It is important to note that these 5912 homes do not include any homes that are now classified as vacant lots in the Mexico Beach region. The study adopts the subset of these 5912 single-family homes that are one-story, wood-frame with asphalt shingle roofs (N=2244). This subset of buildings was previously utilized to support the calibration of the component-level fragility functions [31] that will be introduced in Section 4. To further illustrate the implications of variances in regional construction practices, as well as modifications to buildings over time, this illustrative example considers the three ruleset cases outlined in Table 6: R2D's default rulesets, which were developed for the State of New Jersey (case #1) [10], and the Bay County-specific rulesets described in the previous section without and with consideration of re-roofing permits (case #2 and case #3, respectively). Note that the consideration of permit information in case #3 specifically demonstrates the implications of roof replacement provisions outlined in the 2009 Supplement to the 2007 FBC. Table 7 provides an overview of the R2D modules utilized in this study to conduct HAZUS-MH-compatible, parcel-level regional loss assessment for each of the three cases described previously. Further details are provided herein regarding the specific input information and parameters adopted for the simulation.

Figure 8: Depiction of this study's building inventory comprised of single-family homes in the coastal zones of Panama City Beach, FL and Mexico Beach, FL. Hurricane Michael wind contours reported in m/s for a 3-s gust at 10 m reference height in open exposure [29].

Table 6: Summary of ruleset cases explored in Section 3.2.

Ruleset Case	**Description**
1	R2D's default rulesets, developed for the State of New Jersey [10]
2	Region-specific rulesets developed for Florida's Bay County, without consideration of re-roof permits [14]
3	Region-specific rulesets developed for Florida's Bay County, with consideration of re-roof permits [14]

Table 7: Overview of R2D modules utilized in this study to conduct HAZUS-MH-compatible, parcel-level regional loss assessments.

Module	**Description**	**Implementation for HAZUS-MH-compatible assessment**
GI: General Information	Allows user to provide general information about the analysis (e.g., analysis name, units)	Specify force, length, and time units; output losses
HAZ: Hazards	Allows user to define or simulate hazards over a region	Provide longitude-latitude of hurricane stations and respective intensity measure (user-specified hurricane)
ASD: Asset Definition	Allows user to import databases containing asset descriptions	Load building inventory information from a comma-separated values file
HTA: Hazard to Asset	Allows user to specify how asset hazard intensities are to be determined	Use nearest neighbor approach
MOD: Asset Modeling	Allows user to specify models for assets	None
ANA: Asset Analysis	Allows users to specify analysis types for assets	IMasEDP analysis engine
DL: Damage and Loss	Allows users to select a damage and loss methodology to estimate losses over a region	HAZUS-MH damage and loss methodology
RES: Results	Allows user to review the results of an analysis	Output damage measures

To conduct regional analyses, R2D first requires the specification of requisite output variables in its general information (GI) module (e.g., engineering demand parameters, damage measures, losses). The hurricane wind hazard is next characterized using either wind speeds or their time histories [8] in R2D's hazards (HAZ) module. In this study, hurricane winds are characterized using wind speeds through an event file with the corresponding hurricane grid from the Hurricane Michael wind field on DesignSafe [29] at which corresponding peak gust wind speeds are reported. In R2D's asset definition (ASD) module, descriptions of wood-frame single family homes are populated using a CSV file with columns corresponding to those attributes previously listed in Table 2, excluding RoofCover and TotalFloorArea, which are not necessary to conduct a HAZUS-MH-compatible, parcel-level assessment of WSF building classes. In the hazard to asset (HTA) module, R2D automatically estimates each home's corresponding peak gust wind speed using a nearest neighbor search algorithm. Given that HAZUS-MH-compatible assessments do not require a structural analysis, no building models are specified in R2D's asset modeling (MOD) module. It follows that the analysis engine in the asset analysis (ANA) module treats each building location's intensity measure (IM) as the Engineering Demand Parameter (EDP). Damage and loss assessments in R2D utilize the NHERI SimCenter's Probabilistic Estimation of Losses, Injuries, and Community resilience Under Natural disasters (PELICUN) Python package [32]. When a home's respective HAZUS-MH building class and attributes are not provided in the previous ASD module, an auto-populate script in Python can be used in the DL module to automatically populate these descriptions using rulesets, such as those developed in Section 3.1. This is the approach implemented herein.

Table 8 summarizes the heuristic rulesets utilized in this study to populate descriptions of HAZUS-MH building classes for wood-frame single-family homes, using assessor-reported descriptions of Occupancy, FrameType, and NumberOfStories attributes. It should be noted that R2D's default rulesets inform this designation using each building's occupancy information and number of stories. Recall from Table 5 that the attributes for WSF buildings consist of the following: SWR, RDAw, RWCw, Shutters, and AugmentedGarage attributes. Given that these class-specific attributes are often populated using code-informed rulesets, it follows that these attribute designations will vary across the three cases considered herein. Figures 9a and b provide schematic representations of the code-informed rulesets used to infer the likely presence of a specific (wood) roof deck attachment (RDA) type using ruleset case #1 and #2, respectively. Beyond differences in code enactment years between the two rulesets, it should also be noted that the region-specific ruleset shown in Figure 9b also considers whether or not the building in question is in the High-Velocity Hurricane Zone (HVHZ). The HVHZ attribute is specific to the State of Florida, which defines Dade and Broward counties as the HVHZ.

Table 8: Rulesets used to designate HAZUS-MH classifications of wood, single family homes using parcel tax assessor data extracted from the Bay County Property Appraiser's website

Building Class Description	**HAZUS Class**	**Frame Type***	**Occupancy Description****	**NumberOf Stories**	**Ruleset**
Wood, Single-Family Homes 1 story	WSF1	Wood	Single Fam (000100)	1	HAZUSClass=WSF1, IF Occupancy=Single Fam (000100) & NumberOfStories=1 & FrameType=Wood
Wood, Single-Family Homes 2+ stories	WSF2	Wood	Single Fam (000100)	2+	HAZUSClass=WSF2, IF Occupancy = Single Fam (000100) & NumberOfStories=2+ & FrameType=Wood
*Assume primary building material is Wood when FrameType is not reported. **Verbatim terminology used by tax assessor website. Single Fam = single family					

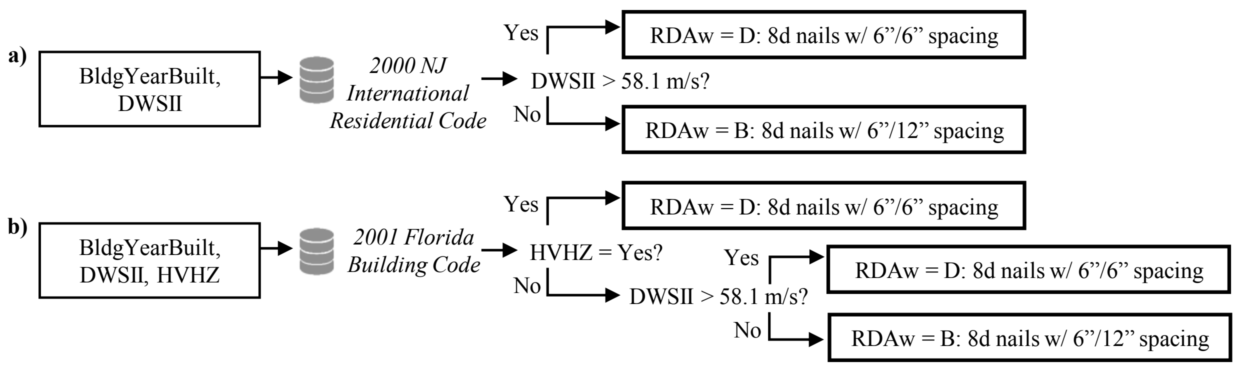

Figure 9: Schematic representation of code-informed rulesets used to determine likely presence of a specific (wood) roof deck attachment type (RDAw) for single family homes considering a) ruleset case #1 and b) ruleset case #2.

As mentioned previously, ruleset case #3 considers the roof replacement provisions outlined in the 2009 Supplement to the 2007 FBC. These roof replacement provisions aim to strengthen the resistance of the roof system during re-roofing activities through the following actions: (1) re-nailing of the roof deck, (2) installation of a secondary water barrier, and (3) retrofit of the roof-to-wall connections (RWCs). Therefore, the provisions of the 2009 Supplement ultimately affect the respective designations of the following attributes for the HAZUS-MH WSF building class: RDAw, SWR, and RWCw. Figure 10 provides a schematic representation of the ruleset used to capture the aforementioned roof replacement provisions using permit-reported roof replacement years (ruleset case #3). Figure 10 reveals that a building's year of construction (BldgYearBuilt) is accordingly utilized to populate these attribute descriptions when there is no evidence of a roof replacement before 2009. After these rulesets are used to assign appropriate HAZUS building classes and corresponding attributes, the auto-populate function supplied in R2D's damage and loss (DL) module identifies each building's corresponding HAZUS-MH archetype so that R2D's backend can query the corresponding databases to quantify damage and loss values for each parcel. The final building inventories used to run R2D for each locality and ruleset case in this study are openly available on DesignSafe [15].

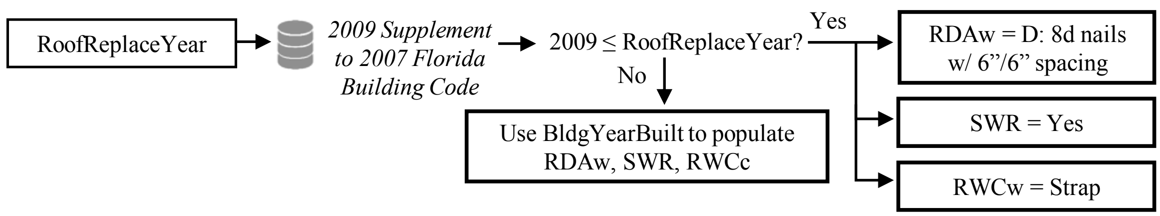

Figure 10: Schematic representation of code-informed ruleset used to capture the roof replacement provisions outlined in the 2009 Supplement to the 2007 FBC (ruleset case #3).

For HAZUS-MH-compatible loss assessments, R2D outputs each parcel's corresponding loss ratio, defined as the total building and content losses normalized by the total building and contents value. This loss ratio is then summed over all buildings in the inventory in Table 9, considering each ruleset case and municipality. Table 9 reveals that total expected losses reduce progressively for both municipalities as the fidelity of the asset description increases to capture region-specific features (case #1 vs. case #2) and building-specific retrofit actions (case #2 vs. case #3). The extent of the inventory affected by these different ruleset cases is captured in Table 10, which reports the total number of buildings populated with each possible description of RWCw, RDAw, and SWR attributes for that case. Comparing cases #1 and #2 in Table 10 reiterates the importance of developing region-specific rulesets to better capture implications of the local code environment, which in the case of a state with rigorous construction provisions, results in a greater number of homes with secondary water resistance and hurricane straps for the roof-to-wall connections. However, roof deck attachment designations using ruleset case #2 are actually weaker than those in ruleset case #1. This can be largely attributed to differences in the years when certain model code provisions were adopted in New Jersey (case #1) versus Florida (case #2) relative to the age of the homes in this inventory, a nuance that is corrected once permits are considered (case #3) to specifically date the roof and thus the codes governing at the time of that re-roofing project. Consideration of roof permit information also increases the total number of homes with hurricane straps for the roof-to-wall connections. These upgrades to the roof system captured by the case #3 rulesets, along with corresponding increase in homes with secondary water resistance, leads to further reduction of losses. These cases illustrate how the use of roof replacement permit information in a municipality with strong code enforcement practices eliminates the need to statistically infer attributes, thereby reducing the uncertainty in inventory generation.

Table 9: Total Expected Losses, calculated as the sum of building-specific mean loss ratios, for homes located in Mexico Beach, FL and Panama City Beach, FL.

	Total Expected Losses (Sum of Loss Ratios)		
Location	Case #1	Case #2	Case #3
Mexico Beach	122.33	115.22	113.64
Panama City Beach	383.81	366.80	354.70

Table 10: Total number of homes with specific roof-to-wall connection (Attribute: RWCw), roof deck attachment (Attribute: RDAw), and secondary water resistance (Attribute: SWR) descriptions, populated considering each of this study's three ruleset cases.

	RWCw		**RDAw**			**SWR**	
	Strap	Toe-nail	A (6d nails, 6"/12" spacing)	B (8d nails, 6"/12" spacing)	D (8d nails, 6"/6" spacing)	Yes	No
Case #1	1142	1102	778	756	710	1488	756
Case #2	1270	974	827	789	628	2058	186
Case #3	1330	914	717	817	710	2049	195

Table 11 lists the total number of single-family homes with a roof replacement permit in the two municipalities, as well as the number of these homes with roof replacement permits dating on/after 2009. Notably, the data in Table 11 reveals that approximately 64% of the total number of reported roof permits actually occurred on/after the enforcement of the FBC's 2009 roof replacement provisions. These roof replacement provisions ultimately affected about 10% of this study's building inventory and resulted in an approximately 7.5% reduction in losses over this 2244 home inventory (see Table 9), reinforcing the importance of capturing the evolution of the regional regulatory environment. It is important to note that

R2D's default rulesets were specified for the State of New Jersey, which is known to have more hurricane-resistant construction practices and better code-enforcement than other parts of the Southeastern United States [25]. Implications of replication of such rulesets in other states are discussed in the second author's recent ground truth evaluation in Louisiana [33]. Thus, while the reductions in total expected losses between default and region-specific ruleset cases are modest for the case of Florida, this implementation still demonstrates the importance of now being able to capture region-specific differences, which can be more pronounced for other localities and potentially under predict losses. Notably, while Table 9 reports aggregate losses for compactness, the fact that the loss ratios for case #3 are significant at a confidence level of 95% relative to case #1 (p-value ~ 0.02), suggests that investments in exposing and capturing time-evolving region and parcel-specific information can have significant effects on expected losses. Ultimately, the parcel-specific data underlying the losses in Table 9 represents a critical first step towards mainstreaming more granular risk communications to drive stakeholder mitigation actions. Beyond the illustrative case shown here, quantifying for policymakers the avoided losses achieved through the state's 2009 roof retrofit requirements, projected parcel-level damage and loss under specific scenarios can be now directly communicated to building owners to counter their current discounting of their home's potential for significant damage in future hurricanes [1] and to policy makers charged with crafting policies incentivizing mitigation investments for properties that meet certain risk profiles.

Table 11: Number of single family homes (i) with roof permits; (ii) with roof permits dating on/after 2009

Location	**Homes with roof permits**	**Homes with roof permits dating on/after 2009**
Mexico Beach	40	30
Panama City Beach	338	213

4. R2D Extension: Component-level Damage Assessments of Wood-frame, Single-Family Homes in Mexico Beach, FL

R2D's damage and loss module is next extended through the introduction of a set of component-level empirical fragilities for asphalt shingle roof covers derived for this region of Florida [31] to demonstrate how the granularity of parcel-level damage assessments can be refined for select buildings. These roof cover fragilities were developed using the HAZUS-MH damage scale for single family homes. Table 12 lists qualitative roof damage descriptions and associated roof cover losses for each damage state in this damage scale. Similar to the previous replication of R2D's HAZUS-MH-compatible regional loss assessments, the use of the aforementioned empirical roof cover fragilities within R2D's computational workflow ultimately requires (1) the population of parcel-specific attributes to correctly identify each building's corresponding roof cover fragility and (2) an auto-population script to facilitate this mapping within R2D. Note that the authors previously detailed their use of a Bayesian model updating framework to quantify parameter estimates for the aforementioned empirical roof cover fragilities using Hurricane Michael damage observations of sample buildings in Mexico Beach, FL and Panama City Beach, FL [31]. Therefore, the parcel-specific attributes that must be populated herein focus on those descriptions imperative to the identification of the sample buildings utilized in the development of these empirical fragilities (Table 13). Note that the discussion in Section 3.1 already detailed how open data can be utilized to populate descriptions for the required attributes (Occupancy, RoofCover, RoofSlope, and RoofShape) listed in Table 13. Details regarding the population of the remaining attributes (RCYearBuilt, BldgHeight, and WHPresence) now follow.

Table 12: Description of HAZUS damage states and associated roof cover loss [34]

Damage State	Qualitative Roof Damage Description	Associated Roof Cover Loss
0: No or Very Minor Damage	Minimal loss of roof cover, with no or very limited water penetration.	≤ 2%
1: Minor Damage	Moderate roof cover loss that can be covered to prevent additional water entering the building.	>2% to ≤ 15%
2: Moderate Damage	Major roof cover damage. Minor roof deck failure. Some resulting damage to interior of building from water.	>15% to ≤ 50%
3: Severe Damage	Major roof cover loss and possible major roof sheathing loss. Extensive damage to interior from water. Limited, local failures to roof structure.	>50%
4: Destruction	Essentially complete roof failure and/or of more than 25% of roof sheathing. Extensive damage to interior.	Typically > 50%

Table 13: Parcel-specific attributes used to identify sample buildings in the development of empirical fragilities for asphalt shingle roof cover

Attribute	Description	Acceptable Values for Sample Buildings
Occupancy	Building occupancy	Single family home
RoofCover	Roof cover material type	Asphalt shingles
RCYearBuilt	Roof cover year of construction	RCYearBuilt < 2002 or 2002 ≤ RCYearBuilt < 2016
RoofSlope	Roof slope	0.12 < RoofSlope ≤ 0.51
RoofShape	Roof shape	Gable or Hip
BldgHeight	Building height	3.35 m < BldgHeight ≤ 10 m
WHPresence	Wind hazard presence	Yes

Herein, building permit data is utilized to populate descriptions of roof cover year of construction (RCYearBuilt attribute) for each building. As shown in Figure 11, for any roof permit revealing the execution of a re-roof, roof replacement, or installation of a new roof, the corresponding permit year is extracted from the PermitIssueDate attribute. Note that roof cover year of construction is assumed to correspond to the building's year of construction unless a permit prior to Hurricane Michael's landfall date of 10 October 2018 suggests otherwise. To populate open data descriptions of the building height (BldgHeight attribute) [24], descriptions of each building's State, County, and YearBuilt are utilized to query the Department of Energy's (DOE) library of prototype residential and commercial building models [35,36]. This implementation serves as an extensible baseline for descriptions of the building height, noting that surface imagery such as Streetview can also be utilized in conjunction with machine-learning algorithms to extract specific building elevation data [11]. The WHPresence attribute is used to verify wind hazard presence (WHP) for each building. Given that wind pressure damage to structures typically initiates from the top-down, the presence of wind hazard can easily be verified using available wind field data for Hurricane Michael [29].

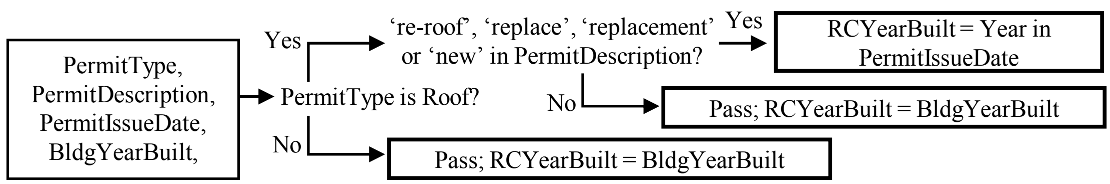

Figure 11: Schematic overview of workflow employed to populate descriptions of RCYearBuilt through queries of building permit information.

Given the aforementioned open data sources and corresponding rulesets, parcel-specific descriptions can then be populated for the 2244 single family homes analyzed in Section 3.2's case study. The corresponding building inventory can be found on DesignSafe [15]. The workflow then samples homes with attributes consistent with those used to generate the empirical fragilities, resulting in 8 and 62 homes in Mexico Beach and Panama City Beach, respectively. Table 14 lists the attribute descriptions utilized herein to select this subset of homes in each municipality. It is important to note that R2D's modular computational workflow allows for the easy exchange of data and models throughout each stage of the loss assessment workflow, allowing component-level damage assessments to be executed on this subset of homes in a manner similar to that described in Section 3.2 for building-level damage assessments. The two primary distinctions between component- and building-level workflows occur within R2D's ASD and DL modules. In the ASD module, the input building inventory information is updated to now describe the parcel-specific attributes listed in Table 13, while the DL module follows the path to the folder containing "User-provided fragilities" adopting the NHERI-SimCenter's established JavaScript Object Notation (JSON) file format [32]. Finally, similar to the replication described in Section 3.2, an auto-populate script must also be supplied to map parcel-specific descriptions to the pre-FBC and FBC (asphalt shingle) roof cover fragilities now specified in R2D's DL module.

Table 14: WSF class attributes of single family homes compatible with available empirical fragilities enabling component-level damage assessments using R2D.

WSF class attributes	**Values for selected homes**
RoofShape	Gable or hip
Garage	False
Shutters	True
RDAw	6d nails, 6"/6" spacing
RWCw	Toe-nail
SWR	False

Figure 12a and 12b display the most probable damage state for each municipality's subset of single-family homes (see (a) for Panama City Beach and (b) for Mexico Beach), using building-level fragilities (i.e., HAZUS-MH-compatible damage assessment) as well as roof cover component fragilities. Both Figure 12a and 12b show that damage assessments of single family homes using the building-level fragilities result in higher simulated damage than an assessment using the empirical roof cover component fragilities. Overall, lower damage is expected for the analysis using roof cover component fragilities, given that these fragilities were calibrated using Hurricane Michael peak gust wind speeds and not those wind speeds that would have instigated individual component failure [31]. It is important to note that, while the damage assessment using building-level fragilities classified many homes in Mexico Beach as being in damage state 3 or 4, recall from Table 12 that there is no increase in roof cover losses between these two damage states; this is due to the fact that a damage state 4 designation in this case is more concerned with failure of the Main Wind Force Resisting System (MWFRS) and subsequent water penetration damage. In contrast, the damage assessment utilizing roof cover fragilities guarantees an increase in roof cover losses with increase in damage state, given its explicit focus on component performance. Importantly, this example demonstrates how R2D's modular computational workflow can be readily extended to facilitate component-level damage assessments using a methodology parallel to the one presented in Section 3, creating opportunities for the wider research community to contribute their own component fragilities to further increase the granularity of the SimCenter's hurricane regional risk assessment capabilities.

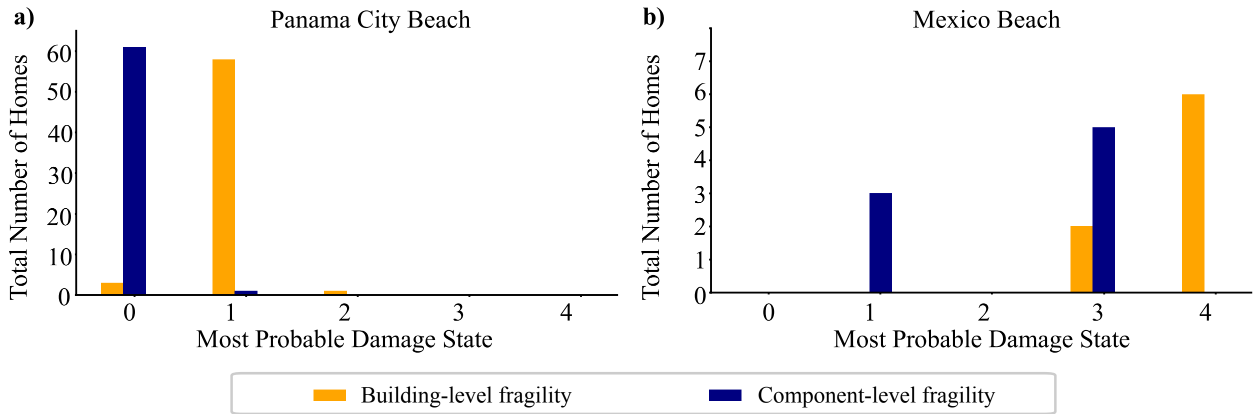

Figure 12: Most probable damage states of asphalt shingle roof covers using building-level and component-level fragilities for a subset of homes in a) Panama City Beach and b) Mexico Beach.

5. Conclusions

In an effort to effectively reduce disaster-related losses and better guide stakeholder mitigation actions, regional loss assessments are now being formalized into open-source, data-enabled scientific workflows by a number of efforts in the private and public sectors, as well as the scholarly community. Notable among these is the NHERI SimCenter' Regional Resilience Determination (R2D) tool, which enables parcel-level damage and loss assessments of entire building portfolios. While the promise of these software environments has been demonstrated through real-world testbeds, they had yet to be (1) replicated for regions outside of the testbed localities and (2) extended to achieve component-level loss assessment for hazards such as hurricanes. This study presented the first such replication and extension of the NHERI SimCenter's R2D tool for hurricane regional loss assessment to demonstrate the robustness of the R2D workflow and importantly illustrate how to leverage diverse sources of local open data to accurately capture regional construction practices and parcel-level features in these assessments.

This study specifically detailed how such replications of open scientific workflows can be accomplished through the use of local open data and heuristic rulesets to generate building inventory information that captures parcel-specific attributes, considering time-varying regional construction practices. The formalized rulesets and supporting data were then utilized to automatically generate building inventory information for 2244 single family homes located in Florida's Bay County, the landfall site of Hurricane Michael in 2018. This building inventory information, as well as available wind field data for Hurricane Michael, was incorporated into the SimCenter's R2D tool to conduct a HAZUS-MH-compatible, parcel-level regional loss assessment, using an auto-population script to facilitate mappings of parcel-specific attribute descriptions to corresponding HAZUS-MH damage and loss models. To further illustrate the importance of capturing the local regulatory environment, default building descriptions used by R2D were compared to those reflecting the region's regulatory environment, including consideration of mandated retrofits during re-roofing actions over time. This comparative analysis demonstrated how loss estimates can be appropriately refined in light of more stringent local building practices to reveal the impact of policies over time. The scraping of parcel-specific roof permit information was particularly critical to capturing the reduction in vulnerability for roofs upgraded since each home's initial date of construction.

The R2D workflow was then extended to refine the granularity of wind damage assessments to the component level. Considering a set of available asphalt shingle roof cover component fragilities empirically developed by the authors for Bay County, the study illustrates how the same open data and regional ruleset approach can be used to further refine the building inventory with information necessary to assign these roof cover component fragilities to compatible buildings within the inventory using the functionalities within R2D's computational workflow. A comparison of the resulting component-level damage with the building-level damage predicted by a HAZUS-compatible loss assessment revealed the enhanced fidelity that is possible when the research community incorporates their component-level fragilities into the SimCenter's open scientific workflows.

The replication and extension of the SimCenter's regional loss assessment capabilities demonstrated by this study provide an important demonstration of the robustness of these workflows, expanding R2D's capabilities for the use of others in the research community. By making the various rulesets [10,14] (including their implementation in Python) and the constructed inventories [15] presented in this study openly available, the authors hope to encourage further replications across Florida and ideally future replications in other states. Those efforts can follow the template provided by this study to identify and parse various open data sources and refine the heuristic rulesets to match the requirements and code adoption years of local codes and standards. It is critical to note that such replication efforts will ultimately rely on the availability and quality of tax assessor data at each locality. Thus, municipal investments in the collection and open access to this information are essential to the realizing the full power of a tool such as R2D to execute risk and loss assessments along the US Gulf and Atlantic coasts. Meanwhile, the faithfulness of these assessments will require commensurate increases in the granularity of loss descriptions, making the extension to component-level loss assessment across different hurricane-exposed regions a priority and one that will only be realized when the research community begins to contribute their fragilities to the libraries backing available to open-source tools like the SimCenter's R2D application. Through the combined efforts of municipalities and the research community along these two dimensions, the resulting parcel-level loss assessments can communicate more actionable risk information to building owners and respond to policy makers' desire for more realistic representation of potential losses to inform policy actions that incentivize mitigation actions.

Acknowledgement

The first author gratefully acknowledges the support of her National Science Foundation (NSF) Graduate Research Fellowship (DGE-1313583) and Dean's Fellowship from the University of Notre Dame. The authors also acknowledge their ongoing collaboration with the NHERI-SimCenter in formulating a research vision for regional simulation capabilities, including the support of the second author as a member of the SimCenter under NSF Awards CMMI 1612843 & 2131111. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NSF.

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