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A Report of the California Seismic Safety Commission

Fire Station Risk Assessment Report

State Of California

California Office of Emergency Services

California Seismic Safety Commission

Photo Credit: Paso Robles Fire Department
Front View of the Paso Robles Fire Department, 900 Park St., Paso Robles, CA

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Disclaimer:

The effects, descriptions, recommendations and suggestions included in this report are intended to improve general earthquake preparedness; however, they do not guarantee the safety of an individual or a structure. The SSC is responsible for the content of this report. The State of California, the SSC, and all contributors to this document assume no liability for any injury, death, property damage, loss of revenue, or any other damages incurred by any person as a result of an earthquake.

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California Fire Station Seismic Risk Assessment and Retrofit Benefit Study Phase I

Executive Summary

Understanding the seismic vulnerability of fire stations across California is important, given their essential role in community safety and resilience. The "California Fire Station Seismic Risk Assessment and Retrofit Benefit Cost Study" initiated by the Seismic Safety Commission (SSC) explores the seismic risks associated with fire stations and evaluates the benefits of potential retrofit solutions. This assessment utilizes the HAZUS ("HAZARDs U.S.") Advanced Engineering Building Module (AEBM) and the BCA ("Benefit-Cost Analysis") Toolkit Earthquake Structural Model developed by FEMA to estimate potential losses. It calculates costs and the benefit-to-cost ratios associated with retrofitting fire stations to various seismic performance standards. Data used in the Phase I analysis is default building data from HAZUS. SSC is further assessing risk and cost benefits based on survey data in Phase II of this project.

Given the capabilities, methodologies, and outputs of the different software applications, the following comparisons are made in Phase I of this report:

- Benefit-to-Cost Ratio HAZUS AEBM vs BCA Toolkit
- Benefit-to-Cost Ratio Inclusion vs exclusion of Loss of Function based on BCA Toolkit
- Benefit-to-Cost Ratio Seismic Retrofit to HC vs HS based on HAZUS AEBM
- AAL Composition Based on HAZUS AEBM

Key Findings

Risk Assessment Methodologies

The study employs HAZUS AEBM for detailed risk assessments, providing insights into probable damages to structural and non-structural components, content losses, and potential casualties. The analysis evaluates the benefit of retrofitting fire stations from Moderate Code (MC) to High Code (HC) and Special High Code (HS) that reflect different levels of seismic design. The most recent update of the BCA Toolkit Earthquake Structural Model, the default tool used for BCA calculation in FEMA grant applications was also used.

The study does not compare the superiority of either method: HAZUS AEBM vs BCA

Toolkit. They share similar methodologies but use different hazard maps, include different benefits, and serve different purposes. Based on our sample data, we observe that the BCA Toolkit Earthquake Structural Module updated in September 2023 improves the quantification of the benefit of seismic retrofit projects. We also observed that HAZUS AEBM's enhancement of its capabilities in the November 2023 release could provide significant insights on potential damage for individual buildings of a large portfolio based on the latest probabilistic seismic hazard map from USGS. It can be a helpful tool for the fire districts and engineers when prioritizing their efforts in selecting buildings and scope given the Average Annual Loss (AAL) from structural, and nonstructural components sensitive to drift or acceleration, or have significant casualty potential.

Benefit-Cost Analysis

The study compares the cost-effectiveness of retrofitting strategies using both HAZUS AEBM and the BCA Toolkit. Often, the results showed a higher benefit-cost ratio (BCR) when using the BCA Toolkit, which indicates that the recent update improves the quantification of the benefit of a seismic retrofit and may enable more applicants to become eligible for a seismic retrofit grant.

The analysis supports including loss of function in benefit calculations, particularly for fire stations that provide emergency medical services (EMS). According to the U.S. Fire Administration, 67.6% of all calls in California are EMS-related (U.S. Fire Administration, n.d.). This inclusion significantly improves the benefits of retrofit initiatives and correctly emphasizes the broader impact of service continuity.

Loss of contents can significantly contribute to monetary damages, but it is not currently captured in the BCA toolkit. However, it can be calculated in HAZUS AEBM post-processing.

Seismic Vulnerability of Fire Station Garage Door Openers

The 2022-23 Ferndale earthquake sequence highlighted the operational challenges and risks posed by roll-up doors that jam due to shaking causing delays in emergency response. This is a widely recognized issue that many believe was addressed by California Building Code years ago. However, research efforts have illuminated that there is no industry specification to achieve the operationality of roll-up doors immediately after an earthquake, even for the new fire stations.

Recommendations

The study underscores the necessity of adopting a holistic approach to seismic risk management for fire stations, integrating technical evaluations with economic analyses to optimize retrofitting strategies. Such approaches ensure not only the structural integrity of these critical facilities but also their important roles in emergency response and safeguarding community resilience against future seismic events. Phase I provides a foundational step toward enhancing the seismic safety of fire stations across California. It encourages FEMA to extend the quantification of broader community benefit from the loss of service in the seismic benefit calculation to other critical lifelines.

Prioritize Retrofitting Based on Service Criticality

Fire stations with large service populations, especially those located far from alternative emergency medical services, should be prioritized when applying for seismic retrofit grants. Loss of contents can also be considered in the benefit calculation.

Adopt and Refine Risk Assessment Tools

Enhancements in tools like HAZUS and the BCA Toolkit should continue, focusing on integrating the latest seismic hazard and more detailed outputs for the batch mode of the BCA Toolkit. Quantification of the possible range of the HAZUS estimate can be helpful for decision-makers. Currently, HAZUS only provides a point estimate.

Evaluate Garage Door Opener Performance

Ensure the industry has a performance standard that is consistent with the intent of the building code for essential facilities and is enforced. Given the known vulnerability of stuck doors, earthquake early warning activated garage door openers should be explored for existing fire stations.

Introduction and Overview

When the earth trembles and the ground beneath us quakes, the resilience of our communities is put to the ultimate test. In the wake of such seismic events, the fire station emerges not merely as a structure of bricks and mortar but as a beacon of hope and a fortress of safety. Not only do emergency services save lives and properties by putting out fires following an earthquake, but they also provide Emergency Medical Services (EMS) to the injured. Fire stations are often where local and regional support networks are coordinated, and where assistance is received and distributed to those in need. When residents no longer feel safe in their own homes because they fear aftershocks and are unaware of the nearest emergency shelter, they tend to congregate at fire stations.

However, recent history has provided us with a cautionary tale. The Ferndale earthquake in 2022 cast a glaring spotlight on the fragility of our presumed readiness. In Rio Dell, the fire station's rollup door became jammed, which led to a critical 20-minute delay in deploying a fire engine. Had there been medical emergencies or fire ignitions, it could have been catastrophic (Commission, 2024).

The Seismic Safety Commission (SSC) acknowledges the importance of the fire stations for the resilience of communities and recognizes that their vulnerabilities are not well documented. The SSC initiated a voluntary statewide survey with assistance from Cal OES Fire and Rescue Unit to collect information on building structures, preparedness levels, and the services provided by the fire stations. Data is collected electronically, a risk assessment will be performed, and the benefit should each vulnerable fire station be retrofitted will be quantified.

The report is the first phase of this endeavor. It delves into the intricacies of risk assessment methodologies and approaches and provides technical guidance on the survey questions to collect data used in the risk assessment. The survey questions are answered by the fire station personnel, who are usually not trained for structural evaluation, but guidance was provided, and the survey instructions encouraged personnel to contact either a licensed engineer or the local building department official if they were unable to answer specific structural questions. A previous study, the "seismic risk assessment for fire stations in San Francisco Bay Area", utilized questionnaires to guide professional engineers' survey of fire stations to determine vulnerability. It provided valuable insights, and we used it as an important reference.

Through seismic risk assessment and benefit-cost analysis, this study illuminates the different approaches such as calculating the benefits of seismic retrofit--considering the fire stations as structures of "bricks and mortar" or as a crucial part of the critical community lifelines, as well as the consequences of the different approaches.

Risk Assessment and Benefit-Cost Analysis Process

HAZUS

The FEMA HAZUS ("Hazards U.S.") risk assessment process is a methodology used by the Federal Emergency Management Agency (FEMA) for estimating potential losses from disasters such as earthquakes, floods, and hurricanes. HAZUS uses Geographic Information Systems (GIS) technology to combine hazard layers with inventoried assets to predict the physical damage, economic loss, and social impacts of potential disasters. The information derived from HAZUS can be used to prepare emergency plans, guide risk management activities, and develop mitigation plans to lessen the impact of future disasters. The process involves four main steps:

1. Hazard Analysis: Evaluating the potential natural hazards that can impact the area. This includes assessing the likelihood of occurrence and the intensity of the hazard.
2. Inventory Collection: Gathering data about the buildings, infrastructure, and population in a specific area.
3. Vulnerability Analysis: Understanding the susceptibility of the inventory to the identified hazards. This involves analyzing how each type of hazard could potentially impact the buildings, infrastructure, and population.
4. Loss Estimation: Using the data from the previous steps to estimate the potential economic and human losses from the identified hazards.

In November 2023, FEMA released HAZUS (6.1), with major inventory data, methodology, and software enhancements, including:

- updated earthquake damage functions, building types, and design levels. This version includes over 4,000 new capacity and fragility functions, making the earthquake model more accurate than ever before.
- earthquake advanced engineering building module (AEBM) with an annualized loss capability. HAZUS can now perform site-specific and detailed annualized loss estimation in earthquake scenarios.

HAZUS AEBM with the latest building inventory is utilized in the fire station risk assessment and benefit analysis. The results include the average annualized loss due to building damages and annualized casualties at various severity levels for both day and night.

FEMA BCA Toolkit

FEMA has developed the BCA Toolkit to allow users to calculate Benefit Cost Ratio (BCR) for mitigation grant applications. However, users of the BCA Toolkit have struggled to generate BCRs above 1.0 (meaning the project is deemed not cost-effective and most likely not eligible for grant funding) for seismic retrofit projects, even for seismic structural retrofit measures that are typically shown to be cost-effective after an in-depth engineering evaluation.

FEMA engaged experts to develop a revised seismic methodology for incorporation into the BCA Toolkit. This new approach aims to streamline and enhance the seismic structural module within the toolkit and was released in September 2023.

BCA Toolkit Seismic Structural Module Methodology Update (FEMA, 2023) built upon California's Office of Statewide Health Planning and Development (OSHPD)'s improvement on HAZUS to analyze life-safety risks (i.e., collapse) associated with older acute-care hospital buildings in 2007. Efforts were made to link HAZUS modeling to critical shortcomings identified using assessment criteria like those in ASCE 41 (ASCE, 2017). Depending on the number and severity of these deficiencies, buildings are categorized as "Baseline" (no serious deficiencies), "Sub-baseline" or "Sub-Base" (some serious deficiencies), or "Ultra Sub-base" (numerous serious deficiencies). The improvement further defined adjusted values for capacity curves, structural fragilities, and K hysteretic degradation (Kappa) that align with these performance levels for collapse. Additionally, the HAZUS-OSHPD methodology introduced the Alpha 3 Modal Shape Factor to address nonuniform drift profiles in multistory buildings, which can arise from higher modes, vertical irregularities, and other structural issues. This methodology also increased the Collapse Factor for Sub-Base and Ultra Sub-base categories, significantly amplifying the effects of collapse compared to the Baseline category. For fire stations with open fronts or split roof/floor levels, which provide a structural weakness due to the irregularity, the use of the typical RM1L and W1 type buildings underestimates the risk.

Cost of Seismic Retrofit

The cost of seismic retrofit is determined based on FEMA-156 "Typical Costs for Seismic Rehabilitation of Existing Buildings," dated December 1994, option 2 Equation 4.4.1 (p. 4-14)

$$C = C_1 \, C_2 \, C_3 \, C_L C_T$$

Where:
C = Typical Structural Cost to Seismically Rehabilitate a Building ($/sq. ft.)

C_1 = Building Group Mean Cost (Table 1)
C_2 = Area Adjustment Factor (Table 2)
C_3 = Seismicity/Performance Objective Adjustment Factor (Table 3)
C_L = Location Adjustment Factor (Tables 4 & 5)
C_T = Time Adjustment Factor (Table 6)

Table 1: Building Group Mean Cost (C_1)

Building Group	Building Type	Group Mean Cost (dollar/sq ft)
1	URM	15.29
2	W1, W2	12.29
3	PC1, RM1	14.02
4	C1, C3	20.02
5	S1	18.86
6	S2, S3	7.23
7	S5	24.01
8	C2, PC2, RM2, S4	17.31

Source: From FEMA-156, p. 4-7

Table 2: Area Adjustment Factor (C_2)

Area (sq ft)	BUILDING GROUP							
	1	2	3	4	5	6	7	8
Small	1.01	0.97	1.13	1.09	1.16	1.18	1.04	1.11
Medium	1.00	1.02	1.07	1.06	1.14	1.12	1.03	1.08
Large	0.95	1.28	0.92	1.01	1.09	0.90	0.99	1.02
Very Large	0.80	1.64	0.57	0.84	0.83	0.51	0.87	0.83

Source: From FEMA-156, p. 4-8

The building sizes used in Table 2 are defined as follows:
Small: less than 10,000 sq ft
Medium: 10,000 to 49,999 sq ft
Large: 50,000 to 99,999 sq ft
Very Large: 100,000 sq ft or greater

Table 3: Seismicity/Performance Objective Adjustment Factor (C_3)

SEISMICITY	PERFORMANCE OBJECTIVE		
	LIFE SAFETY	DAMAGE CONTROL	IMMEDIATE OCCUPANCY
Low	0.61	0.71	1.21
Moderate	0.70	0.85	1.40
High	0.89	1.09	1.69
Very High	1.18	1.43	2.08

Source: From FEMA-156, p. 4-15

C_3 is calculated as the difference between damage control and life safety as well the difference between immediate occupancy and life safety. Specifically, for Seismic retrofit of MC to HC in Seismic Zone 4 (very high seismicity), 0.25 is used; for seismic retrofit of MC to HS in Seismic Zone 4, 0.9 is used; for Seismic retrofit of MC to HC in Seismic Zone 3 (high seismicity), 0.2 is used; for seismic retrofit of MC to HS in Seismic Zone 3, 0.8 is used.

C_L Location Adjustment Factor from HAZUS 6.1 is used instead of Tables 4 and 5.

Table 4: Location Adjustment Factor (C_L)

STATE	LOCAL ADJUSTMENT FACTOR
ALABAMA	0.83
ALASKA	1.25
ARIZONA	0.91
ARKANSAS	0.83
CALIFORNIA	1.12
COLORADO	0.91
CONNECTICUT	1.05
DELEWARE	1.05
DIST. OF COLUMBIA	0.96
FLORIDA	0.86
GEORGIA	0.84
HAWAII	1.21
IDAHO	0.91
ILLINOIS	0.99
INDIANA	0.97
IOWA	0.90
KANSAS	0.86

KENTUCKY	0.88
LOUISIANA	0.85
MAINE	0.88
MARYLAND	0.98
MASSACHUESETTS	1.10
MICHIGAN	0.97
MINNESOTA	0.97
MISSISIPPI	0.80
MISSOURI	1.00
MONTANA	0.90
NEBRASKA	0.84

Source: From FEMA-156, p. 4-9

Table 5: Location Adjustment Factor (Selected Cities)

CITY	LOCAL ADJUSTMENT FACTOR
BOSTON	1.10
CHARLESTON	0.80
DENVER	0.91
LOS ANGELES	1.12
MEMPHIS	0.86
NEW YORK	1.07
PORTLAND	0.99
SALT LAKE CITY	0.89
SAN DIEGO	1.12
SAN FRANCISCO	1.12
SEATTLE	1.02
ST. LOUIS	1.00

Source: From FEMA-156, p. 4-11

Table 6: Time Adjusted Factor (C_T)

YEAR	VALUE OF TIME ADJUSTMENT FACTOR				
	0%	2%	4%	6%	8%
1993	1.00	1.00	1.00	1.00	1.00
1994	1.00	1.02	1.04	1.06	1.08
1995	1.00	1.04	1.08	1.12	1.17
1996	1.00	1.06	1.12	1.19	1.26
1997	1.00	1.08	1.17	1.26	1.36

1998	1.00	1.10	1.22	1.34	1.47
1999	1.00	1.13	1.27	1.42	1.59
2000	1.00	1.15	1.32	1.50	1.71
2001	1.00	1.17	1.37	1.59	1.85
2002	1.00	1.20	1.42	1.69	2.00
2003	1.00	1.22	1.48	1.79	2.16
2004	1	1.24	1.54	1.9	2.33

Source: From FEMA-156, p. 4-11

C_T Time Adjustment Factor is calculated using the DGS California Construction Cost Index CCCI published in DGS website. Mean values of annual percentages between 1996 and 2023 are used to impute the missing years 1993, 1994, and 1995.

Table 7: Annual Percentage of California Construction Cost Index

Year	Annual Percentage
2023	9.4
2022	9.3
2021	13.4
2020	2.8
2019	3.6
2018	1.3
2017	3.5
2016	4.4
2015	2.2
2014	1.3
2013	2.3
2012	1.5
2011	1.5
2010	6.3
2009	-1.1
2008	6.8
2007	2.1
2006	2.1
2005	6
2004	8.3
2003	1
2002	2.1
2001	-0.1

2000	3.03
1999	-0.72
1998	2.31
1997	5.75
1996	-0.6
1995	3.56
1994	3.56
1993	3.56

Finally, the Benefit-Cost Ratio is calculated for both retrofitting scenarios: MC to HC and MC to HS. This is done by dividing the loss avoidance by the cost of retrofitting. This ratio helps determine the economic feasibility and effectiveness of two retrofitting efforts.

Results and Discussion

The default building inventory shows that fire station building types are mainly RM1L, W1, W2, or URM (see Appendix A for building classifications and Design Code Designations). Fire stations with Moderate Code (MC, 1941 through 1975) Design Level with Building Type RM1L and W1 in seismic zone 4 were selected for analysis to determine if the Benefit Cost Ratio (BCR)of seismically retrofit fire stations differed utilizing the HAZUS AEBM and BCA Toolkit. The same building inventory for the selected buildings was used and changes were made to the Design Level to High Code (HC) and Special High Code (HS). This represents the retrofitted performance level of damage control and immediate occupancy respectively. The MC buildings and their retrofitted versions were uploaded to CDMS for the HAZUS run. The seismic retrofit is assumed to be comprehensive instead of incremental improvement because the Design Level is increased by a full level (MC to HC), like the approach by (Park et al., 2004).

The results reported from HAZUS AEBM include the loss due to structural damage, non-structural damage, casualty, and loss of content but not the loss of function avoidance. HAZUS AEBM provides detailed outputs on the probability of structural damage in each damage state, and acceleration-sensitive nonstructural damage in each damage state, which allows the post-processing of estimating content loss, and loss of function. Additionally, HAZUS AEBM results include the benefit of loss avoidance should the building be retrofitted to higher performance category HS.

The results from the BCA toolkit include benefits due to loss avoidance from structural and non-structural damage, casualty, and loss of function. Comparison can be made between the two scenarios- including or excluding the loss of function-firefighting and EMS. However, the BCA toolkit earthquake model's batch mode doesn't provide the breakdown of these benefits, nor does it provide the probability of acceleration-sensitive nonstructural damage states. Therefore, the loss of content cannot be added through post-processing.

Given the different capabilities, methodologies, and outputs, the following comparisons are made:

- Benefit-to-Cost Ratio HAZUS AEBM vs BCA Toolkit
- Benefit-to-Cost Ratio Inclusion vs exclusion of Loss of Function based on BCA Toolkit
- Benefit-to-Cost Ratio Seismic Retrofit to HC vs HS based on HAZUS AEBM
- AAL Composition Based on HAZUS AEBM

Benefit-to-Cost Ratio HAZUS AEBM vs BCA Toolkit

The benefit-to-cost ratio presented below excludes the loss of function.
Figure 1 compares the distributions of benefit-to-cost ratios of seismic retrofits from MC to HC across two building types, "RM1L" and "W1" for two methods, identified as "Blue-HAZUS" and "Orange-BCA Toolkit".

Figures 2 and 3 are histograms and scatter plots of the benefit-to-cost ratios of seismic retrofits from MC to HC for RM1L & W1 Building Types for two methods: HAZUS VS BCA Toolkit.

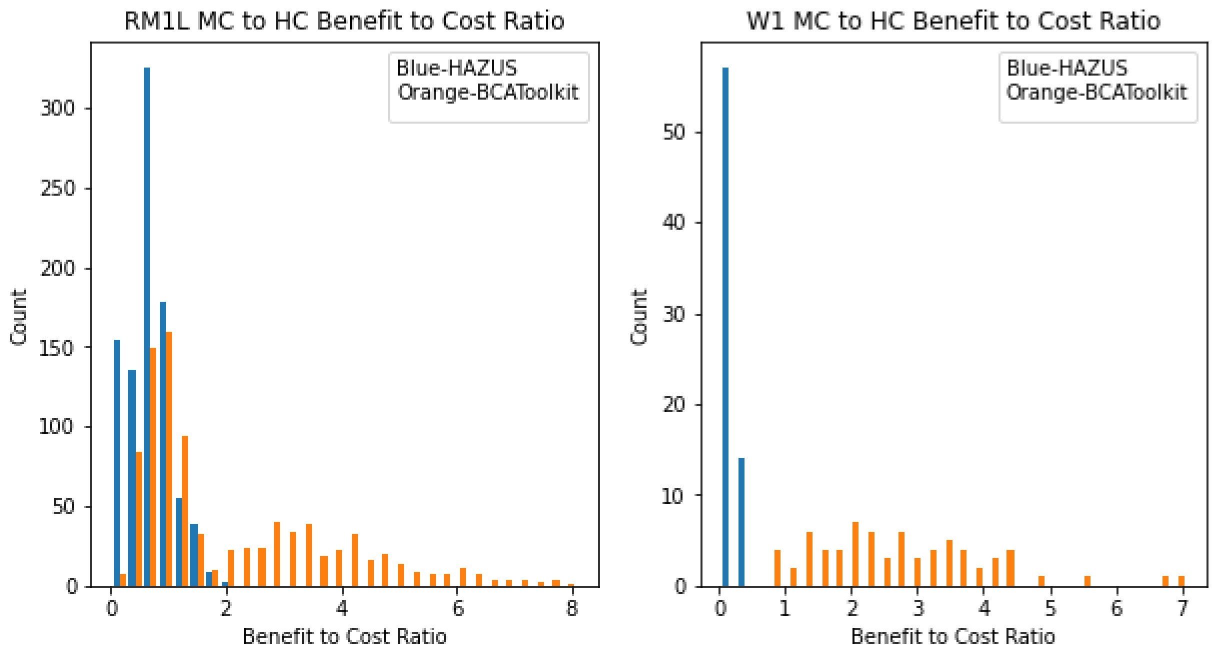

Figure 1: Histogram of Benefit-to-Cost Ratio of HAZUS vs BCA Toolkit for RM1L & W1 (MC to HC Retrofit)

Tables 8 and 9 are the numerical statistics of the Benefit-to-Cost Ratio of HAZUS vs BCA Toolkit for RM1L and W1 Type Building should they be retrofitted from MC to HC.

Table 8: Numerical Statistics of Benefit-to-Cost Ratio of HAZUS vs BCA Toolkit for RM1L Type Building (MC to HC Retrofit)

	BCR_MC_to_HC_HZ	BCR_MC_to_HC_BCA_exc_func
count	896.00	896.00
mean	0.69	2.07
std	0.36	1.70
min	0.02	0.25
25%	0.46	0.81
50%	0.69	1.21
75%	0.89	3.19
max	2.16	8.08

Table 9: Numerical Statistics of Benefit-to-Cost Ratio of HAZUS vs BCA Toolkit for W1 Type Building (MC to HC Retrofit)

	BCR_MC_to_HC_HZ	BCR_MC_to_HC_BCA_exc_func
count	71.00	71.00
mean	0.19	2.73
std	0.10	1.29
min	0.04	0.78
25%	0.11	1.84
50%	0.15	2.42
75%	0.25	3.49
max	0.45	7.05

Observations from the Histograms indicate that for the 896 RM1L type buildings, the BCR ratios from HAZUS are generally less than 2, with the majority less than 1. BCA Toolkit method shows a significantly broader benefit-to-cost ratio distribution, with the most lying between 1 and 3. The 71 W1 type buildings in the dataset have benefit-to-cost ratios less than 0.5 from HAZUS and the majority of the ratios range from 1 to 4.5 from BCA Toolkit.

These observations can be refined further with numerical statistics which can provide mean, median, standard deviation, and perhaps skewness of these distributions. RM1L from HAZUS shows a mean BCR of 0.69, which indicates that on average, the benefit-to-cost ratio is below 1, suggesting the benefits are generally less than the costs. Standard Deviation (std) is 0.36, which is relatively low, implying that the data points are not spread out widely from the mean. The range of BCR is from 0.02 to 2.16. 25% of the values are below 0.46 while 75% of the data points are below 0.89, further showing the concentration of lower ratios. In contrast, RM1L from BCA Toolkit shows a mean of 2.07, indicating a favorable benefit-cost scenario on average. The std is 1.70, a higher spread indicating more variability in the data compared to HAZUS. Twenty-five percent (25%) of observations lie below 0.81, 50% of the observations are less than 1.21 and 75% of the observations are below 3.19.

For the W1 type buildings in the dataset, HAZUS output has a mean of 0.19, indicating that on average, the benefits are significantly lower than the costs.
The std is 0.10, a low variability suggesting consistent outcomes across evaluations.
Seventy-five percent (75%) of the buildings in the dataset have BCR less than 0.25.

The BCA toolkit output has a mean of 2.73, much higher than HAZUS, suggesting a favorable average outcome where benefits substantially outweigh costs.
The std is 1.29, indicating considerable variabilities in the outcomes, confirmed by the wide range from 0.78 to 7.05.

Figures 2 and 3 are histograms and scatter plots of BCR of RM1L and W1 building types (MC to HC) based HAZUS and BCA Toolkit. The x coordinate of the point in scatter plot shows the BCR using HAZUS while the y coordinate shows the same building analyzed using BCA Toolkit. BCR using BCA toolkit often yields higher results.

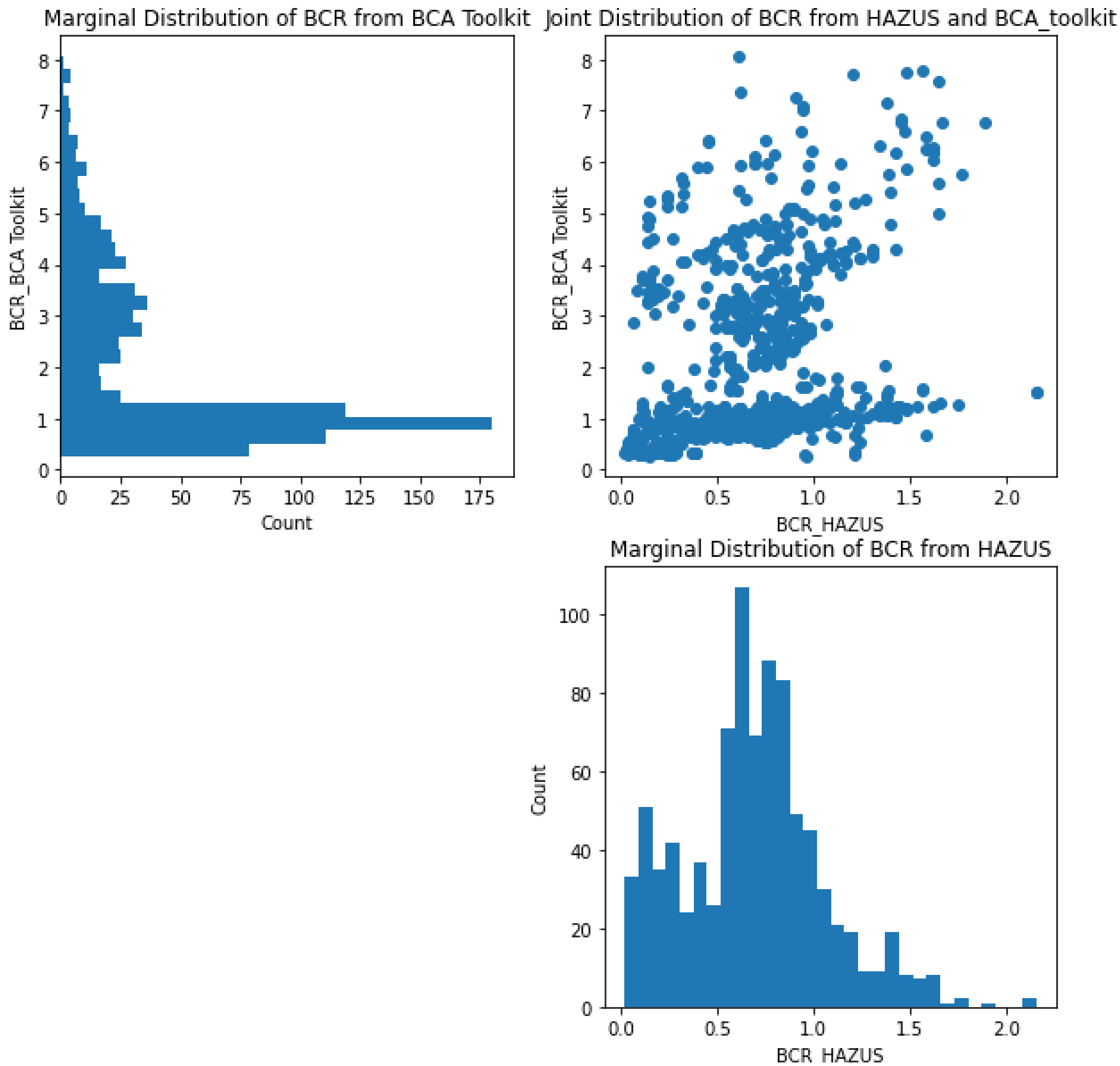

Figure 2: Histograms and Scatter Plot_RM1L Type MC to HC HAZUS VS BCA Toolkit

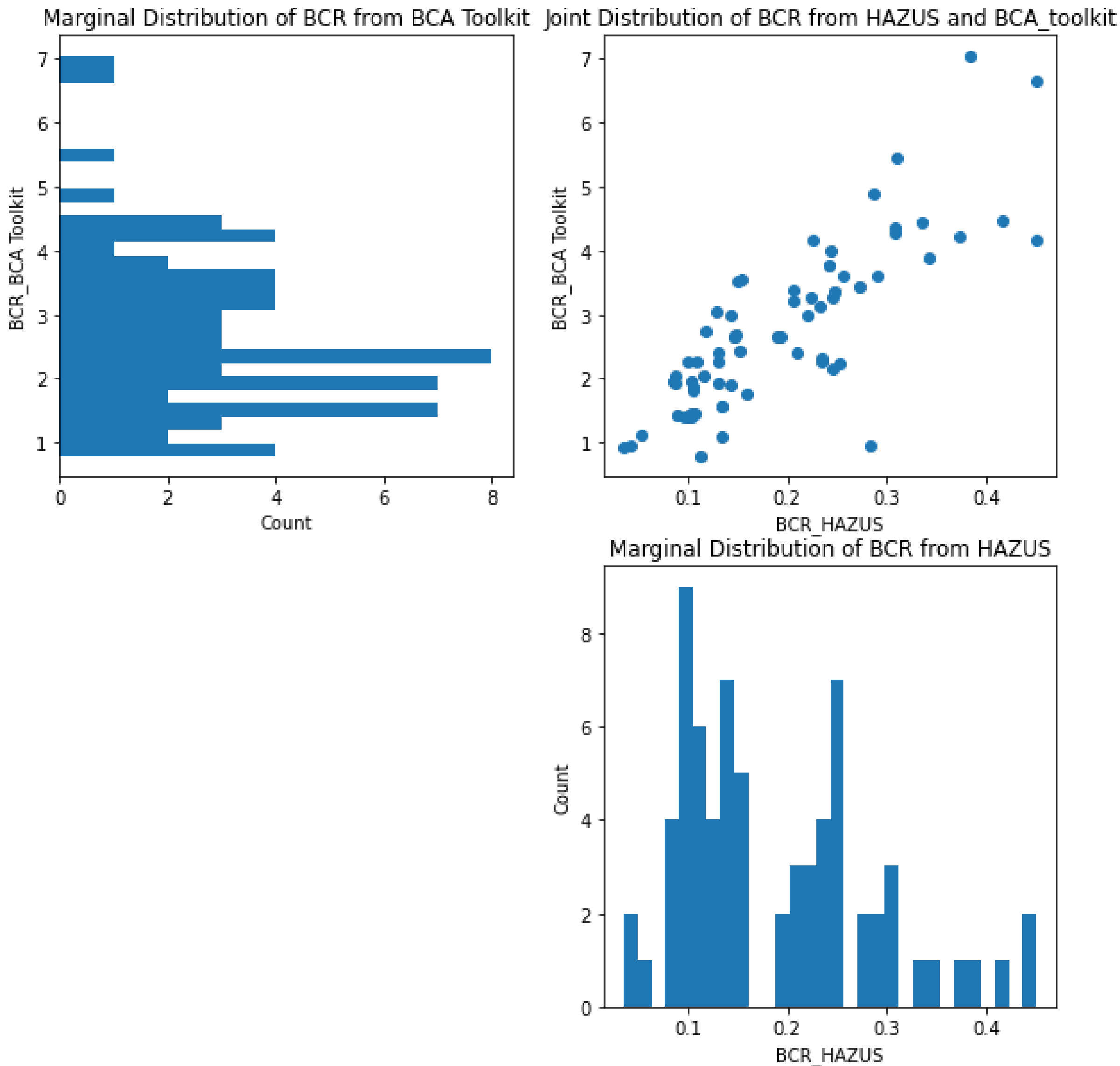

Figure 3: Histograms and Scatter Plot_W1 Type MC to HC HAZUS VS BCA Toolkit

Benefit-to-Cost Ratio Inclusion vs Exclusion of Loss of Function

Below are detailed visualizations (histogram and scatter Plot) and statistical data related to the Benefit-to-Cost Ratio (BCR) of RM1L and W1 for two types of assessments, specifically analyzing the impact of including versus excluding loss of function using the BCA Toolkit.

Figure 4: BCR for the RM1L type, comparing scenarios that include versus those that exclude loss of function. The histograms show the distribution of BCR values, and a scatter plot depicts the relationship between the two scenarios for each data point.

Figure 5: Like Figure 4 but specific to the W1 type.

Table 10 Numerical Statistical Summaries of RM1L MC to HC BCR Including vs. Excluding Function (BCA Toolkit). The information includes count, mean, standard deviation, minimum, maximum, and quartiles. This data helps quantify the central tendency and dispersion of BCR values.

Table 11 is like Table 20 but specific to W1 building type.

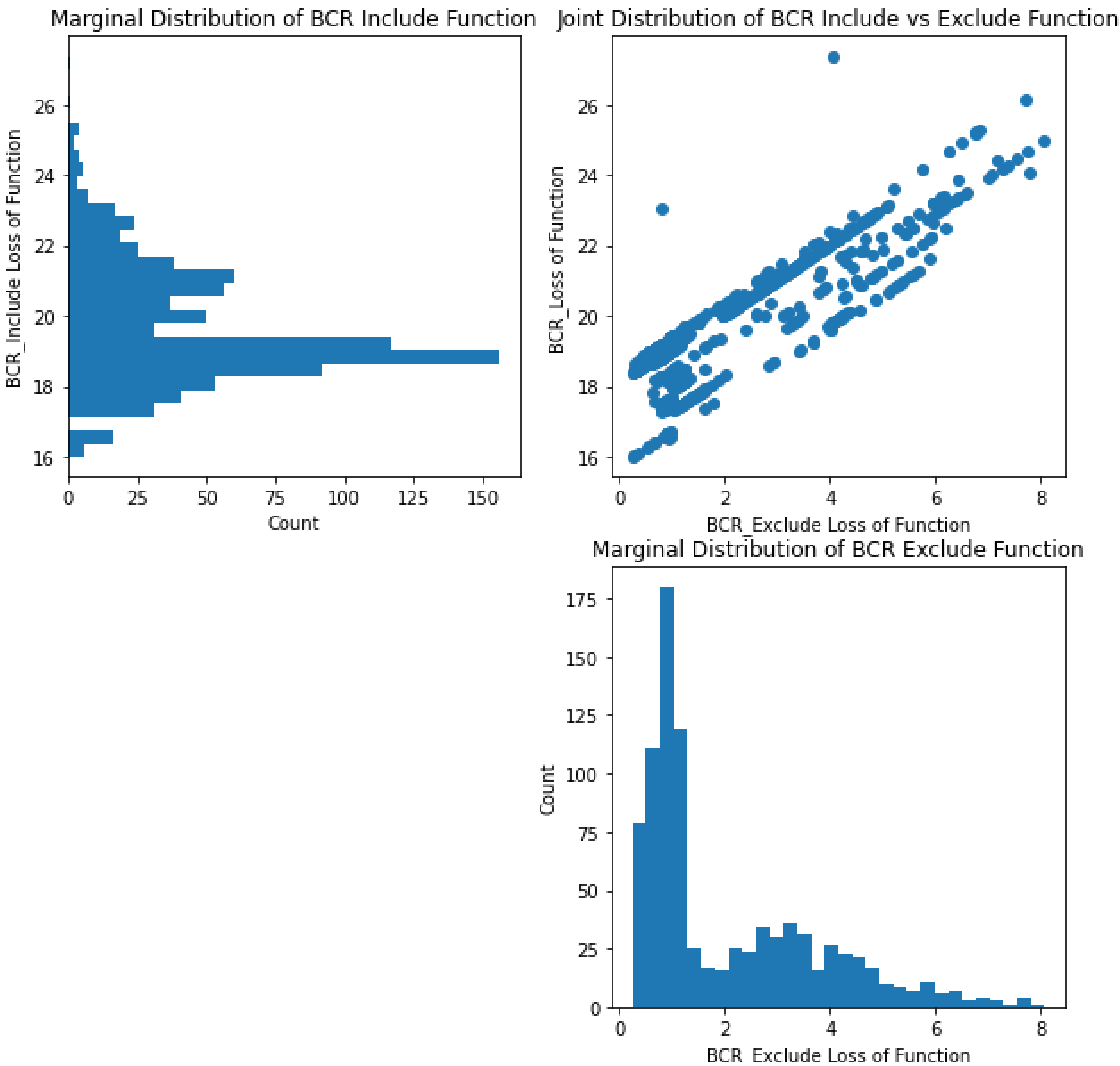

Figure 4: BCR RM1L Type MC to HC Include vs Exclude Loss of Function BCA Toolkit

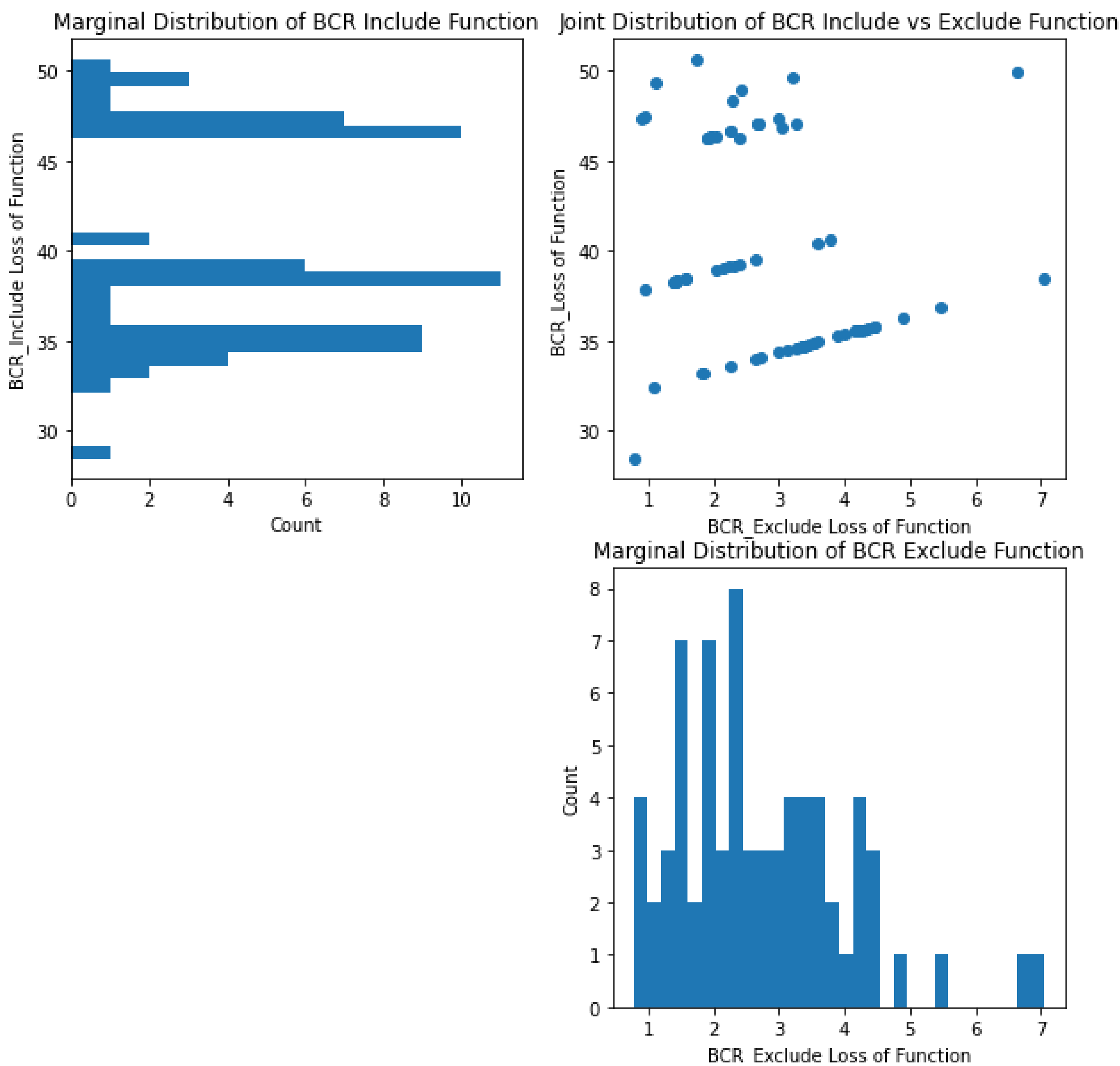

Figure 5: BCR W1 Type MC to HC Include vs Exclude Loss of Function Toolkit

Table 10: Numerical Statistics of RM1L MC to HC BCR Including vs Excluding Function_ BCA Toolkit

	BCR_MC_to_HC_BCA_exc_func	BCR_MC_to_HC_BCA_inc_func
count	896.00	896.00
mean	2.07	19.69
std	1.70	1.69
min	0.25	15.99
25%	0.81	18.56
50%	1.21	19.13
75%	3.19	20.85
max	8.08	27.37

Table 11: Numerical Statistics of W1 MC to HC BCR Including vs Excluding Function_ BCA Toolkit

	BCR_MC_to_HC_BCA_exc_func	BCR_MC_to_HC_BCA_inc_func
count	71.00	71.00
mean	2.73	39.94
std	1.29	5.64
min	0.78	28.44
25%	1.84	35.30
50%	2.42	38.30
75%	3.49	46.32
max	7.05	50.65

The histograms and scatter plots together with the numerical summaries provide a comprehensive view that including loss of function into benefit calculation significantly increase the BCR. The assumptions used in the analysis are that the fire station also serve as EMS to 30,000 people and the alternative EMS and fire protection is 5 miles away.

Benefit-to-Cost Ratio Seismic Retrofit to HC vs HS

Comparison on BCR between retrofitting to HC vs HS are made using detailed visualizations (histogram and scatter Plot) and statistical data related to the Benefit-to-Cost Ratio (BCR) for two types of assessments using HAZUS.

Figure 6: BCR for the RM1L type, comparing scenarios that retrofit to HC or HS performance category. The histograms show the distribution of BCR values, and a scatter plot depicts the relationship between the two scenarios for each data point.

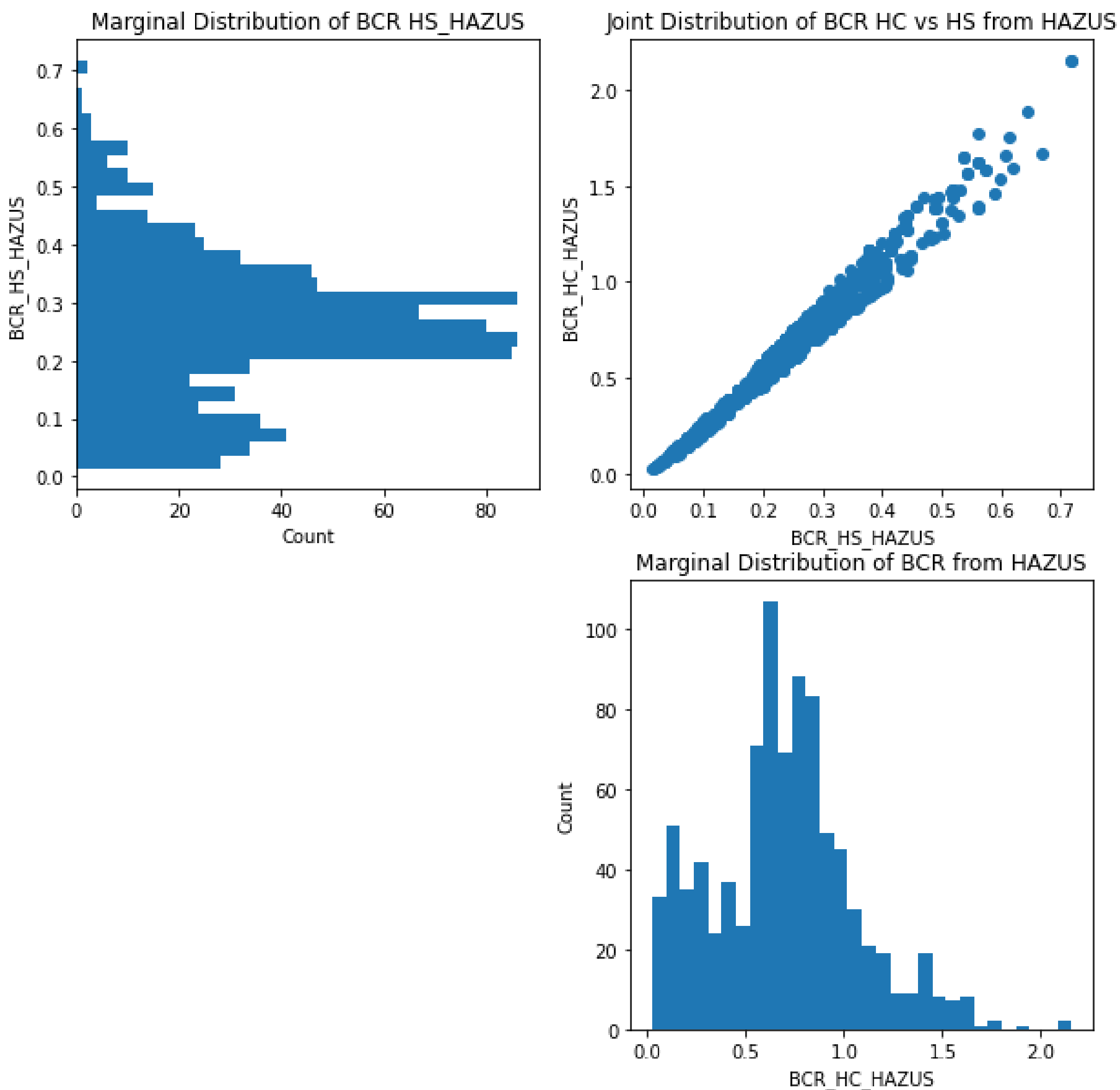

Figure 6: BCR RM1L Type MC to HC vs MC to HS_HAZUS

Figure 7: Like Figure 6 but specific to the W1 type.

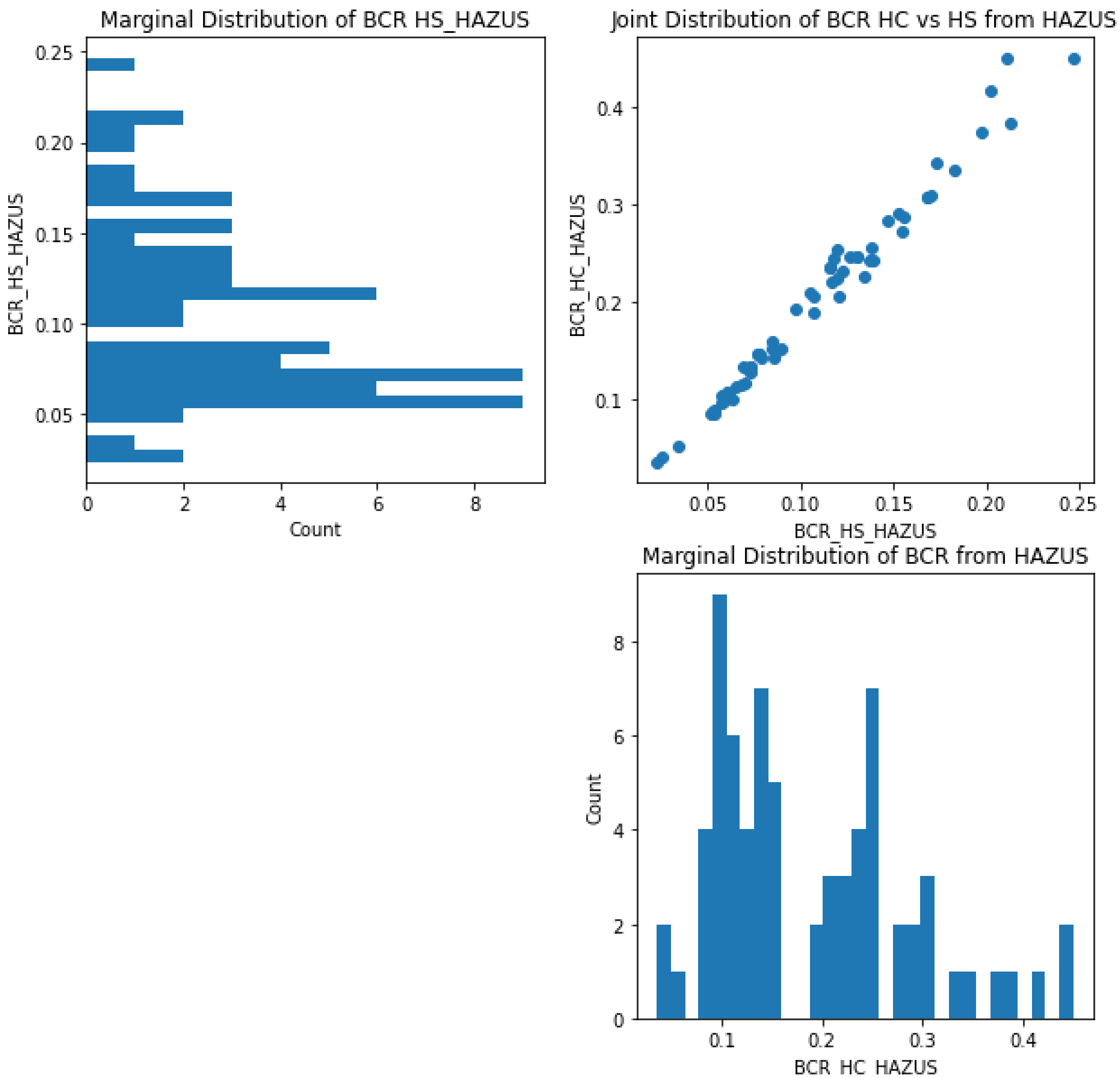

Figure 7: BCR W1 Type MC to HC vs MC to HS_HAZUS

Table 10 shows Numerical Statistical Summaries of RM1L MC to HC or HS Benefit Cost Ratio. The information includes count, mean, standard deviation, minimum, maximum, and quartiles. This data helps quantify the central tendency and dispersion of BCR values.

Table 10: Numerical Statistics of RM1L Benefit Cost Ratio HC vs HS_ HAZUS

	BCR_MC_to_HS_HZ	BCR_MC_to_HC_HZ
count	896.00	896.00
mean	0.26	0.69
std	0.13	0.36
min	0.01	0.02
25%	0.18	0.46
50%	0.25	0.69
75%	0.33	0.89
max	0.72	2.16

Table 11 is like Table 10 but specific for W1 building type.

Table 11: Numerical Statistics of W1 Benefit Cost Ratio HC vs HS_ HAZUS

	BCR_MC_to_HS_HZ	BCR_MC_to_HC_HZ
count	71.00	71.00
mean	0.10	0.19
std	0.05	0.10
min	0.02	0.04
25%	0.06	0.11
50%	0.09	0.15
75%	0.13	0.25
max	0.25	0.45

The histograms, scatter plots, and numerical summaries indicate that the current methodologies as applied to this case study supports retrofit to high code. Retrofit to special high code likely requires more detailed and project-specific calculation of the benefit to justify the higher upfront costs.

AAL Composition Based on HAZUS AEBM

The stacked bar charts below show the composition of Average Annual Loss (AAL) for different building types and design levels using the HAZUS Advanced Engineering Building Module (AEBM). The specific building types examined are RM1L and W1 and the design levels are Moderate Code (MC), High Code (HC), and Special High Code (HS).

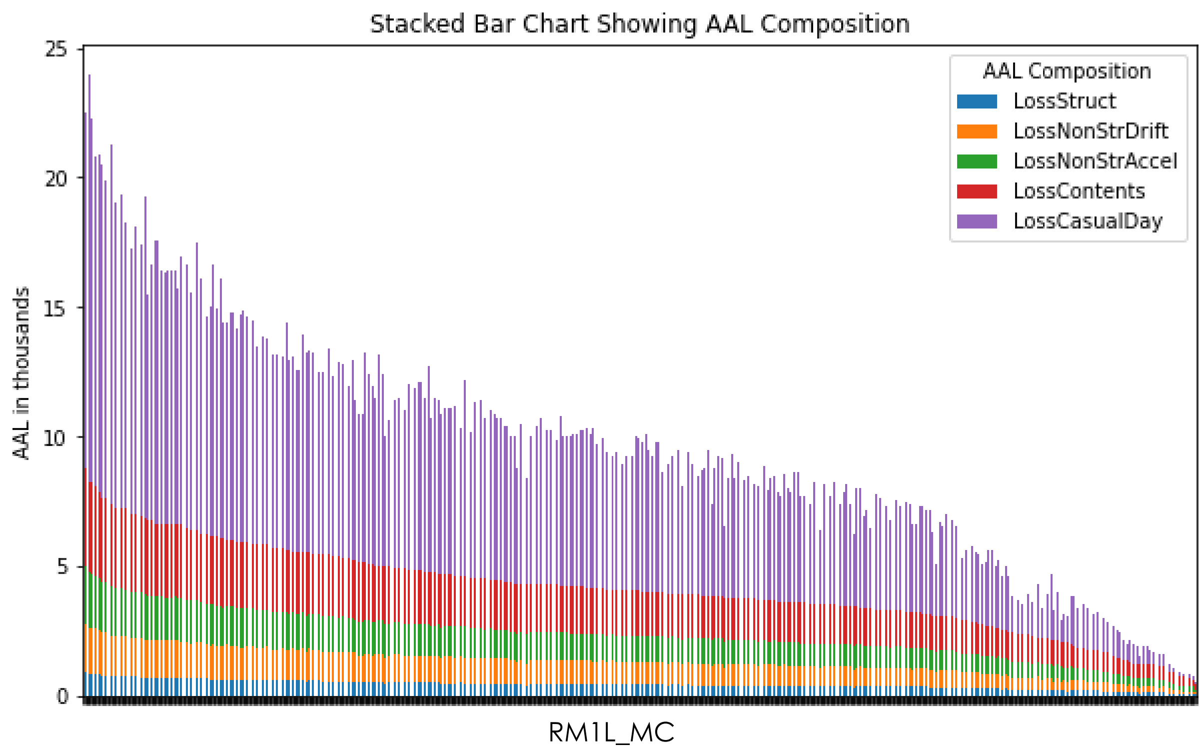

Figure 8: AAL composition for RM1L_MC_HAZUS

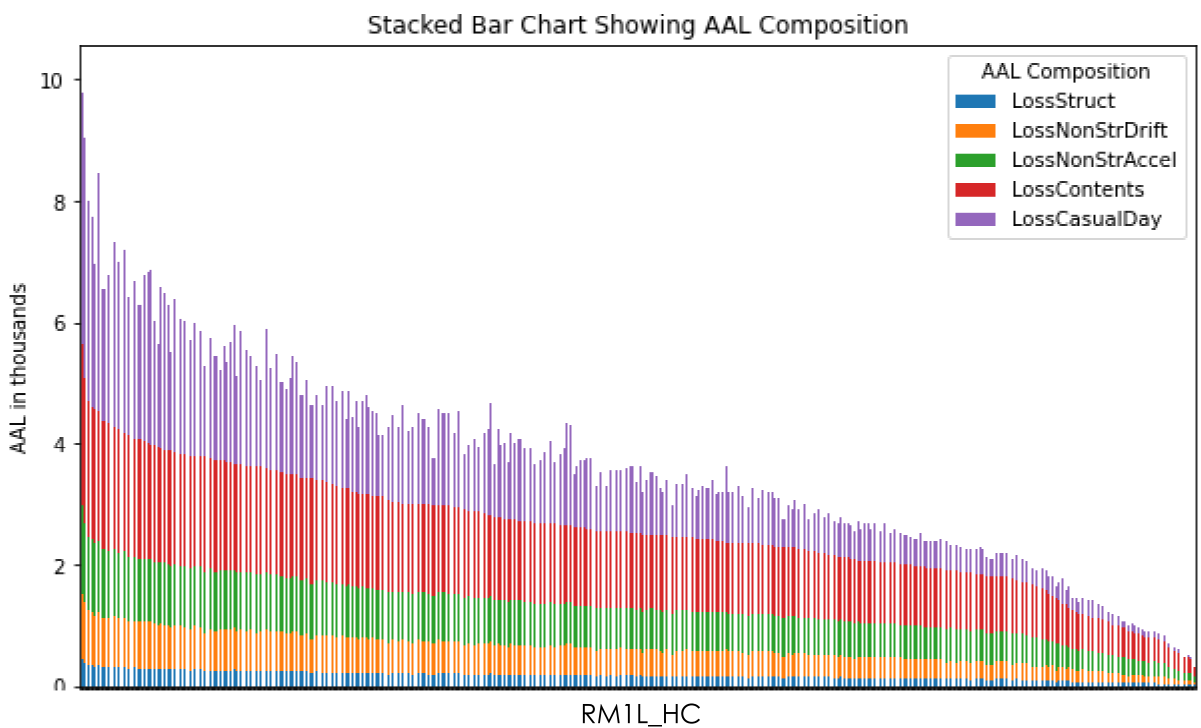

Figure 9: AAL composition for RM1L_HC_HAZUS

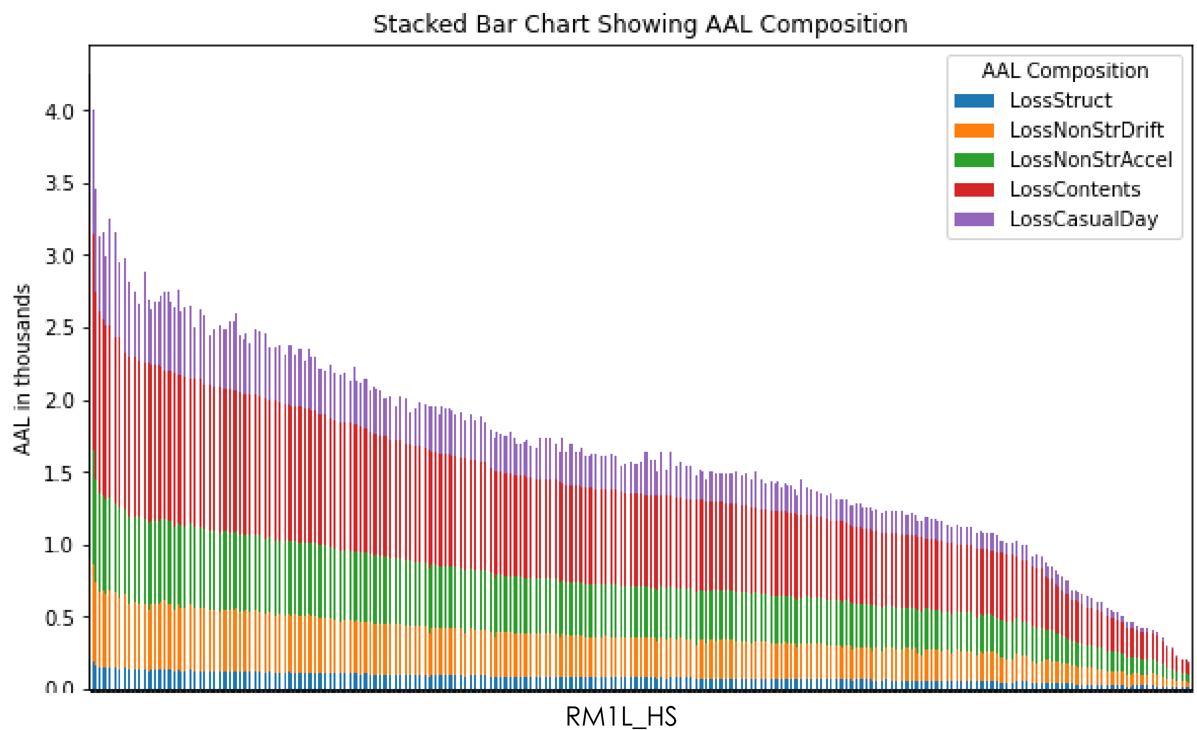

Figure 10: AAL composition for RM1L_HS_HAZUS

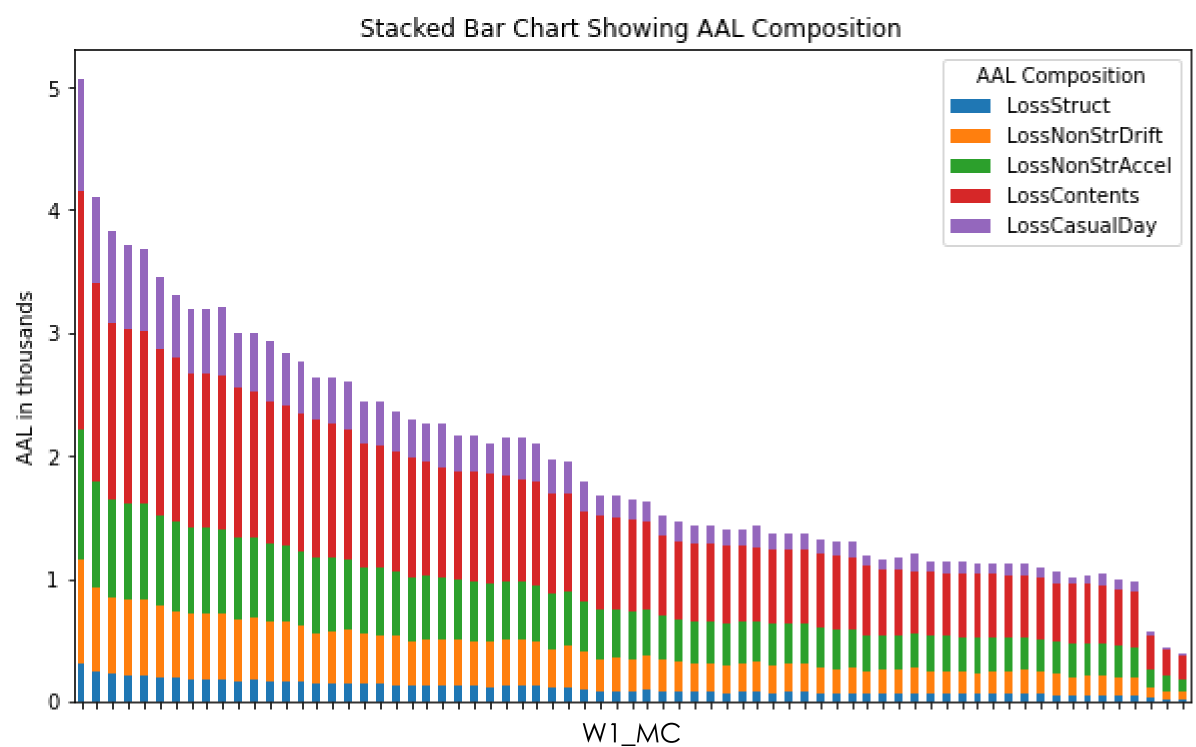

Figure 11: AAL composition for W1_MC_HAZUS

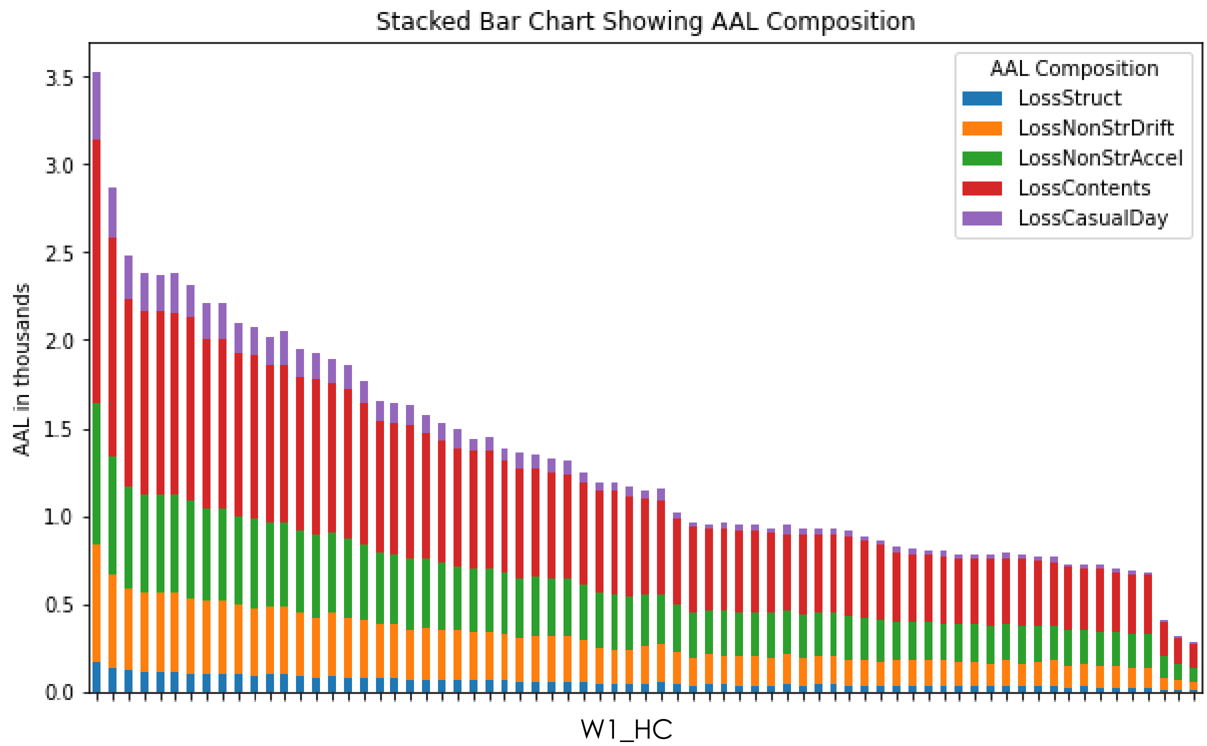

Figure 12: AAL composition for W1_HC_HAZUS

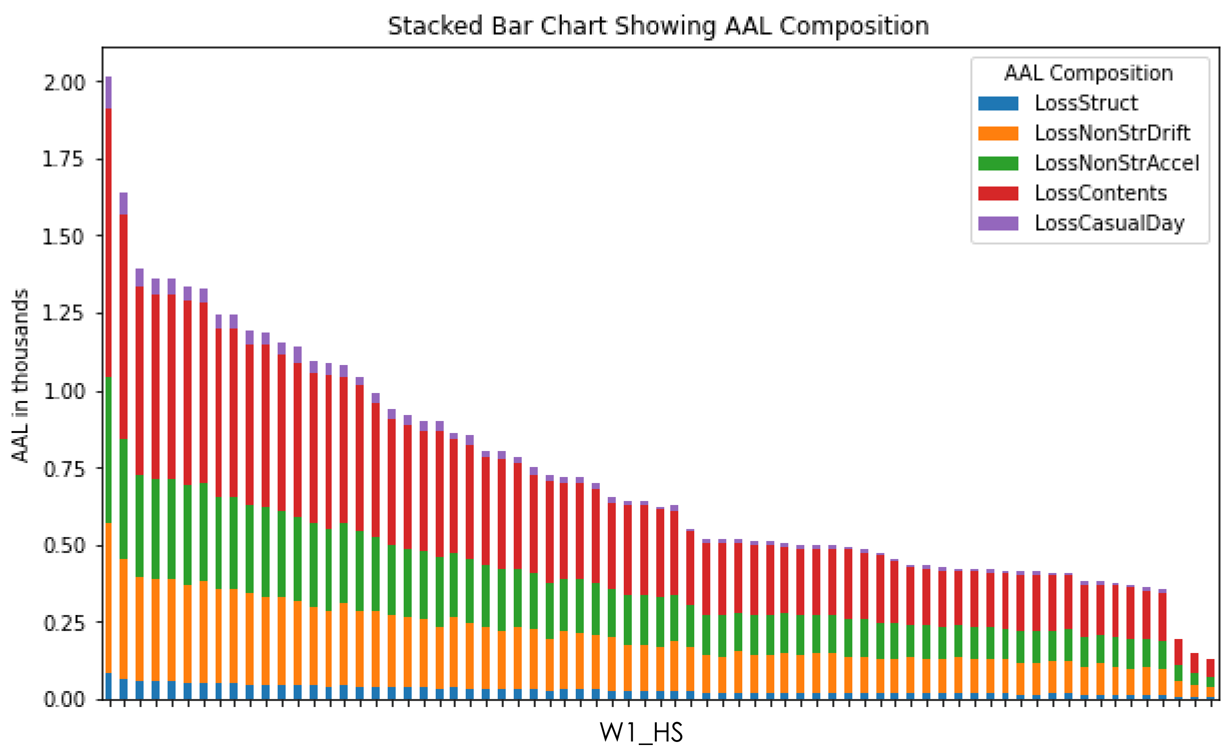

Figure 13: AAL composition for W1_HS_HAZUS

Assuming there are 26 occupants on average in the fire station, average annual loss due to casualty appears to be a major contributor to RM1L's total AAL, especially for lower design levels, likely due to the high standard economic value of life. In contrast, average annual loss due to casualty appears to be a less significant contributor to W1, likely due to the lower rates of casualty severity level 3 and 4 for W1 than for RM1L in HAZUS AEBM profiles.

AAL due to Loss of content appears to be a significant contributor for both RM1L and W1, especially for higher design levels.

Additional Discussion

The study is not intended to document or construe the superiority of the two methods HAZUS AEBM vs BCA Toolkit. They share similar methodologies but use different hazard maps, include different benefits, and serve different purposes. Based on our sample data, we observe that BCA Toolkit Earthquake Structural Module update in September 2023 improves the quantification of the benefit of seismic retrofit projects. We also observed that HAZUS AEBM's enhancement of its capabilities in the November 2023 release can provide significant insights on potential damage for individual buildings of a large portfolio based on the latest probabilistic seismic hazard map from USGS. It can be a helpful tool for the fire districts and engineers to prioritize their efforts in selecting buildings and the scope given the AAL from structural, and nonstructural components sensitive to drift or acceleration, or have significant casualty potential. Incorporating uncertainty in the output will provide additional insight for the decision-makers.

The absolute value of the benefit-to-cost ratio and if it is above or below the 1.0 threshold are not as important as the relative values in comparisons, not only because the assumptions in SSC's Phase I study do not necessarily reflect the specific conditions of each fire station, but also because of the uncertainty of the seismic retrofit cost. The confidence range of the cost of the seismic retrofit in FEMA-156 varies depending on several factors including the number of buildings being considered. Moreover, the construction cost varies significantly over time, geographic location, project scope etc. Conversations with capital outlay project managers who recently completed a seismic retrofit project of their fire stations or concluded a cost study confirmed the regional cost difference. The survey aims to collect information on individual fire stations to reduce uncertainty, but the cost will still be unknown. However, the methodology presented can indicate a higher bound to meet the BCR requirement. Ultimately, professional engineers should be consulted when calculating cost benefits and submitting a grant application. For example, the study selected "unknown" for all items in the structural and nonstructural evaluation statements. After their examination, the project engineers can provide more information which will affect the final BCR. However, it appears that for fire stations with a significant service population further away from the alternative facilities that can provide a replacement, the benefit due to loss of function especially for EMS will likely overshadow the other calculated benefits.

The study demonstrates the significant difference when loss of function is considered in the benefit calculation. It is a step forward to capture the broader community benefit of essential facilities for the low-probability but high-impact natural hazards such as earthquakes. An operable fire station after a major earthquake event contributes more to community resilience than the loss avoidance of its building.

Lastly, the study should not be construed as deterring fire districts from retrofitting their fire stations to higher performance criteria, not only because of the limitation of our seismic retrofit cost information but also because of the difficulty of quantifying community benefit holistically in the real world.

Garage Door Openers

In the wake of the recent Ferndale earthquake, the performance of garage door openers in fire stations has come under scrutiny. Notably, during this seismic event, a garage door malfunctioned and became stuck, resulting in a delayed response as firefighters struggled to deploy their fire engines. This incident highlights a critical vulnerability in emergency response infrastructure, emphasizing the need for robust and reliable door-opening mechanisms in such facilities.

"Performance of Roll-up Garage Doors" (Turner, 1998) underscores that the incident is not isolated. Similar issues with garage door openers occurred in previous earthquakes, suggesting a pattern that necessitates urgent attention.

Although many sectional and rolling door manufacturers are members of the Door and Access Systems Manufacturing Association (DASMA), and adhere to an ANSI standards development process, current standards do not cover operational requirements for design-level earthquake and the methods to achieve these requirements, leaving the performance of door openers during seismic events ambiguous. Even though the current building codes mandate exterior nonstructural wall panels or elements to accommodate seismic displacements, the enforcement of these requirements during plan review and inspection phases appears unclear, partly due to the absence of specific industry standards for door opener performance under seismic events. This oversight may compromise the operational reliability of fire station garage doors, ultimately affecting the readiness and effectiveness of emergency response operations.

The survey in SSC's Phase II report will collect some basic information on the garage doors such as height, material, age, etc. HAZUS AEBM outputs the spectral displacement at the intersection of the capacity and demand spectrum at each fire station based on the location and building information given seismic hazards at various return periods. If research on the fragilities of these garage door openers is available in the future, their performance can be estimated. Earthquake early warning (EEW) activated garage door openers can be a good option given the lack of reliability of the garage door openers if the building drift is expected to be significant.

Recommendations

The study underscores the necessity of adopting a holistic approach to seismic risk management for fire stations, integrating technical evaluations with economic analyses to optimize retrofitting strategies. Such approaches ensure not only the structural integrity of these critical facilities but also their important roles in emergency response and safeguarding community resilience against future seismic events. This report provides a foundational step toward enhancing the seismic safety of fire stations across California. It encourages FEMA to extend the quantification of broader community benefit from the loss of service in the seismic benefit calculation to other critical lifelines.

Prioritize Retrofitting Based on Service Criticality

Fire stations with large service populations, especially those located far from alternative emergency medical services, should be prioritized when applying for seismic retrofit grants. Loss of contents can also be considered in the benefit calculation.

Adopt and Refine Risk Assessment Tools

Enhancements in tools like HAZUS and the BCA Toolkit should continue, focusing on integrating the latest seismic hazard and more detailed outputs for the batch mode of the BCA Toolkit. Quantification of the possible range of the HAZUS estimate can be helpful for decision-makers. Currently HAZUS only provides a point estimate.

Evaluate Garage Door Opener Performance

Ensure the industry has a performance standard that is consistent with the intent of the building code for essential facilities and is enforced. Given the known vulnerability of stuck doors, earthquake early warning activated garage door openers should be explored for existing fire stations.

Conclusion

The comprehensive analysis of the benefit-cost ratio (BCR) of seismic retrofitting fire stations has presented valuable insights, revealing critical factors influencing the effectiveness and efficiency of retrofit initiatives. Through an extensive comparison between HAZUS AEBM and the BCA Toolkit, alongside consideration of loss function inclusion and exclusion, the study has underscored the complexity inherent in assessing the true benefits and costs of such projects.

Firstly, the examination of BCR using both HAZUS AEBM and the BCA Toolkit illuminates the differing scopes and capabilities of these tools. HAZUS AEBM's strength lies in its detailed output regarding probable structural, non-structural damages and the subsequent financial implications, as well as making possible post-processing to include other benefits such as content loss, casualty expenses, and loss of function. Conversely, the BCA Toolkit extends its analysis to include benefits stemming from the avoidance of functional loss within the module.

The data indicates a significant discrepancy in BCR outcomes between the two methodologies. Specifically, the BCA Toolkit generally exhibits higher BCR values. However, the BCA Toolkit doesn’t output probabilities in the nonstructural damage state to allow the post-processing of calculating benefit due to content loss avoidance.

Furthermore, the inclusion versus exclusion of loss of function in the analysis has a significant difference on the BCR, especially for fire stations serving a large population and further away from the alternative emergency medical services providers. This highlighted the vital impact of operational continuity in emergency services--the benefit of the fire station to the community exceeds the dollar amount assigned to the damage avoidance of the building itself.

Moreover, the current methodologies as applied to this case study supports retrofit to high code. Retrofit to special high code likely requires more detailed and project-specific calculation of the benefit to justify the higher upfront costs.

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Appendix A

HAZUS Risk Assessment and Benefit-Cost Analysis Implementation

Hazard Analysis

The 2018 national seismic hazard model of the United States Geological Survey (USGS) was used in HAZUS AEBM. To ensure compatibility with the HAZUS framework, this data was transformed through a structured three-phase approach.

Phase One involved the calculation of the Peak Ground Acceleration (PGA), and the spectral accelerations at 0.3 seconds (SA0.3) and 1.0 seconds (SA1.0) across a matrix of 611,309 grid points, which span the contiguous states of the U.S., for a series of eight predetermined return intervals (100, 250, 500, 750, 1,000, 1,500, 2,000, and 2,500 years).

In the Second Phase, adjustments were made to the calculated PGA, SA0.3, and SA1.0 values to align with the localized site-soil conditions. The original USGS data presumed a NEHRP soil class type of B/C, which corresponds to medium rock or very dense soil. However, to tailor the data more accurately to the specific soil classifications of each grid cell, Vs30 values—a measure of soil stiffness—sourced from the USGS and the NEHRP's site soil correction factors were used to adjust the seismic hazard values accordingly. In California, the local soil data was provided by the California Geologic Survey (CGS).

The Third Phase required the calculation of PGA, SA0.3, and SA1.0 for every site location based on the adjacent site corrected USGS grid.

Inventory Upload and HAZUS AEBM Run

The process begins with downloading the inventory dataset from the newly released HAZUS 6.1 via the Comprehensive Data Management System (CDMS). For essential facilities, the dataset is informed by multiple sources such as Homeland Infrastructure Foundation-Level Data (HIFLD) and local sources such as parcel-level data if available.   Once the dataset is obtained, the next step involves verifying and updating the design levels within the dataset. The design level follows the rules in the Table1A below.

Table 1A California Design Level Matrix

California Design Level Matrix "pre-IBC - Era"			
Construction Year	**Pre-1941**	**1941 through 1975**	**1976 through 1996**
UBC Zone 4 (MA 7)	Pre-Code (assume MC for W1)	Moderate-Code	High-Code (HS for Essential Facilities (COM6, GOV2, EDU1&2))
UBC Zone 3 (MA 6)	Pre-Code (assume MC for W1)	Moderate-Code	Moderate-Code (MS for Essential Facilities (COM6, GOV2, EDU1&2))

Source: Bausch et al., 2023 and additional rules:

1. W1 >5000 sqrt ft, treat as W2
2. Special High Code (HS) for essential facilities from 1976 until 2008 for UBC Zone 4 (even though IBC doesn't have UBC zones anymore)
3. Special Moderate Code (MS) for essential facilities from 1976 until 2008 for UBC Zone 3. See Figure 14 for UBC Seismic Zone Map.

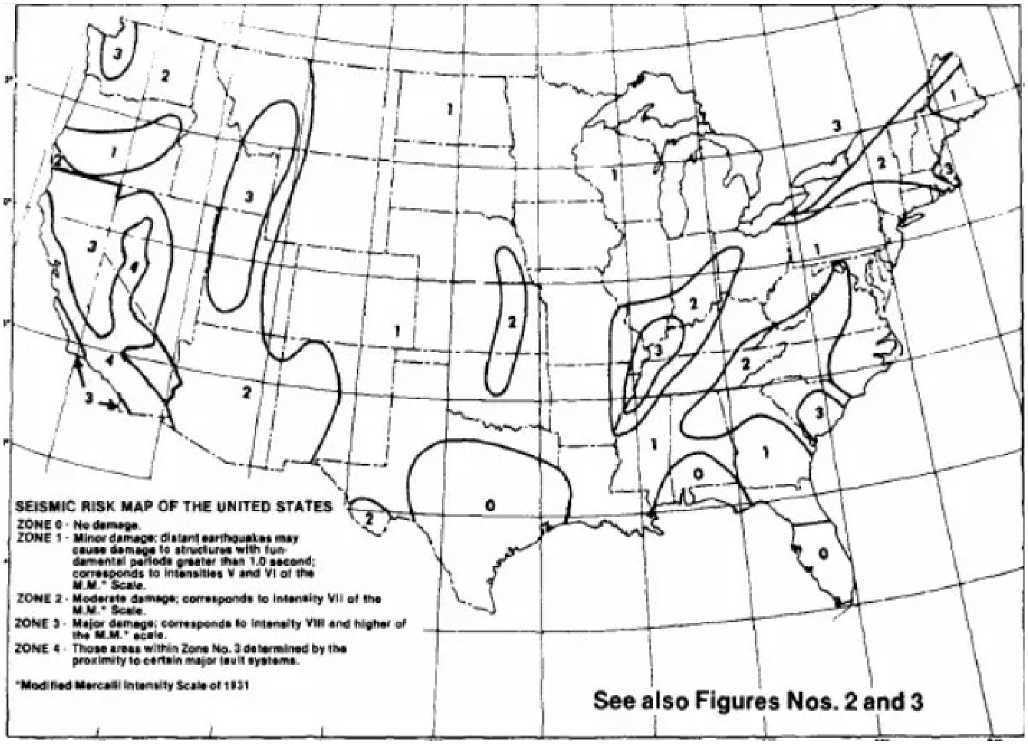

Figure 14: Seismic Zone Map of the US

Source: 1976 UBC, Table No. 23-K

1976 UBC introduced 1.5 importance factor for essential facilities as in Table 2A below.

Table 2A Values for Occupancy Importance Factor

TYPE OF OCCUPANCY	I
Essential Facilities[1]	1.5
Any building where the primary occupancy is for assembly use for more than 300 persons (in one room)	1.25
All others	1.0

[1]See Section 2312 (k) for definition and additional requirements for essential facilities.

Source: 1976 UBC

Essential facilities are those structures or buildings which must be safe and usable for emergency purposes after an earthquake in order to preserve the health and safety of the general public. Such facilities shall include but not be limited to:

- Hospitals and other medical facilities having surgery or emergency treatment areas.
- Fire and police stations.

- Municipal government disaster operation and communication centers deemed to be vital in emergencies.

1976 UBC also states “The design and detailing of equipment which must remain in place and be functional following a major earthquake shall be based upon the requirements of Section 2312 (g) and Table No. 23-J. In addition, their design and detailing shall consider effects induced by structure drifts of not less than (2.0/K) times the story drift caused by required seismic forces nor less than the story drift caused by wind. Special consideration shall also be given to relative movements at separation joints.” HS and MS design level designations for post-1976 GOV2 in Table 1 are due to the more stringent requirements for essential facilities in 1976 UBC.

HAZUS classifies buildings into one of the thirty-six specific building types (see Table 3A below).

Table 3A Specific Building Types

No	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1	W1	Wood, light frame (<5000 sq.ft.)		All	1	14
2	W2	Wood (>5000 sq.ft.)		All	2	24
3	S1L	Steel Moment Frame	LR	1-3	2	24
4	S1M		MR	4-7	5	60
5	S1H		HR	8+	13	156
6	S2L	Steel Braced Frame	LR	1-3	2	24
7	S2M		MR	4-7	5	60
8	S2H		HR	8+	13	156
9	S3	Steel Light Frame		All	1	15
10	S4L	Steel Frame with Cast-in-Place Concrete Shear Walls	LR	1-3	2	24
11	S4M		MR	4-7	5	60
12	S4H		HR	8+	13	156
13	S5L	Steel Frame with Unreinforced Masonry Infill Walls	LR	1-3	2	24
14	S5M		MR	4-7	5	60
15	S5H		HR	8+	13	156
16	C1L	Concrete Moment Frame	LR	1-3	2	20
17	C1M		MR	4-7	5	50
18	C1H		HR	8+	12	120
19	C2L	Concrete Shear Walls	LR	1-3	2	20
20	C2M		MR	4-7	5	50
21	C2H		HR	8+	12	120
22	C3L	Concrete Frame with Unreinforced Masonry Infill Walls	LR	1-3	2	20
23	C3M		MR	4-7	5	50
24	C3H		HR	8+	12	120
25	PC1	Precast Concrete Tilt-Up Walls		All	1	15
26	PC2L	Precast Concrete Frame with Concrete Shear Walls	LR	1-3	2	20
27	PC2M		MR	4-7	5	50
28	PC2H		HR	8+	12	120
29	RM1L	Reinforced Masonry Bearing Walls /w Wood or Metal Deck Diaphragms	LR	1-3	2	20
30	RM1M		MR	4+	5	50
31	RM2L	Reinforced Masonry Bearing Walls /w Precast Concrete Diaphragms	LR	1-3	2	20
32	RM2M		MR	4-7	5	50
33	RM2H		HR	8+	12	120
34	URML	Unreinforced Masonry Bearing Walls	LR	1-2	1	15
35	URMM		MR	3+	3	39
36	MH	Mobile Homes		All	1	12

Source: From HAZUS Earthquake Model Technical Manual, p. 5-5

HAZUS uses the capacity spectrum method, which is a form of nonlinear static analysis mentioned in the NEHRP (National Earthquake Hazards Reduction Program) Guidelines for Seismic Rehabilitation of Buildings and further detailed in works like the Seismic Evaluation and Retrofit of Concrete Buildings, helps in determining building performance under seismic loads. This method includes the demand spectrum, which is essentially the ground motion's response spectrum modified for actual damping levels, encompassing both the inherent elastic damping and the additional hysteretic damping that occurs during inelastic building behavior.

A graphical representation in HAZUS, identified as Figure 15 below, shows the point at which a typical building capacity curve meets the demand spectrum (which accounts for effective damping rates higher than 5% critical damping). The form of the capacity curve is delineated by specific points representing design, yield, and ultimate capacity, which together define the potential displacement or acceleration of a building. It's at this juncture—the intersection of the building capacity curve and the demand spectrum—that the peak response of the building is determined. This peak response is then used alongside fragility curves to calculate the likelihood of various damage states occurring within the structure.

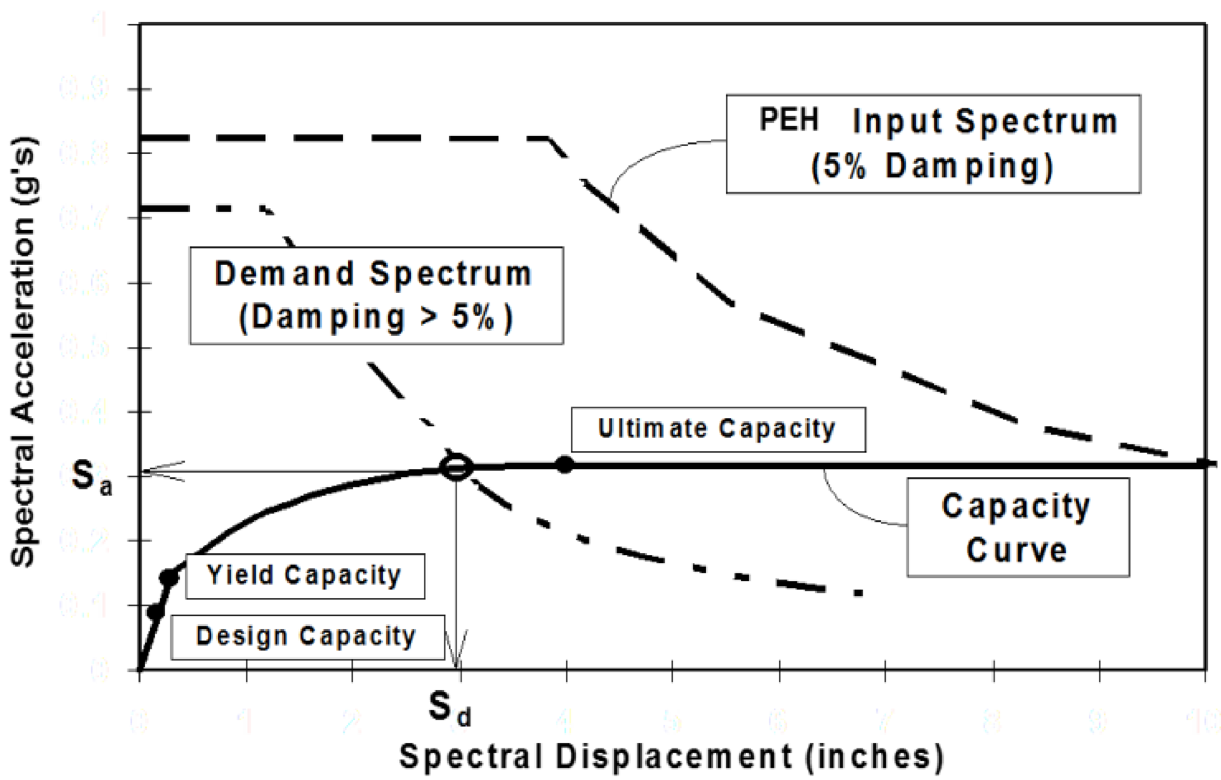

Figure 15: Example Building Capacity and Demand Spectrum

Source: HAZUS Earthquake Model Technical Manual, p. 5-5.

Building fragility curves are used to estimate the probability of different levels of damage occurring. These levels are categorized as Slight, Moderate, Extensive, and Complete, and they apply both to the structural and nonstructural components of a building. Fragility curves are defined by two statistical measures: the median value and the lognormal standard deviation, which are applied to the seismic demand parameters expected from earthquake hazards (PEH).
For the assessment of structural damage, as well as damage to nonstructural elements that are sensitive to story drift, spectral displacement is the chosen PEH. Conversely, for evaluating nonstructural damage to components that are particularly sensitive to acceleration, spectral acceleration is utilized as the PEH. An example of fragility curve is shown in Figure 16 below.

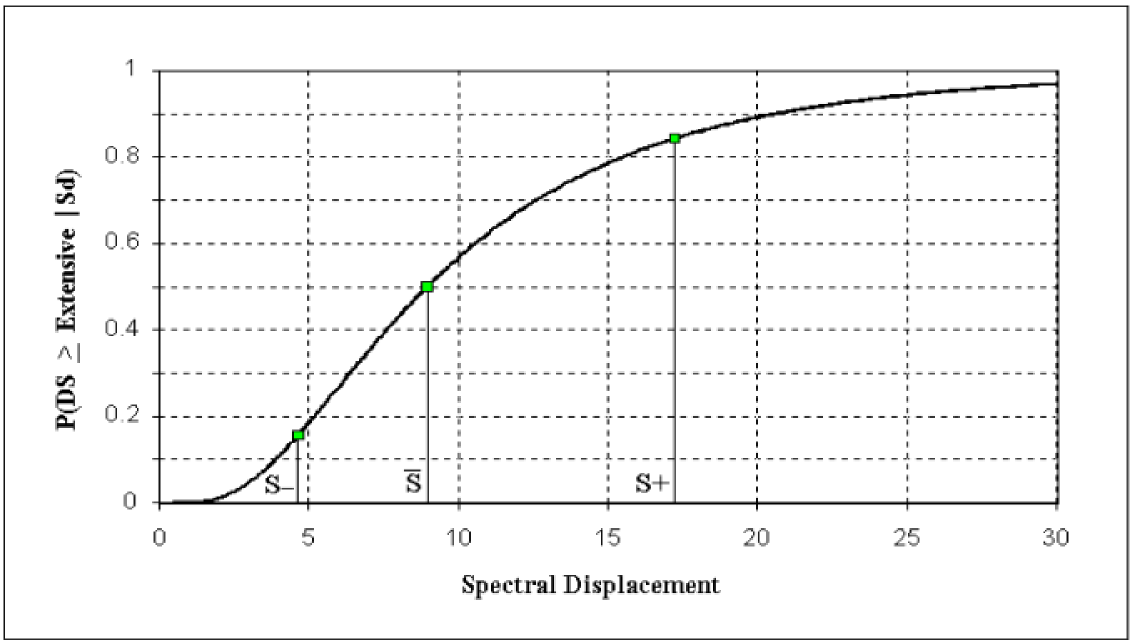

Figure 16: Example Fragility Curve - Extensive Structural Damage, C1M, High Code
Source: HAZUS Earthquake Model Technical Manual, p. 5-33

When considering the seismic demands relating to permanent ground deformation (PGD) due to ground failure, the probability that a building will experience Extensive/Complete damage is calculated using fragility curves. These curves are conceptually akin to those used for evaluating shaking-induced damage but are specifically tailored to account for different types of ground failure, such as lateral spreading or settlement, as well as the building's foundation type. The model does not differentiate between building types with respect to damage. The type of foundation is, however, a crucial element in how a building withstands permanent ground deformation (PGD). Buildings with deep foundations, such as piles, tend to fare better compared to those with spread footings in events of ground settlement. When it is known that a building has a deep foundation, the estimated probability of Extensive or Complete damage due to settlement is reduced tenfold compared to the same building presumed to have a shallow foundation.

In cases of lateral spreading, deep foundations do not confer the same degree of protection as they do for settlement. Thus, if a building is recognized to have a deep foundation, the likelihood of Extensive or Complete damage due to lateral spreading is halved compared to the prediction for a similar building on a shallow foundation. For this reason, foundation type is asked in the Survey. However, HAZUS AEBM AAL does not consider surface rupture in the loss calculation. If landslide and liquefaction susceptibility maps are provided, the damage can be estimated in AEBM AAL. FEMA's BCA Toolkit Earthquake Structural Module does not include the loss due to ground failure. For the consistency of the comparison as well as the lack of landslide and liquefaction susceptibility map compatible with HAZUS input format at the state level, the effect of ground failure is not included in the study.

AEBM Analyzing Annual Average Loss (AAL)

The outputs for the damage assessment are the probabilities of the building's structure, and the non-structural system falls into each of the damage states. The loss estimate is determined based on the damage state probabilities and the replacement value. The replacement values for fire stations are based on Table 4Abelow. The Average losses are calculated per Table 5A. Once average loss is computed, the average annualized loss (AAL) is the summation of the product of the average loss and the differential probability of experiencing this loss. The results are stored and can be queried using MySQL. The "dbo.eqAebm" table holds the inventory data, which is sorted based on the HAZUS ID. The AAL results are stored in "dbo.eqAebmRes" table.

Table 4A Replacement Cost Models for Fire Stations

Model Description	Assumed Building Size (ft^2)	Replacement Cost/ft^2 (2022)	Application Criteria: HIFLD Fire Stations
Non-Urban Fire Station for Volunteer Fire Department	4,000	$229.74	Volunteer[1] Fire Departments in non-Urban Areas
Non-Urban Fire Station for Traditional Fire Department	5,500	$216.16	All Other Fire Departments in non-Urban Areas
Urban Fire Station for Volunteer Fire Department	6,000	$211.94	Volunteer[1] Fire Departments in Urban Areas
Urban Fire Station for Traditional Fire Department	8,000	$203.84	All Other Fire Departments in Urban Areas

[1] *Volunteer fire departments have been identified as facilities whose name contains "VFD," "Vol.," or "Volun."*

Source: HAZUS Inventory Technical Manual, p. 7-7

Table 5A Annualized Loss Calculations

Return Period	Annual Probability	Differential Probabilies		Annual Losses	Average Losses	Annualized Losses
		Formula	Values			
2500	0.00040	P2500	0.0004	L2500	L2500	P2500 * L2500
2000	0.00050	P2000 – P2500	0.0001	L2000	(L2000+L2500)/2	(P2000-P2500) * (L2000+L2500)/2
1500	0.00067	P1500 – P2000	0.00017	L1500	(L1500+L2000)/2	(P1500 – P2000) * (L1500+L2000)/2
1000	0.00100	P1000 – P1500	0.00033	L1000	(L1000+L1500)/2	(P1000 – P1500) * (L1000+L1500)/2
750	0.00133	P750 – P1000	0.00033	L750	(L750+L1000)/2	(P750 – P1000) * (L750+L1000)/2
500	0.002	P500 – P750	0.00067	L500	(L500+L750)/2	(P500 – P750) * (L500+L750)/2
250	0.004	P250 – P500	0.002	L250	(L250+L500)/2	(P250 – P500) * (L250+L500)/2
100	0.01	P100 – P250	0.006	L100	(L100+L250)/2	(P100 – P250) * (L100+L250)/2

** After FEMA, 2017*

Source: HAZUS Earthquake Model Technical Manual, p. 15-3

Calculate Content Loss

HAZUS AEBM reports economic loss due to building damages which include structural, non-structural components sensitive to drift and acceleration. Content loss is calculated in post-processing stage using the formula below from HAZUS Earthquake Model Technical Manual (FEMA, 2016, p. 11-11):

The cost of contents damage is calculated as follows:

Equation 11-10

$$CCD_i = CRV_i * \sum_{ds=2}^{5} CD_{ds,i} * PONSA_{ds,i}$$

Where:

CCD_i	is the cost of contents damage for occupancy class, i
CRV_i	is the contents replacement value for occupancy class, i, as described in the *Hazus Inventory Technical Manual*
$CD_{ds,i}$	is the contents damage ratio for occupancy class, i, in damage state, ds (from Table 11-5)
$PONSA_{ds,i}$	is the probability of occupancy class, i, being in acceleration-sensitive nonstructural damage state ds

Table 6A Contents Damage Ratios (in % of contents replacement cost)

Occupancy Class	Acceleration Sensitive Nonstructural Damage State			
	Slight	Moderate	Extensive	Complete
All Occupancies	1	5	25	50

* *At the "Complete" Damage State, it is assumed that some salvage of contents will take place.*

Source: HAZUS Earthquake Model Technical Manual, p11-11

Contents replacement value is estimated as a percentage of structure replacement value as part of the original development of HAZUS by the National Institute of Building Sciences (NIBS) in 1999. HAZUS Inventory Technical Manual (FEMA, 2020) Table 6-10 summarizes these values for all HAZUS-specific occupancies. The GOV2 Baseline HAZUS Contents Value is 150 Percent of Structure Value, which is used in the study. The content loss for hazard at each return interval is calculated before being integrated into the Annualized Loss. The total economic loss includes the annualized content loss.

Calculate Cost Due to Casualty

HAZUS AEBM estimates the number of occupants in each of the four Injury Severity Levels, as described in Table 7A below.

Table 7A Injury Classification Scale

Injury Severity Level	Injury Description
Severity 1	Injuries requiring basic medical aid that could be administered by paraprofessionals. These types of injuries would require bandages or observation. Some examples are a sprain, a severe cut requiring stitches, a minor burn (first-degree or second-degree on a small part of the body), or a bump on the head without loss of consciousness. Injuries of lesser severity that could be self-treated are not estimated by Hazus.
Severity 2	Injuries requiring a greater degree of medical care and use of medical technology such as x-rays or surgery, but not expected to progress to a life-threatening status. Some examples are third-degree burns or second-degree burns over large parts of the body, a bump on the head that causes loss of consciousness, or fractured bone.
Severity 3	Injuries that pose an immediate life-threatening condition if not treated adequately and expeditiously. Some examples are uncontrolled bleeding, punctured organ, other internal injuries, spinal column injuries, or crush syndrome.
Severity 4	Instantaneously killed or mortally injured

Source: HAZUS Earthquake Model Technical Manual, p. 12-2

Standard Economic Value Methodology Report by FEMA (FEMA, 2023) assigns the cost of injury and un-survivable values based on the Abbreviated Injury Scale (AIS) Code below. See Table 8A and 9A.

Table 8A Cost of Injury and Un-survivable Values Used in the Earthquake Model

Injury Severity Levels	*AIS Code*	*Economic Value*
Unsurvivable	6	$ 12,500,000
Major	2,3,4,5	$ 3,160,000[a]
Minor	1	$ 38,000

[a] Calculated as the average of the values for the multiple AIS Codes from Table 6

Source: BCA Sustainment and Enhancements (FEMA, 2023), p. 20

Table 9A Injury Classes Used in the Earthquake Models

Injury Classes	*AIS Code*[1]
Unsurvivable	6
Major	2,3,4,5
Minor	1

[1] Source: FEMA, 2008a and FEMA, 2008b

Source: BCA Sustainment and Enhancements (FEMA, 2023), p. 20

The AIS codes offer a detailed system for classifying the severity of a specific injury in a particular body region. HAZUS Injury Severity Levels are assigned to their equivalent AIS codes per Table 10A below.

Table 10A AIS Code and the Equivalent HAZUS Injury Severity Level

AIS Code	Description	FEMA HAZUS Injury Severity Level
1	Minor injury	Level 1: Minor injuries requiring basic first aid
2	Moderate injury	Level 2: More serious injuries requiring medical attention but not life-threatening
3	Serious injury	Level 2: More serious injuries requiring medical attention but not life-threatening
4	Severe injury	Level 3: Life-threatening injuries requiring hospitalization
5	Critical injury	Level 3: Life-threatening injuries requiring hospitalization
6	Maximum severity	Level 4: Fatalities

The Average Annualized Loss due to casualty is calculated as the sum of the Average Annualized number of occupants in Level 4 * $12,500,000, Average Annualized number of occupants in Levels 2&3 * $3,160,000 and Average Annualized number of occupants in Level 1 * $38,000. The higher of either the day or night casualty is used.

The total economic loss includes the loss due to building (structural and non-structural), content, and casualties. The loss due to service interruption is not included but can be added through post-processing.

Benefit Calculation-Loss Avoidance from Retrofitting

Loss avoidance is assessed by comparing AAL before and after retrofitting buildings from MC to HC or HS.

Appendix B

FEMA BCA Toolkit Earthquake Structural Module Methodology

Hazard Input

Seismic hazard data is a critical component of the Earthquake Module, varying by location and automatically populated in the tool based on the latitude and longitude of the structure. The BCA Tool utilizes "Peak Ground Acceleration" (PGA) and Spectral Acceleration (Sa) as its primary earthquake hazard measures.

The tool also considers the Site Class, a key input that helps predict the level of ground shaking at a site. The United States Geological Survey classifies soil types into Site Classes A through E, as applied in the BCA Tool.

HAZUS incorporates the 2018 USGS dataset, which includes updated basin effects in areas like the LA Basin and Seattle Basin, differences not reflected in the 2014 USGS hazards used by the BCA toolkit. Additionally, the BCA toolkit accounts for ground motion hazards with return periods under 100 years, whereas HAZUS AEBM considers those with 100 years or longer.

BCA Toolkit feeds these hazards into its damage model similarly to HAZUS, to calculate building responses such as damage costs, loss of function, and life-safety impacts, including casualties.

Structural Evaluation

This section outlines a process where statements from the ASCE 41-17 Tier 1 Evaluation, aligned with the OSHPD-HAZUS standard, serve as a conduit to defining building vulnerability parameters. Once these statements are completed, they are assessed by the BCA Toolkit to ascertain the Collapse Performance Category for both structural and non-structural deficiencies. This category, along with the Building Parameter data, forms a linkage between the identified deficiencies and the Building Vulnerability Parameters, which are essential for calculating the benefit-cost ratio. Users are required to fill out the Structural and Non-Structural Evaluation statements both before and after mitigation.

Based on inputs from the user, the Collapse Performance Category scores are classified into Baseline, Sub-Base, or Ultra Sub-Base, depending on the identified deficiencies. It is recommended that a Professional Engineer (Civil or Structural) conducts at least a Tier 1 evaluation of the building's structural and non-structural components and offers seismic retrofit recommendations as needed. The findings from a Tier 1 evaluation will equip the engineer with the necessary data to participate effectively in the benefit-cost analysis.

Benefit Calculation

For seismic structural mitigation projects, considered effects include:

Avoided Repair Costs: Reduction in repair expenses for structural and nonstructural elements.

Casualties Avoided: Determined by the facility's occupancy at various times, the probability of each damage state and collapse rate, etc. It is calculated similar to the "Calculate Cost due to Casualty" section in Appendix A.

Loss of Function: This section assesses the daily economic impact of the services provided by the critical facility undergoing mitigation.

It is presumed that a fire station's loss of function will lead to increased fire damage due to longer response times. Moreover, if the fire station also offers emergency medical services (EMS), the economic impact of delayed medical response should be considered. The key inputs to calculate the loss of function include:

- Population Served by the Fire Station;
- Type of Area Served by the Fire Station: Users can select whether the area served is urban, suburban, rural, or wilderness. This choice affects assumptions about fire response times, with urban areas having the shortest and wilderness areas the longest;
- Distance to Alternative Fire Station: The distance (in miles) to the nearest alternative fire station that would provide fire protection;
- Provision of Emergency Medical Services: If the fire station provides EMS, the distance (in miles) to the nearest alternative fire station that would offer EMS should be entered.

The BCA Tool measures damage in pre- and post-mitigation scenarios to assess the project's effectiveness in reducing physical damage, loss of function, and casualties. The difference between these scenarios indicates the project's benefit.

Benefit-to-Cost Ratio

Finally, the annual benefits are translated into present value and compared with the total project cost (including ongoing maintenance) to derive the benefit-cost ratio. Specifically, assuming the loss of function is displayed for a non-residential structure, the resulting $/day value is a line-item number that is added to the rest of the benefits to the estimated annual benefits before mitigation, which is then put into the present value using the project useful life and discount rate. This is the same as the other modules (i.e. critical facility structure type, flood hazard, or historical or professional expected damages), outlined in the Standard Economic Values methodology report, Benefit-Cost Analysis Sustainment and Enhancements: Standard Economic Values Methodology Report (FEMA, 2023)

BCA Toolkit Implementation

The project utilizes the BCA toolkit's batch mode and calculates the benefit-to-cost ratio of the default fire station building inventory with Building Type RM1L and W1 in seismic zone 4 should they be retrofitted to design level HC from the current MC design level. The following assumptions are made:

- Project useful life: 30 years
- Annual maintenance cost: $0
- SiteClass: D-stiff soil
- Building Parameters: default values are used
- Structural and Nonstructural evaluation before and after mitigation: Unknown
- Location of Acceleration-Sensitive Components: Uniformly distributed
- Average of Building Occupants: 26 (same with HAZUS input)
- Loss of Rental Income: $0
- Loss of Business Income: $0
- Number of Volunteers Required: 0
- How many people are served by this fire station: 0; 30,000(two scenarios)
- Type of area served by this fire station: as discussed in the "Additional Discussions" Section below.
- What is the distance in miles between this fire station and the fire station that would provide fire protection for the geographical area normally served by this fire station: 5 miles
- Does the fire station provide Emergency Medical Services (EMS)? Yes
- What is the distance in miles between this fire station and the fire station that would provide EMS for the geographical area normally served by this fire station: 5 miles
- Discount Rate: 7%

Additional Discussions - Loss of Function

Since HAZUS doesn't calculate the economic value due to loss of function, BCA toolkit has two runs: one with input to calculate the loss of function to understand the impact and the other one excludes the benefit from the loss of function so the comparison with HAZUS analysis can be made.

The urban influence code from the US Department of Agriculture Economic Research Service in 2013 is used to map each county into urban, suburban, rural or wilderness areas (see results below) [reference: Economic Research Service, 2013]

Table 1B Type of Area Served by the Fire Station

California County	Census Track State and County Code	Designation
Alameda County	6001	Urban
Alpine County	6003	Rural
Amador County	6005	Rural
Butte County	6007	Urban
Calaveras County	6009	Rural
Colusa County	6011	Rural
Contra Costa County	6013	Urban
Del Norte County	6015	Rural
El Dorado County	6017	Urban
Fresno County	6019	Urban
Glenn County	6021	Rural
Humboldt County	6023	Rural
Imperial County	6025	Urban
Inyo County	6027	Wilderness
Kern County	6029	Urban
Kings County	6031	Urban
Lake County	6033	Suburban
Lassen County	6035	Rural
Los Angeles County	6037	Urban
Madera County	6039	Urban
Marin County	6041	Urban
Mariposa County	6043	Rural
Mendocino County	6045	Suburban
Merced County	6047	Urban
Modoc County	6049	Rural
Mono County	6051	Wilderness
Monterey County	6053	Urban
Napa County	6055	Urban
Nevada County	6057	Suburban
Orange County	6059	Urban

Placer County	6061	Urban
Plumas County	6063	Wilderness
Riverside County	6065	Urban
Sacramento County	6067	Urban
San Benito County	6069	Urban
San Bernardino County	6071	Urban
San Diego County	6073	Urban
San Francisco County	6075	Urban
San Joaquin County	6077	Urban
San Luis Obispo County	6079	Urban
San Mateo County	6081	Urban
Santa Barbara County	6083	Urban
Santa Clara County	6085	Urban
Santa Cruz County	6087	Urban
Shasta County	6089	Urban
Sierra County	6091	Rural
Siskiyou County	6093	Rural
Solano County	6095	Urban
Sonoma County	6097	Urban
Stanislaus County	6099	Urban
Sutter County	6101	Urban
Tehama County	6103	Suburban
Trinity County	6105	Rural
Tulare County	6107	Urban
Tuolumne County	6109	Suburban
Ventura County	6111	Urban
Yolo County	6113	Urban
Yuba County	6115	Urban