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COASTAL HOME ELEVATION FOR FLOOD MITIGATION: STRUCTURAL SAFETY AND BENEFIT/COST ANALYSIS

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COASTAL HOME ELEVATION FOR FLOOD MITIGATION: STRUCTURAL SAFETY AND BENEFIT/COST ANALYSIS

By

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ABSTRACT

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Elevating concrete slab-on-grade homes above the base flood elevation is one of the well-known methods of mitigating damage caused by repeated flooding events along the Gulf of Mexico and other coastal areas. This is typically accomplished by placing new pier supports with additional beams, if necessary, under a raised slab home. As a result, the slab support conditions are changed from uniform soil to column and beam supports, leading to unanticipated stress/strain changes, concrete cracks, and slab failure. The current study experimentally evaluated the structural performance of elevated home slabs built per the construction practice along the Texas Gulf coast under uniform floor live load. The first specimen had four panels with monolithically poured grade beams around each panel, while the second specimen had two panels with monolithically poured grade beams supported by additional steel beams. The second specimen also included carbon fiber reinforced polymer (CFRP) laminate retrofitting under one of the panels. The slabs were supported by concrete block masonry piers with various contact conditions. It was found that the typical contractor-determined elevation layout can withstand the building code-mandated floor live load. Increased column spacing decreased slab load capacity as expected. The CFRP layer did not contribute to the moment capacity as the concrete slab itself was able to carry the applied loads and the CFRP layer was not engaged.

The results obtained through running those models through a parametric study were then compiled into a database where each model is categorized into a series of parameters ranging from material properties to support configurations. Finally, an interface was created that allows the user to pick and choose a specific elevated slab and support configuration within the database that would inform the user of the configuration's capacity and whether it meets the minimum design live load established by the International Residential Code.

Flood mitigation methods, including the likes of elevation and demolition, are of very high importance for decreasing flood damage and casualties. A benefit-cost analysis (BCA) is generally performed to compare the cost of mitigation projects versus the benefits, which are avoided costs incurred through loss of property or life. The Federal Emergency Management Agency (FEMA) had compiled a BCA calculator that includes several factors to quantify the benefits from undertaking a flood mitigation project. Despite its importance, the underlying methodology employed by the calculator has inherent flaws in both usage and interpretation of results. In this study, a few published concerns about the omission of important parameters in the BCA were examined, specifically the shortcomings and safety concerns for the methods of elevation and demolition.

Examples are the unintended wealth inequality of users, missing benefits for specific mitigation methods and the relative merits of home elevation vs. home demolition, among others. For coastal Texas areas, the enhancement of the benefit-cost ratios (BCRs) from considering additional logical factors is examined. The risk premium factor increased the BCR with severity of flood damage and depletion of the user's yearly income. The social welfare factors also multiplicatively affected the BCR depending on the property location. The BCR increased at locations with less average income-per-capita and vice versa. Two additional factors related to demolition as a mitigation method were examined - recycling of construction demolished material (CDM) and the cost of landfill usage. The BCR could increase by the market cost of the CDM and with increased recycling of the demolished products. The enhanced BCA approach is

more realistic and will allow users and funding agencies to logically select flood mitigation projects. This will allow enhanced flood resiliency for coastal communities.

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CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

Severe flooding causes extensive economic losses in coastal communities like those in Texas along the Gulf of Mexico. A Federal Emergency Management Agency (FEMA) press release covering the scope and aftermath of Hurricane Harvey tallies 80,000 Texas homes that were inundated by at least 457 mm of water (a sample neighborhood can be seen in Figure 1); 23,000 of that number saw more than 1.5 m of water within its walls. Parts of Harris County reported rainfall of intensity between a 100-year and a 500-year event. Further south in the state, 209 kph winds blew in Aransas County when Harvey passed through.

Figure 1: Harris County Neighborhood Flooded During Hurricane Harvey (HCFCD, 2018)

Homeowners who live in flood-prone areas have taken precautions against repeated flooding events by modifying their home to mitigate the damage caused by rising water levels. The methods include home elevation, relocation, demolition, wet/dry floodproofing, and barrier systems. In the case of homes that have previously been significantly damaged by flooding, only the elevation, relocation, demolition, or wet floodproofing methods may be used to bring the structure to the level of compliance with the community's floodplain management ordinance. It is worth noting that, compared to the other mitigation methods of buyout and demolition, home elevation does produce more economic benefit on average (Mobley, 2020).

As such, the research covered in this report examines the method of home elevation, which seeks to raise a home above the base flood elevation (BFE) level. These slabs are typically cast in-situ directly upon soil and are about 102 mm thick while being minimally reinforced by a single layer of welded wire fabric (WWF). However, the amount of steel present may not satisfy the flexural strength requirement as defined by the American Concrete Institute (ACI) 318 Building Code (2019) once the slab is elevated with a different support condition.

The home elevation method under investigation involves raising the slab-on-grade (SOG), and the attached beams, above the soil to as much as 4.6 m and placed on supports. For economy and practicality, the columns are typically solid concrete or stacked concrete masonry units (CMU). These are typically placed below the concrete grade beams or placed below newly added steel beams wherever more support is required. As a result, the load action of the slab can either be one-way or two-way depending upon the aspect ratio of the original grade beams or the added steel beams.

Concerning the mechanical behavior of concrete slabs, previous experimental and numerical studies evaluated reduced or full-scale slabs with rigid support systems. Lyse and Wernisch (1936) performed testing on one-way, reinforced-concrete slabs with vary concrete compressive strength, steel strength, slab span length, and reinforcement size and spacing. It was discovered that WWF and regular deformed bars performed similarly for resisting flexural moments and the steel yielded fully despite the strength of the surrounding concrete. Sakka and Gilbert (2017) performed explored the behavior of two-way slab systems with low-ductility WWF typical in many existing structures. These slabs were found to fail in a brittle manner, without undergoing significant plastic deformation. However, these systems do not accurately reflect the continuous-panel slab structure with grade beams and non-rigid support systems provided by the beam-to-column connections present in typical home elevation installations.

1.2. PROBLEM STATEMENT

When Hurricane Harvey came ashore to the Texas Gulf Coast in 2017, it brought with it torrential rain and destructive wind. In total, the damage estimate from this storm event comes to 125 billion dollars, making it the second most costly hurricane after Hurricane Katrina (Lindner, 2018). Due to catastrophic flooding in nearly every watershed, Harris County witnessed storm surge as high as 3.4 m. About 154,170 structures were flooded, and the county sought 1.12 billion dollars in federal housing aid. Elsewhere in Texas, Nueces County saw storm surge as high as 1.7 m, damaging 6,600 homes and incurring 179 million dollars' worth of FEMA aid. While Aransas County saw a 1.5 m storm surge, most of the affected 3264 homes were damaged by the wind, incurring 162 million dollars' worth of FEMA aid.

Even if Hurricane Harvey were not an exceptional hurricane event, the residents that live along the Texas Gulf Coast are no strangers to flooding caused by storms. Flood mitigation retrofitting, such as home elevation, becomes a more enticing proposition if the alternative is to pay for extensive repairs after each event or move out of the area.

There exists a knowledge deficit in the design of elevated slabs. No established structural code, such as the ACI Building Code, or governing body, such as FEMA, features explicit instructions on the procedure. Specifically, the ACI Building Code provides guidance on the design of concrete slabs for set support conditions, however, it does not contain rules for retrofitting slab-on-grade to slab-on-columns. Likewise, the FEMA *Homeowner's Guide to Retrofitting* (2014) only defers the design aspect to trained contractors. Seniwongse (2010) performed a comparative study between the observed behavior of slabs on grade versus framed slabs. For optimum design, the SOG can be made skinnier and with less reinforcement than the framed slab. However, that point only highlights the uncertainty of converting an SOG into a condition like a framed slab while keeping the same traits.

1.3. OBJECTIVE

The objectives of this study are listed below.

- Understand the effects of hurricane events and their effects upon the residential structures of the Texas Gulf Coast.
- Gather and check with the expertise of elevation contractors as well as local/state/federal officials.
- Create a rational and scientific solution to determine safety in the home elevation process.
- Produce a software application that allows users with minimal engineering knowledge to access this solution and run the safety check not explicitly covered by FEMA or ACI guidance.
- Publicize and educate the stakeholders (i.e., homeowners, elevation contractors, emergency management officials, and policy makers, etc.) in this solution.
- Optimize the flood mitigation evaluation process by examining the current process to decide on a mitigation method and refine the process.

The paper presented in chapter 2 addresses the experimental and initial numerical modeling that would develop the background for the rational solution to determine slab safety. Following on that, the paper in chapter 3 details the steps taken to refine and expand on the numerical modeling to produce a software interface that would allow the stakeholders to learn about and interact with the solution. The final paper, shown in chapter 4, covers the procedures to modify the flood mitigation decision making process.

1.4. METHODOLOGY

Due to the cooperative nature of the project being handled by both the University of Texas at Arlington (UTA) and Texas A&M University (TAMU), the tasks performed in this study were handled in the manner listed in Table 1.

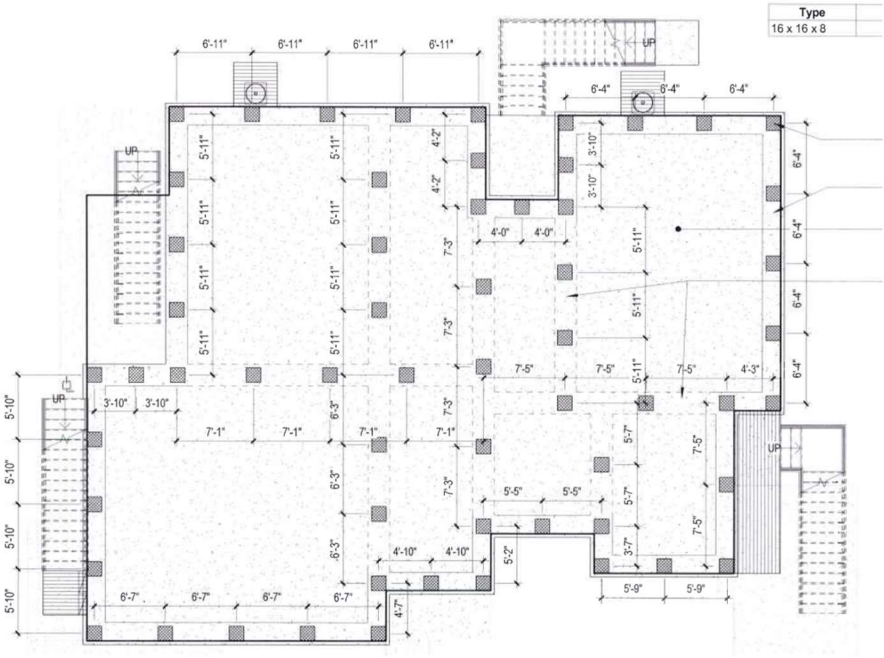
Table 1: Methodology and Responsible Parties

Tasks	Party Responsible
Harvey-affected area elevated slab research.	UTA: C. Ling
Experimental slab drafting and design.	UTA: C. Ling
Experimental slab construction and testing.	UTA: C. Ling
Slab specimen numerical modeling.	UTA: C. Ling
Full-slab numerical modeling.	TAMU: Y. Yoo
Slab model parametric study.	TAMU: Y. Yoo
Software application programming and logic.	UTA: D. Kar, C. Ling
Public education and outreach.	UTA: D. Kar, C. Ling TAMU: Y. Yoo
Flood mitigation decision making improvement.	UTA: C. Ling

1.5. LITERATURE REVIEW

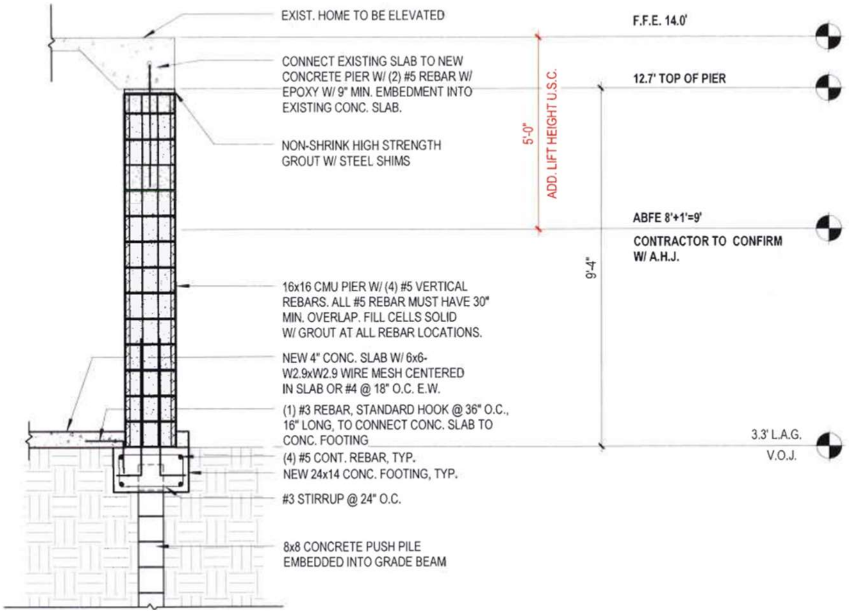
1.4.1. The Condition of Elevated Homes in the Harvey-affected Areas

One of the stated objectives was to produce experimental slab specimens that resemble those used in homes across the Texas Gulf Coast. The findings from the elevation plan study and the site research were used to produce a couple, common configurations for homes with concrete slabs. Ducky Johnson Home Elevation, a contractor firm that specializes in flood mitigation retrofitting, provided sample plans from previous projects that showed the techniques being used in contemporary construction practice. Figure 2(a) shows a sample floor plan in which the slab panel sizes and column spacings were gleaned, and Figure 2(b) shows an example of a column-to-beam connection found in a few of the home elevation plans.



1 ft. = 304.8 mm.

(a) Floor Plan and Column Spacings (Robert, 2015)



(b) Pier Support Connection (Robert, 2015)

Figure 2: Sample Home Elevation Plans

The site research was conducted in the neighborhoods of Nassau Bay, Texas, a city directly on the shoreline. Each elevation project was to be subsidized by the local government via funds procured from FEMA. The procedure is performed in stages. First, the immediate area around the slab of the home is hollowed out to make room to insert jacks beneath the slab. The slab and house superstructure are lifted to an initial height of about 1.2 m, as seen in Figure 3. Once lifted, temporary shoring is constructed to allow the home to settle and be set level. Afterwards, the home is lifted to its final height, set level, and a new, concrete slab is cast in the location of the original. Columns (either made of CMU or pure concrete) are constructed atop the new slab to support the old slab and the home. Figure 4 shows an example of a home supported by a steel beam system.

Figure 3: Nassau Bay Home in the Process of Being Elevated

Figure 4: Elevated Home Supported by CMUs and Steel Beams

From these sources, the features of the experimental slabs can be determined. These features include panel size, panel aspect ratio, the presence of grade beams, pier dimensions, and pier connection types. To be conservative, there are common features that are assumed between all slab samples. The concrete compressive strength of the slabs is assumed to be between 13.8 and 20.7 MPa, due to the age of the homes under examination. The overall thickness of the slab is assumed to be 102 mm. Welded wire fabric is assumed to be the only source of tensile reinforcement in the slab, and it is placed at the very bottom to emulate the poor construction or deterioration of the slab with time, as seen in Figure 5. Monolithic grade beams line the perimeter of the slabs, as well as divide each up into separate panels; the beams are reinforced with a rebar cage tied by stirrups. The piers are composed of reinforced and grouted CMU with the maximum contractor-specified spacing of 3.0 m center-to-center.

Figure 5: Exposed WWF Under a Raised Slab

1.4.2. Slab Strengthening Retrofit Solution

A retrofit solution has been tested using carbon-fiber-reinforced polymer (CFRP) wrap to increase the flexural strength of concrete slabs. Qian and Li (2013) performed a study by applying load onto CFRP-strengthened slabs to test their peak capacities. They found that CFRP application would increase the peak capacity of lightly reinforced slabs up to 111.8% and moderately reinforced slabs up to 57.3%. A pilot study was performed at the University of Texas at Arlington concerning the effect of CFRP in retrofitting elevated house slabs to increase load-carrying capacity (Chaiwino et al., 2021). This was done by constructing a two-panel experimental concrete slab elevated on columns and then applying a strip of CFRP upon the expected region of failure, seen in Figure 6. Water load was applied to the top of the slab to simulate a uniform live load until failure of the slab was induced. This study found that the application of CFRP on the negative bending surface could increase its capacity by about 30%.

(a) Water Loading

(b) Experimental Setup

Figure 6: CFRP Retrofit Experimental Testing (Chaiwino et al, 2021)

However, when compared to housing slabs in a real-world scenario, the slab designs used in the previous studies did not match those observed in the research performed for the experimental slab design, now. The main difference is the existence of monolithic grade beams under the slab of actual homes, whereas the studies previously used only flat plate-type slabs. Furthermore, the application of CFRP in the pilot study was applied without the obstructions that a house superstructure would impose on such a configuration. This study will examine the performance of slabs that mirror those used in practice and evaluate their performance when elevated, as well as CFRP retrofit application that would be feasible under those conditions.

1.4.3. Retrofit Decision Making with Benefit Cost Analysis

According to the Homeowner's Guide to Retrofitting (FEMA, 2014), there are a list of decisions to consider when choosing the type of hazard mitigation to undertake, listed below.

- Appearance.
- Cost.
- Accessibility.
- Code-required Upgrades.
- Human Intervention.

To maintain an objective perspective, the measure of cost was the focus of the study. Assisting with the decision making, FEMA had also created a software calculator that allows a user to determine the benefit cost analysis (BCA) of a hazard mitigation retrofit project and compare it with another. The outcome of this function is the benefit-cost ratio (BCR) which is the value of the benefits (costs of damage caused by the hazard to an unmitigated structure) divided by the costs (expenses made to perform the mitigation project). What constitutes a benefit is provided in Table 2.

Table 2: Types of Benefits in FEMA BCA Toolkit

Category	Specifics
Avoided Costs	- Physical damage - Loss of service/function - Injury or death - Displacement costs - Emergency management costs - NFIP administration costs
Social	Costs associated with mental duress and lost wages
Environmental	Projects that benefit the natural environment

The toolkit is not without its limitations. Table 3 provides a summary of what is not considered a benefit or shortcoming of the calculations present in the BCA software sorted by literature, and it also provides suggestions authors have made, if applicable.

Table 3: Considerations that Are Not Benefits and Shortcomings of the FEMA BCA Toolkit

Not Benefits And Limitations	Suggestions	Source
- Changes in gross regional economic product - Changes in future economic development or tourism - Avoided criminal justice system costs for disaster-related crime (i.e., looters)	n/a	Office of Management and Budget (1992)
Social effects that would occur because of displacement due to unmitigated home damage: - Unemployment. - Homelessness. - Long term harm to health.	- Expand category of benefits - Weighting costs and benefits to account for wealth effects - implementing a multifactor analysis that considers distributional concerns - integrating social vulnerability into long-term planning - providing support for those who must relocate	McGee, K (2021)

Not Benefits And Limitations	Suggestions	Source
The BCA's software and policy issues negatively affect hazard mitigation funding processes. The policy issues are as follows. 1. The precision requirements for some inputs can strain subapplicant and applicant resources. 2. The volume of inputs and backup data required can strain subapplicant resources and prevent subapplicants from receiving benefits. 3. FEMA's range of acceptable inputs provides less opportunity for less populated communities to add benefits. 4. There seem to be gaps in FEMA's technical assistance for the BCA.	Six recommended actions to make the BCA program more usable are proposed, organized into three shorter-term solutions and three longer-term solutions based on their expected timeframes for implementation. In the shorter term, FEMA should: 1. Offer more software training and technical assistance to users. 2. Increase maximum funding for project scoping. 3. Allow applicants and subapplicants to use other federally approved BCA tools.' To improve the BCA Program, in the long run, FEMA should: 1. Fix the BCA software. 2. Alter FEMA policy on data inputs and backup documents. 3. Create a review program to accept additional FEMA-approved BCAs.	Natural Hazard Mitigation Association (2021)
FEMA acquisitions favor counties with: - Higher per capita income - Higher education levels - Larger workforce Within counties administering buyout programs, buyout neighborhoods tend to be: - less well educated - less diverse Minority homeowners that receive a buyout may be poorly compensated relative to others in a county. Black populations are: - increasingly less likely to receive buyouts - likely to receive increasingly lower buyout compensation over time	n/a	Nelson and Malloy (2021)

CHAPTER 2: EXPERIMENTAL EVALUATION OF ELEVATED HOME SLABS FOR FLOOD MITIGATION

ABSTRACT

Elevating concrete slab-on-grade homes above the base flood elevation is one of the well-known methods of mitigating damage caused by repeated flooding events along the Gulf of Mexico and other coastal areas. This is typically accomplished by placing new pier supports with additional beams, if necessary, under a raised slab home. As a result, the slab support conditions are changed from uniform soil to column and beam supports, leading to unanticipated stress/strain changes, concrete cracks, and slab failure. The current study experimentally evaluated the structural performance of elevated home slabs built per construction practice along the Texas Gulf coast under uniform floor live load. The first specimen had four panels with monolithically poured grade beams around each panel, while the second specimen had two panels with monolithically poured grade beams supported by additional steel beams. The second specimen also included carbon fiber reinforced polymer (CFRP) laminate retrofitting under one of the panels. The slabs were supported by concrete block masonry piers with various contact conditions. It was found that the typical contractor-determined elevation layout can withstand the building code-mandated floor live load. Increased column spacing decreased slab load capacity as expected. The CFRP layer did not contribute to the moment capacity as the concrete slab itself was able to carry the applied loads and the CFRP layer was not engaged.

ADDITIONAL INDEX WORDS: CFRP, Concrete Strengthening, Elevated Homes, Flood Mitigation, International Residential Code (IRC), Slab Testing

2.1. INTRODUCTION

2.1.1. Home Elevation as a Flood Mitigation Method

Severe flooding causes extensive economic losses in coastal communities like those in Texas along the Gulf of Mexico. A Federal Emergency Management Agency (FEMA) report covering the scope and aftermath of Hurricane Harvey (FEMA 2017) tallies 80,000 Texas homes inundated by at least 4.6 m of water; 23,000 had more than 1.5 m of water within its walls. A popular mitigation strategy to reduce or eliminate flood damage is to raise a home above the base flood elevation (BFE) level. The concrete slabs are typically cast in-situ directly upon soil and are about 100 mm thick while being minimally reinforced by a single layer of welded wire fabric(WWF).

The home elevation method involves raising the slab-on-grade (SOG) and the attached beams above the soil to as much as 4.6 m height and placing them on new supports. For economy and practicality, the new piers are typically solid concrete or stacked concrete masonry units (CMU). These are typically placed below the existing concrete grade beams or newly added steel beams wherever more support is required. As a result, the load action of the slab can either be one- or two-way, depending upon the aspect ratio of the original grade beams or the added steel beams.

Elevating a home above the BFE is a viable option for flood damage reduction. However, the process causes unexpected stresses due to the changed support conditions. Such slabs are lightly reinforced and low-quality concrete that degrade with age, reducing capacity and safety. The elevated slabs, therefore, must be supported appropriately if necessary. Inadequacies in these areas can result in slab failure or collapse of the home, which may lead to casualties and economic losses. Examples are a home being raised in Louisiana collapsing during the elevation process (Hammer,

2011) and a New Jersey house sliding and colliding with the home next door while being raised, as seen in Figure 7. With the proliferation of home elevations in flood-prone areas, the structural safety of such projects is a critical concern.

Figure 7: New Foundation Construction Collapses During the Elevation Process (Robbins, 2013)

2.1.2. Problem Statement

There exists a knowledge deficit in the design of elevated home slabs. No established structural code, such as the ACI Building Code (2019), or governing body, such as FEMA, provides explicit instructions on the procedure. The ACI 318 Building Code (2019) provides guidance on the design of concrete slabs for set support conditions; however, it does not have provisions for retrofitting SOG to slab-on-columns. Likewise, the FEMA Homeowner's Guide to Retrofitting (2014) only defers the design aspect to trained contractors. Seniwongse (2010) compared the observed behavior of SOG versus framed slabs. For optimum design, the SOG can be made skinnier with less reinforcement than the framed slab. However, that point only highlights the uncertainty of converting a SOG into a framed slab while keeping the same traits.

A retrofit solution has been tested using external carbon fiber reinforced polymer (CFRP) laminate to increase the flexural strength of concrete slabs. Qian and Li (2013) found that CFRP-strengthening of lightly and moderately reinforced concrete slabs increased their ultimate capacities by up to 112% and 57%, respectively. A pilot study was conducted at the University of Texas at Arlington as a precursor to the current study to investigate the flexural behavior of full-scale elevated home slabs reinforced with a low-ductility WWF and supported by the typical steel-beam-and-concrete-masonry-pier configuration (Chaiwino et al., 2021). The study investigated the effect of CFRP in retrofitting elevated home slabs to increase load-carrying capacity. It was found that applying CFRP on the negative bending moment surface could increase the capacity by about 30%.

The slabs investigated in past studies were not fully representative of home slabs in a real-world scenario. The main difference was the existence of monolithic grade beams under the slab of actual homes, whereas the cited studies used only flat plate-type slabs. Furthermore, the CFRP laminate in the pilot study (Chaiwino et al., 2021) was applied without obstructions on top of the concrete slab (where the negative moment would occur) from interior walls and floor finish. The current study examined the performance of home concrete slabs that resembled those used in practice and evaluated their performance when elevated, with CFRP retrofit applications that would be feasible under those conditions.

2.2. METHODS

2.2.1. Test Specimen Design

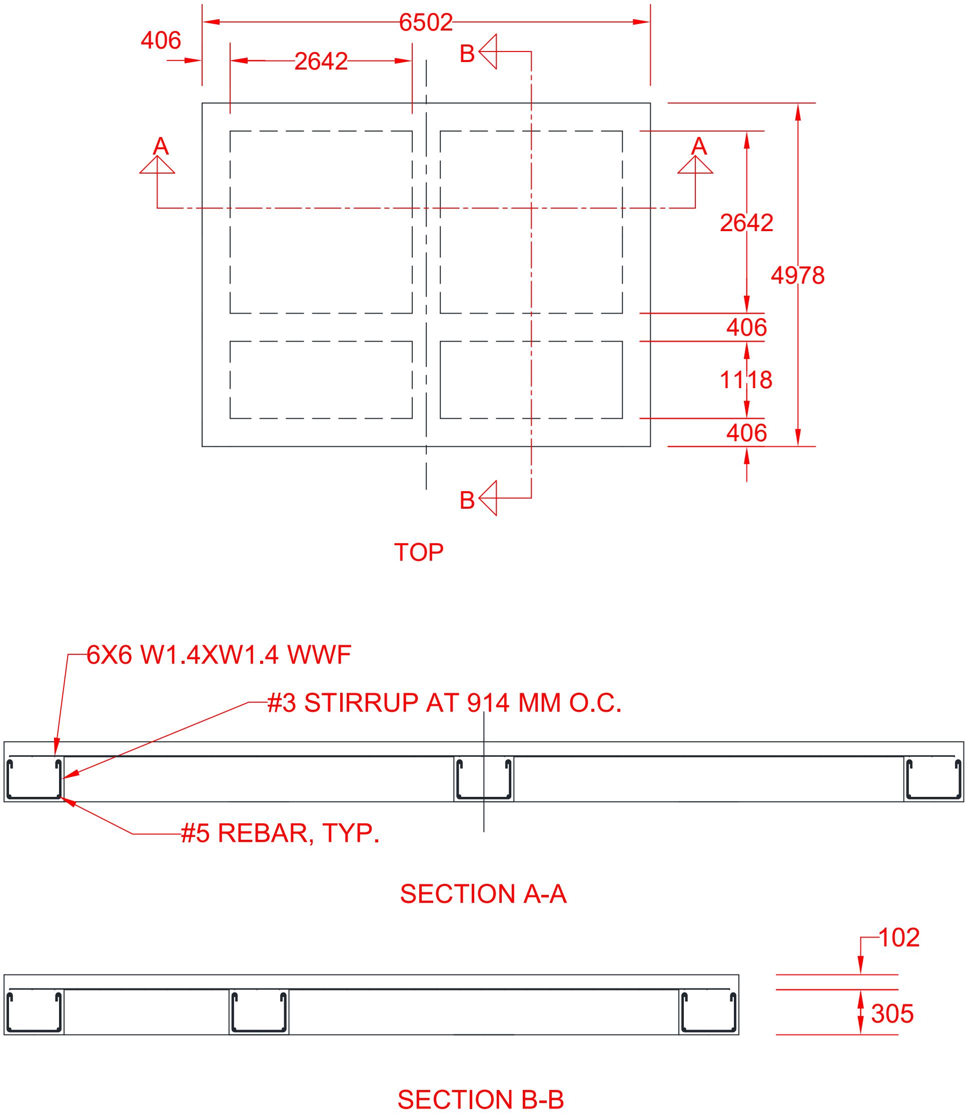
Two full-scale concrete test slabs were designed based on the properties of homes along the US Gulf Coast from Texas and Louisiana [Figure 8(a)]. The design is composed of information gathered from home elevation construction plans and site research on home elevation projects. The contractor-provided plans showed how the existing foundation slabs are typically sized and shaped, along with details on how the new columns and foundations are constructed. The design slabs' thickness (102 mm), column dimensions (406 mm x 406 mm), and grade beam sizes were determined using this information. The site research provided insight into the quality of the existing slabs, the occurrence of different support conditions and the home elevation procedure. For example, Figure 8(b) shows that some elevation projects incorporated steel beams below the concrete slab. In contrast, Figure 8(c) shows an elevated house with columns directly interfacing with the grade beams below the slab.

(a) Homes in the Process of Being Elevated

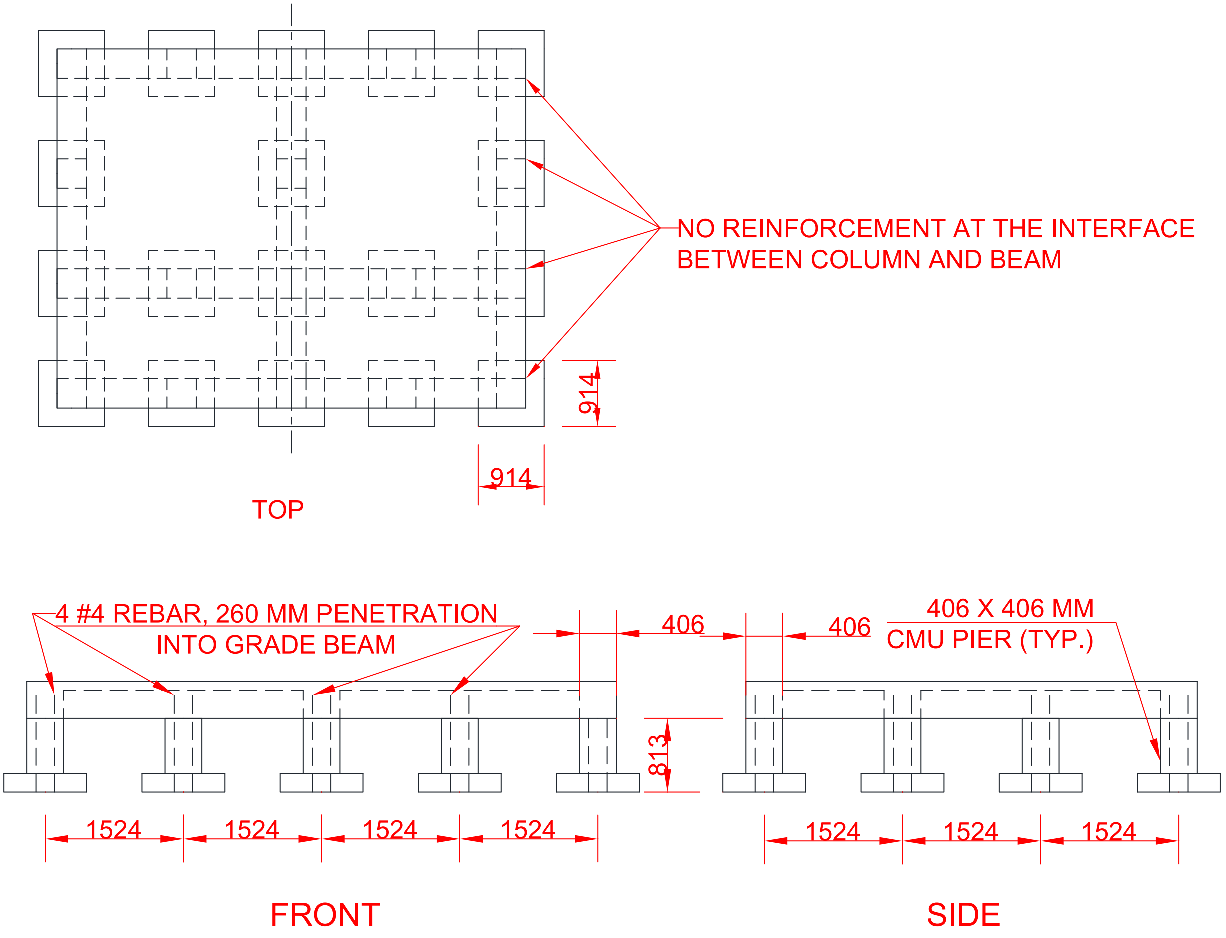
(b) Elevated Slab with Steel Beam Supports (c) New Pier under Existing Grade Beam

Figure 8: Nassau Bay, Texas, Home Elevation Examples

The differing features of the two test slabs were their geometrical configurations and support conditions. Slab 1 consisted of four continuous panels, with the two larger panels shaped to induce two-way action for flexural bending. Figure 9(a) and Figure 9(b) show the slab details with and without the footing. The grade beams were 406 mm thick, projected 305 mm below the bottom of the slab and reinforced by a cage of 15.9 mm diameter longitudinal rebars tied together by 9.5 mm diameter stirrups. The CMU piers were directly connected with the grade beams, with the pier reinforcement extending into the beams. The pier reinforcement was intentionally cut short on a single row of columns to prevent embedment into the grade beam, as seen in Figure 9(b). The purpose was to test whether the reinforcement interaction affected the slab's performance. The theoretically calculated flexural capacity of the critical panel was 2.4 kN.m, equivalent to 0.46 kPa of applied load.


406
6502
2642
B
A
A
2642
4978
406
1118
406
B
TOP
6X6 W1.4XW1.4 WWF
#3 STIRRUP AT 914 MM O.C.
#5 REBAR, TYP.
SECTION A-A
102
305
SECTION B-B

(a) Slab Only

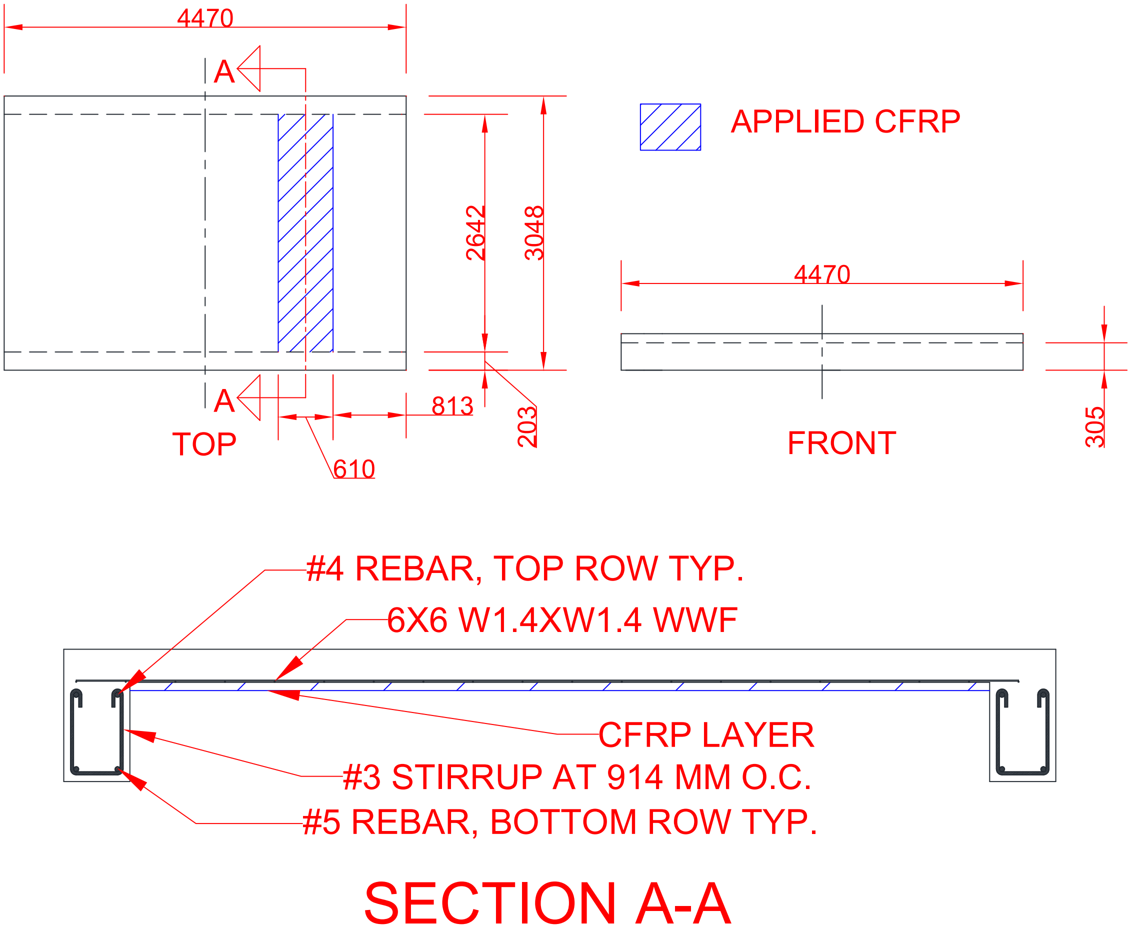


(a) Slab with Footing

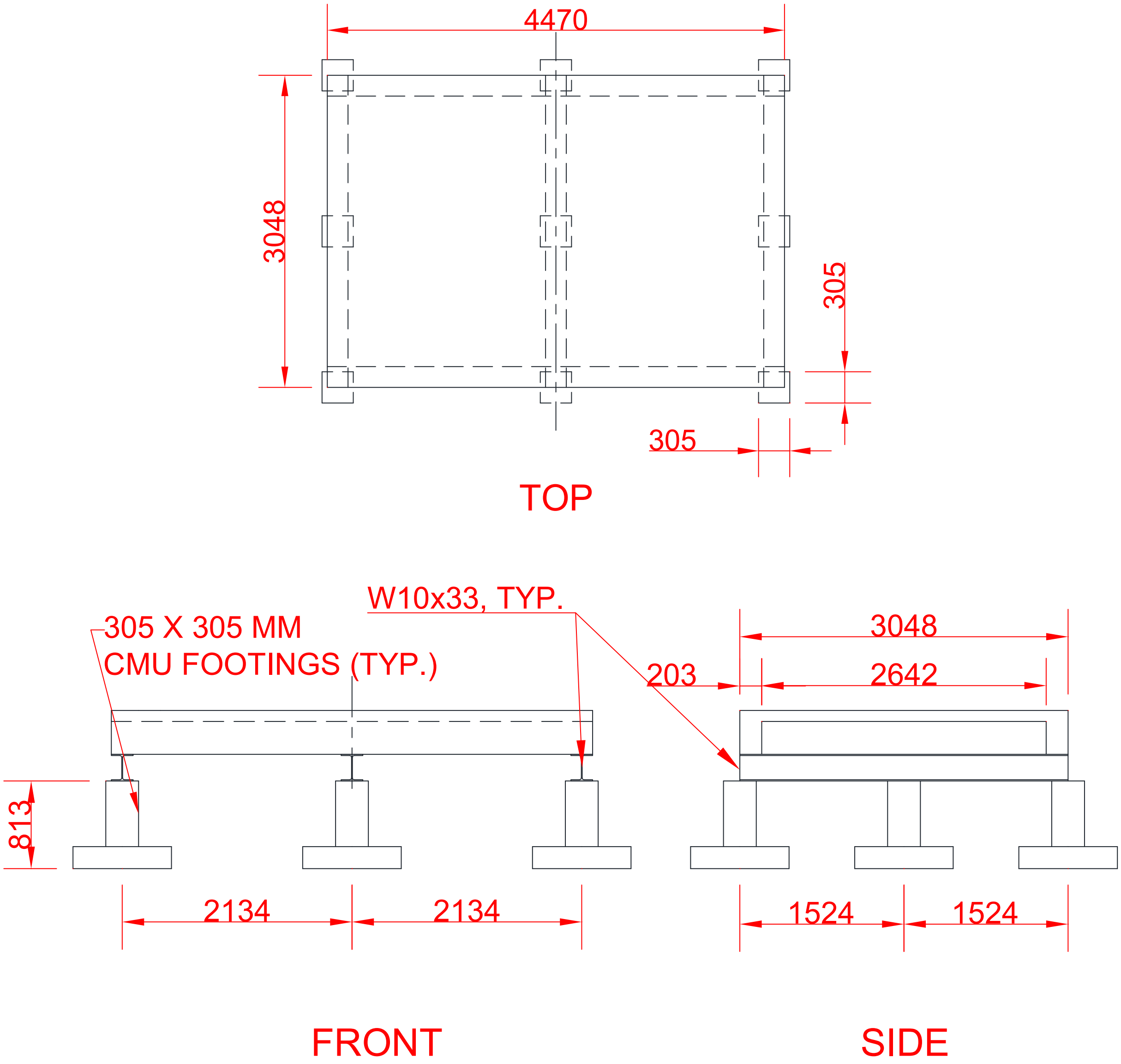
Figure 9: Four-Panel Slab Specimen (All dimensions in mm)

Slab 2 was comprised of two panels. Figure 10(a) and Figure 10(b) show the slab details with and without the footing. The dimensions were designed to generate one-way action in bending. Similar to the four-panel slab, the grade beams were 203 mm thick and projected 305 mm below the bottom slab surface. The main difference between this specimen and the first was the application of CFRP retrofitting under the slab and wide-flange beams between the grade beams and piers. This configuration relies on gravity to keep the slab atop the support structure. While the study by

Chaiwino et al. (2021) showed a considerable increase in the flexural capacity of the slab due to the CFRP application on the top surface of the slab, this experiment was to check if any increase in the slab flexural capacity could be achieved through the CFRP application on the bottom surface. The proposed configuration allows for a more convenient form of strengthening without accounting for top obstacles in real-world applications. The theoretically calculated flexural capacity of the critical panel was 2.4 kN.m, equivalent to 2.35 kPa of applied floor load.



(b) Slab Only



(c) Slab with Footing

Figure 10: Two-Panel Slab Specimen (All dimensions in mm)

2.2.2. Slab Construction

We constructed the test specimens in a step-by-step process. The footings and columns were assembled and arranged as seen in Figure 11(a). The steel beams were arranged atop the piers for the two-panel slab. The formwork was constructed on top of the column assembly, shown in Figure 11(b), to allow the slabs and beams to be poured in the elevated configuration.

a) Pier and Footing Assembly

b) Slab Formwork Assembly

Figure 11: Experimental Slab Construction Process

We used a target concrete compressive strength of 13.8 MPa for the slabs and grade beams to account for lower concrete strength (ACI 501-36T, 1936) due to concrete deterioration from direct exposure to the soil. Most elevated homes are not new and the age effect on the concrete can be significant. The target fresh concrete slump was 10 +/- 2.5 mm. The concrete mix design is provided in Table 1. The yield strengths of the steel rebars and WWF used were 345 and 415 MPa, respectively. We used two concrete batches to construct the slabs. The two-panel slab was entirely made from Batch 1, while the four-panel slab was constructed from a mixture of Batches 1 and 2 due to the arrival delays of ready-mix trucks. After the concrete was poured and cured, the formwork was removed. The area under the two-panel slab, designated in Figure 10 for CFRP application, was roughened to a Concrete Surface Profile 3 (CSP 3) per the CFRP manufacturer specifications using sandpaper grinding. The surface was then cleaned thoroughly of residue from the grinding or other sources using rubbing alcohol. A layer of epoxy was applied to the roughened concrete, followed by a single layer of CFRP and then sealed with a second layer of epoxy. The CFRP and the epoxy were obtained from a well-known manufacturer and their properties are summarized in Table 2.

Table 4: Concrete Mix Design Per One m^3

Materials	**Weight per 1.0 m^3 (kg)**
Cement	183
Fly Ash	40
Coarse Aggregate	1129
Fine Aggregate	867
Water Reduction Admixture	0.697
Air Entraining Admixture	0.0704
Water	133

Table 5: Properties of CFRP Laminate and Epoxy

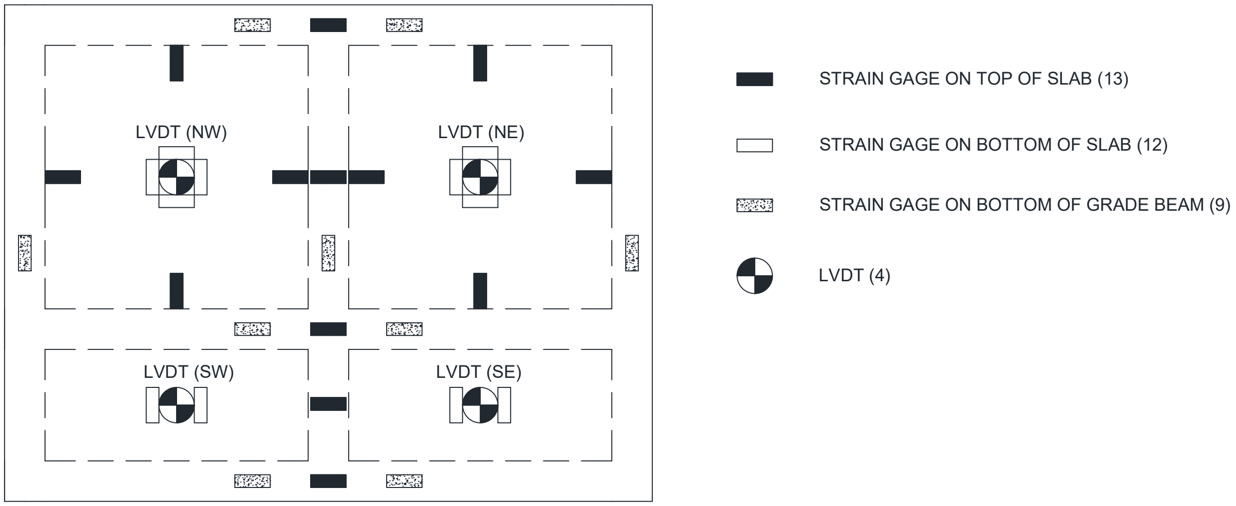
Material	Property	Value
Cured CFRP Laminate	Thickness (mm)	0.51
	Longitudinal Tensile Strength (MPa)	724
	Longitudinal Modulus of Elasticity (GPa)	56.5
Two-Part Epoxy Adhesive	Tensile Strength (MPa)	33.8
	Flexural Strength (MPa)	60.6
	Flexural Modulus (GPa)	3.5

2.2.3. Instrumentation and Testing

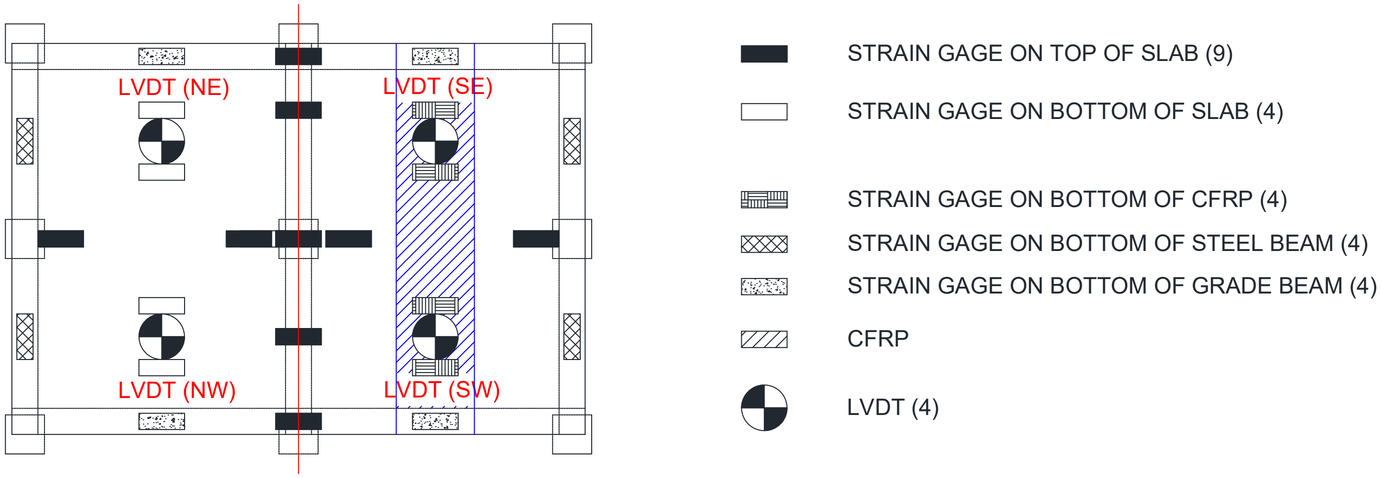
The flexural capacity of the experimental slabs was found by applying a uniform floor load onto the slab surfaces until failure. The goal was to simulate the International Residential Code (IRC, 2021) specified 1.9 kPa maximum live load for residential buildings. Gradually increasing level of tap water was conveniently used as the medium to apply uniform pressure with sealed plywood barricades constructed atop each experimental slab before testing, as shown in Figure 12. The four- and two-panel slab basins were expected to hold up to an equivalent of 11.2 and 11.95 MPa floor load, respectively, roughly six times the IRC (2018) imposed minimum live load capacity. The self-weights of any potential superstructure atop the home slabs were not included. The four-panel slab was filled at a near-constant water application rate of 8,300 m^3/s until about half the basin height was filled. The two-panel slab was filled at a near-constant rate of 6,700 m^3/s of water until about 75% of the basin height was filled. Once the four- and two-panel slabs reached these water levels, the water level stopped changing as the water in-flow reached equilibrium with the water escaping through cracks.

Figure 12: Waterproof Basin Constructed on Top of Slab

Linear Variable Differential Transformers (LVDTs) were set up at locations beneath each slab where maximum deflections were expected, and uniaxial strain gages were applied on the slab surfaces at critical points. The instrumentation plan for the test specimens is shown in Figure 13. The strain gages were oriented considering the bending direction of each slab panel and beams. Data was collected at a rate of eight per second from all sensors. Photos of the strain gages may be found in Appendix A.



(d) Four-Panel Slab



(b) Two-Panel Slab

Figure 13: Slab Instrumentation Plans

2.2.4. Numerical Modeling

The experimental four-panel slab was modeled using the finite element software package ABAQUS (2021) to serve as the basis for the parametric study in which the flexural capacity is predicted while adjusting multiple slab parameters. The slabs, columns, and beams were modeled with 8-noded brick elements, C3D8. The WWF and reinforcing steel were modeled with 2-node wire elements, T3D2. Furthermore, the reinforcement was embedded into the concrete elements. The beam-column interface was defined as a “rough” surface contact, which allows the software to use an infinite coefficient of friction to prevent slipping. The concrete was modeled using the Concrete Damage Plasticity (CDP) model with parameters shown in Table 3 (Carreira and Chu, 1985). Different values for the moduli of elasticity were used for the two concrete batches. The distribution of the two batches in the model can be seen in Figure 14, where the white shading represents the combined mixture of Batches 1 and 2, and the dark shading represents the portion cast with Batch 2 concrete. The average elastic moduli of the two batches were set as the lower and upper bounds to calibrate the model. Then, the model was run using the full range of values between the boundaries until the closest matching result to the experimental data was obtained. Both the WWF and rebar steel used an elastic-perfectly plastic model as visualized in Figure 15 because only the initial steel yielding was the concern, as far as the failure condition was concerned. The water load or the simulated live load was modeled as a uniform pressure on the top surface of the slab. It was applied as a general static analysis stair-step function broken into eight increments to facilitate convergence as shown in Figure 16.

Table 6: Material Properties Used in the Numerical Model

Property	Concrete (Batch 1)	Concrete (Batch 2)	WWF Steel	Rebar Steel
Density (kg/m^3)	6.095	6.095	20.36	
Elastic Modulus (MPa)	5,489	9,683	199,948	
Poisson's Ratio	0.15	0.2	0.3	
Yield Stress (MPa)	--		275.8	413.7
Plastic Strain	--		0.02	
Viscosity	0.01		--	
Dilation Angle (°)	31		--	
Eccentricity	0.1		--	
Ratio of Biaxial to Uniaxial Compression Yield Stresses (f_{b0}/f_{c0})	1.16		--	
Ratio of Tensile to Compressive Second Stress Invariants (K)	0.666		--	

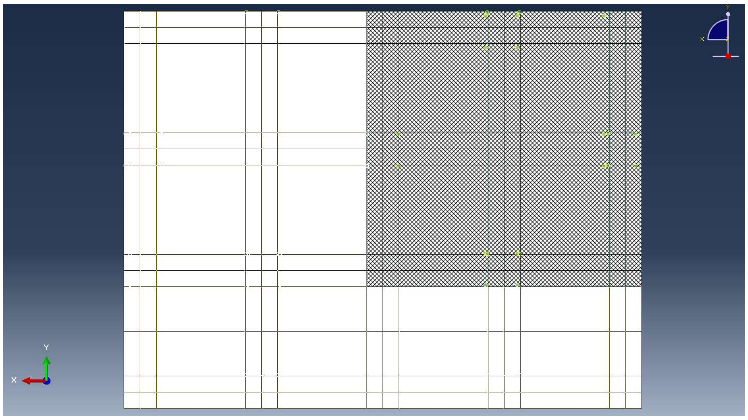


Figure 14: Concrete Batch Distribution

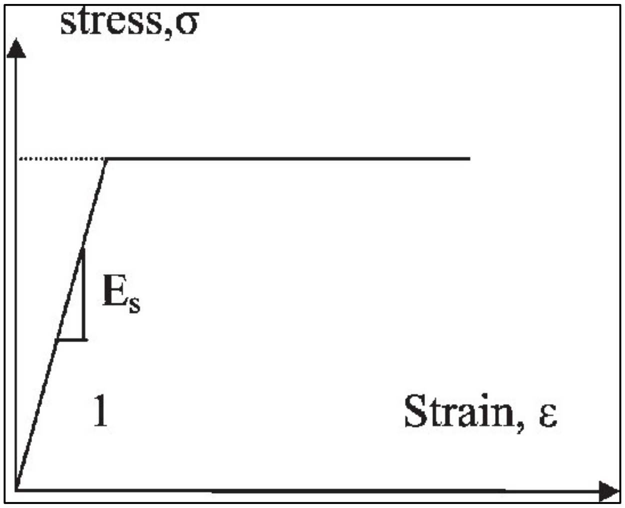


Figure 15: Elastic-Perfectly Plastic Model for Steel Reinforcement (Wu and Hemdan, 2007)

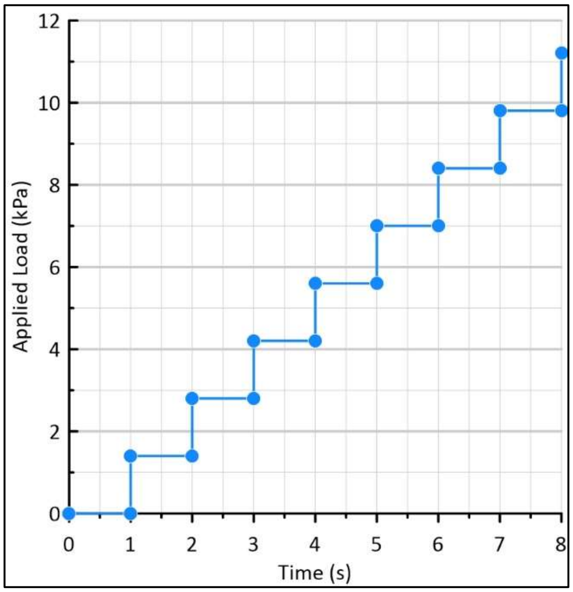


Figure 16: Applied Load Versus Time Function for the Model

An optimal 50 mm mesh size with a linear geometric order and full integration was employed to balance accuracy and processing time for the model. The mesh size was determined using the finite element mesh extrapolation method by Cook (2001), given in Eq. (1).

$$\phi_\infty = \frac{\phi_1 h_2^q - \phi_2 h_1^q}{h_2^q - h_1^q} \tag{1}$$

Where:

ϕ_n = Quantity of interest or any derivative

ϕ_∞ = Quantity observed from an infinitely small mesh

h_n = Size of the mesh element

q = Exponent that is chosen such that ϕ versus h^q plots as a straight line

If the original mesh is too coarse, ϕ may not lie on a straight line for any value of q. The more points are plotted, the more accurate estimation of the quantity for infinitely small mesh size, ϕ_∞, can be achieved. In this way, the percent error for a given mesh size can be found using Eq. (2).

$$e = \frac{\phi_n - \phi_\infty}{\phi_\infty} * 100\% \tag{2}$$

Where:

e = Percent error between the extrapolated quantity and that from any arbitrarily sized mesh

2.3. RESULTS AND DISCUSSION

2.3.1. Material Properties

The compressive strength, f'_c, and elastic modulus, E_c, determined at 50 days from the concrete cylinder testing of five samples per ASTM C39 (2020) standard are provided in Table 4. The moduli of elasticity were computed using the stress values obtained from the load cell and the elastic strain values obtained from an extensometer attached to the cylinders during the compression tests (please see Appendix B for test results).

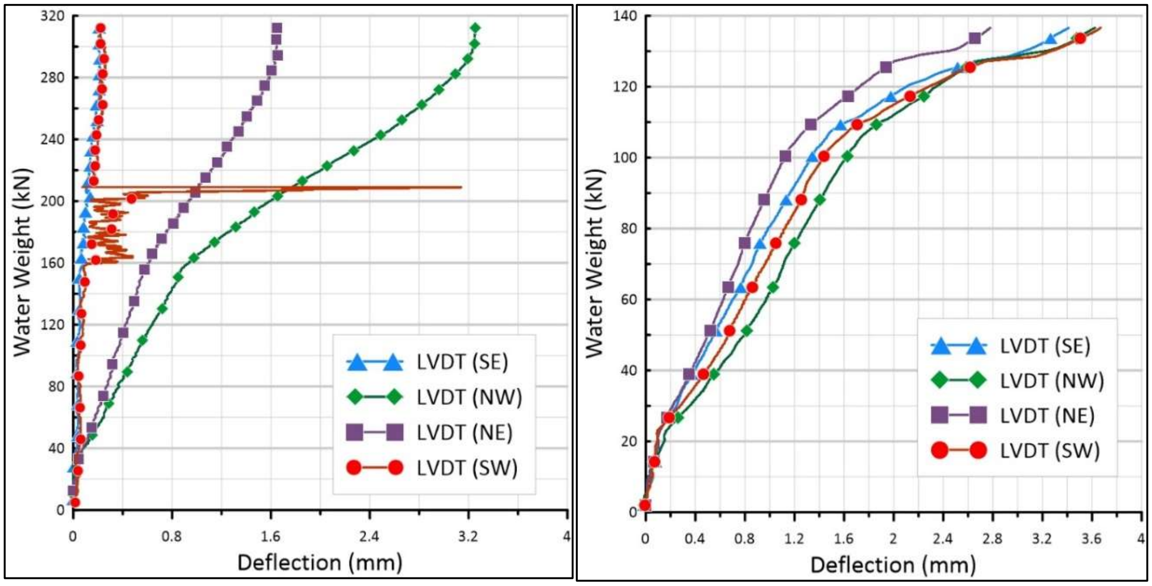
Table 7: Concrete Properties

Properties	**Batch 1**	**Batch 2**
Modulus of Elasticity, E_c (MPa)	2,340	6,225
Concrete Compressive Strength, f'_c (MPa)	11.83	23.72

2.3.2. Load Deflection Response

In both slab specimens, the water level reached near the maximum height capacity of the basins before spillage prevented further weight from being applied. Based on the load-deflection graph seen in Figure 17(a), the deflections of the two-way panels were larger than that of the one-way panels. The deflection differences between the two symmetrical panels in the four-panel slab were most likely caused by the specimen being cast by a mixture of the two concrete batches, which had different properties. The noise reported by LVDT (SW) was likely due to the vibrations caused by the water spigot directly above pouring down water. In the two-panel slab, the CFRP laminate did not affect the overall performance since the applied load was not large enough to induce high stress and engage the laminate.

Based on the load-deflection graph in Figure 17(b), the deflections for the two-panel slab under the non-CFRP panels and the CFRP-reinforced panels were not significantly different.



(a) Four-Panel Slab (b) Two-Panel Slab

Figure 17: Slab Midspan Load-Deflection Curves

2.3.3. Failure Modes and Cracking

The applied loading was not high enough to cause failures in both concrete and WWF in each slab. Cracking was observed in the areas where tensile stresses were expected to occur due to the applied loading. The negative moment produced highly visible cracks on the top surfaces of both slabs where the flat slab connected to the grade beam, as seen in Figure 18(a). The cracking propagated through the flat slab portions, as evidenced by water leakage in Figure 18(b) and Figure 18(c).

(a) Top Surface of Four-Panel Slab

(b) Bottom Surface of Two-Panel Slab

(e) © Bottom Surface of Four-Panel Slab

Figure 18: Load-Induced Cracking in Slabs

Figure 19 shows a comparative analysis of the model run with full integration versus the reduced integration with hourglass control. Due to the more linear behavior of the trend for the full integration method, it was chosen as the desired method along with the quantity *q* being taken as 6.8. Additionally, the 50 mm mesh size was chosen to optimize processing time.

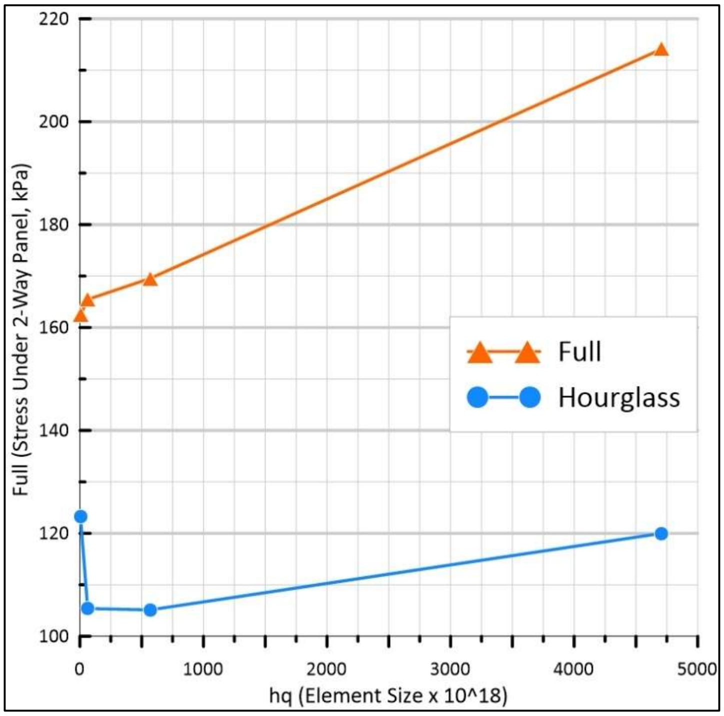


Figure 19: Mesh Sensitivity Comparison Between Integration Methods

The model for the four-panel slab is shown in Figure 20. Figure 21 compares the displacement values from the experimental and the model slabs. The full strain and deflection data set may be found in Appendix C.

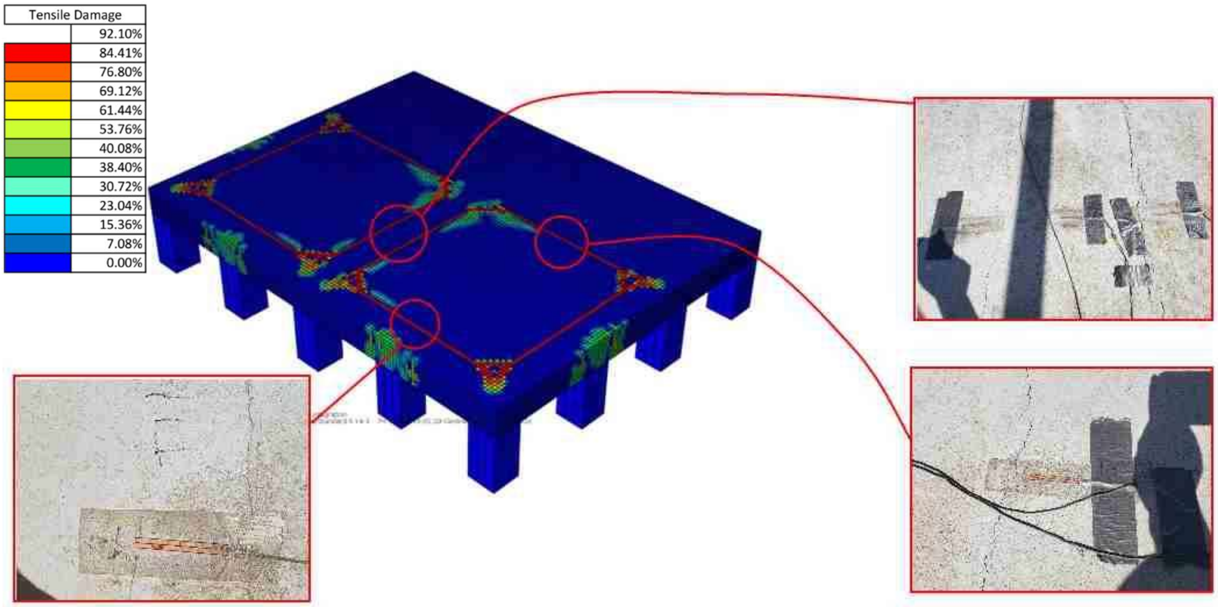
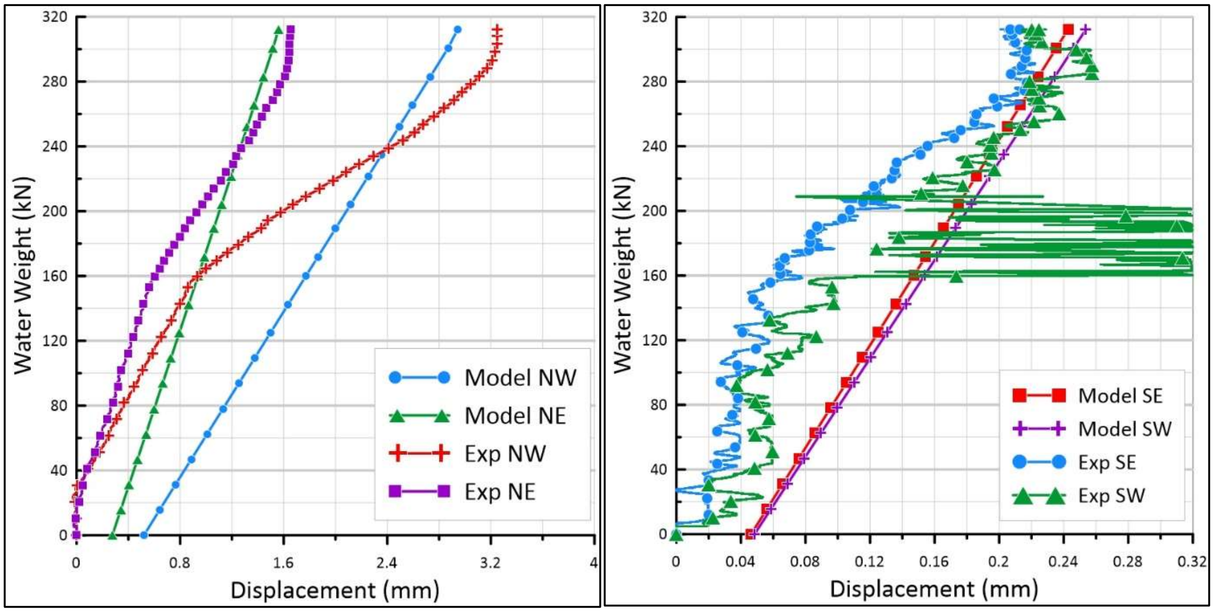


Figure 20: Four-Panel Slab Model-Predicted Versus Experimental Results



(a) Two-Way Slab Panels (b) One-Way Slab Panels

Figure 21: Experimental versus Model Comparison for Midspan Slab Deflections

The observed crack patterns in the experiment agreed well with the model-predicted damage. The first cracking occurred around the borders of the two-way slab panels where the grade beams enclosed the panels. The model exhibited the same pattern, with the highest tensile damage around the perimeter of the two-way slab panels (Figure 14). The discrepancy between the experimental and model displacement values may be attributed to the limitation of the model in capturing the water leakage from the basins during testing, which caused the load on the slabs to fluctuate over time.

2.4. CONCLUSIONS

2.4.1. Conclusions

1. Typical concrete slab-on-grade foundations are designed to be continuously supported by the underlying soil. There is currently no design code that considers how to account for changes in the support condition of these slabs when they are elevated for flood mitigation. This study shed light on the performance of these elevated home slabs under the changing support conditions that may make the slabs unsafe to carry the expected floor loads. To accomplish this objective, experimental concrete slabs resembling the configuration of the homes along the Gulf Coast were tested under simulated live loads. A numerical model calibration was conducted employing the experimental result for future parametric studies.
2. An increase in the applied simulated floor live load directly correlated to an increase of induced downward deflection of the slab panels. Strain readings for the slab, grade beams, CFRP laminate, and steel beams also showed direct increases as the water load increased. These relationships were approximately linear until the stage when the tension cracking caused additional displacement and strain.

3. The maximum deflection in the two-way slab panels was higher than that in the one-way panel, as expected. This observation is especially relevant to the existing condition of homes in the target coastal areas where most home slabs behave as two-way systems. The CFRP laminate did not affect the overall performance since the applied floor load was not large enough to induce high stresses and engage the laminate.
4. The investigated slabs were provided with a 3 m typical elevation column spacing used in Texas coastal construction. It was found that they can safely support the IRC (2018) prescribed 1.9 kPa uniform floor live loading for residential structures.

Compared to the flat plate configuration without any support beams, the slab with monolithically poured grade beams exhibited better performance. As such, the elevated foundation slabs with existing grade beams inherently have better flexural capacity than those without existing grade beams. However, the flat plate slabs can be strengthened with additional steel beams in their elevated support conditions.

2.4.2. Recommendations

This research aimed to examine the current practice of home elevation; however, given the physical limitations of the testing procedure, caution should be taken when considering the results. Due to space and resource restrictions, only two slab specimens could be designed and built for testing. The maximum column spacing used in the test slabs was 3 m, as recommended by contractors. As a follow-up, the below parameters could be examined in the future:

- Larger size slab panels, representative of those under existing homes.
- An in-depth study of column-beam connection.
- Less intrusive methods of slab retrofitting.

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CHAPTER 3: DEVELOPMENT OF SOFTWARE TOOLS TO SIMPLIFY THE PROCESS OF HOME ELEVATION DECISION MAKING

ABSTRACT

Elevating concrete slab-on-grade homes above the base flood elevation is a method of mitigating damage caused by repeated flooding events along the Gulf of Mexico coast and other coastal areas. This changes the slab support condition from uniform soil support to column and beam supports, leading to unanticipated stress/strain changes, concrete cracks, and slab failure. There are documented instances were slabs would fail during the elevation process, whether it be from mishandling or improper design, and design guidelines do not cover the retrofitting of existing buildings. To cover this knowledge gap, the study was undertaken to produce a database of various slab-on-column configurations that would simulate real-life behavior when load is applied; check at which column spacings those slab models would no longer be able to carry the minimum live load stipulated in the International Residential Code; and create a software interface so that the typical homeowner could check slab safety with minimal engineering experience. A software application was developed that would take the physical characteristics of the elevated slab as inputs and output whether that specific configuration could safely carry the minimum live load. From the home models currently available, it was found that the welded wire fabric reinforcement always failed first and that the slab configurations with smaller, more tightknit panels hemmed in by concrete grade beams would be able to hold more weight.

ADDITIONAL INDEX WORDS: Elevated Homes, Flood Mitigation, Concrete Slab Elevation, Safety, International Residential Code, IRC, Software App, Mobile App, Computer App

3.1. INTRODUCTION

3.1.1. Elevating Homes as a Flood Mitigation Method

Coastal communities along the United States Gulf Coast experience severe flooding events that cause extensive casualties and property damage. In 2005, Hurricane Katrina generated a storm surge as high as 3.5 m to the state of Louisiana and cost $161 billion in damage, according to the National Oceanic and Atmospheric Administration. Berg (2009) reported that, in 2008, Hurricane Ike inundated the coastal communities of Texas with as much as 3 m of water and left damage worth $19.3 billion. Figure 22 shows the state of a community in the aftermath.

Figure 22: A Texas Neighborhood Under High Water (Pool, Houston Chronicle, 2018)

After those and similar flooding events, homeowners may choose to elevate their homes above the base flood elevation (BFE), a popular mitigation method to reduce or eliminate flood damage. Existing residential foundation slabs are typically 102 mm thick cast-in-place (CIP) concrete with minimal single-layer welded wire fabric (WWF) reinforcement directly supported by soil. The slab perimeter is typically provided with a monolithically cast concrete-grade beam for added stiffness.

The home elevation method involves raising the slab to as much as 4.6 m and placing it on solid concrete or stacked concrete masonry units (CMU) pier supports. The supports are typically placed below the grade beams or newly added steel beams if additional supports are required. As a result, the concrete slab can behave as one- or two-way, depending upon the aspect ratio between the original grade beams or the added steel beams.

3.1.2. Problem Statement

Elevating a home above the BFE is a viable option for flood damage mitigation. However, the elevation process may cause unanticipated stresses and strains due to the changed support conditions. Such slabs are typically lightly reinforced and degrade with age, reducing their capacity and safety. The elevated slabs, therefore, must be properly supported and retrofitted if necessary. Inadequacies in these areas can result in possible slab failure leading to casualties and economic losses. With the proliferation of home elevations in flood-prone areas, the structural safety of such projects is of critical concern.

There exists a knowledge gap in the design of elevated home slabs. The ACI 318-19 Building Code (2019) or governing bodies such as FEMA do not provide specific guidelines or instructions. The latter provides guidance on the design of concrete slabs for specific support conditions; however, it does not cover retrofitting of elevated home slabs. The FEMA Homeowner's Guide to

Retrofitting (2014) only defers such design aspects to trained contractors. Seniwongse (2010) compared the behavior of slabs on grade versus framed slabs. By design, a framed slab is always thicker and more reinforced than an equivalent slab-on-grade (SOG) design, resulting in better quality and serviceability. On the other hand, the SOG has found more acceptance amongst developers due to its low construction costs and simple design, at the expense of a higher risk of cracking, greater deflection, and more maintenance costs when elevated. This only highlights the uncertainty of converting a soil-supported slab into an elevated frame slab while keeping the same traits. Furthermore, per the International Residential Code (IRC, 2021), the floor of a single-family residence must be able to support a minimum of 1.9 kPa of distributed live load. The structure will fail if elevating the slab prevents it from meeting this requirement.

Perhaps, because of the weakness of the new slab support configuration, several elevated home collapses have been reported. In 2011, a home in Louisiana collapsed while it was being lifted as part of the post-Hurricane Katrina relief effort (Hammer, 2011). Later, in 2013, after Hurricane Sandy, a home in New Jersey in the process of being elevated slid off its foundation and collided with another as the former was being raised (Robbins, 2013). Finally, a house in New York also collapsed as it was being raised in the wake of Hurricane Sandy (Cushman, 2016). To overcome possible deficits in the load-carrying capacity, a carbon fiber reinforced polymer (CFRP) retrofit solution has been tested to increase the flexural strength of concrete slabs. Qian and Li (2013) experimentally evaluated the peak capacities of CFRP-strengthened slabs. The CFRP application increased the peak capacity of lightly and moderately reinforced slabs by up to 112 and 57%, respectively. Chaiwino et al. (2021) experimented to evaluate the structural performance of CFRP retrofitted elevated house slabs. This study found that applying CFRP on the negative bending moment surface could increase its capacity by about 30%.

The experimental work and resulting software were performed to fulfill the following objectives.

- Realistically simulate slab behavior with software by sampling existing concrete slab support arrangements for elevated homes that exist along the Texas Gulf Coast communities, building test slab samples to determine how the real slabs perform under applied load, and see if a realistic application of a slab strengthening CFRP retrofit could improve load capacity.
- Use the slab software models to determine how they would react to applied load when changing the arrangement and increasing the spacing of the support conditions. These tests would also involve checking to see whether the set arrangement would be able to safely support the minimum required floor live load described by the IRC (2021), which neither FEMA or ACI has guidance for, as those organizations only provide general guidance or code for new construction, respectively.
- Build a database using the induced stress data, sorted into discrete support arrangements, and design a user interface to grant users access to the database based on the input slab support arrangement. This would allow homeowners to quickly check whether the induced stresses of their desired elevated slab design would be able to pass the IRC-mandated minimum live load requirement without needing prior engineering knowledge.

3.2. METHODOLOGY

The methodology of this study, including the experimental testing, the numerical modeling, and the software development, is shown in Figure 23. Each is described in subsequent sections.

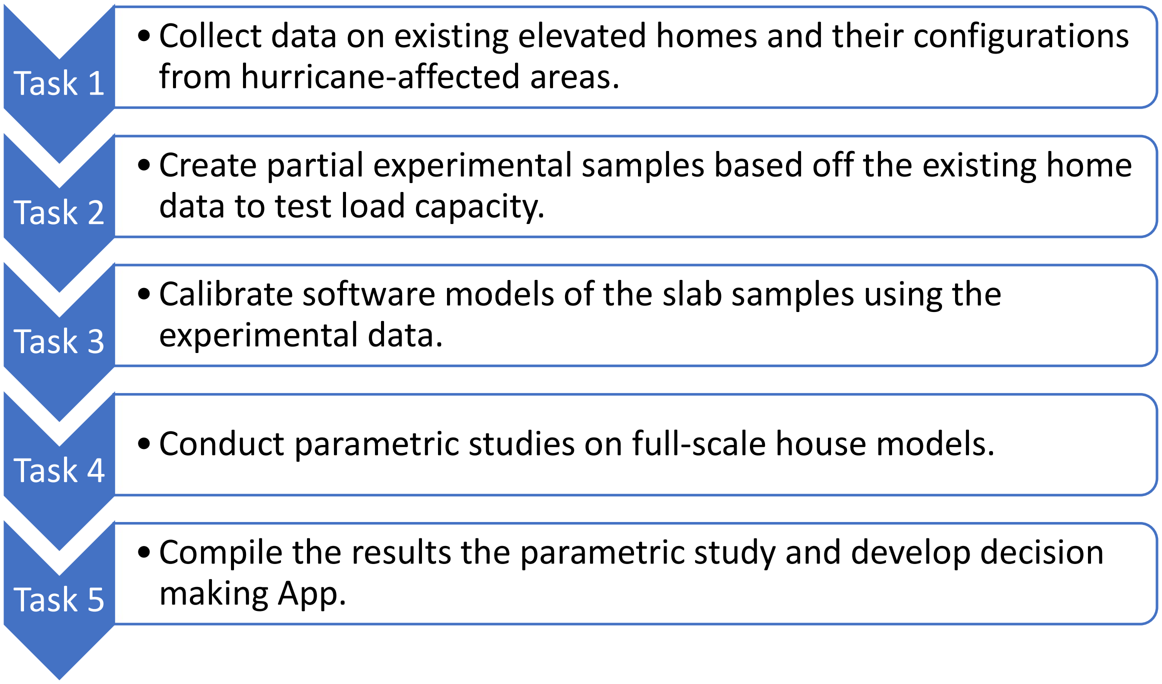
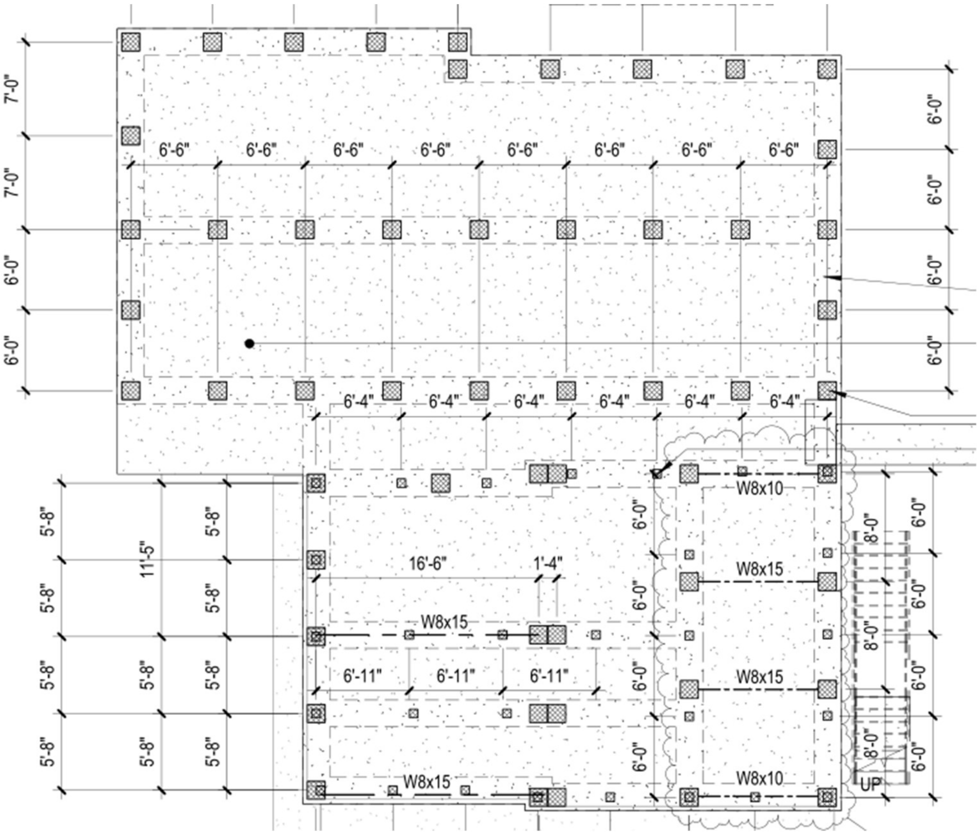


Figure 23: Software Application Development Methodology

3.2.1. Elevated Homes in the Hurricane-Affected Regions

Understanding the nature of the issue began with understanding the status of elevated homes around the U.S. Gulf Coast. For that reason, a combination of site research and literature review, such as the elevation plan shown in Figure 24, was conducted to gather information such as the column size, number of columns, column spacing, types of beams, and support conditions commonly used in home elevation construction practice.



1 ft. = 304.8 mm

Figure 24: Home Elevation Construction Plan (Robert, 2015)

3.2.2. Elevated Slab Experimentation

An experiment that sought to test the flexural capacity of elevated concrete slabs was performed. The study involved constructing two concrete slab specimens raised upon CMU piers in sizes and shapes comparable to those homes around the Texas Gulf Coast. Slab 1 consisted of four continuous panels, with the two larger panels shaped to induce two-way action for flexural bending (Figure 25). Slab 2 comprised two panels, and a strip of CFRP laminate was applied on the bottom face to see if it could improve the load-carrying capacity. Simulating the construction practices used to build those homes, the specimens were constructed using concrete with a compressive strength of 13.8 MPa and WWF with a yield strength of 415 MPa.

Figure 25: Experimental Elevated Slab Specimen

To find the capacities of the specimens, water was poured into the wooden troughs constructed above each slab to simulate the applied live load. Displacement and strain data were collected during the test to highlight which areas would fail first and in which manner, such as in Figure 26. Overall, it was found that the higher the applied, the higher the induced stresses within all components (slab, grade beam, and WWF) of the slab. The two-way slab showed more deflection than the one-way slab for a given load level. The spacing of columns also impacted the slab's load-carrying capacity with smaller column spacings allowing more load to be applied, and the typical construction practice of spacing columns out no more than 3 m could safely support the IRC (2021) prescribed 1.9 kPa minimum live load.

It was found that the CFRP laminate did not affect the overall performance since the applied load was not large enough to induce high stress and engage the laminate. Ultimately, the deflections for the two-panel slab under the non-CFRP panels and the CFRP-reinforced panels were not significantly different. The detailed setup and more in-depth test results may be accessed from literature (Ling et al., 2023).

Figure 26: Observed Cracking in Slab

3.2.3. Finite Element Model Calibration

The experimental results of the four-panel slab were used to calibrate the finite element model created using the ABAQUS (2014) , as seen in Figure 27. The slabs, columns, and beams were modeled with 8-noded brick elements, C3D8. The WWF and reinforcing steel were modeled with 2-node wire elements, T3D2. Furthermore, the reinforcement was embedded into the concrete elements. The beam-column interface was defined as a "rough" surface contact, which allows the software to use an infinite coefficient of friction to prevent slipping. The concrete was modeled using the Concrete Damage Plasticity (CDP) model with parameters shown in Table 8 (Carreira and Chu, 1985). Ling et al. (2023) provides detailed information on the model calibration, including the composition of the concrete batches and reinforcement placement.

Table 8: Numerical Model Material Properties

Property	Concrete (Batch 1)	Concrete (Batch 2)	WWF Steel	Rebar Steel
Density (kg/m^3)	6.095	6.095	20.36	
Elastic Modulus (MPa)	5,489	9,683	199,948	
Poisson's Ratio	0.15	0.2	0.3	
Yield Stress (MPa)	--		275.8	413.7
Plastic Strain	--		0.02	
Viscosity	0.01		--	
Dilation Angle (°)	31		--	
Eccentricity	0.1		--	
Ratio of Biaxial to Uniaxial Compression Yield Stresses (f_{b0}/f_{c0})	1.16		--	
Ratio of Tensile to Compressive Second Stress Invariants (K)	0.666		--	

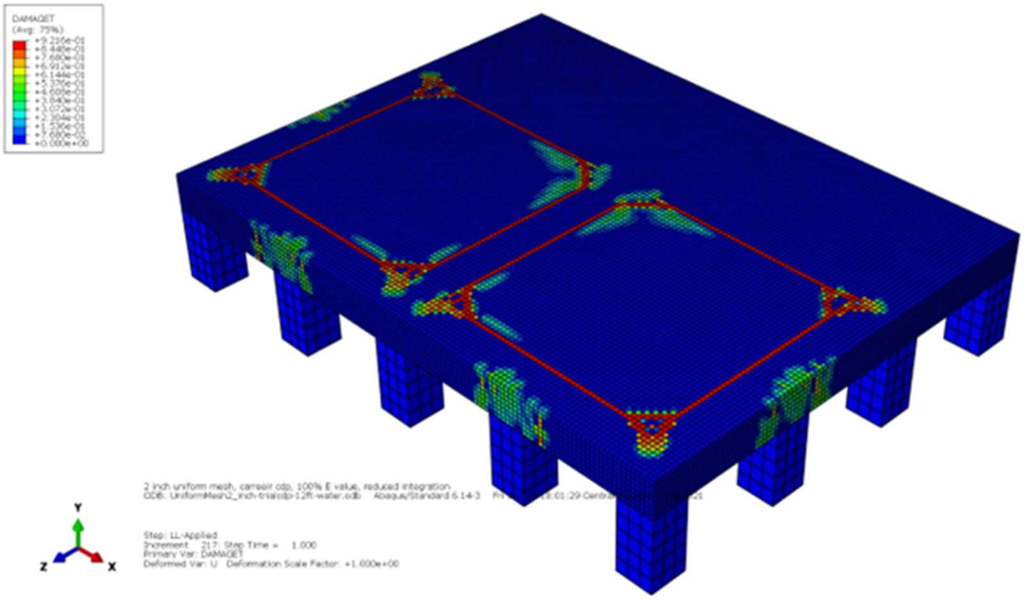
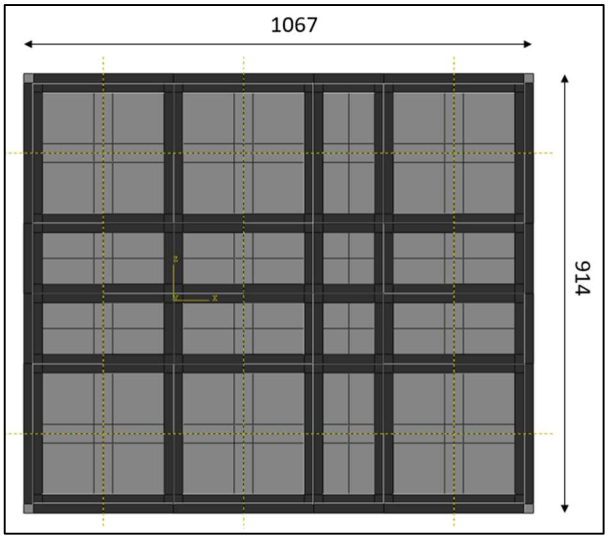


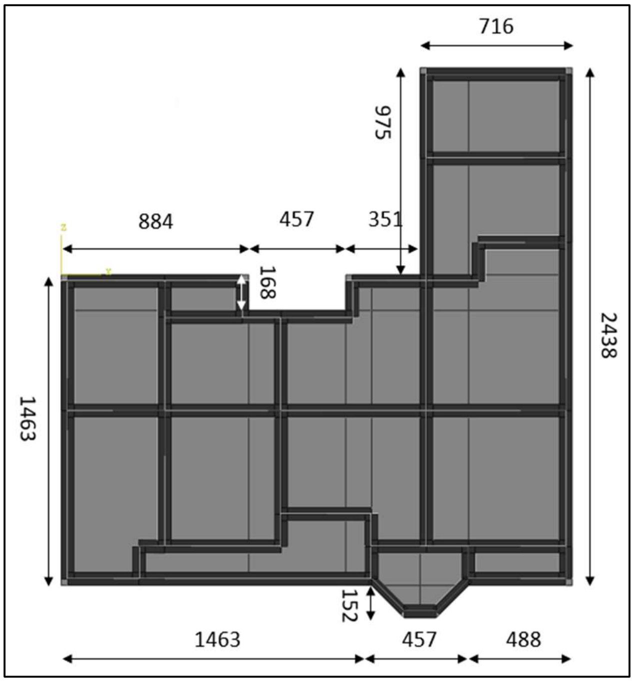
Figure 27: Software Model of Experimental Slab

3.2.4. Parametric Study

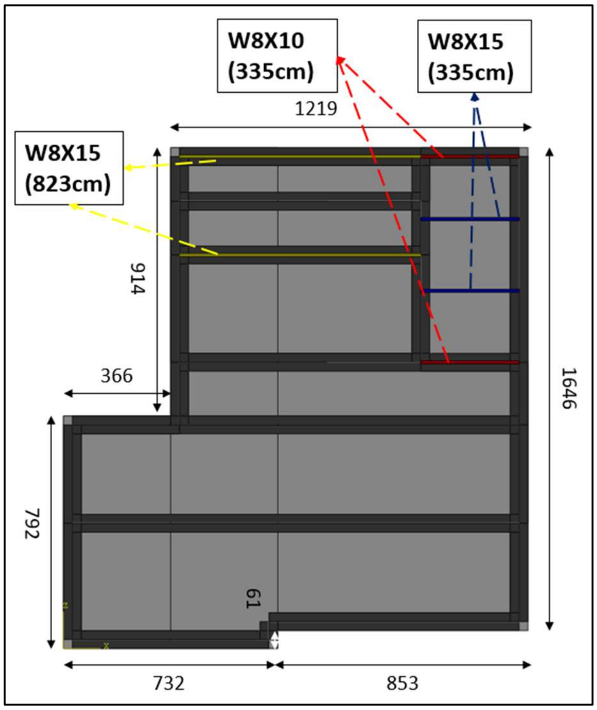
The experimental slab model data was extrapolated into a full-sized home model, seen in Figure 28(a). In addition, four other plans provided by elevation contractors that retrofit existing Texas and Louisiana houses were chosen as templates for the parametric study [Figures 5(b) to 5(e)]. Table 9 provides the total area of each floorplan. Within these images, the dark lines are the concrete grade beams that form the perimeter around the slab and divide the interior sections into panels. Within Building C [Figure 1(c)], there are instances of steel beams being used concurrently with concrete beams.



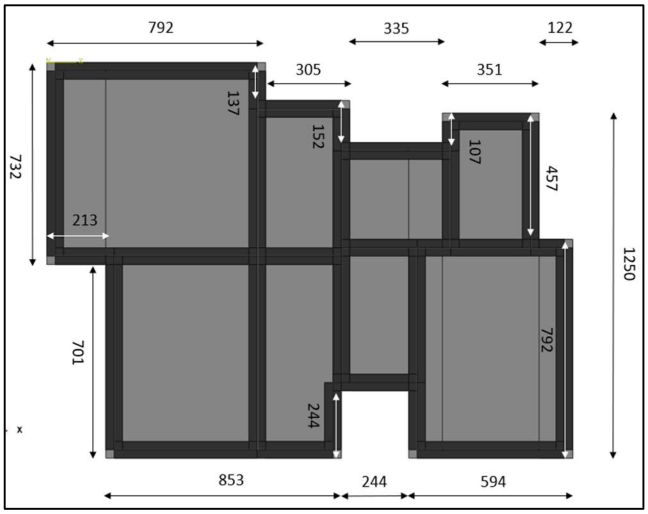
a) Building A



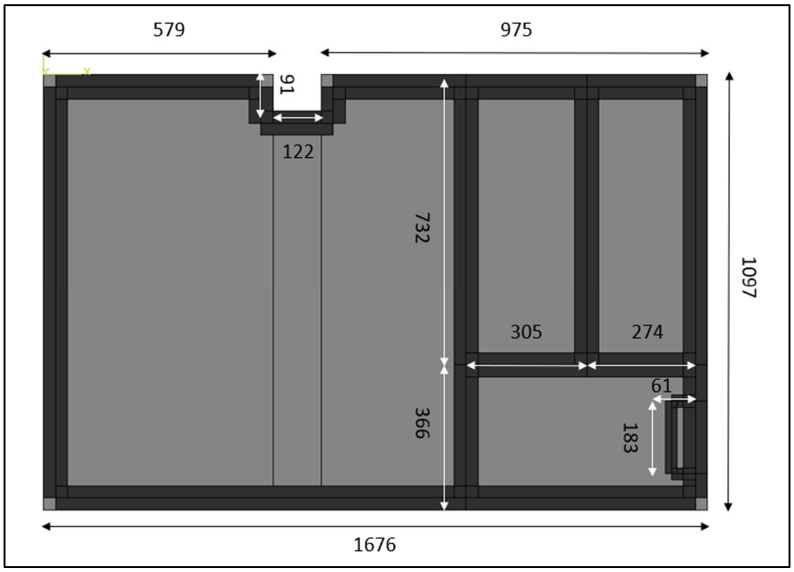
b) Building B



c) Building C



d) Building D



e) Building E

Figure 28: Model House Floorplan Types (Dimensions in cm)

Table 9: Floorplan Total Area

Home Floorplan Type	Area (m^2)
A	97.5
B	427
C	172
D	232
E	176

The parametric study on the house models involved changing the spacing and number of columns and then applying simulated gravity load and live load on the slab to determine the magnitude of the load-inducing failure for each column configuration. "Failure," as defined by this study, is the first point any of the following modes occur: yielding of the steel WWF, crushing of the concrete slab/beams/columns, or tensile failure of the concrete in those same elements. As a sample of the parametric study performed on all the building models, Figure 29 demonstrates the variance of the column spacing for Building A. Table 10 shows the exact dimensions and number of columns in each relative to the cardinal direction of the model. Due to differing geometry, the other building types feature differing numbers of column configurations with the associated column spacings.

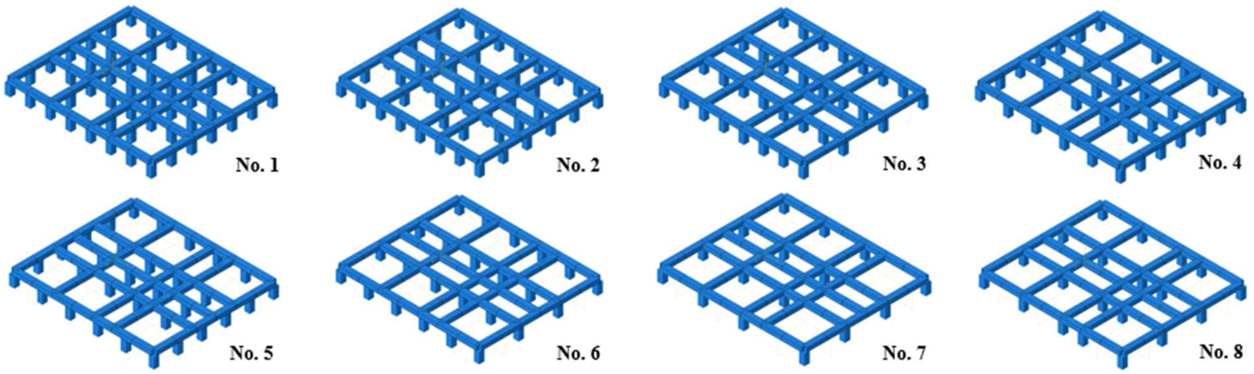


Figure 29: Parametric Study Models of Building A

Table 10: Summarized Parametric Model Specifications for Building A

Case No.	X-axis		Z-axis	
	Number of Piers	Max Pier Spacing (mm)	Number of Piers	Max Pier Spacing (mm)
1	8	1,524	7	1,524
2	8	1,524	6	1,829
3	8	1,524	4	3,048
4	6	2,134	7	1,524
5	6	2,134	6	1,829
6	6	2,134	4	3,048
7	4	4,572	4	3,048
8	5	3,048	4	3,048

3.2.5. Parametric Study Results

The specific failure modes observed for each model house are listed in Table 11.

Table 11: Failures Modes for Each Home Model

Home Model	Failure Mode
A	No failure modes were observed for each column spacing for live load cases.
B	The WWF yielded soon after applying a live load of 479 Pa when the column spacing was only 1,524 mm. Spacing the columns any further apart would cause the WWF to yield from just the self-weight of the slab
C	A live load of 2,873 Pa yielded the WWF at columns spacing of 1,829 mm.
D	Regardless of column spacing for this slab configuration, the WWF yielded soon after an applied live load of 239 Pa. The assumption is that the actual home was built with a higher yield strength steel reinforcement than the 280 MPa strength steel used in the model.
E	The WWF yielded after a live load application of 2,394 Pa for the 1,829 and 2,438 mm column spacings. In the case of the 3,048 mm column spacing, the yielding occurred at an applied live load of 1,436 Pa.

The results were presented as tables of induced stresses within key elements of the elevated slabs: the WWF and slab, grade beam, and column concrete. A sample of this data, specifically for the WWF in Building A, may be found in Table 12, where each case number refers to the same column cases laid out in Table 10. For each model home study, the maximum applied live load was 3.83 kPa, double the value specified by the IRC (2021) for single-family residential homes. The full results from the parametric study may be found in Appendix D.

Table 12: Induced Stresses in the WWF for Building A (kPa)

Live load kPa	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
0.239	2,956	2,910	1,782	2,491	2,498	1,809	1,589	1,118
0.479	3,293	3,245	2,041	2,780	2,788	2,059	1,808	1,314
0.718	3,636	3,587	2,305	3,076	3,085	2,317	2,029	1,514
0.958	3,973	3,923	2,565	3,366	3,376	2,567	2,222	1,710
1.197	4,317	4,265	2,830	3,661	3,674	2,821	2,443	1,910
1.436	4,655	4,602	3,090	3,952	3,966	3,070	2,673	2,107
1.676	5,000	4,945	3,356	4,249	4,264	3,324	2,918	2,308
1.915	5,329	5,280	3,610	4,538	4,553	3,574	3,152	2,479
2.394	5,991	5,934	4,119	5,108	5,119	4,052	3,677	2,865
2.873	6,670	6,611	9,065	5,682	5,705	9,532	9,223	4,792
3.352	10,848	10,607	12,972	10,762	10,390	13,923	12,321	10,669
3.830	13,555	13,423	13,444	14,078	13,726	14,936	13,822	11,264

3.3. HOME ELEVATION DECISION TOOL

3.3.1. Data Processing

At the center of the Home Elevation Decision Tool (HEDT) is the stress data compared to the IRC (2021) threshold to make the technical checks the output screen delivers to the user. The induced stress is a direct function of the applied load for each structural element – WWF, slab, grade beam, and column. While the dead load of the home remains constant, the live load is variable and causes the stress upon the structural members to change.

In addition, several factors affect how the structural elements respond to stress. The main ones considered in this tool are concrete compressive strength, steel yielding strength, slab thickness, column spacing and foundation area.

Depending on the data availability, the software analyzes user input employing linear, bilinear or Barycentric interpolation. The ability to calculate intermediate values is due to the characteristic of concrete having a generally linear relationship between applied stress and strain while still in the elastic region. Extrapolation of data is to be avoided in post-processing this type of data since there is no guarantee of accuracy.

If the user inputs a combination of column spacings such that one of the values points to data that does exist in the database, one-dimensional, linear interpolation may be employed. Table 13 demonstrates the range of values that would be interpolated if an X-column spacing of 1,524 mm and a Z-column spacing of 2,438 mm were chosen. The induced stress for this pair of column spacings would be interpolated using (3, employing the stresses at coordinates (1,524, 1,828) mm and (1,524, 3,048) mm. The resultant stress for a column spacing set of (1,524, 2,438) mm would thus be around 13,431 kPa, and a new table of values for this set can be generated and compared with the yield stress and IRC (2021) threshold.

$$y = mx + y_1 \qquad (3)$$

$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

Where:

$y = Stress\ at\ the\ desired\ spacing\ set$

$x = Column\ spacing\ of\ the\ variable\ orientation$

$x_n = Upper\ or\ lower\ bound\ column\ spacing$

$y_n = Upper\ or\ lower\ bound\ stress$

Table 13: Linear Interpolation Example

		X-Axis Column Spacing (mm)					
		1,524	1,829	2,134	2,438	2,743	3,048
Z - Axis Column Spacing (mm)	1,524	13,555		14,078			
	1,829	13,423		13,726			
	2,134	↑					
	2,438	●					
	2,743	↓					
	3,048	13,444		14,936			11,264

Table 14 shows a visualization if a column spacing set of (1,829, 2,438) mm is chosen. The resultant stresses can be interpolated using the four points that form the vertices of the bounding box around the data coordinate using two-dimensional, bilinear interpolation depicted in Eq. (4(4). The resultant stress for the input column spacing set of (1,829, 2,438) mm would be around 13,879 kPa.

$$Q(x,y) = \left(Q_{11} * \frac{x_2 - x}{x_2 - x_1} + Q_{21} * \frac{x - x_1}{x_2 - x_1}\right) * \frac{y_2 - y}{y_2 - y_1} + \left(Q_{12} * \frac{x_2 - x}{x_2 - x_1} + Q_{22} * \frac{x - x_1}{x_2 - x_1}\right) * \frac{y - y_1}{y_2 - y_1} \qquad (4)$$

Where:

$Q(x,y) = Stress\ at\ the\ chosen\ input\ set$

$Q_{nn} = Stress\ at\ any\ of\ the\ four\ boundary\ points$

$x = Input\ X - column\ spacing$

$y = Input\ Z - column\ spacing$

$x_n = Boundary\ X - column\ spacing$

$y_n = Boundary\ Z - column\ spacing$

Table 14: Bilinear Interpolation Example

		X-Axis Column Spacing (mm)					
		1,524	1,829	2,134	2,438	2,743	3,048
Z - Axis Column Spacing (mm)	1,524	13,555		14,078			
	1,829	13,423	↔	13,726			
	2,134	↕		↕			
	2,438		●				
	2,743						
	3,048	13,444	↔	14,936			11,264

In a unique circumstance where only three points bound a chosen data set, Yiu (2001) provided a two-dimensional interpolation, given by Eq. (5) is used. The method includes checks to ensure that the chosen coordinate set is bound within the confines created by the vertices. If any of the "λ" values are negative, the chosen coordinate set exists outside the bounding triangle, and the resulting stress would be considered extrapolation. Table 15 shows how the app would process the data if the column set of (2,438, 2,743) mm was to be input. The resultant stress for the input column spacing set of (2,438, 2,743) mm would be around 13,410 kPa.

$$\lambda_1 = \frac{(y_2 - y_3)(x - x_3) + (x_3 - x_2)(y - y_3)}{(y_2 - y_3)(x_1 - x_3) + (x_3 - x_2)(y_1 - y_3)}$$

$$\lambda_2 = \frac{(y_3 - y_1)(x - x_3) + (x_1 - x_3)(y - y_3)}{(y_2 - y_3)(x_1 - x_3) + (x_3 - x_2)(y_1 - y_3)} \qquad (5)$$

$$\lambda_3 = 1 - \lambda_1 - \lambda_2$$

$$Q(x, y) = Q_1\lambda_1 + Q_2\lambda_2 + Q_3\lambda_3$$

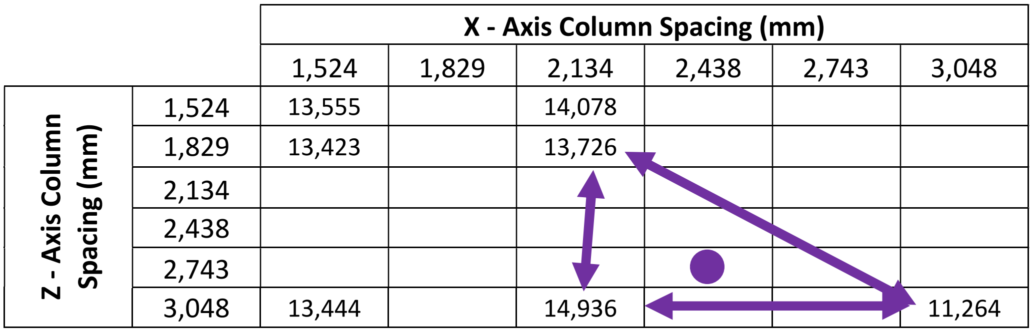
Where:

$Q(x, y) = Stress\ at\ the\ chosen\ input\ set$

$Q_n = Stress\ at\ any\ of\ the\ three\ boundary\ points$

$\lambda_n = Barycentric\ coordinate$

Table 15: Barycentric Interpolation Example



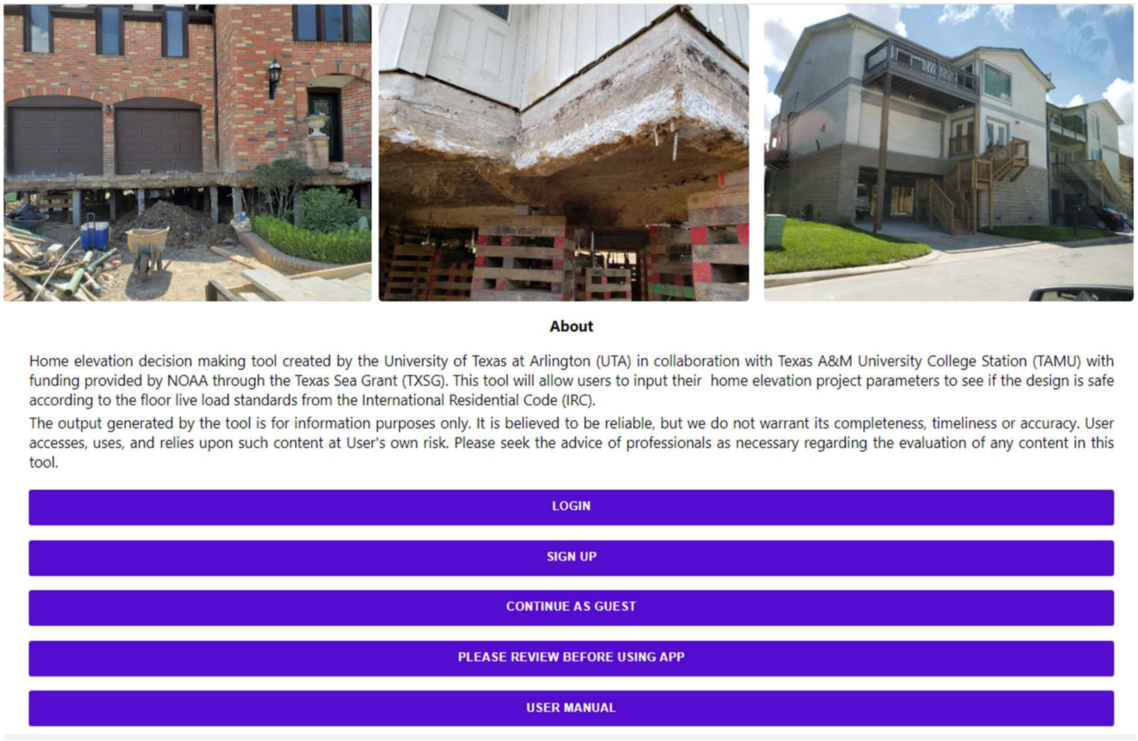
		X - Axis Column Spacing (mm)					
		1,524	1,829	2,134	2,438	2,743	3,048
Z - Axis Column Spacing (mm)	1,524	13,555		14,078			
	1,829	13,423		13,726			
	2,134						
	2,438						
	2,743				●		
	3,048	13,444		14,936			11,264

3.3.2. Overview and Usage Example

The HEDT is software for rapidly determining the moment capacity of an elevated slab and comparing its live load capacity to the minimum IRC (2021) specified value for residential structures. To begin, the user must log in or create a new account to access the full data set of features, or they may proceed as a guest to use a more limited portion of what the application offers. The disclaimers and user manual are also available from the home screen, as seen in Figure 30(a).

The user chooses the home model that most resembles the one being retrofitted, which is tied to the floor area and the number of stories in the current build. The column spacing parameters in two cardinal directions are then selected, which determines the number of columns set into the configuration, shown in Figure 30(b).

By pressing "Submit," the program compares it with an internal database containing the modeled induced stresses. It will then output whether the specific configuration can safely support the typical residential live loading. A sample results screen from the application is shown in Figure 30(c), which displays what the output looks like when all slab elements can support the stresses induced by the minimum live load.

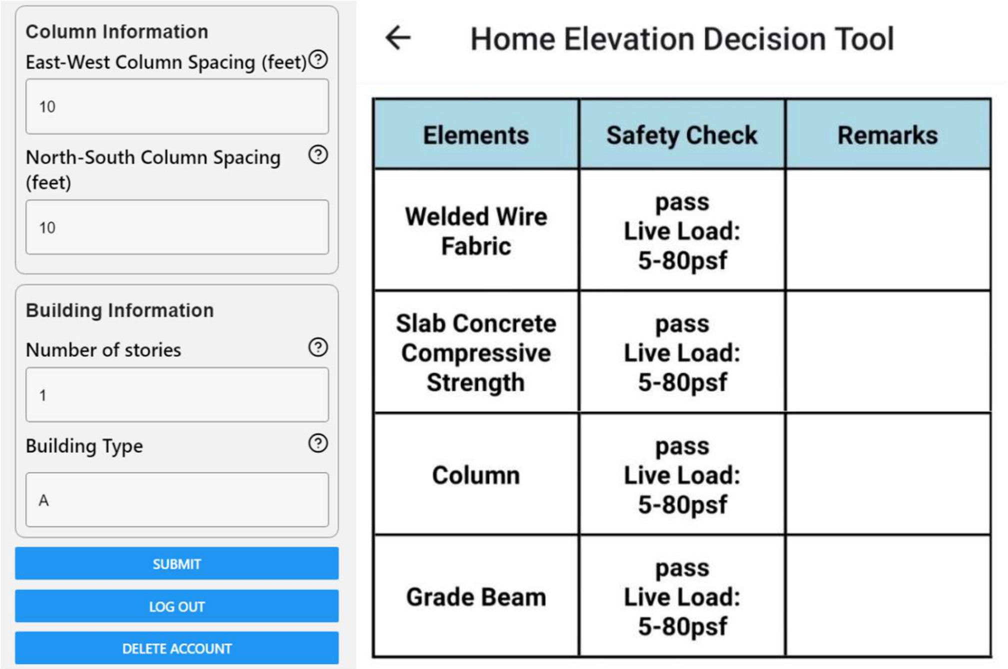


About

Home elevation decision making tool created by the University of Texas at Arlington (UTA) in collaboration with Texas A&M University College Station (TAMU) with funding provided by NOAA through the Texas Sea Grant (TXSG). This tool will allow users to input their home elevation project parameters to see if the design is safe according to the floor live load standards from the International Residential Code (IRC).

The output generated by the tool is for information purposes only. It is believed to be reliable, but we do not warrant its completeness, timeliness or accuracy. User accesses, uses, and relies upon such content at User's own risk. Please seek the advice of professionals as necessary regarding the evaluation of any content in this tool.

(a) Home Screen



Column Information

East-West Column Spacing (feet): 10

North-South Column Spacing (feet): 10

Building Information

Number of stories: 1

Building Type: A

Home Elevation Decision Tool

Elements	Safety Check	Remarks
Welded Wire Fabric	pass Live Load: 5-80psf	
Slab Concrete Compressive Strength	pass Live Load: 5-80psf	
Column	pass Live Load: 5-80psf	
Grade Beam	pass Live Load: 5-80psf	

(b) Parameter Select Screen (c) Results Screen

Figure 30: HEDT Software Application Screen Captures

3.3.3. Limitations

At the time of release, the software only allows the user to change the shape and size of the home and its foundation footprint and the number and spacing of columns supporting the slab. Material and other geometric properties were fixed due to constraints in the experimental phase. The following were those set parameters:

- No load is assumed to be transferred from the superstructure to the slab and its grade beams.
- Steel yielding and concrete compressive strength are defaulted to 276 MPa and 13.8 MPa, respectively.
- The minimum column spacing is 1.5 meters.
- The maximum column spacing is 3 meters, as dictated by certain elevation contractors.

Through experimental testing and further parametric studies conducted with numerical software modeling, the induced stresses for each structural element could be computed for each factor and stored in the tool's database.

The ideal situation is that, with time, the database would eventually expand to encompass induced stress data for each structural element for each controllable factor. In the state of ideal database completion, when the user inputs the desired home and elevation design, the application searches for the exact set match in the database and returns the safety check.

However, due to time and resources, there are still gaps in the stress data stored away. At the time of the initial release, given a slab thickness of 102 mm, a steel yielding strength of 276 MPa, and a slab concrete compressive strength of 13.8 MPa, the induced stresses on the WWF of Building A with an applied live load is 3.8 kPa can be visualized in Table 16.

Table 16: Example of Induced Stresses (kPa) Stored in Database at Time of Release

		X-Axis Column Spacing (mm)					
		1,524	1,829	2,134	2,438	2,743	3,048
Z - Axis Column Spacing (mm)	1,524	13,555		14,078			
	1,829	13,423		13,726			
	2,134						
	2,438						
	2,743						
	3,048	13,444		14,936			11,264

While most data points for every combination of column spacings between 1,524 mm and 2,438 mm are currently unavailable, the results can still be calculated using numerical interpolation. Furthermore, several interpolation methods will have to be employed due to the scattered nature of the available data.

3.4. CONCLUSIONS AND RECOMMENDATIONS

3.4.1. Conclusions

- This study was approached to address the issues of home elevated concrete slab safety. Since there is no official code for the design and construction of this flood mitigation method, several factors, such as column spacing, column number, beam placement, and support conditions are completely left to the experience of the hired engineers. To compound the problem, the state of existing slabs being elevated is typically deteriorated and may not be suitable for the change in support arrangements. The software application developed in this study built upon the findings of the experimental testing from Ling et al. (2023) to create a data table showing how slabs with varying footprints and support configurations perform under different levels of live load. It would allow the user to choose one of these setups and inform them if it meets the minimum floor live load stated in the IRC (2021).

- The Ling et al. (2023) study constructed experimental elevated slab models based on the standard elevation practices around the Gulf Coast region. Those slab specimens were tested for their load capacity, and it was found that the maximum column spacing of 3 m designated by contractors was enough to hold the minimum live load safely. The applied CFRP retrofit provided negligible benefit to the support capacity considering this.
- The experimental studies allowed the initial numerical slab model to be calibrated for real-life behavior, and the five full-sized models were created from that. The parametric study of applying increasing live load on various column configurations was then successfully conducted on those five models. The type A home did not experience failure during any of the applied live loading, between 239 Pa to 3,830 Pa, for any column spacing configuration. However, the other types of homes experienced WWF failure after different levels of live loading once the column spacing grew sufficiently long.
    - House type B could not safely carry the minimum live load for any of its examined column spacings.
    - House type C could safely carry the minimum live load for both the 1.8 m and 2.4 m column spacing configurations, but the 3.0 m configuration parametric study results were inconclusive due to convergence errors.
    - House type D could not safely carry the minimum live load for any of its examined column spacings.

  - House type E could safely carry the minimum live load while the column spacings were shorter than 2.4 m. At 3.0 m, the WWF would yield at an applied live load of 1676 Pa.
- The results from the parametric studies showed that the general failure occurs in the WWF yield before all others, meaning that all the models are designed to be tension-controlled.
- A software application was successfully developed to determine the safety of an elevated slab configuration relative to the IRC-mandated minimum live load for house slabs. This would allow people not versed in technical engineering analysis to swiftly check whether a desired configuration passes the basic code-mandated live load threshold.
- The interpolation function devised for the software enables the analysis of column configurations that were not discretely modeled for the database. The linear behavior of concrete strain to stress in its elastic phase also allows the interpolation function to be linear.

3.4.2. Recommendations and Future Research

The stated goal of this project was to create a software application that could quickly assess the safety of a given elevated slab configuration. While that goal has been achieved, it is still limited in its breadth and depth of parameters available for input. As such, further parameters and features could be added in the future.

- More home types could be modeled and added to the database to account for more slab footprint types.

- Material property parameters could be added to consider varying concrete and steel strengths.
- Slab thickness and grade beam dimension input fields would be able to consider variable geometric properties of the slab.
- The various failure modes involved with column designs could be examined as each home elevation varies with height.
- Differing support conditions might also affect the performance of the slab, as there may or may not be a rebar interface between columns and slabs.
- Incorporating more parameters would necessitate a multi-variable interpolation formula to unify and handle data processing.
- A targeted damage index could be implemented to be able to simulate higher resolution deterioration of specific slab elements.

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CHAPTER 4: ADDED BENEFITS AND IMPROVING ON THE FEDERAL EMERGENCY MANAGEMENT AGENCY'S BENEFIT COST ANALYSIS METHOD FOR FLOOD RETROFIT PROJECTS

ABSTRACT

Coastal flooding in low lying areas due to rain or tropical storms is a common hazard along the U.S. Gulf Coast and elsewhere. With climate change, the intensity and frequency of such flooding will only increase with associated property damage and casualties. Flood mitigation and methods are, therefore, of very high importance for decreasing flood damage and casualties. A benefit-cost analysis (BCA) is generally performed to compare the cost of mitigation projects versus the benefits, which are avoided costs incurred through loss of property or life. The Federal Emergency Management Agency (FEMA) had compiled a BCA calculator that includes several factors to quantify the benefits from undertaking a flood mitigation project. Despite its importance, the underlying methodology employed by the calculator has inherent flaws in both usage and interpretation of results. In this study, a few published concerns about the omission of important parameters in the BCA are examined. Examples are the unintended wealth inequality of users, missing benefits for specific mitigation methods and the relative merits of home elevation vs. home demolition, among others. For coastal Texas areas, the enhancement of the benefit-cost ratios (BCRs) from considering additional logical factors is examined. The risk premium factor increased the BCR with severity of flood damage and depletion of the user's yearly income. The social welfare factors also multiplicatively affected the BCR depending on the property location. The BCR increased at locations with less average income-per-capita and vice versa. Two additional factors related to demolition as a mitigation method were examined - recycling of construction demolished material (CDM) and the cost of landfill usage. The BCR could increase by the market cost of the CDM and with increased recycling of the demolished products. The enhanced BCA approach is more realistic and will allow users and funding agencies to logically select flood mitigation projects. This will allow enhanced flood resiliency for coastal communities.

ADDITIONAL INDEX WORDS: Disaster Mitigation, Flood Mitigation, Acquisition, Demolition, Hurricane, Cost Benefit Analysis

4.1. INTRODUCTION

4.1.1. Background

Flooding is a hazard that occurs in residential zones along coastal regions, especially those along the Texas Gulf of Mexico coastline. The causes of flooding are typically from prolonged rainfall, like that during Tropical Storm Allison, which produced upwards to 457 mm of rain in a 24-hour period, causing widespread flooding in the Houston metropolitan area seen in Figure 31.

Figure 31: Tropical Storm Allison, June 5, 2001 (National Weather Service)

After homes are flooded out during these disaster events, the homeowners have the option to retrofit their homes to lessen or prevent future flood damage from similar events. There are several options from which to choose which offer ranges of price and efficacy. For this study, the methods that are applicable to bring homes into compliance with floodplain management regulations according to FEMA (2014) will be examined: home elevation, demolition, and relocation. Home elevation is the method by which a home is separated from its original foundation, lifted above the base flood elevation height, and perched atop and newly built support system attached to a new foundation, seen in Figure 32(a). Relocation is the mitigation method in which the home is lifted from its foundations and hauled to an area outside the flood hazard zone to be resettled onto a new foundation [Figure 32(b)]. Finally, demolition is the tearing down of a damaged home and either rebuilding a compliant home or moving to another structure [Figure 32(c)].

(a) Elevation (b) Relocation (c) Demolition

Figure 32: Methods of Home Flood Mitigation (FEMA, 2014 and Zaveri, 2017)

The measure by which these retrofit methods were compared was via cost effectiveness, using a cost-benefit analysis (BCA). To streamline this process, FEMA had developed a software toolkit to calculate the benefit to cost ratio (BCR) of a hazard mitigation project for a chosen structure, like a single-family home. The costs of the project include the initial construction, maintenance, and other related expenses, such as permit costs. The toolkit provides a series of metrics to calculate the costs saved from damage incurred if no mitigation action were taken against a selected hazard. These avoided damages, or benefits, are provided by FEMA (2019) and listed in Table 17.

Table 17: Definitions of Benefits in the FEMA BCA Methodology

Avoided Immediate Costs	Environmental Benefits	Social Benefits
- Structural and property damage - Loss of service or function - Injury or death - Displacement expenses - Emergency management expenses - National Flood Insurance Program administration expenses	- Projects that bring value from preserving or improving the natural environment	- Avoided costs associated with mental stress, anxiety, or lost wages that disaster survivors would otherwise experience

4.1.2. Problem Statement

Though the FEMA BCA methodology is used to compute value and dictate governmental policy, it is not without its flaws. The failings of the methodology have been a subject of criticism and are constantly being scrutinized by many individuals for improvement. The following is a list of the focal issues gathered from the National Hazard Mitigation Association (2021) and Nelson and Malloy (2021), which range from technical usability to unintended consequences.

- The precision requirements of the toolkit are a strain on applicant and FEMA technical assistance resources due to how few assistance officers are available.

- Larger, simpler projects in urban, more populated, and more affluent areas are favored by the calculation outputs.
- FEMA's range of acceptable inputs provides less opportunity for less populated communities to add benefits.
- FEMA acquisition projects favor counties with higher per capita income, higher education levels, and larger workforce.

Additionally, while the FEMA BCA method does include a variety of hazard options to mitigate for, it does not consider the complications that arise from multiple hazards that would occur during a single disaster event. In the case of hurricanes, McCullough et al. (2013) examined that a single hurricane event produced both wind and storm surge damage upon the structures in its path. The authors suggest that a more comprehensive approach for mitigation retrofit should be considered when a structure is in the vicinity of a disaster event that produces multiple types of damage, which runs counter to the current FEMA methodology of only considering a single disaster type at a time and an associated retrofit type. In this instance, the BCA toolkit provides mitigation options for both flooding and hurricane winds, but not both simultaneously.

To address the criticisms of the current toolkit, McGee (2021) offered up a list of suggestions, listed below.

- The bounds of benefits should be expanded. More social and environmental benefits such as homelessness services and toxic waste cleanup could be explored.
- The weights to costs and benefits should be altered. Applying weights to account for wealth distribution could better increase the likelihood that investments are made in low-income communities.

- The BCA calculation method should be transformed into a multi-factor analysis. Instead of one metric determining whether a project is "cost effective," there could be more categories to rate projects, such as flood-risk reduction, project efficiency, and social vulnerability.
- Long-term planning should include distributional considerations. Plans to reduce social vulnerability should be included with projects, creating a more even distribution of flood mitigation. This way, property values for a wider area may be sustained.

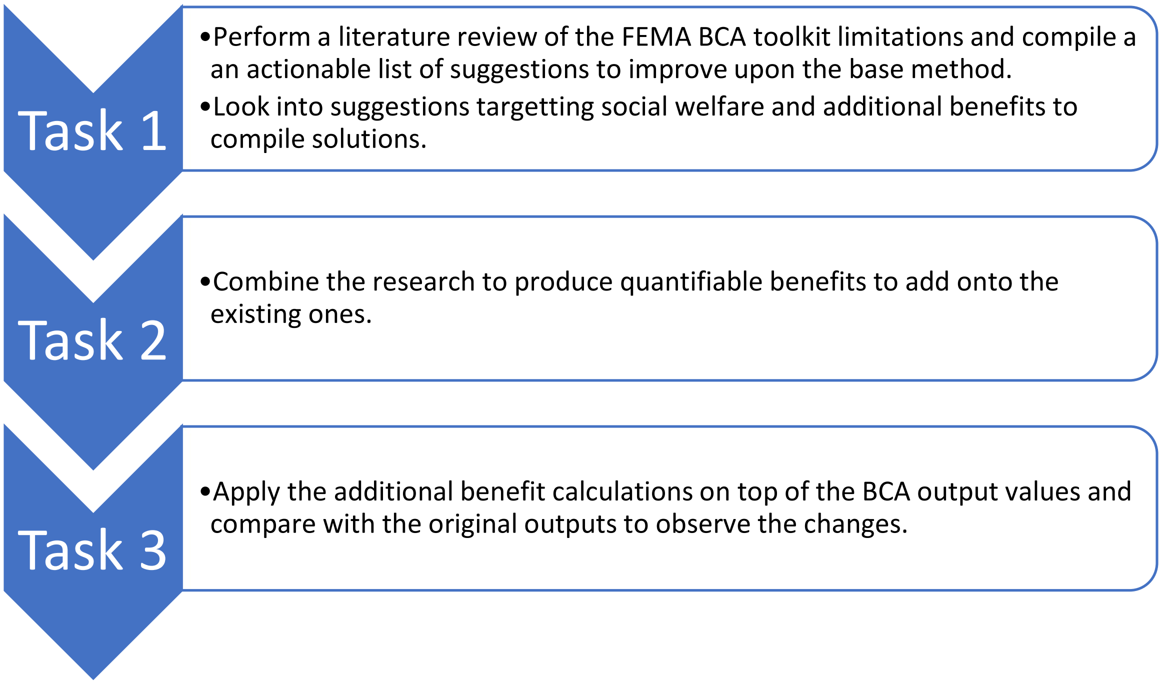
4.1.3. Objectives

The objectives of this study are stated below and will be based upon the suggestions provided above.

- Identify the FEMA BCA calculation limits and definitions of what constitutes a benefit with respect to flood mitigation projects. This would include gathering criticisms of the shortcomings of the method and toolkit from outside sources.
- Use quantitative methods to produce a more well-rounded calculation of benefits that address the issues and allow for a more detailed comparison between flood mitigation methods. Specific targets to address include income disparity and costs/benefits specific to certain methods of flood mitigation.

4.2. METHODS

To address the stated objectives of the study, Figure 33 lists the steps taken.


Task 1

- Perform a literature review of the FEMA BCA toolkit limitations and compile a an actionable list of suggestions to improve upon the base method.
- Look into suggestions targetting social welfare and additional benefits to compile solutions.

Task 2

- Combine the research to produce quantifiable benefits to add onto the existing ones.

Task 3

- Apply the additional benefit calculations on top of the BCA output values and compare with the original outputs to observe the changes.

Figure 33: BCA Tool Refinement Methodology

This study examined the current output of the FEMA BCA methodology using the existing toolkit to generate BCRs for multiple flood mitigation projects. Applying additional methods or benefits provided through literature, per the improvement suggestions in the previous section, the impacts on the results were determined. This was conducted by running the calculations upon different home archetypes with the flood retrofit methods described before. The following sections illustrate the details that went into this analysis.

4.2.1. Inputs for Retrofit Comparison

4.2.1.1. House Archetypes

The house types used in this comparison are meant to be represent the commonly built archetypes that exist along the U.S. Gulf Coast. Five models were developed by Amini and van de Lindt (2014) to develop tornado fragility curves. Table 18 lists the physical dimensions of the archetypes. The archetypes are wood-frame homes that are constructed atop concrete, slab-on-grade (SOG) foundations. They will be used to examine the change in BCA values between each flood retrofit method.

Table 18: Representative Home Archetype Properties

Archetype	Stories	X-Dim (m)	Y-Dim (m)	Perimeter (m)	Total Area (m^2)
1	1	16.2	7.2	46.8	116.6
2	2	13.8	12.3	52.2	169.7
3	1	12.5	17.4	59.8	217.5
4	2	16.2	9.1	50.6	147.4
5	2	21.3	13.7	70.0	291.8

4.2.1.2. Storm Data

The design hurricane used in this study was based off Hurricane Harvey. Specifically, the aspect of flooding it brought to the Texas Gulf Coast communities in its passing. According to the United States Geological Study storm tide sensor data gathered by Blake and Zelinsky (2018), the highest water levels produced by storm surge were 3.35 to 3.66 meters. However, due to wave runup effects, these values would be considered too high to represent true inundation, so storm tide sensor data, with consideration of sampling gaps, suggest that the highest inundations from Harvey were 2.44 to 3.05 meters. However, this only takes into consideration the communities closer to the shore. In the Houston metropolitan area, certain areas saw as much as almost a meter of rainfall. As such, for this study, the level of damage to be used was produced by flooding at 3.05 meters in a single event.

4.2.1.3. Flood Mitigation Project Costs

Amini and Memari (2021) performed a comparative cost analysis study for various flood mitigation project types. The values gathered in that study are shown in Table 19 and were used to compute the total cost of each project as a function of the size of the house archetype to feed into the base BCA toolkit calculator. When asked for project useful life, the default value for each type of mitigation method was chosen, which was 30 years for elevation and 100 years for both demolition and relocation.

Table 19: Approximate Retrofit Costs Based on 2009 the Dollar Value

Retrofit Method	Construction Type	Existing Foundation	Description	Cost (USD/m^2)
Elevation	Frame	Slab-on-grade	Elevate 2.44 m	977.8
Relocation	Frame	Slab-on-grade	Relocate less than 8 km	1,211
Demolition	Frame	-	Rebuilt on an open foundation	1,500

4.2.1.4. BCA Toolkit Default Values

The common inputs used in the project configuration fields are as follows: for property structure type, “residential building” was chosen and for hazard type, “coastal V flood” was chosen. Coastal V flood was chosen as the hazard on the basis that FEMA (2005) recommends that design for V zone design is recommended even in coastal A zones. Table 20 provides the common input values for calculating benefits. As the focus is on concrete slab foundation homes along the Gulf Coast, there are no expected basements to be found, and the street maintenance is kept at zero for the sake of even comparison.

Table 20: Common Benefit Input Values for FEMA Toolkit

Field	Value
Lowest Floor Elevation of Property (m)	0
Ground Level of Property (m)	0
Base Flood Elevation (m)	3.05
Additional Sea Level Rise (m)	0
Use Default Recurrence Intervals?	Yes
Open Foundation?	No
Foundation Type	Slab
Basement?	No
NFIP Policy?	No
Damage Curve	Expert Panel - Slab
Contents Value	Default
Elevated Utilities?	No
Number of Residents for Social Benefits	1
Displacement Lodging and Meals	Default
Street Maintenance Benefit	0
Volunteers	0
Ecosystem Services Project Size	Home Footprint

4.2.2. Risk Aversion and Income Distribution Factors

4.2.2.1. Risk Aversion

A study performed by Kind et al. (2017) examined the relationship between income value and well-being. For BCAs, this relationship would quantify the willingness for an individual to pay for a good or how much they are willing to accept to give up a good or service. In the context of risk mitigation, individuals that are risk adverse are willing to protect themselves against the price that is greater than that used to reduce the expected damage, as shown in Eq. (6).

$$R_{WTP/ED} = \frac{willingness\ to\ pay}{expected\ damage} \tag{6}$$

$$= \frac{1 - [1 + P\{(1-z)^{1-\gamma} - 1\}]^{1/(1-\gamma)}}{Pz}$$

Where:

$P = Probability\ of\ flooding$

$z = Fraction\ of\ consumption\ lost\ due\ to\ flooding$

$\gamma = Elasticity\ of\ marginal\ utility\ of\ consumption$

For a storm comparable to Hurricane Harvey, the value “P” was set to 0.01 to represent the likelihood of flooding in a year. The elasticity of marginal utility, “γ,” describes the curvature of the relationship between income and well-being; based upon various sources of literally, it is typically set as a constant of 1.2. The resulting value of “$R_{WTP/ED}$” is used as a multiplier on the cost of expected damages.

4.2.2.2. Income Distribution

The same study also considered the applications of social welfare into the CBA calculation. The value of the equity weight multiplier can be given by Eq. (7).

$$\omega_{Yi} = \left(\frac{Y_i}{Y_{avg}}\right)^{-\gamma} \tag{7}$$

Where:

$Y_i = Income\ for\ individual, i$

$Y_{avg} = Average\ income\ for\ all\ individuals$

$\gamma = Elasticity\ of\ marginal\ utility\ of\ consumption$

For the scope of this study, various counties affected by Hurricane Harvey were used to compare the weights for each given income per capita value. These values are provided in Table 21.

Table 21: Harvey-Affected County Per Capita Income, 2017-2020 Average (U.S. Census Bureau)

County	**Per Capita Income Per Year (USD)**
Harris	$35,103.00
Aransas	$35,527.00
Galveston	$39,573.00
San Patricio	$28,529.00
AVERAGE	$34,683.00

4.2.3. Home Demolition Considerations

Considerations uniquely for the flood retrofit method of home acquisition and demolition were examined in this study. The first consideration was the monetary benefit of recycling of construction and demolition material (CDM). Additionally, if the CDM is reused instead of sent to a landfill, then the cost of landfilling could be avoided, and the material value could be returned as an added benefit. According to Burns McDonnell (2021), the costs of various types of recyclable material in Texas is shown in Table 22 based upon commodity prices. The tipping fees were counted separately.

Table 22: Estimated Value of Recyclables in Texas

Material	Value (USD/metric ton)
Glass	71.7
Metal - Ferrous	130
Metal - Non-Ferrous	1305
Paper	82.7
Plastics	960
CDM	6.61

The next step was to use the material breakdown of the average wooden frame home to calculate the expected quantity of each material with the matching price to obtain the total monetary return. Cochran et al. (2007) reported the following composition for demolition waste produced by typical homes in Table 23. By multiplying the density by the overall home footprint, the estimated value of each material was found along with the associated cost.

Table 23: CDM Waste Produced by Timber-Frame Home Demolition

Waste Type	Density (kg/m^2)
Concrete	240
Wood	90.0
Dry-Wall	30.0
Asphalt Roofing Materials	15.0
Misc.	60.0

The second consideration was the additional cost to use landfill space. Based upon statistics collected by Alves (2023), the cost to use landfill space in the south-central region of the U.S. averaged around $41.74 USD/metric ton in 2021. The total cost to landfill all waste matter was calculated by multiplying the tipping fee value by the total mass of CDM produced. The percentage of the material recycled was varied to observe the effect it would have on the overall CBA. At 0% material recycled, the entire home's worth of CDM would be calculated as a cost generated purely through landfill tipping fee, but at 100% material recycled, the entire home's worth of material would be refunded.

4.3. RESULTS AND DISCUSSION

Table 24 shows the results of the FEMA BCA toolkit output without any alterations. The values correspond to the nature of the calculation favoring more affluent properties larger properties produce more benefit if retrofitted, thus generating a higher BCR value.

Table 24: Default FEMA BCA Outputs (in $1000s)

	FEMA BCA Imported Values								
	Elevation			**Acquisition - Relocation**			**Acquisition - Demolition**		
Home Archetype	Cost	Benefit	BCR	Cost	Benefit	BCR	Cost	Benefit	BCR
1	220	7,137	**32**	354	8,218	**23**	376	8,218	**22**
2	273	10,278	**38**	418	11,833	**28**	467	11,833	**25**
3	321	13,175	**41**	476	15,165	**32**	539	15,165	**28**
4	251	9,006	**36**	391	10,369	**27**	434	10,369	**24**
5	398	17,712	**45**	566	20,384	**36**	650	20,384	**31**

Once the social welfare multiplier was applied, the values were changed in such a way displayed in Table 25. Here, a copy of home archetype 1 was placed in each county for comparison. The projects' BCR were weighted more inversely related to the county's income per capita.

Table 25: BCA with Social Welfare Factor Included (in $1000s)

			Social Welfare Factors Included					
Home Properties			**Elevation**		**Relocation**		**Demolition**	
Home Archetype	Size (m^2)	Stories	Modified Benefit	BCR	Modified Benefit	BCR	Modified Benefit	BCR
1	116.6	1	7,034	**32**	8,100	**23**	8,100	**22**
1	116.6	1	6,934	**32**	7,984	**23**	7,984	**21**
1	116.6	1	6,092	**28**	7,015	**20**	7,015	**19**
1	116.6	1	9,022	**41**	10,389	**29**	10,389	**28**

Risk factor was applied to the BCA and the results are shown in Table 26. Again, the archetype was kept constant, and the only value that was changed was the social vulnerability factor, testing the change as it increased. Indeed, it could be seen that the perceived benefit of a mitigation project increased as the potential of spending more annual income on repairs also increased.

Table 26: BCA with Risk Premium Included (in $1000s)

	Risk Premium Included					
Home Properties	**Elevation**		**Relocation/Demolition**		**Demolition**	
Home Archetype	Modified Benefit	B/C	Modified Benefit	B/C	Modified Benefit	BCR
1	8,438	**38**	9,717	**27**	9,717	**26**
1	10,565	**48**	12,166	**34**	12,166	**32**
1	15,057	**69**	17,338	**49**	17,338	**46**
1	52,107	**237**	60,002	**170**	60,002	**160**

The benefits from recycling material are touched upon, next. The material composition of each home archetype is shown in Table 27. These are calculated using the overall area of each archetype and the density breakdown provided in Table 23. This is followed up by Table 28, which provides the market value of each material and the total price of the sum in each home archetype. The assumption, here, is that all the materials could be completely recycled.

Table 29 shows the final comparison with the other methods if all of the material is fully recycled.

Table 27: Material Breakdown of CDM from Demolition

	Material Breakdown (Timber based home) (kg)				
Archetype	**Concrete**	**Bricks**	**Timber**	**Metals**	**Gypsum C&D Waste**
1	25,475	10,144	20,112	1,591	6,780
2	36,904	14,694	29,135	2,305	9,821
3	47,439	18,889	37,452	2,964	12,625
4	32,276	12,851	25,481	2,016	8,590
5	63,942	25,460	50,481	3,995	17,017

Table 28: CDM Cost by Category

	Price Breakdown (Timber based home) (US$)					Total Returns (US$)
Archetype	**Concrete**	**Bricks**	**Timber**	**Metals**	**Gypsum C&D Waste**	
1	168.49	67.09	133.02	1,142	44.84	**1,555.47**
2	244.07	97.18	192.69	1,654	64.96	**2,253.26**
3	313.75	124.93	247.70	2,127	83.50	**2,896.52**
4	213.46	84.99	168.52	1,447	56.81	**1,970.68**
5	422.90	168.39	333.87	2,866	112.55	**3,904.17**

Table 29: CBA with Recycling Benefits (in $1,000s)

	FEMA BCA Imported Values						**With Applied C&D Recycling Benefits**		
	Elevation			**Acquisition - Relocation**			**Acquisition - Demolition**		
Home Archetype	Cost	Benefit	B/C	Cost	Benefit	B/C	Cost	Benefit	B/C
1	220	7,137	**32**	141	8,218	**58**	371	8,220	**22**
2	273	10,278	**38**	206	11,833	**58**	442	11,835	**27**
3	321	13,175	**41**	263	15,165	**58**	507	15,168	**30**
4	251	9,006	**36**	179	10,369	**58**	413	10,371	**25**
5	398	17,712	**45**	353	20,384	**58**	610	20,388	**33**

If not all the material can be recycled, Table 30 shows how changing the percentage of the material being sent to the landfill can affect the overall benefit. Due to the tipping costs being relatively low, even recycling half of the material obtained through demolition would net a positive benefit.

Table 30: Net Benefit with Various Percentages of Recycled Material

Archetype	**Percentage Recycled**	**Total Cost to Landfill**	**Net Benefit**
1	0	2,676	-1,120
1	25	2,007	-451.4
1	50	1,338	217.5
1	75	669	886.5
1	100	0	1,555

4.4. CONCLUSIONS AND RECOMMENDATION

4.4.1. Conclusions

- The flood mitigation projects of elevation, demolition, and relocation are undertaken to lessen or prevent damage to previously flooded homes which would allow the structures to comply to flood regulations. The cost effectiveness of each project is checked through a CBA. FEMA had developed a BCA calculator explicitly for use in computing CBAs for hazard mitigation projects, but the current methodology is too narrowly focused and ignores costs and benefits from specific mitigation methods and benefits more affluent communities to the detriment of low-income ones. Combining suggestions to address a few of the criticisms from literature, a more comprehensive comparison was compiled focused on the three mitigation projects.
- The results from the base FEMA toolkit computed using the house archetypes support the criticism that the methodology favors the more affluent communities. As a property increased in size, the overall BCR increased, leading to the conclusion that mitigating more wealthy homes from flood damage is a more cost-effective option from an objectively numerical perspective.
- The risk multiplier adds a measure of subjectivity based upon the amount of damage the structure is expected to receive based on the flood- the more money that is spent to repair damage, the more likely the user is willing to spend for mitigation projects, increasing the BCR. In the way it is formulated, the multiplier is impartial to whichever retrofit method is chosen.
- The social welfare multiplier was used to address the wealth distribution effects the base calculator ignores. Based upon the individual counties chosen, it allowed the projects located in those with less average income per capita to be weighted more heavily compared to those on the higher end of the spectrum.

- The demolition considerations demonstrated that while recycling enough of the CDM could produce an overall benefit, a greater cost would be incurred if all of it were sent to the landfill. Due to much of the material being produced from timber-framed homes being valued cheaply, the return value on recycling this material is consequently low when compared to the benefits obtained through the standard BCA analysis.

4.4.2. Recommendations and Follow-Up Research

- While the BCA toolkit provides many hazards to choose from, it only allows mitigation for each hazard, independently. For example, in the case of hurricanes, there is the possibility of facing both wind and flood hazards; however, the toolkit cannot account for both simultaneously. Further research could be done into mixed hazard analysis for a more thorough calculation.
- The discount rate used in default BCA calculation was based upon default values. In the future, it is subject to change depending on economic factors. A more specific application may be applied to change the cost of a mitigation project over its lifetime.
- The values for the home material composition were sourced from a combination of literature not specifically limited to the U.S. Gulf Coast region. Values more closely related to the user's target region should be used to ensure accuracy if using the BCA in practice.
- The research for the material composition of single-family homes in the U.S. is dated and there do not exist test cases for all regions of the country. More research could be performed to enhance the accuracy of the recycling benefit estimates.
- Another cost that goes unseen is the fact that homes that are relocated or demolished no longer generate any property tax values for the communities where they were located.

Considerations should be taken when calculating the BCR that this factor may produce a significant cost.

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CHAPTER 5: GENERAL CONCLUSIONS

5.1. CONCLUSIONS

- Typical concrete slab-on-grade foundations are designed to be continuously supported by the underlying soil. There is currently no design code that considers how to account for changes in the support condition of these slabs when they are elevated for flood mitigation. This study shed light on the performance of these elevated home slabs under the changing support conditions that may make the slabs unsafe to carry the expected floor loads. To accomplish this objective, experimental concrete slabs resembling the configuration of the homes along the Gulf Coast were tested under simulated live loads. A numerical model calibration was conducted employing the experimental result for future parametric studies.
- An increase in the applied simulated floor live load directly correlated to an increase of induced downward deflection of the slab panels. Strain readings for the slab, grade beams, CFRP laminate, and steel beams also showed direct increases as the water load increased. These relationships were approximately linear until the stage when the tension cracking caused additional displacement and strain.
- The maximum deflection in the two-way slab panels was higher than that in the one-way panel, as expected. This observation is especially relevant to the existing condition of homes in the target coastal areas where most home slabs behave as two-way systems. The CFRP laminate did not affect the overall performance since the applied floor load was not large enough to induce high stresses and engage the laminate.
- The investigated slabs were provided with a 3 m typical elevation column spacing used in Texas coastal construction. It was found that they can safely support the IRC (2018) prescribed 1.9 kPa uniform floor live loading for residential structures.

- The parametric studies show mixed results depending on the house type for slab safety. The general results from the parametric studies showed that the general failure occurs in the WWF yield before all others, meaning that all the models are designed to be tension-controlled.
- A software application for determining the safety of an elevated slab configuration relative to the IRC-mandated minimum live load for house slabs was successfully developed. This would allow people not versed in technical engineering analysis to swiftly check whether a desired configuration passes the basic code-mandated live load threshold.
- The interpolation function devised for the software enables the analysis of column configurations that were not discretely modeled for the database. The linear behavior of concrete strain to stress in its elastic phase allows the interpolation function to be linear as well.
- The flood mitigation projects of elevation, demolition, and relocation are undertaken to lessen or prevent damage to previously flooded homes which would allow the structures to comply to flood regulations. The cost effectiveness of each project is checked through a CBA. FEMA had developed a BCA calculator explicitly for use in computing CBAs for hazard mitigation projects, but the current methodology is too narrowly focused and ignores costs and benefits from specific mitigation methods and benefits more affluent communities to the detriment of low-income ones. Combining suggestions to address a few of the criticisms from literature, a more comprehensive comparison was compiled focused on the three mitigation projects.
- The results from the base FEMA toolkit computed using the house archetypes support the criticism that the methodology favors the more affluent communities. As a property

increased in size, the overall BCR increased, leading to the conclusion that mitigating more wealthy homes from flood damage is a more cost-effective option from an objectively numerical perspective.

- The risk multiplier adds a measure of subjectivity based upon the amount of damage the structure is expected to receive based on the flood- the more money that is spent to repair damage, the more likely the user is willing to spend for mitigation projects, increasing the BCR. In the way it is formulated, the multiplier is impartial to whichever retrofit method is chosen.
- The social welfare multiplier was used to address the wealth distribution effects the base calculator ignores. Based upon the individual counties chosen, it allowed the projects located in those with less average income per capita to be weighted more heavily compared to those on the higher end of the spectrum.
- The demolition considerations demonstrated that while recycling enough of the CDM could produce an overall benefit, a greater cost would be incurred if all of it were sent to the landfill. Due to much of the material being produced from timber-framed homes being valued cheaply, the return value on recycling this material is consequently low, as well.

5.2. RECOMMENDATIONS FOR FUTURE RESEARCH

- Further testing of concrete slab panel parameters.
    - Larger size slab panels, representative of those under existing homes.
    - An in-depth study of column-beam connection.
    - Less intrusive methods of slab retrofitting.
- Extend parametric studies using numerical models.

  - More home types could be modeled and added to the database to account for more slab footprint types.
  - Material property parameters could be added in to consider varying concrete and steel strengths.
  - Slab thickness and grade beam dimension input fields would be able to consider variable geometric properties of the slab.
  - The various failure modes involved with column designs could be examined as each home elevation varies with height.
  - Differing support conditions might also affect the performance of the slab, as there may or may not be rebar interface between columns and slabs.
  - The incorporation of more parameters would necessitate a multi-variable interpolation formula to unify and handle the processing of data.
  - A targeted damage index could be implemented to be able to simulate higher resolution deterioration of specific slab elements.
- More fundamental research to be performed on various factors pertaining to elements of the BCA calculation and benefits that lack data to quantify.
  - While the BCA toolkit provides many hazards to choose from, it only allows mitigation for each hazard, independently. For example, in the case of hurricanes, there is the possibility of facing both wind and flood hazards, however, the toolkit cannot account for both simultaneously. Further research could be done into mixed hazard analysis for a more thorough calculation.

- The discount rate used in default BCA calculation was based upon default values. In the future, it is subject to change depending on economic factors. A more specific application may be applied to change the cost of a mitigation project over its lifetime.
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