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A Simple Decision Tool to Ensure the Safety of Coastal Home Elevation Process for Flood Mitigation

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Abstract Slab-on-grade (SOG) homes along the Gulf of Mexico and other coastal areas are elevated above the base flood elevation to mitigate damage caused by repeated flooding events. This changes the slab support condition from uniform soil to column and beam supports, leading to unanticipated stress/strain changes, concrete cracks, and slab failure. However, no state or national code has design provisions for such risky operations. The current research was conducted to bridge this knowledge gap by developing a user-friendly App utilizing experimental and numerical study results. The experimental investigation evaluated the performance of elevated two- and four-panel specimens built per the construction practice along the Gulf Coast. The gathered deflection data from the test was used to calibrate a finite element model. Extrapolating on the slab model, five full-sized home foundation slab models were developed with differing support conditions, such as the number and spacing of columns and the presence of concrete grade or steel support beams. Model A could support up to 3.8 kPa without failure, while models B through E experienced welded wire fabric yielding at various configurations of column spacing. The induced stresses in the slab elements obtained from the parametric study were then compiled into a database used as the building block of the decision-making App. The tool allows users to choose a specific elevated slab and support configuration. It then outputs capacity and checks if it meets the minimum design live load established by the International Residential Code.

Keywords: elevated homes, flood mitigation, concrete slab elevation, safety, International Residential Code, software App, mobile App, computer App

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1. INTRODUCTION

1.1 Elevating Homes as a Flood Mitigation Method

Coastal communities along the U.S. 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 in the state of Louisiana that caused $108 billion (in unadjusted 2005 dollars) in damage, according to the National Oceanic and Atmospheric Administration (NOAA) (2005). Berg (2009) reported that, in 2008, Hurricane Ike inundated the coastal communities of Texas with as much as 3 m of water and caused $19.3 billion in damage. Figure 1 shows the state of a Houston, TX, community in the aftermath of Hurricane Ike.

After flooding events, homeowners may choose to elevate their homes above the base flood elevation (BFE), a popular method to reduce or eliminate flood damage. An example of an elevated home is shown in Figure 2. Existing residential foundation slabs are typically 100 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 height and placing it on solid concrete or stacked concrete masonry unit (CMU) column 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.

Figure 1. A Texas neighborhood under high water (Houston Chronicle, 2022)

Figure 2. An elevated home in Nassau Bay, TX

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 critical knowledge gap in the design of elevated home slabs. The ACI 318-19 Building Code (2019) or governing bodies such as the Federal Emergency Management Agency (FEMA) do not provide such 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. The Slab on Grade foundation has been widely accepted amongst home 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. Furthermore, per the International Residential Code (IRC) (2021), the floor of a single-family residence must support a minimum of 1.9 kPa distributed live load. The elevated slab may thus be unable to carry this load safely.

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). 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) evaluated the structural performance of CFRP retrofitted elevated house slabs. This study found that applying CFRP on the negative bending moment surface could increase the capacity by about 30%.

This study was undertaken as a response to the lack of established guidance in the realm of home elevation and to assist homeowners in making informed decisions about optimum elevation parameters for flood mitigation. The study resulted in a rational, safe, and scientific methodology for the design of the home elevation process.

The experimental work was undertaken, and the resulting software was developed to fulfill the following objectives.

- Sample concrete slab support arrangements for elevated homes along the Texas Gulf Coast communities and build full-scale test slab specimens to evaluate their performance under applied load. A realistic application of a slab strengthening CFRP retrofit was also tested to check its efficacy.
- Develop Finite Element Models that emulate the behavior of real-life slabs and determine how the slab behavior changes with changing support conditions. The modeling also involved checking whether the arrangement would safely support the minimum floor live load prescribed by the IRC (2021).
- Develop a tool that allows users to input desired slab support arrangements and determine the associated structural safety of elevated slab homes per IRC (2021).

2. METHODOLOGY

The methodology of this study, including the experimental testing, the numerical modeling, and the software development tasks, is shown in Figure 3. Each is described in subsequent sections.

2.1 Elevated Homes in Flood-Affected Regions

The scope of the project covers the Texas coastal counties most affected by the passage of Hurricane Harvey in 2017 as defined by Ling et al. (2023) which includes Harris and Galveston counties. A combination of site research and literature review, such as the review of several as-built elevation plans from coastal areas was conducted to gather information on home size, support placement and configuration. These plans were provided by collaborating elevation contractors performing work in the relevant areas. A sample plan is shown in Figure 4. Information gathered included column size, number of columns, column spacing, types of beams, and support conditions commonly used in home elevation construction practice. A total of eight home elevation plans from Louisiana and Texas were reviewed.

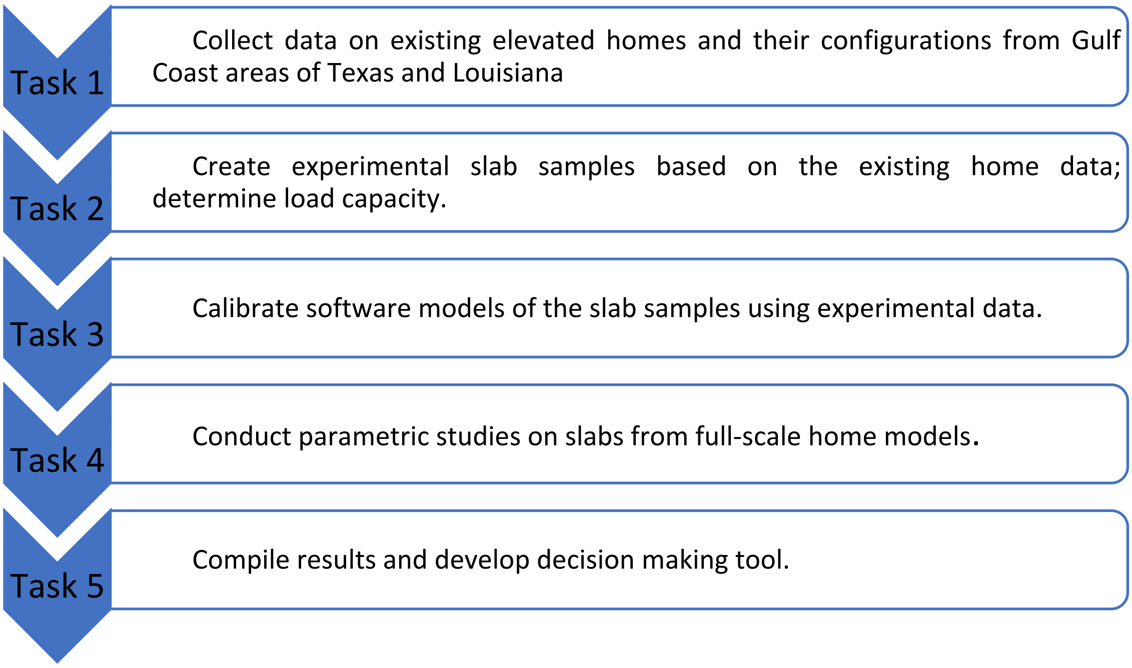
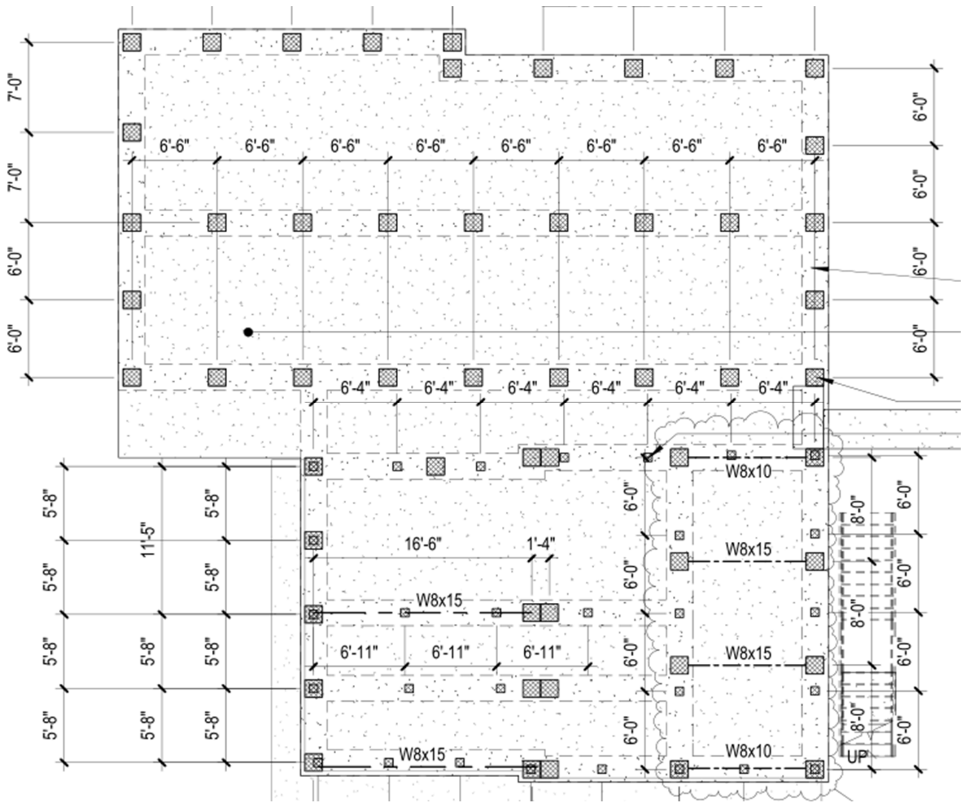


Figure 3. Software tool development methodology



1 ft.= 305 mm

Figure 4. Sample home elevation construction plan (Robert, 2015)

2.2 Elevated Slab Testing

An experimental study was performed to determine the flexural capacity of representative elevated concrete slabs . The study involved constructing two concrete slab specimens raised upon Concrete Masonry Unit (CMU) columns in sizes and shapes comparable to the sample 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 5). Slab 2 consisted of two panels, and a strip of CFRP laminate was applied on the bottom tension face to improve the load-carrying capacity. Simulating the general practice used to build the home slabs, the specimens were constructed using concrete with a compressive strength of 13.8 MPa and Welded Wire Fabric (WWF) with a yield strength of 415 MPa.

Figure 5. Experimental elevated slab specimen

To find the load capacities, tap water was gradually added into plywood troughs constructed above each slab to simulate the applied live load. Loading at any time was back-calculated using the time required to fill the troughs to specific depths. Displacement and strain data were collected during the test to highlight which areas would fail first and the associated failure modes, such as in Figure 6. Overall, it was found that the higher the applied load, the higher the induced stresses in all components (slab, grade beam, and WWF). The two-way slab had more deflection than the one-way slab for a given load. Smaller column spacings allowed more load to be applied, and the typical construction practice of spacing columns no more than 3 m could safely support the IRC prescribed 1.9 kPa minimum floor 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 stresses and engage the laminate. 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 in-depth test results may be accessed from the literature (Ling et al., 2023).

Figure 6. Observed cracking in slab

2.3 Finite Element Model Calibration

The experimental results from the four-panel slab were used to calibrate the finite element model (FEM) created using the ABAQUS software (Dassault Systèmes, n.d.), as seen in Figure 7. The slabs, columns, and beams were modeled with eight-noded brick elements, C3D8. The WWM and reinforcing steel were modeled with two-node wire elements, T3D2. Furthermore, the reinforcement was embedded into the concrete elements. The beam-column interface was defined as a "rough" surface contact, allowing 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 1 (Carreira & Chu, 1985). Ling et al. (2023) provides detailed information on the model calibration, including the composition of the concrete batches and reinforcement placement.

2.4 Parametric Study

The experimental slab model data was extrapolated into a full-sized representative home footprint, as seen in Figure 8(a). Four other existing elevated home plans previously studied were chosen as templates for the parametric study [Figures 8(b) to 8(e)]. Table 2 provides the total area of each floorplan and the number of stories in each home. Within these images, the dark lines represent the original concrete grade beams around the slab perimeter and in between interior panels. For Building C, new elevation steel beams are sometimes used together with concrete beams. The concrete material properties used in these models are the same as shown in Table 1. A yield strength of 250 MPa is the only differentiating element used for the steel beams compared to the other steel elements, also shown in Table 1.

The parametric study 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 live load that induced failure for each column configuration. "Failure," as defined herein, is the initial stage when one of the following modes occurred: WWF steel yielding, concrete crushing in slab/beam/column, and concrete tensile failure. For example, Figure 9 shows the used variances of the column spacings for Home A. Table 3 shows the number and spacing of columns in each cardinal direction of the models. Due to differing geometry, the other building types feature differing numbers of column configurations with the associated column spacings.

Table 1. Material properties for numerical modeling

Property	Concrete	Steel
Density (kg/m^3)	6.095	20.36
Elastic Modulus (MPa)	7,586	199,948
Poisson's Ratio	0.175	0.3
Yield Strength (MPa)	--	276 for rebars; 414 for WWM
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	--

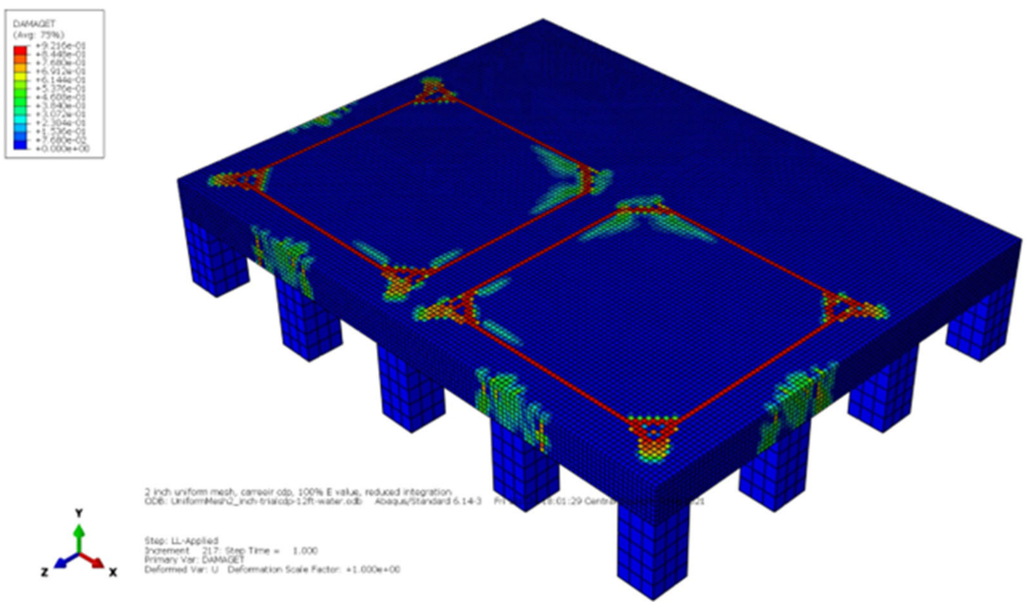


Figure 7. FEM of experimental slab

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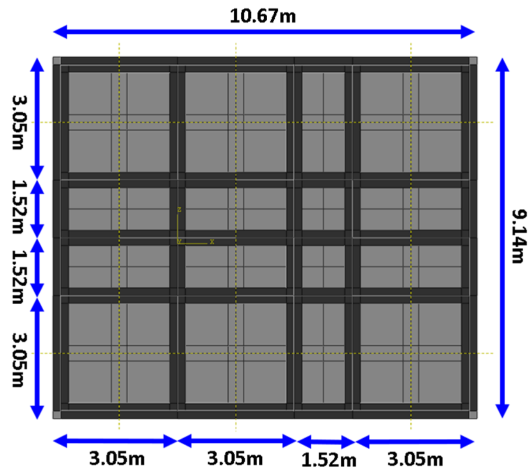
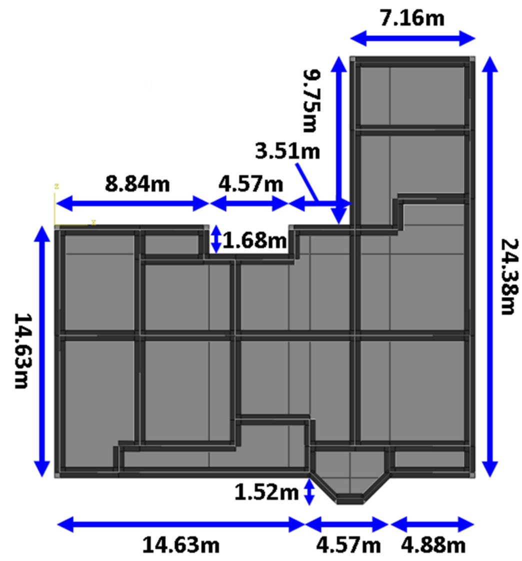
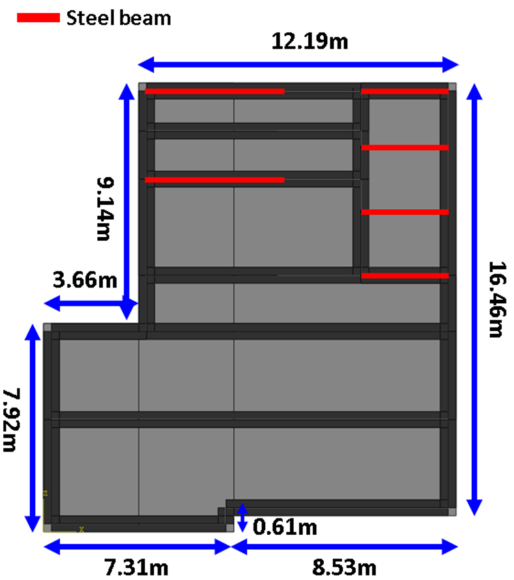


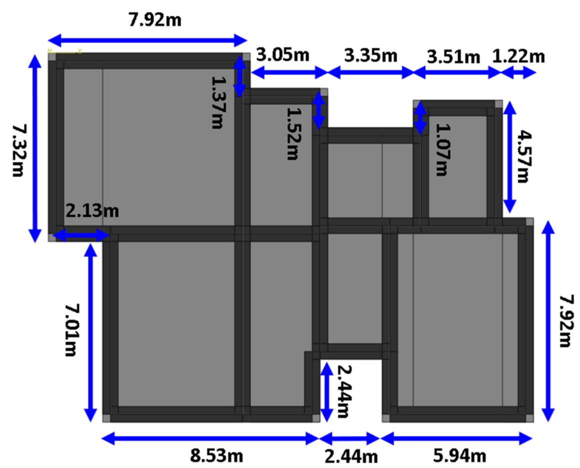
(a) Building A



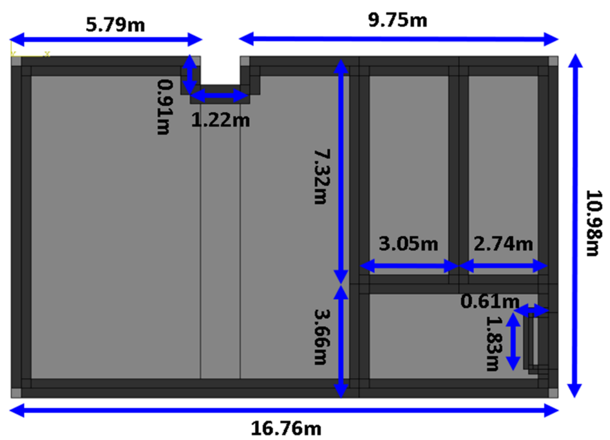
(b) Building B



(c) Building C



(d) Building D



(e) Building E

Figure 8. Model home floorplan types (Dimensions in m)

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Table 2. Floorplan total area and stories

Home Type	Area (m^2)	Number of Stories	Roof Type
A	97.5	2	Gable
B	427	1	Gable and Hip
C	172	1	Gable and Hip
D	232	1	Gable
E	176	2	Gable

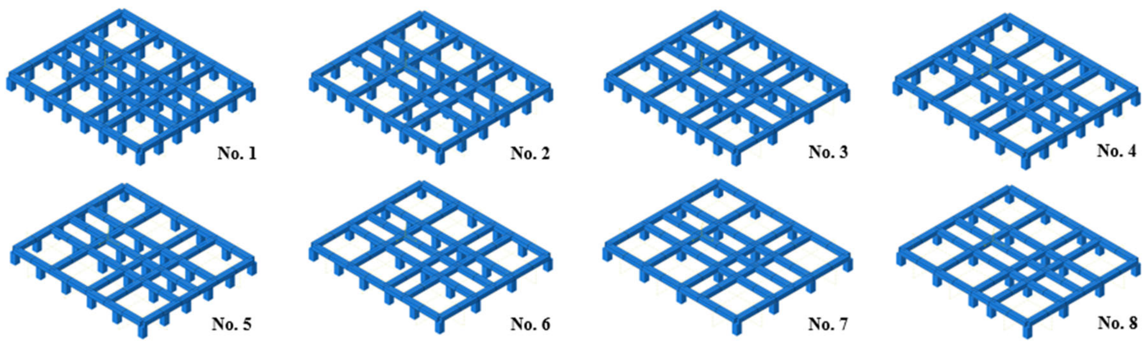

Figure 9. Parametric study models for Home A

Table 3. Summary parametric model cases for Home A

Case No.	x-axis		y-axis	
	Number of Columns	Max. Column Spacing (m)	Number of Columns	Max. Column Spacing (m)
1	8	1.52	7	1.52
2	8	1.52	6	1.83
3	8	1.52	4	3.05
4	6	2.13	7	1.52
5	6	2.13	6	1.83
6	6	2.13	4	3.05
7	4	4.57	4	3.05
8	5	3.05	4	3.05

2.5 Parametric Study Results

The specific failure modes for each model home are listed in Table 4. The results were stored as tables of induced stresses within elements of the elevated slabs: the WWF and slab, grade beam, and column. A sample of this data for the WWF in Home A is presented in Table 5, where case numbers are from Table 3. For each model home study, the maximum applied live load was 3.83 kPa, double the value the IRC (2021) specified for single-family residential homes.

Table 4. Failure modes for home models

Home Type	Governing Failure Mode
A	No failure modes observed for any case.
B	WWF yielding at a live load of 479 Pa with only 1.52 m column spacing. Increased spacing caused WWF yielding from just the slab self-weight.
C	WWFF yielding at a live load of 2.9 kPa at 1.83 m column spacing.
D	WWF yielded at a live load of 239 Pa for any case.
E	WWF yielding at a live load of 2.4 kPa for 1.83 and 2.44 m column spacings. For 3.05 m column spacing, WWF yielded at a live load of 1.4 kPa.

Table 5. Sample induced stresses in Home A elements

Applied Live Load (kPa)	Tensile Stresses in WWF per Case Numbers (kPa)							
	1	2	3	4	5	6	7	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
Applied Live Load (kPa)	**Shear stresses in Slab Concrete per Case Numbers (kPa)**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0.239	53	39	27	51	52	33	13	20
0.479	60	44	31	57	58	37	15	24
0.718	66	49	35	62	63	41	18	28
0.958	72	54	39	67	68	45	21	31
1.197	79	59	43	73	74	50	24	35
1.436	85	63	47	78	79	54	27	39
1.676	91	68	51	84	85	58	31	42
1.915	98	73	55	89	90	63	33	46
2.394	110	83	63	99	100	71	39	53
2.873	123	93	66	110	111	101	44	56
3.352	126	112	96	141	140	135	71	80
3.830	133	119	97	162	158	137	84	73

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3. HOME ELEVATION DECISION TOOL

3.1 Data Processing

A the Home Elevation Decision Tool (HEDT) was developed to aid stakeholders in the following aspects of the home elevation process: (a) Understand the relative role each structural component of an elevated home slab plays in carrying the floor live loads; (b) Estimate the structural safety of such slabs in terms of carrying the building code mandated minimum floor live loads; (3) Determine the effect of varying spacings of the elevation beams and columns on potential failure of the elements; and (4) Determine the optimum support spacings to ensure elevated slab safety. While the dead load (self-weight) of the slab remains constant for the thickness selected, the floor live load is a variable and that causes stress changes in the structural members.

Depending on the data availability, the tool analyzes user input employing linear, bilinear or Barycentric interpolation. The ability of the tool to calculate interpolated values is due to the characteristic of concrete having a generally linear relationship between applied stress and strain in the elastic range. Table 6 shows the range of values that would be interpolated if column spacings of 1.52 m and 2.44 m are chosen for the two directions. The induced stress for this pair of column spacings is interpolated using Eq. 1, and the resultant stress is around 13,431 kPa. A new table of values for this set can be generated and compared with the steel yield strength and IRC (2021) live load threshold.

$$y = mx + y_1$$

$$m = \frac{y_2 - y_1}{x_2 - x_1} \tag{1}$$

Where:

$$y = Stress\ at\ the\ desired\ column\ spacing\ set$$
$$x = Column\ spacing\ of\ the\ variable\ orientation$$
$$x_n = Upper\ or\ lower\ bound\ column\ spacing$$
$$y_n = Upper\ or\ lower\ bound\ stress$$

Table 6. Linear Interpolation Example (Stresses in kPa)

		X-Axis Column Spacing (mm)					
		1.52	1.83	2.13	2.44	2.74	3.05
Y - Axis Column Spacing (mm)	1.52	13,555		14,078			
	1.83	13,423		13,726			
	2.13						
	2.44						
	2.74						
	3.05	13,444		14,936			11,264

Table 7 shows a bilinear interpolation scheme for a column spacing set of 1.83 x 2.44 m. 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 shown in Eq. 2. The resultant stress for the input column spacing set is around 13,879 kPa.

$$Q(x,y) = \left(Q_{11} * \frac{x_2 - x}{x_2 - x_1} + Q_{21} * \frac{x - x_1}{x_2 - x_1}\right) * \frac{y_2 - y}{y_2 - y_1} + \left(Q_{12} * \frac{x_2 - x}{x_2 - x_1} + Q_{22} * \frac{x - x_1}{x_2 - x_1}\right) * \frac{y - y_1}{y_2 - y_1} \quad (2)$$

Where:

$$Q(x,y) = Stress\ at\ the\ chosen\ input\ set$$
$$Q_{nn} = Stress\ at\ any\ of\ the\ four\ boundary\ points$$
$$x = Input\ X - column\ spacing$$
$$y = Input\ Y - column\ spacing$$
$$x_n = Boundary\ X - column\ spacing$$
$$y_n = Boundary\ Y - column\ spacing$$

Table 7. Bilinear Interpolation Example

		X-Axis Column Spacing (mm)					
		1.52	1.83	2.13	2.44	2.74	3.05
Y - Axis Column Spacing (mm)	1.52	13,555		14,078			
	1.83	13,423		13,726			
	2.13						
	2.44						
	2.74						
	3.05	13,444		14,936			11,264

With only three points in the chosen data set, a two-dimensional interpolation given by Eq. 3, is used (Yiu, 2001). The method includes checks to ensure that the chosen coordinate set is bound within the confines created by the vertices. If any resulting values are negative, the chosen coordinate set is outside the bounding triangle, and the resulting stress is extrapolated. Table 8 shows how the tool processes the data if a column spacing set of 2.44 and 2.74 m is used, yielding a resultant stress of around 13,410 kPa.

$$\lambda_1 = \frac{(y_2 - y_3)(x - x_3) + (x_3 - x_2)(y - y_3)}{(y_2 - y_3)(x_1 - x_3) + (x_3 - x_2)(y_1 - y_3)}$$
$$\lambda_2 = \frac{(y_3 - y_1)(x - x_3) + (x_1 - x_3)(y - y_3)}{(y_2 - y_3)(x_1 - x_3) + (x_3 - x_2)(y_1 - y_3)} \quad (3)$$
$$\lambda_3 = 1 - \lambda_1 - \lambda_2$$
$$Q(x,y) = Q_1\lambda_1 + Q_2\lambda_2 + Q_3\lambda_3$$

Where:

$$Q(x,y) = Stress\ at\ the\ chosen\ input\ set$$
$$Q_n = Stress\ at\ any\ of\ the\ three\ boundary\ points$$
$$\lambda_n = Barycentric\ coordinate$$

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Table 8. Barycentric Interpolation Example

		X-Axis Column Spacing (mm)					
		1.52	1.83	2.13	2.44	2.74	3.05
Y-Axis Column Spacing (mm)	1.52	13,555		14,078			
	1.83	13,423		13,726			
	2.13						
	2.44						
	2.74						
	3.05	13,444		14,936			11,264

3.2 Overview and Usage Example

The HEDT tool is configured to rapidly determine the floor live load capacity of an elevated concrete home slab and compare the capacity to the minimum IRC (2021) specified value for residential structures. To begin, the users 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 limited portion of what the application offers. The disclaimers and user manual are also available from the home screen, as seen in Figure 10(a).

The users select any of the five built-in home models that most resembles the target home being elevated or is already elevated, which specifies the plan configuration, floor area and the number of stories. The column spacing parameters in two cardinal directions are then selected, determining the number of columns in the set [Figure 10(b)].

When "Submitted," the tool compares the input with the internal database from the study. It then outputs whether the specific configuration can safely support the code specified live loading. A sample results screen is shown in Figure 10(c), displaying the output when all slab elements can safely support the stresses induced by the minimum live load.

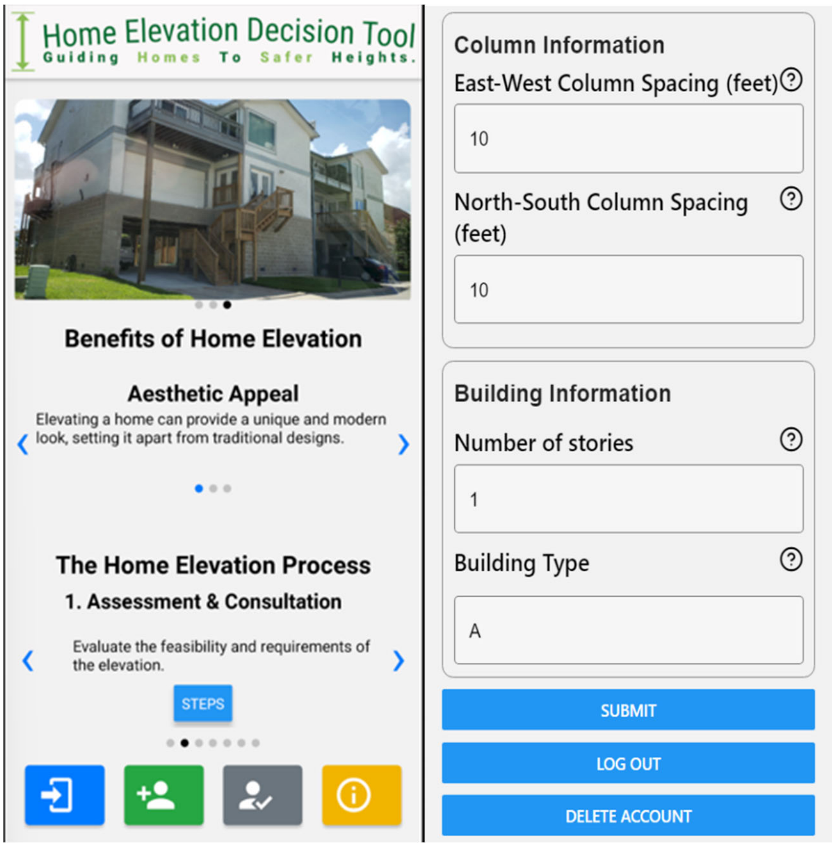
The free decision tool is currently available in Google Play Store in the Android, iPhone, and desktop formats.

3.3 Limitations

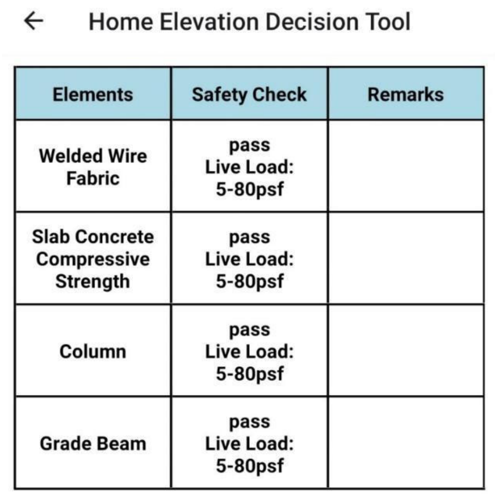
At the time of release, the free tool only allows the users to change the home type, foundation footprint, and the number and spacing of support columns. Material and other geometric properties are currently with default values with no user inputs. No load is assumed to be transferred from the home superstructure to the slab and grade beams. The following fixed and default parameters are used:

- Steel yield and concrete compressive strengths of 276 MPa and 13.8 MPa, respectively.

- The minimum and maximum column spacings of 1.5 and 3 m, respectively. These values were selected based on the review of representative as-built plans for coastal homes.
- A slab thickness of 100 mm. This is by far the most common slab thickness used in coastal homes.



(a) Home screen (b) Parameter selection screen


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	

(c) Results screen

Figure 10. HEDT screen captures

The tool is currently being enhanced with ongoing research under a grant from NOAA through the Texas Sea Grant program to the University of Texas at Arlington and Texas A&M University College Station. Wind and flood lateral loads on the elevated home superstructure are being considered.

The study can be further enhanced in the future with the following considerations:

- Additional home types may be modeled and the ability to interpolate between hole types may be considered.
- Material properties and slab thickness may be added as input options.
- Column failure modes resulting from combined wind, flood and live load may be considered.

Connection types between the support beams and columns may be considered.

4. CONCLUSIONS

The following conclusions may be made based on the results of this study:

1. The study was undertaken to address the structural safety issues of elevated slab on grade homes, an available flood-mitigation practice along the Gulf of Mexico and other coastal areas. Since there is no available code or guideline for the design and construction of such slabs, several factors, such as supporting column spacing and number and beam placement are selected by the judgment of the engineer on record. Additionally, the typical existing concrete slabs in older homes are extensively deteriorated and may add to the unsafe conditions.

2. The current study developed a decision-making tool utilizing sound experimental and numerical modeling results with typical inputs for coastal buildings. The tool is to aid stakeholders (designers, contractors, homeowners, community officials) in ensuring elevated slab structural safety in consideration of governing building codes.
3. The study experimentally evaluated slab specimens constructed per the typical elevation practices around the Gulf Coast. It was found that the maximum column spacing of 3 m designated by contractors was enough to hold the minimum live load. Any external carbon fiber retrofitting of vulnerable slabs has negligible benefit in increasing the slab capacity.
4. It was found that increased support column spacing results in failure occurring at a lower applied live load for all home types except Type A. The failure mode was controlled in most cases due to the yielding of the WWF, implying tension-controlled failure.

5. The developed free user-friendly decision tool allows stakeholders to verify the structural safety of elevated home concrete foundation slabs quickly and conveniently in conformance with the IRC (2021) building code provisions for minimum floor live loads. Optimum spacings for support beams and columns may also be obtained through this tool.

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