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The economic argument for amphibious retrofit construction

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Abstract

Smart economic frameworks and policies to inform investments in resilience and disaster risk reduction are receiving increasing attention. In an era of accelerating risk, communities need expanded sets of economically viable options to reduce risk and promote adaptation. Amphibious architecture utilizes low-cost buoyant foundations to provide existing structures with the ability to "float when it floods" rather than suffer repetitive loss or be required to implement an approach such as permanent static elevation that may be both culturally and economically objectionable. Amphibious construction offers significant cost savings in comparison to permanent static elevation. This paper will discuss the potential for measurable savings that accompanies the implementation of amphibious retrofit construction, by describing 1) the installation process and why it can be so inexpensive, 2) two loss avoidance studies that were performed for amphibious retrofit installations and the range of high loss avoidance ratios that resulted, and 3) analysis of the wind vulnerability of permanent static elevation and consequent increases in expected annual loss compared to amphibious retrofit construction. Amphibious construction is shown to be an innovative and economical approach to reducing flood risk and adapting to climate change.

Keywords: buoyant foundation, amphibious architecture, flood risk reduction, loss avoidance study, expected annual loss, climate change adaptation

1. Introduction

Amphibious retrofit construction is a small-scale and building-specific intervention for flood risk reduction and climate change adaptation that works in harmony with a flood-prone region's natural flooding cycles. An amphibious foundation maintains a building's connection to the ground by resting firmly on the earth under ordinary circumstances, and when flooding occurs, it ensures that the building floats on the surface of the water, using a vertical guidance system to prevent any lateral movement. Figure 1 shows post-flood conditions of undamaged homes fitted with buoyant foundations compared to damage to a home with permanent static elevation (PSE) (left photo) and a two-storey house (right photo). The high-water marks on the static buildings indicate the level of water damage experienced by these buildings. Unlike PSE, amphibiation adapts to varying levels of floodwater, an increasingly important consideration as flood levels become higher and more

Figure 1: Comparison of houses employing buoyant foundations to one with permanent static elevation (left) and a two-storey house (right); note the high-water lines on static houses (BFP / Elizabeth English)

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unpredictable in coastal and riverine communities. Amphibious retrofit construction, as practiced by the Buoyant Foundation Project (BFP), provides a financially advantageous strategy for long-term flood mitigation. This paper explains the economic benefits of buoyant foundations including their low-cost installation process, the avoidance of losses due to flood damage and displacement, and reduced wind vulnerability in comparison to permanent static elevation.

2. Installation process and cost-efficiency of amphibious retrofits

2.1. *Installation Process*

A buoyant foundation is a system designed to be retrofitted to an existing structure to make it amphibious (Fig. 2). Buoyancy elements can be made of any non-absorptive low-density material or assembly that will displace water. They are attached to a structural subframe that has been secured to the underside of the building. To accommodate the buoyancy elements, a building is usually raised to a level approximately one meter above the ground. Figure 2 shows one iteration of the retrofit strategy, where the subframe is attached to telescoping vertical guidance posts, which flank the building. Another option is to attach the subframe with loosely sliding sleeves to static vertical guidance posts embedded in the ground adjacent to the building. The vertical guidance posts resist lateral forces from wind and water to ensure that the building will only move up and down while floating. During a flood, the structural subframe distributes the uplift forces from the buoyancy blocks to support the weight of the building, allowing the buoyancy to carry it on the surface of the water. The subframe and the blocks can be installed beneath the building in pieces, since the individual elements are small and light enough to be installed manually by two people without machinery; this keeps the retrofit construction costs very low.

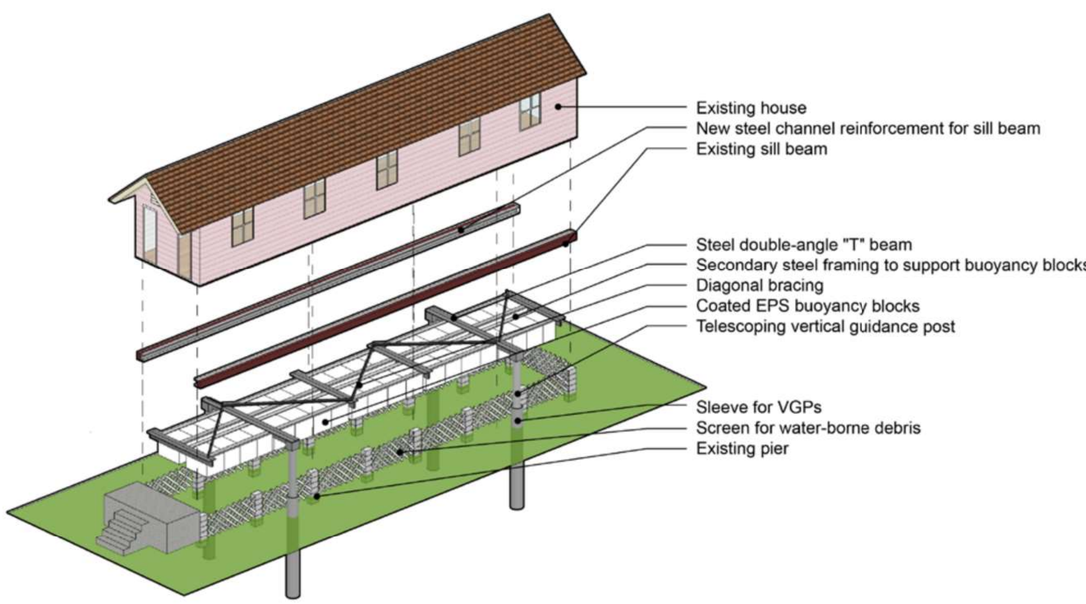

Figure 2: Exploded axonometric drawing of buoyant foundation system components, as designed for a Louisiana "shotgun" house (BFP)

2.2. *Economic benefits and cost considerations*

Amphibious retrofitting offers significant cost savings when compared to permanent static elevation (PSE). PSE requires the complete replacement of a building's foundation system, usually with deep piles, while amphibious retrofits continue to rest on their existing foundations in dry conditions and simply require installing vertical guidance posts to prevent lateral movement and assembling and attaching the buoyancy system to provide flotation. Detailed cost comparisons show that amphibious retrofits, calculated to be approximately $300/m^2, will typically cost between 20 and 45 percent of PSE renovations. Amphibious construction can be adapted to accommodate a variety of housing typologies and vernacular constuction techniques. Amphibious designs can encourage the use of locally available and recycled materials, and local sourcing of labor can further reduce costs and support sustainable construction practices. Buoyant foundations are economically viable because the materials are inexpensive to procure and the system components are simple to install.

In Jamaica, the most common housing type is a single-storey building constructed either with concrete masonry units on a concrete slab-on-grade or a timber pier-and-beam structure raised on foundation piers. The pier-and-beam system is highly suitable for amphibious retrofit because the flotation substructure (subframe and buoyancy elements) can easily be installed beneath the existing floor structure, and the height of the piers can be increased if necessary.

The house selected for this case study is in the flood-prone community of Port Maria in Saint Mary Parish, in northeastern Jamaica. Houses located along the Outram River in Port Maria are at a constant risk of flooding during heavy rainfall. Even without rainfall, the ground is supersaturated when river levels are high. This house has pier-and-beam construction with wood foundation posts that elevate the floor structure above grade, creating a crawl space. This provides the key pre-condition for the inexpensive application of a buoyant foundation because the flotation substructure can be easily installed beneath the existing floor structure (Fig. 3). The design strategy employs cost-effective local materials and local construction practices as primary considerations for the amphibious retrofit, such as using readily available timber telephone poles for the vertical guidance posts and bundled plastic jugs for the buoyancy elements (Fig. 4) (Turner & English, 2015). Recycled plastic 20-liter jugs are a readily available local commodity and can be easily assembled into an inexpensive and effective buoyancy system.

Figure 3: Render of a buoyant foundation retrofit for house in Port Maria, before (left) and during (right) flooding (BFP)

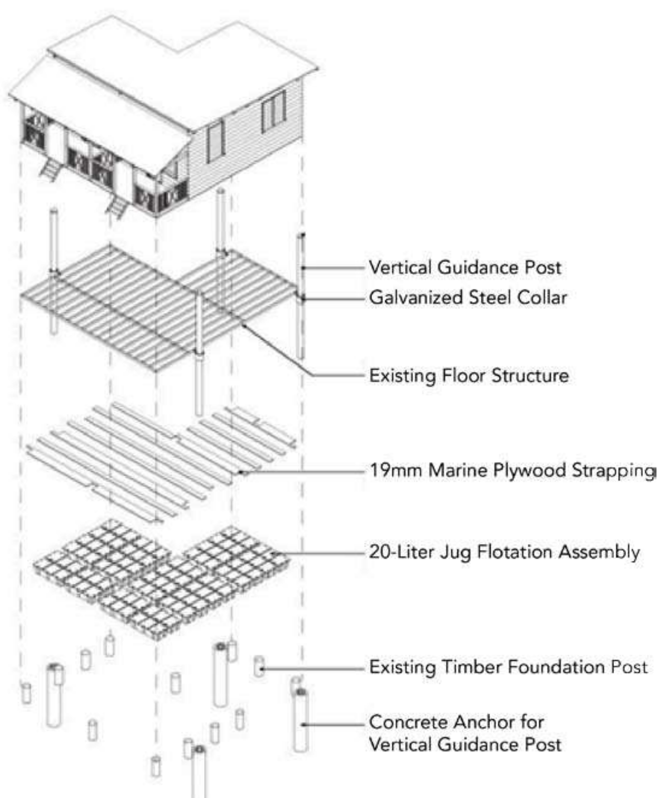

Figure 4: Schematic drawing of a buoyant foundation retrofit for Port Maria house (BFP / Scott Turner)

In the Port Maria house, 370 jugs assembled beneath the reinforced floor structure would provide approximately 7,000 kg of buoyancy. The construction cost for the buoyant foundation is estimated at $3,765 USD (approximately $100/m^2), which could be further reduced to $2,000 USD if the labor were donated (English et al., 2016). The cost drops significantly, by about 40%, with self-labor. The construction could easily be done by the homeowners themselves, encouraging the sharing of knowledge and ultimately promoting resilience and self-sufficiency in vulnerable communities. Buoyant foundation retrofits are an inexpensive solution compared to the potential costs of repairing flood damage or relocating residents. Affordable amphibious housing provides an economically viable flood risk reduction strategy for marginalized communities that require a cost-sensitive solution.

3. Loss Avoidance Studies

Loss avoidance studies quantify the economic advantages of a mitigation measure by comparing the cost of damages incurred from flooding, without the mitigation measure in place, to the installation cost of the mitigation measure. Loss avoidance studies combine three categories of losses: building repair costs, contents losses, and displacement costs. A loss avoidance ratio greater than 1.0 indicates that the cost of installing the mitigation measure is less than the cost of the damages in a single flood event for the same building without the installation; in other words, that the mitigation measure pays for itself in a single flood event (Bourdeau, 2015; Laatsche, 2015). Table 1 shows the cost of damage to a building as a percentage of the total building value, for three building types, as a function of the depth of the flood relative to the finished floor level of the lowest floor of the building.

Table 1: Percent Building Damage for Three Residential Typologies Relative to Flood Depth (after Bourdeau, 2015)

Building Type	Mobile Home	1 Story without a Basement	2 Story without a Basement
Flood Depth in Meters	**Percent Damage**	**Percent Damage**	**Percent Damage**
-0.46 to -0.15	0	2.5	3
-0.15 to 0.15	8	13.4	9.3
0.15 to 0.46	9.4	23.3	15.2
0.46 to 0.76	63	32.1	20.9
0.76 to 1.07	73	40.1	26.3
1.07 to 1.37	78	47.1	31.4

Loss avoidance case studies conducted for amphibious retrofits in two North American locations (Louisiana, USA, and Manitoba, Canada) resulted in high loss avoidance ratios, demonstrating the potential for dramatic cost savings that could come from implementing buoyant foundation retrofits in these locations. Detailed discussions of these two case studies follow in the next sections.

3.1. Louisiana case study: Leeville

The following case study is a summary and update of a study described in a paper presented at the First International Conference on Amphibious Architecture, Design and Engineering, held in Bangkok, Thailand, in August 2015 (Sumanth & English, 2015).

Located in southeast Louisiana, Leeville was formerly an industrialized oil port and served as a junction point between Port Fourchon, a major Gulf Coast oil port through which passes roughly 18 percent of the total US oil supply, and Golden Meadow, the southern-most town along Highway LA-1 that is contained within the levee protection system. Leeville, which lies well outside the boundaries of the levee system, has been bypassed by the reconstruction of Highway LA-1 as an elevated highway, stretching south of Golden Meadow to Port Fourchon. This area is now prone to frequent flooding that has been exacerbated by rapidly disappearing wetlands and high rates of erosion. A loss avoidance study of a property in the area helps to determine the effectiveness of implementing buoyant foundations in Leeville. Amphibious retrofits would be an efficient and cost-effective flood mitigation strategy for existing houses in Leeville to mitigate increasing flooding and enhance community resilience (Fig. 5). The location is a site along the non-elevated Old Highway 1 near Bayou Lafourche, on which stands a house of roughly 100m^2, elevated off the sloped ground at a height of 0.4m to 0.6m.

The flood depth associated with the percent damage calculations is given relative to the original interior floor elevation. The flood depth value is calculated by subtracting the height of the existing finished floor elevation from the high-water mark of previous floods.

Figure 5: Current house condition (left) and render of retrofitted house during flood (right) (BFP / Elizabeth English, Ivee Wang)

The damage repair cost for the house considers the damage to the structure, utility systems, and finishes in a flood prior to mitigation. The percent damage is calculated based on flood depth. The building replacement value for this house is estimated at $70,000. This value is multiplied by the percent damage given in Tables 1 and 2 to obtain estimated building repair costs. In this example, a flood depth of 1.4m would on average cause damage costing 47.1 percent of the value of the house and therefore would anticipate requiring $32,970 in repairs to the house itself. Rounded to the nearest $100, that becomes $33,000 as shown in Table 2.

Table 2: Building Damage Repair Cost for Building Replacement Value of $70,000

Flood Depth in Meters	Percent Damage	Cost in Dollars (USD)
0.5	32.1	$22,500
1.0	40.1	$28,100
1.4	47.1	$33,000

Contents losses refer to the costs of repairing or replacing damaged furniture, appliances, and material possessions, including electronics and clothing. The contents value is projected to be 30 percent of the building replacement value or in this case equal to $21,000 for a $70,000 house. For a flood depth of 1.4m it is estimated that contents damage costs would be 25.7 percent of their value of $21,000, requiring $5,397 in repairs or replacement (Bourdeau, 2015). This is shown in Table 3.

Table 3: Contents Repair and Replacement Cost for Contents Value of $21,000

Flood Depth in Meters	Percent Damage	Cost in Dollars (USD)
0.5	17.9	$3,800
1.0	22	$4,600
1.4	25.7	$5,400

Displacement costs refer to living expenses required for relocation during a flood and after when damages are under repair, including rental expenses and meals. Displacement costs are based on an average household size of 2.7 people and local per-diem rates for lodging and meals in southeast Louisiana. The displacement cost has been calculated to be an average of $220/day. A flood depth of 1.4m and a corresponding displacement length of 180 days results in $39,600 of displacement costs, as shown in Table 4 below.

Table 4: Displacement Living Expense Cost for Displacement Cost of $220/day

Flood Depth in Meters	Days of Displacement	Cost in Dollars (USD)
0.5	90	$19,800
1.0	135	$29,700
1.4	180	$39,600

By taking the sum of building damage costs, contents repair and replacement costs, and displacement accommodation costs, the total losses for a flood depth of 1.4m equal $78,000. The mitigation cost of retrofitting the house with a buoyant foundation is approximately $30,000, which includes the individual costs of vertical guidance posts, dock floats, marine plywood, and hurricane ties and fasteners. The loss avoidance ratio compares the cost of losses avoided to the mitigation cost:

[(Building Damage) + (Contents Losses) + (Displacement Costs)] : (Mitigation Costs of a Buoyant Foundation).

This is shown in Table 5, for flood depths relative to finished floor levels of 0.5m, 1m and 1.4m.

Table 5: Total Losses Avoided

Flood Depth in Meters	Total Losses Avoided in Dollars (USD)	Loss Avoidance Ratio (LAR)
0.5	$46,000	1.5
1	$62,400	2.1
1.4	$78,000	2.6

For a flood depth of 1.4m, the Loss Avoidance Ratio (LAR) is 2.6 ($78,000/$30,000). The LAR ranges from 1.5 to 2.6 for flood depths from 0.5m to 1.4m. These values indicate that installing buoyant foundations would be economically beneficial. In this case, for a flood depth of 1.4m, every $1 spent on flood mitigation through amphibious retrofits would avoid $2.60 of repair and displacement costs. The LARs, however, only measure the results of a single flood event. Since the buoyant foundation system requires little maintenance beyond periodic visual inspections, a buoyant foundation will continue to mitigate losses in subsequent floods with minimal further expenditures.

3.2. *Manitoba case study: Lake St Martin Reserve*

This section is a modification and summary of the results of the paper presented by Jason McMillan at the Second International Conference on Amphibious Architecture, Design and Engineering, held in Waterloo, Ontario, Canada, in June 2017 (McMillan et al., 2017).

Seasonal flooding is a natural occurrence that affects the Pinaymootang and Lake Saint Martin communities of the Interlake First Nations Reserve in central Manitoba. However, the implementation of water control infrastructure to manipulate flow rates for the benefit of urban areas elsewhere in the province has increased the severity of floods (Fig. 6) and resulted in the displacement of thousands of indigenous people who live near the lake (Ropel-Morski et al., 2015). The repercussions of massive displacements in 2011 continue to be felt today (Fig. 7).

Figure 6: Flooding in Manitoba during Spring 2011 (courtesy CBC)

Figure 7: Members of Lake St. Martin First Nation protest long-term displacement from their homes (courtesy CBC)

To conduct the loss avoidance study, the Buoyant Foundation Project proposed retrofitting a pre-existing house; the house could be either stick-built, prefabricated or premanufactured (Tramontini & English, 2015). This study analyzed the losses avoided for three Building Replacement Values (BRVs) of $70,000, $120,000, and $250,000, and three mitigation cost scenarios. The mitigation costs of installing amphibious retrofits can be estimated at roughly $100/m^2, $250/m^2 or $400/m^2, depending on the materials used and labor costs. Tables 6-8 below show the three categories of losses (building repair costs, contents losses, and displacement costs), for a 1-storey house with no basement and a BRV of $70,000, where the value of the contents is assumed to be 30% of the BRV. In Table 8, the displacement cost of housing and meals is calculated for an average household size of 3.8 people, resulting in approximately $180 USD per day (McMillan et al., 2017).

Table 6: Building Damage Repair Costs vs. Flood Depth for a 1-Storey House, no Basement, $70,000 BRV

Flood Depth in Meters	Percent Damage	Cost in Dollars (USD)
0	13.4	$9,400
0.5	32.1	$22,500
1.0	40.1	$28,100
1.4	47.1	$33,000

Table 7: Contents Damage Losses for Four Flood Depths for Contents Valued at $21,000

Flood Depth in Meters	Percent Damage	Cost in Dollars (USD)
0	8.1	$1,700
0.5	17.9	$3,800
1.0	22	$4,600
1.4	25.7	$5,400

Table 8: Displacement Costs for Average Household at $180/day

Flood Depth in Meters	Days of Displacement	Cost in Dollars (USD)
0	0	$0
0.5	90	$16,200
1.0	135	$24,300
1.4	180	$32,400

The study was expanded to investigate costs for a broader range of BRVs ($70,000, $120,000, and $250,000), and for three mitigation system cost (MSC) scenarios estimated at $100/m^2, $250/m^2 and $400/m^2. The cost of the retrofitted mitigation system depends on the choice of materials and how much of the labor is contributed by the homeowners. Assuming that the least expensive house is most likely to be retrofitted with the least expensive mitigation system, and likewise that the corresponding higher MSCs will be selected for the higher BRVs, those results, ranging from 0.8 to 16.9, are shown bolded in Table 9. The average of these LARs is 1.0 for a flood that just reaches the level of the finished floor, and for a flood of 1.4m in depth it is 5.1, meaning that the costs of damages and displacement from a single flood event would be more than five times the cost of the amphibious retrofit that could prevent these losses.

Since a loss avoidance ratio any greater than 1.0 indicates that the cost of the retrofit would be less than the sum of the building damage, contents damage, and displacement losses sustained in a single flood event, this study demonstrates the financial advantages of installing buoyant foundations on houses in the Pinaymootang and Lake St. Martin communities. Given the certainty of seasonal flooding on the Interlakes Reserve, the economic benefits of the amphibious retrofit will multiply over time.

Table 9: Loss Avoidance Ratios for Three Values of a 100m² House and Three Retrofit Mitigation Cost Scenarios

Building Value	Cost of Buoyant Foundation	Loss Avoidance Ratio			
Replacement Value in dollars (USD)	**Mitigation Cost in dollars (USD)**	**Flood depth of 0m**	**Flood depth of 0.5m**	**Flood depth of 1.0m**	**Flood depth of 1.4m**
$ 70,000	**$10,000 ($100/m²)**	**1.1**	**4.2**	**5.7**	**7.1**
	$25,000 ($250/m²)	0.4	1.7	2.3	2.8
	$40,000 ($400/m²)	0.3	1.1	1.4	1.8
$ 120,000	$10,000	1.9	6.1	8.0	9.8
	$25,000	**0.8**	**2.4**	**3.2**	**3.9**
	$40,000	0.5	1.5	2.0	2.5
$ 250,000	$10,000	4.0	11.0	14.1	16.9
	$25,000	1.6	4.4	5.6	6.8
	$40,000	**1.0**	**2.7**	**3.5**	**4.2**
Average of bolded LARs		**1.0**	**3.1**	**4.1**	**5.1**

4. Wind Vulnerability Analysis of Permanent Static Elevation

Permanent static elevation increases a building's vulnerability to wind because wind speed increases with height above the earth's surface (Fig. 8). For example, a house with a 4m mean roof height elevated to a 10m mean roof height experiences an 11% increase in wind speed at roof height, a 19% increase in wind pressure, and a 75% increase in expected annual insurable losses due to wind damage (English et al., 2015). This effect results in a significantly greater risk of damage during hurricanes and windstorms compared to houses without PSE (English et al., 2017). Houses permanently raised to higher elevations are more vulnerable to wind damage, thus requiring more frequent maintenance and repair. In comparison, an amphibious foundation maintains a house's proximity to the earth's surface, and even during a flood it remains close to the surface of the water, therefore avoiding exposure to increased wind forces. While houses in flood zones within the US are often

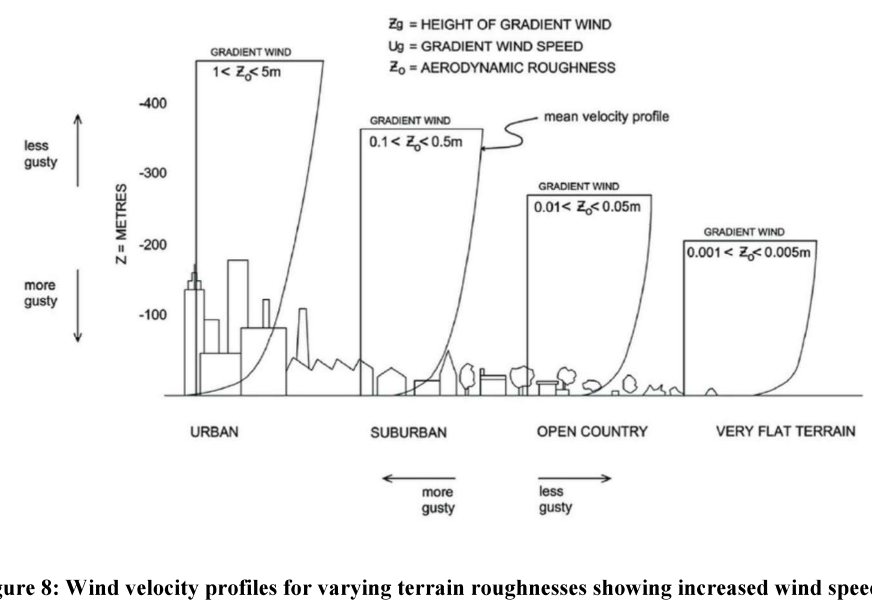

Figure 8: Wind velocity profiles for varying terrain roughnesses showing increased wind speeds with increased height above the ground (ASCE / Leighton Cochran)

elevated to comply with Federal Emergency Management Agency (FEMA) regulations, these studies demonstrate that they are considerably more likely to suffer roof damage from the higher wind forces that occur much more frequently than severe floods (Fig. 9). Buoyant foundation retrofits are a flood mitigation solution that avoids this significant drawback of permanent static elevation.

Figure 9: Houses with permanent static elevation with roof damage due to high winds (William Widmer; FEMA / Greg Henshall)

5. Conclusions

Buoyant foundations offer a solution for communities that face chronic or increasing exposure to flooding. This flood mitigation system provides a cost-effective and easily implemented disaster risk reduction strategy that promotes community resilience. The loss avoidance case studies for Leeville and Pinaymootang demonstrate that buoyant foundations are a highly effective solution for buildings that experience flooding, in most instances achieving loss avoidance ratios well above 1.0. Amphibious retrofits challenge the conventional flood mitigation method of permanent static elevation and provide a more flexible and sustainable strategy that responds directly and effectively to flooding.

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