

Impact of Flash Flood Loading on Unreinforced Masonry Structures

Shujahat Anwar^{1*}, Misha Sultana², Murad Ali³, Farhan Javed³, Ayesha Parveen⁴

¹College of Civil and Transportation Engineering, Shenzhen University, Shenzhen, China

²NED University of Engineering and Technology, Karachi, Pakistan

³Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), University of Bologna, 40136, Bologna, Italy

⁴National University of Technology (NUTECH), 44000, Islamabad, Pakistan

DOI: <https://doi.org/10.36348/sjce.2026.v10i02.001>

| Received: 15.12.2025 | Accepted: 11.02.2026 | Published: 26.02.2026

*Corresponding author: Shujahat Anwar

College of Civil and Transportation Engineering, Shenzhen University, Shenzhen, China

Abstract

Unreinforced masonry (URM) structures in less developed areas are at great risk from the rapid flow of water resulting from flash floods. This study investigates how susceptible unreinforced masonry walls are to the loads produced by flash floods via testing, simulating, and gathering field measurements of existing URM structures. Rather than simulate everything on the computer, the study compiled and reviewed published documents that reported results pertaining to performance trends of different wall configurations, as well as slenderness ratio, strength of mortar, and other boundary conditions, and developed an understanding of performance trends among URM walls. The earliest damage begins with the combined action of hydrostatic and hydrodynamic pressure, which has the greatest effect on slender walls with weak mortar. Walls that contained more reinforced concrete or brick demonstrated better performance, with longer crack propagation before catastrophic failure and higher critical flow rates before cracking. The assessment of fragility determined that the likelihood of a catastrophic failure increases greatly when the water flow velocity exceeds a certain threshold, and that how the structure is designed (geometry) and what it is made of (material quality) are two of the key factors in determining the likelihood of failure during a flash flood event. The results of this study indicate the need to develop new methods for designing and selecting retrofitting systems that will improve the level of flood resistance for masonry structures in areas susceptible to flooding.

Keywords: Unreinforced masonry (URM), Flash floods, Structural, Hydrodynamics loading, Finite element modeling.

Copyright © 2026 The Author(s): This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY-NC 4.0) which permits unrestricted use, distribution, and reproduction in any medium for non-commercial use provided the original author and source are credited.

1. INTRODUCTION

Natural disasters like floods have led to the loss of human lives and immeasurable impacts, including damage to urban areas affecting both buildings and infrastructure, significant economic losses, and challenging reconstruction efforts. In recent decades, the assessment of vulnerability and risk in urban areas facing extreme flood conditions has become a burgeoning area of research, particularly as severe flood events have resulted in disasters and extreme stress on these areas [1], [2]. In recent times, there has been a significant rise in the number and severity of hydro-meteorological disasters, which cause infrastructure mainly in flood-prone areas to be questioned and their resilience tested. Among all the types of flooding, flash floods are the most damaging ones because of their very quick occurrence, fast development, and great destructive power. Flash floods, unlike river or seasonal floods that are almost or completely without warning, are mainly caused by heavy

rain, the burst of a dam, or the unrestrained release of water from the upper region. Their dynamic character, wherein an instantaneous rise in water level and high transport of debris occur, involves extreme risks to both structural integrity and human life, especially in mountainous and densely populated areas, where topography intensifies the flow dynamics. One of the most important benefits of flash flooding is that it creates an increasing number of financial losses and, devastatingly, the loss of physical structures across the world. Evidence from several flash flood events in recent months illustrates clearly the need to design our infrastructure to accommodate the unexpected and intense forces of water. A critical aspect of flash flood risk needs to include debris flow hazard evaluation because this phenomenon generates sudden, intense forces that standard structural analysis methods fail to identify. The debris, which contains vehicles, logs, and sediment, raises both the flow density and strength,

which causes immediate wall collapses through the impact of punch-through failures. [3].

The primary focus in areas affected by earthquakes and floods revolves around understanding how unreinforced masonry (URM) buildings respond to these situations. Nevertheless, URM structures, being cheaper and using local resources and construction

techniques, are still the preferred mode of building in low and medium-high-density urban areas, especially in poor countries. The URM systems lack high structural ductility and reinforcement, resulting in their extreme vulnerability to seismic and flood lateral loads. The URM system walls lack sufficient structural ductility and reinforcement, which makes them highly vulnerable to lateral loads from earthquakes and floods [4].

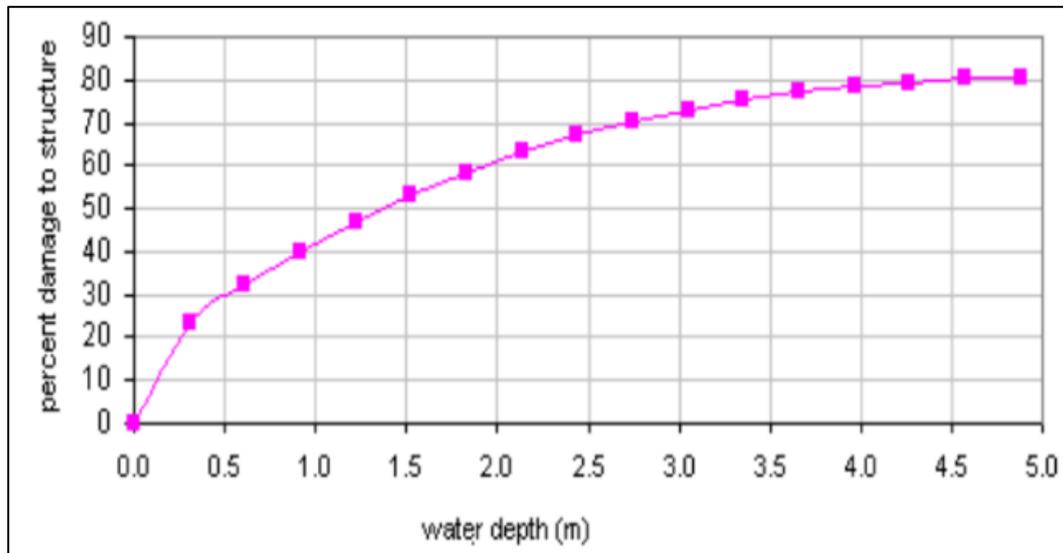


Figure 1: Example of damage curves as function of the flow depth

Recent experimental investigations and in-situ testing emphasize the exposure of these structures to multi-hazard conditions. The collapse of the whole building can happen due to damage to any one load-bearing wall that is directly exposed to flood flow, as shown in **Figure 1**. These research findings demonstrate the urgent need to assess URM building hydrodynamic performance and create design standards that boost their resistance capabilities. The low tensile strength, weak wall-to-roof joint, and brittleness of URM structures considerably reduce their energy dissipation capacity under dynamic stress. These structures typically lack proper reinforcement, are built using weak mortar, and often exhibit poor connection between walls and roofs or floor systems [5]. Flood scenarios pose a huge risk for masonry since they are characterized by a lack of ductility, low tensile strength, and brittleness, which contribute to poor energy absorption and very fast deterioration of structures during and after the dynamic or prolonged hydraulic forces. Therefore, it is very important to study the flow vulnerability of these structures. The low tensile strength of unreinforced

masonry (URM), which is generally between 0.1 MPa and 0.8 MPa depending on the mortar quality, makes the material very susceptible to the out-of-plane bending moments that are caused by the lateral flood pressure. This out-of-plane failure mechanism is different from in-plane shear failures that are frequently examined in seismic evaluation, and is the primary cause of total collapse during floods [6].

2. LITERATURE REVIEW

For many centuries, the impact of flooding on structural stability was regarded as short-lived and minor. Therefore, the impact of floods was grossly underrated in structural design standards and hazard assessments. Conventional engineering education has prioritized seismic vulnerability of Unreinforced Masonry (URM) structures over special and extreme flood loads, including hydrostatic pressure, hydrodynamic force, and impact due to buoyant debris [4].

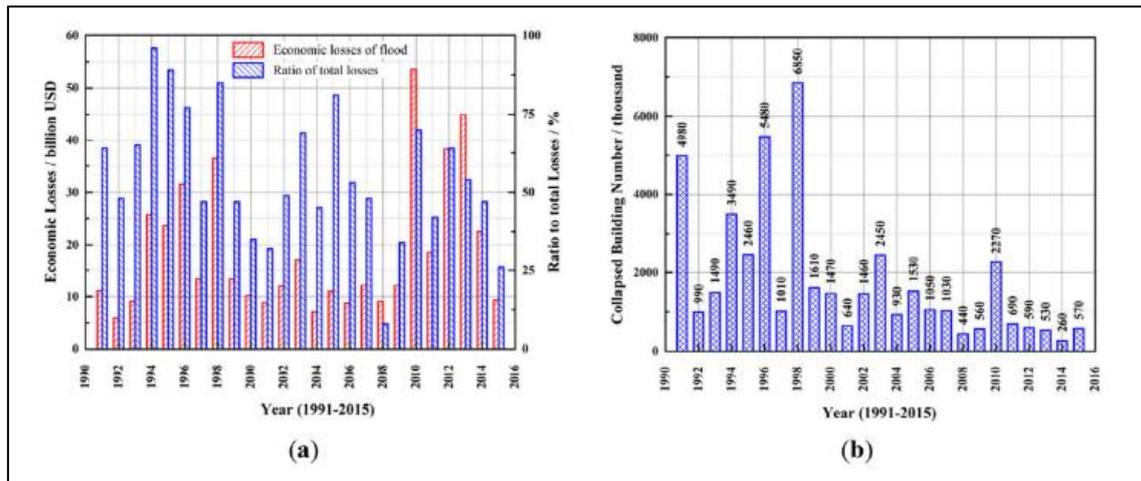


Figure 2: Economy and building losses caused by flooding in China from 1991 to 2015 (a) economy loss caused by flooding and its ratio to the total loss caused by disasters (b) collapsed buildings caused by flooding

This is all the more significant considering the accelerated frequency and magnitude of flash flooding under the impacts of climate change and urbanization [7]. Flash floods, for example, are highly complex and multi-directional in their stresses on facades of buildings and cause concurrent vertical and horizontal bending of URM walls. Combined stresses have been shown to create brittle modes of failure, particularly in rural structures that were not reinforced adequately. Literature has established the principal mechanisms of failure under such loading, namely, out-of-plane bending, overturning, and collapse of the walls, each of which is aggravated by the presence of low-grade mortar or suboptimal inter-block connections [8]. Computational and analytical modeling techniques used historically for masonry structures have included substantial simplifications. Although some finite element (FE) calculations consider the tensile properties of masonry, the majority continue to model masonry as a continuous and homogeneous material, thus overlooking its inherent heterogeneity and laminar nature. Practically, URM systems fail by disaggregation, where blocks lose all cohesion, which is a failure mode insufficiently covered in existing codes and literature [9], [10].

In Turkish provinces such as Sanliurfa and Adiyaman, large-scale failure of masonry structures was noted, especially those directly exposed to water flows or hit by floating objects. Such examples in Australia, China, and South Asia warrant the reason why URM buildings tend to be the weakest point in disaster-hit areas [11], [12]. In China, a 25-year analysis came out with the fact that from 1991-2015, an average of 1.79 million buildings collapsed because of flood annually, whereas economic loss averaged \$18.6 billion USD per year, which is shown in **Figure 2** [5], [13].

Even though mapping of flood hazard and demarcation of risk areas have evolved, conversion of hydraulic loads to predictive statements of structural response for URM structures is still limited. Analytical

methods like yield line theory or elastic beam models are used in most studies, which simplify the structural response in its constituents and don't account for nonlinearities due to material deterioration or interaction of dynamic loads [14], [15].

Specifically, the yield line approach involves a linear kinematics analysis, modeling walls as rigid blocks with predetermined crack patterns that result in failure through overturning or bending collapse mechanisms. This mechanism is evaluated using the virtual work principle, which compares the stabilizing moments provided by the wall's weight and any axial loads applied to the wall against the overturning moments generated by flow actions on the wall. The majority of research depends on two approaches, which include basic analytical models through yield-line theory and deterministic methods that ignore flood event probabilities and structural variability [16], [17]. On the other hand, Real-life scenarios present multiple unpredictable elements, which include wall material characteristics and boundary conditions, structural design and debris movement, and flash flood unpredictability that causes complex structural reactions.

Advancements in Finite Element Methods have led to an improvement in model accuracy by incorporating strain-rate effects, anisotropic behavior, and no-tension assumptions for the masonry material [18]. Several researchers have reported a rise in temporary strength due to the high strain-rate conditions, which was measured by the Dynamic Increase Factor (DIF). The models denote wall slenderness ratios as decisive factors, where taller walls are at higher risk of failure caused by sudden hydrodynamic loads, whereas thicker walls can withstand the collapse but are at risk of getting submerged for a long time.

Deterministic models, nonetheless, are frequently incapable of reflecting the complete variability and uncertainty tied to real-world flood

situations, hence drawing researchers to investigate probabilistic methods like fragility curves. To equate probabilistic hazard assessment and structural performance modeling, the researchers suggested collapse fragility curves, which indicate the conditional probability of a structure undergoing failure provided that the "hazard demand" imposed has exceeded the "hazard capacity" of the structure. These curves, derived from parametric finite element (FE) analyses and logistic regression models, establish a probabilistic function between flood parameters, including depth, velocity, impact force, and structural collapse probability [17]. Although they can be effective for emergency planning, insurance risk modeling, and retrofit prioritization, they are highly reliant on high-fidelity validation, which is presently constrained by the scarcity of full-scale experimental data.

Experimental research supplements simulation-based methodologies with background information. [12], for instance, suggested amended failure criteria for three- and four-edge restrained walls based on yield-line and fracture energy approaches, following experience gained from the 2020 Damawu Gully flash flood. Their studies revealed the significant influence of the self-weight of walls, mortar cohesion, and detailing of reinforcement in resisting failure delay. Ring beam addition during the construction process and the use of high-grade mortar were recognized as effective countermeasures, but inadequate for high-intensity flow action.

Other studies have demonstrated that flood-resistant design is no longer possible using greater mortar strength or greater wall weight. Rather, hybrid methods, which integrate traditional masonry with contemporary reinforcement systems, such as RC tie beams, vertical confinement, and reinforced columns, significantly increase resistance by lowering lateral load distribution and crack development [5].

Apart from that [19], encapsulated the principal parameters determining the performance of masonry walls under floods. They are hydrostatic and hydrodynamic pressure, buoyancy, erosion, impact from drifting debris, and chemical degradation due to prolonged water exposure. Among them, lateral hydrostatic loads and water contact are still the most catastrophic.

Despite greater recognition of these risks, quantification of URM behavior under flood loading is scattered. The current study adopts a comparative synthesis of literature approach and integrates results from analytical, numerical, and empirical domains to yield a comprehensive view of the behavior of URM when poured with water. The research mainly focuses on the area of identifying weaknesses in the structures, evaluating the widely used prevention methods, and proposing more areas for study to improve the

adaptability of the places safeguarded from the recurring problem of flash floods.

2.1 Detailed Characteristics of Flood Loading

Accurate structural vulnerability assessment requires that the flood load does not act as a single force; it is an aggregate of different actions that take place at the same time and one after another:

- **Hydrostatic Pressure:** This is a static force that grows linearly at water depth. It is the continuous lateral pressure that acts on the submerged wall, and its primary influence is to create a significant bending moment that is countered by the wall's self-weight and flexural capacity.
- **Hydrodynamic Pressure (Drag Force):** This is a dynamic load that is proportional to the square of the velocity of the flow, i.e., V^2 . It means the transfer of momentum from the water to the structure, which is usually the decisive factor for flash floods with high flow rates. The instant action of this force plays a significant role in the high-strain-rate effects noticed in the dynamic models.
- **Debris Impact Load:** This short-term, sporadic load is the result of floating materials (e.g., cars, logs, containers) colliding with the structure. The force is difficult to model, but its effects may be represented through a static load that has the same magnitude, or as a dynamic impulse that lasts for a very short time, which normally leads to either minor damage or, importantly, the collapse of a wall under hydrostatic pressure that has already been stressed. The use of advanced numerical methods, such as the Coupled Eulerian-Lagrangian (CEL) method or the Structured Arbitrary Lagrangian-Eulerian (S-ALE) solver in explicit finite element platforms, is required to obtain an accurate representation of the interaction between the fluid and the structure, as well as the high-speed impact [6].

2.2 Advancements in Structural Modeling and Fragility Assessment

Moving past traditional analytical methods, such as simplified yield-line theory that presumes linear kinematics and failure by rigid blocks, has led to the adoption of quite advanced numerical procedures.

- **High-Fidelity Numerical Modeling:** Micro-modeling, which distinguishes each brick and mortar joint with different finite elements, makes it possible to present explicitly the anisotropic and heterogeneous character of the masonry and to directly observe its failure modes like joint crushing and interface sliding. Macro-modeling, on the other hand, characterizes the masonry as a non-linear equivalent continuum that offers computational efficiency of full-scale building analysis.

Selecting the proper model is essential as macro-models might fail to detect the localized impact of hydrodynamic and impact loads, hence might underestimate the effects.

- **Performance-Based Fragility:** Fragility analysis has developed from basic failure threshold analysis into a fundamental evaluation method for assessing flood resistance through performance-based approaches. These models, which can be derived empirically from observed damage, analytically from simplified mechanics, or numerically from extensive FE simulations, link a single hazard intensity measure (IM) like flow velocity to a probabilistic measure of damage or collapse. The research regarding masonry structures primarily focuses on three main Intensity Measures (IMs), which include flood depth (H) and flow velocity (V), and their combined effect (H. V). The flow velocity (V) stands out as the most important factor for URM

structures because it generates hydrodynamic forces that affect these buildings. The output displays a log-normal cumulative distribution function, which serves three essential purposes for urban development planning, insurance risk assessment, and retrofitting program implementation in vulnerable areas [3].

3. RESEARCH METHODOLOGY

This research conducts a comparative analysis of how unreinforced masonry (URM) structures perform when flash floods happen. The study evaluates URM wall types through experimental data, numerical modeling, and field research to determine their performance characteristics and failure points under various flood loading conditions.

3.1 Selection of URM Wall Typologies for Analysis

Table 1: URM wall Typologies selected for comparative analysis

Wall Typology	Dimension (H*L*t)	Slenderness Ratio (H/t)	Boundary Conditions	Material Properties
Type A: Single-wythe slender wall	2.4mx4.0mx0.1m	24.5	3-edge fixed	Clay bricks, weak mortar (2-5 MPa)
Type B: Double-wythe medium wall	2.4mx4.0mx0.2m	12	4-edge fixed	Concrete blocks, medium mortar (5-10 MPa)
Type C: Solid URM Robust Wall	2.4mx4.0mx0.3m	8	4-edge fixed	Solid bricks, strong mortar (10-15 MPa)

The literature review identified three main URM wall typologies, which served as the basis for comparative analysis. The typologies represent the most frequent building methods used in flood-prone areas throughout the world. The characteristics of selected wall typologies are summarized in the **Table 1**.

This selection includes all standard slenderness ratios with boundary conditions that exist in practice for complete vulnerability evaluation.

3.2 Flood Loading Parameters and Simulation Data

The parameters for flood loading analyzed in this report are the results obtained from laboratory experiments and computer simulations that have been thoroughly validated. The applied loads follow the standard flash flood patterns, which previous research has documented. **Table 2** presents the main loading parameters which form the basis for the comparative assessment.

Table 2: Flood Loading Parameters and Simulation Data

Loading Condition	Pressure Range (kPa)	Duration/Application	Velocity Range (m/s)	Source study
Hydrodynamic Impulse	5-25 kPa	0.5-2.0 seconds	2-5 m/s	[19]
Hydrostatic Pressure	10-40 kPa	Gradual (1-4 hours)	-	[20]
Combined Loading	15-50 kPa	Sequential application	2-4 m/s	[21]

The given pressure ranges are associated with flow velocities of 2-5 m/s and water depths of 0.5-2.0 m, representing less than moderate to severe flash flood conditions.

The comparative assessment considers the structural performance, which is adversely affected by significant parameters taken from the literature. The weaknesses and strengths of different URM types are qualitatively evaluated through these parameters. The performance metrics are summarized in

3.3 Performance Assessment Parameters

Table 3.

Table 3: Key Performance Parameters for Vulnerability Assessment

Performance Parameter	Type A wall	Type B wall	Type C wall	Assessment Method
Critical Flow Velocity	2.0-2.5 m/s	2.5-3.5 m/s	3.5-4.5 m/s	Yield- line analysis
Critical Flow Depth	0.5-0.8 m	0.8-1.2 m	1.2-1.8 m	Virtual work method
Failure Initiation Time	30-60 seconds	60-120 seconds	120-300 seconds	FE Simulation data
Crack Propagation	Rapid, brittle	Moderate	Slow, controlled	Experimental observation

3.4 Material Properties Data Compilation

The properties of the materials used in the analysis were obtained from the experimental studies of masonry elements. These values reflect the usual

characteristics of URM structures situated in flood-risk areas. The adopted properties are summarized in Error! Reference source not found..

Table 4: Material Properties for URM Components

Material Property	Weak Masonry	Medium Masonry	Strong Masonry	Test Standards
Compressive Strength	2-5 MPa	5-10 MPa	10-15 MPa	ASTM C67
Tensile Strength	0.1-0.3 MPa	0.3-0.5 MPa	0.5-0.8 MPa	ASTM C1006
Modulus of Elasticity	1000-3000 MPa	3000-5000 MPa	5000-8000 MPa	ASTM C469
Fracture Energy	30-80 N/m	80-150 N/m	150-250 N/m	RILEM Standard

3.5 Analytical Framework Implementation

The overall goal of the research is to present a systematic process for assessing the vulnerability of unreinforced masonry (URM) walls under flooding conditions, and therefore, a four-step analysis has been developed. The first step of the process involved evaluating the different types of URM wall configurations identified from case studies by analysing the modes of failure associated with each configuration type due to exposures to flood loads; different forms of collapse were observed with respect to the various URM wall configurations tested.

Step 2 involved defining the most important flood characteristics that were responsible for causing the collapse of the URM wall structures; these characteristics were determined through a review of the findings and analysis of nearly twenty (20) previous studies conducted on this topic. Since the majority of URM wall structures are constructed using multiple layers of brick, the flow rates and heights of the floodwaters that caused the initiation and spread of damage to the various bricks used in the construction of the URM walls were identified.

Step 3 consisted of a systematic risk ranking of the URM wall configurations based on a comparative scale developed using multiple resilience indicators, including loading capacity, deformation behaviour, and the patterns of the chain reaction of wall failure that were reported in many of the twenty (20) studies reviewed.

The final step of the analytical process was to evaluate the effectiveness of the various methods of retrofitting the URM wall configurations; to accomplish this, the documented performances of the different strengthening methods were examined and compared in order to determine the best protection methods for each URM wall configuration under flood conditions.

3.6 Data Validation and Quality Assurance

We have employed multiple verification methods to ensure our data's reliability. Confirming duplicate failure mechanisms and performance data was achieved by cross-referencing the results produced by independent studies.

We validated laboratory results by comparing the same results in an independent laboratory with evidence from real-world applications. The relationship between academic conclusions and actual flood damage confirmed that the academic conclusions corresponded to the actual behavior of structures.

We verified the predictive models by performing correlation analyses on both experimental and numerical data. To confirm the accuracy of the predictive models, correlation analysis of experimental and numerical data was conducted. By this step, it was proved that the simulation results were in accordance with the empirical findings throughout the different research methods.

Rigorous source verification ensured that all data were drawn from peer-reviewed publications. Each source's methodology was scrutinized in a critical approach in order to keep high-quality standards applied to the whole analysis.

3.7 Limitations and Assumptions

- **Variability in data across experiments:** The differences in specimen sizes and testing methods employed by different researchers created inconsistencies, which in turn, limited the direct comparability of the results.
- **Simplified loading conditions:** In laboratory tests, the researchers usually applied simplified loading patterns; however, real flood events generated

complex forces in multiple directions with varying intensity, and hence, they could not be simulated.

- **Assumption of uniform material properties:** Numerical models generally assumed homogeneous masonry characteristics, despite significant variations in actual construction materials.
- **Limited long-term durability insights:** The majority of the investigations have been limited to the study of one-time floods and hence, the issue of the cumulative impact of repeated flooding remains largely unaddressed.

- **Scale effects in laboratory models:** Small-scale experiments could not simulate the behavior of the full-scale structures subjected to real flood conditions.

The given systematic procedure not only ensures a complete evaluation but also supports the scientific nature of the process through in-depth comparison and validation of the data.

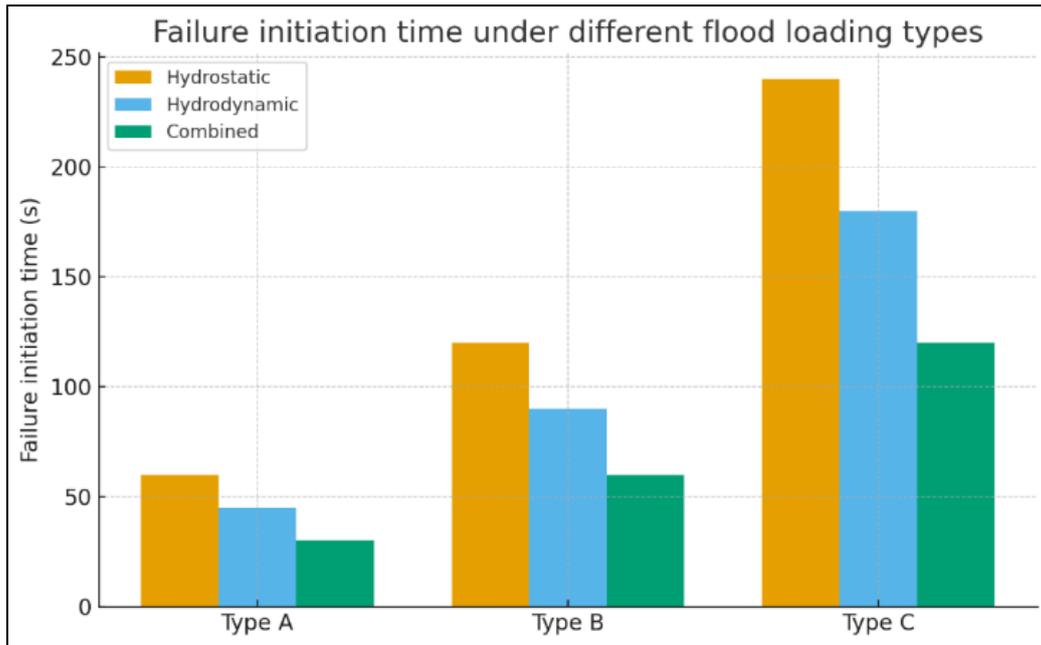


Figure 3: Failure initiation time under different flood loading types

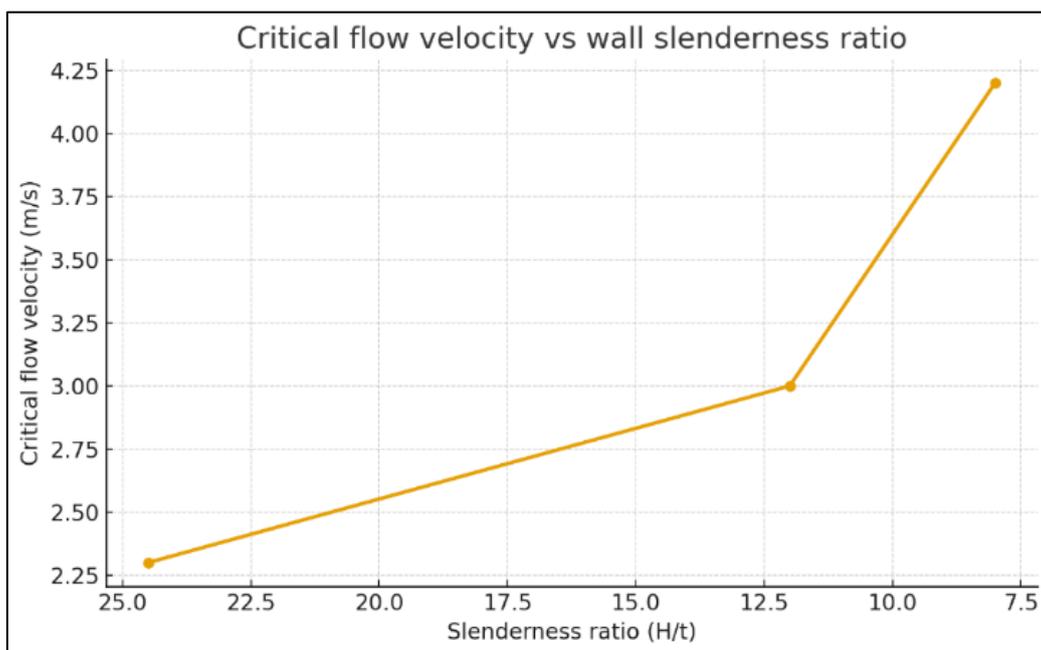


Figure 4: Critical flow velocity vs wall slenderness ratio

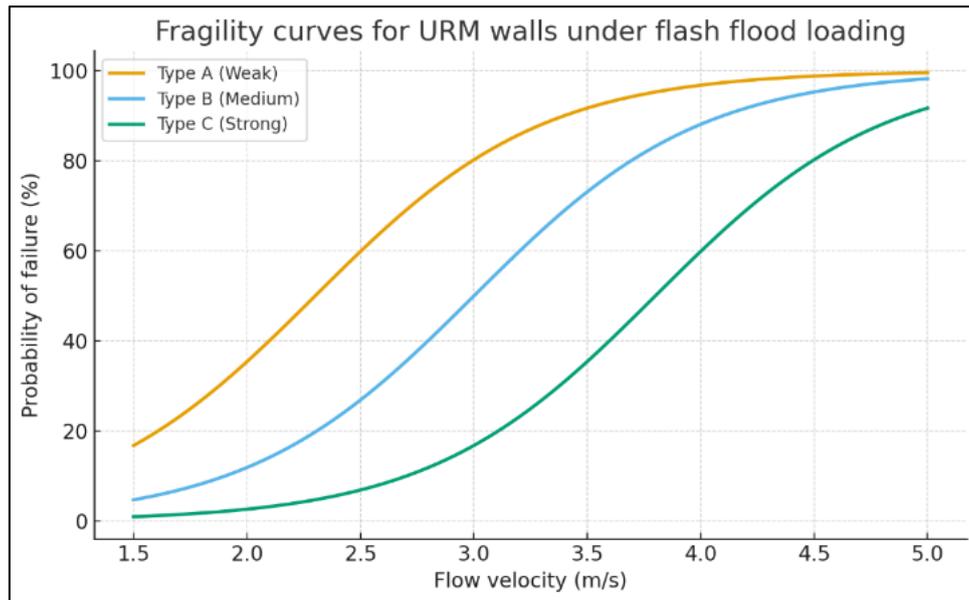


Figure 5: Fragile curves for URM walls under flash flood loading

4. RESULTS AND DISCUSSIONS

This chapter analyses how unreinforced masonry (URM) walls handled different flood loads. The focus is on three key points: when the wall first cracks, the water speed that causes failure, and the chance of collapse. The data and the charts show the effect that wall thickness, mortar strength, and support conditions have on the response. Results are compared to see how flood pressure and material strength change the behavior, service life, and failure pattern of the wall types.

4.1 Evaluation of Structural Response and Failure Initiation

The comparison of different URM wall types under various loading conditions. **Figure 3** shows a strong link between the types of loading and the way failure begins. Under hydrostatic loading, all wall types failed later because the pressure was applied gradually and moved evenly. While hydrodynamic loading led to faster crack formation and stress concentration in certain areas, combined flood loading, closer to real-life conditions, caused failure to start the earliest.

Type A masonry wall was the first to go, collapsing in approximately 30-45 seconds under the combined load of the flood. This indicates that slender walls with poor bonding are very susceptible to the sudden flow forces. The Type B Walls were able to withstand moderate impacts, while the Type C Walls (made from a stronger mortar mix with less slenderness) were able to withstand the same conditions for significantly longer periods before collapsing. These results suggest that thicker masonry and stronger mortar provide the greatest resistance to sudden shocks caused by hydraulic forces, consistent with previous research indicating that hydrodynamic impacts are the major contributor to the instability of unreinforced masonry structures during flash floods. The results also

demonstrate the importance of boundary conditions on the time of collapse. Walls anchored on all four sides survived almost twofold longer before collapse than walls anchored on three sides, thus demonstrating better stiffness and load redistribution. Adding confinement elements like ring beams could therefore further improve performance under flood pressure. The observed rapid failure under combined loading is mechanically linked to the wall's out-of-plane flexural capacity. The initial hydrostatic pressure reduces the effective compression across the mortar joint at the toe of the wall, lowering its resistance to bending. Subsequently, the hydrodynamic impulse introduces a high-frequency excitation, effectively exceeding the now-reduced moment of resistance and leading to sudden, brittle collapse. This failure mode is characteristic of a low moment capacity, which is inherent to slender, weak-mortar URM walls (Type A) [22].

4.2 Relationship between Wall Geometry and Flow Resistance

Figure 4 shows the link between the wall slenderness ratio and critical flow velocity. The results make it clear that the wall's geometry is recognized as the main variable affecting the resistance ability. Type A walls, with the highest slenderness ratio ($H/t=24.5$) and thus most affected by this factor, were the first to be breached by water at the lowest rates of about 2.3 m/s, which is a clear indicator of their inability to hold back the strong lateral forces exerted by the water. Types B and C, with significantly lower slenderness ratios of 12 and 8, were more withstandable and resilient, and they even held up to flow velocities of approximately 4.2 m/s before their failure.

This demonstrates that fatter walls with lower slenderness ratios have larger moments of inertia and thus can resist more bending and overturning forces from

floods. the larger walls eventually reached their limit and broke due to out-of-plane bending after a long saturation period. Hence, it was proved that just geometry is not sufficient; material strength and confinement have to be improved to obtain better performance.

These results agree with [14], who also found that masonry walls with lower slenderness ratios are stiff and more stable against hydrodynamic loads. The present study confirms that optimizing wall geometry can delay damage and increase flood resilience in masonry structures. This protective effect of lower slenderness (higher thickness, t) is mathematically explained by the relationship between wall thickness and the lateral moment of resistance. The self-weight and stress distribution through the wall's depth primarily determine the wall's failure threshold. Increasing the thickness from 0.1m (Type A) to 0.3m (Type C) significantly increases the moment of inertia and thus the wall's capacity to resist the maximum bending moment induced by the lateral flood pressure. However, the ultimate failure observed in Type C walls due to out-of-plane bending confirms that even walls designed for seismic robustness lack the necessary specific detailing (e.g., waterproofing and confinement) required for extreme flood conditions [23].

4.3 Failure Probability and Fragility Assessment

Figure 5 presents the fragility analysis of wall performance through a probabilistic assessment of wall failure for different wall types due to increased flow velocity. The results demonstrate that the most susceptible wall type is Wall Type A, with a near 90% to 100% chance of failure at relatively low flow velocities (slightly greater than 3 m/s).

Wall Type B represents a mid-range of wall failure resistance. The failure probability for Type B is much more gradual than that of Type A at increasing flow velocities.

The failure probability for Wall Type C increases considerably, also providing a reliable means of wall support until approximately Flow velocity measurements reach 3.8 m/s.

The differences in the curve slopes for the various wall types illustrate that increased mass in combination with a decreased slenderness ratio delays not only the onset of failure but also maintains material stability against dynamic water pressure.

The steep incline observed for the Type A curve is due to the brittle nature of the material, due to inadequate bonding between the weak mortars, and introducing dynamic loads to the wall through water, resulting in rapid and continuous crack propagation; ultimately leading to an ultimate state of failure when the structural force exceeds that required for stability.

The data presented correlate with the work of Moaiyedfar and Deniz (2025), who reported that flow velocity is one of the main contributors to greater risk for flood-related failures. The fragility curves created during this research can be used to assess the probability of wall response to flood conditions and can help engineer plans for retrofitting or building new structures that will withstand floods in high-risk zones.

4.4 Implications for Structural Safety and Resilience

The combination of all results in figures 3 through 5 shows that URM wall performance from floods is primarily a function of three basic factors: Material Strength, Geometry, and Type of Loads. While URM walls built of stronger materials have additional time until failure compared to those of weaker material and also URM walls built of thicker (greater) geometry will have extra time until they fail, However, None of the wall types could sustain the flood loads continuously or repeated, This suggests the need for Flood Resiliency Strategies such as reinforcing Concrete Tie Beams, Improved Mortar Mixes and External Confinement Systems on Masonry Walls for Improved flood resistance against future events and damage to the building structures due to flash flooding.

In addition, the research also indicates that Future Building Codes for URM Structures need to include Hydrodynamic and Debris Impact in addition to Hydrostatic Pressure and/or Loading. As such, just as Earthquake-Resistant Design requires the use of Performance-Based Philosophy towards Building Codes, Flood Resiliency requires a Performance-Based Approach to Building Codes as well. Similar to Earthquakes, the Performance-Based Design approach towards Flood Resilience must take into account all the Various Levels of Damage Stages of the Structure.

In general, four major states are identified for flood assessment: the first state is Negligible Damage (Immediate Occupancy) which corresponds to no loss at all; the second is Moderate Damage (Requires repair, Life Safety) representing some loss of utility and risk to life; the third is Severe Damage (Extensive repair, Collapse Prevention) reflecting that the structure cannot be used and that there is a need for preventive measures against the possible total loss; the fourth and final state is Collapse (Total loss) meaning that nothing is left of the structure. By correlating the critical flow velocity (Figure 4) and the probability of failure (Figure 5) with these damage states, the engineers can define the minimum acceptable wall typology (A, B, or C) required for a structure to sustain a given performance level under a specified flood return period [23].

4.5 Advanced Retrofitting Strategies for Enhanced Resilience

Given that a large fraction of the worldwide building stock is made up of unsafe Type A and Type B unreinforced masonry (URM) structures, it is usually the

only reasonable option to enhance resilience by retrofitting. Proper methods to do so should mainly concentrate on the resistance to bending and shear of the walls that are out of the plane. Along with that, they need to deal with the material saturation and degradation problem as well.

- **FRP/TRM Confinement:**

The application of Fiber Reinforced Polymer (FRP) or Textile Reinforced Mortar (TRM) jackets to the exterior of URM walls is highly effective. These composite materials not only make the building walls pretty much stronger but also considerably more flexible by the passive support of the jackets, thus, along with the wall's flexural and shear capacity, the brittle failure mode is turned into a ductile one. Different tests carried out have shown that the lateral load capacity of URM walls can be increased through wrapping with FRP by more than 50%, and so on it usually makes such walls able to bear flow velocities which are much greater than 5 m/s.

- **RC Tie-Beam and Column Systems:**

Integrating the URM wall with reinforced concrete (RC) tie-beams at the floor and roof levels, and RC columns at corners, transforms the wall into a confined masonry system. This approach fundamentally changes the load distribution mechanism, ensuring that the lateral flood forces are transferred to the vertical and horizontal confining elements, which possess significantly higher ductility and strength than the unreinforced panel. This system is particularly effective in preventing the global overturning failure mechanism observed in Type A walls.

- **Chemical Grouting and Coatings:**

Besides the structural strengthening, the durability and water-resistant quality of the masonry is crucial. The application of chemical grouting into the mortar joints not only enhances the strength but also increases the cohesion and stiffness of the masonry, while the external application of hydrophobic coatings can greatly cut down the water ingress and the associated saturation-induced strength loss. While these methods do not prevent ultimate structural failure, they are cost-effective measures to delay the onset of damage and protect the material over the long term [23].

5. CONCLUSIONS

The study shows that unreinforced masonry (URM) walls respond differently to flash-flood loading depending on material strength, wall geometry, and boundary conditions. Walls with lower slenderness ratios and stronger mortar performed better under both hydrostatic and hydrodynamic forces. The combined flood loading situation is proven to be the most crucial, causing the wall to fail much quicker than with just hydrostatic or hydrodynamic forces acting upon it, particularly in slender Type A walls. The derived fragility curves confirm that flow velocity is the

dominant hazard parameter, and there is a direct correlation between improved material quality (Type C) and reduced failure probability. The results presented in figures 3, 4, and 5 demonstrate that flood performance for URM walls is based on the three basic properties of Material Strength, Geometry, & Load Type. URM walls constructed of higher strength materials can endure longer before failure, versus URM walls constructed of lower strength materials, and URM walls constructed with thicker (larger) geometry will also endure longer prior to failure, versus URM walls of thinner (smaller) geometry. However, all URM wall types were unable to support continuous or repetitive loads impacting them during a flood. Therefore, it is vital to develop Flood Resiliency Strategies that can include enhanced integration of Concrete Tie Beams, improved Mortar Mixes, & External Confinement Systems on URM Walls in order to improve flood resistance to the threat of future flooding events/damage to buildings resulting from flash flooding events.

Additionally, the findings of this research indicate that the Building Codes of the Future must encompass Hydrodynamic & Debris Impact loading (forces) in addition to Hydrostatic Pressure loading/forces for URM buildings. Building Codes must follow the Performance-Based Philosophy approach described within Earthquake-Resistant Design when defining their Flood Resiliency Performance-Based Design approach. The Flood Resilience Performance-Based Design approach will also necessarily need to take into account the Various Levels (Stages) of Damage that could occur as a result of floods occurring to URM buildings.

REFERENCES

1. R. Custer and K. Nishijima, "Flood vulnerability assessment of residential buildings by explicit damage process modelling," *Nat. Hazards*, vol. 78, no. 1, pp. 461–496, Aug. 2015, doi: 10.1007/s11069-015-1725-7.
2. P. Lonetti and R. Maletta, "Dynamic impact analysis of masonry buildings subjected to flood actions," *Eng. Struct.*, vol. 167, pp. 445–458, July 2018, doi: 10.1016/j.engstruct.2018.03.076.
3. F. Greco and P. Lonetti, "Vulnerability Analysis of Structural Systems under Extreme Flood Events," *J. Mar. Sci. Eng.*, vol. 10, no. 8, p. 1121, Aug. 2022, doi: 10.3390/jmse10081121.
4. W. W. El-Dakhkhni, A. A. Hamid, Z. H. R. Hakam, and M. Elgaaly, "Hazard mitigation and strengthening of unreinforced masonry walls using composites," *Compos. Struct.*, vol. 73, no. 4, pp. 458–477, June 2006, doi: 10.1016/j.compstruct.2005.02.017.
5. S. Xiao, N. Li, and X. Guo, "Analysis of flood impacts on masonry structures and mitigation measures," *J. Flood Risk Manag.*, vol. 14, no. 4, p. e12743, Dec. 2021, doi: 10.1111/jfr3.12743.

6. Q. Fang, S. Liu, G. Zhong, H. Zhang, J. Liang, and Y. Zhen, "Nonlinear Simulation and Vulnerability Analysis of Masonry Structures Impacted by Flash Floods," *Shock Vib.*, vol. 2021, no. 1, p. 6682234, Jan. 2021, doi: 10.1155/2021/6682234.
7. S. L. Platt *et al.*, "Improving the lateral load resistance of vernacular masonry walls subject to flooding," *Proc. Inst. Civ. Eng. - Constr. Mater.*, vol. 176, no. 3, pp. 94–105, May 2023, doi: 10.1680/jcoma.20.00004.
8. A. Bouyahyaoui, S. Elmalyh, and T. Cherradi, "Behaviour of masonry walls reinforced by fiber reinforced polymers," *Mater. Today Proc.*, p. S2214785323035939, June 2023, doi: 10.1016/j.matpr.2023.06.197.
9. P. Foraboschi, "Masonry does not limit itself to only one structural material: Interlocked masonry versus cohesive masonry," *J. Build. Eng.*, vol. 26, p. 100831, Nov. 2019, doi: 10.1016/j.job.2019.100831.
10. N. Sathiparan and U. Rumeskumar, "Effect of moisture condition on mechanical behavior of low strength brick masonry," *J. Build. Eng.*, vol. 17, pp. 23–31, May 2018, doi: 10.1016/j.job.2018.01.015.
11. W. S. W. Mendis, S. De Silva, and G. H. M. J. S. De Silva, "Performance and Retrofitting of Unreinforced Masonry Buildings against Natural Disasters – A Review Study," *Eng. J. Inst. Eng. Sri Lanka*, vol. 47, no. 3, p. 71, July 2014, doi: 10.4038/engineer.v47i3.6896.
12. G. Si, X. Chen, J. Chen, W. Zhao, S. Li, and X. Li, "Failure criteria of unreinforced masonry walls of rural buildings under the impact of flash floods in mountainous regions," *J. Mt. Sci.*, vol. 19, no. 12, pp. 3388–3406, Dec. 2022, doi: 10.1007/s11629-022-7491-6.
13. M. Postacchini, G. Zitti, E. Giordano, F. Clementi, G. Darvini, and S. Lenci, "Flood impact on masonry buildings: The effect of flow characteristics and incidence angle," *J. Fluids Struct.*, vol. 88, pp. 48–70, July 2019, doi: 10.1016/j.jfluidstructs.2019.04.004.
14. L. Jansen, P. A. Korswagen, J. D. Bricker, S. Pasterkamp, K. M. De Bruijn, and S. N. Jonkman, "Experimental determination of pressure coefficients for flood loading of walls of Dutch terraced houses," *Eng. Struct.*, vol. 216, p. 110647, Aug. 2020, doi: 10.1016/j.engstruct.2020.110647.
15. I. Kelman and R. Spence, "An overview of flood actions on buildings," *Eng. Geol.*, vol. 73, no. 3–4, pp. 297–309, June 2004, doi: 10.1016/j.enggeo.2004.01.010.
16. R. Sisti, M. D. Ludovico, and A. Prota, "Effectiveness of traditional strengthening measures on historic masonry buildings: the seismic performance of Palazzo Comunale in Camerino after 2016–2017 seismic sequence," *Procedia Struct. Integr.*, vol. 44, pp. 1116–1123, 2023, doi: 10.1016/j.prostr.2023.01.144.
17. P. Zhang, L. Chen, T. Wei, P. Huang, H. Wang, and X. Chen, "Multi-Hazard Assessment of Masonry Buildings: A State-of-the-Art Review," *Buildings*, vol. 14, no. 12, p. 3711, Nov. 2024, doi: 10.3390/buildings14123711.
18. Y. Moaiyedfar and D. Deniz, "Collapse fragility models for unreinforced masonry buildings under flood and flow-type landslide actions," *J. Build. Eng.*, vol. 101, p. 111895, May 2025, doi: 10.1016/j.job.2025.111895.
19. I. Kelman and R. Spence, "An overview of flood actions on buildings," *Eng. Geol.*, vol. 73, no. 3–4, pp. 297–309, June 2004, doi: 10.1016/j.enggeo.2004.01.010.
20. P. E. Raad and R. Bidoae, "The three-dimensional Eulerian–Lagrangian marker and micro cell method for the simulation of free surface flows," *J. Comput. Phys.*, vol. 203, no. 2, pp. 668–699, Mar. 2005, doi: 10.1016/j.jcp.2004.09.013.
21. Z. U. Rahman *et al.*, "GIS-based flood susceptibility mapping using bivariate statistical model in Swat River Basin, Eastern Hindukush region, Pakistan," *Front. Environ. Sci.*, vol. 11, p. 1178540, July 2023, doi: 10.3389/fenvs.2023.1178540.
22. C. Galasso, M. Pregolato, and F. Parisi, "A model taxonomy for flood fragility and vulnerability assessment of buildings," *Int. J. Disaster Risk Reduct.*, vol. 53, p. 101985, Feb. 2021, doi: 10.1016/j.ijdr.2020.101985.
23. D. M. Herbert, "An investigation of the strength of brickwork walls when subject to flood loading".
24. A. Mebarki, N. Valencia, J. L. Salagnac, and B. Barroca, "Flood hazards and masonry constructions: a probabilistic framework for damage, risk and resilience at urban scale," *Nat. Hazards Earth Syst. Sci.*, vol. 12, no. 5, pp. 1799–1809, May 2012, doi: 10.5194/nhess-12-1799-2012.