The impact of floods can be devastating to buildings, especially in countries and villages in mountainous areas. Based on the flood impact risk analysis results, two methods are suggested by authors to improve the flood impact defense capability of rural buildings in this paper: increasing the strength of the mortar used in masonry structures, as well as adding reinforced concrete (RC) columns and circle beams to masonry structures. The impact of floods on the reinforced masonry structures is simulated numerically, and the failure process, stress, and deformation behaviors of masonry structures are analyzed. Compared to the computational results of normal masonry structures, the advantages of the two methods proposed in this manuscript are studied. Increasing the mortar strength slows the rate of damage to the masonry structure but does not improve the deformation or the failure behaviors. Increasing the mortar strength slightly decreases the first principal stress on the mortar and brick elements but has no effect on the third principal stress. Adding the RC frames not only delays the damage to the building and improves the failure behavior of the masonry structure but also decreases the first and third principle stresses of the brick and mortar elements.

**KEYWORDS**
defense measure, flood, impact, masonry structure, risk analysis

**1 | INTRODUCTION**

China experiences a large number of natural disasters. The intensities and frequencies of these disasters are some of the highest in the world. Of all disasters, floods are one of the most frequent and damaging natural disasters and have caused the most casualties and economic losses. They accounted for up to 40% of the total losses caused by all disasters in China after 1949 (Wang, 1995). Figure 1a lists the economic losses of floods in China and their ratio to total economic losses every year from 1991 to 2015 (part of the data comes from reference (Wan & Wang, 2011)). The maximum economic loss of flooding was as high as 53.5 billion USD in 2010 and the maximum ratio was as high as 96% in 1994. During the past 25 years, the average economic loss of flooding was 18.6 billion USD and the average ratio of flood to total economic losses was as high as 51%. To most Chinese village residents, their buildings are their most important personal property. Unfortunately, rural buildings were nearly always damaged and destroyed by flood impact. Figure 1b lists the collapsed building number caused by flooding in China every year from 1991 to 2015. Recently, the number of collapsed buildings has decreased slightly.
due to the establishment of an early warning system for floods in some flood basins. However, during the past 25 years, the average number of collapsed buildings is still as high as 1.793 million very year.

Floods have dramatically destroyed buildings in countries and villages of mountainous areas. For many years, researchers thought that the effective time of the flooding impact was short and that the range of the impact was limited. Thus, the impact of flooding did not be considered as a primary factor during the design of buildings and the studies about this are sparse. Jones (1997) reported on the impact of floods and wind on structures in coastal areas. Kelman studied the damage to unreinforced masonry buildings in England at risk to storm surges (Kelman, 2002) and presented an overview of flood characteristics with respect to their applicability for estimating and analyzing direct flood damage to buildings (Kelman & Spence, 2004). Mire and Juichiro (2003) used numerical simulation and experiments to study two-dimensional flood flows and the hydrodynamic forces acting on structures. Van Liew (2004) simulated the impact of floods on flood-retarding structures in south-western Oklahoma under dry, average, and wet climatic conditions. To improve knowledge regarding efficient precautionary measures, approximately 1200 private households affected by the 2002 flood of the Elbe river and its tributaries were interviewed about the flood damage of their buildings and contents as well as about their precautionary measures taken (Kreibich et al., 2005). Schwarz and Maivald (2007) developed a method to determine the structural damage of a single building or of an affected building stock for any given flood scenario. Zhang et al. (2008) investigated pavement structural damage caused by Hurricane Katrina flooding in September of 2005. Witzany et al. (2008) studied the failure of a historic stone bridge structure, the Charles Bridge, due to flooding. A new set of experiments suggested that the use of existing prediction methods might be unsafe and that impulsive loading might be critical for both the assessment of the vulnerability of existing structures and the design of new flood-proof buildings (Cuomo et al., 2009). Drdáčky studied the impact of flooding on heritage structures (Drdáčky, 2010a) and presented typical examples of damage to immovable cultural heritage structures, including historic architecture and infrastructure, due to flooding (Drdáčky, 2010b). Kingston et al. (2011) used an artificial neural network method to simulate the 17th Street Canal flood wall which catastrophically failed in New Orleans during Hurricane Katrina in 2005. Andrea et al. (2011) developed a theoretical model to describe flood impacts on wood-frame residential buildings and related building response to flood depth and velocity. Liu (2013) analyzed disasters of flooding and waterlogging impacts on agricultural production and water conservancy facilities in China from 2006 to 2010. Pasek and Frankl (2014) focused on analyses of the links influencing the extent and character of damage to wooden structures and other wood elements in buildings due to floodwater and its contaminants. Hung and Yau (2014) examined the influence of scour on the behavior of bridge piers subjected to flood-induced loading. Lonetti and Maletta (2018) proposed a comprehensive numerical approach simulating the fluid–structure interaction to study dynamic impact damage behavior of masonry buildings subjected to flood actions. Nasim et al. (2019) simulated the flood effect on
piers using a finite volume method in the ANSYS-FLUENT package. Postacchini et al. (2019) carried out experimental tests to study flood impact pressure acting on the masonry building in different manner for the frontal, lateral, and rear walls.

From the above literature review, it can be seen that research on building damage due to flood was mainly based on the flood surveys (Drdácký, 2010a, 2010b; Hung & Yau, 2014; Jones, 1997; Kelman, 2002; Kelman & Spence, 2004; Kreibich et al., 2005; Liu, 2013; Witzany et al., 2008; Zhang et al., 2008). Some researchers were interested in the flood impact load behavior (Drdácký, 2010a; Mire & Juichiro, 2003; Nasim et al., 2019; Postacchini et al., 2019) and the impact action of flood on structures (Cuomo et al., 2009; Kingston et al., 2011; Pasek & Frankl, 2014; Schwarz & Maiwald, 2007; Van Liew, 2004). But the study about the impact action of flood on masonry structures was rare (Lonetti & Maletta, 2018), and the research about the mitigation measures is absent from the literature at present.

It is difficult to forecast the direction and range of floodwaters. As a result, many buildings are washed away due to flooding. Recently, there have been calls for higher building security standards. Studying the impact of flooding on buildings and improving their ability to resist flood damage is an interested research area.

To study the impact action of flooding on rural buildings, the computational formula (Xiao & Wang, 2010) for impact loading of a flood model was deduced (Xiao & Li, 2013; Xiao & Wang, 2010). The impact loading formula is described as follows:

\[
p = \gamma z_1 + \frac{\gamma u_1^2}{2g} - \frac{2\gamma}{3g t_2^2} \left[ \frac{(9g t_2^2)^2}{64} - (2\sec^3 \alpha \cdot \tan \alpha - \sec \alpha \cdot \tan \alpha - \ln|\sec \alpha + \tan \alpha|) \right] + h_2 \cdot s_2 \\
- \frac{2^2 m_1^2}{9g t_1^2} \left[ \frac{12g H_0}{5} m_1 - 18g t_2 \sqrt{g H_0 m_1} - 27g H_0 m_1^2 \right] m_2 \left[ 1 \right] \times m_1
\]

(1)

The study on impact loading began with floods caused by gravity waves, which can be generalized as the movement of shallow waters. When the horizontal scale is much larger than the vertical scale in wide and shallow river channels or flood plains, the change of water depth and current velocity in the vertical direction is smaller than those in the horizontal direction. In these cases, the application of shallow water theory for flooding is possible due to the movement of shallow waters and the shallow water equations are used to describe the flood.

Based on the one-dimensional Saint-Venant water equation explicit difference scheme, the computational formula for the impact loading of a flood model was calculated by the authors: increasing the strength of mortar and the use of a reinforced structure in which reinforced concrete columns and circular beams are added to a structure. Finally, flood damage by means of two case-based numerical models is analyzed to prove their effectiveness against flooding.

## 2 | Amplitude and Distribution of Impact Loading

### 2.1 | Amplitude of impact loading

The study on impact loading began with floods caused by gravity waves, which can be generalized as the movement of shallow waters. When the horizontal scale is much larger than the vertical scale in wide and shallow river channels or flood plains, the change of water depth and current velocity in the vertical direction is smaller than those in the horizontal direction. In these cases, the application of shallow water theory for flooding is possible due to the movement of shallow waters and the shallow water equations are used to describe the flood.

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- \frac{2^2 m_1^2}{9g t_1^2} \left[ \frac{12g H_0}{5} m_1 - 18g t_2 \sqrt{g H_0 m_1} - 27g H_0 m_1^2 \right] m_2 \left[ 1 \right] \times m_1
\]

(1)

the impact loading of a flood model was deduced and an impact experiment of a flood on buildings (Xiao et al., 2010) was carried out in order to study the magnitude and distribution of forces. Rural buildings were then analyzed to investigate their destruction due to flooding (Xiao & Li, 2013). The displacement and the stress of rural buildings were studied and the destruction process was documented. The results show that the impact of flooding should cause the severe collapse of rural buildings. In this paper, based on the flood impact risk analysis results of the reference Xiao and Li (2013), two methods are suggested by the authors: increasing the strength of mortar and the use of a reinforced structure in which reinforced concrete columns and circular beams are added to a structure. Finally, flood damage by means of two case-based numerical models is analyzed to prove their effectiveness against flooding.
\[ \alpha_1 = \arctg \frac{4\sqrt{gH}}{9g_l}, \quad \alpha_2 = \arctg \frac{2\left(2\sqrt{gH} - \frac{v}{9g_l}\right)}{9g_l} \]

\[ m_1 = 4\sqrt{gH}, \quad m_2 = \frac{2\left(2\sqrt{gH} - \frac{v}{9g_l}\right)}{9g_l} \]

Compared to the theoretic values and the experimental impact pressures of the model (Xiao & Li, 2013), it illustrated that the theoretical values were greater than the experimental values, but the errors were less than 15%. So, in the paper, the simplified formula was used to calculate the amplitude of impact loading.

2.2 | Distribution of impact loading

For a typical rural masonry building shown in Figure 2a, the impact of flooding is illustrated in Figure 2b. A flood wave with height \( H \) and velocity \( v \) impacts the rural building when it encounters the surface of the masonry. The impact pressure decreases approximately linearly with the distance from the bottom of the building.

The impact pressure distribution on the surface of building should be affected by the door, the window, and the boundary conditions. Thus, in order to study the distribution rule, the impact experiment of flooding on a building model was carried out on a large wave-current tank and the distribution of impact loading was investigated (Xiao et al., 2010). According to test results, the effects of door, window, and boundary condition were investigated and the impact loading contour on the impact surface of the building should be plotted.

In this paper, the large flood and the medium flood are simulated to impact the masonry structures. Figure 3a and b shows the impact pressure distribution of the large flood and the medium flood in the vertical and horizontal direction at the flow surface, respectively. It is concluded that the impact pressure decreases approximately linearly from the bottom to the top of the model. Because of the boundary and holes, the flood still has a certain velocity after impact. So, the impact pressure around the boundary and holes is less than that of the middle part at the same height. So, in the horizontal direction, the impact pressure on both sides is less than in the middle at the same height.

3 | DEFENSE MEASURE I: INCREASING THE SHEAR STRENGTH OF MORTAR

Considering economic factors, the simple masonry structure buildings have been applied for many years in most rural areas of China. But, especially in mountainous areas, because of the lack of corresponding materials, mortar was often replaced by mud and its strength was very low and not up to the standard value. So, the simplest defensive measure is to increase the shear strength of mortar.

3.1 | Structural FE model and material behavior

Figure 4 gives a representative FE model of normal structures (masonry structure I and structure II). The normal two-bay brick masonry structure is 4.8 m in width, 8.04 m in length, and 3.60 m in height. The ratio of holes of the rural building is 0.298. This model consists of two kinds of elements: 7950 brick elements and 4098 mortar elements. The wall is made of brick by mortar and its thickness is 0.12 m. The dimension of each brick is 0.24 m × 0.12 m × 0.06 m, and each is divided into two 8-node brick elements. The size of the brick element is 0.12 m × 0.12 m × 0.06 m. All bricks are adhered together by mortar. Mortar and two contact interfaces
bonding two bricks are simulated by a cohesive friction element. Because the contact interface between mortar and brick is the weakest link, the material parameters of the cohesive friction element are mainly determined by that of the interface. Normally, the thickness of mortar is smaller than that of the brick; in order to facilitate the division of elements, the cohesive friction element is always simplified to the element without thickness. The sizes of cohesive friction elements without thickness are 0.12 m x 0.12 m or 0.12 m x 0.06 m. The dimensions of the building structure with increased mortar strength (structure II) are same as the structure I. The sloping lightweight wooden roof of masonry structure is neglected because it is not the main load-bearing member and its vertical self-weight has little effect on the horizontal damage of structure due to flood. The fix displacement boundary is adopted on the bottom of building structure. The gravity load and the flood impact loading of incident flow surface are considered. According to the damage results of masonry (Xiao & Li, 2013), the brick column

**FIGURE 3** Impact pressure contour on the incident impact surface of the building (a) a large-sized flood (the height of the flood is equal to or greater than the building height) and (b) a medium-sized flood (the height of flood is approximately equal to three quarters of the building height)

**FIGURE 4** FE model of masonry structure I and II
between door and right window and the wall above the column were seriously destroyed. Point A is the middle point of the brick column between the door and right windows, which is the weakest part of the masonry structure, and it should be failed firstly due to flood impact. After this wall is failed, the top wall should be failed next and the point B could record the fail process of the brick column and top wall. So, the two points are the two important joints of column and wall and their displacements are tracked.

The cohesive friction element, listed in Figure 5, is adopted to simulate mortar. The element provides frictional and gapping connections between any two bricks. The load on the element consists of pressure and friction. The element shear could be calculated by the equation:

\[
\begin{align*}
\tau_x &= G\mu_x + \mu P \\
\tau_y &= G\mu_y + \mu P
\end{align*}
\]

(2)

where \(\tau_x\) and \(\tau_y\) are the shears in the x and y directions respectively, \(G\) is the shear modulus, \(\mu\) is the friction coefficient, \(P\) is the pressure, \(u_x\) and \(u_y\) are the slip displacements between the upper and lower surfaces in the x and y directions, respectively.

The cohesive friction element should fail when one of three conditions is satisfied:

\[
\begin{align*}
P &> 0 \quad \text{(tension)} \\
-P &> \sigma \\
\tau &= \sqrt{\tau_x^2 + \tau_y^2} > \tau_{\text{lim}}
\end{align*}
\]

(3)

A brick of MU25 strength grade is chosen for these structures. The brick element is considered an elastic element. According to the code for the design of masonry structure (GB, 2009), the compressive strength of brick is 11.25 MPa, the Poisson’s ratio is 0.15, and the density is 1.8 \times 10^3 kg/m^3. According to references, an elastic modulus of 10,886 MPa is chosen. Failure of brick element is considered to have been reached when the maximal stress is equal to the compressive strength 11.25 MPa, or when the relative displacement exceeds 0.06 m.

Mortar of M10 strength grade is chosen in the structure I. The compressive strength is 4 MPa, the Poisson’s ratio is 0.15, and the shear strength is 0.27 MPa (Xiao & Qi, 1995). According to the reference Li et al. (2009), the elastic modulus is 10,012 MPa, and the shear modulus is 4354 MPa. The mortar element reaches failure when the shear stress is equal to the shear strength. Mortar of M20 strength grade is chosen in the structure II and its shear strength is increased to 0.60 MPa. The material parameters of structure I and II are listed in Table 1.

### Table 1: Material parameters of the building structure I and II

| Element       | Material   | Parameters                  | Structure I | Structure II |
|---------------|------------|-----------------------------|-------------|--------------|
| Cohesive friction | Mortar     | Grade                       | M10         | M20          |
|               |            | Compressive strength        | 4 MPa       | 10 MPa       |
|               |            | Shear strength              | 0.27 MPa    | 0.60 MPa     |
|               |            | Elastic modulus             | 10,012 MPa  | 10,012 MPa   |
|               |            | Shear modulus               | 4354 MPa    | 4354 MPa     |
|               |            | Poisson’s ratio             | 0.15        | 0.15         |
| Brick         | Block      | Grade                       | MU25        | MU25         |
|               |            | Compressive strength        | 11.25 MPa   | 11.25 MPa    |
|               |            | Elastic modulus             | 10,886 MPa  | 10,886 MPa   |
|               |            | Poisson’s ratio             | 0.15        | 0.15         |
|               |            | Density                     | 1800 kg/m^3 | 1800 kg/m^3 |

### 3.2 Analysis method and program

In this paper, the impact analysis on masonry structures was carried out by the program FEARBF (Finite Element Analysis of Rural Buildings due to Flood), which was developed by authors. The FEARBF program was verified.
by ANSYS (Sun, 2011, Xiao & Li, 2013). In order to compare the results between different masonry structures, the analysis method is same as reference (Xiao & Li, 2013). The impact analysis on the structures was carried out and the stress, deformation, and destruction process of the masonry were studied and compared to the results of the models.

To study the destruction process of masonry structures, a large sized flood is chosen and the final impact pressure distribution is plotted in Figure 4a. The impact load is divided into 50 load-steps imposed on the structure. The structure is tested according to the extended elastic model to determine the elastic limit loading in which the maximal stress of one or more mortar elements reaches failure stress. The elastic limit loading is defined as the first load-step. The maximal loading of the first load-step is 6.727 KPa. Then, the remaining loading is divided into equally between the 2nd and 50th load-step and the individual load-step is 1.477 KPa.

### Table 2

Failure element numbers of the building structure I and II

| Load-step | Loading (KPa) | Failure mortar elements | Failure brick elements |
|-----------|---------------|-------------------------|------------------------|
|           |               | Structure I | Structure II | Structure I | Structure II |
| 1         | 6.727         | 1           | 0           | 0           | 0           |
| 7         | 15.594        | 155         | 1           | 0           | 0           |
| 16        | 28.895        | 1681        | 50          | 78          | 0           |
| 22        | 37.762        | 2495        | 301         | 314         | 0           |
| 25        | 42.195        | 2796        | 475         | 443         | 0           |
| 27        | 45.151        | 2959        | 694         | 516         | 48          |
| 28        | 46.629        | 3210        | 858         | 656         | 79          |
| 31        | 51.063        | 3443        | 1163        | 1006        | 135         |
| 36        | 58.452        | 3608        | 1585        | 1278        | 204         |
| 44        | 70.275        | 3810        | 2205        | 1528        | 577         |
| 50        | 79.142        | 3896        | 2776        | 1637        | 896         |

**3.3 Failure process of masonry structures**

Table 2 lists the failure evolution of the two kinds of element in structure I and structure II. At the end of the first load-step, one mortar element exhibits failure in structure I. However, the first mortar element in structure II does not exhibit failure until the seventh load-step. With increasing loading, more mortar elements exhibit failure. There are 2796, 3608, and 3896 failed mortar elements on structure I at the end of 25th, 36th, and 50th load-step, respectively. Compared to structure I, fewer mortar elements failed at the same load-step on structure II, and

**Figure 6** Failure of building at the 16th load-step (a) structure I and (b) structure II
there are 475, 1585, and 2776 failed mortar elements on structure II at the end of 25th, 36th, and 50th load-step, respectively.

The brick element fails because the bond losses of action caused by the cohesive friction element adhered to it. Similarly, there are 443, 1278, and 1637 failed brick elements on structure I at the end of 25th, 36th, and 50th load-step, respectively. However, there are only 0, 204, and 896 failed brick elements at the same load-steps on structure II, respectively.

Figures 6–8 illustrate the destroyed models of the two structures at the 16th, 28th, and 50th load-steps. From these figures, the wall between the door and the right window fails first because the door and the right window reduce the stiffness of the wall. With increasing impact load, the top wall of the left window begins to fail. Compared to the two structures, it is clear that the failure process of structure II is similar to that of structure I, but the increased strength of mortar in structure II postpones the damage of masonry structure. At the 16th load-step, the wall between the door and the right window is nearly completely damaged on structure I but remains undamaged on structure II. At the 28th load-step, the right wall is completely destroyed and some elements of the left wall fail on structure I, but on structure II, the right wall is only partly damaged, and it is in a similar state to that of the 16th load-step on structure I. At the last load-step, the incident impact wall is completely destroyed on structure I, but on structure II, only the right wall is completely destroyed, and certain elements of the left wall fail, which is similar to that of the 28th load-step on structure I. It is concluded that increasing mortar strength delays the damage of the building but does not improve the failure behavior of the masonry building.

### Stress analysis

Figures 9–12 illustrate the first principal stress contour of the two structures at the 1st, 16th, 28th, and last load-steps. It is determined that the maximal stress is located on the impact surface. The maximal first principal stress of
FIGURE 9  First principal stress at the first load-step (a) structure I and (b) structure II

FIGURE 10  First principal stress at the 16th load-step (a) structure I and (b) structure II

FIGURE 11  First principal stress at the 28th load-step (a) structure I and (b) structure II

FIGURE 12  First principal stress at the last load-step (a) structure I and (b) structure II
brick elements on structure I is less than on structure II. Compared to the structure I, the maximal first principal stresses of structure II increase from 1.44 to 1.51 MPa, 6.94 to 9.02 MPa, 10.05 to 11.00 MPa, and 10.06 to 10.08 MPa at the first, 16th, 28th, and last load-step, respectively.

Figures 13-16 plot the third principal stress contour of two structures at the 1st, 16th, 28th, and last load-steps. It is determined that the maximal stress is located on the corner of the wall. Compared to the third principal stress and its distribution, the maximal third principal stress of brick elements on structure I is nearly identical to structure II, and the stress distributions on structure I and II are similar.

Compared to the first and third principal stress of structure I with those of structure II, it is clear that the method slightly decreases the first principal stress of the mortar and brick elements but has no effect on the third principal stress.

**Figure 13** Third principal stress at the first load-step (a) structure I and (b) structure II

**Figure 14** Third principal stress at the 16th load-step (a) structure I and (b) structure II

**Figure 15** Third principal stress at the 28th load-step (a) structure I and (b) structure II
3.5 | Deformation analysis

Figures 17–20 illustrate the horizontal displacement contour of two structures at the 1st, 16th, 28th, and last load-steps. It is determined that the maximal horizontal displacement is located on the wall between the door and the right window. With increasing impact load, the wall is destroyed and the maximal horizontal displacement is located on the top of the window wall. The maximal horizontal displacement of brick elements in structure I is approximately 60 mm, which is the same as in structure II, because according to the failure criterion of the bricks, a brick should slide from the wall when its horizontal displacement exceeds 60 mm. Additionally, it is clear that the displacement contours on structure I and II are similar.

The maximal displacements of structure I and II are located in the middle of the wall between the door and the right window, shown as the red zone in Figure 8a, b. To compare the displacement of two structures,
Figure 21 gives the load–displacement curves of points A and B (listed in Figure 4). It is determined that the displacements increase linearly with the increasing load at the beginning of the analysis. When the load is increased, the cohesive friction element and the brick element began to fail, and the load–displacement curves became nonlinear. The curve of the structure I becomes flatter because more elements fail on structure I at the same displacement. At the 15th load-step, point A is destroyed on structure I but at the 26th load-step on structure II. Similarly, the conclusion about point B is same where point B is destroyed at the 20th load-step on structure I but at the 38th load-step on the structure II.

### 4  |  MEASURE II: ADDING THE RC FRAME

RC frame in masonry structure could increase effectively the lateral stiffness to decrease the horizontal deformation of the structure. Adding a RC frame in masonry structure has been a common measure in seismic mitigation. Same as in earthquake engineering, in the paper, RC frame is adopted as the second mitigation measure.
4.1 | Structural FE model and material behavior

Figure 22 presents FE model of the reinforced structure (structure III). In the reinforced masonry structure, four reinforce concrete (RC) columns are embedded into the impact wall and a circular reinforced concrete beam is set over the windows and doors to increase the stiffness of the masonry structure. RC columns are placed at the junction of the two walls and their cross-sectional dimensions are 0.12 m × 0.12 m. Circular RC beams are embedded into the walls on the top of doors and windows, and their cross-sectional dimensions are 0.12 m × 0.12 m.

For structure III, the material parameters of the mortar and brick are same as those on structure I. The grade of concrete is C25, the compressive strength is 25 MPa, the Poisson’s ratio is 0.17, and the elastic modulus is 2.11 × 10⁴ MPa. The reinforced concrete beams and columns are discretized into eight-node block elements and are considered to be the elastic elements.

4.2 | Analysis method and program

To study the effects of the RC frame on the failure behavior of the masonry structure, a medium-sized flood is chosen and the final impact pressure distribution is plotted in Figure 4b. The impact load is divided into 27 load-steps imposed on the structure. Similar to method I, the structure is first determined to have an elastic limit loading of 6.727 KPa. Then, the remaining loading is divided into 26 equal parts forming the second to 27th load-steps with a load-step of 1.493 KPa.

4.3 | Failure process of masonry building

Table 3 lists the failure evolution of the two kinds of element on structure I and III. At the end of the first load-step, one mortar element experiences the first failure on structure I. However, the first mortar element failure does not occur until the fourth load-step on structure III. With increasing impact loading, more mortar elements experience failure. There are 1110, 2386, and 2959 failed mortar elements on structure I at the end of the 13th, 21st, and last load-step, respectively. Compared to structure I, less mortar elements fail at the same load-step on structure III, and there are 245, 1595, and 2574 failed mortar elements on structure III at the end of 13th, 21st, and last load-step, respectively. Similarly, there are 126, 255, and 516 failed brick elements on structure I at the end of the 17th, 21st, and last load-step, respectively. However, only 13, 29, and 264 brick elements fail at the same load-step on structure III, respectively.

Figures 23 and 24 illustrate the destroyed models at the 25th and last load-step, respectively. It is clear that the wall between the door and the right windows is almost completely damaged at the 25th load-step on
structure I but is on good condition in structure III. At the last load-step, the wall is destroyed in structure I, but it is only partly damaged in structure III. At the same time, the left wall of the left window is damaged at the last load-step in the structure III but it is on good condition in structure I. Additionally, the damage behavior is different as compared to that of structure I employing method I, in which the top wall of the left window is damaged. This finding is observed because the RC frame improves the structural integrity of the weak wall. It is concluded that this method not only delays the damage of the building but also improves the failure behavior of the building.

4.4 Stress analysis

Figures 25 and 26 illustrate the first principal stress contour of structure I and structure III with and without the RC frame at the first and last load-step, respectively. Compared to structure I and structure III, the maximal values of the first principal stress obviously increase on structure III. The maximal values increase from 1.44 to 7.48 MPa and from 10.3 to 21.0 MPa at the first and last load-step, respectively. However, in structure III, the maximal first principal stress is located on the RC elements. Compared to Figures 25a,c and 26a,c, the maximal values of the first principal stress on the masonry elements decrease 35% and 17% at the first and last load-step.

Figures 27 and 28 illustrate the third principal stress contour of structure I and structure III with and without the RC frame at the first and last load-step, respectively. Similarly, compared to structure I and structure III, the maximal values of the third principal stress increase on structure III. The maximal values increase from 1.59 to 8.07 MPa and from 9.87 to 23.7 MPa at the first and last load-step, respectively. However, in structure III, the maximal first principal stress is located on the RC elements.
Compared to Figures 27a,c and 28a,c, the maximal values of the third principal stress on the masonry elements decrease 39% and 9% at the first and last load-step.

It is clear that the method decreases the first principal stress and the third principal stress of the mortar and brick elements. This finding is observed because the RC frame not only shares some partial impact load but also increases the stiffness of the masonry structure, which causes the deformation decrease and the stress reduction of the brick and mortar elements.

Compared to the first and third principal stress of structure I and III, it is clear that this method decreases the first and third principle stress of the brick and mortar elements.
4.5 | Deformation analysis

Figures 29 and 30 illustrate the horizontal displacement contour of the two structures at the first and last load-steps. It is determined that at the first load-step, the maximal horizontal displacement is located on the wall between the door and the right window on structure I but on the left wall with the left window on structure III. With increasing load, the wall between the door and the right window on structure I is destroyed and the maximal horizontal displacement is located on the left wall with the left window at the last load-step. However, on
structure III, the wall between the door and the right window is not completely destroyed because of the RC frame and the maximal horizontal displacement which is located on the top wall of the left window at the last load-step.

At the first load-step, the maximal horizontal displacement on structure III is smaller than that on structure I because that the RC frame increases the stiffness of the masonry structure. At the last load-step, the maximal horizontal displacements are the same (approximately 60 mm) on both structures I and III, because according to the failure criterion, the bricks should slide from the wall when their horizontal displacement exceeds 60 mm.

Figure 31 gives the load–displacement curves of point A on structure I and structure III. The initial curve slope on structure III is larger than on structure I because the RC frame increases the stiffness of structure. At the 16th load-step, point A is destroyed on structure I, but point A is not destroyed until the 24th load-step on structure III.

Compared to the stress and deformation of structure I and III, it is clear that, on the one hand, the mitigation measure decreased the stress and deformation of the structure because it increased the lateral stiffness of the masonry structure, and on the other hand, it mitigated and delayed structure damage because it increased the integrity of the masonry structure.

5 | CONCLUSIONS AND REMARKS

The effects of flooding on three structures are analyzed numerically and compared to one another. The stress, displacement, and failure process of the building are studied. The following conclusions could be drawn:

1. The impact of flooding can severely damage masonry structures, especially the weak parts such as the...
wall between windows and doors and the walls around windows.

(2) Compared to the computational results of structure I and II, it is concluded that increasing the mortar strength delays the onset of damage to the building but does not improve the deformation and the failure behavior of the masonry structure. The method slightly decreases the first principal stress of the mortar and brick elements but has no effect on the third principal stress.

(3) Compared to the computational results of structure I and III, it is concluded that adding the RC frame not only reduces the number of failure brick and mortar elements at the same loading, but also decreases the displacement of masonry structure and the first and third principle stress of the brick and mortar elements.

(4) Compared to two reinforced masonry structures, the masonry with RC frame has better structural integrity and can delay the flood damage to protect people’s life and property safety.

The conclusion above is based on some limitations and assumptions, such as simplified impact load, elastic material model, simple material failure criterion. Accurate impact load behavior, nonlinear material behavior, and reasonable failure criteria of mortar and brick should be taken into account during the analysis of masonry due to the impact of floods in future.

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DATA AVAILABILITY STATEMENT
I confirm that my article contains a Data Availability Statement even if no data is available (list of sample statements) unless my article type does not require one. I confirm that I have included a citation for available data in my references section, unless my article type is exempt.

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