Experimental Study on Earthquake-induced Falling Debris of Exterior Infill Walls and its Impact to Pedestrian Evacuation

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Under the combined effects of in-plane deformation and out-of-plane acceleration during an earthquake, cracking occurs in the exterior infill walls of buildings causing debris to fall. The falling debris ineluctably blocks roads and hinder fast pedestrian evacuations. To identify the failure criterion for exterior infill walls, specialized test apparatus was designed, and pseudo-static experiments of infill walls were conducted in this work. The influences of different height-to-thickness ratios, drift ratios and out-of-plane accelerations on falling debris were taken into consideration in the proposed apparatus design. The experiment indicated that the infill blocks fell sooner and the falling area was larger for a thinner infill wall with a larger tilting angle. Based on the experimental results, a prediction model was proposed to evaluate the percentage of falling area of infill walls. Using the proposed failure criterion, a pedestrian evacuation simulation was conducted on the Tsinghua University campus as a case study. Moreover, the debris distribution and evacuation results under different earthquake intensities were also analyzed. The results of the case study revealed that a considerable area of roads located in densely built-up areas was covered by debris, resulting in a more than 30% increase in time for people in the nearby buildings to evacuate. Compared to the scenario without falling debris, the evacuation time with debris was 5% longer when subjected to MCE (Maximal Considered Earthquake). The proposed failure criterion for masonry infill walls can be employed in debris distribution calculation, which offers technical support for urban planning and evacuation drills.

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1 INTRODUCTION

Masonry infill walls are a type of construction widely used as the envelope of multistory and high-rise buildings in urban areas. Infill walls were observed to have been severely damaged in past earthquakes [1–6], and blocks fell from the attached walls owing to the combined effects of infill wall damage and seismic acceleration. According to field investigations, these masonry infill walls usually have weak boundary connections with the main structure [7,8]. This is especially true for the developing countries where quality control of the connection between the infill masonry walls and the main structures is difficult to be ensured. Statistics also show that earthquake-induced falling debris can cause a significant number of casualties [9–11]. Moreover, falling debris can seriously hinder fast emergency evacuations and rescues [12,13]. For people living in densely built-up areas, the presence of debris may increase the total evacuation time up to 30% [14]. Therefore, it is necessary to conduct a comprehensive research to examine the impact of falling debris of masonry infill walls and the associated influencing factors. In addition, debris distribution and its impact on pedestrian evacuations must be quantified for better disaster management.

There are some existing studies on the falling debris of masonry infill walls. For instance, Xu et al. [15] predicted the distribution of falling debris from tall buildings. Their study assumed that when the drift ratio of a masonry infill wall exceeded a certain value, cracking of the wall and falling of debris were triggered. The failure criteria for nonstructural components proposed in ASCE-07 [16] was adopted in their work, in which different nonstructural components had their own damage criteria. Liu et al. [17] analyzed the falling debris of indoor partition walls and suspended ceilings based on the fragility curves of the nonstructural components. In Liu et al.'s work [17], the drift ratio was also used as the failure criterion. Lu et al. [14] selected two drift ratio limits for masonry infill walls to calculate and compare debris distributions under different scenarios. Review of literature indicates that the existing studies mainly adopted the drift ratio limit as the failure criterion for a masonry infill wall. It should be noted that the out-of-plane acceleration and height-to-thickness ratio of walls also have some impact on the damage of masonry infill walls and falling debris. As such, the existing failure criteria require further development and improvement.

The test apparatus for a pseudo-static experiment is relatively simple. Therefore, pseudo-static experiments are widely employed to study the behavior of masonry infill walls. Load-displacement behaviors of unreinforced masonry walls were obtained through displacement-

controlled lateral loading in Heydariha et al.'s work [18]. In order to evaluate the influence of the in-plane damage on the out-of-plane behavior of infill walls, cyclic in-plane tests were first carried out and out-of-plane tests were subsequently performed in Angel et al.'s work [19]. Furtado et al. [20] applied the out-of-plane monotonic and cyclic loading on three infill panels to study the influence of in-plane drifts on their out-of-plane performances. In addition, airbag testing was adopted to apply out-of-plane distributed surface loads [21–23]. In the abovementioned experiments, the in-plane damage of masonry infill walls was predetermined before performing the out-of-plane tests. For masonry infill walls weakly connected to the main structure, the infill block failure normally takes the form of combined effects of the out-of-plane acceleration and the in-plane drift. However, previous studies, dealing with the in-plane and out-of-plane loading procedures separately, cannot fully represent such combined effects. Many researchers also conducted shaking table tests to study the seismic performance of masonry infill walls [24–26]. Based on the tests of four multi-wythe walls, Meisl et al. [24] investigated the influence of the ground motion and the construction quality on masonry infill walls. Through the shaking table tests of three masonry infill walls, Tu et al. [7] found that the thickness/slenderness of the walls had a significant influence on the out-of-plane strength and stiffness, which led to a proposed analytical model accounting for the out-of-plane behavior of masonry walls. It is well recognized that the dynamic and spatial effects of ground motions can be simulated through shaking table tests. Nevertheless, a large number of infill wall specimens are required to establish the failure criteria, and numerous factors need to be determined. This makes the shaking table tests too complicated and expensive to perform this task.

In view of the research gaps described above, a pseudo-static test apparatus considering both the in-plane drift ratio and out-of-plane acceleration is designed in this work. Masonry infill wall specimens with different height-to-thickness ratios and out-of-plane accelerations are tested, and a new failure criterion for predicting the percentage of falling area of the infill wall is proposed based on the experimental results. Employing this criterion, the Tsinghua University campus is selected to perform a case study, by which the earthquake-induced debris distribution is demonstrated and the impact of falling debris on pedestrian evacuation is also analyzed.

89 **2 EXPERIMENTAL RESEARCH**

90 **2.1 Experimental Design**

91 The in-plane stiffness of a masonry infill wall is much larger than its out-of-plane
92 stiffness. Cracking of an infill wall is induced by the in-plane deformation, and subsequently
93 infill blocks will fall from the wall due to the out-of-plane acceleration, resulting in falling
94 debris. To accurately replicate the cracks in the wall and the falling debris subject to seismic
95 loading, a new experimental method for earthquake-induced falling debris from a masonry
96 infill wall is proposed herein.

97 **2.1.1 Design of specimens**

98 Owing to their low density and outstanding soundproofing performance, autoclaved
99 aerated concrete blocks are widely used in the infill walls of buildings [27–30]. These kinds
100 of solid blocks were also selected to build the infill wall specimens. The nominal size of the
101 main blocks was 400 mm × 250 mm, while the sizes of the auxiliary blocks were 200 mm ×
102 250 mm and 400 mm × 100 mm. The standard thickness of the infill walls used in buildings
103 normally varies from 100 mm to 240 mm [31–33]. To cover this practical range, two types of
104 specimens with different wall thicknesses (i.e., 100 mm and 200 mm) were designed to
105 consider the influence of the height-to-thickness ratios. The size of the two infill wall
106 specimens were 1600 mm × 1600 mm × 100 mm (Fig. 1a) and 1600 mm × 1600 mm × 200
107 mm (Fig. 1b), respectively.

Figure 1. Specimens of masonry infill walls (unit: mm). (a) 100 mm in thickness. (b) 200 mm in thickness.

2.1.2 Test setup

A specialized pseudo-static loading apparatus is designed in this work, taking into account both the in-plane drift ratio and the out-of-plane acceleration. This apparatus is assembled using a steel frame and two concrete supports. The steel frame consists of two steel columns connecting to two steel beams with hinges, as shown in Fig. 2a. The steel frame serves as a structural frame that restrains the exterior infill wall in real buildings. The bottom of the steel frame is bolted to the two concrete blocks which are fixed to the laboratory strong floor. The masonry infill wall specimen is attached to the steel frame with mortar, ensuring the deformation compatibility of the infill wall and the frame. A cyclic load is horizontally applied to the specimen with a 200-kN actuator, which is connected to the upper steel beam. When subjected to the horizontal loads, the initially rectangular-shaped steel frame deforms to a parallelogram. The infill wall specimen correspondingly deforms, which simulates the deformation of an exterior infill wall owing to inter-story drift during an earthquake.

Figure 2. Loading apparatus (unit: mm). (a) Front view. (b) Side view.

To simulate the out-of-plane acceleration on the masonry infill wall during an earthquake, the steel frame is mounted to the concrete supports at different tilting angles. The acceleration component of gravity of the tilted infill wall represents the out-of-plane acceleration during an earthquake. A total of five pairs of concrete supports are designed for the experiment (i.e., 10 supports in total), with detailed bolt positions shown in Fig. 3

representing five different tilting angles (0° , 15° , 30° , 45° , and 60°) (Fig. 4). The out-of-plane accelerations corresponding to the five angles are 0.0 g, 0.26 g, 0.50 g, 0.70 g, and 0.87 g. Consequently, ten specimens were tested with two different thicknesses (i.e., 100 mm and 200 mm) and five tilting angles. During the experiment, the out-of-plane tilting angle maintained constant throughout.

Figure 3. Side view of concrete supports with different bolt positions (unit: mm). (a) 0° . (b) 15° . (c) 30° . (d) 45° . (e) 60° .

Figure 4. Side view of steel frame at different tilting angles.

2.1.3 Loading protocol

A pseudo-static in-plane loading procedure with a 24-cycle displacement control was applied to the specimens. For each cycle, the same displacement was repeated twice [34], as shown in Fig. 5.

Figure 5. Loading protocol.

2.2 Experimental Observations and Results

Cracks occurred in the infill walls under the in-plane shear deformation during the experiment. When the tilting angles of the infill wall were 15° and 30° , several inclined cracks were unidirectionally aligned (Fig. 6). For the tilting angles of 45° and 60° , major cracks were mostly crossed (Fig. 7). With an increase in deformation, these cracks became wider and more cracks were observed. When the tilting angle was 0° (i.e., no out-of-plane acceleration), no matter how severely the specimen was damaged, the infill blocks did not fall from the wall. In contrast, when the specimen tilted, the blocks fell progressively after cracking of the infill wall.

Figure 6. Specimens with unidirectional inclined cracks. (a) Tilting angle 15° . (b) Tilting angle 30° .

Figure 7. Specimens with crossed cracks. (a) Tilting angle 45° . (b) Tilting angle 60° .

Varying damage states of the 100-mm and 200-mm-thick infill wall specimens with different drift ratios are summarized in Tables 1 and 2, respectively. When the drift ratio reached $1/75$, the blocks started to fall from the 100-mm-thick infill wall. When the drift ratio reached $1/50$, falling blocks were observed from three 100-mm-thick specimens. By contrast, for the 200-mm-thick infill wall, only when the drift ratio reached $1/50$ and the specimen was

at the largest tilting angle (i.e., 0.87-g out-of-plane acceleration) did the blocks begin to fall, while the other three specimens did not experience falling blocks. This comparison indicated that, subjected to the same out-of-plane acceleration, the 100-mm-thick infill wall specimens were more prone to suffer from falling debris than the 200-mm-thick infill wall specimens. In addition, more blocks fell from the 100-mm-thick specimens when subjected to the same drift ratio and out-of-plane acceleration. In summary, infill blocks fell earlier and the falling area was larger for a thinner infill wall with larger tilting angle.

Table 1. Damage states of 100-mm-thick infill wall specimens

Out-of-plane acceleration	Drift ratio				
	1/100	1/75	1/50	1/30	>1/30
0.26 g
0.50 g
0.70 g
0.87 g

Table 2. Damage states of 200-mm-thick infill wall specimens

Out-of-plane acceleration	Drift ratio				
	1/100	1/75	1/50	1/30	>1/30
0.26 g
0.50 g
0.70 g

The percentage of falling area of the infill wall can be obtained by dividing the total area of falling blocks by the total area of the infill wall. The experimental results under different out-of-plane accelerations and drift ratios are listed in Table 3.

Table 3. Percentages of falling areas of infill wall specimens

Out-of-plane acceleration		Drift ratio							
		1/100	1/80	1/60	1/50	1/40	1/35	1/30	> 1/30
100-mm infill wall	0.26 g	0	0	0	0	6.0%	47.4%	68.8%	68.8%
	0.50 g	0	0	0	32.4%	60.1%	60.1%	88.7%	88.7%
	0.70 g	0	0	38.2%	52.5%	87.3%	87.3%	87.3%	87.3%
	0.87 g	0	48.1%	62.5%	62.5%	93.8%	93.8%	93.8%	93.8%
200-mm infill wall	0.26 g	0	0	0	0	0	0	0	2.1%
	0.50 g	0	0	0	0	0	0	3.1%	36.5%
	0.70 g	0	0	0	0	0.3%	0.3%	52.1%	52.1%
	0.87 g	0	0	0.3%	33.2%	68.8%	68.8%	68.8%	68.8%

2.3 Prediction Model for Falling Area of Infill Walls

For a masonry infill wall without out-of-plane acceleration (which means that the test specimen stood vertically), when the drift ratio exceeded 1/30, the test specimen was severely damaged. Some blocks were detached from others because of large cracks in the wall. However, these detached blocks were still interlocked with the surrounding blocks. Given nil out-of-plane resultant force, these blocks did not fall. Consequently, two conditions are required for the blocks to fall: (1) cracks continuously develop through the masonry infill wall, and (2) the out-of-plane resultant forces of the blocks are larger than the friction forces between the blocks. The falling area of the infill wall is related to its drift ratio, out-of-plane acceleration, and height-to-thickness ratio. According to the experimental results presented in Table 3, a logistic regression function is adopted leading to the proposed prediction model of the falling area, which is expressed as:

$$A_{debris} = A_{wall} \left(\frac{\lambda_{max}}{1 + e^{9.87 \times (1 - \gamma \Delta)}} \right), \quad (1)$$

where A_{debris} and A_{wall} represent the debris falling area and the total area of the masonry infill wall, respectively. λ_{max} represents the maximum percentage of the falling area, $\lambda_{\text{max}} = 1 - e^{-0.15\eta}$. η denotes the height-to-thickness ratio, Δ stands for the drift ratio, and γ is the correction factor, which is calculated using Eq. (2).

$$\gamma = 183.1\alpha^3 - 86.6\alpha^2 - 12.46\alpha^2\eta - 15.38\alpha + 13.36\alpha\eta, \quad (2)$$

where $\alpha = a_{\text{max}} / g$, and a_{max} denotes the maximum out-of-plane acceleration of the infill wall, and g represents the acceleration of gravity.

The comparison of experimental results and predictions of Eq. (1) is shown in Fig. 8. The proposed model can be used as the failure criterion of masonry infill walls to calculate the debris distribution of buildings.

Figure 8. Comparison of experiment results and predictions of Eq. (1) on falling area

3 CASE STUDY OF PEDESTRIAN EVACUATION CONSIDERING THE INFLUENCE OF FALLING DEBRIS

3.1 Brief Introduction of Evacuation Simulation Methodology

Falling debris from buildings hinders fast pedestrian evacuation. To quantify the influence of the falling debris, the framework of pedestrian evacuation simulation proposed by Lu et al. [14] is adopted herein (Fig. 9). This framework consists of four modules: (1) database of regional buildings and roads, (2) nonlinear time-history analysis of regional buildings, (3) prediction of falling debris distribution, and (4) pedestrian evacuation simulation considering the influence of the falling debris. Details of the methodology can be found in Lu et al. [14], and four modules are briefly introduced as follows.

Figure 9. The framework of pedestrian evacuation simulation [14].

In Module 1, a database of regional buildings and roads needs to be established first. This database contains building information, road information, emergency shelter locations, and population distribution. The attribute data of buildings (e.g., building height, number of stories, and structural type) can be obtained from a city database [35] or field investigation [36]. The locations of buildings and emergency shelters, as well as the road information, can be obtained from Google Maps [37] or OpenStreetMap [38].

In Module 2, nonlinear multi-degree-of-freedom models (including the multiple degree-of-freedom (MDOF) shear model for multi-story frame and masonry structures, and the MDOF flexural-shear model for tall buildings) are adopted to complete the regional building modeling [39,40] through a nonlinear time-history analysis, by which satisfactory computational accuracy and efficiency can be achieved. Subsequently, time histories of the displacement, velocity, and acceleration for each story of each building are obtained.

In Module 3, when a masonry infill wall reaches a certain drift ratio and out-of-plane acceleration, crack starts to develop and falling debris is induced. It should be noted that, due to considerable deviations of the drift ratio limits of masonry infill walls, a parametric discussion was conducted in Lu et al.'s work [14]. As the failure criterion for masonry infill walls has been proposed in Section 2, it is thus adopted herein to determine the percentage of falling area of the infill wall. Subsequently, based on the debris distribution models of each floor [14], the hazard range of falling debris and the debris coverage percentages on roads can be identified.

In Module 4, the simulation of pedestrian evacuation, taking into account the falling debris, covers two parts: construction of evacuation environment and modeling of human behavior. The evacuation environment can be determined by employing the road information and the locations of buildings and emergency shelters. Debris distribution obtained in Module 3 will also be employed in the evacuation environment. When the pedestrians pass through the areas covered by falling debris, their moving speed will change, which can be determined by the pedestrian speed models considering debris proposed by Lu et al. [14]. According to the experiment of the pedestrian movement [14], it is found that when the percentage of debris coverage on the road reaches 25%, pedestrians can hardly pass through. Therefore, these roads are set as blocked areas. Meanwhile, roads with the percentage of debris coverage being lower than 25% are set as reduced-speed areas. After establishing the evacuation scenario, simulation of pedestrian evacuation can then be performed by using the widely used evacuation software, Viswalk [41,42].

3.2 Introduction of the Case Study Area

The teaching areas of Tsinghua University consists of 15 buildings, most of which are teaching buildings and research laboratories. This area houses a significant number of students and academics during lecture and tutorial times. Therefore, this area is selected to perform a case study of the earthquake-induced debris calculation and pedestrian evacuation. A playground located in the northeast of the teaching area is designated as the emergency shelter [43,44]. The building occupants are required to be evacuated to the playground during emergencies. The teaching area, shown in Fig. 10, has a gross area of approximately 0.22 km², where the blue slashes polygons denote the buildings, the solid green areas denote the roads, and the green rectangle with grids denotes the emergency shelter.

Figure 10. Schematic diagram of teaching areas.

FEMA P-58 defines the number of people in buildings with different occupancies [45]. Consequently, the population in each building can be predicted using FEMA P-58 and building attribute data. The basic information of the buildings is given in Table 4.

Table 4. Basic information of the buildings

No.	Number of stories	Building occupancy	Population
1	5	Education	1190
2	9	Education	740
3	4	Education	360
4	4	Research laboratories	265
5	2	Research laboratories	75
6	1	Research laboratories	70
7	3	Education	450
8	3	Education	490
9	5	Education	590
10	4	Commercial office	430
11	5	Education	660
12	2	Education	480
13	2	Research laboratories	235
14	5	Research laboratories	125
15	2	Research laboratories	70

According to the Chinese Code for Seismic Design of Buildings [46], this area has an eight-degree seismic design intensity. The peak ground acceleration (PGA) is 200 cm/s^2 for a Design Basis Earthquake (DBE) with a return period of 475 years, and the PGA is 400 cm/s^2 for a Maximum Considered Earthquake (MCE) with a return period of 2475 years.

The widely used El-Centro ground motion record is selected as a typical ground motion input. Three evacuation scenarios are then established herein:

Scenario 1: Pedestrian evacuation scenario without debris;

Scenario 2: Pedestrian evacuation scenario with debris, where the peak ground acceleration is scaled to 200 cm/s^2 ; and

Scenario 3: Pedestrian evacuation scenario with debris, where the peak ground acceleration is scaled to 400 cm/s^2 .

Note that according to the Chinese seismic design codes [46], the building should be prevented from collapse when subjected to DBE or MCE. As a consequence, no collapsed building is considered in this simulation.

When calculating the debris distribution, Eq. (1) proposed in Section 2 is adopted as the failure criterion for the masonry infill walls. The height-to-thickness ratio of an infill wall is determined according to the design information. The other two parameters in Eqs. (1) and (2), i.e., the drift ratio and out-of-plane acceleration, can be acquired from the time history analysis results.

3.3 Simulation Results and Discussion

The debris distributions of the two evacuation scenarios (2 and 3) are illustrated in Fig. 11. The red polygons denote the blocked areas, where pedestrians cannot pass through; the yellow polygons represent the reduced-speed areas, suggesting reduced speed of people when passing through owing to falling debris. Compared to Scenario 1, where there is no debris, the evacuation of people in Scenario 2 is seldom influenced by falling debris. As the figures reveal, in Scenario 2 ($\text{PGA} = 200 \text{ cm/s}^2$), only 1-m wide reduced-speed areas exist around Building #1, and there is no debris around the other buildings. However, in Scenario 3 ($\text{PGA} = 400 \text{ cm/s}^2$), some areas of the 7-m wide road adjacent to Building #1, Building #2, and Building #3 are covered by falling debris. The blocked width of Road A is 3 m, while that of Road B is 5 m, which indicates that these two roads are at higher risk from falling debris. In

addition, a 2-m wide passage of Road C is blocked. There are no blocked areas on other roads in Scenario 3, but the reduced-speed areas are more than those in Scenario 2, where the pedestrians' speed are affected.

Figure 11. Debris distribution. (a) $PGA = 200 \text{ cm/s}^2$ (Scenario 2). (b) $PGA = 400 \text{ cm/s}^2$ (Scenario 3).

Pedestrian evacuations under the abovementioned three scenarios are simulated. The falling debris mainly cover the roads around Building #1, Building #2, and Building #3, and the number of occupants in these densely built-up areas accounts for more than 36% of the entire teaching area. Therefore, the evacuation process for these people is analyzed in particular, and the evacuation outcomes are shown in Fig. 12. For occupants in Building #1 and Building #3, the average evacuation distances in the three scenarios are almost the same

(Fig. 12a). The reason is that the roads in these three scenarios are not entirely blocked despite the existence of falling debris (Fig. 11). Consequently, people do not need to detour. As Fig. 11a shows, in Scenario 2, the roads around Building #1 only have a 1-m wide blocked area, and there is no debris around Building #3, which has almost no effect on the pedestrian evacuation. Therefore, the average evacuation times in Scenario 1 and Scenario 2 are identical for people in Building #1 and Building #3. In Scenario 3, there is basically no change in the average evacuation distance, which means that falling debris does not change the original evacuation routes of most pedestrians. However, the presence of falling debris results in a 41% increase in the average evacuation time for people in Building #1 and a 31% increase for people in Building #3 (Fig. 12b). These increased rates are significant.

Figure 12. Comparison of evacuation outcomes (Building #1 and Building #3). (a) Average evacuation distance. (b) Average evacuation time.

The evacuation times of the three scenarios are shown in Table 5 and Fig. 13. It takes 707 s for all the people to reach the emergency shelter in Scenario 1 (i.e., without debris). The evacuation time of Scenario 2 (PGA $\frac{1}{4}$ 200 cm/s²) is almost equal to that of Scenario 1, which is consistent with the aforementioned analysis of the debris distribution. Compared to Scenario 1, the total evacuation time is approximately 5% longer in Scenario 3 when subjected to MCE. Similar conclusions can be drawn when considering the clearance time of 95% of the evacuees: the evacuation times of Scenario 1 and Scenario 2 are still close, and that of Scenario 3 increases by approximately 8% compared to that of Scenario 1.

Table 5. Comparison of evacuation time in different scenarios

No.	Evacuation scenario	Clearance time (95% evacuees) (s)	Total evacuation time (100% evacuees) (s)
1	No debris	565	707
2	Debris, PGA = 200 cm/s ²	568	708
3	Debris, PGA = 400 cm/s ²	609	741

333 **Figure 13.** Comparison of different evacuation scenarios.

334

335 The results of this case study reveal that a considerable area of roads located in densely
336 built-up areas is covered by debris, resulting in a significant increase in the evacuation time
337 of people in the nearby buildings. These people are at higher risk during the emergency
338 evacuation. Therefore, when conducting a regional evacuation analysis, we should focus not
339 only on the total evacuation process but also pay more attention to people in densely built-up
340 areas and quantify the influence of falling debris on their evacuation time and distance.

341 **4 CONCLUSIONS**

342 In order to study the seismic performance of masonry infill walls and the initiation of
343 falling debris, a new experimental methodology of earthquake-induced debris from masonry
344 infill walls is proposed. This methodology considers the influence of the in-plane drift ratio
345 and the out-of-plane acceleration. Ten infill wall specimens were then tested. Based on the
346 experimental results, a case study of the teaching area on the Tsinghua University campus
347 was selected to perform a seismic debris distribution calculation and pedestrian evacuation
348 simulation. The following conclusions were obtained:

- 349 (1) The percentage of falling area of the infill wall is related to its drift ratio, out-of-plane
350 acceleration, and height-to-thickness ratio. Subjected to the same out-of-plane acceleration,
351 the 100- mm-thick infill walls are more prone to produce falling debris than the 200-mm-
352 thick infill walls. In addition, more blocks fall from the 100-mm-thick walls when subjected
353 to the same drift ratio and out-of-plane acceleration.

(2) A larger drift ratio, out-of-plane acceleration, and height-to-thickness ratio lead to a higher percentage of falling area. When the out-of-plane acceleration is zero, no falling debris was observed even if the infill wall was severely damaged.

(3) A prediction model of the falling area is proposed based on the experimental results. This can be adopted as the falling criteria for a masonry infill wall and applied for the earthquake-induced debris calculation.

(4) The case study shows that the total evacuation time in Scenario 2 is close to that in Scenario 1, and that of Scenario 3 is approximately 5% longer compared to Scenario 1.

(5) When the falling debris does not entirely block a road, the evacuation distance changes little for people in densely built-up areas. However, the presence of large amounts of debris was found to significantly increase the evacuation time. This should be taken into sufficient consideration during evacuation drills and emergency rescue operations.

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