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Overview and Progress of Research on the Seismic Performance of Masonry Walls with Openings

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Abstract

This paper reviews recent progress in research on the seismic performance impacts of openings in masonry walls. The article provides a comprehensive analysis from three aspects: performance characteristics of walls with openings, finite element analysis, and reinforcement techniques. It discusses how the size, shape, and location of openings affect the structural performance of walls and how various reinforcement measures can enhance the seismic capacity of these walls. The study demonstrates that rational design of openings and effective reinforcement measures can significantly improve the safety and seismic resilience of masonry structures.

Keywords

Masonry Wall Openings; Seismic Performance; Finite Element Analysis; Reinforcement Techniques.

1. Introduction

Recent years have seen continuous advancements in architectural design concepts and rapid developments in building technology, making openings in building walls an important method for achieving diversified architectural functions and flexibility in interior spaces. The technical issues related to wall openings and their impact on the structural performance of buildings have thus become a focal area in engineering and technological research.

Masonry walls, as traditional and widely used load-bearing structures, are directly related to the safety, reliability, and functionality of buildings. With constant innovation in architectural design and increasing demands for building functions, creating openings not only has to consider aesthetic and practical requirements but also minimize the impact on the mechanical performance of the walls. Consequently, scholars both domestically and internationally have conducted extensive research on masonry wall openings, examining their effects on the walls' load-bearing capacity, stiffness, durability, and seismic performance, while also exploring various reinforcement and optimization design methods to ensure that structural performance remains secure while meeting functional requirements.

This paper aims to provide a comprehensive review of the latest developments in the study of masonry wall openings worldwide. By comparing the performance of masonry walls before and after the creation of openings, assessing the impact of different opening parameters on structural performance, and summarizing the application of current reinforcement technologies, this review seeks to guide future research and offer theoretical references and technical support for practical engineering projects.

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2. Experimental Studies on Masonry Wall Openings

Experimental research on masonry walls with openings aims to assess their seismic performance under various conditions. These experiments typically involve designing openings of different shapes, sizes, and positions within the walls, and applying vertical axial loads and horizontal low-cycle reciprocating external loads to simulate real earthquake scenarios.

To compare the seismic performance of intact walls versus those with openings, researchers such as Liu Xianming [1] and Tian Shuming [2] have found that walls undergo a prolonged elastic phase before reaching ultimate load capacity. Walls with openings show a similar trend in stiffness degradation as intact walls, but intact walls exhibit greater stiffness and maintain higher stiffness even when damaged. Compared to walls without openings, walls with openings have significantly increased crack displacement, cracking loads, and ultimate loads, while their ultimate displacement decreases; walls with openings also deform more quickly, have reduced ductility, and have diminished energy absorption capabilities.

Research from practical engineering projects has found that the variation in the opening ratio is becoming one of the important factors affecting the seismic performance of masonry walls. Studies by Yáñez F[3], Liu Guiqiu[4], and Voon K C[5] on the impact of the opening ratio on wall seismic performance reveal that when the opening area is below 11%, there is no significant decrease in wall stiffness; the material and size of the opening play a decisive role in wall performance. Even with larger openings, reinforced brick walls retain good deformability. An increase in the opening ratio has a significant impact on the stress at the corners of the openings, hence during design, the size of the openings should be controlled to avoid overly large openings; when openings are moved downwards or offset, the wall is more likely to suffer from bending failures, so openings should be avoided in unfavorable positions. The main study focused on the impact of opening size on the lateral load-bearing capacity of the wall, showing that as the size of the opening increases, the lateral strength of the wall significantly decreases. Scholars compared these experimental results with the New Zealand masonry design standard NZS4229 and found that the standard is conservative in predicting the lateral load capacity of walls with small openings, but overly optimistic for walls with larger openings.**

In recent years, to better innovate and develop masonry structural systems, scholars have further discussed how changes in various parameters, including the position, size, and shape of openings, affect the seismic performance of walls. Research by Parisi F[6], Jasiński R[7][8], and Li Chao[9] on the impact of openings on the seismic performance of brick walls shows that the closer the openings are to the top of the wall, the lower the load-bearing capacity of the wall; circular openings in walls have higher load-bearing capacity than rectangular openings; when the opening area increases, the load-bearing capacity of the wall significantly decreases. The shape of the opening significantly affects the wall stiffness, crack development, and stress at failure; as the size of the opening increases, the wall's shear strength and stress at failure decrease. The shear strength of unreinforced walls increases with the addition of pre-stress; using reinforced materials can effectively improve the wall's crack resistance and damage capacity. Openings weaken the wall's horizontal load-bearing capacity and lateral stiffness, and opening a single small hole reduces the ductility of the wall; both the load-bearing capacity and initial stiffness of the wall decrease with an increasing opening ratio, but ductility first decreases then increases; in terms of opening positions, openings near the base significantly reduce the wall's seismic performance, while openings in the middle to upper part of the wall have less impact on seismic performance.

3. Finite Element Analysis of Masonry Wall Openings

In recent years, with the application of finite element software, numerical simulation has become an important method for engineering research and analysis. To expand engineering applications and save on testing costs, scholars have proposed various finite element calculation models to analyze the seismic performance of masonry walls.

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Following the experimental studies mentioned above, it has been found that the configuration of wall openings is closely related to their seismic performance. To enhance the practical application of the seismic performance of masonry shear walls with openings, researchers like Gouda Ghanem[10] have used finite element software to analyze the effects of changing the position and size of openings in reinforced masonry shear walls. The studies found that wall stiffness and load-bearing capacity decrease with an increasing opening ratio, while energy dissipation capacity and non-linear deformation capabilities are enhanced. Compared to the position of openings, the opening ratio has a greater impact on the wall's seismic performance. Gao Qiumei[11] analyzed the performance of masonry structural load-bearing walls after openings were made, investigating the impact of different shaped openings on the mechanical properties of walls and using finite element software to determine the relationship between opening size and stress distribution. The study showed that different shaped openings lead to stress concentration and increased localized strain, thereby exacerbating wall deformation and damage; wall stiffness decreases, and horizontal displacement increases after openings are made. Wei Yingrong[12] used Abaqus to analyze the mechanical performance of brick masonry shear walls under the influence of openings, revealing that the size of the opening has the most significant impact on the wall's load-bearing capabilities; stress concentration near the openings leads to "X" shaped cracks, significantly reducing load capacity. Bagheri H[13] and others used the finite element method (FEM) to study the impact of different sizes and positions of openings on the mechanical performance of unreinforced brick walls, finding that circular openings distribute stress more evenly and reduce edge effects, optimizing structural performance, while sharp-angled, square openings at the corners of openings tend to concentrate stress, affecting wall stability. Thus, it is necessary to identify better shapes for openings to enhance the wall's seismic performance.Huang Yi and others [14] used software to analyze the effects of different opening ratios and numbers of openings on the structural performance of walls. The results indicate that as the opening ratio increases, the load-bearing capacity of the wall decreases, the rate of degradation in relative stiffness increases, and the more openings there are, the quicker the lateral stiffness of the structure decreases. Therefore, buildings with higher opening ratios and more openings are more susceptible to damage during earthquakes. Mughal U A and others [15] conducted studies using a simplified model to investigate the effects of different sizes of openings and the aspect ratios of walls on the strength of masonry walls. The model included openings of 0%, 1.85%, 3.66%, 10.91%, and 16.5% of the total wall area. The studies show that when the opening area reaches 4%, the strength and stiffness of the masonry wall decrease by approximately 50%, and as the opening area increases beyond 4%, the strength and stiffness of the wall continue to decline linearly.

To better understand the impact of wall openings on the overall structure, Xinren [16] and Zhang Wangxi [17] conducted numerical simulations to analyze the stress distribution in walls with openings under seismic effects. The research found that walls develop stress concentrations at the edges of openings after being opened, making them prone to forming cracks. As the intensity of earthquakes increases, the expansion and damage of these cracks intensify. The structural support capacity of buildings significantly weakens with an increase in the number of openings in the lower horizontal walls, leading to a higher likelihood of collapse or instability.

4. Reinforcement Measures for Masonry Walls with Openings

In recent years, as national attention to building safety has increased, research into masonry wall openings has become an imperative trend. Appropriate reinforcement methods can not only prevent structural damage but also accommodate the functional needs of buildings.

Initially, scholars employed traditional methods for reinforcement. Zhang Hong [18] conducted a mechanical performance analysis of a beam-column masonry load-bearing wall with openings, confirming that openings lead to stress redistribution and weaken the overall integrity of the wall; experiments using beam-columns effectively enhanced the wall's load-bearing capacity, ensuring the overall safety of the building. Yang Wei [19] and others conducted quasi-static tests on open-hole brick walls in rural areas around Beijing, comparing three groups of walls in terms of their damage

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processes, load-bearing capacity, and displacement changes. They found that the corners of the openings were weak spots for seismic resistance. Detailed analyses of these weak spots were followed by reinforcement using galvanized iron wire mesh, brickwork, and twisted wire mesh.

With the advancement of science and technology, an increasing number of new materials have been applied in actual engineering projects. Gu Qian [20] and others explored the damage morphology, force characteristics, and reinforcement effects of carbon fiber cloth and sprayed GFRP on masonry walls with door and window openings. Experimental results showed that applying carbon fiber cloth can improve the seismic performance and shear load capacity of walls with door and window openings. The authors proposed a shear load capacity calculation model for reinforced masonry wall sections with openings, and validated it against experimental results; the specimens reinforced with sprayed GFRP showed significantly improved ultimate load capacity, ductility, and energy absorption capabilities, offering better protection for door openings and enhancing displacement ductility and ultimate load capacity. Cheng Shuaian [21] and others conducted experimental studies on the performance of brick walls reinforced with different fiber-reinforced materials. The results indicated that different reinforcement methods impacted the shear performance, pseudoplasticity, and energy absorption capacity of brick walls. Among these, Textile Reinforced Concrete (TRC) showed better reinforcement effects, while Fiber Reinforced Polymer (FRP) was slightly less effective.

5. Conclusion and Future Outlook

5.1 Conclusion

(1) Wall openings typically result in a reduction of the overall stiffness, load-bearing capacity, and shear strength of the wall. The size, position, and shape of the openings significantly impact the performance of the wall. For instance, larger openings or openings in disadvantageous positions worsen the structural performance of the wall. However, when the opening area is relatively small, the reduction in wall stiffness is not significant. Walls with openings are more susceptible to cracks and damage under the influence of external forces such as earthquakes, with stress concentrations likely to occur around the edges of the openings.

(2) Using different reinforcement materials and techniques can effectively enhance the seismic performance of masonry walls with openings. For example, reinforcing methods such as carbon fiber cloth and sprayed GFRP can significantly improve the load-bearing capacity and ductility of the walls, thereby increasing their seismic resilience. The reinforcement with Engineered Cementitious Composites (ECC) also shows potential in enhancing the ductility and seismic performance of masonry walls.

(3) In the design and construction of masonry structures, the size and location of openings should be considered to avoid placing large openings in structurally disadvantageous positions. At the same time, appropriate reinforcement methods should be selected based on specific circumstances to enhance the safety and functionality of masonry structures during earthquakes.

5.2 Future Outlook

Scholars have conducted in-depth studies on the impact of changing hole parameters on the seismic performance of masonry walls, and these studies have played a significant role in advancing the development of open-hole masonry walls. Future discussions and analyses could be expanded in the following areas:

(1) To promote sustainable development, further research could be conducted on the seismic performance of open-hole ecological composite masonry walls to better advance the application of ecological composite masonry walls in practical engineering.

(2) Develop more effective reinforcement technologies to better meet the requirements for building seismic performance.

(3) Integrate open-hole research with actual engineering cases, study the effect of theoretical research and practical application, and thereby better guide practical engineering.

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