Finite Element Analysis of NPR Steel Reinforcement for Enhancing Seismic Resistance of Masonry Walls

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Abstract

Masonry structures are widely used in industrial and civil buildings in China and are a structural form with a long history and widespread application. However, masonry structures have a high self-weight and low resistance to shear, bending, and tensile forces, as well as poor seismic performance. When an earthquake strikes, masonry structures are severely damaged, posing a great threat to our lives and property safety. Many masonry structures in use today have been in service for a long time, and their seismic resistance may no longer meet the requirements of current regulations. Reinforcement is the best solution to this problem. The NPR material and structure developed by academician He Manchao will contract horizontally (expand laterally) under uniaxial pressure (tension), and it has excellent impact resistance, shear resistance, and energy absorption properties. The "steel bar mortar strip reinforcement method" is a new method of reinforcement that can comprehensively improve the wall's seismic performance.

Keywords

NPR Steel-Concrete Strip Reinforcement; Masonry Walls; Finite Element Analysis; Shear Resistance.

1. Introduction

Masonry structure is a load-bearing structure made of brick or stone and cement mortar. It has the advantages of convenient materials, low price, simple construction and high structural strength, and was widely used in religious, military and political buildings in the past. Wan Li Great Wall in northern China, Zhao Zhouqiao in Shijiazhuang, pyramids in Egypt, Colosseum in Rome and other famous buildings represent the lofty position of masonry structure in the history of world architecture.

Since the reform and opening up, China's economy has developed rapidly, and the number of Chinese people has exploded. A large number of civil houses, factories and warehouses have been built, most of which are brick masonry structures, and the annual output of bricks once accounted for half of the world's total output. Due to the lack of seismic awareness, and limited by traffic conditions and economic level, masonry houses are built with the purpose of saving money while meeting the use function. The building site selection is random, the design and construction are not standardized, and the structure is simple [1]. Without necessary anti-seismic measures, the wall may crack in the event of a minor earthquake. With the increase of living time, influenced by factors such as freezing and thawing, high temperature, wind and rain, the wall is prone to cracking and tilting in different degrees, but it lacks necessary maintenance and repair, and the security risks are increasing. Most of the existing masonry buildings in China cannot meet the current seismic codes and regulations [2], and their ability to cope with earthquake disasters is unimaginable. The survey results after many earthquakes show that the masonry structure is the most seriously damaged building in the earthquake, and the failure forms of masonry structure are generally shear failure and bending failure.

2. Strengthening method of masonry structure

At present, there is an urgent need for seismic strengthening of various building structures in China, and appropriate strengthening measures can effectively improve the seismic performance of masonry structures [4]. Scholars at home and abroad have carried out many relevant experimental studies, and the research on masonry reinforcement has developed rapidly. Masonry reinforcement in China mostly adopts traditional reinforcement methods [5], which are mainly divided into two types:

2.1. Direct reinforcement method

2.1.1. Paste material reinforcement method [6]

By riveting and binding high-performance materials, the materials are stuck on the wall surface along the direction of crack propagation. The method of strengthening by sticking materials is easy to operate, and it can effectively improve the cracking performance and bearing capacity of masonry without changing the original structural size. However, the materials that meet the reinforcement conditions are often expensive and difficult to popularize in a large area. And because the reinforcement materials are often exposed to the air, the requirements for the reinforcement environment are high during long-term reinforcement.

2.1.2. Bonding steel plate reinforcement method [7]

Bonding steel plate reinforcement method sticks steel plates with appropriate thickness to the surface of masonry wall by adhesive, so that they are firmly combined together and the steel plates can strengthen the wall. Its advantage is that it can ensure the integrity of the wall; Simple construction; The construction period is short. However, the bonding effect of adhesive will become worse when heated, and the cost of this reinforcement method is high.

2.1.3. Reinforcement method of cement mortar surface with steel mesh [8]

This method is suitable for the wall which is not seriously damaged. By setting steel mesh on the wall surface and spraying cement mortar to cover it, a plywood wall of 20~30mm is formed. When the wall is reinforced on both sides, 500mm through-wall steel bars can be used for anchoring, and when the wall is reinforced on one side, U-shaped steel bars can be used for anchoring the steel mesh into the wall. The construction site of cement mortar surface reinforcement method with steel mesh is flexible; The economic benefit is higher than other methods. The construction period is short, and the construction period is almost unaffected by external factors.

2.2. Indirect reinforcement method

2.2.1. Adding buttress column reinforcement method [9]

Adding buttress column reinforcement method Setting buttress columns on the outside of masonry has indirect reinforcement effects such as supporting and limiting the wall. This method has the advantages of low cost and flexible location, and can strengthen the integrity and stability of masonry structure. However, the effect of improving the seismic performance of the wall is poor, so the cast-in-place concrete must be supported by formwork, and the construction time is relatively long.

2.2.2. The method of strengthening with external steel.

Steel-wrapped reinforcement method is to wrap steel or angle steel around brick columns and connect them with battens in the transverse direction to form the whole force. According to whether there is shear force transfer between steel and the original structure, it can be divided into two reinforcement methods: wet steel-wrapped reinforcement and dry steel-wrapped reinforcement [10]. This method has the advantages of simple construction, less on-site workload and wet work, and more reliable stress. It is suitable for strengthening masonry columns that are not allowed to increase the cross-sectional size of the original members, but require a substantial increase in the cross-sectional bearing capacity. Its disadvantage is that the cost of reinforcement is high, and protective measures similar to steel structures need to be adopted.

To sum up, experts at home and abroad put forward a variety of masonry reinforcement methods, and carried out many tests and analysis. The above reinforcement methods can effectively improve the seismic performance of masonry structures, and can meet most reinforcement requirements in practical projects. However, these methods all have certain shortcomings, and some have high requirements for the environment; Some construction periods are too long; Some will greatly affect the appearance of the building. Therefore, we need to constantly seek new reinforcement methods, and strengthen and transform the masonry that needs to be strengthened in strict accordance with the requirements of national codes [11]. In this paper, the strip reinforcement method of steel bar-mortar surface layer is adopted. Compared with the existing reinforcement method of steel mesh cement mortar surface layer, this method has clear mechanical mechanism, can greatly improve the bearing capacity on the basis of the mother wall, has less improvement on stiffness, lower construction technical difficulty, wide material sources and less material requirements.

3. NPR reinforcement research status

Poisson's ratio is an important physical parameter to characterize the properties of metals, also known as transverse coefficient of variation, which is the ratio of transverse strain to longitudinal strain when metals are stretched or compressed. It is an important parameter to reflect the shape of metal materials. In the world we live in, most substances are positive Poisson's ratio, that is, they will contract laterally under pressure and expand under tension. NPR The study of negative Poisson's ratio first appeared in the west. In 1927, AEH.LOVE[12] first discovered the negative Poisson's ratio effect in pyrite. In 1982 [13], Professor Ashby of Cambridge University discovered cellular materials with Negativepoisson,sration effect when deformed, and put forward the concept of negative Poisson and Sration.

In recent years, in order to give full play to the excellent performance of NPR materials in impact resistance, shear resistance and energy absorption, He Manchao first put forward the concept of NPR support and mechanical behavior, and invented a new type of constant resistance and large deformation anchor cable with NPR structure [14]. He Manchao, Guo Zhibiao and others [15] found through experiments that the large deformation anchor cable absorbs energy through structural deformation to ensure the stability of working resistance and deformation.

He Manchao put forward micro-NPR material (the concept of NPR steel material) in 2014. By changing the molecular state of the structure, it can produce lower Poisson's ratio in the plastic stage. A metal material NPR steel bar with microscopic negative Poisson's ratio effect was studied by metallurgical method. NPR steel bar has microscopic negative Poisson's ratio performance, tensile strength can reach 300-1200MPa and elongation can reach 30%-70%. In fact, it can produce obvious volume expansion and achieve high uniform elongation when it is under plastic strain.

NPR steel bars have great potential application value, and are very suitable for occasions requiring large deformation, high stress and ductility, and large strain value, such as energy mines, traffic tunnels, bridge engineering, etc. After several years of research, NPR steel bar has been successfully developed, which has high strength, high toughness and high uniform extension, and has the characteristics of non-magnetic and anti-magnetic field strengthening and energy absorption. Effectively improve the seismic performance and safety of the project.

Gu[16] and others studied the mechanical properties and plastic constitutive model of NPR steel in the monotonic tensile mechanics experiment. In this experiment, NPR steel achieved the combination of high strength and high ductility, with yield strength of 398MPa, tensile strength of 880MPa, uniform elongation of 55.3% and elongation after fracture of 61.7%. Uniform elongation accounts for a high proportion in the total elongation, so NPR steel has a small size effect. The Poisson's ratio of steel is defined as 0.5 in the classical plastic theory, while the Poisson's ratio of NPR steel drops to 0.44 in the plastic stage, showing a high volume expansion rate.

Shang Huaishuai [17][18] analyzed the chemical composition, Rockwell hardness and metallographic structure of NPR steel bar, and carried out the static tensile mechanical properties test. It is found that the yield strength, tensile strength, tensile rate after breaking and total tensile rate of maximum force of NPR steel bars are obviously improved compared with ordinary steel bars. In order to find out whether NPR steel bars can be applied to marine concrete structures, the bond performance between NPR steel bars and marine concrete was studied by center pull-out experiment. It is found that the bond performance of NPR reinforcement is worse than that of ordinary reinforcement, and the diameter and bond strength of reinforcement have similar influence laws on the two types of reinforcement.

4. Research status of masonry reinforcement at home and abroad

4.1. Experimental study on strengthening masonry wall at home and abroad

Masonry structure is the most widely used building structure, and how to enhance its seismic performance has been widely concerned by experts and scholars at home and abroad. Reliable data can be obtained by trial and error in experimental research. The relevant experimental research on masonry structure reinforcement is as follows:

Medeiros[19] and others studied the seismic performance of six brick walls with different reinforcement methods. The test shows that wall reinforcement can improve the rigidity and integrity of the wall, horizontal reinforcement can improve the bearing capacity and ductility of the wall, and different reinforcement anchorage methods have different improvement effects. CAPOZUCCA[20] and others used GFRP to strengthen historical brick walls unilaterally, and carried out quasi-static tests on them. It is found that GFRP is gradually strengthened with the increase of experimental load, which improves the deformation and energy consumption of the wall. When GFRP debonds, the masonry cracks.

Lv Beiyun [21] carried out horizontal monotonic loading tests on five masonry walls strengthened with prestressed steel plates, and analyzed the variable parameters with the factors such as the spacing of transverse steel plates, the prestress of steel plates and the strength of steel plates. The failure characteristics of the wall under different parameters are compared, and it is found that the shear bearing capacity of the strengthened masonry wall is increased by 30%~60% on the basis of unreinforced masonry wall.

LuisMercedes[22] and others strengthened masonry structures with plant fibers and carried out reciprocating loading tests. The experimental structure shows that plant fiber reinforcement can effectively enhance the shear bearing capacity, energy consumption capacity, crack generation and propagation and ductility of the wall; With the increase of plant fiber content, the ductility of the wall first increases and then decreases. The wall transformed with plant fiber can realize the reuse of resources.

Yu Jianmin [23] strengthened five brick walls with the size of 1000mm×1200mm×240mm by shotcrete with steel mesh, and there were concrete ring beams on the top and bottom of the brick walls, and the influence of the thickness of concrete panels on the reinforcement effect was studied. The results show that the bearing capacity of concrete slab wall increases first and then decreases with the increase of slab thickness under the same reinforcement conditions.

4.2. Numerical analysis and research on masonry wall reinforcement at home and abroad

Although the experimental research is intuitive and reliable, it also has the problems of long period and high cost. With the continuous development of computer technology and the gradual maturity of masonry theory, there are more and more numerical analysis on masonry. Combining experiments with finite element analysis can not only verify the correctness of simulation, but also expand the research field, which has become an efficient research approach. Related masonry reinforcement research is as follows:

Amjadj. Aref, Kiarashm. Dolat Shahi [24,25,26], etc. used ABAQUS to analyze the failure mode of the unit reinforced masonry wall in the horizontal direction, and analyzed it with the number of cycles as a variable parameter. When the horizontal load is monotonous, the shear inclined cracks are formed when the wall is destroyed. X-shaped shear cracks are formed in the wall when cyclic horizontal load is applied. Compared with the experimental results, the feasibility of modeling is verified. MohammedS.Mohammed[27] simulated and analyzed the shear performance of unreinforced masonry walls. In this paper, a new modeling idea is adopted, and the role of mortar is simulated by defining the contact surface model. Compared with the experiment, it is found that this modeling can simulate the slip and crack between mortar and block well.

In 2014, Dai Ruzhi et al. [28] put forward the embedded reinforcement method, and used ANSYS to model the masonry separately by coupling method. Because the masonry structure is a composite material, three elements were selected to model it. The extraction principle of calculation results is expounded, and the error between theoretical calculation results and model extraction results is less than 3%, which shows that it is feasible to use ANSYS to simulate the reinforcement of masonry. Because the coupling method fails to consider the bond-slip effect between mortar and brick, it cannot simulate the real stress state between brick and mortar.

In 2017, Qin Yu et al. [29] used LS-DYNA to simulate the discrete model of two-story masonry structure with three different reinforcement measures (no reinforcement, only one-story reinforcement and double-story reinforcement), and studied its mechanical response and cracking and collapse behavior under earthquake. However, the bilinear relationship can not simulate the plastic behavior of mortar well; Treating the ground as a rigid body ignores the difference between site soil properties and near-far field seismic characteristics.

In 2013, Xu Zhijian et al. [30] established a finite element model of masonry structure strengthened with externally bonded steel plates by using MARC, and analyzed the shear performance of the wall under monotonic loading according to factors such as steel plate thickness and steel yield strength. The "dispersed steel plate model" is used to disperse the steel into the masonry, so the model can not simulate the failure mode of the wall.

In 2017, Chu Shaohui [31] and others used ABAQUS software to establish an integral model of masonry walls strengthened with carbon fiber sheets, and studied the strengthening performance, and made variable parameter analysis on the vertical compressive stress, height-width ratio and number of layers of carbon fiber sheets on the walls. Because the S4R shell element is used to simulate the carbon fiber cloth, it can not simulate the collapse phenomenon of the carbon fiber cloth in the test process, and the calculated ultimate load, ductility coefficient and other indicators have great deviations.

In 2015, Zhang Si [32] and others established a separate model of masonry strengthened with fiber cloth by ABAQUS, and used zero-thickness unit COH3D8 to simulate mortar. The reinforcement effect of the wall is studied by simulating low-cycle reciprocating loading, and compared with the experimental results and code calculation results, which proves the correctness of the modeling. Because the carbon fiber cloth is bound to the surface of masonry in the modeling process, it is impossible to simulate the sliding and peeling between the carbon fiber cloth and masonry.

In 2019, G.P.Lignola[33] and others established a plane finite element model of masonry with finite element software DIANA, and analyzed the diagonal compression performance of fiber reinforced cement-based masonry (FRCM). Because of the limitation of two-dimensional plane, the model can not reflect the overall spatial performance of masonry.

Yang Xubo [34] established a masonry model strengthened with bonded steel-polymer mortar surface by ABAQUS, and studied the cracking performance of the wall with the aspect ratio, axial compression ratio and mortar strength as variables. It is found that the overall simulation result is good, but the simulation error is large, and the modeling method needs to be further improved. Fan Wangsheng [35] established the model of unreinforced masonry wall by ABAQUS, and studied the different failure modes of the wall with the factors of wall height-width ratio, limb node height-width ratio and vertical compressive stress as variables. Because of the integral modeling, the damage of the bottom of the wall is not considered.

5. Conclusion

In this paper, the shortcomings of masonry walls are summarized, and the methods of masonry reinforcement at home and abroad are analyzed. Combined with the advantages of NPR steel bars, the reinforcement method of NPR reinforced mortar strips for masonry walls is put forward.

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