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New Low-interference Seismic Strengthening Method for Masonry Structures

Lei Zhu[1] and Congfeng Sun[2]

[1] *Department of Civil Engineering, Hefei University, Hefei, Anhui, 230601, China*
[2] *The Fourth Company of China Railway NO.5 Engineering Group Co., LTD., Shaoguan, Guangdong, 512000, China*

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Abstract

The current seismic strengthening methods for masonry structures usually require the removal of wall decoration and superficial mortar, and the wet work during indoor construction takes a long time, which seriously interferes with the normal life of residents. To realize the low-interference construction in the seismic strengthening process of masonry residences, a new seismic strengthening method was proposed in this study. The reinforcement was performed by adding the ring beam and constructional column into the exterior wall and the ring beam into the interior transverse wall. Based on field detection and appraisal, the following three seismic strengthening methods were compared: steel mesh mortar splint, sticking carbon fiber reinforced plastic composite materials, and the addition of constructional column and ring beam. The seismic behavior of the building was investigated by using the JGJD module of PKPM structure design software. The following parameters were calculated: average seismic capacity index (ASCI), compound seismic capacity index (CSCI) of the floor, the resistance to load effect ratio (RLER) of the wall. Results show that the ASCI and CSCI of the floor after reinforcement are both >1.0 and the RLER of the wall is >1.0. Thus, the seismic behavior of the building is improved and meets the grade-2 appraisal requirements in the Standard for Seismic Appraisal of Buildings. Moreover, low-interference construction is achieved. This study provides references for the new low-inference seismic strengthening design of masonry structures.

Keywords: Masonry structure, Low inference, Seismic strengthening design

1. Introduction

In the past ten years, the multi-story masonry civil buildings were frequently damaged seriously in earthquakes; limited by social, economic, and technological conditions, earthquake-resistant protection was considered in their structure design [1]. These buildings cannot meet the requirements of the current codes with respect to bearing capacity. They have potential safety hazards, and seismic strengthening is urgently needed. Many strengthening technologies and methods for masonry structures have been proposed in recent years, and study achievements are numerous. For example, after strengthening by a steel mesh cement mortar splint, the masonry walls exhibited ductile failure, and the bearing capacity was markedly improved [2]. When the reinforcement was completed by steel mesh cement mortar + steel wire mesh concrete splint, the bearing capacity, deformability, and energy dissipation capacity of the masonry walls were all significantly increased; thus, the brittleness of the walls became better [3]. For masonry walls strengthened by a steel concrete splint in a double-surface manner, the bearing capacity, rigidness, and ductility were greatly enhanced [4]. When the single or double-surface strengthening of walls were finished by superficially embedding glass fiber reinforced plastic, carbon fiber reinforced plastic (CFRP) or steel wires, the ultimate bearing capacity was increased to a big extent, the deformability and ductility were evidently improved, and the energy dissipation capacity was improved [5-6]. Despite effectively improving the bearing capacity of masonry structures, the abovementioned methods change the original appearance of buildings to different degrees, damage the original decoration of walls, contaminate the indoor environment, and have a great impact on the life of residents; the strengthened buildings have a smaller use space. Thus, they are difficultly accepted by residents; they are also inapplicable to the buildings with a strict requirement for construction interference or with a protective layer of indoor decoration. Therefore, a new low-interference method for improving the seismic behavior is urgently required in the current seismic strengthening of masonry buildings.

The actual engineering of seismic strengthening for a building was investigated. Two models were established for the proposed design, and the seismic behavior of the building was analyzed before and after strengthening. This study was aimed to prove that the average seismic capacity index (ASCI) and compound seismic capacity index (CSCI) of the reinforced floors met the grade-2 appraisal requirements in the Standard for Seismic Appraisal of Buildings and provide references for the modification and optimization of new low-interference seismic strengthening designs.

2. State of the art

Scholars have completed a large number of studies on the seismic strengthening of masonry structures and proposed a

*E-mail address: zhuleianhui@163.com
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series of new methods. Wu Hao et al. [7], Cheng Shaoge et al. [8], Liu Pei [9], Ashraf M et al. [10], and De Santis S et al. [11] reinforced the brick walls with a steel mesh cement mortar splint and investigated the shear-bearing capacity and ductility of walls. However, such a seismic strengthening method damaged the superficial decoration layer of walls and required a long maintenance cycle, and the reinforced buildings had a small use area and cannot be used during construction and maintenance. In the studies of Luo Rui et al. [12] and Tang Caoming [13], the brick walls were strengthened by a steel mesh cement mortar splint, the low-strength mortar masonry brick walls were constructed, and the seismic performance test was conducted; this method required long wet work, had a big impact on the production and living, and influenced the use space of buildings after reinforcement. Elgawady M A et al. [14], Maalej M [15], Bae B I [16], Mahmood H et al. [17], Capozucca R [18], Deng Mingke [19], Pan Hua et al. [20], Zhang Si [21], Shakib H [22], and F Valvona et al. [23] adopted the compound materials to strengthen the masonry walls and analyzed the seismic performance of two types of materials before and after reinforcement; the abovementioned method damaged the interior wall decoration of buildings, and the buildings cannot be employed during construction and maintenance, which influence the normal life of residents. In the study conducted by Elgawady M A et al. [24], the double surfaces of brick walls were strengthened by using steel mesh concrete slabs, and the bearing capacity and ductility of the reinforced walls were investigated; the used strengthening method required the removal of decoration and superficial mortar on the indoor walls; thus, it was not accepted by the residents. Taghdi M et al. [25] and Farooq S H [26] studied the bearing capacity and ductility of masonry walls after strengthening with steel strips; the steel strip strengthening damaged the interior wall decoration of buildings, and the residents cannot live in the buildings under construction. Moghaddam H.A [27] and Jiang H [28] completed the reinforcement of masonry walls by external steel encasing and tested the seismic behavior; the employed method was not applicable to the strengthening of interior transverse walls, and the strengthened buildings had relatively poor rigidness. Yu Jiang et al. [29] conducted a study on wall strengthening with lattice steel plates and then analyzed the strength, rigidness, and ductility of walls before and after reinforcement; the lattice steel plate strengthening method cannot be used to reinforce the interior transverse walls. Kadam S.B et al. [30] performed a reversed cyclic quasi-static loading test on the non-strengthened walls and the walls strengthened by high-strength steel wire + polymer mortar splint, and compared their hysteretic behavior, damage patterns and rigidness; however, such seismic strengthening seriously damaged the wall decoration, and the residents cannot use the buildings, which affected their normal life.

The above studies reveal that different seismic strengthening methods can improve the structural integrity and rigidness of buildings, but the wall decoration is nearly removed during reinforcement, and the residents must move out the furniture, which seriously interferes with the normal life and increases the costs of reinforcement and reconstruction. Therefore, these designs cannot meet the actual demands, and a new low-interference seismic strengthening method is needed to ensure that the normal life of building owners are not influenced during seismic strengthening. This study investigated Zhenxiang Block 12 Residential Building in Qinhuai District of Nanjing, which had a masonry structure and was built in the 1970s. First, several seismic strengthening methods were compared on the basis of field detection and appraisal. Second, a new seismic strengthening method was proposed, and the idea was to add the steel–concrete ring beam and constructional column into the exterior wall and the new internal ring beam into the interior transverse wall by using through-wall prestress pull rod grouting. Finally, the JGJD module of the PKPM structure design software was used to calculate and analyze the ASC and CSCI of floors, and the resistance to load effect ratio (RLER) of walls in the reinforced buildings.

The remainder of this study is organized as follows. Section 3 describes the ideas and methods for the seismic strengthening appraisal of the building. A low-interference seismic strengthening method is then selected by comparison, and the pre-reinforcement and post-reinforcement 3D building models are established with PKPM software according to the basic conditions. Section 4 calculates the seismic capacity indexes (SCIs) of the building under the current conditions after strengthening with the methods for the seismic strengthening appraisal of buildings, and the changes of SCI are comparatively analyzed before and after building reinforcement. The final section summarizes the study and draws relevant conclusions.

3. Methodology

3.1 Methods for seismic appraisal of buildings

3.1.1 Grade-1 appraisal

The basic contents of the grade-1 appraisal mainly include the following five aspects: (1) general specifications (e.g., height, floors, and floor height), (2) structural system, (3) strength of materials, (4) integral connection and construction, and (5) local collapsible components and their connecting construction.

3.1.2 Grade-2 appraisal

If needed by Category A masonry structures, then the grade-2 appraisal shall be performed according to the specific conditions in that the buildings fail to meet the grade-1 appraisal requirements by using one or more methods: floor ASCI method, floor CSCI method, and wall CSCI method.

(1) Floor ASCI method

The grade-2 appraisal can be performed with floor ASCI method if the structural system, integral connection, and collapsible parts of buildings all meet the grade-1 appraisal requirements. However, the interval between the transverse walls or the width of the buildings exceeds the limits in the grade-1 appraisal requirements.

The formula is as follows:

$$\beta_i = A_i / (A_{bi} \xi_{oi} \lambda) \tag{1}$$

where

β_i is the ASCI of the longitudinal or transverse wall in Floor i,

A_i is the total net cross-sectional area of longitudinal or transverse seismic wall in Floor i that is one-half of the floor height,

A_{bi} is the planar building area of Floor i,

ξ_{oi} is the characteristic ratio of longitudinal or transverse seismic wall in Floor i, and

λ is the intensity influencing coefficient.

(2) Floor CSCI method

The grade-2 appraisal can be performed with a floor CSCI method if the structural system, the integral connection of building roofs, layout and construction of the ring beam, and local collapsible structural components do not meet the grade-1 appraisal requirements.

The formula is as follows:

$$\beta_{ci}=\psi_1\psi_2\beta_i\,, \tag{2}$$

where

β_{ci} is the CSCI of the longitudinal or transverse wall in Floor i,

ψ_1 is the systematic influencing coefficient, and

ψ_2 is the local influencing coefficient.

(3) Wall CSCI method

The grade-2 appraisal can be performed with the wall CSCI method if the actual interval between the transverse walls exceeds the maximum value specified in the rigid system, the torsion effect is evident, and the local collapsible structural components do not meet the grade-1 appraisal requirements.

The formula is as follows:

$$\beta_{cij}=\psi_1\psi_2\beta_{ij}\,, \tag{3}$$

$$\beta_{ij}=A_{ij}\,/\,(A_{bij}\xi_{oi}\lambda)\,, \tag{4}$$

where

β_{cij} is the CSCI of Wall j in Floor i,

β_{ij} is the SCI of Wall j in Floor i,

A_{ij} is the net cross-sectional area of Wall j in Floor i that is one-half of the floor height, and

A_{bij} is the tributary area of Wall j in Floor i, which includes the influence of building roof rigidness.

3.2 Establishment of Models

3.2.1 Grade-1 appraisal

Zhenxiang Block 12 Building in Qinhuai District of Nanjing was constructed in 1978, and it was a six-story masonry residential building. The building plane was a rectangle of 55 m × 9.1 m (length × width). The building area was 2,670 m^2. The building adopted a load-bearing structure of 240 mm brick walls. the floor slabs were the precast concrete cellular slabs. The cast-in-place slabs were used in kitchens and bathrooms. The stairs were comprised of steel reinforced concrete. In addition to the ground and top ring beams, the ring beam was present in Floors 1, 3, and 5 but not in Floors 2 and 4. No constructional column was found. The ordinary cement ground was constructed. The building appearance is shown in Fig. 1.

Zhenxiang Block 12 Building was located at the west of the newly built Subway Line 3 Fuzimiao Station in Qinhuai District. The shortest distance to the edge of the foundation pit was only 10 m. Given the excavation of the Fuzimiao Station's foundation pit, the building demonstrated large non-uniform subsidence at an east-to-west direction, and the load-bearing walls had multiple cracks, which seriously influenced the safety and normal service of the building.

3.2.2 Field detection of the building

3.2.2.1 Appearance inspection of the building

On the basis of field detection, Zhenxiang Block 12 Residential Building in Nanjing was found with the following major problems:

Fig. 1. Physical view of the building

(1) No ring beams and constructional columns were found on Floors 2 and 4.

(2) With a long time of use, the building exhibited the damage and loosening of concrete and the exposure and rustiness of steel reinforcement at the bottom. The balconies were reconstructed into the fully enclosed ones privately by residents, and most of them were the ordinary clay brick masonry walls, which greatly increased the load. Therefore, potential safety hazards were found.

(3) The owners dismantled and modified the load-bearing walls, which weakened the seismic behavior of the building. Thus, the building was exposed to a big hidden danger.

(4) The walls and floor slabs had obvious cracks, and the maximum crack was up to 1.2 mm wide. The cracks are shown in Fig. 2–4.

3.2.2.2 Structure detection of the building

(1) Cracks

Thirteen typical cracks were selected, and the width was precisely measured as 0.3–1.2 mm with a crack width meter. The cracks with the biggest width were separately located in the walls beneath the windows of the southwest bedroom of Room 503 in Unit 1 and the southeast bedroom of Room 408 in Unit 3.

(2) Baked bricks

In the 18 groups of baked bricks selected, the compressive strength was 10.13–10.69 MPa, which met the requirements of MU10.

(3) Compressive strength of the mortar

Eighteen groups of masonry mortar were collected with a chisel from 18 selected walls. Three test samples were chosen from each group, placed separately, numbered, hammered, dried, and placed into the simple barometer for testing. The measured compressive strength was 5.3–6.80 MPa, which meets the requirements of M5.

(4) Static load of floor slab

When the uniform live load of floors reached 2.0 kN/m^2, the measured deflection of five concrete floor slabs was 0.42–0.51 mm, and the floor span was <7 m, both of which are lower than the values in the L0/200 standard. The load effect of the floor slabs was measured by a static load test, which suggest that the floor slabs met the designed load standard and the requirements of a normal service.

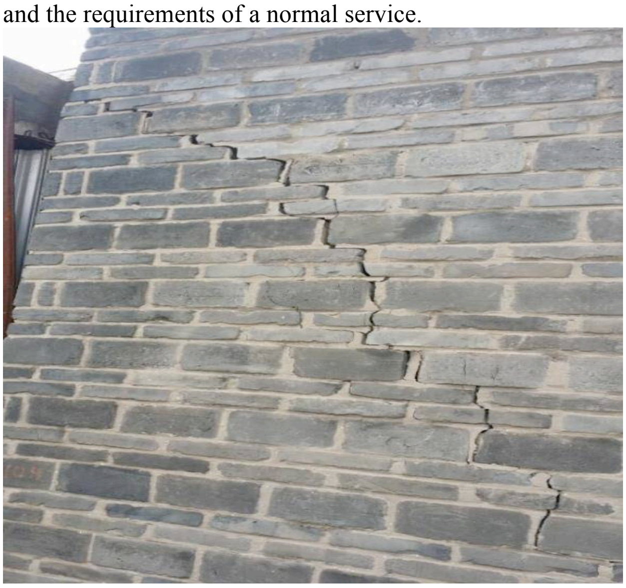

Fig. 2. Oblique cracks of walls

Fig.3. Wall crack lateral to the doorframe

Fig. 4. Wall crack beneath the window

3.2.3 Comparison and selection of seismic strengthening designs

For the seismic strengthening engineering of buildings, the design methods, which have a good efficacy of seismic strengthening, reliable technologies, convenient and low-interference construction, and economic and affordable costs, are preferably selected according to the actual conditions of the masonry structure. Based on the current service status, damage situations, and field construction environment of Zhenxiang Block 12 Building in Nanjing, three feasible design methods of seismic strengthening are proposed: steel mesh mortar splint, sticking CFRP composite materials, and the addition of a constructional column and a ring beam. Their advantages and disadvantages are comparatively analyzed. The practical seismic strengthening method is the first choice.

(1) Strengthening by steel mesh mortar splint

The procedure is to anchor the steel mesh bilaterally into the original wall and spread a certain thickness of cement mortar splint in that the steel mesh forms an entirety with the original wall via the sticking of a mortar splint to jointly bear the load. The overall seismic capacity of buildings has a difference from the designed value. Its advantages include a small thickness of the cement mortar splint, low consumption of steels and mortar, and low costs.

(2) Strengthening by sticking CFRP composite materials

The procedure is to stick the fiber fabrics onto the wall surface with the high-performance adhesive in that the fiber fabrics and the wall can jointly improve the bearing capacity, seismic capacity, energy dissipation capacity, and ductility of structural components and thus strengthen and reinforce the building.

(3) Strengthening by adding the constructional column and ring beam

The procedure is to add the constructional column into the four corners of the exterior wall and the junction of the interior and exterior walls of buildings, the external ring beams into the exterior walls of various floors without ring beams, and the new internal ring beam into the interior transverse wall by through-wall prestress pull rod grouting. The strengthening method enhances the seismic capacity and overall stability of the structure and reduces the occurrence of cracks. The constructional column and external ring beam are located at the exterior wall of buildings. Thus, the construction process is simple and has little influence on the life of residents. However, the new internal ring beam is in the middle of 240 mm brick walls and thus has a complex construction process. Drilling a hole in the middle of the brick wall is difficult, while hole-drilling is a key node in the implementation of new seismic strengthening methods for buildings. This study used the self-made laser-guided super-long high-precision horizontal driller to drill the holes on the interior transverse walls of the building, then the non-sticking steel wires were anchored into the newly added ring beams of the exterior wall to form an entirety, and the high-strength cement mortar was perfused into the holes to form the internal ring beam of the transverse wall.

According to the computing results of PKPM structure design software, the above three strengthening methods can achieve seismic strengthening, and their features are shown in Table 1.

Table. 1. Features of seismic strengthening design methods

No.	Strengthening Design Method Qmax	Construction Convenience	Life Interference
1	Strengthening by steel mesh mortar splint	Requires the indoor operation and a long construction time but has a small construction difficulty and low engineering costs	The indoor construction is necessary, which damages the indoor decoration and environment and thus has a large interference with the life of residents.
2	Strengthening by sticking CFRP composite materials	Requires the indoor operation; has rapid and convenient construction and a short construction cycle but high engineering costs	The indoor construction is necessary, which damage the indoor decoration and environment and has large interference with the life of residents.
3	Strengthening by adding the constructional column and ring beam	Only requires an outdoor operation and has a short construction cycle, low engineering costs, and convenient construction; has a big difficulty in the construction process of adding the new ring beam into the interior transverse wall	All construction is performed in the outdoor environment, which does not damage the indoor decoration and environment and thus nearly has no impact on the life of residents.

A comparison of the above three seismic strengthening design methods shows that Method 3 has an outstanding advantage in the aspects of strengthening efficacy, construction convenience, and life interference. Method 3 effectively improves integrity and rigidness and significantly increases the seismic capacity of masonry structures, and its construction operations are all performed in the outdoor environment. Thus, the limitations are few, the construction is convenient, the actual usable space for residents is not reduced, the indoor decoration and environment are little influenced, and the life interference is low. Therefore, the new seismic strengthening method proposed in this study only requires outdoor construction and nearly does not affect the production and life of residents. It realizes the low-interference construction and provides references for the seismic strengthening design of similar engineering.

3.2. 4 Models

According to the design drawings and field detection results of the building, the compressive strengths of the masonry mortar and baked bricks were set to MU5.0 and MU10.0, respectively. By referring to the Load Code for the Design of Building Structures and combining the actual utilization of floors, the live load of the floor was set to 2 kN/m^2, and the constant load should be set to 3 kN/m^2 but was actually set to 4 kN/m^2 given the balcony modification (e.g., the balcony was modified into the kitchen or for storing the messes). The block density was 22 kN/m^2, and the corrected reference wind pressure was 0.35 kN/m^2. By combining the geographical location and structural characteristics of the building and according to the Code for Seismic Design of Buildings, the seismic precautionary intensity was 7, the designed basic earthquake acceleration was 0.10 g, the designed earthquake group was Group 1, and the field type was Category II. After the floor assembly, the overall model of the pre-strengthening masonry building is shown in Fig.5.

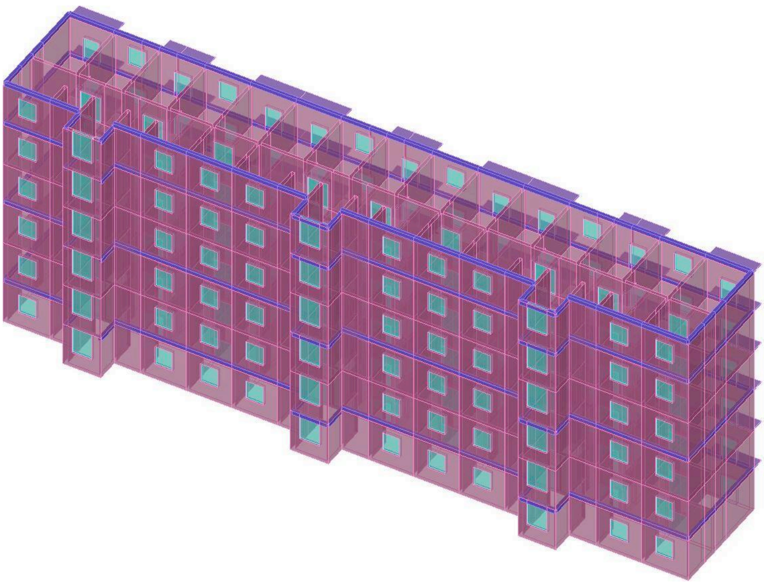

Fig. 5. Pre-strengthening building model

Based on the original building model and the proposed low-interference seismic strengthening method, the steel–concrete constructional column was added into the four corners of the exterior wall and the junction of the interior and exterior walls of the building. The steel–concrete ring beam was added to the exterior wall of Floors 2 and 4. The new internal ring beam was added to 11 transverse walls in the middle of Floor 2 and 5 transverse walls in the middle of Floor 4. The strength of newly added structural concrete was C30. The model of the masonry building added the constructional column and ring beam, as shown in Fig. 6.

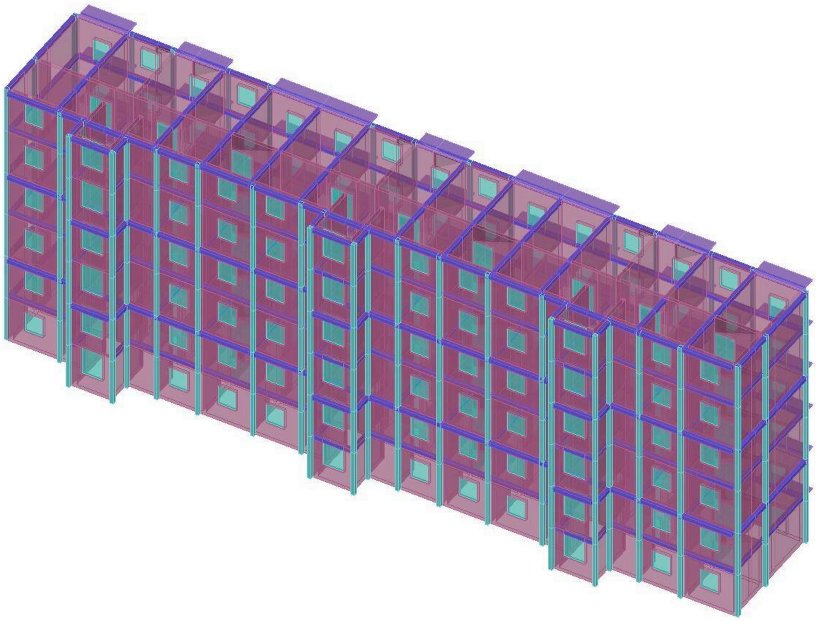

Fig. 6. Post-strengthening building model

4. Result Analysis and Discussion

4.1 Seismic appraisal before strengthening

4.1.1 Grade-1 appraisal

The studied building was constructed in 1978 and belonged to Category A buildings according to the division of subsequent service life based on the appraisal standard in the Load Code for the Design of Building Structures (GB50009-2012). The basic contents of grade-1 appraisal in the Code mainly include general specifications (e.g., height, floors, and floor height), the strength of materials, structural system, integral connection and construction, local collapsible components, and their connecting construction. The grade-1 appraisal data of the building were obtained according to the field detection and the indoor testing (Table 2).

Table. 2. Results of grade-1 appraisal

No.	Strengthening Design Method Qmax	Construction Convenience	Life Interference	Compliance
General specifications	Total height of the building	22 m	18.6 m	Yes
	Floors of the building	7	6	Yes
Strengthen of materials	Brick strength of load-bearing wall	M7.5	Mu10	Yes
	Mortar strength of load-bearing wall	M2.5	M5	Yes
Structural system	Maximum interval between transverse walls in the rigid system	11 m	6.8 m	Yes
	Height-width ratio of the building	2.2	1.98	Yes
	Regularity of the building			Yes
Integral connection and construction	Closure of the wall layout	Yes	Yes	Yes
	Layout of constructional column	Four corners of exterior wall, junction of interior and exterior walls, and four corners of staircase	No	No
	Layout of ring beam	The ring beam shall be present in the ceilings and building roofs.	The ground and top ring beams and the ring beams in Floors 1, 3, and 5.	No
	Connection of building roofs			Yes
Local collapsible components and connection	Minimum width of load-bearing walls between doors and windows	⩾0.8 m	0.9	Yes
	Distance between the dead-end of exterior wall and the edge of openings for doors and windows	⩾0.8 m	0.9	Yes

Table 2 shows that the general specifications, the strength of materials, structural system, local collapsible components, and their connecting construction of the building meet the grade-1 appraisal requirements, but the integral connection and construction do not comply with these requirements. Therefore, the constructional column layout of the building fails to meet the grade-1 appraisal requirements, and the grade-2 appraisal shall be performed.

4.1.2 Grade-2 appraisal

In accordance with the Standard for Seismic Appraisal of Buildings, if Category A masonry buildings do not comply with the grade-1 appraisal requirements, the grade-2 appraisal shall be performed with one or more of the following methods: floor ASCI, floor CSCI, and wall CSCI. If the ASCI or CSCI of the weakest floor or the CSCI of the weakest wall is ⩾1.0, then the building is appraised as compliant with the seismic appraisal requirements. If any of the above figures has values <1.0, then the building shall be reinforced or treated with other corresponding measures. The seismic behavior of the original structure was calculated by using the JGJD module of the PKPM structure design software. The results of grade-2 appraisal for the original building are shown in Fig. 7 and 8.

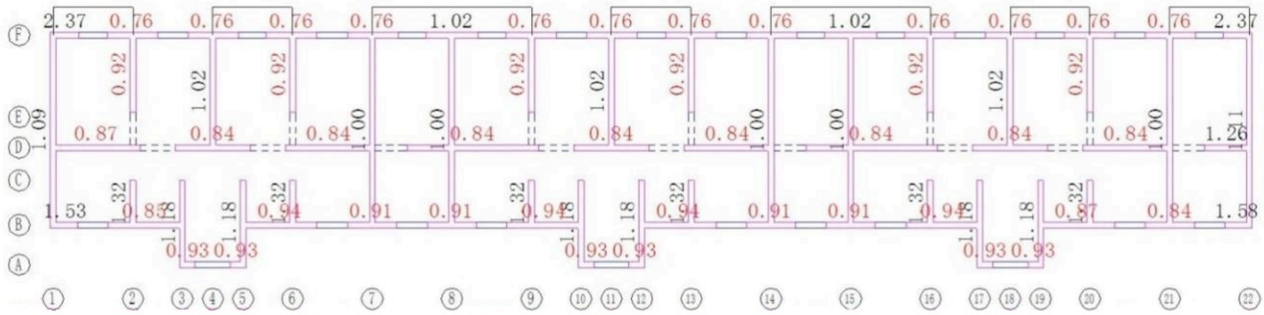

Fig. 7. Chart of grade-2 appraisal results of Floor 1 in the original building

Fig. 7 shows that the ASCIs of longitudinal and transverse floors were 1.09 and 1.32. The CSCIs of transverse and longitudinal floors were 1.06 and 0.88. The CSCI of floors failed to meet the seismic requirements because the later was <1.0. The minimum RLERs of the transverse and longitudinal walls were 0.92 and 0.76, both <1.0. Thus, the RLER of the wall did not comply with the seismic requirements of >1.0. Therefore, the seismic behavior of Floor 1 in the building does not meet the grade-1 appraisal requirements, and the seismic strengthening must be performed.

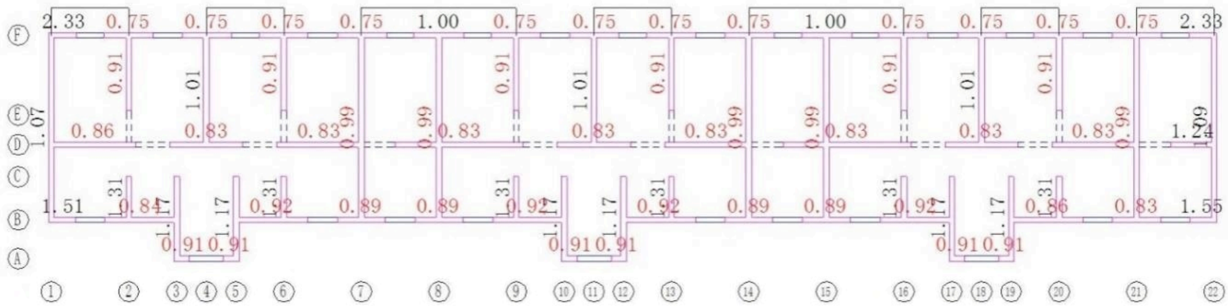

Fig. 8. Chart of grade-2 appraisal results of Floor 2 in the original building

As shown by Fig. 8, the ASCI of longitudinal and transverse floors met the seismic requirements of >1.0. The CSCI of transverse and longitudinal floors was 1.04 and 0.86, respectively. Thus, the CSCI of floors failed to meet the seismic requirements of >1.0. The RLER of the partial transverse and longitudinal walls was <1.0, which fails to comply with the seismic requirements of >1.0. Therefore, the seismic behavior of Floor 2 in the building does not meet the grade-2 appraisal requirements, and the seismic strengthening is essential.

4.2 Seismic appraisal after strengthening

4.2.1 Results of grade-2 appraisal

By using the proposed method, the steel–concrete constructional column was added into the four corners of the exterior wall and the junction of interior and exterior walls of the building. The steel–concrete ring beam was added to the exterior wall of Floors 2 and 4. The new internal ring beam was added to 11 transverse walls in the middle of Floor 2 and 5 transverse walls in the middle of Floor 4. C30 concrete was employed to strengthen the structure. After seismic strengthening, the relevant calculations of the building were completed with the JGJD modules of PKPM structure design software, and the results are shown in Fig. 9 and 10.

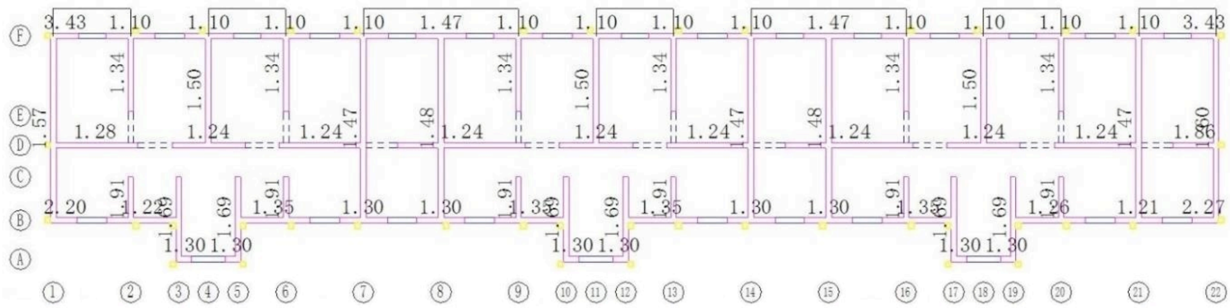

Fig. 9. Chart of grade-2 appraisal results of Floor 1 after strengthening

Fig. 9 shows that the ASCIs of longitudinal and transverse floors in Floor 1 after strengthening are 1.27 and 1.53. The CSCIs of the longitudinal and transverse floors are 1.27 and 1.53. The RLER of transverse and longitudinal walls is >1.0. Therefore, the presumption is according to the appraisal standard of the Load Code for the Design of Building Structures (GB50009-2012), and the seismic behavior of Floor 1 in the reinforced building meets the requirements in the Code.

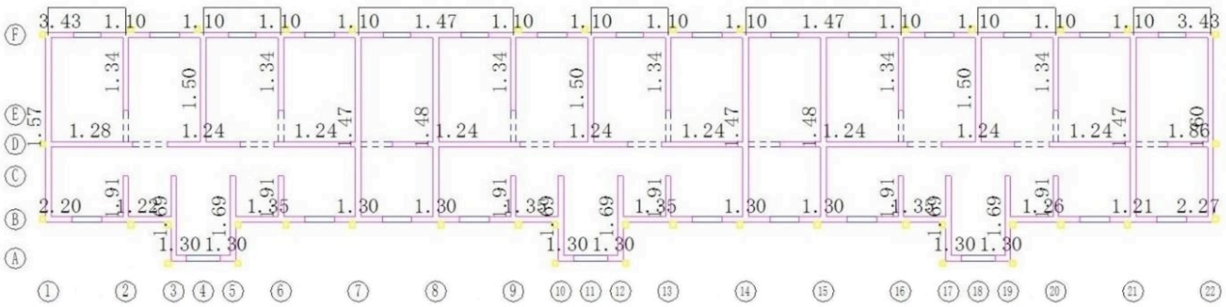

Fig. 10. Chart of grade-2 appraisal results of Floor 2 after strengthening

Fig. 10 shows that the ASCI for the strengthened Floor 2 is 1.24 and 1.56, and the CSCI is 1.24 and 1.56, respectively. RLER is >1.0. Therefore, the seismic behavior of Floor 2 in the reinforced building meets the requirements in the appraisal standard of the Load Code for the Design of Building Structures (GB50009-2012).

From Fig. 9 and 10, after reinforcement with the proposed new method, the masonry structure complies with the grade-2 appraisal requirements, and its seismic behavior meets the seismic requirements and thus realizes seismic strengthening. The findings suggest that the new low-interference seismic strengthening method proposed in this study is feasible.

4.2.2 Comparison of seismic behavior before and after strengthening

To demonstrate the role of the proposed new method in improving the seismic behavior of the current masonry structure, the calculation results of seismic behavior in the grade-2 appraisal of Floors 1 and 2 were compared before and after strengthening, as shown in Tables 3 and 4.

Table. 3. Grade-2 appraisal results of Floor 1 before and after strengthening

Computing Conditions	Direction	A_i(m^2)	A_{bi}(m^2)	ξ_{0i}	λ	β_i	ψ_1	ψ_2	β_{ci}	Compliance
Before strengthening	Longitudinal	25.65	441.8	0.0354	1.00	1.09	0.80	1.00	0.88	No
	Transverse	31.35	441.8	0.0359	1.00	1.32	0.80	1.00	1.06	Yes
After strengthening	Longitudinal	25.65	441.8	0.0365	1.00	1.27	1.00	1.00	1.27	Yes
	Transverse	31.35	441.8	0.0370	1.00	1.53	1.00	1.00	1.53	Yes

In Table 3, the ASCIs of longitudinal and transverse floors in Floor 1 after strengthening are 1.27 and 1.53 (increase: 16.5% and 15.9%, compared with 1.09 and 1.32 before strengthening), and the CSCIs are 1.27 and 1.53 (increase: 44.3% and 44%, compared with 0.88 and 1.06). The minimum RLERs of longitudinal and transverse walls are 1.10 and 1.34 (increase: 44.7% and 59.5%, compared with 0.76 and 0.84).

Table. 4. Grade-2 appraisal results of Floor 2 before and after strengthening

Computing Conditions	Direction	A_i(m^2)	A_{bi}(m^2)	ξ_{0i}	λ	β_i	ψ_1	ψ_2	β_{ci}	Compliance
Before strengthening	Longitudinal	25.65	441.8	0.0360	1.00	1.08	0.80	1.00	0.86	No
	Transverse	31.35	441.8	0.0363	1.00	1.30	0.80	1.00	1.04	Yes
After strengthening	Longitudinal	25.65	441.8	0.0376	1.00	1.24	1.00	1.00	1.24	Yes
	Transverse	31.35	441.8	0.0365	1.00	1.56	1.00	1.00	1.56	Yes

In Table 4, the ASCIs in Floor 2 after reinforcement are 1.24 and 1.56 (increase: 14.8% and 20%, compared with 1.08 and 1.30 before strengthening), and the CSCIs are 1.24 and 1.56 (increase: 44.2% and 50%, compared with 0.86 and 1.04). The minimum RLERs are 1.07 and 1.36 (increase: 42.7% and 49.5%, compared with 0.75 and 0.91).

To sum up, after the reinforcement with the new low-interference seismic strengthening method, the seismic behavior of the masonry building is greatly improved. The ASCI and CSCI of floors and the RLER of longitudinal and transverse walls are >1.0, which meets the requirements for the seismic performance of buildings in the Standard for Seismic Appraisal of Buildings (GB 50023-2009). The abovementioned method improves the seismic behavior and enhances the integrity and rigidness of the building. The building construction has no impact on the indoor decoration and realizes interference-free construction.

5. Conclusions

To guarantee the low interference during the strengthening of masonry residential buildings, the present study was conducted as follows. First, the appearance inspection and structure detection of the building were completed. Second, a new low-interference seismic strengthening method of masonry structures was proposed by comparative analysis, and it involved adding the steel–concrete ring beam and constructional column into the exterior wall and the new internal ring beam into the interior transverse wall by using through-wall prestress pull rod grouting. Finally, the SCIs of the building were calculated and analyzed before and after strengthening with the PKPM software. The following conclusions can be drawn:

(1) After adding the constructional column and ring beam, the ASCI and SCI of longitudinal and transverse floors in the building are significantly increased. The ASCI and CSCI of the strengthened floors are >1.0, and the RLER of both longitudinal and transverse walls is >1.0. Therefore, the reinforced building meets the grade-2 appraisal requirements in the Standard for Seismic Appraisal of Buildings.

(2) The new low-interference seismic strengthening method of the masonry structure proposed improves the seismic behavior and enhances the integrity and rigidness of the building. Moreover, the strengthening work is conducted in an outdoor environment, which is nearly impossible to damage the original indoor decoration of the building and has low interference with the work and life of residents. Thus, the low-interference construction is achieved.

The present study combined filed detection with structure calculation. The new recognition was proposed for the low-interference seismic strengthening by adding the constructional column and ring beam, and the proposed seismic strengthening method was more suitable for on-site conditions. This study provides references and guidance for the seismic strengthening of buildings in the design and construction phases of similar engineering. However, no actual data from field monitoring was used in this study. To improve the accuracy of the evaluation on the design and construction quality of seismic strengthening for masonry structures, the monitoring data and indoor test data after building reinforcement will be integrated into incoming studies.

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