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THE CALCULATION ANALYSIS OF DIFFERENT MORTAR MATERIALS ON THE MECHANICAL PROPERTIES OF THE GROUTING STRENGTHENING MASONRY STRUCTUREG

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ABSTRACT

The reduced mortar strength of the existed masonry structures is the main reason for deterioration of their seismic performance. The use of the grouting strengthening method is by improving the performance of masonry mortar to enhance the integrity and strength of the masonry structures. It opens one of new ways for strengthening the existed masonry structures. The compressive strength and shear mechanical properties of the grouting strengthening masonry structures were calculated and analyzed by using the discrete mechanical model in finite element method and compared with the experimental results. Because of the old and new alternating mortar layers in masonry structures after grouting strengthening, the uniformity of mortar layers is exacerbated , leading to cracks in these regions to carry out more likely. Mortar layer consists of two quite different mechanical material compositions, which induce stress redistribution in mortar layer. The bond strength between new mortar and bricks made the masonry structure have overall higher integrity and improve the shear and compressive bearing capacity. The calculating results show that the shear strength after grouting can be improved by 118%, the compression capacity can be improved by 42%.

***Keywords*:** masonry structure, grouting strengthening method, finite element analysis, compressive strength, shear strength

1. INTRODUCTION

Experience has shown that much earthquake damage, losses and casualties caused by the earthquake was mainly due to the damage of housing, engineering facilities and equipment. A variety of secondary disasters and casualties is mainly the direct cause of the collapse of buildings [1]. In 2007, the houses destructed by earthquake are 1370605 m^2, in which 301919m^2 are serious damage, 5809546m^2 are medium damage, 2817720m^2 are minor damage, over 7.48 million m^2 are above medium damage [2,3]. Lower level of seismic defense in economically underdeveloped regions and old housing in old city and villagers are the main reasons resulting in huge loss in the earthquake. Such as the 2008 Wenchuan earthquake, the seismic intensity far exceeds the fortification intensity, in a lot of economic underdevelopment earthquake zone, the old city and more, only the collapse of housing is estimated to reach 84.88 million m^2, the masonry structure are the most severe damage buildings [4].

The existed buildings in many cities are in lower level of seismic fortification criterion. According to the statistics of Shenyang, Anshan and Baoding, about 1/3 the existing buildings are less than the seismic capacity [5]. As disrepair, the action of natural factors and man-made comprehensive reasons, the historic buildings are in the different degrees of damage, and some very serious damage [6]. The main reason for the masonry structure collapse in earthquake can be classified into two categories: one is lack of shear strength of the wall, the other is the defects of details of seismic design, such as the lack of reliable connection between the wall and the wall or between the wall and plate, element connection damage, loss of integrity, the wall collapse out of its plane, floor sliding down [7]. The seismic capacity of masonry structure mainly depends on the shear capacity of wall. The investigation of

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history and culture existing houses and buildings shows that masonry structures, affected by various natural factors, such as wind corrosion, leaks, plaster layer falling, etc., are without mortar strength, or mortar strength becoming much lower. Especially in the lime clay masonry, mortar is almost no strength. But the strength of brick maintains the original level. The tensile and shear strength of masonry have small relationship with the block, it is depends on the strength grade of mortar between the blocks, but also depends on the contact surface between mortar and block [8]. Improving the mortar strength plays a significant role to on masonry seismic fortification capacity. Such as MU10 level of ordinary brick, mortar strength changed from the M2.5 to M5.0, the compressive strength increased by about 15% , shear capacity increase of about 37%; mortar strength changed from the M5.0 to M7.5 the compressive strength increased by about 13% and shear capacity increased by about 27%. By increasing the strength of mortar in masonry structure, the tensile performance improvement is obvious, and the compression increase about 10%. Grouting strengthening method is an effective way to increase the seismic performance of masonry [9].

Unreinforced masonry consists from the mortar and brick. After grouting strengthening the masonry is a combination of three materials: brick, old mortar and grouting mortar. Brick is made from clay. Old mortar is mixed clay mortar. Grouting cement mortar is mixed with colloidal crystal. Since the mechanical properties of brick and mortar have nonlinear characteristics, in the loading process, the masonry behave in the nonlinear state. Using the finite element method the grouting strengthening and ordinary masonry specimens are analyzed, and their calculation results are compared with the experiments, to study the influence of grouting on the mechanical properties of masonry structures.

2. MODEL OF FINITE ELEMENT ANALYSIS AND MODELING

The finite element model of masonry structure can be divided into two types: the discrete model and the continuum model [10, 11, and 12]. The discrete model takes into account the composed of two materials: block and mortar. The continuum model takes the whole masonry as homogeneous materials, does not consider the two different materials, the masonry materials parameters are calculated from the whole masonry test results. Considering the advantages of continuum model and the materials dispersion, the application of the continuum model is popular, such as Liu Li *et al.* [13] in the study of high breadth ratio on the shear behavior of masonry walls when using continuum model analyzing the impact of the overall macro-size on the integrity, the results are satisfied, Zhou Pingkui [14] in the analysis of two-story masonry structures collapse under earthquake, using continuum model this choice is feasible in the overall perspective, Song Yang *et al.* [15] in the analysis of brick structure with structural columns using ANSYS, in order to the overall macro reaction the continuum model is used and obtained good agreement with the experimental results. Grouting improves the mortar joint between mortar and bricks; thereby enhance the carrying capacity of masonry. The mechanical property between the mortar and bricks become the research focus, so the discrete model is choose to analyze the interaction between the block and mortar.

The hexahedral solid element Solid65in ANSYS is selected. It can simulate nonlinear material tensile cracking, compression crushing, plastic deformation, creep, large deformation and large strain. Solid65 element has eight nodes; each node has 3 degrees of freedom (Fig. 1).

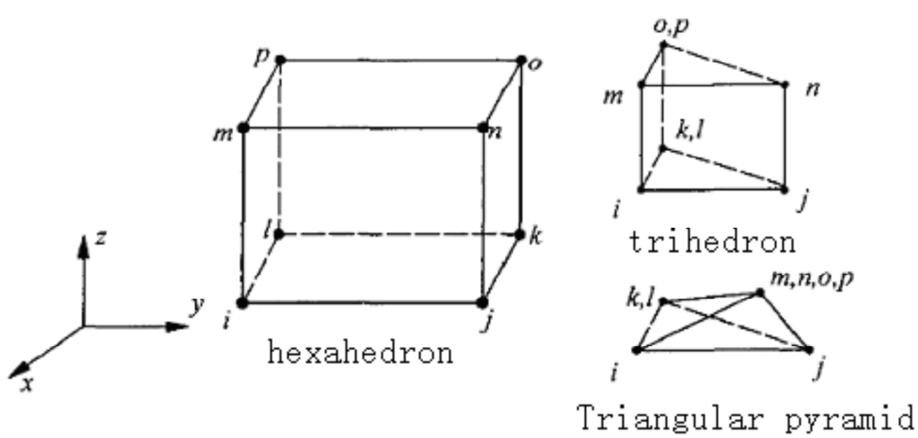

Figure 1: Solid65 Element in ANSYS

The brickÿthe old and new mortar layer are separately simulated. The elastic modulus and stress - strain constitutive curve of brick and clay mortar are determined from the curve suggested by the scholar Zhu Bolong in Tongji University [16] and the results tested by Liu guiqiu in Hunan University [17]. The elastic modulus of brick is 13000MPa, Poisson's ratio is 0.2, the elastic modulus of clay mortar is 818MPa, and its Poisson's ratio is 0.24. Grouting mortar is similar to the fine aggregate concrete; its modulus of elasticity take 16020MPa and Poisson's ratio take 0.18. The constitutive curves take the concrete stress - strain curve in ⟨⟨Code for design of concrete structures⟩⟩ GB 50010-2002, as follows:

$$\sigma = f_c[1 - (1 - \varepsilon_c / \varepsilon_o)^2] \tag{1}$$

Where $f_c = 18.3$ MPa, $\varepsilon_c = 0.002$; $\varepsilon_o = 0.0033$

In summary, three constitutive curve of the material are shown in Fig. 2.

Shear specimens are uniformly loaded in the middle of the specimen sides. Making use of symmetry, half of the shear specimen can be taking to model as shown in Fig. 3. Specimen is regular hexahedral body. Elements are manually divided. The block is divided into hexahedral elements, along the length they are 37 elements, along the thickness they are 4 and 6 along the width, and a total of elements are 2,664 units.

Compressive specimens are uniformly loaded on the top. The bottom vertical displacement is restricted. Specimen is the rule body, divided as above. Specimen is divided into hexahedral elements. Along the length they are 37 elements, along the thickness they are 2 and 6 along the width, and a total of elements are 11,100 units. Mesh is shown in Fig. 4.

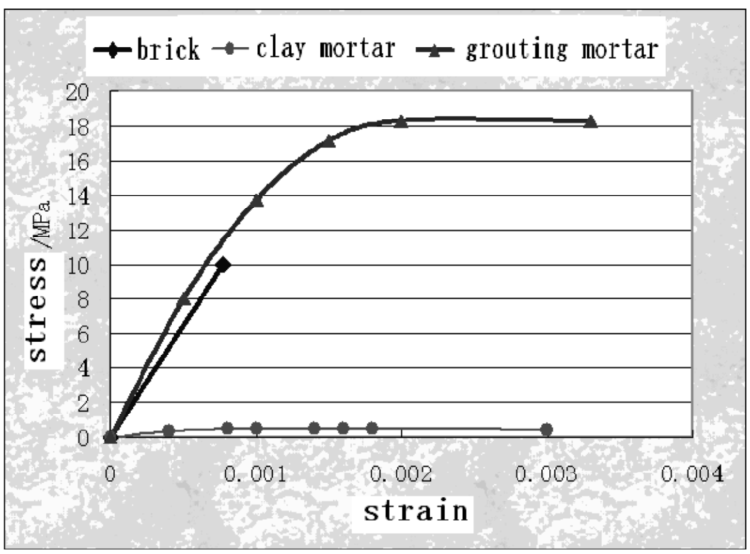

Figure 2: The Constitutive Curve of Brick, Clay Mortar and Grouting Mortar

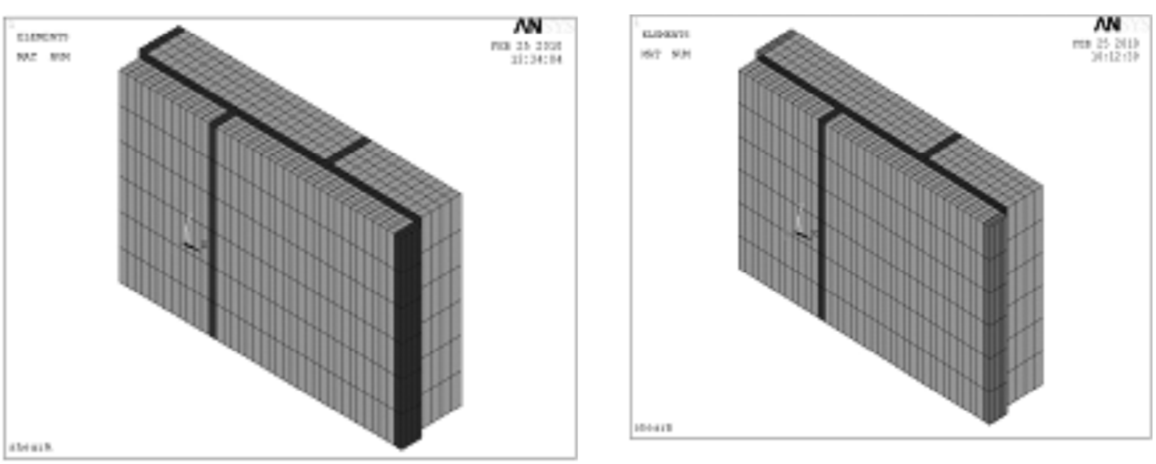

Figure 3: Shear Specimens Mesh of Original (left) and with Grouting Strengthening (right)

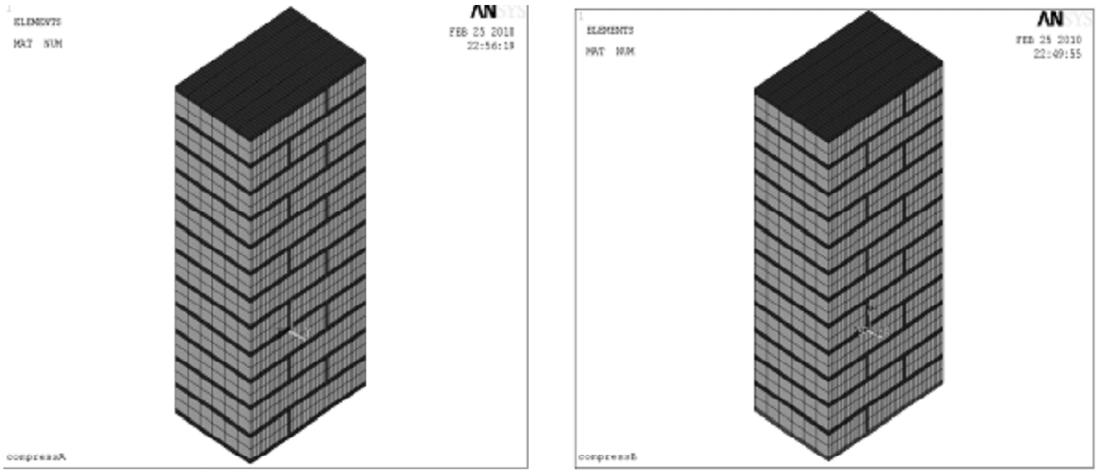

Figure 4: Compressive Specimens Mesh of Original (left) and with Grouting Strengthening (right)

3. TEST AND CALCULATION RESULTS

3.1. Shear Specimens

Vertical loading is acted on the area of 240mm × 26.5mm. Ultimate load test and calculated results of shear test specimen are shown in Table 1.

Table 1
Ultimate Load of Shear Test Specimen

specimen	*Ultimate load*		
	test values f1	*ANSYS calculated f2*	*f2/f1*
original	2.21MPa	3.43MPa	1.55
grouting strengthened	6.47MPa	7.48MPa	1.16
strengthening efficiency	293%	118%	

Comparing the finite element analysis and experimental results, the same conclusion can be obtained that the grouting strengthening has been the significant effect. Finite element results is high than the actual test value, without grouting strengthening it is high 55%, with grouting strengthening it is high 16%. These differences may be due to the discrete nature of the material and the deviation of the actual loading in test.

Comparing the central node load and displacement values in mortar layer, it can be found that shear failure did not have the yielding stage, behave the obvious fragility. This phenomenon can be found in the actual test. the ultimate load and displacement of the grouting strengthening specimen is about 2 times larger than the original specimen (Fig. 5).

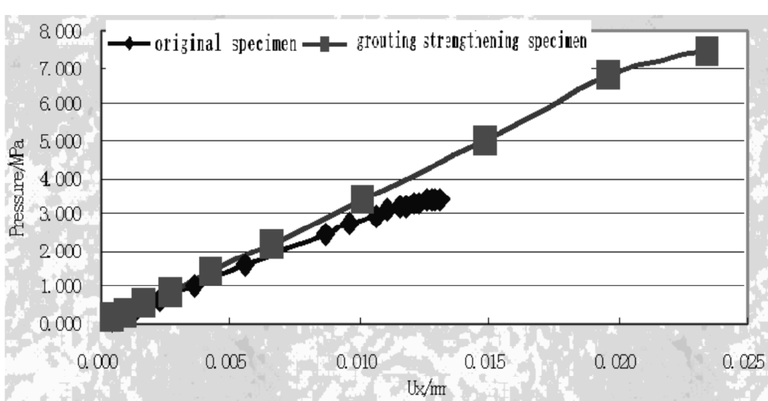

Figure 5: The Central Node Load -Displacement Curve of Mortar Layer

From the first principal stress distribution (Fig. 6), it can be seen that the first principal stress is positive at original clay mortar and more evenly distributed, the stress in grouting mortar layer changes with the mechanical properties of grouting mortar. Because the grouting mortar has high mechanical properties, its first principal stress is high than the original mortar, which is similar the stress redistribution phenomenon.

From the first principal strain (Fig. 7) can clearly be seen that the original mortar strain near the loading position is greater. Strain of grouting strengthening mortar changes with mortar materials. The large strain occurs in the original mortar. The strain is small in mortar and bricks than original mortar because of theirs gooddeformation properties.

From the vertical shear stress distribution of original mortar specimen (Fig.8) it can be seen that shear stress mainly distribute in the upper part, the shear stress is relatively small in the left lower mortar. Because the mortar in the upper and lower brick on the left side is the plastic zone compared to the brick, transmission force is limited. From the vertical shear stress distribution of grouting strengthening specimen it can be seen that vertical shear stress distribution is obviously different with the mortar, the vertical shear stress is larger in new mortar area. The stress redistribution phenomenon is evident. The shear strain distribution is similar with shear stress distribution (Fig. 9).

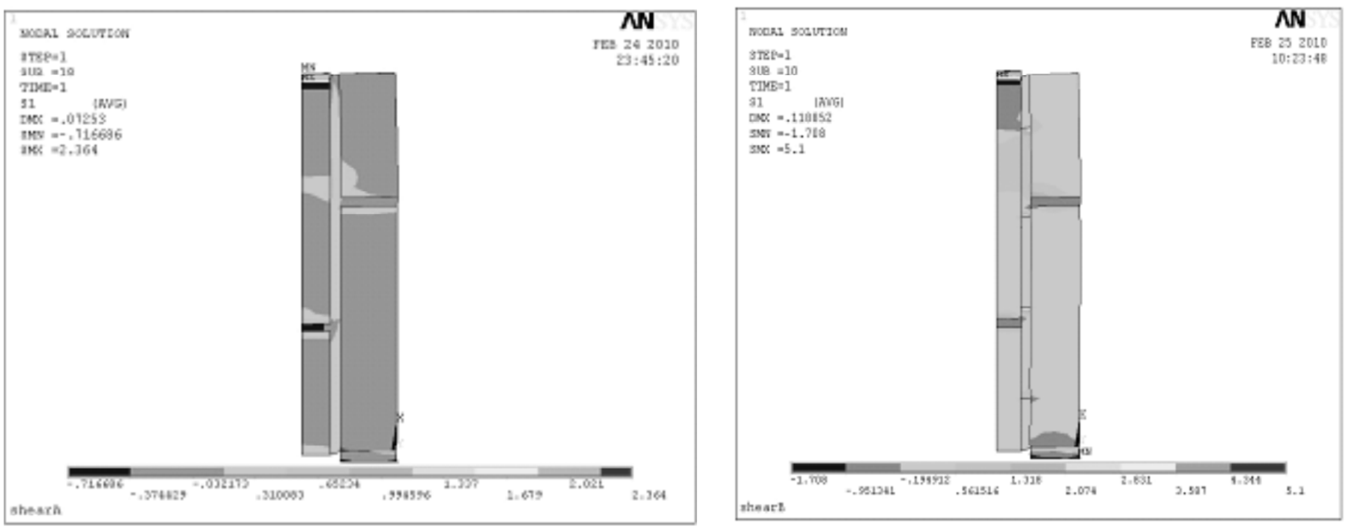

Figure 6: The First Principal Stress of Shear Specimens of Original (left) and with Grouting Strengthening (right)

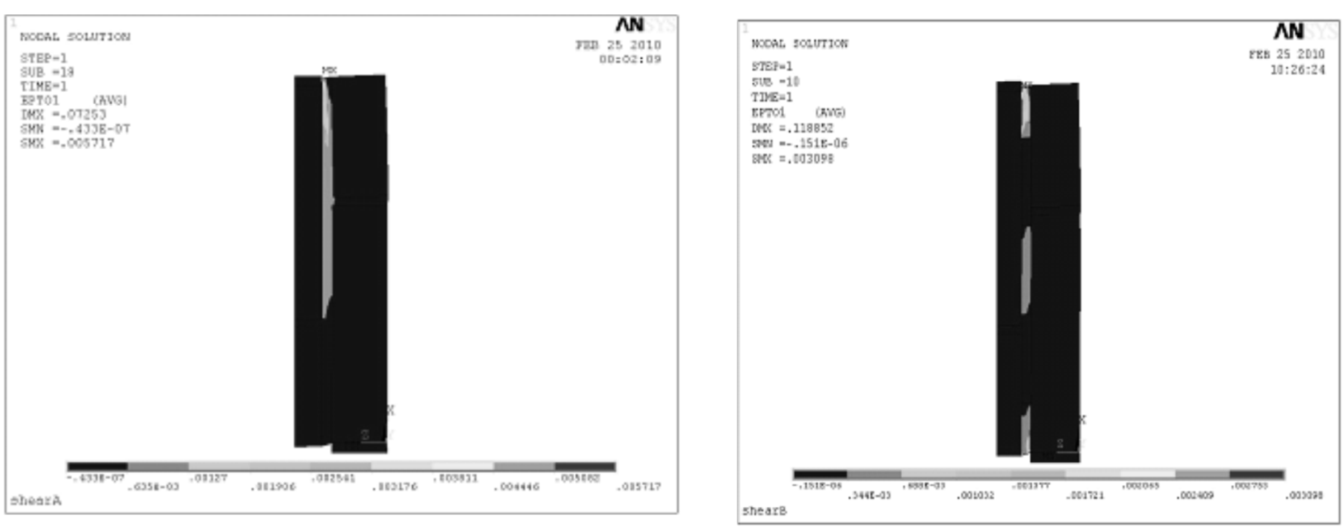

Figure 7: The First Principal Strain of Shear Specimens of Original (left) and with Grouting Strengthening (right)

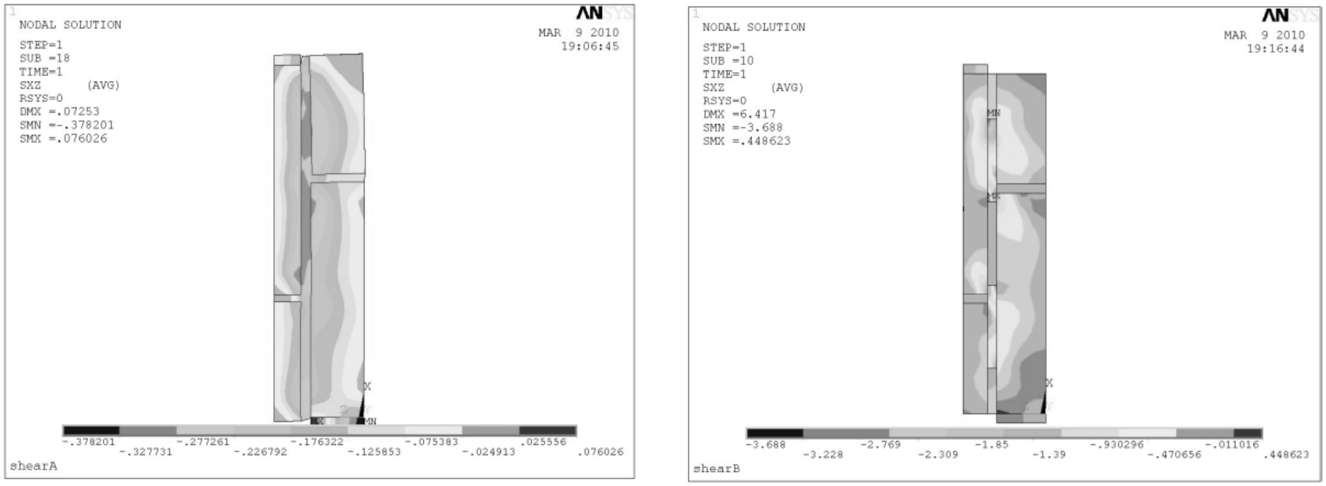

Figure 8: The Shear Stress of Shear Specimens of Original (left) and with Grouting Strengthening (right)

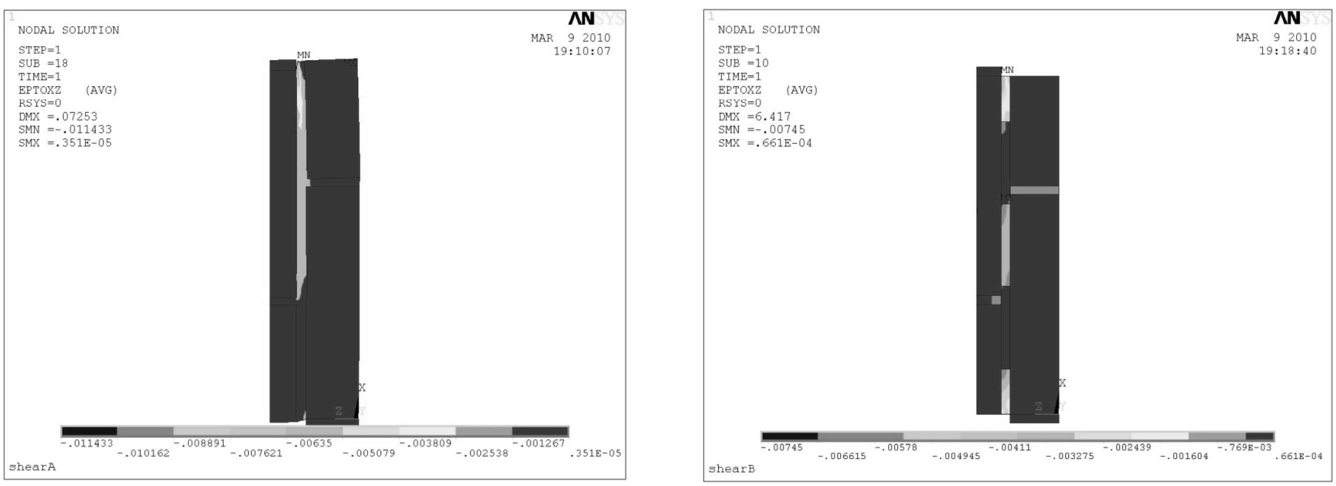

Figure 9: The Shear Strain of Shear Specimens of Original (left) and with Grouting Strengthening (right)

3.2. Compressive Specimens

The uniform distribution vertical loading is acted on the area of 240mm × 26.5mm. Ultimate load test and calculated results of compression test specimen are shown in Table 2.

Table 2
Ultimate Load of Compression Test Specimen

specimen	*Ultimate load*		*f2/f1*
	test values f1	*ANSYS calculated f2*	
original	3.23MPa	3.39MPa	1.05
grouting strengthened	4.05MPa	5.00MPa	1.23
strengthening efficiency	25%	42%	

The results from the finite element analysis and experiment show that the grouting strengthening is obvious. The compression capacity is increased by 25%. FEA results is high than the experiment. The original experiment is high about 5% and the grouting strengthened specimen is high about 23%.

The load and displacement relationship of central node in mortar layer is showed in Fig. 10. It can be found that the bearing capacity of the grouting strengthened specimens is significantly improved than the original specimen, but the ductility decreased.

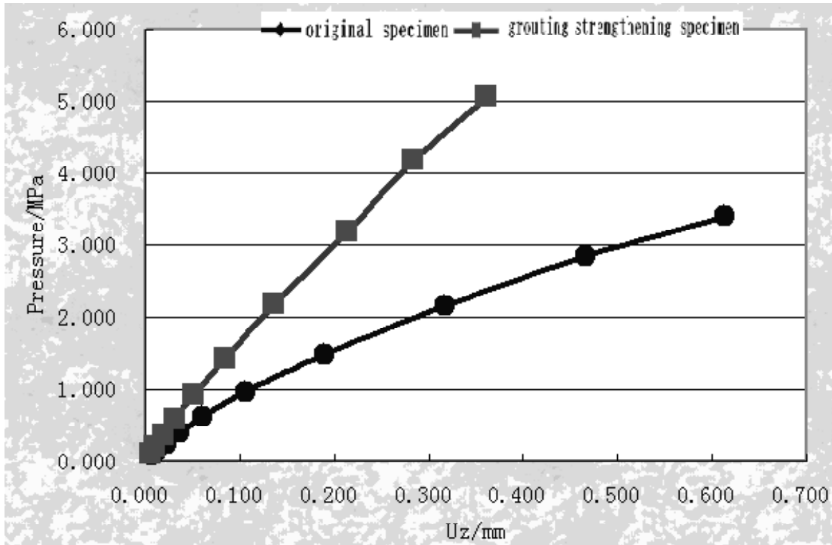

Figure 10: The Central Node Load - Displacement Curve of Mortar Layer

From the first principal stress distribution (Fig. 11), it can be seen that the first principal stress is uniformity at original clay mortar and more unevenly distributed in the grouting mortar. Form the junction area of the original mortar and grouting mortar it can be seen that the stress changes in bricks is larger, indicating that a brick in the junction area is more complex. The cracking is more likely to occur in the junction area. This agrees with the actual cracks distribution.

From the vertical stress distribution (Fig. 12) can be seen that the original specimen stress is more uniform and grouting strengthening specimen stress is obvious differences. The stress distribution is significantly different in the grouting strengthening area and the original area. The grouting strengthening area stress was significantly greater than original area. With the increase of external loading the original mortar first enter into the plastic state and the grouting strengthening mortar which has high mechanical properties carry the additional vertical load. The stress redistribution occurs in mortar layer, thereby increase the vertical bearing capacity.

From the vertical strain distribution (Fig. 13) can be seen that the vertical strain distribution in original specimen is uniform, in grouting strengthening mortar layer the strain changes with mortar materials and the original mortar strain is significantly greater than the grouting strengthening strain. The deformation property of grouting strengthening mortar and bricks is much better than the original mortar, so its strain is smaller. The grouting strengthening mortar is slightly smaller than bricks.

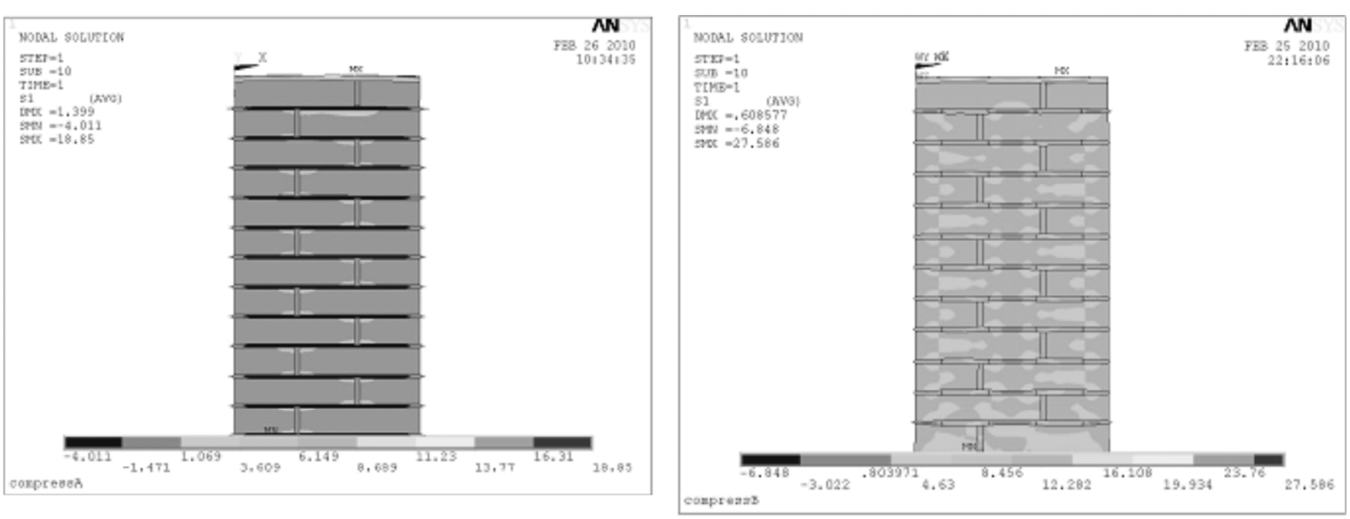

Figure 11: The First Principal Stress of Compression Specimens of Original (left) and with Grouting Strengthening (right)

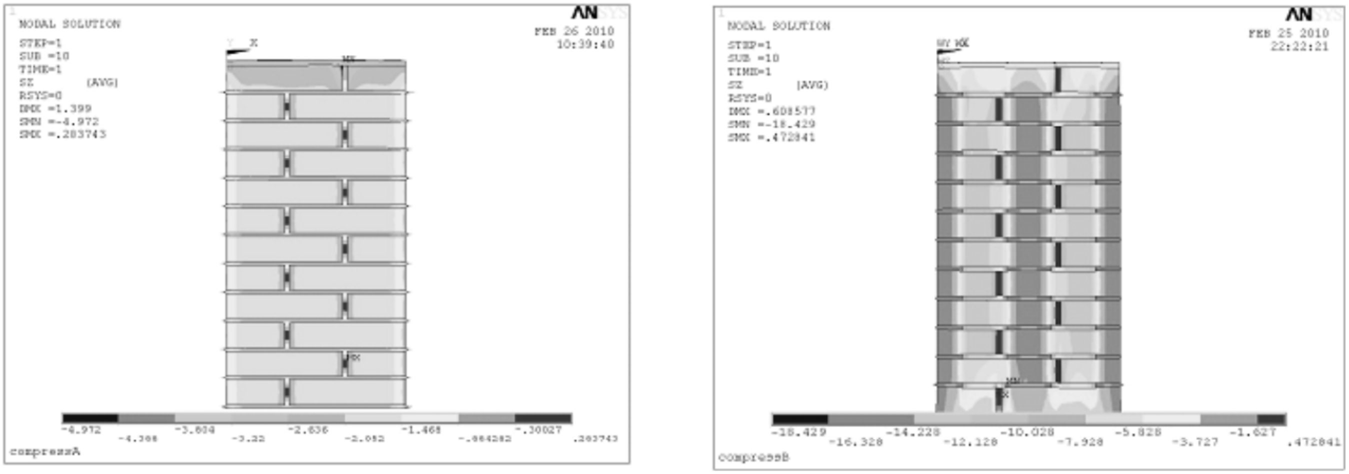

Figure 12: The Vertical Stress Distribution of Original Specimen (left) and with Grouting Strengthening (right)

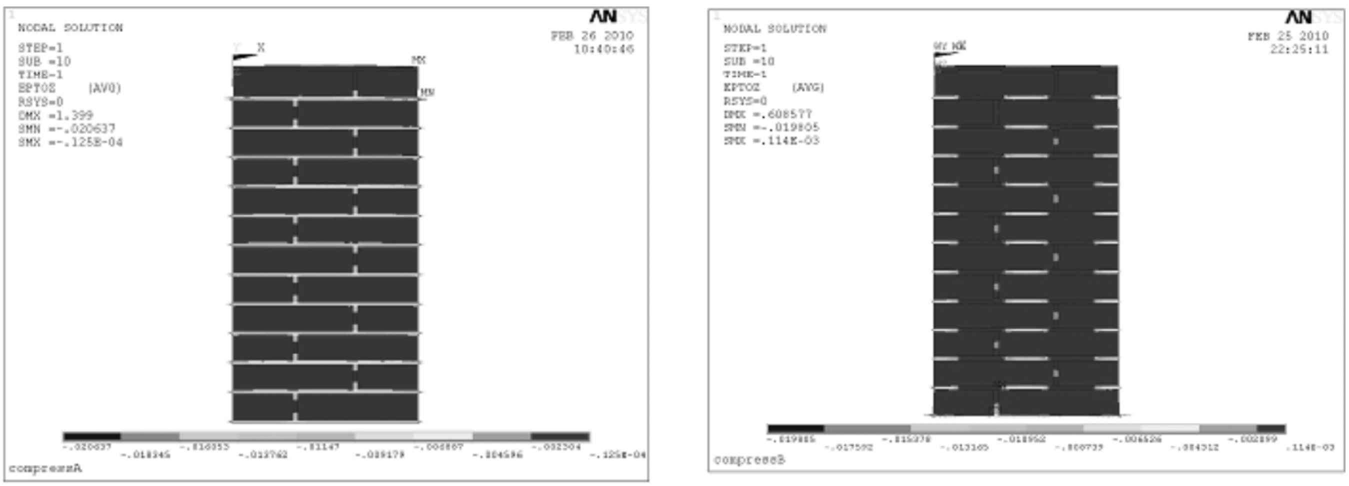

Figure 13

4. CONCLUSIONS

In summary, the finite element results show that the shear capacity of the grouting strengthening specimens is increased by 118% than the original specimen, compressive strength is increased 42%. Grouting strengthening is proved theoretically valid to improve carrying capacity of masonry. The calculated bearing capacity values are difference with the measured. This may be due to the discrete nature of masonry materials and test loading error. From the two kinds of model it can be seen that the capacity trends is consistent with the actual. The finite element discrete model is feasibility to masonry specimens. After grouting, the stress uniformity of mortar is exacerbated, particularly in the junction area of old and new mortar, thus, leads to cracks in this region. The stress redistribution occurs in the mortar layer. The grouting strengthening mortar have good mechanical and cohesive properties, thus grouting can increase the overall carrying capacity.

Acknowledgement

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References

[1] Yang Junwei, Research on Strategies and Countermeasures in Seismic Strengthening of Urban BuildingsÿBeijing University of Technology, Master Degree Paper (2006).

[2] Mi Hongliang, Li Yang, Hou Jiansheng, "Earthquake Disasters in Chinese Mainland in 2007," *Recent Developments in World Seismology*, **2**, 42-46, (2008).

[3] Shi Jianguang, Deng Hua, "Estimating Building Waste after Wenchuan Earthquake and Discussion on Recycling way," *Highlights Science Paper on Line*, **2**(2), 150-157, (2009).

[4] Guo Jiwu, Seismic Design of Buildings, China Building Industry Press, 2004.

[5] Tian Jie, Liu Zhigang, "Review and Suggestions of Aseismatic Reinforcement in China," *Earthquake Resistant Engineering and Retrofitting*, **28**(6), 32-36, (2006).

[6] Shi Chanfeng, Study of the Damage Detection and Remedial Technology for Wuhan Historical Buildings, Huazhong University of Science, Master Degree Paper (2005).

[7] Chen Zhaoyuan, Qian Jiaru, Earthquake Damage Investigation and Reconstruction Building Analysis Report, China Building Industry Press, 2008.

[8] Si Yingcai, Liu Xingyuan, Wang Wei, "On Masonry Structure Safety of Mortar Strength Downgrading," *Chongqing Science and Technology Institute*, **3**, 23-26, (2006).

[9] Deng Hua, Estimation and Recycling of Post-earthquake Construction Waste and Grouting Strengthening Method of Masonry Structures, Xiamen University, Master Degree Paper (2010).

[10] Li Yingmin, Han Jun, Liu Liping, "Application of ANSYS to Finite Element Analysis for Nonlinear Masonry Structures," *Journal of Chongqing Jianzhu University*, **28**(5), 90-105, (2006).

[11] Patrick De Buhan, Gianmarco De Felice, "A Homogenization Approach to the Ultimate Strength of Brick Masonary," *Mech. Phy. Solids*, **45**(7), 1085-1104, (1997).

[12] Giovanni Formica, Vittorio Sansalone, Raffaele Casciaro, "A Mixed Solution Strategy for the Nonlinear Analysis of Brick Masonry Walls," *Computer Methods in Applied Mechanics and Engineering*, **191**(5), 5847-5876, (2002).

[13] Liu Li, Wang Yonghu, Gu Qian, "Finite Element Analysis on Shear Behavior of Unreinforeed Masonry Wall," *The World of Building Materials*, **30**(1), 72-74, (2009).

[14] Zhou Pinghuai, "Simulation and Analysis on the Collapsing of Mason Building in Earthquake," *Zhejiang Construction*, **26**(8), 27-30, (2009).

[15] Song Yang, Gao Junzhao, Zhao Jun, "Application of ANSYS in the Nonlinear Finite Element Analysis of Masonry Structure," *Journal of Anyang Institute of Technology*, **6**, 69-71, (2009).

[16] Zhu Bolong, Masonry Structure Design Principle, Tongji University Press, 1991.

[17] Liu Guiqiu, The Research on the Basic Mechanical Behavior of Masonry Structure, Hunan University, Doctor Degree Paper (2005).