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Research progress of FRP in steel and masonry bridge structures reinforcement

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Abstract. Fiber reinforced polymer (FRP) has been widely used in the reinforcement of concrete bridge structures, and it still has a good application prospect in the reinforcement of steel and masonry bridge structures. In order to summarize the research results of FRP in the reinforcement of steel and masonry structures, broaden the ideas of FRP strengthening bridges in China and promote its wide application in the field of bridge structure reinforcement, it is summarized from the aspects of anti-fatigue reinforcement, anti-buckling reinforcement, bearing capacity reinforcement and seismic reinforcement according to the different reinforcement mechanisms. The shortcomings of the existing studies were analyzed, some problems and ideas that can be further studied were put forward. Analysis result shows that the prestressed FRP reinforcement technology has a good application prospect because of its high material strength utilization rate. Generally, the method of prestressing FRP is used to strengthen the bridge steel members with fatigue cracks, and FRP and filler materials are used to form an external reinforcement system to improve the buckling resistance of steel members. FRP reinforcement can improve the bearing capacity and seismic performance of masonry structures. Follow-up studies should be continued to develop standardized prestressed FRP reinforcement and anchorage system with long-term reliable performance, further promote the engineering application of prestressed FRP reinforced steel structures and establish the specification system of FRP reinforced masonry bridges. The durability of FRP reinforced bridges under complex environment and coupling of various factors should be deeply studied.

Keywords: bridge engineering; FRP reinforcement; review; steel structure; masonry structure

1. Introduction

Due to the influence of heavy traffic and corrosive environment, many existing steel structures have the problems of fatigue cracking and buckling instability, which seriously affect the safety of structures. The maintenance and reinforcement of steel structure has always been the focus of research at home and abroad. The common reinforcement methods include welding, riveting, outsourcing concrete, pasting steel plate and pasting FRP cloth and FRP plate. Among them, FRP reinforcement technology stands out because of its fast construction and durability. After continuous development in recent years, China has promulgated the relevant specification for reinforcement and repair of steel structure with fiber reinforced composites. In addition, there are still many old masonry arch bridges in China. The compressive strength of masonry structure is high, but the tensile and shear strength are very low. Therefore, the integrity and seismic performance of masonry structure are poor. Because FRP has the advantages of light weight, high strength, convenient construction and good durability, strengthening masonry bridges with FRP can improve the bearing capacity of damaged masonry structures and limit the development of cracks. It can not only meet the safety and durability of structures, but also ensure the aesthetic requirements of masonry bridges. It shows a good application prospect in the bearing capacity reinforcement and seismic reinforcement of masonry bridges.

Based on the latest research results in recent years, this paper systematically summarizes the research status of FRP reinforced steel and masonry structures from the aspects of fatigue resistance reinforcement, buckling resistance reinforcement, bearing capacity reinforcement and seismic reinforcement, analyzes the shortcomings of the current research, and then puts forward the problems to be further studied, so as to promote the development and engineering application of

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FRP reinforcement methods in the field of bridge reinforcement and meet the diversified development needs of engineering operation and maintenance.

2. FRP reinforced steel bridge structure

2.1 Anti-fatigue reinforcement

The steel structures or connections that need fatigue reinforcement are mainly divided into two categories: one is the reinforcement with fatigue cracks, and the other is the reinforcement when the fatigue cracks have not appeared but the design fatigue life has been reached or the fatigue bearing capacity does not meet the requirements. For the former, the fatigue crack needs to be repaired first, and then FRP reinforcement can be carried out. The types of FRP used for reinforcement are mainly FRP plate and FRP cloth. FRP plate is suitable for flat reinforcement surface, and FRP cloth is suitable for uneven reinforcement surface with cracks and so on. When strengthening with FRP sheet, the fiber direction shall be perpendicular to the propagation direction of the existing crack or parallel to the main tensile stress direction at the stress concentration.

Like RC beams, if the initial prestress is applied to FRP, it can also effectively reduce the stress level of steel structure and limit the generation and development of cracks. Chen et al. [1] conducted an experimental study on the fatigue performance of steel beams with cracked rectangular hollow section repaired by prestressed CFRP plates. The test results show that FRP plates with higher elastic modulus or larger prestress level can improve the fatigue performance of steel beams. For damaged steel beams, the driving mechanism of fatigue crack growth is the basis for evaluating the reinforcement effect and fatigue life of FRP. Ye et al. [2] proposed a new two parameter driving force model. Through the existing fatigue test and numerical analysis, it is verified that the model can reasonably reflect the crack propagation behavior of steel structures strengthened with prestressed CFRP plates. In order to obtain the magnitude of the pre stress required when FRP is used for fatigue reinforcement of steel structures, Seyed et al. [3] Based on the numerical analysis method of linear elastic fracture mechanics, proposed a method that can predict the minimum pre stress required for the crack surface of steel members to remain closed under large external load. This method can obtain the minimum pre stress required to effectively prevent fatigue crack propagation.

According to whether there is bonding at the reinforcement interface, the steel structure strengthened with prestressed FRP can be divided into prestressed bonded FRP reinforcement (Fig. 1a) and prestressed unbonded reinforcement. Hosseini et al. [4] developed a new type of unbonded mechanical anchorage system (Fig. 1b), and proved through a series of static and fatigue tests that the system can effectively transfer the prestress of CFRP plate to the steel plate, and there was no slip failure during the test.

The change of temperature has an obvious influence on the performance of the resin, and then affects the fatigue life of the reinforcement system. In order to study the effect of temperature on fatigue strengthening efficiency, Feng et al. [5] studied the performance of cracked steel plates strengthened with CFRP sheets at different temperatures, modified the existing analysis method of fatigue life of CFRP strengthened steel plates at room temperature, and then put forward the design guide for fatigue of steel structures strengthened with CFRP sheets and the program for calculating the residual fatigue life and allowable stress of steel plates [6].

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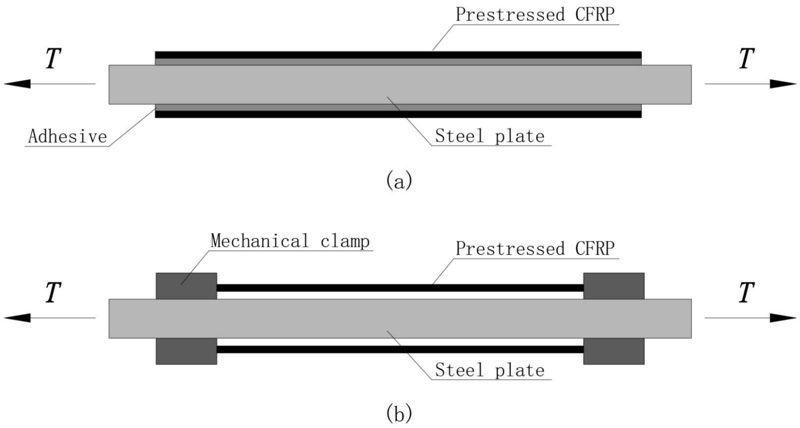

Figure 1. Schematic view of: (a) Prestressed bonded reinforcement and (b) prestressed unbonded reinforcement.

2.2 Anti-buckling reinforcement

For steel members with insufficient axial compression stability bearing capacity, the FRP reinforcement methods are mainly divided into two categories: one is to coat the steel member with FRP pipe and fill mortar between the pipe and the steel member [7] (Fig. 2a); the other is use light materials (such as bamboo wire) to clamp steel members to form a larger section, and paste longitudinal FRP cloth and wrap transverse FRP cloth outside the light materials [8] (Fig. 2b). FRP cloth and filler materials form an external reinforcement system, which can effectively restrain the core steel members and significantly improve the buckling resistance of steel members.

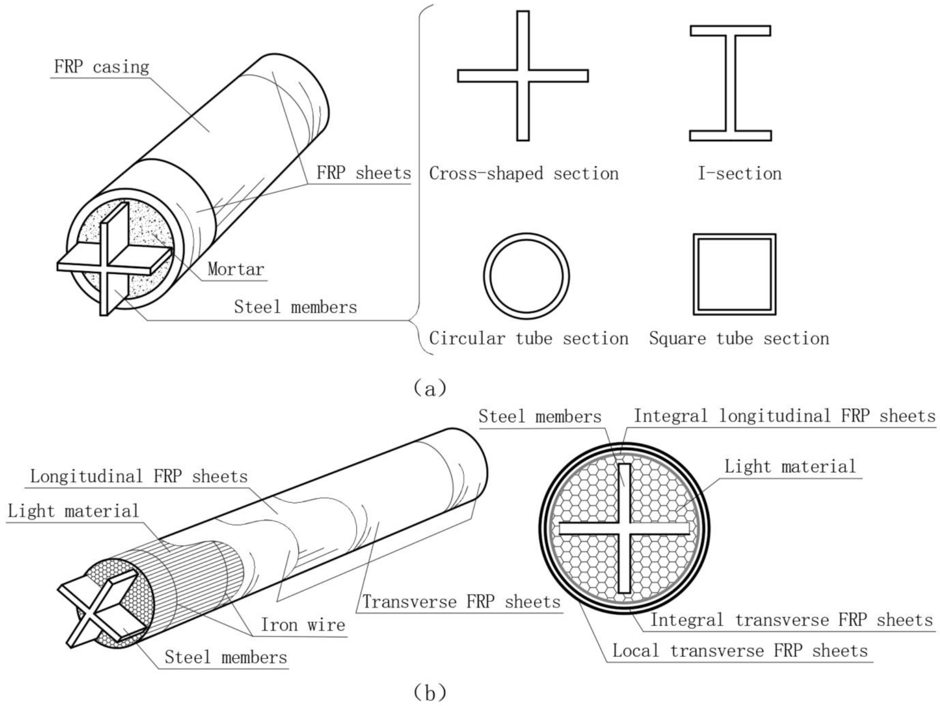

Figure 2. Anti-buckling reinforcement of steel member.

For the method of strengthening slender steel members with FRP pipes filled with mortar or concrete, most of the existing studies allow the filling material to bond directly to the steel member. The load will be borne by the core steel member, filler and FRP sleeve, which may lead to the extrusion failure of filler or the rupture of FRP sleeve. MacEachern et al. [9] used the method of coating lubricant on the steel core, so that the steel core can independently bear most of the axial load. Then a simple linear elastic model is established to predict the failure mode of the hybrid system. The optimal FRP pipe outer diameter and filling material strength are determined by

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establishing the design optimization system, so that the failure mode of the system changes from bending failure to yield failure.

For steel pipe reinforcement, FRP cloth can be pasted directly on the surface of the steel pipe, eliminating the steps of filling materials such as mortar or bamboo, and increasing the convenience of construction. El-Kholy et al. [10] used the three-dimensional nonlinear finite element analysis method to study the performance of FRP reinforced steel pipe. The local and global buckling deformation of the structure obtained from the finite element analysis results are highly consistent with the test results. Zhi et al. [11] and Wu et al. [12] studied the performance of GFRP reinforced circular steel pipe under low-speed transverse and axial impact load by combining numerical and experimental methods. They analyzed the effects of steel pipe thickness and outer diameter, GFRP thickness and winding angle, specimen length, drop weight mass and impact speed on specimen failure, and introduced the prediction formulas of peak impact force and average impact force during specimen failure. A program to simulate the failure and damage evolution process of GFRP is compiled, and the calculated results are in good agreement with the experimental results. Dikshant et al. [13] conducted experimental research on the impact resistance of concrete filled steel tubular (CFST) beams strengthened with CFRP and developed a section analysis method, which can provide researchers with an easy to implement program to determine the material selection and correct configuration required for CFST beam reinforcement.

However, the difficulty of strengthening steel members with bonded FRP sheets is concentrated in the bonding technology. The surface treatment process of this reinforcement method is complex. The bonded FRP sheets are prone to interface peeling failure. In order to solve the above problems, Yoresta et al. [14] proposed the method of strengthening steel members with unbonded CFRP sheets, using vacuum assisted resin transfer molding (VARTM) technology to make the gap between CFRP sheets and steel members zero. The test results show that this method can effectively enhance the buckling performance of steel members and improve their axial bearing capacity. Feng et al. [15] proposed the method of strengthening steel compression bar with unbonded prestressed CFRP plate based on the concept of self-balancing system. The CFRP plate produces axial preload and lateral support force on the steel column, which can increase the structural stiffness, effectively limit the occurrence of overall buckling and increase the buckling load by 150%.

In addition to the anti-fatigue and anti-buckling reinforcement described above, the FRP reinforcement method of steel structure can also improve its anti-corrosion performance. Steel structures are prone to corrosion when directly exposed to the environment. However, by pasting FRP layer on the steel structure surface, the steel surface can be effectively isolated from moisture and air contact. And the FRP itself has good durability, which can effectively improve the corrosion resistance of steel structures.

To sum up, in the aspect of FRP strengthening steel structure bridges, the current research mainly focuses on anti-fatigue reinforcement and anti-buckling reinforcement. In the aspect of anti-fatigue reinforcement, the reinforcement mode, fatigue crack propagation mechanism and residual fatigue life analysis method are mainly studied. In the aspect of anti-buckling reinforcement, it mainly studies the reinforcement method, parameter optimization of reinforcement system and unbonded reinforcement technology. In the future, we should further establish the standardized calculation method of allowable stress or residual fatigue life of different forms of steel structures strengthened with FRP, the high-temperature softening of different FRP, the aging of bonding layer and the bond slip model of reinforcement interface, and constantly promote the engineering application of prestressed FRP in strengthening steel structures.

3. FRP reinforced masonry bridge structure

3.1 Bearing capacity reinforcement

Strengthening Masonry bridges with FRP can improve the shear, tensile and flexural capacity of masonry structures. The reinforcement methods are mainly divided into two categories: Externally

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Bonded FRP (EB-FRP) and near-surface mounted FRP (NSM-FRP) reinforcement method. The analysis methods mainly include theoretical research and experimental research.

For EB-FRP method, in terms of theoretical research, Chen [16] first proposed the calculation method of ultimate bearing capacity of masonry arch bridge strengthened with FRP, and get the conclusion that pasting a small amount of GFRP sheet on the inner surface of masonry arch bridge can significantly improve the structural strength. Foraboschi et al. [17] studied the reinforcement of masonry arch surface with FRP strips and pointed out that there are four possible failure modes: block crushing, masonry sliding, FRP peeling and FRP fracture, which laid a foundation for the in-depth study of masonry structure bridges strengthened with FRP. Szołomicki et al. [18] established the numerical model of masonry vault strengthened with FRP sheet and found that strengthening masonry vault with FRP sheet can limit structural deformation, reduce tensile stress in masonry, reduce crack width and improve fatigue strength of masonry. In terms of experimental research, Castori et al. [19] found that pasting FRP sheets in the mortar joint and on the outer surface of the vault can provide additional tensile strength for the structure.

For NSM-FRP method, it not only increases the bonding area between FRP sheet and structure, improves the strength utilization rate and durability of materials, but also does not change the surface shape of the structure. It has more advantages for the protection of Masonry bridges with a long history. In terms of theoretical research, Petersen [20] established the masonry finite element model by using the micro modeling method to simulate the shear performance of clay brick masonry wall strengthened with NSM-CFRP strip. The load displacement response, FRP reinforcement stress and crack development obtained from the results are highly consistent with the test results. It is concluded that the main shear mechanism is the increase of friction caused by FRP shear expansion. Casacci [21] concluded that the masonry wall strengthened with NSM-BFRP reinforcement can increase the ultimate load, shear stiffness and ductility of the structure, and the increase effect is not proportional to the reinforcement ratio. In terms of experimental research, Turco [22] found that the shear strength of masonry wall strengthened with NSM-FRP reinforcement can be increased by 2.5 times and the flexural strength can be increased by 4.5-26 times; Low bond FRP plain round bars are suitable for shear reinforcement, while rectangular FRP bars are suitable for flexural reinforcement. Petersen [23] conducted an experimental study on the in-plane shear performance of masonry slab strengthened with NSM-CFRP strips. The results show that vertical FRP can effectively inhibit the generation and development of inclined cracks. Setting two NSM-CFRP strips vertically on both sides of masonry slab is the most effective reinforcement scheme.

In addition, the reconstruction of masonry structure bearing uneven foundation settlement is an important and challenging practice. Stockdale [24] established a finite element analysis model with the help of ABAQUS software and found that the actual damage of the masonry structure may come from the shear slip of the hinge. He proposed a progressive reinforcement strategy and found that the reinforcement effect of the system at the key parts is better than that of the full reinforcement, which can be used for the optimal design of FRP reinforcement positions.

3.2 Seismic reinforcement

Due to the change of service function, environmental effect and lack of maintenance, masonry structures will be damaged to varying degrees under earthquake. At present, hundreds of masonry bridges in China are in earthquake prone areas. FRP reinforcement method shows a good application prospect in improving the seismic performance of the structure.

The seismic performance of masonry structure is mainly reflected in the ductility, integrity, deformation capacity and shear capacity of masonry structure. Many scholars have carried out experimental research on it, which is mainly divided into two aspects: shaking table test of integral structure and quasi-static test of masonry members.

In shaking table test, the change of seismic performance of masonry structure can be measured by the change of peak ground acceleration (PGA) before and after reinforcement. Giamundo et al.

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[25] and Ramaglia et al. [26] conducted several shaking table tests on the masonry arch without reinforcement and strengthened with FRP woven mesh reinforced cement-based material (FRCM). The results showed that the PGA value of the structure with cracks after FRCM reinforcement increased significantly, indicating that this method can significantly improve the seismic performance of the masonry arch crown.

In terms of quasi-static test, Tao et al. [27] respectively loaded the three-story masonry perforated wall specimens without reinforcement and strengthened with CFRP mesh to failure through quasi-static test. It was found that the shear bearing capacity of masonry wall strengthened with CFRP mesh was significantly improved, and it was suggested that the minimum repair area of wall body was 22%. Sun et al. [28] obtained through experimental research that spraying GFRP can effectively improve the seismic performance of masonry wall. The test also proved that the reinforcement effect of spraying GFRP is better than that of pasting CFRP cloth. Konthesingha [29-30] conducted an experimental study on the seismic performance of masonry walls strengthened with NSM-CFRP strips and plates. The results show that the deformation capacity and energy dissipation capacity of the strengthened walls are significantly improved, and the seismic effect of combined reinforcement in horizontal and vertical directions is better than that of reinforcement only in horizontal direction.

To sum up, the FRP reinforcement method started relatively late in the reinforcement of masonry bridges, and there are only a few research results on improving the bearing capacity and seismic performance of masonry arch bridges. Masonry structure is very different from concrete structure. The failure mechanism of FRP reinforced concrete structure and the theory of interface bonding and sliding are not necessarily suitable for masonry structure. There is still a lack of systematic analysis methods, industry specifications and design guidelines for FRP strengthened masonry bridges, which need a lot of experimental research as support.

4. Conclusion

a) Among various reinforcement methods, prestressed FRP reinforcement technology shows a better application prospect because of its high material strength utilization. In addition, partial bonded FRP reinforcement, FRP grid reinforcement and section penetrating FRP reinforcement are also suitable for some other reinforcement conditions. But we should further improve the research and development of long-term and reliable standardized prestressed FRP anchorage system.

b) For the reinforcement of bridge steel members with fatigue cracks, prestressed FRP reinforcement method is generally needed to improve their fatigue resistance. FRP with higher elastic modulus or larger prestress level can better improve the fatigue performance. The buckling resistance of steel members can be improved by using FRP and filler materials to form an external reinforcement system to restrain the core steel members. But the standardized calculation method of allowable stress or residual fatigue life of different forms of steel members strengthened with FRP should be further established and the engineering application of prestressed FRP reinforced steel structures should be further promoted.

c) FRP reinforcement of damaged masonry bridges can limit structural deformation, reduce tensile stress in masonry, reduce crack width, and improve the bearing capacity and seismic performance of the structure, which shows a good application prospect. But further experimental research and systematic theoretical analysis are carried out, and the industry specifications for FRP strengthening masonry bridge structures should be established.

d) In the future, we can further study the impact resistance of FRP reinforced bridge structure under the coupling action of dynamic load, complex environment and other factors, and clarify the long-term performance of FRP reinforced concrete structure under high stress state and complex environment.

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References

[1] Tao Chen, Xianglin Gu, Ming Qi, et al., Experimental study on fatigue behavior of cracked rectangular hollow-section steel beams repaired with prestressed CFRP plates, Journal of Composites for Construction 22 (2018) 04018034.

[2] Huawen Ye, Shiqing Tang, Dejun Liu, Two-parameter crack driving force model for crack growth of damage steel structures strengthened with prestressed CFRP, China Journal of Highway and Transport 34 (2021). (in Chinese)

[3] M. H. Seyed, M. Jakob, I. Mohammadreza, et al., Fatigue crack arrest in steel beams using FRP composites, Engineering Failure Analysis (2021) 105397.

[4] A. Hosseini, E. Ghafoori, M. Motavalli, et al., Development of prestressed unbonded and bonded CFRP strengthening solutions for tensile metallic members, Engineering Structures 181 (2019) 550-561.

[5] Peng Feng, Lili Hu, Xiaoling Zhao, et al., Study on thermal effects on fatigue behavior of cracked steel plates strengthened by CFRP sheets, Thin-Walled Structures 82 (2014) 311-320.

[6] Lili Hu, Peng Feng, Xiaoling Zhao, Fatigue design of CFRP strengthened steel members, Thin-Walled Structures 119 (2017) 482-498.

[7] Peng Feng, Yanhua Zhang, Lieping Ye, Experimental study on compressed bisymmetrical cross-section steel members strengthened by mortar-filled FRP tubes, China Civil Engineering Journal 46 (2013) 29-37. (in Chinese)

[8] Peng Feng, Yan-hua Zhang, Yu Bai, et al., Combination of bamboo filling and FRP wrapping to strengthen steel members in compression, Journal of Composites for Construction (2013) 347-356.

[9] D. Maceachern, P. Sadeghian, Hybrid FRP strengthening of slender steel members for buckling control, Journal of Composites for Construction 24 (2020): 04020039.

[10] A. M. El-Kholy, S. A. Mourad, A. A. Shaheen, et al., Finite element simulation for steel tubular members strengthened with FRP under compression, Structural Engineering and Mechanics 72 (2019) 569-583.

[11] Xudong Zhi, Qijian Wu, Chen Wang, Experimental and numerical study of GFRP-reinforced steel tube under axial impact loads, International Journal of Impact Engineering 122 (2018) 23-37.

[12] Qijian Wu, Xudong Zhi, Qixun Li, et al., Experimental and numerical studies of GFRP-reinforced steel tube under low-velocity transverse impact, International Journal of Impact Engineering 127 (2019) 135-153.

[13] S. Dikshant, S. Behrouz, Investigation of concrete-filled steel tube beams strengthened with CFRP against impact loads, Composite Structures 208 (2019) 744-757.

[14] F. S. Yoresta, R. Maruta, G. Mieda, et al., Unbonded CFRP strengthening method for buckling control of steel members, Construction and Building Materials 241 (2020) 118050.

[15] Peng Feng, Lili Hu, Steel columns strengthened/reinforced by prestressed CFRP strips: concepts and behaviors under axial compressive loads, Composite Structures 217 (2019) 150-164.

[16] J. F. Chen, Load-bearing capacity of masonry arch bridges strengthened with fibre reinforced polymer composites, Advances in Structural Engineering 5 (2020) 37-44.

[17] P. Foraboschi, Strengthening of masonry arches with fiber-reinforced polymer strips, Journal of Composites for Construction 8(2004) 191-201.

[18] J. Szołomicki, P. Berkowski, J. Barański, Computer modelling of masonry cross vaults strengthened with fiber reinforced polymer strips, Archives of Civil and Mechanical Engineering 15 (2015) 751-766.

[19] G. Castori, A Borri, M Corradi, Behavior of thin masonry arches repaired using composite materials, Composites Part B 87 (2016) 311-321.

ISSN:2790-1688 DOI: 10.56028/aetr.2.1.529
[20] R. B. Petersen, M. J. Masia, R. Seracino, In-Plane Shear Behavior of Masonry Panels Strengthened with NSM CFRP Strips. II: Finite-Element Model, Journal of Composites for Construction 14 (2010) 764-774.

[21] S. Casacci, C. Gentilini, D. A. Tommaso, et al., Shear strengthening of masonry wallettes resorting to structural repointing and FRCM composites, Construction and Building Materials 206 (2019) 19-34.

[22] V. Turco, S. Secondin, A. Morbin, et al., Flexural and shear strengthening of un-reinforced masonry with FRP bars, Composites Science and Technology 66 (2006) 289-296.

[23] R. B. Petersen, M. J. Masia, R. Seracino, In-plane shear behavior of masonry panels strengthened with NSM CFRP strips. I: experimental investigation, Journal of Composites for Construction 14 (2010) 754-763.

[24] G Stockdale, G Milani, FE model predicting the load carrying capacity of progressive FRP strengthening of masonry arches subjected to settlement damage, Key Engineering Materials 4516 (2017) 128-133.

[25] V. Giamundo, G. P. Lignola, G. Maddaloni, et al., Experimental investigation of the seismic performances of IMG reinforcement on curved masonry elements, Composites Part B 70 (2015) 53-63.

[26] G Ramaglia, G P Lignola, A Balsamo, et al., Seismic strengthening of masonry vaults with abutments using textile-reinforced mortar, Journal of Composites for Construction (2016) 04016079.

[27] Yi Tao, Jinben Gu, Ren Xin, et al., Seismic performance of multi-storey masonry wall repaired by carbon fiber reinforced polymer grids, Journal of Southwest Jiaotong University 54 (2019) 1258-1267. (in Chinese)

[28] Chengfang Sun, Xiaoyan Zhang, Qian Gu, Experimental study on cracking load and ultimate load of masonry walls with window openings strengthened with sprayed GFRP, Applied Mechanics and Materials 3306 (2014) 1357-1360.

[29] K. M. C. Konthesingha, M. J. Masia, R. B. Petersen, et al., Experimental evaluation of static cyclic in-plane shear behavior of unreinforced masonry walls strengthened with NSM FRP strips, Journal of Composites for Construction 19 (2015): 04014055.

[30] K. M. C. Konthesingha, M. J. Masia, R. B. Petersen, et al., Static cyclic in-plane shear response of damaged masonry walls retrofitted with NSM FRP strips-An experimental evaluation, Engineering Structures 50 (2013) 126-136.