ISSN 2663-1563 Vol. 5, Issue 2: 24-28, DOI: 10.25236/AJAGE.2023.050205

Overview of Conservation and Concealed Reinforcement Techniques for Timber Beams in Ancient Buildings

Zhaoyang Zhu[1], Tao Zhang[2]

[1]*North China University of Technology, Beijing, China*
[2]*Beijing Academy of Cultural Heritage, Beijing, China*

Abstract: *The special feature of restoration and strengthening of timber beam elements in ancient Chinese buildings is that it is not only necessary to prolong their life, but also to protect their value to the greatest extent possible. The traditional restoration and strengthening techniques commonly used are difficult to quantify the results, and there is a risk of over-intervention in the determination of damage and restoration work, which can easily lead to changes in the original appearance of ancient buildings and loss of value information. By exploring concealed restoration and strengthening techniques at the component and node levels, we aim to further enrich preventive conservation methods and better protect and pass on valuable cultural heritage.*

Keywords: *Ancient buildings, timber beam elements, concealed reinforcement*

1. Introduction

The timber structures of ancient buildings in China are of very high historical, artistic and scientific value. As wood is a biomass material, it is susceptible to cracking, decay, deterioration, insect infestation and flexural deformation due to natural and man-made factors. Especially under the effect of cumulative damage, beams are generally damaged before columns, and can even induce partial or overall collapse of the timber structure, thus requiring constant restoration and reinforcement of the timber beam elements of ancient buildings. As the painted and carved surfaces of timber beams contain a wealth of historical and cultural information. The traditional restoration and reinforcement methods currently in use can easily lead to changes in the original appearance of the wooden elements and loss of value information, making it difficult to adapt to the current concept of ancient building conservation[1-5].

With the development of technological conservation methods, scholars at home and abroad have made many achievements in conservation and restoration theories, survey and assessment methods, and restoration and reinforcement techniques. This paper focuses on the assessment of the performance of timber beams prior to restoration and on the techniques and methods of FRP material reinforcement.

2. Assessment of the degradation of the load bearing performance and residual load capacity of timber beams in ancient buildings

Obtaining the degradation of the force properties of old timber beams and assessing the residual load capacity is an important basis for determining the continued use of a member and its restoration and strengthening. There is no complete failure criterion for old timber members. Gerhards (1987) proposed a cumulative model based on the miner criterion to reflect the continuous strength damage of timber, and subsequent studies have modified it by adding factors such as ambient temperature and humidity and moisture content of timber. Based on these models, Xueliang Wang (2008, 2009), Yu Li (2008) and Yang Wang (2015) used reliability and probabilistic model analysis methods to predict the residual load capacity of timber beams under the action of multiple factors such as residual damage, ambient temperature and humidity, and sustained load. In addition, Calderoni (2006), Yang Xiaojun et al. (2007), Zhou Qian et al. (2012), Wang Xueliang et al. (2015), Zhu Zhongman (2015), Song Xiaobin et al. (2016) and Peng Lei et al. (2016) conducted mechanical tests and finite element simulations of foot and shrinkage specimens, respectively, to predict the law of residual load bearing capacity of timber beams under the influence of residual damage factors such as cracking and decay and calculation methods were investigated.

In recent years, under the principle of protecting the originality of ancient buildings, the application of non-destructive testing techniques to investigate the timber properties and residual damage of ancient old wooden beams has gradually increased. Zhang Jin et al. (2011) used a nail shooting instrument and a wood impedance instrument to inspect old wooden beams and finally obtained the residual strength values of the members considering the effects of decay and insect infestation. Gu Yu (2016) used an ultrasonic non-metallic flaw detector to test decayed wooden beams and proposed a prediction method for assessing the flexural load capacity of decayed wooden beams. Dai Jian et al. (2017) conducted a timber and residual damage survey of ancient wood members by means of stress waves in conjunction with impedance meters, and the average value of detection accuracy was higher than that of applying a single device[6-9].

Remaining problems and shortcomings: (1) There are many random influencing factors in the reliability and probability model analysis, and some of the parameter values lack experimental basis, so it is difficult to accurately assess the strength degradation and residual bearing capacity of wooden beams. (2) Wood will naturally age over time, resulting in significant differences in the properties of old and new timber, and previous studies have mostly used the mechanical properties of new timber for theoretical derivation and simulation.

3. Restoration and strengthening techniques for timber beams in ancient buildings

Traditional restoration and reinforcement techniques include roofing, nailing, hooping, additional sections and replacement of new elements, which are often passed down from craftsman to craftsman by word of mouth, by 'eye, hand, ear', and so on. Therefore, there is a risk of over-intervention in the determination of deterioration and repair work, which can easily lead to changes in the original appearance of ancient buildings and loss of value information.

In addition to the traditional techniques mentioned above, many achievements have been made in the field of restoration and strengthening of timber beams in ancient buildings through the application of new materials and technologies. For example, WER Systems and BETA Systems in Europe have used metal materials embedded in wooden beams to reinforce them, but the surface of the metal materials generates condensation in response to changes in ambient temperature and humidity, which accelerates the decay of the wood, making it difficult to apply this method to ancient buildings in cold regions[10-15].

In recent years, with the development of Fiber Reinforced Polymer (FRP), the use of FRP materials (e.g. CFRP, GFRP, BFRP) to enhance the mechanical properties of wooden structures of ancient buildings can avoid the damage and chemical contamination of the original members by traditional reinforcement methods, while enhancing the strength and durability performance of timber structures. As an early application in the restoration and reinforcement of wooden structures in ancient buildings, FRP cloth wrapped around the surface of members and FRP sheeting techniques have been used to great effect in the conservation projects of the Yingxian Wooden Pagoda and the Zhonghe Hall of the Forbidden City (Figure 4). However, the above methods are not suitable for use on timber beams with painted or carved surfaces, as they alter the original appearance of the elements, have poor permeability at the wrapped area, and tend to accelerate the ageing of FRP materials by UV light. Therefore, the method of reinforcing timber beams with Near-Surface Mounted FRP (NSM FRP), which has the advantage of improving the force performance and preserving the value information, has obvious advantages in the field of timber structure conservation and restoration of ancient buildings.

Research on the bonding performance of concealed FRP materials to wood: As concealed FRP materials and wood are bonded and transfer loads through an adhesive layer, bonding performance is the key to the two materials working together and is a core fundamental issue in concealed FRP panel reinforcement methods.Vahedian et al. (2017) proposed a single shear test of FRP panel specimens bonded to the surface of broadleaf hardwoods that can effectively predict the theoretical model for the relationship between interfacial bond length and bond performance. Zhang Fuwen et al. (2014) and Zhu Zhaoyang et al. (2019) confirmed that the improved BPE model can effectively predict the bond performance at the interface through double shear tests of embedded FRP reinforcement with new and old Douglas-fir and embedded CFRP panels with new larch from Northeast China, respectively.

Short-term mechanical properties of concealed FRP reinforced timber beams: Gentile C et al. (2002) conducted flexural strengthening tests on cedar beams by embedding glass fibre reinforced plastic (GFRP) tendons and showed that the flexural strength of the reinforced beams increased by 18% to 46%, and proposed a calculation model that could be used to predict the flexural load capacity of the reinforced

ISSN 2663-1563 Vol. 5, Issue 2: 24-28, DOI: 10.25236/AJAGE.2023.050205

beams. Chun et al. (2016) carried out tests on the flexural strength of cedar and pine beams reinforced with embedded CFRP plates and tendons, and the results showed that the results showed that the flexural load capacity and stiffness of the reinforced beams were improved, and the calculation formulae applicable to the flexural load capacity of reinforced timber beams were proposed. Xu Qingfeng et al. (2009, 2012) conducted experimental studies on the flexural performance of new and old timber beams reinforced with embedded CFRP bars and plates, showing that the flexural load capacity of the reinforced beams was significantly increased, with an average increase of 39% and an average increase in damage displacement of 32%. Chunqing et al. (2012, 2013) confirmed that the flexural load capacity of reinforced timber beams could be increased by up to 35.1%, 16.9% (pine) and 37.4%, 21.6% (fir) by embedding CFRP plates and tendons to reinforce new pine and fir beams in flexural tests. Pu Fahong (2018) investigated embedded basalt fibre (BFRP) tendons for reinforcing round-section timber beams and found that the increase in flexural load capacity and stiffness of the embedded tendons reinforced beams was better than that of the reinforced beams wrapped in BFRP fabric. Zhu Zhaoyang et al. (2019) compared the effects of FRP panels and other factors on the flexural performance of reinforced beams through concealed FRP panel reinforcement of reduced-foot and full-foot new pine beams, and proposed a calculation method for the flexural load capacity of reinforced timber beams[16-23].

Study on the long-term mechanical properties of wood beams reinforced with concealed FRP material: Xu et al. (2017) conducted a static load test on footprint reinforced wood beams with embedded CFRP tendons for 1200 days and combined it with finite element simulation analysis to propose a wood creep curve model applicable to beams reinforced with embedded CFRP tendons, which can better predict the effect of wood creep on the mechanical properties of reinforced beams under the effect of ambient temperature and humidity.

Problems and shortcomings: (1) The combination of the restoration and strengthening of timber beams and the assessment of the residual bearing capacity is not yet sufficient, and a complete system of techniques and methods has not yet been formed. (2) Research on the bonding performance of concealed FRP materials and old timber is weak, and the bonding performance of FRP materials and old timber under the coupling effect of multiple factors such as environmental temperature and humidity, ultraviolet light and continuous loading is not yet understood. (3) The results of the research on the stress performance of concealed FRP materials reinforced timber beams are mainly based on the short-term flexural performance. As the long-term performance of the constituent materials of the reinforced beams varies under temperature, humidity and continuous loading, the mechanical properties of these materials are subject to constant change, so whether the conclusions obtained from short-term mechanical tests can guarantee the long-term effectiveness of the reinforcement remains to be answered[24-29].

4. Suggestions for further research

(1) Study of shear performance of concealed reinforced timber beams

Due to the weak shear resistance of the timber with the smooth grain, concealed reinforcement of timber beams can be carried out by means of shear nails, while the effect of reinforcement with FRP plates in combination with shear nails remains to be studied.

(2) Study on concealed reinforcement of beam-column nodes

The nodes of beams and columns are prone to tensile damage and the use of new materials such as memory alloys for concealed reinforcement of nodes is still to be studied in depth.

Acknowledgements

Supported by the Scientific Research Initiation Fund of North China University of Technology.

References

[1] Gerhards C C, and Link C L. A cumulative damage model to predict load duration characteristics of lumber [J]. Wood Fiber Science,1987,192,147-164.
[2] Wang Xueliang. A residual life assessment method based on reliability theory for wooden structures of historical buildings [D]. Wuhan: Wuhan University of Technology, 2008.
[3] Wang Xueliang, Qu Weilian. A model for long-term strength decay of wood members under temperature and humidity variations [J]. Journal of China University of Mining and Technology, 2009,

ISSN 2663-1563 Vol. 5, Issue 2: 24-28, DOI: 10.25236/AJAGE.2023.050205

38(05): 634-639.
[4] Li Yu. Residual life assessment of wooden elements of ancient buildings based on cumulative damage model [D]. Wuhan: Wuhan University of Technology, 2008.
[5] Wang Yang, Yang Na. A method for calculating the remaining life of ancient wood members based on cumulative damage theory [J]. Journal of Beijing Jiaotong University, 2015, 39(01): 45-51.
[6] Calderoni C, Matteis G D, Giubileo C, et al. Flexural and shear behaviour of ancient wooden beams: Experimental and theoretical evaluation [J]. Engineering Structures, 2006, 28/5(5): 729-744.
[7] YANG Xiaojun, SUN Youfu, WU Miao, ZHANG Tao. Effect of cracks on the compressive and flexural strength of wood beams [J]. Wood Processing Machinery, 2007(06): 11-13.
[8] Zhu Zhongman. Experimental study on the effect of dry shrinkage cracks on the force performance of wooden members of historical buildings [D]. Southeast University, 2015.
[9] SONG Xiaobin, WU Yajie, GU Xianglin, JIANG Yingmin. Research on flexural load bearing capacity and repair method of wooden beams with longitudinal joints [J]. Journal of Tongji University (Natural Science Edition), 2016, 44(04): 528-535+592.
[10] Zhou Qian, Yan Weiming, Ji Jinbao. Numerical simulation study on the bending performance of damaged wooden beams of ancient buildings [J]. Journal of Shandong University of Construction, 2012, 27(06): 570-574.
[11] Wang Xueliang, Guo Junhui, Wang Xiaoli, Tan Zhu. Residual life assessment of decaying wooden beams based on reliability theory [J]. Journal of Wuhan University of Technology, 2015, 37(07): 74-77.
[12] Peng L, Wang Xueliang. Strength degradation analysis of dry split wood beams[J]. Wood Processing Machinery, 2016, 27(06): 31-35.
[13] Zhang J, Wang Yachao, Xu Qingfeng, Yang Xiaojing, Li Xiangmin. Residual strength analysis of over-service yellow fir and fir members based on non-destructive testing [J]. Journal of Central South University (Natural Science Edition), 2011,42(12): 3864-3870.
[14] Gu Yu. Effects of decay on the mechanical properties of ancient wooden building elements [D]. Southeast University, 2016.
[15] Dai Jian, Chang Lihong, Qian Wei, Chang Hao. Research on the method and application of nondestructive detection of internal defects in wooden elements of ancient buildings [J]. Journal of Architecture, 2017(02): 7-10.
[16] Li Aiqun, Zhou Kunpeng, Wang Chongchen, Xie Linlin. Analysis and prospect of wood structure restoration and reinforcement technology for ancient buildings in China [J]. Journal of Southeast University (Natural Science Edition), 2019, 49(01): 195-206.
[17] Vahedian A, Shrestha R, Crews K. Effective bond length and bond behaviour of FRP externally bonded to timber [J]. Construction and Building Materials, 2017, 151(oct.1): 742-754.
[18] Zhang Fuwen, Xu Qingfeng, Li Xiangmin et al. Experimental study on the bonding and anchoring performance of embedded CFRP reinforcement with wood [J]. 2014, 30(05): 146-153.
[19] Zhaoyang Zhu, Jian Dai, Wei Qian, Experimental Research on NSM CFRP Plate-to-Ancient Building wood Bond Behavior. IPPTA: Quarterly Journal of Indian Pulp and Paper Technical Association. 2018, 30(6), 34-42.
[20] Gentile C, Svecova D, Rizkalla S H. Timber Beams Strengthened with GFRP Bars: Development and Applications [J]. Journal of Composites for Construction, 2002, 6(1): 11-20.
[21] Yan Yaning, Chen Changliang. Study on the concealed restoration method of wooden beam elements of ancient monuments. Chinese residential architecture yearbook (2008-2010) [M]. China Construction Industry Press, 2010. 1698-1704.
[22] Xu Qingfeng, Zhu Lei. Experimental study on the repair and strengthening of aged damaged old wooden beams with embedded CFRP bars [J]. Journal of Civil Engineering, 2009, 42(03): 23-28.
[23] Xu Qingfeng, Zhu Lei, Chen Jianfei, Li Xiangmin, Zhang Fuwen. Experimental study on the flexural performance of wood beams reinforced with embedded CFRP bars/sheets[J]. Journal of Building Structures, 2012, 33(08): 149-156.
[24] Chun Q, Zhang Y, Pan JW. Experimental study on the flexural performance of embedded carbon fiber plate reinforced wood beams [J]. Journal of Southeast University (Natural Science Edition), 2012, 42(06): 1146-1150.
[25] Chun Q, Zhang Y, Pan JW. Testing of flexural performance of wood beams reinforced with embedded carbon fiber reinforcement [J]. Journal of PLA University of Technology (Natural Science Edition), 2013, 14(02): 190-194.
[26] Pu Fahong. Research on basalt fiber (BFRP) reinforcement technology for round section timber beams [D]. Southwest University of Science and Technology, 2018.
[27] Zhu Zhaoyang, Qian Wei, Cheng Liting, Dai Jian. Flexural performance of FRP panels for concealed reinforcement of wooden beams in ancient buildings [J]. Journal of Beijing University of Technology, 2019, 45(02): 160-167.

ISSN 2663-1563 Vol. 5, Issue 2: 24-28, DOI: 10.25236/AJAGE.2023.050205

[28] Chun, Q., Van Balen, K., Pan, J. Flexural Performance of Small Fir and Pine Timber Beams Strengthened with Near-Surface Mounted Carbon-Fiber-Reinforced Polymer (NSM CFRP) Plates and Rods [J]. International Journal of Architectural Heritage, 2016, 10(1): 106-117.
[29] Xu Q, Chen L, Harries K A, et al. Experimental study and numerical simulation of long-term behavior of timber beams strengthened with near surface mounted CFRP bars [J]. Materials and Structures, 2017, 50(1): 45.