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Structural detection and reinforcement methods for existing buildings

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Abstract. With the popularity of building construction worldwide, building design, construction technology and quality are faced with inherent deficiencies and may be hit by disasters. Therefore, the diagnosis and reinforcement of building structure has become a major problem to be solved urgently in the current building construction. This paper introduces simple detection methods of different building structures and reinforcement techniques under different conditions. In the part of detection methods, various basic detection methods of normal building structure are studied. Then, a special damage appearance is discussed. Besides the traditional electronic imaging method to detect cracks, a special method is proposed to solve the crack problem, namely Min-Max Gray Level Discrimination (M2GLD). This method can improve the detection accuracy and reduce the influence of human factors. At the same time, several different reinforcement techniques are proposed, including traditional reinforcement techniques and advanced reinforcement techniques. This paper introduces the traditional technology of ancient timber structures and the technology of spraying and external bonding FRP to enhance flexural, shear and compressive strength. This paper can be used as reference for structural inspection and reinforcement of existing buildings.

Keywords: structural detection, crack detection, reinforcement methods, sprayed FRP, externally boned FRP.

1. Introduction

In modern society, with the continuous deepening of urbanization worldwide, the city is filled with various buildings, and people are also surrounded by various buildings. Thus, the safety and stability of existing buildings appear particularly significant. As to assessing the safety and stability of existing buildings, building structural detection will be used. Buildings with potential risks in general consist of ancient traditional buildings, aged buildings approaching their expiry date and building areas after natural disasters. Firstly, most traditional buildings were made of wood, which means they are easy to be cracked and deformed. After decades of rain, wind and other extreme natural disasters preserved, ancient wooden buildings have received different degrees of damage typically. Most of the old wooden buildings are precious national cultural treasures and unrecoverable [1]. Therefore, it is particularly important to take detection and renovate these ancient buildings to extend presence time. Secondly, it is undoubtedly unwise to carry out post-disaster relief and repair activities in a situation with unknown risks. Activities in post-disaster building debris with potential safety risks not only cause unnecessary casualties but are also likely to cause secondary damage and collapse of the building debris, making rescue and reconstruction more complex. As a result, structural detection is often used in post-disaster preparation. The accelerating construction of building projects has improved the living environment, structural detection and reinforcement are not only used in the renovation of old and dilapidated buildings, but many new buildings also require testing and reinforcement treatment. Through the inspection of the building, problems with the structure of the building can be detected promptly, and if there are structural problems with the building, the construction company needs to take immediate reinforcement measures to ensure the quality of the entire building project and to extend the life of the building as far as possible.

It can be seen that structural testing and identification are needed to evaluate the stability of new buildings, the actual damage of post-disaster buildings and the safety of ancient buildings. Then, according to the test results, appropriate management and maintenance are carried out to extend the running time [2]. There is no doubt that the task of structure detecting and reinforcing is extensive and has a great impact on existing buildings around the world. With the structure detection approach has been comprehensively carried out, and has achieved a certain effect, in the future development process needs to strengthen the improvement of detection technology, and promote the development of the entire construction industry. Based on the above situation, this paper introduces the structure detection technology and the corresponding reinforcement method under different conditions.

2. The detecting techniques for building structures

Structure detection has a wide range of applications, including structural performance detection, surface crack detection, mechanical properties of structural materials detection, structure and component deformation detection. In addition to different contents, different building materials also correspond to different detection techniques [3].

2.1. Detection of concrete structure

(1) Rebounding technology

This technique is based on using rebound machines to determine the strength of building surface, and the thickness of structure is calculated through data [4]. The benefits of rebounding technology are convenient to apply and no need to damage the component. Meanwhile, the boundedness is obvious, it is susceptible to be interfered by various instability factors resulting in low measurement accuracy.

(2) Concrete core drilling method

The core drilling method is used to test the compressive strength of concrete by drilling core samples from the main building elements and processing the samples. Results are accurate and reliable [3]. Due to it is possible to cause local damage, especially for important structural parts, conducting a large number of tests is impractical.

(3) Concrete pulling method

The pulling method is an intermediate method between core drilling method and non-destructive testing methods. It is simple and easy to use with minimal damage to the structure and has sufficient accuracy [3]. In practice, it is common to use a combination of various techniques. The results of different detecting techniques are carried out through functional inference and then weighted averaging. The final average is often highly accurate and widely used.

2.2. Detection of masonry structures

For the detection of masonry, it can be divided into detection of whole masonry structure and detection of masonry materials. The methods for detecting masonry structure strength include in-situ axial compress method, flat top method, in-situ single shear method, in-situ single brick double shear method, etc. As to the methods for detecting masonry mortar include push-out method, cylinder press method, mortar sheet shear method, point load method, etc. [2].

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2.3. Detection of steelwork

The homogeneous material of the steel structure makes it easier to test the quality of its structural properties such as plasticity, toughness and strength. The material of the steel structure is poorly fire-resistant, sensitive to temperature and humidity, and easily corroded is its main weakness [5]. Thus, when performing steelwork detections, quality of materials, defects in connection areas, fixing of steel fasteners, and rust and corrosion need to be a priority. The methods commonly used are ultrasonic non-destructive testing, penetration testing, radiofrequency testing, eddy current testing, magnetic particle testing, steel corrosion testing and coating thickness testing, etc..

2.4. Detection of wood structures

In a general situation, visual detection method is used for wood structures. The classical Chinese wooden buildings are highly known when it comes to wooden buildings. Decay of wood due to fungal and insect infestation, resulting in deterioration of its physical and mechanical properties. In wet climates, decay can occur at the ends of wood members, particularly at the roots of columns and at the corner beams of roofs [1, 6]. Meanwhile, mortise and tenon structure are a basic connection form between members of Chinese ancient wooden buildings. The mortise and tenon structure have been deformed and destroyed partly over the years of geological movement and human impact. Main situations include sliding deformation, elastic-plastic deformation, and loose connection of mortise and tenon joints, leading to joint skipping [7]. Moreover, scale and probe methods can also be used for the detection of wood structure.

2.5. Surface crack detection

Surface crack detection is an essential task for monitoring structural stability and ensuring structural security. The situation of buildings deteriorates overtime and cracking is almost inevitable, which can occur in all types of structures, such as concrete walls, beams, floor slabs and brick walls (as shown in Figure 1) [8].

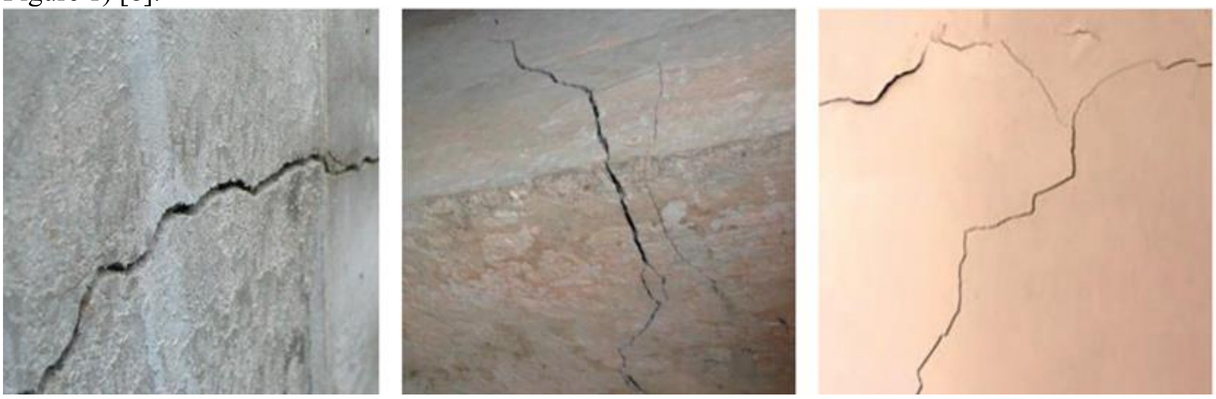


Figure 1. Cracks in concrete wall, concrete beam, and brick wall from left to right [8].

The concrete crack width gauge is commonly used to detect the width of cracks on the surface and then uses modern electronic imaging technology to create the original crack in the structure being measured on the mainframe display, and reads out the true and reliable crack width data via a highly accurate laser scale on the screen. Therefore, the process of crack detection is time consuming and it is affected by the subjective judgement of the inspector. In order to solve this phenomenon, an intelligent model which is based on the image of Otsu method and Min-Max Gray Level Discrimination (M2GLD) was published. In this model, M2GLD is a gray intensity adjustment method.

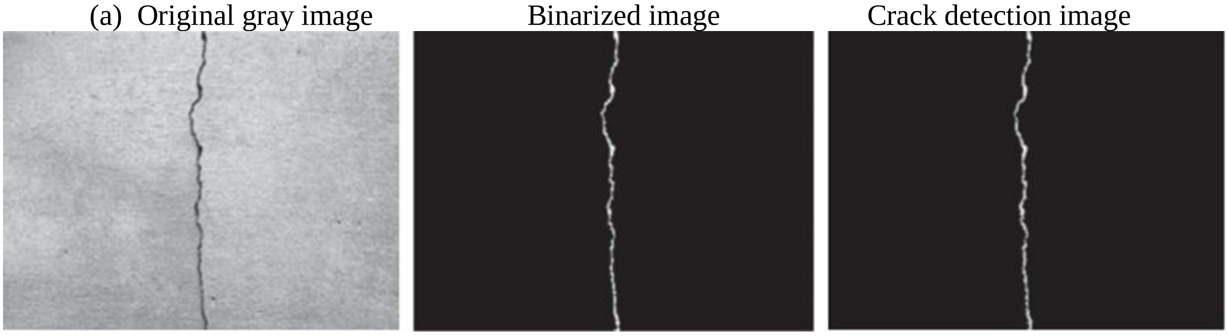
Due to the influence of image quality, surface features of test objects, and other related parameters, it is not acceptable to use the Otsu method individually as a standard image binary method for crack detection [9]. The new model has been created based on Otsu method, which can able to accurately identify objects that produce cracks and analysis their morphological feature data. There are two steps in image cleaning process:

(1) Objects are cast out with a certain number of pixels.
(2) The ratio of the major axis length to the minor axis length of an object defines an axis ratio index (ARI):

$$\mathrm{ARI} = \frac{L_M}{L_N} \tag{1}$$

where L_N and L_M are the minor axis length and the major axis length. When the value of ARI tens to 0 or 1, it is worthless. The crack properties of image boundary extraction and image framework will be computed after all crack pixels have been recognized. Figure 2 shows the comparation between Otsu method and M2GLD method.

(a) Original gray image Binarized image Crack detection image



(b) Original gray image Binarized image Crack detection image

Figure 2. Testing image using: (a) the Otsu method and (b) the M2GLD method [8].

3. Structural reinforcement techniques for buildings

Since various reasons, some buildings have structural problems during construction or using period, which affect the stability and security of buildings. After rigorous scientific detecting, determine the problems and severity of the structure, and then use corresponding reinforcement techniques to repair and rectify the building structures.

3.1. Strengthening of reinforced concrete (RC) structures

Steel reinforcement has been used to strengthen concrete structures in a considerably period. Easily corroded and conductive are main weaknesses of this type of reinforcement material [10]. Compared to non-metallic materials, reinforcing steel is very strong in physical properties, highly resistant to various impacts, including chemical attacks. It is flexible enough for construction operations and can be joined by welding [11]. The use of steel reinforcement to strengthen a single floor under construction is the most economical scheme, in the case of vertical extensions (as shown in Figure 3).

3.2. Reinforcement techniques of wood structure

3.2.1. Reinforcement techniques to combat wood decay. For timber columns only decayed on the surface and can satisfy force requirements and never affect the stability of the structure, elimination and repair reinforcement techniques can be used. The detail process of this technique is the decay part is eliminated, preservative treatment for the remaining wooden columns and then repaired and glued with dry homogeneous wood. If the wooden elements are decayed or cracked heavily and difficult to repair, the elements should be replaced. The new construction members after replacement need to be provided with same size, material and texture as the original [1].

3.2.2. Reinforcement techniques to repair the crack. Small cracks and cavities in wooden elements caused by insects can be effectively repaired by chemical grouting method. This is a simple method, not only can repair and strengthen the wooden elements, but it also can improve insect-resistant capacity and anti-corrosion capacity of reinforced members [12]. In addition, under load and erosion of rain and water for a long period, the columns, beams and the other members may appear cracking. At this time, the cracked member need be packed with iron hoop and fixed with rivet to improve its capacity and rigidity (as shown in Figure 4). The problems of this technique are also obvious. Firstly, the property of wood makes its volume changing by humidity level, and the added iron straps is easy to be deformed and rusted. All of these situations may threaten the stability and safety of integral wood structure. Moreover, iron reinforcement is irreversible, and it may cause secondary damage when iron and rivet are used. As the property that iron reinforcement is hard to change, the aged and non-removable members can use it frequently [1].

Figure 3. Vertical extension by steel reinforcement [11].

Figure 4. Reinforced timber beam of ancient buildings with iron strap [1].

3.3. Reinforcement methods with fiber-reinforced polymers (FRPs)

3.3.1. Sprayed FRPs reinforcing method. The reinforcing method which is designed systemically for concrete structure, called Sprayed Fiber Reinforced Polymer (FRP). The components of sprayed mixture include vinyl ester resin and fiber, with the fiber is glass or carbon chopped fiber in general. 1.5 or 2 inches of glass or carbon fiber and vinyl ester resin are sprayed on the surface of concrete structures directly by using the air-compressed spray machine. With the same mechanical properties of vinyl ester resin and epoxy resin, compared with epoxy resin, vinyl ester resin uses less time to stabilize the shape [13, 14].

Figure 5 shows the sketch of the sprayed FRP strengthening method. Figure 6 shows the construction site of sprayed column specimens. Short carbon or glass fiber with vinyl ester resin are sprayed from air-compressed spray machine through a tip of the narrow hose. Then, a roller is used to flattening the sprayed surface. This technique can be applied on all structure elements, which makes interior structure and seismic strengthen in buildings possible.

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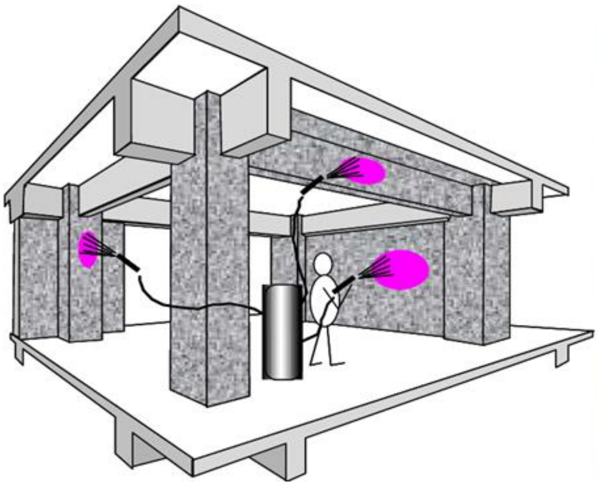

Figure 5. Sketch of sprayed FRP strengthening technique for structural element [13].

Figure 6. The process of sprayed FRP at construction site [14].

3.3.2. Externally bonded FRP method of RC structures. In RC reinforcing applications, externally bonded FRP systems have convenient and time saving features. Typically, FRP may be boned on the RC structure surface to support extra tension and shear strength. For different requirement, FRPs are boned on concrete slabs, girders and beams (as shown in Figures 7-8). In areas with a relatively high frequency of earthquakes, as for the columns against seismic loads through wrapping the columns with FRP systems. The durability, stiffness and strength in a certain operation leads to different selection of basic FRP materials. Meanwhile, different exposing environment and applying method also effect the selection of resins. According to the method of fabrication and application of FRP systems, boned FRP systems can be classified as pre-cured systems and wet lay-up systems. The biggest difference of pre-cured systems and wet lay-up systems lies in the different site for making usable finished products. For wet lay-up FRP systems, dry FRP strips or fibers are saturated with resin on-site, but pre-cured FRP systems are made off-site. When pasting FRP systems, the holes on the concrete are filled with putty and primer typically, making it smooth and improving the stickability of the concrete surface [15]. Then, the FRP systems are applied. If the aim is to increase the stiffness of the structure, then FRP reinforcement techniques are not applicable, as the stiffness properties of the existing RC elements cannot be changed by using FRP reinforcement.

Figure 7. Reinforcing of beams [15].

Figure 8. Reinforcing of RC slabs and Columns [15].

(1) Reinforcing of beams

Reinforcing of beams with externally boned FRP systems can be divided into flexural strengthen and shear strengthen. Due to the corrosion and degradation of steel bars, concrete structure cracking, surface coating cracking, and external load changes require reinforcement and repair of the beam structure. For flexural strengthening, the fibers are oriented along the longitudinal axis of beam to provide external tensile strength. The shear strengthening is considered to apply at the moment of lacking shear strength. Generally, when the maximum stress value is consistent with the direction of pasting FRP fibers, the FRP system is subjected to the maximum shear force.

(2) Reinforcing of RC slabs

Compared to bidirectional slabs, FRP strips need to be reinforced in both horizontal and vertical directions to prevent collapse. When unidirectional slabs are supported, only unidirectional reinforcement is needed at the weak points.

(3) Reinforcing of RC columns

In construction engineering, it is a consensus that using FRP systems to wrap existing columns can effectively improve the axial compressive strength and ductility of columns by strengthening lateral constraints. Compared to other common wrapping reinforcement methods, using FRP strips to hoop columns can keep the overall stiffness of the structure not change. As mentioned earlier, this method is also commonly used for seismic resistance in areas with frequent earthquakes.

4. Conclusion

The scientific detection and reinforcement of building structure is an important part of the quality and safety guarantee system of building engineering. This paper lists various detection methods and reinforcement techniques, including traditional methods and innovative methods. In the aspect of innovative methods, M2GLD crack detection method and external bonding FRP method are given. M2GLD method can improve the accuracy of Otsu method and is relatively simple to use. Although the convenience and wide range of applications of FRP systems are excellent, it still has its limitations. FRP systems are subject to significant external extreme environments, such as wear, fire, etc.

The future direction of detection is likely to be more towards non-destructive testing, which will reduce secondary damage to the structure being detected. At the same time, machine learning and more computerization analysis are likely to be used in structural detection techniques, which will greatly reduce costs and the impact of human factors in the detection. In the case of reinforcement technology, it is possible to move towards the invention of new construction materials, the invention of which often means the creation of new reinforcement technology. Methods of detection and reinforcement must be continually developed and innovated. In addition, detection and reinforcement methods need to be used flexibly to achieve double results with half the effort.

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