High-Rise Building Preservation – A Comprehensive Method with Material Innovation

Yang Shen*

ZJUI institute, Zhejiang University
**Corresponding author. Email: Yang.19@intl.zju.edu.cn*

ABSTRACT

The treatment for high-rise buildings is significant, while the number of skyscrapers is increasing at a higher rate year by year. A comprehensive method is put forward in the paper to discuss its feasibility in order to develop customized strategies for high-rise building preservations worldwide. Digital twin with Unmanned aerial vehicle (UAV) is applied as a monitoring technique to save labor and time. FRP is selected as a repairing material because of its outstanding properties under changeable circumstances. The diffusion rate, fracture toughness under different moisture conditions, and residual fracture toughness after a different number of cyclic moisture conditions are mentioned in conditions to prove the qualification of the material, FRP. Further research should be conducted in this area to customize the process of this method.

Keywords: *High-rise building, digital twin, FRP, comprehensive method*

1. INTRODUCTION

Under the background of a series of population boom, numerous high-rise buildings have been built in the metropolitan in recent years. However, while people are building higher and higher structures, the challenge they face is growing as well. For example, the tallest building in China, Shanghai Center Tower, has a total height of 632m, leading to a tremendous amount of wind load. Additionally, earthquakes will cause severe consequences due to their size. According to the study from Tongji University, when there is a coupling of earthquake and wind effect, the damage possibility will climb to 11.75%. In comparison, the case of severe damage with earthquake alone will be just 0.01% [1]. Although there has been a long time since no earthquake was detected in Shanghai, the wind load on the tower will drive the building to the fatigue point. Even with numerous amounts of money invested in the maintenance, the estimated life span of the Shanghai Center Tower is only 50 years.

Therefore, there is a urgent need for a comprehensive method for preservation of those high-rise buildings, not only for maintenance for localized buildings, but also for the future construction.

Since high-rise buildings are built to save urbanization space, practical and economical methods must be adopted to avoid losses. The core preservation problems in high-rise buildings can be concluded into three points. 1) Although the damper will reduce the displacement of buildings over a specific elevation, the continuous movement of buildings will quickly lead to fatigue. 2) The scale of the buildings with a great height will usually be significantly large. It is impossible to use labor to detect the defects of materials. 3) Due to the height of the building, the transportation of repairing materials will be challenging without shutting down the whole building.

The research method in this paper is mainly based on the existing data of present popular fields including digital twins and FRP material. These two fields divided the methods into two parts, which are monitoring and repairing. Though there are numerous studies have been engaged in these fields, the combination of them has seldom shown to the public, which may be a potential solution for this paper.

If a practical method can be concluded to preserve the skyscrapers existing, there will be enormous economic benefit due to the possibility to improve structure health condition and extend estimated lifespan for the existing high-rise buildings, moreover, the future construction can consider this method and customize the structure design for an easier maintenance. The comprehensive method can apply to maintenance of dwellings in high-density residential aera as well.

2. METHODOLOGY

To solve the three core problems, a systematic solution will be put forward. It contains two parts: inspection and repair.

2.1. Digital Twins

Digital Twin is an integrated way of transferring isolation data from different building parts into a comprehensive model. The idea of digital twins combined many fields into one application, including production agility, design thinking, open innovation, and resource-efficient production [2]. The benefits of digital twins are not only restricted in the economic field, which means that companies can save a large amount of money on labor-consuming inspections and get a fully designed, automatic, up-to-date model of structures they are monitoring.

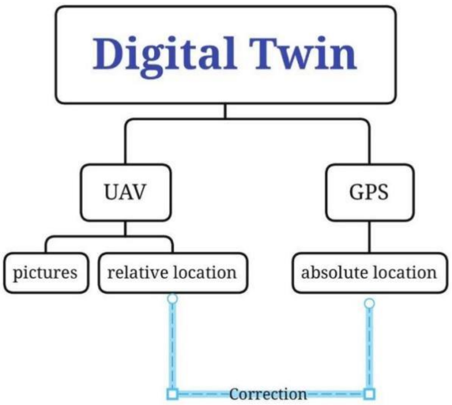

Figure 1. Process of creating digital Twins utilizing UAV

The process of constructing digital twins can be handled by UAV, an innovative field of health monitoring [3]. The drone can fly around the exteriors and interiors of the building to capture pictures and then load the images into the computer. A 3D model can be built utilizing computer vision. A brief process can be referred to in Figure 1. The UAV will report its relative location with the structure, and GPS will record the absolute location of the UAV; those locations can correct each other to get an optimal flight path. A more accurate and reliable model can be generated if more sensors can be applied to the structure. When adapting this technique to local establishments, the most challenging difficulty is the obstacles. Therefore, it is feasible to the second core problem.

A sample model can be referred to in Figure 2. It was initially built by selecting 400 pictures captured around the building. Although there are a lot of details that should be improved, it can be seen as a practical way to create the digital twins.

Figure 2. Sample 3D Model constructed by UAV

2.2. FRP materials

To solve problems one and three mentioned above, a new material with good resistance to fatigue and a flexible shape should be used to repair the existing high-rise buildings. Fiber-reinforced polymer (FRP) is a well-known material in the construction field. Due to the high price of FRP, it is used as a repairing material universally. The third problem can be solved by FRP easily since FRP can be transported in the liquid phase and will not have a significant impact on the accessibility of the high-rise building, which means that FRP can be transported from the ground to the target structure by elevators inside the high-rise building. However, since the climate conditions are changeable at such a high elevation, more emphasis should be placed on the durability of FRP material.

The climate conditions contain moisture, temperature, wind, and illumination typically. Among them, the moisture condition is essential for estimating the durability of the FRP. Therefore, there is already a wide range of studies doing experiments about how the moisture will affect the FRP in different types of defects. Thus, the feasibility of FRP applied in the high-rise preservation should have more experimental proof.

3. MATERIAL REQUIREMENTS

To fit in the application of repairing high-rise buildings, the materials selected for this purpose should meet specific requirements. Due to the high elevation of the building, the materials will undergo significant temperature changes. The second requirement is that the material should have a relatively large tolerance to moisture conditions. Suppose the material is sensitive to the moisture conditions with shape changes or chemistry property changes. In that case, many problems such as debonding problems cracking will occur, leading to severe structural load and material waste.

3.1. Moisture effect on FRP

There is a wide range of studies targeting the moisture problems in FRP. However, considering the application of this article, the critical problem of FRP is its debonding problem under different moisture conditions.

The most usual mode of moisture change is precipitation, including rain and snow, which are all external effects. To identify the change rate of moisture, Frick's first law can be applied,

$$J = -D\frac{\partial c}{\partial x} \tag{1}$$

where J refers to the diffusion flux, D denotes the diffusion coefficient or "diffusivity", and dc/dx denotes the concentration gradient. To define the 1-D diffusion condition, a semi-infinite assumption can be assumed in this model, which means there is a continuous transition of moisture from the surface of FRP covering the construction material to the inner part of construction material, in that case, the FRP will have a different moisture condition.

The validation of semi-infinite condition can be proved by the equation

$$x > 10\sqrt{Dt} \tag{2}$$

where x is the thickness of the construction material and t is the time of diffusion. The different diffusion coefficients of common construction materials are listed in Table 1[4].

Table 1. Diffusion coefficients of concrete, CFRP, and epoxy in different temperate [4]

Material	Temperature (°C)	Diffusivity (10^{-11} m^2/s)	Solubility (wt.%)
Concrete	23	3.24	7.71
	50	3.24	7.76
CFRP	23	0.068	0.34
	50	0.081	0.9
Epoxy	23	0.023	2.58
	50	0.048	5.42

The initial comparison of diffusion coefficients can indicate that FRP materials have a relatively low diffusivity for moisture, leading to the fact that it can make the repaired position in the structure waterproof under a minor moisture condition. However, the moisture conditions are likely to change in various regions. Taking the location of Shanghai Center Tower as an example, the annual precipitation in Shanghai is over 1000mm [5]. It is evident that FRP material in regions like Shanghai should have undergone moisture changes.

Shahrooz Amidi and Jialai Wang have mentioned their experiment about the surface between FRP and concrete [6] in their works. They immersed the specimen into a water tank for 1, 3, 6 weeks to let the moisture diffusion happen. After that, they divided the specimen into "wet" and "dry" groups. Those specimens tested right after being removed from the water tank are identified as "wet." Those specimens tested after two days of dehydration in the laboratory are identified as "dry." The results of the test are recorded in Table 2 [6].

Table 2. Experimental results of the fracture toughness of FRP-to-concrete interfaces [6]

Time (months)	Control	Wet-untreated			Wet-silane			Dry-untreated			Dry-silane		
		1	3	6	1	3	6	1	3	6	1	3	6
Fracture toughness (N/mm)	1.013	0.448	0.224	0.245	0.477	0.226	0.347	0.390	0.524	0.510	0.680	0.600	0.491
	1.174	0.306	0.293	0.259	0.583	0.318	0.314	0.700	0.605	0.479	0.770	0.677	0.528
	1.183	0.418	0.192	0.205	0.628	0.385	0.229	0.576	0.400	0.580	0.640	0.634	0.604
	1.084	–	–	–	–	–	–	–	–	–	–	–	–
Average	1.11	0.39	0.24	0.24	0.56	0.31	0.30	0.56	0.51	0.52	0.70	0.64	0.54
$\sigma_{\bar{x}}$	0.081	0.075	0.052	0.028	0.078	0.080	0.061	0.156	0.103	0.052	0.067	0.038	0.057

From Table 2 [6], the average values of fracture toughness of interface between FRP and concrete are calculated with their standard deviation σ_x. Although the fracture toughness has significantly decreased after the moisture ingress, which is evident while comparing the fracture toughness of treated groups with the controlled group, two days of dehydration and silence treatment can compensate for a large portion of toughness at a maximum rate of 79%.

3.2. Moisture cyclic effect

Regarding the real world, moisture ingress and dehydration will not only happen one time in the life span of the material, therefore, the cyclic effect of moisture should also be stressed. Tuakta and Buyukozturk have done the experiment in their work published in 2011 [4].

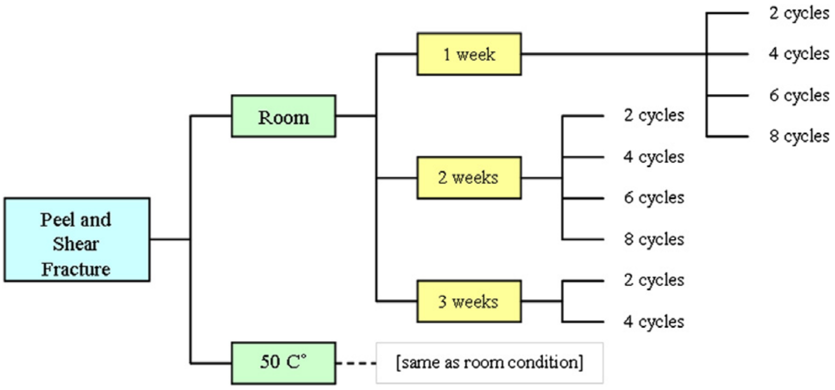

Figure 3. Condition groups in the cyclic moisture study of FRP [4]

The experimental set of groups is shown in Figure 3, where Room denotes the room temperature, and the number of weeks represents the duration time of intermediate conditioning of continuous moisture condition. After the duration, the specimens are left in the laboratory for four days to dehydration, and approximately 60% of the moisture rate will be retained after dehydration.

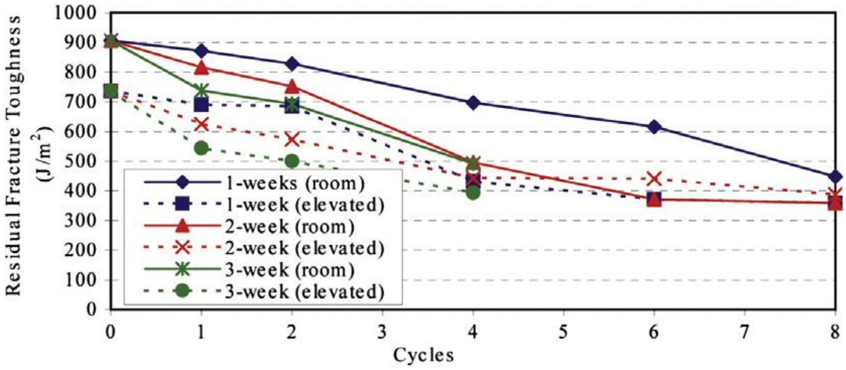

Figure 4. Effect of number of wet–dry cycles on the residual fracture toughness of peel specimens [4]

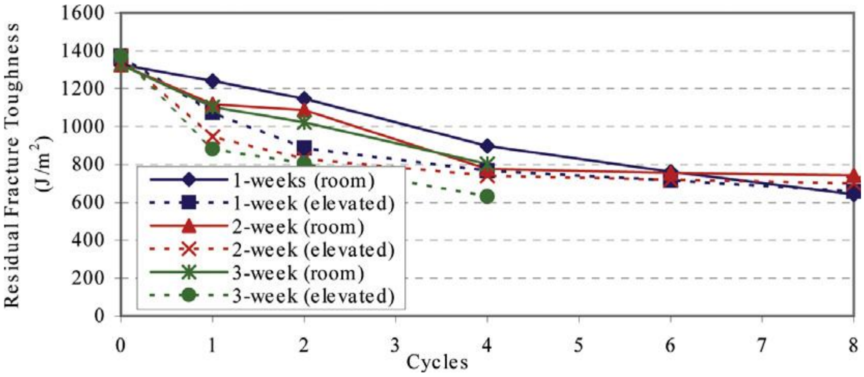

Figure 5. Effect of number of wet－dry cycles on the residual fracture toughness of shear specimens [4].

According to Figure 4 and Figure 5, the residual fracture toughness of specimens will decrease dramatically after the first four cycles. Besides, during the first four cycles, the differences between different groups are distinct. The maximum difference can reach 300J/m2 approximately. However, after the fourth cycle, the residual fracture toughness curve trend will approximately remain constant. Although it cannot conclude that the minimum residual fracture toughness of FRP during the moisture cycle is between 600J/m2 and 800J/m2, it can be seen as a lower boundary of residual fracture toughness while applying the FRP to repair structures.

3.3. Load ability of FRP-reinforced concrete

To simulate the deformation reaction after applying FRP to the fracture of construction materials, the FRP-reinforced concrete will be a great example, since most of the structures will use concrete as the main construction material. Therefore, universality can be guaranteed.

Considering the situation described in this paper, the initial fracture has occurred on the structure, therefore, what will happen after the initial fracture is fatigue. The extension of the fracture will occur if the stress intensity factor KI exceeds the critical stress intensity factor KIc, which can be expressed as

$$K_{Ic} = f\sigma_c\sqrt{\pi a} \quad (3)$$

Where f is a dimensionless parameter that accounts for crack and specimen size, σ c is the critical stress concept and a is the crack length [7]. For those stress acting on the crack, the force will be transferred by the initial crack along the whole plane due to the fracture toughness. At this time, the fracture deformation of the material will no longer be the same as the original stage. According to experimental research, the proportional magnitude of punching shear force carried by aggregate interlock in slabs without shear reinforcements is between 33 percent and 50 percent of the total punching shear strength of uncracked concrete. For FRP-reinforced concrete slabs, on the other hand, fracture width and deformation increase, lowering the punching shear force carried by aggregate interlock. As a result, for FRP-reinforced concrete slabs, the punching shear transferred across a crack is substantially minimized [8].

3.4. Temperature effects on FRP-reinforced material

Under the condition that the temperature changes can be relatively large during the year in some regions, the temperature factor should also be included as an affecting parameter. For most of the polymers, the increasing temperatures can result in the liquidation of the material thus Young's modulus, ultimate strength will be weakened significantly. However, the deformation property of FRP-reinforced will be boosted as the temperature increases, which is universal among different effect load ration(β)[9].

according to the Figure 6, a linearity has been shown on the load capacity versus temperature curve.

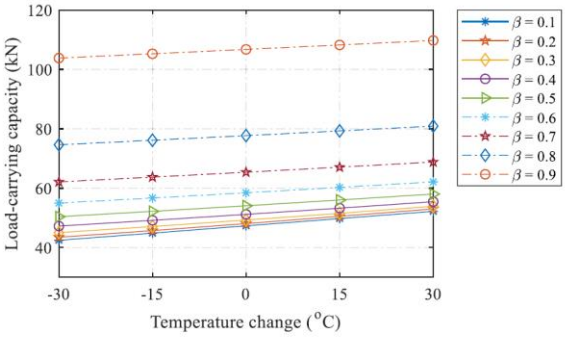

Figure 6. Load-carrying capacity with different β and temperature changes [9].

From Figure 6, the variation of load-carrying capacity can be calculated, which is within 30% in the temperature range of -30 Celsius to 30 Celsius. Therefore, if the effect load ratio is larger than 0.5, the variation of load-carrying capacity will be relatively stable, which means the ultimate strength and yield strength of the FRP-reinforced material will not undergo significant changes. To sum up, the stability of FRP-reinforced material under temperature change is verified. For higher temperatures (e.g. 500℃-600℃), it is even possible to regain the full capacity of damaged columns if the heat treatment is proposed appropriately [10].

4. CONCLUSION

Some evaluations can be drawn from the above sections.

1. This comprehensive method is a practical approach before developing a customized structure monitoring and maintenance plan according to different climate conditions and defect types.

2. The selection of FRP material as a repairing material is qualified due to its flexibility and excellent tolerance of moisture change and temperature change.

3. More experimental data are needed for a precise decision while applying FRP to the defect of structures, including types of FRP, the dosage of FRP, and a standard for re-treatment of FRP to retain the deformation property after moisture change.

From existing experimental data, the validity of FRP repairing application can be verified, however, safety concepts and economic considerations are not included in this paper. The flammability of FRP-reinforced material should also be studied before the application of this method for safety concerns. Although using more layers of FRP can increase the function of load-supporting, the economic considerations should be calculated to find the feasible usage of FRP in case of waste.

ACKNOWLEDGMENT

This paper was under the instruction of professor Oral Buyukozturk, and the idea of digital twins was inspired by assistant professor Yasutaka Narazaki.

REFERENCES

[1] Zhou Y, etc, Study on vulnerability of Shanghai Tower under combined actions of wind and earthquake, *WORLD EARTHQUAKE ENGINEERING,* Vol 36, No.2, April 2020.

[2] Turan, E., Konuşkan, Y., Yıldırım, N., Tunçalp, D., İnan, M., & Yasin, O. et al. (2022). Digital twin modelling for optimizing the material consumption: A case study on sustainability improvement of thermoforming process. *Sustainable Computing: Informatics And Systems*, *35*, 100655. doi: 10.1016/j.suscom.2022.100655

[3] Turan, E., Konuşkan, Y., Yıldırım, N., Tunçalp, D., İnan, M., & Yasin, O. et al. (2022). Digital twin modelling for optimizing the material consumption:

A case study on sustainability improvement of thermoforming process. *Sustainable Computing: Informatics And Systems*, *35*, 100655. doi: 10.1016/j.suscom.2022.100655

[4] Tuakta, C., & Büyüköztürk, O. (2011). Deterioration of FRP/concrete bond system under variable moisture conditions quantified by fracture mechanics. *Composites Part B: Engineering*, *42*(2), 145-154. doi: 10.1016/j.compositesb.2010.11.002

[5] The annual precipitation of major cities in 2017, Shanghai. (2022). Retrieved 5 March 2022, from https://wenku.baidu.com/view/1bdb1371cd84b9d528ea81c758f5f61fb73628af.html

[6] Amidi, S., & Wang, J. (2016). Deterioration of the FRP-to-concrete interface subject to moisture ingress: Effects of conditioning methods and silane treatment. *Composite Structures*, *153*, 380-391. doi: 10.1016/j.compstruct.2016.06.035

[7] Callister, W., & Rethwisch, D. *Materials science and engineering*.

[8] Deifalla, A. (2022). Punching shear strength and deformation for FRP-reinforced concrete slabs without shear reinforcements. *Case Studies In Construction Materials*, *16*, e00925. doi: 10.1016/j.cscm.2022.e00925

[9] Zhou, H., Gao, W., Biscaia, H., Wei, X., & Dai, J. (2022). Debonding analysis of FRP-to-concrete interfaces between two adjacent cracks in plated beams under temperature variations. *Engineering Fracture Mechanics*, *263*, 108307. doi: 10.1016/j.engfracmech.2022.108307

[10] Moghtadernejad, N., Jamshidi, M., Maheri, M., & Keong, C. (2021). Repair of post-heated short rectangular reinforced concrete columns with FRP jackets. *Structures*, *34*, 4269-4283. doi: 10.1016/j.istruc.2021.10.038