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Research Article

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Structural adhesive damage identification of hidden frame glass curtain wall based on discrete wavelet transform and vibration transmissibility

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Abstract

In order to establish a degumming damage identification method for hidden frame glass curtain wall (HFSGCW) which can be used in engineering practice. In this paper, a damage identification method based on discrete wavelet analysis (DWT) combined with vibration transmissibility is proposed to detect structural adhesive of HFSGCW. The vibration transmissibility is used as damage parameter to characterize the damage degree of structural adhesive. The results show that rubber hammer is an effective method to obtain accurate vibration spectrum of glass plate. In order to obtain accurate vibration transmissivity, it is suggested to select the edge of glass plate as the measuring point. Under six different structural adhesive damage conditions, the damage parameters of vibration transfer rate increase with the increase of structural adhesive damage degree. The damage parameters of vibration transmissibility obtained by DWT can identify the initial small damage of structural adhesive. A safety state evaluation model of HFSGCW glass plate based on vibration transfer rate is proposed. It is of great significance to evaluate the safety state of HFSGCW glass plate.

Key words: discrete wavelet transform; vibration transmissibility; hidden frame glass curtain wall; damage identification; safety status assessment;

1. Introduction

The HFGCW has many advantages such as energy saving, beauty, lightness and so on. It is widely used in the non-load-bearing structure of modern buildings [1,2]. HFSGCW is the glass plate bonded to the metal frame by structural sealant [3]. The quality shelf life of structural adhesive is about ten years [4,5]. Over time, there is a potential safety risk of glass panels falling off due to structural adhesive aging. Structural adhesives cannot be directly tested, and practical nondestructive testing methods are lacking [6,7]. Therefore, the research on adhesive damage identification method of HFSGCW has important engineering significance.

The research on safety state of HFSGCW mainly adopts ultrasonic detection and vibration measurement method. Mojskerc et al. [8] used pulse-echo ultrasound to detect bonding joints of glass curtain wall. Hong et al. [9,10] used ultrasound to detect the bond strength of HFSGCW structural adhesive, and introduced deep learning technology into the ultrasonic detection process. However, ultrasonic is a local damage identification method. It is difficult to identify the overall health state of glass curtain wall glass plate. Rubber hammer and pulse excitation are effective methods to stimulate vibration response of HFSGCW in safety state detection. Huang et al. [11,12] proposed a remote vibration measurement method based on laser doppler vigrometer, and took the first-order peak frequency as an indicator to evaluate the safety state of HFSGCW. Miao et al. [13] proposed a measurement method based on the power spectrum of FFT pulse transient dynamic response to detect the damage length of adhesive in HFSGCW structure. At present, vibration damage identification methods can be divided into traditional and modern ones. However, the existing research on structural adhesive damage identification of glass curtain wall mainly adopts traditional damage identification methods based on its own mechanical properties such as natural frequency, modal damping, modal strain energy and modal shape [14-18]. These methods often require experimental modal analysis and require a variety of measurements and manual operation, which makes it very inconvenient to monitor the glass curtain wall online.

The modern damage identification method mainly refers to the identification of structural damage status by using the response signals measured online and in real time [19]. This method has become one of the important research hotspots in recent years because it is simple to implement and can conduct real-time and automatic damage monitoring for in-service structures [20,21].Wavelet analysis is a representative modern damage identification method. The wavelet analysis method was first proposed by Newland to analyze and process structural damage signals [22]. It can provide localization information of vibration signals in time domain and frequency domain at the same time. These characteristics provide powerful tools for non-stationary description of vibration signal, separation of characteristic frequency of structural damage and early damage identification.

Damage identification methods based on wavelet analysis have been widely used in machinery[23], Bridges[24], concrete material [25] and other fields. Kim et al. [26] used Fourier transform and discrete wavelet transform to detect the fatigue life of prestressed beams under fatigue damage, and the results show that discrete wavelet transform is an effective damage detection tool. The DWT reduces the redundancy of information, ensures that the damage information of structural adhesive of HFGCW will not be lost and improves the speed of calculation. However, the research of damage identification method based on discrete wavelet analysis in glass curtain wall health monitoring is rarely carried out.

The significance of vibration-based damage identification method lies in structural damage prediction and damage development monitoring. This means it is more important to identify minor damage at the initial stage of service. However, the influence of small structural damage on structural response signal is multifaceted. It is difficult to identify small damage directly from structural response signals. Therefore, it is necessary to use a variety of comprehensive damage identification methods to construct and extract damage parameters that are more sensitive to small damage. Traditional dynamic parameters are obtained by modal analysis on the basis of dynamic response [27]. However, many load spectra in engineering practice are difficult to accurately measure, such as wind load, earthquake load and other environmental excitation situations[28]. Therefore, the traditional dynamic parameters have certain limitations in engineering application. In 1998, Zhang et al.[29,30] proposed the dynamic parameter of vibration transmissivity. The vibration transmissibility only reflects the dynamic characteristics between two test points, which makes up for the deficiency of traditional dynamic parameters. Therefore, vibration transmissibility is used as dynamic parameter to construct damage. The method of DWT combined with vibration transmissibility is easy to realize on-line health monitoring because it is less dependent on experiment and completely gets rid of load spectrum measurement. This method can identify the small damage at the initial stage of structural damage by extracting the damage characteristics of vibration response signals.

In this paper, the excitation mode of HFSGCW, the selection of measuring point, structural adhesive damage identification and safety state are studied. A nondestructive testing method combining DWT and vibration transfer function is proposed to detect adhesive damage of HFSGCW structure and evaluate the safety state of glass plate. On this basis, the safety state evaluation model of HFSGCW plate based on vibration transfer rate is established.

The rest of this article is organized as follows. In section 2, the theoretical background of wavelet transform and vibration transmissivity is described. In Section 3, numerical models and modeling parameters are described. Experimental studies are described in Section 4. Finally, the results and discussion are given in Section 5.

2. Theory

2.1 Wavelet analysis

Wavelet transform is developed on the basis of Fourier transform. The principle of wavelet transform is that any signal can be converted into a set of local functions. The wavelet transform is very sensitive to the mutation component in the signal. This property can be used to detect abrupt changes in modal shapes, which usually indicate structural damage [31,32]. Its window function can change the size, so the local analysis ability of the wavelet transform to the structural adhesive damage signal of HFGCW is significantly improved. The characteristic signal of structural adhesive damage can get better results by selecting proper wavelet basis function.

Wavelet analysis generally divided into continuous wavelet transform (CWT) and DWT. CWT produces a lot of redundant information in the calculation process, and the calculation method is relatively complicated. The DWT reduces the redundancy of information, ensures that the damage information of structural adhesive of HFGCW will not be lost and improves the speed of calculation. By comparing the above two methods, the DWT is finally used to study the structural adhesive damage signal of HFGCW.

The scale parameters and translational parameters are discretized [33].

$$\alpha = \alpha_0^m, \tau = n\tau_0\alpha_0^m, m \in Z, \mathrm{n} \in \mathrm{Z} \tag{1}$$

The discrete wavelet function formula is as follows:

$$\psi_{m,n}(t) = \alpha_0^{-\frac{m}{2}} \psi\left(\frac{t - n\tau_0\alpha_0^m}{\alpha_0^m}\right) \tag{2}$$

The inner product of discrete wavelet functions is obtained by the following formula：

$$WT_x(m,n) = \langle x, \psi_{m,n} \rangle = \alpha_0^{-\frac{m}{2}} \int_R x(t)\psi\left(\frac{t - n\tau_0\alpha_0^m}{\alpha_0^m}\right)dt \tag{3}$$

a is the scale factor; b is the displacement factor; m and n are integers; t is the time change of different parent wavelet function definitions; Ψ is the parent wavelet function; Ψ* is a complex conjugate.

2.2 Vibration transmissibility

The vibration transfer function reflects the response transfer characteristics between adjacent nodes of the structure. When the single point excitation is applied on the HFSGCW, the vibration transfer rate function is the function of frequency response function. The frequency response function contains a lot of structural modal parameters, which can reflect the damage state of structural adhesive. The vibration transfer function is defined as [34]:

$$T_q^{\mathrm{p}}(\omega)\frac{R_p(\omega)}{R_q(\omega)}=\frac{H_{\mathrm{p}}(\omega)}{H_{\mathrm{m}}(\omega)} \tag{4}$$

Rp(ω) and Rq(ω) are the response signals at two points; Rp(ω) and Rq(ω) are the Fourier transforms of the two point response signals; Hp(ω) and Hq(ω) are frequency response functions at two points.

3 Numerical modeling

3.1 Model establishment

According to the composition form of glass plate and hidden frame and considering the bonding form of structural adhesive layer, spring element is used to simulate structural adhesive layer. Tempered glass is defined by plate elements [35]. Structural adhesive damage is simulated by removing the bounding spring element [36]. Due to the fact that glass structural adhesive is a very thin layer, the material nonlinearity of structural adhesive model is not considered temporarily in order to simplify the problem. When the number of meshes is large, the calculation precision is higher. The grid is divided by parameterization control. According to the calculated results, there is little difference when the number of grids is increased in grid division of HFGCW model. Finally, the optimal grid division of HFGCW model is obtained as shown in Fig.1 (a).

HFGCW model is established by ANSYS finite element software. The finite element model of HFGCW is shown in Fig. 1(a). The HFGCW model adopts SHELL63 element with elastic modulus of 70GPa, density of 2500kg/m^2 and Poisson's ratio of 0.22. The size of the HFGCW model is 60cm×60cm, and the thickness is 0.5cm. The damaged area is shown in Figure 1(b). The relationship between damage parameters and damage degree is studied by presetting damage state of structural adhesive at 6cm, 12cm, 18cm, 24cm and 30cm. A surface load is applied to the center of the model to simulate the excitation of the glass plate. The acceleration response signal of the glass plate model is obtained by four sensitive measuring points.

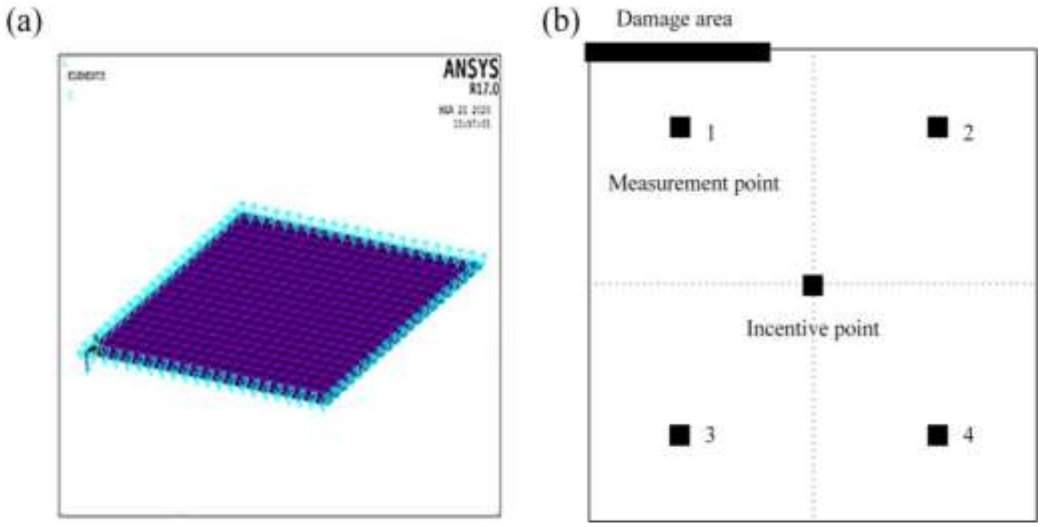

Fig. 1 (a) Finite element model of HFGCW; (b) Layout of measuring points

3.2 Frequency response function and vibrational transmission rate

In view of the damage state of structural sealant, several measurement indexes such as change rate of vibration transmission (TCR), frequency response function change rate (HCR), vibration transmissivity cumulative change rate (TACR) and frequency response function cumulative change rate (HACR) are established. The calculation expression of TCR is as follows：

$$TCR = T^d - T^h / T^h \tag{5}$$

The calculation expression of HCR is as follows:

$$HCR = H^d - H^h / H^h \tag{6}$$

The calculation expression of TACR is as follows:

$$TACR = \int_{f_1}^{f_2} \left| T^d - T^h \right| df \,/ \int_{f_1}^{f_2} \left| T^h \right| df \tag{7}$$

The calculation expression of HACR is as follow:

$$HACR = \int_{f_1}^{f_2} \left| H^d - H^h \right| df \,/ \int_{f_1}^{f_2} \left| H^h \right| df \tag{8}$$

Where T represents vibration transmissibility, H represents frequency response function, h and d represent health and damage respectively, and f represents frequency.

Damage sensitivity is quantified by the relative rate of change of these indicators. The frequency response function is the ratio of the acceleration response signal to the Fourier transform of the excitation. The frequency response function change rate is determined by the relative rate of change of the peak frequency response function in lossy and lossless states. The cumulative rate of change of the frequency response function is determined by the relative rate of change of the integral value of the frequency response function in lossy and lossless states over the whole frequency range. The vibration transmissibility is the ratio of the acceleration response of two adjacent measuring points. The change rate of vibration transmissibility is determined by the relative change rate of peak vibration transmissibility in lossy and lossless states. The cumulative change rate of vibration transmissibility is determined by the relative change rate of the integral value of vibration transmissibility in lossy and lossless states over the whole frequency range. TACR and HACR are shown in Table 1. With the increase of structural adhesive damage degree, TACR and HACR also increase. Only the HACR at point 1 is larger, while that at point 2, 3 and 4 is smaller. The TACR at each point is large. TACR can well reflect the damage degree of HFGCW model. The sensitivity of HACR values at each measurement point is not consistent, so the method of reflecting the degree of degumming damage as a parameter has some limitations. Based on ANSYA finite element analysis, it is feasible to judge the safety state of HFGCW by taking TCR as damage parameter.

Table 1 Comparison of TCR and HCR

Length(cm)	TACR1-2	TACR1-3	TACR1-4	HACR1	HACR2	HACR3	HACR4
6	0.1817	0.2464	0.1970	0.1071	0.0021	0.0028	0.0013
12	1.1031	1.3294	1.2172	1.4614	0.2203	0.2025	0.2126
18	14.3165	14.7432	14.9908	14.0475	2.4180	1.7696	1.6144
24	28.6151	25.0208	27.0429	26.3702	3.7139	3.4742	3.3672
30	44.3422	44.2011	43.2346	42.7127	7.4368	7.2478	7.3213

4. Experiment

4.1 Experimental method

In this experiment, the DASP vibration analysis system produced by The Oriental Institute of Vibration and Noise Technology was used to obtain the acceleration response signal of the measuring point. During the experiment, the acceleration sensor was bonded to the measured point with 502 glue. The acceleration response signal of the measured point was obtained. The excitation signal was applied through the rubber hammer. The acceleration signal of all response points was measured by hitting the center of the glass plate with single input and multiple output method. The defect of structural adhesive of HFSGCW was simulated by artificial cutting structural adhesive. Fig. 2 shows the DASP vibration analysis system. DASP vibration analysis system is mainly composed of vibration acquisition instrument, analysis software and vibration sensor. The sensor model is INV9812. Technical parameters of the sensor are shown in Table 2. DASP vibration analysis system has the advantages of high sensitivity, easy to operate, not affected by external environment and so on. Fig. 3 is the principle diagram of structural adhesive damage identification method for HFGCW of DASP vibration analysis system. The obtained acceleration response signal is decomposed by DWT to obtain the detail signal of each order. The damage characteristics of the signal are found by DWT, and then the damage degree of HFGCW is characterized by the change rate of vibration transmissibility.

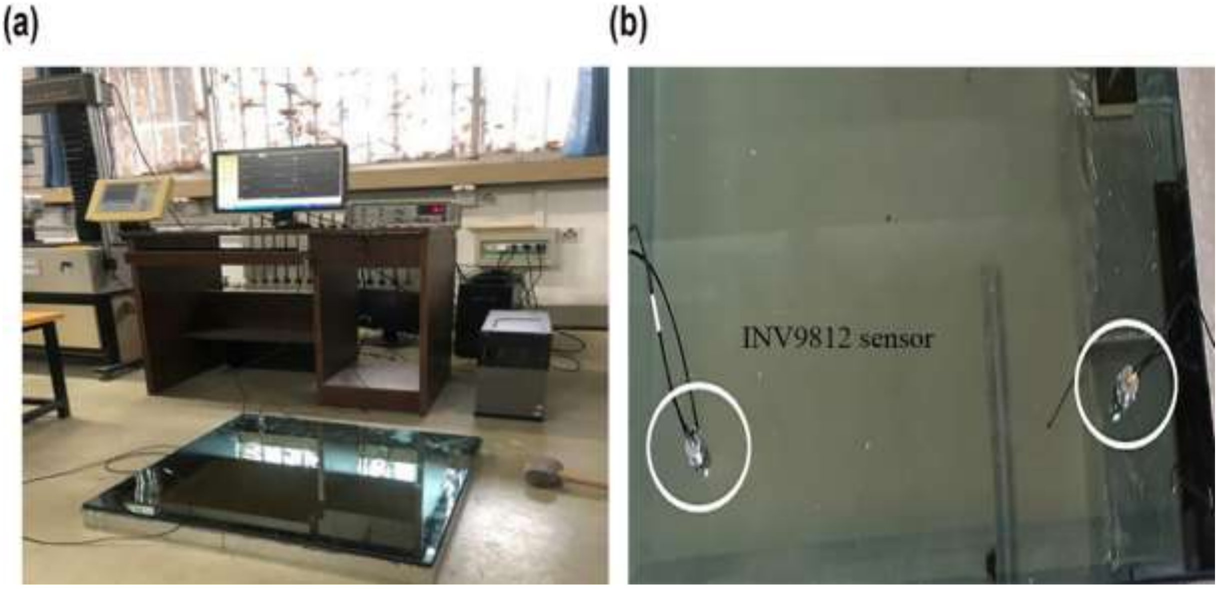

Fig. 2 (a) DASP vibration analysis system; (b) INV9812 sensor

Table 2 Parameters of the sensor

Type	Sensitivity	Frequency	Resolution ratio	Range
INV9812	100mv/g	0.5-0.8kHz	0.002m/s^2	60g

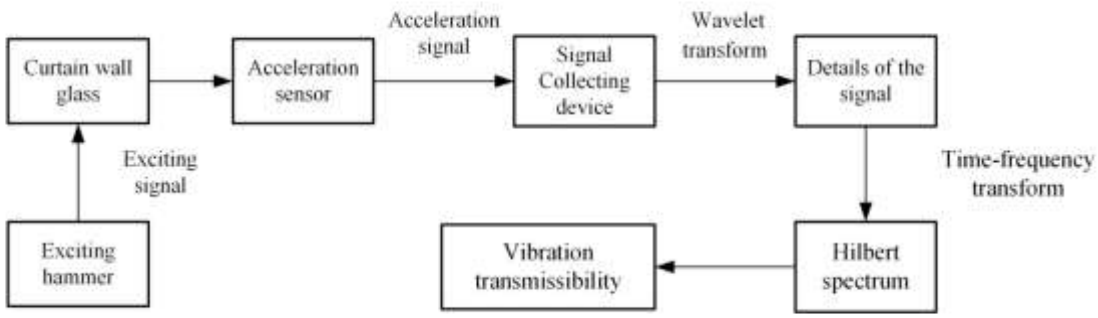

Fig. 3 Schematic diagram of structural adhesive damage identification method

4.2 Experimental Realization

The HFGCW model is fixed on the ground with screws to simulate the frame support structure system of the HFGCW. The external size of the steel frame is 60cm×60cm and the internal size is 50cm×50cm as shown in Fig. 4 (a). Silicone structural adhesive is used to bond the coated glass onto the aluminum alloy frame as shown in Fig. 3 (b) and (c). The width of the silicone structural adhesive is 5cm and the thickness is 0.5cm. Performance parameters of ordinary toughened glass and silicone structural sealant (MF899) are shown in Table 3 and Table 4[37]. The DASP sensor is glued to the measuring point with glue for analysis to find the sensitive position of the measuring point. The structural adhesive damage is approximately replaced by cutting the structural adhesive manually. According to the failure situation of silicone glue, this paper is divided into 6 different damage conditions as shown in Fig. 5.

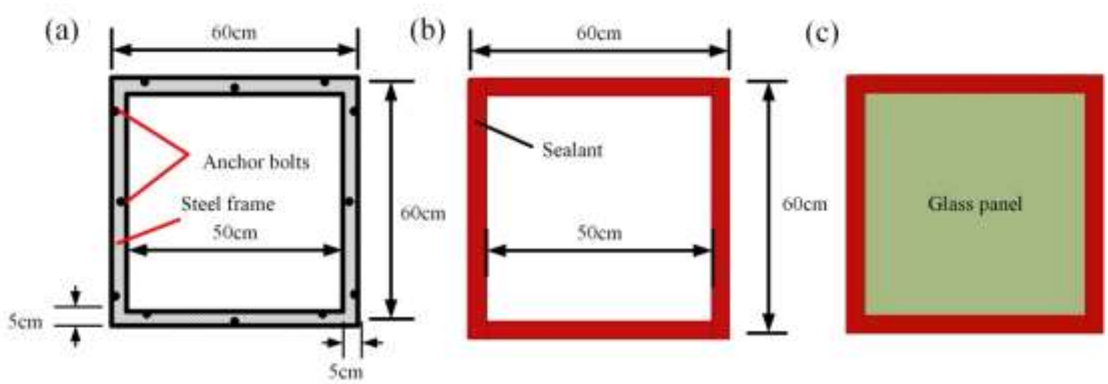

Fig. 4: (a) Anchor the steel frame (b) Steel frame gluing (c) Experimental device

Table 3 Basic parameters of glass sample

Side length, a/cm	Side length, b/cm	Thickness/cm	Density/(kg·m^{-2})	Elasticity Modulus/GPa	Poisson ratio, ν
60	60	0.5	12.3	70	0.22

Table 4 Performance of structural sealant

State	Shore hardness	Tensile strength/MPa	Extrusion/s
Pasty fluid	40	2.0	1.8

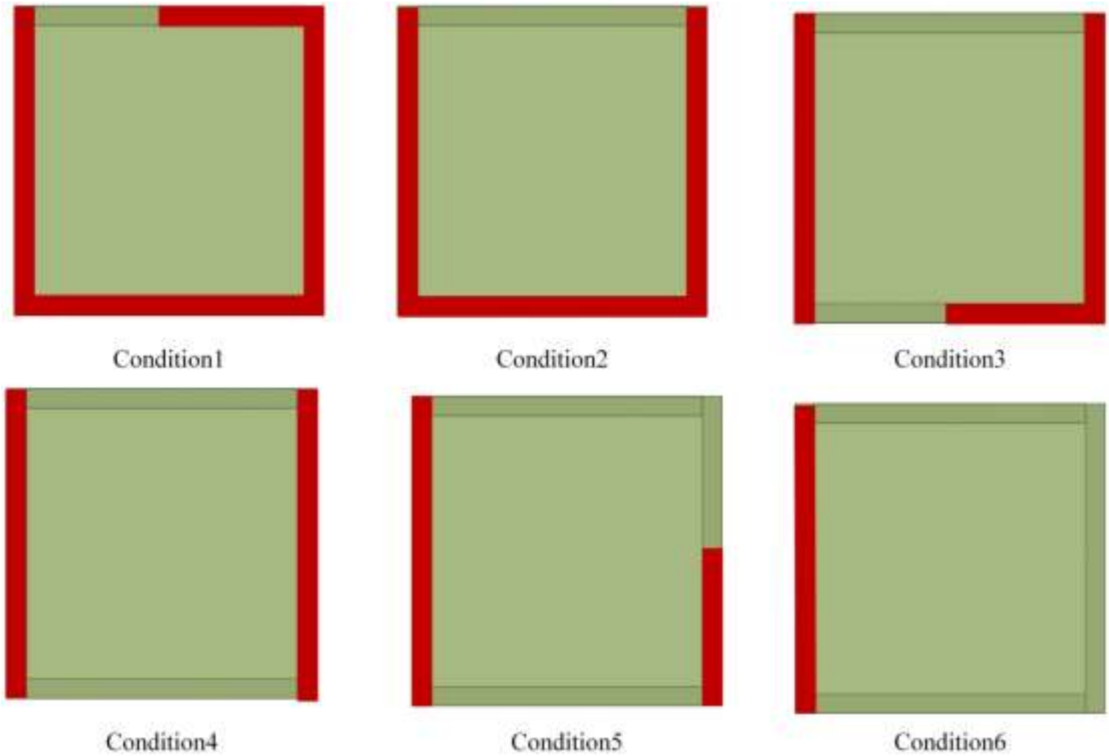

Fig. 5 Structural sealant failure under different damage conditions

5 Results and discussion

5.1 Incentive method

The experimental model of HFGCW is stimulated by manual trigger. The main trigger methods for obtaining dynamic parameters are Vibration hammer and vibration exciter. Because of the inconvenient installation and debugging operation of the shaker and the inadaptability to a large number of detection objects. According to the characteristics of the experimental structure, the vibration hammer is used to excite the HFGCW model as shown in Fig. 6(a). The influence of rubber hammer and steel hammer on the spectrum curve is studied respectively. The research results are shown in Fig. 6(b). It can be seen from the figure that steel hammer and rubber hammer with different hardness can stimulate the ideal spectrum curve. In order to avoid scratching the curtain wall glass plate, rubber hammer is used to excite the experimental structure.

(a)

(b)

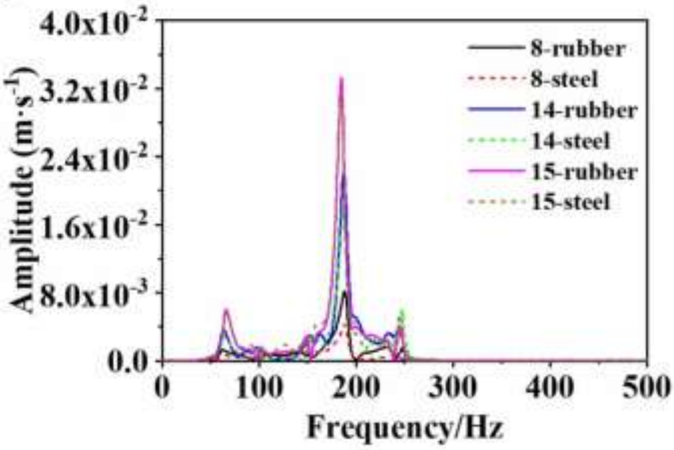

Fig. 6 (a) Spectrum of rubber hammer and steel hammer (b) under different excitation tools

5.2 Measure point

The experimental model of HFGCW is selected to study the influence of experimental measurement points on vibration transmissibility. In order to select sensitive measurement points and simplify the number of measurement points, the sensitive points are analyzed based on the selection of measurement points in previous studies. Existing studies have taken the natural frequency as the damage parameter and found that the location near the plate center is more sensitive to the damage parameter [11].The same method is followed to analyze the measured points along the diagonal and it is found that the vibration transmissivity is more sensitive away from the center of the plate. This method can quickly screen out sensitive sites and avoid a lot of repeated experiments. Fig. 7(a) is the layout of the test measuring points. Point 5 is the center of the plate. Starting from point 5 in the center of the plate, 4 points, 3 points, 2 points and 1 point are arranged in the diagonal direction upward with an interval of 7cm. Finally, the position coordinates of the selected measuring point are 14cm away from the edge of the glass plate. The positions of the final selected measuring points are shown in Fig. 7(b).

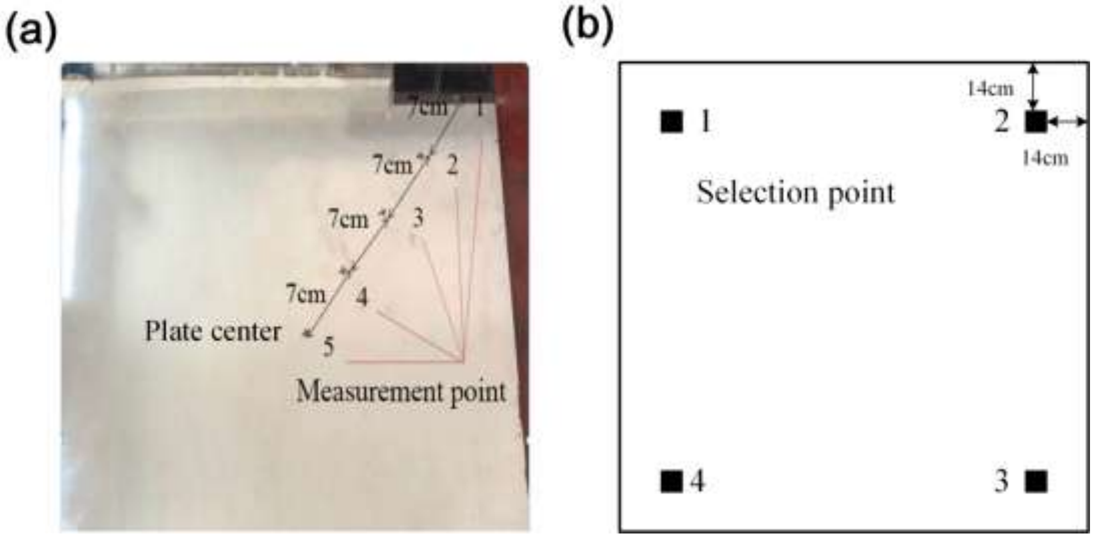

Fig. 7 (a) Arrangement of experimental measuring points (b) Selection of optimal measuring points

DASP vibration analyzer is used for testing. The Fig. 8 shows T (vibration transmissivity) and TCR (change rate of vibration transmission rate) of the five measurement points under the same damage degree. As can be seen from Fig. 8 (a), the closer to the center of the glass plate, the greater the amplitude of T. It can be seen from Fig. 8 (b) that the amplitude of TCR decreases as it is closer to the center of the glass plate. This indicates that the vibration transmissivity is more sensitive when the measuring point is far from the center of the glass plate. Therefore, in order to obtain accurate dynamic information, it is necessary to select the edge point of the glass plate as the measuring point to evaluate the safety state of the HFGCW.

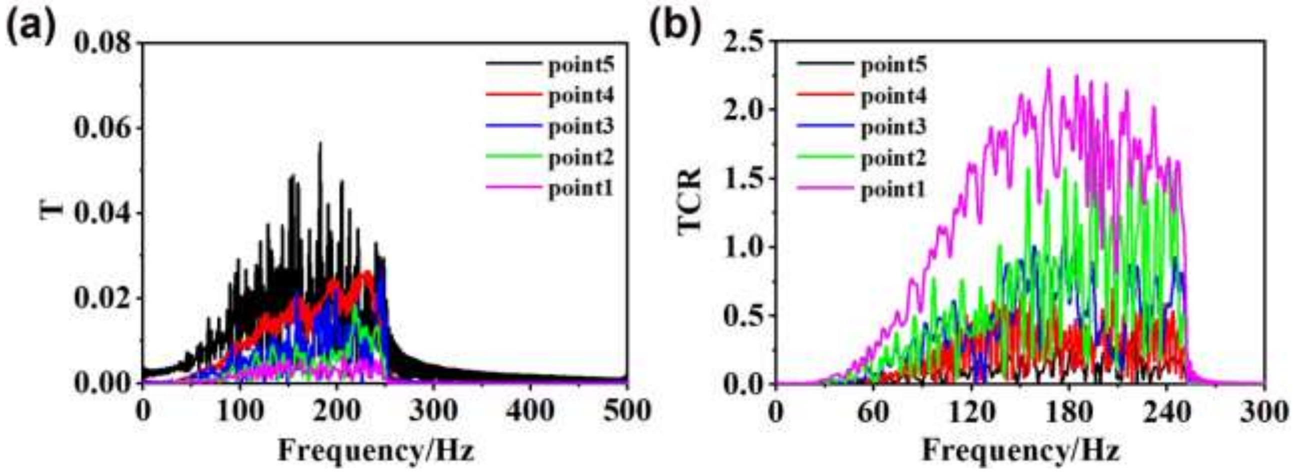

Fig. 8 Test results of experimental measuring points (a) T amplitude spectrum (b) TCR amplitude spectrum

5.3 Damage identification of degumming based on vibration transmissibility

Fig. 9 shows TCR curves of measuring points 1-2 under different working conditions (Fig. 5). It can be seen from the figure that the safety state of structural adhesive under different working conditions has a significant influence on the vibration transmissibility. Under the condition of the minimum failure length of structural sealant in working condition 1, the amplitude of TCR curve is the smallest. The amplitude and area of vibration TCR increased obviously with the increase of sealant failure length.

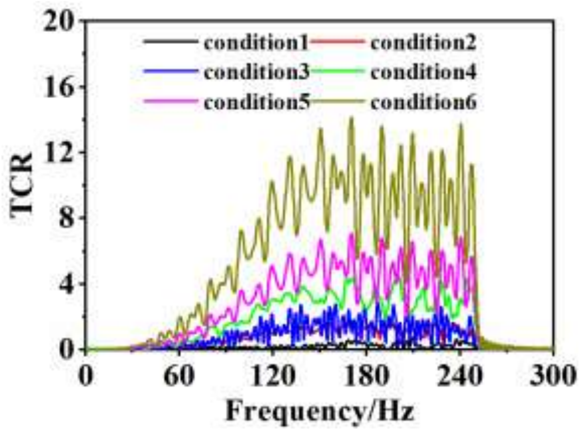

Fig. 9 TCR amplitude spectrum of measuring points 1-2 under different working conditions

Compared with Fourier transform, wavelet function used in wavelet analysis is not unique. The detection of adhesive damage in hidden frame glass curtain wall involves the selection of wavelet function. How to correctly select wavelet basis function to analyze and deal with the characteristics of glass curtain wall damage signal affects the success or failure of the whole experiment. If the selected wavelet basis function does not satisfy the signal analysis characteristics of degumming damage of glass curtain wall, the obtained results cannot reflect the degumming damage degree of glass curtain wall structural adhesive. Therefore, the selection of appropriate wavelet basis function for the characteristics of degumming damage signal of glass curtain wall has important research significance to reflect the damage degree of structural adhesive of glass curtain wall. Different parent wavelet functions have different properties. Common parent wavelet functions include db4, coiflet, sym3, sym4, etc. DbN wavelet has good regularity and tight support. Regularity makes the results obtained from the deguming damage signal of glass curtain wall have good smoothing effect, and tight support performance has good local analysis ability for the deguming damage signal of glass curtain wall. It is easy to find the damage characteristics hidden by the degumming damage signal. Bouzida et al. [38] found that various wavelet functions showed similar results in the field of motor fault diagnosis. However, satisfactory results can be obtained by using higher order wavelets. In addition, the existing work pays more attention to the fact that Daubechies family is highly utilized in the field of fault detection [39]. In this paper, the db4 is selected as the parent wavelet. In the process of fault detection, it is very important to determine the layers of damage signal decomposition. At the same time, it is also an important part of wavelet analysis. On the one hand, damage signals may be highly sensitive to multiple levels of decomposition. Several levels of poor analysis can miss important information about the failure. On the other hand, as the number of decomposition layers increases, more detailed information and subbands of signals will appear at a larger scale. However, setting more decomposition layers will cause low computational efficiency and reduce the stability of the system. The number of decomposed layers follows this setting [40].

According to decomposition and reconstruction of HFGCW acceleration response signal, five-layer detail signal is obtained as shown in Fig. 10. As can be seen from the figure, with the increase of damage length, the detail coefficient also increases. The detail signal obtained by DWT represents the high frequency part of the peel damage signal [41,42]. The damage characteristics of

HFGCW degumming damage signals are found by Hilbert transform and spectrum analysis of the detailed signals. The amplitude of the spectrum represents the energy value at each frequency point. Fig. 11 represents the Hilbert envelope spectrum at different damage lengths. The peak value of Hilbert envelope spectrum of HFGCW increases with the increase of damage degree.

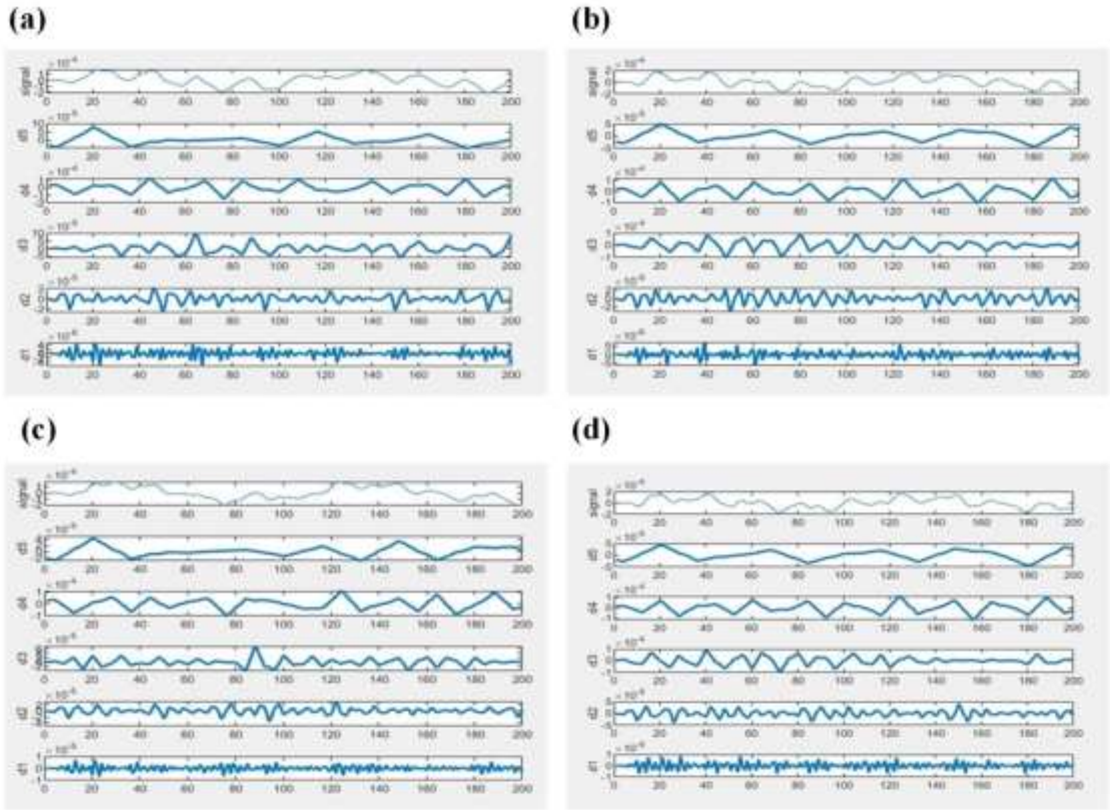

Fig.10 Detail signals at different damage lengths (a) 0cm (b) 6cm (c) 18cm (d) 30cm

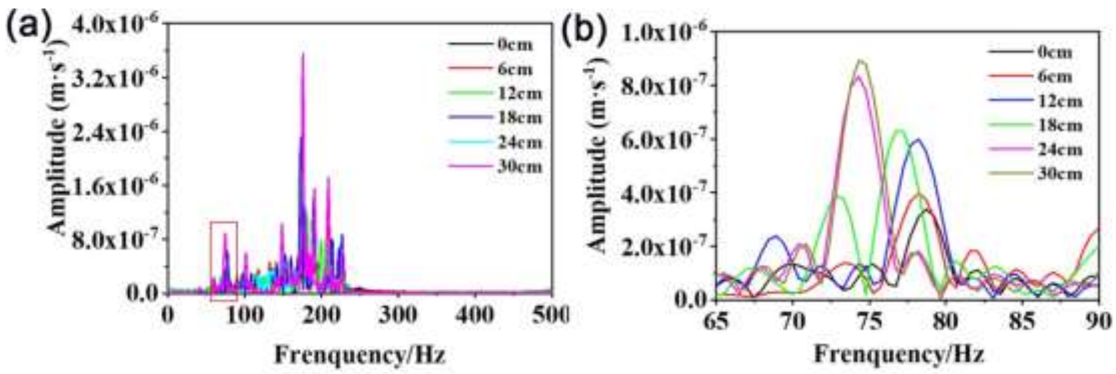

Fig. 11 Hilbert envelope spectrum at different degumming lengths (a) 0 ~ 500Hz (b) 65 ~ 90Hz

The acceleration response signal is decomposed by DWT, then convert into frequency domain by Fourier transform (FFT) and Hilbert transform (HT), and finally convert into vibration transfer function. TCR values under 10 damage conditions are obtained in Fig. 12 and Fig. 13. With the increase of damage degree of HFGCW, TCR values of different measuring points and different orders also increase. After comparative analysis, the TCR obtained by FFT and the TCR obtained by HT can identify the damage of structural sealant. However, TCR obtained by HT is more sensitive to structural adhesive damage than TCR obtained by FFT. Therefore, TCR obtained by HT can be used as the damage parameter value to better evaluate the safety state of HFGCW.

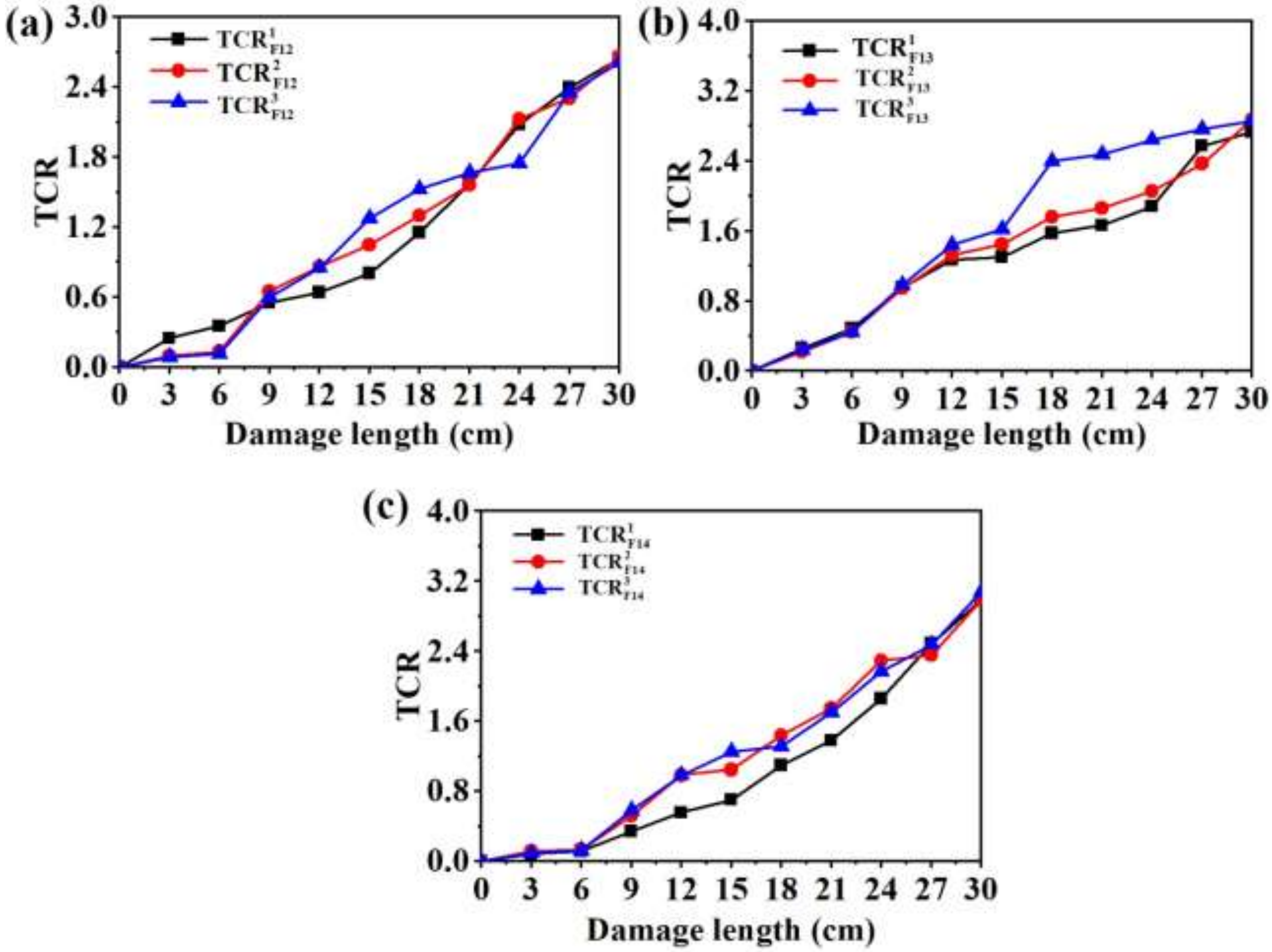

Fig. 12 TCR values (FFT) (a) 1-2 combinations; (b) 1-3 combinations; (c) 1-4 combinations under 10 damage conditions

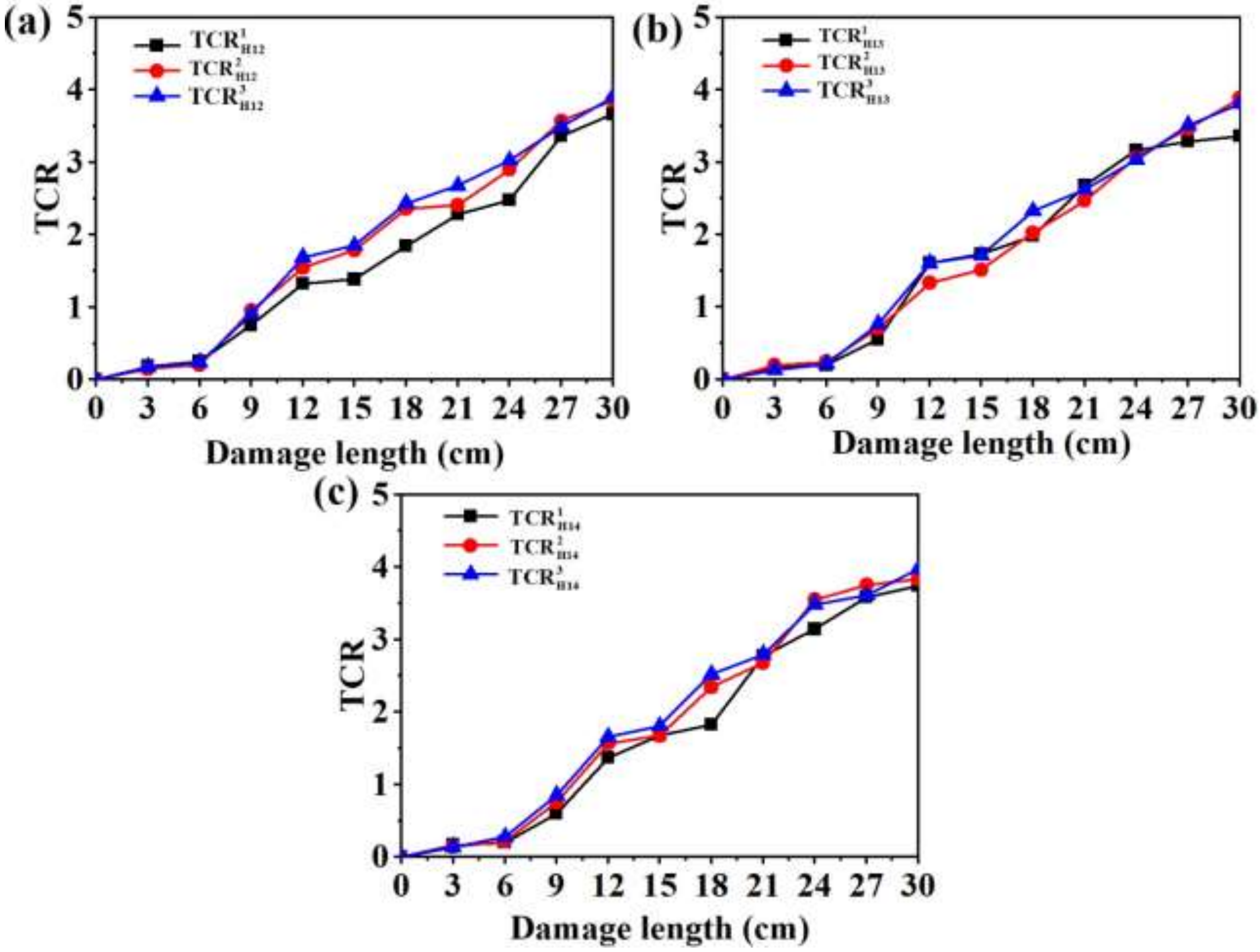

Fig. 13 TCR values (HT) (a) 1-2 combinations (b) 1-3 combinations (c) 1-4 combinations under 10 damage conditions

5.4 Discussion

According to the test results under different working conditions, the security status of HFGCW is divided into three levels as shown in Table 5. According to TCR damage parameters, a rapid evaluation model for the safety state of HFGCW is established as shown in Fig. 14. Finding the critical value of different safety levels is the key to establish the safety evaluation model. The boundary constraints are four elastic connections and four free connections. Under the finite element simulation, the vibration transfer rate of the elastic connection is TCR′ =3.6 and the vibration transfer rate of free connection of four sides is TCR" =8.7. According to the safety state evaluation model of HFGCW, working conditions 1, 2 and 3 in Fig. 5 are in the safe state, working conditions 4 and 5 are in the relative safe state, and working conditions 6 are in the dangerous state.

The established safety state evaluation model is a very important conceptual model to evaluate the safety of HFGCW. The damage degree of structural sealant and its damage position in the HFGCW will have an important impact on the critical value. The safety state evaluation model is applicable to all HFSGCW. In practical engineering applications, the model critical value will change.

Table 5 HFSGCW safety state evaluation model

Safety levels	Vibration trasmissibility	Safety state	Solutions
A	$TCR \le TCR'$	Absolute safety state	Regular management
B	$TCR' < TCR \le TCR''$	Relative safety state	Strengthening management
C	$TCR > TCR''$	Dangerous state	Replacement or Reinforcement

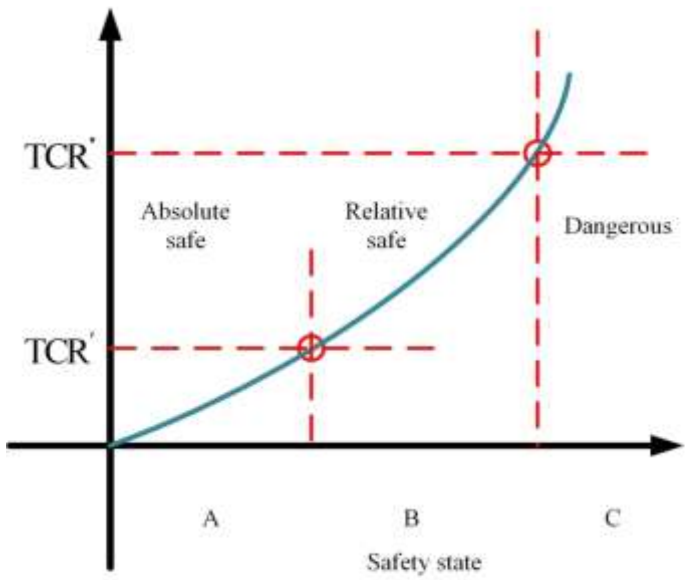

Fig. 14 Rapid evaluation model of safety state of HFGCW

6. Conclusions

In this paper, ANSYS finite element software and DASP vibration analysis system were used to simulate and experiment the HFGCW under different damage conditions. The research was carried out from the aspects of excitation mode, selection of measuring points, damage signals, etc., and the following conclusions were drawn:

(1) In the finite element simulation experiment, both vibration transmissibility and frequency response function can be used as degumming damage parameters, and vibration transmissibility is better than frequency response function;

(2) Steel and rubber hammers with different hardness can excite ideal spectral curves. In order to avoid scratching the glass plate, a soft rubber hammer was selected for excitation. At the edge of the glass plate, the change rate of vibration transmissibility is large, so the edge of the glass plate is selected as the measurement point to obtain the acceleration response;

(3) Both the change rate of vibration transmissibility obtained by fast Fourier transform and the change rate of vibration transmissibility obtained by Hilbert transform can identify the small damage of structural adhesive at the initial stage. However, the change rate of vibration transmissibility obtained by fast Fourier transform is more sensitive to small damage of structural adhesive than that obtained by Hilbert transform;

(4) The safety state of HFSGCW glass plate is divided into three levels. The safety state evaluation model based on vibration transfer rate can effectively evaluate the safety state of glass panel of hidden frame glass curtain wall.

Reference

[1]Q. Li, X. Zhu, Risk identification and its preventive measures of glass curtain wall, Urban Probl. 246 (1) (2016) 42–46.

[2]N. Wang, J. Ma, H. Liu, Influence of structural sealant on mechanical behavior of hidden frame curtain wall, Appl. Mech. Mater. 44–47 (2011) 2534–2538.

[3] L. Qing, H. Cui, F. Xing, et al., Reasons for glass plate falling in hidden frame glass curtain wall, China Build. Water. (17) (2013) 18-20.

[4]S.J. Jang, H.D. Yun, M.S. Lee, Localization of rattle noise sources in the vehicle underbody using acceleration signals, Arch. Civ. Mech. Eng. 17 (1) (2017) 65–74.

[5] C. Bedon, A. Claudio, N. Salvatore, Safety issues in the seismic design of secondary

frameless glass structures, Safety 5 (4) (2019)1-31.
[6] H. Puga, B.A. Olmos, L. Olmos, et al., Damage assessment of curtain wall glass, J. Phys.: Conf. Ser. IOP Publishing 628 (1) (2015) 012052.
[7]H. Wu, S. Zeng, Z. Li, Study on safety evaluation method of glass curtain wall, J.Nat. Disaters 19 (5) (2010) 96–100.
[8]B. Mojˇskerc, T. Kek, J. Grum, Pulse-echo ultrasonic testing of adhesively bonded joints in glass facades, Strojniski Vestnik/J. Mech. Eng. 62 (3) (2016) 147–153.
[9] X. Hong, B. Zhang, Y. Liu, Deep-learning-based guided wave detection for liquid-level state in porcelain bushing type terminal, Struct. Control Health Monit. 28 (1) (2021) 1-17.
[10]X. Hong, Y. Liu, Y. Liufu, et al., Debonding detection in hidden frame supported glass curtain walls using the nonlinear ultrasonic modulation method with piezoceramic transducers, Sensors 18 (2018) 1-18.
[11]Z.D. Huang, M. Xie, J. Zhao, et al., Rapid evaluation of safety-state in hidden-frame supported glass curtain walls using remote vibration measurement, J. Build. Eng. 19 (2018) 91–97.
[12] Z.D. Huang, M.W. Xie, C. Chen, Y. Du, J.H. Zhao. Engineering application of a safety-state evaluation model for hidden frame-supported glass curtain walls based on remote vibration, J. Build. Eng. 26 (2019) 1-6.
[13]X. Liu, Y. Bao, Safety evaluation for frame supported glass curtain wall based on modal frequency change, J. Shenyang Univ. Technol. 33 (5) (2011) 595–600.
[14]X. Liu, Y. Bao, Y. Song, et al., Safety evaluation of glass curtain walls by using dynamic method, China Civ. Eng. J. 42 (12) (2009) 11–15.
[15]J.J. Liu, J.H. Li, L. Ding, et al., Research and development in safe inspection and evaluation for existing building curtain walls, Constr. Technol. 42 (24) (2013) 9-14.
[16]X.G. Liu, Y.W. Bao, Safety evaluation for frame supported glass curtain wall based on natural frequency change, J. Shenyang Univ. Technol. 33 (5) (2011) 595–600.
[17]X.G. Liu, Y.W. Bao, Y. Qiu, et al., In-situ detection technology for failure of curtain-wall insulating glass, China Civ, Eng. J. 44 (11) (2011) 52–58.
[18]S.J. Jang, H.D. Yun, M.S. Lee, Effects of stiffening sealant thickness on the structural performance of structural silicone glazing (SSG) sealant connections in curtain wall systems, Arch. Civ. Mech. Eng. 17 (1) (2017) 65–74.

[19] X. Liu, Y. Bao, Y. Song, et al., Safety evaluation of glass curtain walls by using dynamic method, China Civ. Eng. J. 42 (12) (2009) 11–15.

[20] J.P. Amezquita-Sanchez, H. Adeli, Signal processing techniques for vibration-based health monitoring of smart structures, Arch. Comput. Methods Eng. (2016)1-15.

[21] C.R. Farrar, S.W. Doebling, D.A. Nix, Vibration-based structural damage identification, Philos. Trans. R. Soc. A Math. Phys Eng. Sci. (2001) 131-149.

[22] D.E. Newland, Wavelet Analysis of Vibration. Part 1: Theory, J VIB ACOUST , 116 (1994) 409-416.

[23] J. Lin, M. Zuo, Gearbox fault diagnosis using adaptive wavelet filter, Mech. Syst. Signal Process. 17 (6) (2003) 1259–1269.

[24] A. Abdelelah, K.S. Ashwin, K.K. Mani. Diagnosis of stator fault severity in induction motor based on discrete wavelet analysis, Measurement. 182(2021)1-12.

[25] B.Zhao，D.Lei, J.Fu, L.Yang,W.Xu, Experimental study on micro-damage identification in reinforced concrete beam with wavelet packet and DIC method. Constr. Build. Mater. 210 (2019) 338–346.

[26] Kim, H., Melhem, H., 2003. Fourier and wavelet analyses for fatigue assessment of concrete beams. Experimental Mechanics 43, 131–140.

[27]H.H. Wu, S.L. Zeng, Z.N. Li, Study on safety evaluation method of glass curtain wall, J. Nat. Disasters. 19 (5) (2010) 96–100.

[28] Z.D. Huang, M.W. Xie, J.H. Zhao, et al., Rapid evaluation of safety-state in hidden-frame supported glass curtain walls using remote vibration measurement, J. Build. Eng. 19 (5) (2018) 91–97.

[29] H.Zhang.Damage detection in a composite beam using transmittance functions[D].North Carolina A and T State University.1998.

[30] H.Zhang, A.S.Naser, M.J.Schulz and P.F.Pai. Health monitoring of composite beams using piezoceramic patches and curvature transmittance functions. ASCE, Engineering Mechanics Div, 1998 17-20.

[31]N.M.M. Maia, J.M.M. Silva, A.M.R. Ribeiro, The transmissibility concept in multiple degrees of freedom systems, Mech. Syst. Signal Pr. 15(1) (2001) 129-137.

[32]Y. Ding, A.Q. Li, Structural damage early warning based on vibration testing and wavelet packet analysis, J. Theor. App. Mech-Pol. 38 (5) (2006) 639–644.
[33]J. Seshadrinath, B. Singh, B.P. Ketan, Incipient turn fault detection and condition monitoring of induction machine using analytical wavelet transform, IEEE Trans. Ind. Appl. 50 (3) (2014) 2235–2242.
[34]H. Zhang, M.J. Schulz, F. Ferguson, P.F. Pai, Structural health monitoring using transmittance functions, Mech. Syst. Signal Pr. 13(5) (1999) 765-787.
[35]W.Q. Luo，Z.H. Fang, Study on Damage Detection of Full-scale Frame-concealed Glass Curtain-walls Based on Modal Curvature, Building Information.44(13) 1-2.
[36]X.G. Liu, Y.W. Bao, Safety evaluation for frame supported glass curtain wall based on modal frequency change, J. Shenyang Univ. Technol. 33 (5) (2011) 595–600.
[37]⟨http://www.cnsealant.com/product/9.html⟩.
[38] A. Bouzida, O. Touhami, R. Ibtiouen, A. Belouchrani, M. Fadel, A. Rezzoug, Fault diagnosis in industrial induction machines through discrete wavelet transform, IEEE Trans. Ind. Electron. 58 (9) (2010) 4385–4395.
[39] J. Faiz, B.M. Ebrahimi, B. Akin, B. Asaie, Criterion function for broken-bar fault diagnosis in induction motor under load variation using wavelet transform, Electromagnetics. 29 (3) (2009) 220–234.
[40] B.A. Vinayak, S. Varma, G. Jagadanand, Precise wavelet selection for condition monitoring of inverter-fed induction machine, in: 2017 IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems, SPICES. (2017) 1–4.
[41]M. Haq, S. Bhalla, T. Naqvi, Fatigue damage monitoring of reinforced concrete frames using wavelet transform energy of PZT-based admittance signals. Meas. 164 (C) (2020) 1-16.
[42] T.Teimoori, M. Mahmoudi, Damage detection in connections of steel moment resisting frames using proper orthogonal decomposition and wavelet transform, Measurement 166 (2020) 1-19.

Statements & Declarations

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Conflict of Interest

The authors declare that they have no conflict of interest.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Guang Yang. The first draft of the manuscript was written by Guang Yang and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The data in the current study cannot be made public due to further analysis but can be obtained from corresponding authors upon reasonable request.