# Simulation Test and Performance Analysis of Sma-Cfrp Composites Fabricated Based on Cfrp Anchorage

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**Abstract:** Shape memory alloy-carbon fiber reinforced composite (SMA-CFRP) is a promising material for repairing and strengthening crack-sensitive metal structures. In this paper, aiming at the anchoring problem in the process of preparing SMA-CFRP composites, a kind of bolt Anchorage made by CFRP is proposed, which optimizes the anchoring effect of SMA. Based on the finite element analysis, the simulated axial tension test of SMA-CFRP composite made by CFRP Anchorage is carried out, and the bearing capacity of the structure and the deformation and failure process of the structure are mainly studied when the Anchorage system fails. The results show that compared with the traditional bonding Anchorage system, the CFRP bolt anchoring system can effectively increase the ultimate load that SMA-CFRP composite can bear when the Anchorage system fails, which increases by 35% compared with the traditional bonding Anchorage system.

## **1. Introduction**

Shape memory alloy (SMA) is a kind of intelligent material with shape memory effect, superelastic effect and elastic modulus varying with temperature[1]. Carbon fiber reinforced composite (CFRP) is a kind of composite material with light weight, good stiffness, high temperature resistance, good fatigue resistance and so on[2]. CFRP plate can improve the strength of reinforced concrete (RC) structure, but the residual deformation of in-service RC structure reduces the strengthening effect of CFRP. On the contrary, SMA can exert restoring force on concrete, thus potentially reducing residual deformation, but it can only be used in urgent damage repair, because SMA needs continuous heating to produce restoring force [3]. It can be seen that although CFRP and SMA have positive significance in building structural damage repair, they both have their own limitations and can not achieve the best repair effect.

In order to realize the complementary advantages of these two materials, a large number of scholars have proposed to prepare SMA-CFRP composites. In 2006, it is concluded that embedding an appropriate amount of SMA in CFRP can effectively improve the fatigue performance of CFRP. [4] In 2009, the scholar Yoji Okabe proposed a lightweight variable geometry sandwich structure composed of SMA honeycomb core and CFRP skin, and a kind of lightweight beam driven by temperature can be generated by this structure.[5-6] In 2016, a kind of ancient wooden mortise and tenon joints reinforced with shape memory alloy laminated carbon fiber sheets was developed, which greatly improved the energy dissipation capacity of the joints, and then improved the strengthening effect of carbon fiber sheets. Until 2018, the scholar Bo-Tong Zhen proposed a SMA-CFRP system for strengthening fatigue-sensitive metal structures. The experimental results show that the SMA-CFRP repair system is a promising scheme for repairing and strengthening crack-sensitive metal structures. [7]

In this paper, aiming at the anchoring problem in the process of preparing SMA-CFRP composite material, a kind of bolt Anchorage made by CFRP is proposed, which optimizes the anchoring effect of SMA. Compared with the traditional bonding Anchorage system, the effect of temperature on anchoring effect is weakened, and the effectiveness of CFRP Anchorage is verified by axial tension test of SMA-CFRP specimen.

#### 2. Cfrp Anchorage

### 2.1 Design Concept

In the preparation of SMA-CFRP composites, the main function of the anchoring device is to anchor the SMA on the CFRP and transfer the prestress built on the SMA to the CFRP effectively and reliably. At present, bonding anchoring system is widely used. They are hot melt adhesive and thermosetting adhesive, but they all restrict the preparation of SMA-CFRP because of effect of temperature. As far as hot melt adhesive is concerned, this kind of binder can anchor the prestressed SMA at low temperature, but its melting point is lower than the austenite temperature of SMA. When SMA is heated, this kind of binder will melt and debonding occurs, so it can not continue to anchor SMA, which makes the SMA-CFRP structure lose its working efficiency. For the thermosetting adhesive, the curing temperature is much higher than the austenite temperature of SMA, that is to say, after the phase transformation of SMA-CFRP, resulting in its failure.

In order to solve the anchoring problems, the CFRP bolt Anchorage is developed, and the traditional bonded anchoring system is replaced by the bolt anchoring system, which avoids the influence of temperature on the anchoring effect. At the same time, because the anchors and plates are made of CFRP composite materials, the mechanical properties of bolts and components can be consistent, the stress concentration caused by material variation can be reduced, and the anchoring effect of CFRP bolts can be optimized.

### **2.2 Production Process**

CFRP bolts are produced by molding method. This method can not only save the auxiliary machining which is harmful to the product performance, improve the thread connection strength, but also improve the product surface quality and shorten the production cycle. At the same time, the size repeatability of the product is good, so it is suitable for mass production. In the process of preparation, a pressing die of carbon fiber reinforced resin matrix composites under axial pressure is selected, as shown in figure 1. The mold material is XMC molded material composed of polyurethane resin and carbon fiber. Considering the glass transition temperature of cyanate ester resin system, the molding temperature is 220°C, the bolt is pressed manually, the molding pressure is 200MPa, and the finished bolt is shown in figure 2. [8]



Fig.1 Mold Engineering Drawing [8]

1-bottom plate; 2-roof plate; 3/4-left and right side plate; 5-left mandrel; 6-right mandrel; 7/ 8-screw nut; 9-stiffener; 10-baffle; 11-inner hexagon bolt



Fig.2 Molded Cfrp Bolts [8]

## 3. Simulated Axial Tension Test of Sma-Cfrp Composites Prepared by Cfrp Anchorage

### **3.1 Experimental Scheme**

Component Size. In order to verify the anchoring effect of CFRP bolts, a three-dimensional model of SMA-CFRP-CFRP bolts is established by using ABAQUS finite element analysis software, as shown in figure 3. The three-dimensional model consists of three parts, namely CFRP, SMA and CFRP bolts. CFRP are 50mm long, 26mm wide and 5mm thick; SMA is 101mm long, 26mm wide , 5mm thick and 25mm deep into CFRP;CFRP bolt is a round head bolt with a diameter of 6mm, a length of 15.77mm, a diameter of 10mm and a thickness of 4mm. The dimensions of each part are shown in figure 4.



Fig.3 3d Model of Sma-Cfrp-Cfrp Bolt



Fig.4 Section View of Each Part

(a) CFRP bolt horizontal section (b) CFRP horizontal section (c) SMA horizontal section

Material Properties. After the above three components are created, they are assigned material properties. Referring to the parameter setting of the scholar M. El-Tahan [9], SMA is defined as an elastic-plastic material with an elastic modulus of 45770MPa, a yield stress of 200MPa and a Poisson's ratio of 0.3. The plastic behavior of SMA is simulated by considering the evolution of shear

damage, and the fracture stress is 0.25. CFRP is defined as an isotropic elastic material, and its are longitudinal modulus (E<sub>1</sub>=86.6GPa), engineering constants transverse modulus  $(E_2=E_3=4.98GPa)$ , transverse shear modulus  $(G_{12}=G_{13}=G_{23}=1.82GPa)$  and Poisson's ratio  $(V_{12}=V_{13}=V_{23}=0.3)$ . Considering the damage evolution of Hashin, the longitudinal tensile and compressive strength is 1200MPa and 800MPa respectively, the transverse tensile and compressive strength is 120MPa and 80MPa respectively, and the transverse and longitudinal shear strength is 60MPa. Referring to the parameter setting of Xiong Jialin [8] in the study, CRRP bolts are defined as isotropic elastic materials. Their engineering constants are longitudinal modulus (E<sub>1</sub>=145.1 GPa), transverse modulus (E<sub>2</sub>=E<sub>3</sub>=8.78 GPa), transverse shear modulus (G<sub>12</sub>=G<sub>13</sub>=4.5GPa, G<sub>23</sub>=3GPa), Poisson's ratio ( $V_{12}=V_{13}=0.22$ ,  $V_{23}=0.28$ ). Considering the evolution of Hashin damage, the longitudinal tensile and compressive strength is 2245MPa and 1800MPa, respectively. The transverse tensile and compressive strength is 92.33MPa and 120MPa respectively, and the transverse and longitudinal shear strength is 60MPa.

Other ParameterSettings. When the above work is completed, each part is meshed. The bolts of CFRP, SMA and CFRP are all divided independently and are meshed automatically by software. CFRP and bolts are divided by eight-node quadrilateral in-plane general continuous shell element (SC8R element), and SMA is meshed by eight-node linear hexahedral element (C3D8R element). They are then assembled into the shape shown in figure 3, and in order to simulate the axial tensile state of the SMA-CFRP composite material, the boundary strip and the approximate bundle of the finite element mold are set to: the end of the CFRP far away from the bolt is fully fixed (U1=U2=U3=UR1=UR2=UR3=0), The end of SMA away from the bolt creates a MPC beam constraint, and adds a horizontal displacement of Amp-1(U1=20,U2=U3=UR1=UR2=UR3=0) to simulate the axial tension. At the same time, the friction coefficient between CFRP and SMA is 0.3. After that, the general analysis step is selected, and the step size is 0.1. At the beginning of the analysis step, the whole model is scaled semi-automatically according to the coefficient of 100 until it converges.

#### **3.2 Results and Analysis**

Failure Process. Under the action of axial tension, both SMA and CFRP bolts move along the direction of axial force, and CFRP remains at rest. In the whole deformation process, the deformation of SMA is concentrated in the bolt Anchorage, and the hole area expands slightly, and the CFRP bolt produces slight bending deformation in the middle of the screw. The completely fixed end of CFRP has almost no deformation, and the deformation is concentrated on the end where it is anchored by bolts. With the movement of SMA and bolts, the shape of the upper CFRP changes from rectangle to irregular cone, and asymmetrical flanges are produced on both sides of the cone, and the lower layer CFRP changes from rectangle to symmetrical spike. The hole area of these two layers of CFRP increases obviously, from round hole to irregular cone. The stress-strain cloud diagram of each component is shown in figure 5.

As shown in figure 5, SMA produces stress concentration at the hole, and the stress radiates around with the hole as the center, and the peak stress at the edge of the hole is 200 MPA. The stress concentration occurs at the screw, and the stress increases from the center axis of the screw to the edge of the screw, and the peak stress distributes to 1366 MPA at the edge of the screw. Both the upper and lower layers of CFRP produce stress concentration at the hole, and in addition, the stress concentration occurs at the longer flange of the upper CFRP, and the peak stress is 1112MPa.



(a) SMA Top View (b) CFRP Bolt Front View (c) Upper CFRP Top View (d) Lower CFRP bottom View

# Fig.5 Stress-Strain Cloud Diagram of Each Component

Anchorage Failure Analysis. By observing the experimental phenomenon, it was found that the beginning of CFRP failure was marked by the displacement of SMA and CFRP bolts in the direction of axial force relative to CFRP, which means that the hole of CFRP will be enlarged, a gap will occur

between CFRP and SMA, and there will be no close contact. So the prestress based on SMA cannot be transferred to CFRP, and this process is a sign that the Anchorage system is beginning to fail. Because of the complexity of CFRP deformation process, in order to accurately obtain the axial tension load value when CFRP begins to fail, it can be transformed into the corresponding load value when CFRP bolt begins to produce displacement. The displacement-load curve of CFRP bolt is shown in figure 6.By observing the curve, it can be found that the displacement change of CFRP bolt is very small at the initial stage of loading, so the approximate vertical AB section is selected for numerical analysis, as shown in Table 1.If point B is taken as the critical point when the CFRP bolt begins to produce displacement, it can be determined that when the CFRP bolt moves 0.01mm relative to the CFRP toward the axial force, the CFRP is also stretched 0.01mm, and at this time the CFRP begins to break, which means that the Anchorage system begins to fail, and the corresponding load is 275.8N.As the load continues to increase, the displacement of CFRP bolts continues to increase, the damage degree of CFRP continues to increase, and the failure degree of bolt system continues to deepen. When the load is loaded to C point, the displacement-load curve of CFRP bolt suddenly changes, and the load value of CFRP bolt suddenly decreases to 0N, which means that the shear failure of CFRP bolt occurs at C point, and the corresponding load value is 9587N.

In summary, when the CFRP bolt anchoring system begins to fail, the tensile force of SMA-CFRP composite material is 275.8N, and that of CFRP bolt is 9587N when shear failure occurs.



Fig.5 Cfrp Bolt Displacement-Load Curve

Table 1	Numerical	Analysis
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	1	2	3	4	5	6	7	8
Load(N)	4.3	15.9	27.5	48.5	83.4	127.1	188.8	275.8
Disp.(mm)	24.8×10 <sup>-6</sup>	197.1×10 <sup>-6</sup>	660.2×10 <sup>-6</sup>	0.001	0.003	0.005	0.008	0.010

#### 4. Discussion

In order to verify the effectiveness of CFRP bolt Anchorage system compared with bond Anchorage system, refer to the study of bond behavior between SMA and CFRP developed by scholar El-Tahan M [9]. In this study, the SMA alloy wire with a diameter of 0.77 mm was embedded on the sandblasted surface into a CFRP patch with a length of 50mm, a width of 26mm and a total thickness of 2mm. The embedded depth of the SMA alloy wire was  $L_d$ , and extended 76mm outside the CFRP. The aluminum sheet was bonded to the end of the CFRP and clamped in the loading frame during the test, and the SMA alloy wire was pulled out of the CFRP at a speed of 0.4 mm/min by applying axial tension, as shown in figure 7. The DIC system is used to help identify the beginning of debonding and the propagation of the debonding front in the pull-out process. When SMA and CFRP are completely debonded, the bond Anchorage system fails, and the complete debonding is characterized by a sudden drop in load. Figure 8 shows the relationship between the load in the SMA alloy wire and the relative displacement of the SMA when the embedded depth of the SMA is 25mm ( $L_d=25mm$ ). By observing figure 8, we can see that the load suddenly decreases at point 6, which means that SMA and CFRP are completely debonded, and the bond Anchorage system begins to fail,

and the corresponding load is 204N. In addition, the scholar El-Tahan M also uses ABAQUS finite element analysis software to establish a model to quantify the material properties (as described in 2.1). After comparing the software simulation results with the actual experimental results, it is proved that the material parameters are correct.



Fig.7 Pull-out Specimen Dimension[9]



Fig.8 Sma Load-Displacement Curve [9]

By comparing the axial tension test results of SMA-CFRP composites prepared by bond Anchorage system and bolt Anchorage system, it is found that under the condition of roughly the same section size, material properties and working conditions, the ultimate load of SMA-CFRP composite material is 204N when the bond Anchorage system begins to fail, while that of SMA-CFRP composite material is 275.8N. Therefore, the CFRP bolt Anchorage proposed in this paper can effectively improve the anchoring effect in the preparation of SMA-CFRP composites.

#### 5. Conclusion

In this paper, aiming at the anchoring problem in the process of preparing SMA-CFRP composite, the concept of CFRP bolt Anchorage is put forward. Based on the finite element analysis, the quasi-axial tension test of SMA-CFRP composite prepared by CFRP Anchorage is carried out, and its anchoring effect is analyzed and compared with the experimental results in reference [9]. The main conclusions are as follows:

1)The finite element analysis results show that, the CFRP bolt anchoring system can effectively improve the ultimate load that SMA-CFRP composites can bear when the anchoring system fails, which increases by 35% compared with the traditional bonding Anchorage system, and improves the utilization rate of SMA-CFRP composites.

2) The finite element analysis results show that, compared with the traditional bond Anchorage system, the SMA-CFRP composite made of CFRP bolt Anchorage will produce a large number of deformation and even damage in the axial tension test, which weakens the recyclability of SMA-CFRP composite.

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