Design, construction, and modeling of aircraft door sealing plate based on SMAs

Chen Zhang, Renhao Liu, Chongcong Tao, Chao Zhang, Hongli Ji and Jinhao Qiu

State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu, China

ABSTRACT
In this work, a novel aircraft door sealing structure driven by shape memory alloys (SMAs) is proposed that offers much improved sealing capability than traditional sealing plates. The two-way shape memory effect (TWSME) of SMAs is utilized so that the proposed sealing plate can change its shape through heating and cooling of the driving SMA unit. Considering the inhomogeneous temperature and recovery strain field the SMA exhibits while being trained, a modified finite element (FE) model of the sealing structure is established to predict the deflection of the SMA-based sealing plate. Finally, verification experiments are carried out. The experimental results show good agreement with the FE predictions, indicating good accuracy of the modified FE model as well as the effectiveness of the proposed sealing structure.

1. Introduction
As an important component of a large passenger aircraft, the reliability of the cabin door has a great effect on flight safety and comfort [1,2]. The door-ladder-integrated form, sideward-opening form, and internal-rotation-opening form are the three main forms of aircraft doors. The doors integrated with ladder are applied at some early airlines such as Ilyushin IL86/96 and some Boeing B747. However, due to its complexity and needing a lot of space, it is no longer considered on modern airlines. The sideward opening passenger doors are used in the latest Boeing airlines such as B777. This kind of door mechanism has
been more and more used because of its well-designed structure, opening mode, and needing less internal space [3]. The passenger plane passenger doors of Boeing B737 and COMAC C919 are opened by retraction and rotation. This kind of door firstly moves inward and then turns outward in an opening sequence. Around the contours of aircraft doors, gaps are necessary to accommodate the mechanical part of the opening and closure mechanisms. As a result, additional door sealing plates are required at the upper and lower ends of the cabin door. Figure 1 shows the position of the sealing structures at Boeing B737 and its CAD model. This kind of sealing structure can fit to the cabin tightly during the flight to reduce the vibration and noise during flight. Although the opening mechanism has been proposed for years, there are still a number of problems in the course of actual use. Take the internal-rotation-opening form aircraft door as an example, in history, due to the poor sealing performance of the sealing plates, this kind of aircraft door is often misaligned or easily worn out, resulting in the door not sealed tight while closed, which affects the takeoff of flights [4–6]. To overcome these difficulties, new materials and designs for these structures should be studied.

With the rapid development of smart materials in aircraft applications, the use of which to improve the aerodynamic performance of aircrafts is promising. Researchers have also set their sights on the applications of smart materials to aircraft doors in order to meet the new requirements. Shape memory alloy (SMA) is a unique class of smart materials capable of sustaining large inelastic strains, which can be recovered by heating or unloading. Shape memory effect (SME) and pseudoelastic effect (PE) are two basic properties of SMAs [7,8]. It owns the ability to change its macroscopic shape via a temperature-induced phase transformation between two phases: the martensitic phase at low temperature and austenitic phase at high temperature. In addition, the property of SMAs, which can remember high-temperature shape and low-temperature shape at the same time, and change between the states, is called the two-way shape memory effect (TWSME). These valuable properties make SMAs widely utilized in aerospace fields [9–11]. The most well-known application of SMAs is in an engine nozzle on a Boeing commercial airplane to reduce jet noise. A large amount of theoretical works and simulations have been done by Texas A&M University and the Boeing Company [12–14]. This structure improved the mixing of the freestream air and the fan

![Sealing structure](image-url)  
(a) Sealing structure around the contours of cabin doors: (a) sealing structures of the B737 aircraft; (b) CAD modeling of the sealing plates.
stream, and reduced the airport operational noise generated during aircraft takeoff and landing efficiently. A novel SMA-based segmented morphing trailing-edge concepts were investigated by Barbarino, which can produce a large trailing-edge angle [15]. A similar approach was also used in the leading edge to increase the lift-to-drag ratio [16]. Mohsen Gol Zardian et al. uses shape memory alloy fibers as a means for influencing and tuning the static and dynamic responses of composite beams [17]. Navid Moslemi et al. proposed a novel smart assistive knee brace mechanism incorporated with wire actuators made of SMAs [18]. Furthermore, SMAs are also applied in many civil engineering applications. Large SMA wires, ropes, springs, and beams are being used as damping elements in bridges, buildings, and also in seismic resisting systems due to their excellent energy dissipation and recentering capabilities [19–21]. More recently, a new type of SMA washer spring-based self-centering rocking (SCR) systems that can safely prevent the rocking bridge pier from excessive rocking are proposed by Cheng Fang et al. [22]. They also created a novel type of SMA cable-restrained high damping rubber bearing to significantly alleviate the pounding effect under the near-fault earthquakes [23].

To accurately predict the SMA responses under different conditions, researchers developed various constitutive models in the last decades. These models evolved from mostly empirical relations to full-fledged mathematical descriptions accounting for many of the effects observed in these materials with an ever-higher degree of detail. The models available today are constructed using various approaches ranging from micromechanics to statistical physics and particle dynamics, to methods of classical plasticity, to energy approaches coupled with thermodynamic and conservation principles. A quick glance at these models suggests that plenty of approaches exist. Brinson and Huang [24], Bernardini and Pence [25], Paiva and Savi [26], Lagoudas [7], and Cisse [27,28] have reviewed models for SMA.

In this paper, the sealing plate, which is used in the internal rotation opening form aircraft door, has been studied. An adaptive aircraft door sealing plate based on SMA, which can change its deflection by controlling the temperature applied on the material, is proposed. The newly designed SMA-based aircraft door sealing plate presented in this paper owns the ability to bend while heating and to straighten while cooling. It can reduce the friction between the passenger door and the body of aircraft efficiently during the opening and closing processes, and fit to the cabin tightly during the flight. In addition, to accurately predict the deformation process of this newly designed structure, a macroscopic model, which describes the behavior of polycrystalline SMAs mainly based on phenomenological considerations, is used to model the SMA-based sealing plate. However, traditional modeling methods can only be used in the conditions that the material exhibits uniform deformation. When the SMA is not fully trained, the deformation performance at different positions of the material varies, and traditional methods do not apply. Therefore, an improved modeling method considering the training conditions is proposed in this work.

This paper is organized as follows. In section 2, a thermomechanical constitutive model proposed by Boyd and Lagoudas is introduced. Based on this model, the maximum transformation strain is discretized to better characterize the inhomogeneous recovery strain in the material. In section 3, we propose the idea of designing an SMA-based sealing plate. Materials used are shown in this part, and material tests are applied to measure the basic properties of SMAs. Training methods for inducing TWSME are also introduced. In
section 4, the experimental platform is established. The inhomogeneous temperature field during training and the recovery strain of the trained SMAs are measured. Then, the deformation performance of the SMA-based sealing plate is tested. In section 5, the relationship between the training temperature and the maximum transformation strain is established to model the inhomogeneous recovery strain in SMA. This modified modeling method is then used to investigate the thermomechanical responses of the SMA-based sealing plate. Simulation results are then compared with the experimental data. Finally, conclusions are drawn in section 6.

2 Constitutive model of SMA

2.1. The model of Boyd and Lagoudas

The constitutive model of SMA used in this paper is based on the model developed by Boyd and Lagoudas in 1996 [29]. This model is based on the assumed form of the total Gibbs free energy of a polycrystalline, and the explicit form of SMA’s Gibbs free energy can be written as:

\[
G(\sigma, T, \xi, \epsilon^t) = -\frac{1}{2\rho} \mathbf{S} : \mathbf{\sigma} - \frac{1}{\rho} \mathbf{\sigma} : [a(T - T_0) + \epsilon^t] + c \left[ (T - T_0) - T \ln \left( \frac{T}{T_0} \right) \right] - s_0 T + u_0 + \frac{1}{\rho} f(\xi)
\]  

(1)

where \( \mathbf{\sigma} \), \( T \), \( T_0 \), \( \epsilon^t \) and \( \xi \) represent the Cauchy stress tensor, temperature, reference temperature, transformation strain, and martensitic volume fraction, respectively. The symbols \( \mathbf{S} \), \( a \), \( c \), \( \rho \), \( s_0 \), and \( u_0 \) are the effective compliance tensor, the effective thermal expansion coefficient tensor, effective specific heat, density, effective specific entropy, and effective specific internal energy at the reference state, respectively. The constitutive relation of shape memory material can be obtained using Gibbs free energy as:

\[
\epsilon = -\rho \frac{\partial G}{\partial \sigma} = \mathbf{S} : \mathbf{\sigma} + a(T - T_0) + \epsilon^t
\]  

(2)

The evolution equation is related to the evolution of the martensitic volume fraction and can be written as:

\[
\dot{\epsilon}^t = \mathbf{\Lambda} \dot{\xi}
\]  

(3)

Where \( \mathbf{\Lambda} \) is the transformation tensor, which determines the transformation strain direction and magnitude. This equation connects the evolution equation of the transformation strain \( \epsilon^t \) to the evolution of the martensitic volume fraction \( \xi \). The transformation tensor usually has the following form:

\[
\mathbf{\Lambda} = \begin{cases} 
\frac{3}{2} H(\sigma) \frac{\epsilon^t}{\sigma^t} & \text{for} \ \dot{\xi} > 0 \\
H(\sigma) \frac{\epsilon^t}{\sigma^t} & \text{for} \ \dot{\xi} < 0
\end{cases}
\]  

(4)

Where \( \sigma^t \), \( \sigma^t \), \( \epsilon^t \), and \( \epsilon^t \) represent the deviatoric stress tensor, effective (von Mises equivalent) stress, transformation strain at the reversal point, and the effective transformation strain at the reversal of the phase transformation, respectively. \( H(\sigma) \) is the maximum transformation strain at a specific stress. Two major methods can influence the
value of the transformation strain: the sufficient material training and the external applied stress. In this paper, training history is the main factor we considered to affect the transformation strain, and the \( H(\sigma) \) is assumed to not change with the applied stress. For simplicity, \( H(\sigma) \) will be written simply as \( H \) temporarily. By determining the maximum transformation strain, the deformation performance of the material is decided.

According to Qidwai and Lagoudas, the following inequality derived from the Clausius-Planck inequality defines the transformation beginning and ending boundaries for all possible thermodynamic paths

\[
\sigma : \Lambda - \rho \frac{\partial G}{\partial \xi} \dot{\xi} = n \dot{\xi} \geq 0
\]  

(5)

where \( n \) is defined as the general thermodynamic force conjugated to \( \xi \). The explicit form of \( n \) is:

\[
n(\sigma, T, \xi) = \sigma : \Lambda + \frac{1}{2} \sigma : \Delta S : \sigma + \sigma
\]  

\[
: \Delta a(T - T_0) - \rho \Delta c \left( T - T_0 \right) - T \ln \left( \frac{T}{T_0} \right) + \rho \Delta s_0 T - \rho \Delta u_0 - \frac{\partial f}{\partial \xi}
\]  

(6)

Under the assumption that the martensitic phase transformation will take place whenever the thermodynamic force reaches a critical value, a transformation function can be introduced:

\[
\Phi = \begin{cases} 
\pi - Y & \text{for } \dot{\xi} > 0 \\
-\pi - Y & \text{for } \dot{\xi} < 0
\end{cases}
\]  

(7)

where \( Y \) is the parameter defined by different models, and can be expressed in terms of experimentally observable material parameters. The transformation function, \( \Phi \), satisfies the condition of \( \Phi = 0 \) during both forward and reverse phase transformations.

The constraints on the evolution of the martensitic volume fraction are expressed in terms of the so-called Kuhn-Tucker conditions, which are expressed as:

\[
\dot{\xi} \geq 0, \quad \Phi(\sigma, T, \xi) \leq 0, \quad \Phi \dot{\xi} = 0
\]

\[
\dot{\xi} \leq 0, \quad \Phi(\sigma, T, \xi) \leq 0, \quad \Phi \dot{\xi} = 0
\]  

(8)

2.2. Discretization of the maximum transformation strain

In available literatures, the \( H \) during the thermal cycles is always considered to be a constant in the material. This will cause the recovery strains to be uniform all over the structure, and the deformation at each point of the material is the same. It works well when the material is fully trained. When it comes to uneven training conditions, however, \( H \) will possibly exist in different values at different positions of the structure, and the existing model will lose the accuracy. For example, during the training process for the TWSME SMAs in this paper, the training temperature at different positions of the structure is not the same, and the trained material will exit different deformations at different positions.
In this paper, instead of using one uniform value for all material points, the $H$ is discretized to each element of the simulation model. In consequence, simulations with higher precision can be achieved. Taking a single-layer solid element mesh in finite element model for example, Figure 2 shows a schematic diagram for the discretization method. Instead of using one single value $H_0$ for all the elements, the modified model assigns different values of the transformation strain to each element of the model. As a result, the transformation strain in the material will vary from $H_{min}$ to $H_{max}$, and a more accurate simulation result can be achieved.

3. Experimental preparations

3.1. Structural design

The sealing mechanism of the designed SMA-based sealing plate of the aircraft door is shown in Figure 3. The SMAs are attached to one side of the traditional sealing plate that is made of aluminum. One end of the aluminum plate is fixed to the aircraft door. The trained SMA has the ability to be shortened when heated, and elongate under cooling. As a result, the aluminum sealing plate will deform when the applied temperature changes. The size of the aluminum plate studied in this paper is shown in Figure 4. The length of

![Figure 2. Schematic diagram for the discretization method.](image)

![Figure 3. Schematic of the deformation of SMA-based sealing plate in heating and cooling processes.](image)
this structure is 1024 mm and the width is 150 mm. The two ends of the top of the plate are rounded with a radius of 100 mm, and the thickness of the plate is 1.6 mm. The shaded part is the area that will be fixed to the aircraft door. To ensure that SMAs can provide sufficient driven forces during deformation, nine SMAs are spaced equidistant from one another on the plate, and the location of the SMAs is shown in Figure 5. The size of the SMAs used is also given, and the thickness of the SMAs is 1.8 mm. Once we determine the size of the sealing plate and the location of the SMAs, the specific material composition will be chosen. In addition, the material property tests and TWSME training procedure will be introduced in the following parts.

3.2. NiTi-based SMA alloys

Of the known SMA compositions, the NiTi alloy system exhibits strong SME, TWSME, and pseudoelastic behavior in various conditions, which makes them ideal materials for a wide range applications. Also, the transformation temperature range of the NiTi system is relatively near the room temperature, which makes the training process easily implemented in laboratories. Among the NiTi alloy systems, the near-equiatomic NiTi with a composition of Ni55Ti45 wt% (Ni50Ti50 at.%) is the most popular and prolific shape memory alloy. It has a high transformation strain level (5–8%) during the phase transition and a high transformation finish temperature (~100°C) of all NiTi compositions is recorded. The nickel-rich material shows excellent repeatability of the response (thermo-mechanical stability) after a relatively small number of training cycles. The increase in the composition of nickel decreases the transformation temperature, with transformation finish temperature becoming as low as −40°C for 51 at.% nickel. This variation in composition can change the ambient room temperature (25°C) characteristics from SME to pseudoelasticity.
Large deformation is required for the sealing plate; thus, a relatively large recovery strain is needed as a basic property for the choice of the specimens. For the work introduced in this paper, a shape memory alloy with a composition of Ni50Ti50 (at.%) is chosen for fabrication of the actuation parts of the sealing plate. Materials used in this research are purchased from Xi’an Saite Metal Materials Development Company, China.

3.3. Heat treatment and material parameter tests

The process of creating TWSMA usually starts with heat treating the raw material to memorize a certain shape as a hot shape. Materials are constrained first in the desired shape, then heated in an oven at an appropriate temperature for a period of time, followed by cooling steps. After the heat treatment procedure, a cold shape is induced in the alloy to bring a two-way shape memory effect into being through training [30,31].

In this work, materials are heated with protective gas at 500°C for 30 minutes and then cooled down in the oven. Four characteristic temperatures are associated with the transformation. The forward transformation from the austenitic phase to the martensitic phase begins at the martensitic start temperature ($M_s$) and completes at the martensitic finish temperature ($M_f$). Similarly, the inverse transformation from the martensitic phase to the austenitic phase initiates at the austenitic start temperature ($A_s$) and completes at the austenitic finish temperature ($A_f$). Differential Scanning Calorimeter (DSC) measurement is taken to determine these critical temperatures of some of the SMA specimens. Equipment from NETZSCH DSC 200 F3 is used in this paper. Small samples (~20 mg) are removed from the materials, and undergo the heat-treating treatment mentioned previously. The DSC result is shown in Figure 6. Peaks in heating and cooling processes are recorded, from which we can obtain the material’s zero-stress transformation temperatures easily.

Thermomechanical loading test is performed on a SUNS 5105 universal testing machine (UTM) loading frame equipped with an environmental chamber (WGDN-7350 L). Heat-treated specimens are uniaxially loaded at two different temperatures (20°C and 120°C) to calculate the elastic stiffnesses at parent phase and martensite. The results are shown in Figure 7. As a result, all the heat-treated material parameters measured are summarized in Table 1.

![Figure 6. DSC results of the heat-treated material (annealing temperature $T = 500°C$).](image)
3.4. Training methods

Without the training process, once after the material undergoes an austenitic transformation, no further strain recovery can occur if the SMA is not strained again. If the structure does not provide a way to strain the SMA again upon cooling, the usefulness of the SME is limited to one cycle [32]. The initial shape of the SMA at high temperature is already obtained by heat treatment, and the fundamental purpose of the training is to induce the low-temperature shape in the material so the SMA can remember two different shapes in two different phases.

One-time martensite deformation, reheat treatment, and thermomechanical cycling treatment are three main kinds of training methods for establishing TWSME. One-time martensite deformation is simple, but only a small two-way memory effect can be produced [33]. The reheat treatment method is a recently reported TWSMA training method involving a second heat treatment procedure on a previously heat-treated alloy specimen, but with it fixed in a different shape from that used in the first heat treatment and for a different heat treatment time [34]. During the reheat treatment, the samples have the risk to ‘forget’ the original shape set during the second heat treatment. In terms of the thermomechanical cycling treatment, specimens undergo repetition of transformation from austenite to preferentially oriented martensite or from deformed martensite to austenite. As a result, specimens with these repeated cycles can usually show better TWSME. In view of the above facts,
the one-time martensite deformation and the reheat treatment method are not pursued in this paper, and instead an appropriate variant of thermomechanical cycling method is chosen. The detailed training procedures are listed in Table 2. According to the measured material parameters, the material will be trained in a temperature range from 20 to 130°C in step 3. Loading process is carried out using the UTM. The maximum loading strain is about 6.5%. For each SMA samples, 20 training thermal cycles are applied.

4. Training and structural test

4.1. Training and deformation testing setup for SMA

To load the material and measure the temperature and strain fields over a material surface, a training and testing platform should be built. The experimental setup is shown in Figure 8, which includes two major systems: the temperature-strain acquisition system and the thermal mechanical loading system. The temperature-strain acquisition system comprises a FLIR A315 infrared camera and two VIC-3D cameras from Correlated Solutions, Inc. Infrared camera is applied to measure the temperature over the surface of the SMA samples. The VIC-3D system is a powerful turn-key solution for measuring and visualizing full-field three-dimensional strain field based on the principle of Digital Image Correlation (DIC). Random speckle pattern should be applied to the surface of the specimen before measuring. Using this method, strains are available at every point on the specimen’s surface. The thermal mechanical loading system consists of a SUNS 5105 universal testing machine and custom-designed cooling and heating equipments. UTM is used to stretch the specimen to a desired cold shape during training. Short cartridge heaters with stainless steel sheath are used to heat the specimens. For temperatures below room temperature, cooling is provided by the use of liquid nitrogen.

4.2. Temperature field of the SMA during training

During training, due to the two ends of the SMA being fixed to the UTM, inhomogeneous temperature distribution over the material can be observed by the thermal camera. The captured temperature graphic is shown in Figure 9(a). While the heating rods are installed around the middle part of the SMA, the temperature distribution presents a phenomenon as high in the middle and low in the two ends because of the heat conduction. Five sample points are picked to see their temperatures in a single thermal cycle of heating and cooling. The results are shown in Figure 9(b). From the figure, we can see that, at the
middle part of the SMA (point a), the material can be heated up to about 15°C. Meanwhile, at the two ends of the material (points d and e), the temperature can only reach up to 75°C during the heating process.

Figure 8. Training and deformation testing setup for SMA.

Figure 9. Temperature field during training: (a) temperature graphic captured by thermal camera; (b) temperature variations at five picked points.
To achieve a relatively high two-way shape memory recovery strain, the material needs to get a complete thermal cycle between $M_f$ and $A_f$. However, due to the low temperature at the two ends, these parts of the material cannot experience a full phase transformation. This inhomogeneous temperature field during training will lead to inhomogeneous deformation performances in the trained material.

4.3. Deformation test for the trained SMA

After training, the recovery strain at zero stress level of the trained material is measured by the DIC. At this time, to eliminate the influence of temperature during testing, the temperature over the material should be as even as possible. To achieve this, the heating rate is controlled at a relatively slow level. This ensures that most of the material can undergo a full phase transition during the deformation test, and the recovery strain measured is the maximum value. Taking one of the nine trained SMAs as an example, Figure 10(a) shows the maximum recovery strain over the trained SMA captured by DIC. The whole measuring process is started when the material is at ambient temperature (fully martensite phase). Material begins to contract when the temperature reaches $A_s$, as a result, the value of the strain is negative. During the phase transformation process of the trained material, a maximum recovery strain about 1.91% is observed. The recovery strain at the two ends of the SMA is smaller, and the minimum value of this value is only about 0.11%.

Corresponding to Figure 9(a), the temperature–strain curves of the five picked points are shown in Figure 10(b). The value of the recovery strain is set to positive after data processing. From the figure, we can see that, the distribution of the temperature is more uniform than that during the training process. When the temperature of point a reaches about 110°C, points d and e can also be heated up to about 90°C. Even though all the picked points are heated above the austenite transformation finish temperature $A_f$, their recovery strains are different. The maximum transformation strain values of points a, b, and c are 1.9%, 1.3%, and 0.5%, respectively. This phenomenon indicates that the

![Figure 10](image-url)
transformation strains at different points are not the same. To predict the thermomechanical response of the structure more precisely, a modified model should be established. From the results, we can also see that, compared to the untrained material, the critical temperatures of the SMA (especially the $M_f$ and $A_f$) are changed by training. The $M_f$ rises to about 30°C, and the $A_f$ rises to over 90°C after training. This may be attributed to the internal stress field formed by the dislocations during training. Consequently, the material parameters of the SMA should be modified during simulation.

4.4. Deformation test for the SMA-based sealing plate

The trained SMAs are attached to the aluminum plate, and a structural test is employed to examine the thermomechanical response of the SMA-based sealing plate after training the SMAs. Testing setup is shown in Figure 11. The trained SMAs and the aluminum plate are bolted together at two ends of the material. The distance between the two holes is 75 mm. Heating films are installed between the SMA and the aluminum plate, which can heat the trained SMA evenly by using a DC power supply. A laser displacement sensor is used to record the deflection of one end of the sealing plate. Temperature change at the surface of the trained SMA is recorded by a K-type thermocouple.

The temperature–deflection curves of the SMA-based sealing plate are shown in Figure 12. Due to the two ends at the top of the plate being rounded, only seven points are measured here. The number of the trained SMAs here corresponds to those shown in Figure 11, and the locations of the observation points are marked. The temperature range of this testing process is from 20°C to about 75°C. From the figure we can see that, by attaching the trained SMAs to the aluminum plate, the structure starts to deform at about 40°C, and the upper edge of this structure can achieve a maximum deflection of approximately 8 mm. In the cooling process, the trained SMAs start to elongate at about 50°C, and finish deforming at about 20°C. Hysteresis curves of the whole deformation process can be seen in the figure. However, curves at different observation points do not correlate

Figure 11. Structural testing setup for the SMA-based sealing plate.
with each other. For example, the maximum deflection of the seventh point is much smaller than the others. This can be explained by the different training effects for those SMAs, and errors during installation.

5. Modeling and simulations

For practical use in real-world applications, this newly designed sealing structure will be used under complex aerodynamic loads. As a result, it sets a higher request to the modeling and prediction of the deformation of the sealing plate before its being used in real aircraft door. Accurate structural modeling and performance prediction can not only reduce the early calculation cost but also effectively control the engineering quantity.

From the structural testing results for the seven measured points in the previous section, we can see that, the deformation performances at these points of the sealing structure are different. For practical use of the sealing plate, the deformation performance over the structure should be as uniform as possible. To achieve this, the SMAs installed at this structure should be controlled separately, and the models of the SMAs should be established individually. However, measuring for all the SMAs used in the sealing plate simultaneously is a tedious task. In this section, for simplicity, all the materials are considered to have the same training effect, and the personal errors during installation are neglected. Therefore, one selected trained SMA specimen is studied, and the experimental result of the trained SMA specimen (corresponding to the No. 4 SMA in Figure 11) is used to model all the SMAs installed in this structure. A modified modeling approach introduced in the previous section is used to simulate the deformation performance of the trained SMA and the SMA-based sealing plate.

Figure 12. Structural testing results for the SMA-based sealing plate.
5.1. Modeling for the trained SMA

The main reason for the different deformation performances over the material is the ununiform distribution of the training temperature. Therefore, before modeling the recovery strain field on the structure, the temperature field during the training process must be established. An SMA model is constructed using the general-purpose FE analysis software ABAQUS. Element type with eight-node linear heat transfer (DC3D8) is chosen to simulate the temperature over the SMA specimen. Due to the temperature of the heating rod is difficult to measure during training. In ABAQUS, a heat source is applied to the middle part of the SMA instead of the heating rods. The temperature of the heat source is 130°C, and the heating time is set to 10 s. The simulation results of the inhomogeneous temperature field are shown in Figure 13(a), and Figure 13(b) compares the simulation data with the experimental data. The y-axis in this figure is the value of the temperature, while the x-axis value is the length of the material. From the results, we get that the simulation data match well with the measured inhomogeneous temperature field. Then, the relation between the temperature and the maximum transformation strain should be established.

In this paper, we establish the relationship between the temperature and maximum transformation strain by using the following expression:

$$H = \frac{\Delta H}{\Delta T} (T - T_{max}) + H_{max}$$  \hspace{1cm} (9)

In this expression, $H$, $H_{max}$, $T$ and $T_{max}$ represent the transformation strain at a material point, the maximum transformation strain over the structure, the training temperature at a material point, and the maximum training temperature over the structure, respectively. $\frac{\Delta H}{\Delta T}$ represents the slope of the transformation strain, which changes with the training temperature. It can be written as: $\frac{\Delta H}{\Delta T} = \frac{H_{max} - H_{min}}{T_{max} - T_{min}}$. By using equation (9), we can get the inhomogeneous recovery

![Figure 13. The simulation results for the training temperature: (a) contour plot of the temperature; (b) comparison of the simulation and experimental data.](image)
strain field in ABAQUS. The thermomechanical responses of SMA during thermal cycles are investigated by the commercial FE program ABAQUS through a user material subroutine (UMAT). A flow chart about how the UMAT works is shown in Figure 14.

Figure 15(a) shows the contour plot of the recovery strain obtained by ABAQUS, and the comparison of the simulation and experimental data along the length of the specimen is shown in Figure 15(b). The five picked points corresponding to Figure 10 are also shown here. From the results, we can see that, different from the satisfactory results of the simulating for training temperature, the recovery strain data obtained by the FE model show noticeable discrepancy compared with the experimental data. The maximum recovery strain does not locate at the middle part of the specimen, and the simulated recovery strain at the upper part of the specimen does not match with the experimental one. This phenomenon can be explained by the uncertain position of the martensite phase transformation. During the uniaxial loading at the training process, the phase transformation can occur at any part of the material, and this will influence the full phase transition in the following thermal training cycles.

The comparison results between the experimental data and the simulated temperature–strain curves for five picked points are shown in Figure 16. The results for points a, c, and e are shown in Figure 16(a). Because these points belonging to the lower part of the SMA, in which the simulation data match well with the experimental data, the temperature–strain curve obtained by the modified model shows good accuracy. However, in Figure 16(b), the simulated results at point b and d have larger differences compared with the experimental result. Taking point b as an example, the simulated recovery strain is 1.7%, while the material only exits about 1.3% strain during the thermal cycle.

![Flow chart](image)

**Figure 14.** Calculation process of the SMA UMAT.
From these results, we can see that, in spite of the discrepancy between the experimental data and simulation, the modified model can still simulate the different recovery strains along the length of the material. As a result, this new modeling method can improve the precision of simulation to a certain extent. However, whether this will influence the overall deformation prediction of the sealing plate, a FE model of the whole structure is still needed. By attaching the trained SMAs to the aluminum plate, modeling of the SMA-based sealing structure will be given in the next section.

5.2. Modeling for the SMA-based sealing plate

Modeling of the SMA-based sealing plate is also achieved by ABAQUS. The element type of both the trained SMAs and aluminum plate is an eight-node linear brick, reduced integration (C3D8R). The mesh of the sealing structure can be seen in Figure 17(a). To
avoid the hourglass phenomenon in the finite element method and ensure the accuracy of the simulation, four layers of grids are applied at the thickness direction of both the SMAs and aluminum material. The mesh sensitivity analysis is an important issue that should be considered during the FE simulation. To decide the number of elements, several different sizes of elements are chosen to see differences between each simulation. The element sizes and simulated deflection of the sealing plate are summarized in Table 3. From the table, we can see that, with the increase of the element number, the simulated result of the deflection of the sealing plate tends to be stable. When the size of the element reaches to 1.5 mm, the simulation results should be considered as a correct one. In this condition, the number of one single SMA is about 4560.

During the simulation, the bottom part of the structure is fixed. The SMAs and the aluminum plate are tied together during the simulation. The temperature range of the thermal cycle is from 15°C to 80°C, which corresponds to the experimental conditions. Figure 17(b) shows the side view of the SMA-based sealing plate. Both the original and deformed shapes are drawn here. The legend represents the deflection along the U3 direction.

Figure 18 shows the simulated temperature–deflection curves of the SMA-based sealing plate. The gray, dashed curves in this figure are the experimental results that are the same with the results in Figure 12, where the solid ones are the simulated results. To

![Figure 17](image)

**Figure 17.** The FE simulation for the SMA-based sealing plate: (a) mesh dividing on the sealing structure; (b) comparison of the original and the simulated deformed configuration.

| Globe size of the element (mm) | Number of SMA elements | Simulated deflection (mm) |
|-------------------------------|------------------------|---------------------------|
| 6.0                           | 280                    | 0.985                     |
| 5.0                           | 408                    | 0.814                     |
| 4.0                           | 672                    | 0.860                     |
| 3.0                           | 1160                   | 0.828                     |
| 2.0                           | 2580                   | 0.804                     |
| 1.5                           | 4560                   | 0.803                     |
| 1.0                           | 10,320                 | 0.803                     |
Figure 18. The comparison between the simulation result and the experiment one for the SMA-based sealing structure.

compare the modified model discussed in this paper with the traditional one, the simulation results obtained by the traditional model with different transformation strain values are also shown here. Among the simulation results, the red lines represent the calculated results of the modified model, in which the transformation strain $H$ is discretized. The yellow and green lines are the results calculated by the traditional model, where
two values of $H$ are used. In the yellow curve, the transformation strain is chosen to be the maximum value measured by the DIC, that is, $H = H_{\text{max}} = 1.9\%$. While for the green one, the transformation strain is chosen to be the average value among the material, that is, $H = H_{\text{average}} = 1.0\%$.

Because all the SMAs installed at the sealing plate are given a same FE model, the simulated curves at different points of the structure are the same. It can be seen from the figure that the simulation results from the improved model are in good agreement with the experimental results, while the results obtained by the original model are either too big or too small. Although the way that using one same value of $H$ in traditional model can also actuate the sealing plate, choosing an appropriate value is hard during simulation. Instead of using one uniform value for the transformation strain, much more accurate result can be obtained by using the discretized form of this value. A maximum deflection of 8 mm of the deformed configuration can be seen from the results. By discretizing the transformation strain, and establishing the relationship with the inhomogeneous temperature field, a satisfactory simulation result is achieved. However, errors still exist in numerical analysis, and they may be caused by many factors. For instance, due to the connection type of the experimental structure and the simulated one is in a different way (bolts connection during the experiment and tied connection during simulation), the simulation results will be too large. Also, due to the discrepancy of the recovery strain, the simulated deflection of the SMA-based sealing structure is generally a little bit larger than the experimental measurement. To get a more precise results, a more detailed structural modeling should be established.
6. Discussion and conclusion

This work proposes and presents a complete procedure for designing, constructing, and modeling a SMA-based aircraft door sealing plate. By repeating the transformation cycle between the martensite phase and the austenite phase with the application of an external stress, the material is capable of shortening during heating and elongating while cooling. With these trained SMAs attached to the aluminum plate, the deformation of the main plate structure can be controlled by manipulating the temperature field. Additionally, considering the inhomogeneous temperature and recovery strain field that the SMA exhibits while being trained, an improved finite element model for the SMA is established to predict the deflection of the SMA-based sealing plate. This newly proposed method establishes a relationship between the temperature and the maximum transformation strain in the SMA, which can model the inhomogeneous recovery strain field more efficiently and accurately. By comparing with the experimental data, the simulation results show that the proposed approach can achieve accurate predictions of the thermal response of the SMA-based sealing plate.

The improved modeling method establishes a relationship between the training conditions and the parameters in the trained materials, which makes the simulation more accurate while the complex training conditions must be considered. For simplicity purpose, one same SMA model is used to simulate the deformation performances of all the trained materials. It works well only when the overall deformation performance of the structure is needed. When it comes to the condition that the deformation at each point of the sealing plate should be studied or controlled in real applications, it cannot reflect the differences between the different positions of the sealing structure, and this modeling approach will be inadequate. As a result, the FE model of each trained SMA should be established individually. This can make the model more fit in application than the existing one in this study, and should be studied in the future works.

This proposed active sealing plate provides a new idea to improve the poor sealing performance of the traditional sealing plate, and reduce the friction between the door and body of the aircraft when the door needs to be opened. However, some practical problems still need to be solved in the future works. The bolt connection between the SMAs and the aluminum plate will cause some problems during the long-term use of the sealing structure. For example, the bolt looseness will influence the deformation performance, and the repeatable deformation certainly will lead to the crack initiation and propagation at the plate holes. For long-term use of this SMA-based sealing structure, more reliable installation method should be considered.

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ORCID

Chen Zhang http://orcid.org/0000-0001-7839-4570

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