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STUDY ON CREEP PERFORMANCE OF LAUNCH CANISTER UNDER LONG-TERM STORAGE

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ABSTRACT

In this paper, the creep performance of multi-barrel rocket launch canister under long-term stacking storage is studied. Based on the Bailey-Norton model, the creep model of the frame material of a launch canister was established. Constant stress tensile creep test at different stress levels under room temperature was carried out on the frame materials of the launch canister and the creep model parameters were obtained by test data fitting. The three-dimensional finite element model of the launch canister was established in the ABAQUS software environment and the creep deformation of the launch canister after long-term stacking storage was studied. The results indicated that the bottom layer of the launch canister frame presented an extended residual deformation when the stacking storage solution with original support pad was used. Therefore a position adjustment program of the support pad was put forward and the residual deformation of the launch canister frame after long-term storage could be significantly reduced, thus the performance requirements for the launch canister are guaranteed.

Keywords: long-term storage; creep at room temperature; residual deformation; finite-element analysis.

1 INTRODUCTION

The launch canister technology is widely applied in improving the loading speed of multi-barrel rocket weapons, shorten the launch preparation time, improve the emergency response capability and achieve the "multi-skill and multi-purpose" target (Yu and Li 2012). A rocket weapon launch canister is illustrated in Figure 1 and mainly consists of the metallic frame, the non-metallic directional device and the rocket components. The carrier of rocket storage, transportation and launch has a direct impact on the operational properties of rocket weapons. Conforming to the design requirements, the launch canister for three-layer stacking storage in the warehouse is appropriate for use within 10 to 15 years. In the storage process, the launch canister frame is subject to the gravity load and therefore, occurring slow creep deformation, resulting in forced deformation of the directional device. In particular, the bottom launch canister not only withstands the gravity of the various parts of the launch canister itself, but also withstands the gravity of the upper two launch canisters. Thus, the deformation of the frame of bottom launch canister will be even greater. If the creep deformation of the launch canister frame is too large during the storage process, the parallelism of the directional device will be inefficient, which will affect the firing accuracy of the rocket weapon and even cause failure of the attack jeopardizing the safety of our own combatants.

In the warehouse environment, humidity, temperature and other environmental factors may affect the launch canister condition. According to GJB2770-1996, the long-term storage temperature of the launch canister should be $-5 \sim +25^{\circ}\text{C}$ and the relative humidity should be 40% to 70%. Since the environment is relatively mild and the launch canister has been treated for rust prevention, this paper assumed that the impact of the warehouse's temperature and humidity environmental conditions on the launch canister could be ignored. Therefore, the creep deformation of the launch canister caused by the gravity load was mainly studied. No research has been conducted in this specific, or a relevant field until now.

Creep reflects the time effect on mechanical properties of materials. Over the past few years, many scholars have conducted in-depth studies on the creep behavior of metal materials at room

temperature (Zhao et al. 2008; Zhang et al. 2016; Gong et al. 2017). Liu et al. (2001) studied the creep behavior of high strength steels at room temperature. The results indicated that high strength steels did not exhibit creep failure when the stress was lower than the yield limit of the material at room temperature. The study on tensile creep of pure iron exhibits that the effect of creep damage can be neglected when the stress is below 90% of the yield stress (Yamada et al 2004). Due to the high requirements of creep test in terms of time and cost, many scholars use the finite element method to study the creep behavior of the structure. Becker et al. (2002) studied the continuous damage mechanism of high temperature creep by numerical simulation, based on finite element method, while uniaxial, biaxial and multiaxial stress state tests were carried out. The experimental results are in accordance to the results of the finite element simulation. Chen et al. (2003) analyzed the allowable strain of 0.5Cr0.5Mo0.25V steel pipe at 530°C with commercial finite element software ABAQUS and performed the creep design of the T-joint. Colombo et al. (1996) used the ABAQUS software for creep damage analysis of the boiler tee joint and the simulation results are consistent with the test results. Mondali et al. (2005) used the finite element method to predict the creep behavior at the second stage of the A16061/SiC metal matrix composites. The finite element method was used to simulate the microscopic degradation of AISI304 steel, to predict its fatigue life by Tai et al. (2000). According to the results of uniaxial and multi-axial creep tests of P91 steel, Liu et al. (2006a 2009b,c) conducted the simulation of the whole creep process of P91 steel under uniaxial and multi-axial stress states, by using the mathematical damage-hardening creep model of P91 steel at high temperature. The results exhibited that there is a complex relationship among creep strain, creep strain rate, stress, time and temperature. Additionally, the creep mechanism of the material is complicated, so it is extremely difficult to get a unified creep model. To this end, many researchers have proposed some assumptions, using minimal variables to reflect the main factors of creep effect in the establishment of creep models. The most typical of them is the Bailey-Norton model, whose application is more convenient since it can accurately reflect the metal creep material at the first and second stage and the material constants in the model can be obtained by creep tensile test.

This paper studies the creep deformation of metallic launch canister under long - term stacking

storage in the warehouse environment. Based on the Bailey-Norton model, the creep model of the frame material of the launch canister was established. The tensile creep tests were carried out at different stress levels on standard specimens made of the frame material at room temperature and the creep model parameters were obtained by test data fitting. According to the above, the finite element analysis model of the launch canister under stacking storage is established, to conduct calculation and analysis for the creep performance of the launch canister under long-term storage. Based on the results of creep deformation analysis, the adjustment program of the position of the stacking support pad is put forward, aiming to improve the mechanical properties of the launch canister under long-term storage.

2 CREEP MODEL

To study the creep performance of the launch canister under long-term storage, it is of great essence to establish an appropriate theoretical model able to describe the creep behavior of the launch canister material. In the uniaxial stress state, the creep strain is related to flow stress (σ), time (t) and temperature (T). The typical uniaxial creep constitutive equation can be expressed as:

$$\varepsilon_{cr} = f_1(\sigma) f_2(t) f_3(T) \quad (1)$$

The relationship between creep strain, time and flow stress can be obtained from the Bailey-Norton model (Harry 1980):

$$f_1(\sigma) f_2(t) = A_1 \sigma^n t^m \quad (2)$$

In addition, creep can be considered a thermal activation process and is related to activation energy. Therefore, the relationship between creep strain and temperature can be expressed as:

$$f_3(T) = A_2 e^{-Q/RT} \quad (3)$$

Substituting Eqs. (2–3) into Eq. (1), the relationship among creep strain of the material, time, temperature and stress is obtained as:

$$\varepsilon_{cr} = B \sigma^n t^m e^{-Q/RT} \quad (4)$$

Where R is universal gas constant, T represents absolute temperature, and Q equals thermal

activation energy. A_1 , A_2 , B , m and n are all constants related to temperature. n is larger than 1 and m is ordinary a fractional number.

To get the derivative of Eq. (4) with respect to time, the creep strain rate can be expressed as:

$$\dot{\varepsilon}_{cr} = Bm\sigma^n t^{m-1} e^{-Q/RT} \quad (5)$$

or

$$\dot{\varepsilon}_{cr} = A\sigma^p t^q e^{-\theta/T} \quad (6)$$

Comparing Eq. (5) and (6), it can be obtained that: $A=Bm$, $p=n$, $q=m-1$, $\theta=\frac{Q}{R}$, where $p > 1$, $-1 < q < 0$. All the parameters in the model are related to the material and should be obtained by corresponding creep test.

The above model is a creep constitutive model of material under uniaxial stress, which needs to be extended to multi-axial stress state. Since the metal frame material of the launch canister is an isotropic and plastically incompressible material, the creep strain rate in the multiaxial stress state is determined by the Mises equivalent stress and the associated flow rule:

$$\dot{\varepsilon}_{ij}^{cr} = \dot{\varepsilon}_{cr} \frac{\partial F(\sigma_{ij})}{\partial \sigma_{ij}} \quad (7)$$

In which $F(\sigma_{ij}) = \sigma_{eq} - \sigma_s$, σ_{eq} is equivalent stress, σ_s is yield stress; $\dot{\varepsilon}_{ij}^{cr}$ equals the equivalent creep strain rate component in multi-axial stress state; $\dot{\varepsilon}_{cr}$ depicts the uniaxial equivalent creep strain rate which was obtained by Eq. (6).

The total strain of the model includes elastic strain and creep strain, i.e. $\varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^{cr}$. The constitutive model in multi-axial stress state then is:

$$\dot{\sigma}_{ij} = D_{ijkl} \dot{\varepsilon}_{kl}^e = D_{ijkl} (\dot{\varepsilon}_{kl} - \dot{\varepsilon}_{kl}^{cr}) \quad (8)$$

Where Eq. (8) is the basis for derivation of finite-element equations and D_{ijkl} equals the elastic stiffness tensor. $\dot{\varepsilon}_{kl}$, $\dot{\varepsilon}_{kl}^e$ and $\dot{\varepsilon}_{kl}^{cr}$ denotes the total strain rate, elastic strain rate and equivalent creep

strain rate, respectively.

3 CREEP TEST

3.1 Material and method

To obtain the parameters related to the material in the creep model, the tensile creep test of the frame material (16Mn) of the launch canister at different stress levels was carried out. The material used for the test was provided by the manufacturer of the launch canister. 16Mn is a low alloy structural steel and has good comprehensive mechanical properties, process performance, welding performance and low temperature impact toughness (Du 2007). The chemical composition and mechanical properties at room temperature are presented in Table 1 and Table 2.

Circular cross-section standard creep specimens were prepared, according to the Chinese national standard GB/T2039-2012. The specimen dimensions and shape are illustrated in Figure 2 (unit: mm).

Tensile creep test was completed by using the TFW-50S computer controlled, universal electronic material test machine. The maximum load of the test machine was 50kN. The deformation was measured by using rod extensometer and the maximum stroke of the rod was 150 mm. The test environment temperature was 25 °C and the relative humidity equaled 60%. In this paper, six stress levels (30%, 40%, 50%, 60%, 70%, 80% of the yield stress) were selected, for constant tensile creep tests. During the test, the load began to rise slowly from 0, to reach within 10 min the test requirements of the load. Then the creep test lasted 200 hours and the deformation of the specimen was recorded.

3.2 Test results and analysis

The tensile creep test results, at different stress levels, are presented in Figure 3. It was pronounced that the creep curve consists of two stages: transient creep and steady-state creep. In the transient creep stage, the creep strain rate was high and the creep strain rate gradually decreased by increasing the test time. In the steady-state creep stage, the creep strain rate was low and the creep strain rate remains overall unchanged, throughout the steady-state creep stage. From the creep test data, it was signified that the creep strain is related to the stress level applied on the specimen. The

greater the stress, the greater the creep strain. However, the relationship between creep strain and stress is nonlinear.

Using the established creep constitutive model, the tensile creep test data at 25 °C and different stress levels were fitted to obtain the parameters in the creep model of 16Mn material: $A=2.6322E-14$, $p = 4.52775$, $q = -0.91435$, $\theta=571$.

3.3 Model verification

To validate the accuracy of the built model, three stress levels were selected to simulate the creep test. The simulation curve and the test curve are compared as shown in Figure 4. As can be seen from Figure 4, the simulation results are consistent with the test results especially at low stress levels. Therefore, the built model and its parameters are suitable for analyzing the creep deformation of the launch canister.

4 STUDY ON CREEP OF THE LAUNCH CANISTER

4.1 Structure of the launch canister and finite-element model

The structure of the launch canister is illustrated in Figure 5. Each launch canister has 20 single-tube sealed cylindrical directional devices and 20 rocket projectiles. The launch canister frame consists of the front splint, the two middle splints and the rear splint, and is welded together with long steel angles, flat steels and inclined ribs. Among them, the long steel angle is divided into four segments by the splints, expressed as segment a, b, c and d, in Figure 5. Each splint has 20 round holes for mounting the directional devices, fixing them to the launch canister frame and preventing them from moving back and forth. When installed, directional devices should be parallel to each other, to meet the requirements of parallelism indicators and ensure the firing dispersion.

The launch canister adopts a three-layer stacking mode for storage while the bottom launch canister was taken as the object of study. The weight of the above two launch canisters was reduced to a uniform load, applied to the corresponding positions of the canister frame and fixed constraints were added to the bottom of the pad as boundary conditions. The structured meshing technique was used to separate the launch canister into 8-node hexahedral elements. The creep deformation in the

long-term stacking storage was calculated by using the creep model established as above and the solving method described in section 4.2. The two years creep deformation of the launch canister was calculated using element sizes 5, 8, 10 and 15mm, respectively. The results show convergence when the element size is less than 8mm. Therefore, we used the element size of 8 mm to calculate the creep deformation of 10 and 15 years. The finite element model of the launch canister is illustrated in Figure 6. During the calculation, three analysis steps were set, namely static analysis step, creep analysis step and unloading analysis step. The static analysis step aimed to calculate the gravity and the pressure load from the upper launch canisters, while the unloading analysis step was used to simulate the residual stress and deformation, after removing the upper launch canisters.

4.2 Solving of creep

In the process of finite element solution, the structural stiffness fluctuated depending on different load stages, due to the nonlinear stress-strain relationship of multi-linearity, plasticity and super-elasticity. The nonlinearity in creep was different from that. The time, the temperature, the rate, the stress-related function and especially the "time" parameter, was of great significance in the creep analysis. Additionally, due to the longer time range of creep analysis, inertial effect was ordinary not considered (Huang and Guo 2014).

Eq. (8) is a constitutive model of the differential form and should be integrated with time for solving. Under the condition of small deformation, the equilibrium equation of the element is:

$$\int_V [B]^T \{\sigma\} dV + \{f\}^e = 0 \quad (9)$$

Where $[B]$ is the strain matrix, $\{f\}^e$ is the nodal force vector of an element, $\{\sigma\}$ is the stress vector. $\{\sigma\} = [\sigma_{11} \quad \sigma_{22} \quad \sigma_{33} \quad \sigma_{12} \quad \sigma_{13} \quad \sigma_{23}]^T$. Writing the Eq. (9) as a differential form:

$$\int_V [B]^T \{\dot{\sigma}\} dV + \{\dot{f}\}^e = 0 \quad (10)$$

Substituting Eq. (8) into Eq. (10) leads to

$$\int_V [B]^T [D][B] \{\dot{\sigma}\}^e dV = \{\dot{f}\}^e + \int_V [B]^T [D][B] \{\dot{\epsilon}^{cr}\}^e dV \quad (11)$$

Thus,

$$[K]^e \{\dot{\delta}\}^e = \{\dot{f}\}^e + \int_V [B]^T [D] [B] \{\dot{\epsilon}^{cr}\}^e dV$$

Where $\{\dot{\delta}\}^e$ is the differential form of the node displacement vector. $[K]^e$ is elastic stiffness matrix of the element, $[K]^e = \int_V [B]^T [D] [B] dV$.

If at the moment t nodal displacement, external force f and creep strain rate are known, the equilibrium equation can be integrated within the time increment Δt to obtain the displacement increment and the strain increment.

$$[K] \{\Delta \delta\} = \{\Delta f\} + \int_V [B]^T [D] [B] \{\Delta \epsilon^{cr}\}^e dV \quad (12)$$

Where $\{\Delta \delta\}$, $\{\Delta f\}$ and $\{\Delta \epsilon^{cr}\}^e$ denotes nodal displacement increment, nodal force increment and creep strain increment, respectively.

The method uses the explicit Euler forward integration method to solve the creep strain and the creep strain rate used in each time incremental step was the same as the strain rate at the beginning of the incremental step. Therefore, it requires a minor time incremental step to reduce the error. In this paper, when creep was calculated, the incremental step was set at 240h. Compared to the 15-year creep time range, the incremental step size is small enough to ensure the accuracy of the calculation.

4.3 Results and analysis

Authors calculated the creep behavior of the launch canister stored for 10 years and 15 years, respectively. Figure 7 illustrates the creep strain curve at the position with maximum deformation in the launch canister. It was pronounced that the creep curve includes both transient creep and steady-state creep. The transient creep stage was between 0 ~ 13140 h, where the creep rate was high in the range of 0 ~ 4380 h after the beginning of creep. Then, within 4380 ~ 13140 h, the creep rate gradually declined and finally entered steady state creep stage. In the steady-state creep stage, the creep rate of the launch canister was low and remained significantly constant.

Figure 8 presents the residual deformation of the launch canister after 10 and 15 years of storage,

due to creep. After 10 years, the maximum value of residual deformation was 4.29mm. After 15 years, the maximum value of residual deformation was 4.67mm. The difference is insignificant, since the launch canister has entered the steady-state creep stage after storage for one and half years. Since then, the creep rate is minor and creep deformation tends to be stable. This is consistent to the characteristics exhibited in the steady-state stage (illustrated in Figure 3) of the creep strain curve obtained from the test. From the residual deformation contour, it can be concluded that the maximum deformation position in the storage process appears in the middle of segment “a”, of the steel angle. This occurs since during the long-term stacking storage process, the gravity load of the upper launch canisters was mainly supported by segments “a” and “d”, while the support effect of the middle two splints was weakened. In addition, due to the large spacing between the front and the middle splints, the deflection deformation of segment “a”, was significantly greater than that of segment “d”.

Figure 9 illustrates the residual stress distribution of the launch canister after storage. The residual stress appears to be almost stable after 10 years and 15 years of storage. Therefore, the residual deformation of the launch canister after two different storage times is close (Figure 8). In addition, the stress throughout the whole storage process can be analyzed, to find that at the beginning of creep, the stress of the launch canister was mainly concentrated on the segment “a” of the steel angles, while the stress of the middle two splints and stress of the inclined ribs on both sides were small. In the creep process, the stress distribution on the launch canister was uniform and the stress decreased primarily with the increase of the storage time and then tended to be stable, which is consistent with the change of the creep strain rate.

In-depth analysis of the results reveals that since the left support pad was located at the end, away from the middle splints, the loads applied on the middle splints and the inclined ribs on both sides are small and the structural strengthening effect weakens. The maximum residual bending deformation of the launch canister frame reaches 4.67mm after 15 years of stacking storage and the parallelism performance of the non-metallic directional tube will reduce, due to the forced deformation, which will affect the firing accuracy. In addition, since the studied creep model ignored the effects of temperature and humidity factors, in reality, the wet and thermal environment will promote creep. As

a result, the residual deformation of the launch canister will be slightly larger than the calculated value after 15 years of stacking storage. Thus, the current use of stacking storage method at two ends, will lead to extent residual deformation of the launch canister after a long time. After long-term storage, the accuracy of firing may not be ensured and therefore, the stacking program should be improved.

4.4 Improvement of stacking program

In view of the above problems of the stacking program, this paper proposes a stacking program that moves the left support pad to the right (middle) by a distance to the middle splints (as illustrated in Figure 10) to make full use of the support effects of inclined ribs and middle splints to reduce creep deformation.

The finite element analysis of the launch canister after the adjustment of the pad position establishes the residual deformation contour after storage of 10 years and 15 years, as presented in Figure 11. The residual deformation of the launch canister after long-term storage was 0.81 mm and 0.86 mm, respectively, according to expectations. Thus, the creep deformation significantly reduced after changing the position of the pad. In the steady-state creep stage, the residual deformation of the launch canister after storage of different times was very small, which is consistent with the original program and the results indicated by the material test. The difference was that the maximum deformation position of the launch canister changed, appearing this time in the flat steel on the right side of the launch canister. Compared with the overall size of the launch canister, the deformation of the improved stacking program can be ignored and does not affect the parallelism between the directional devices.

The residual stress of the launch canister frame after adjusting the pad position, is illustrated in Figure 12. It was demonstrated that the stress of the middle splints and the inclined ribs was high and they were subjected to more load. The residual stress after storage of different times indicates the same rule as the original program. In addition, the residual stress of the launch canister frame with different stacking programs is compared and is found to be significantly reduced after the adjustment of the pad position. The residual stress and deformation of the launch canister after long-term storage

were obviously reduced after the stacking program was improved.

Based on the analysis results, the adjustment of the support pad position for the launch canister in stacking storage was recommended to the relevant units, who adopted the recommendation. The program has been applied in the warehouse storage and satisfying results were achieved.

5 CONCLUSION

The deformation of the launch canister in long-term storage process is mainly caused by creep. In this paper, the material creep model parameters were obtained by constant tensile creep tests of the frame material (16Mn) at different stress levels at room temperature. In the ABAQUS software environment, the three-dimensional finite element model of the launch canister was established and the creep behavior of the launch canister in the long-term stacking storage was investigated. The main conclusions are as follows:

- (a) At room temperature, stress constitutes an important factor affecting creep rate and the relationship between stress and creep strain is non-linear.
- (b) Using the original stacking program, the maximum residual deformation of the launch canister frame after 10 years and 15 years of storage reached 4.29mm and 4.67mm, which are a large deformation. The main reason was that the distance between the front splint, the left support pad and the middle splint was large and the gravity of the upper launch canisters was mainly carried by segment “a” of the steel angles, which makes the frame present large residual deformation. After the stacking program was improved, the gravity load of the upper launch canisters was transferred at the middle splints and the inclined ribs. The maximum residual deformation of the frame is 0.81mm and 0.86mm after 10 years and 15 years of stacking storage. Compared with the original program, the residual deformation was significantly reduced, thus the performance requirements for parallelism of directional devices in the launch canister are ensured.
- (c) After storage for 10 years and 15 years, the residual deformation difference of the launch canister frame was very small, due to low creep rate and stable creep deformation in the steady-state creep stage.

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Table 1. Chemical composition of 16Mn low alloy structural steel

Composition	C	Mn	Si	P	S	V
% WT	0.20	1.6	0.55	0.04	0.04	0.02

Table 2. Mechanical properties of 16Mn low alloy structural steel (25°C)

Poisson ratio/ ν	Yield strength/Mpa	Tensile strength/Mpa	Elastic modulus/Gpa	Elongation after rupture/%
0.3	345	582	219.45	21

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Figure caption list

Fig.1. Rocket weapon launch canister

Fig.2. Schematic of circular cross-section creep specimen

Fig.3. Creep curves of 16Mn at different stress levels

Fig.4. Comparison between experimental curves and simulation curves

Fig.5. Structure of the launch canister and position of the support pad; 1—Front splint; 2—Middel splint; 3—Steel angle; 4—Inclined rib; 5—Directional device; 6—Rear splint; 7—Support pad; 8—Flat steel

Fig.6. Finite-element model of the launch canister

Fig.7. Creep strain curve

Fig.8. Residual deformation contour of the launch canister: (a) Storage for 10 years, (b) Storage for 15 years

Fig.9. Residual stress contour of the launch canister: (a) Storage for 10 years, (b) Storage for 15 years

Fig.10. Adjustment program for the position of support pad

Fig.11. Residual deformation contour of the launch canister after changing the position of support pad: (a) Storage for 10 years, (b) Storage for 15 years.

Fig.12. Residual stress contour of the launch canister after changing the position of support pad: (a) Storage for 10 years, (b) Storage for 15 years

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