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Relaxation Characteristics and Modeling of Cargo Package Binding in Cargo Spacecraft

Hailin Dai¹, Weifeng Yuan¹, Ruizhao Du¹ and Dong Li¹

¹Beijing Institute of Spacecraft Environment Engineering, Beijing 100094
hailind@sina.com

Abstract. At the site of cargo package binding in cargo spacecraft, the structure of the binding belt will produce plastic deformation, slip and fracture over time, which will cause tension relaxation and it’s hard to predict the value of tension at steady state. A cargo packing test platform was established. Through which the tension data of sufficient time test are obtained by the serial tension sensor in the binding belt. Based on the Analysis of Therbligs a standard cargo packing operation procedure was developed. And based on the least square method, the tension data of the binding belt are fitted with quartic polynomial and the tension relaxation model is established. Test results show that the calculated values of the binding tension are in good agreement with the measured values, most errors are less than 5%, so that it can be used for predicting that tension relaxation of the binding belt of cargo package.

1. Introduction
The cargo spacecraft is one of the main research models of space laboratory and space station of China’s manned space engineering, it’s the essential cargo support aircraft to implement the third step in the long-term manned space station. The vast majority of the goods are packed in flexible soft package when transporting the space station supplies. In order to prevent the cargo package from slipping off during launch and flight, the binding belt is usually used for binding. The binding belt is the structure of thick cotton silk ribbon. In addition to the elastic deformation caused by tension, there is also the tension relaxation caused by the time slip and fracture of the structure. On one hand, it is difficult to predict the tension value when the tension relaxation reaches steady state by theoretical model, i.e. the tie-down tension eventually loaded on the package; On the other hand, the binding belt is a shaped product and does not allow additional sensors to monitor the tension of the binding belt over time. At present, most of the research focuses on the tensile fracture performance, safety and comfort of seat belts for automobile and aircraft passengers, as well as the tension measurement, damage mechanism and detection of wire rope and distribution of stress and strain. However, there is little research on the relaxation characteristics of binding package and binding belts, thus there is no similar research experience and model for reference [1][2][3][4][5][6].

According to the condition of cargo package binding, a cargo package binding test platform was built, and the binding belt tension was measured by series tension sensors at the end of the binding belt. Based on the Analysis of Therbligs, a set of standard binding process is proposed to improve the reproducibility of the binding reproducibility. Based on the principle of least square method, an appropriate polynomial is selected to fit the tension data of the binding belt by FFT filtering, and then a relaxation model of the binding belt is established. The verification shows that the calculated values are in good agreement with the measured values, and majority of the error is less than 5 %. Therefore, applying the relaxation model to the packing binding can predict the tension of the binding band after
long-term relaxation and stability, and has important engineering application value for improving the packing binding quality and reliability.

2. Cargo package, binding belts and fillings

In binding test, the package used is a double package (length × width × height 470 mm × 360 mm × 285 mm, maximum wall thickness 10 mm, maximum weight 0.9 kg, loading capacity 20 kg). The binding belt is made of grass green thick cotton ribbon, and the simulation package base is made of aluminum alloy, as shown in Figure 1.

![Figure 1. Test package](image.png)

Considering that there are not only instruments and equipment in the package, but also soft food and clothing and so on, the flexible paper filler with moderate hardness was selected. The filling rate was 95% that a proper amount of space was left inside, therefore the package could be easily closed.

3. Construction of test platform

3.1 Test platform

According to the operation and actual working conditions of the cargo package binding on the cargo spacecraft assembly site, a binding test platform is established, as shown in Figure 2. In order to realize the long-term measurement of the tension of the binding belt, the tension sensor is connected in series between the end of the binding belt and the base of the simulation package through an adapter buckle, so that the tension of the binding belt can be measured and recorded for a sufficient time through a tension measuring instrument.

![Figure 2. Experiment platform for package binding](image.png)

The tension sensor F2808 is developed from Tecsis company, and is matched with Tecsis B6480 hand-held tension tester and tension measurement software. After binding, four tension measurements
are synchronously started, and a series of corresponding binding belt tension data can be obtained by software, so that the relaxation process of the binding belt tension can be studied through the data.

3.2. Analysis of Therbligs

The initial tension, binding sequence, and binding process of the binding belt are important factors that affect the relaxation characteristics of the binding belt. In order to reduce the influence of the binding operation on the accuracy of the relaxation model and improve the reproducibility of the relaxation model, Analysis of Therbligs was used to analyze the binding process of the cargo package, and the standard binding process of the binding belt was established. Analysis of Therbligs was founded by American engineer Frank Girberth, whose core idea is to establish a standardized operation process through the analysis and reasonable adjustment of workers' action factors, so as to reduce labor intensity and shorten operation time, thus improving the overall efficiency of the operation[7][8][9][10][11][12]. Therefore, applying Analysis of Therbligs to study the binding process of the cargo package, establishing a standardized operation flow, determining key steps key actions and quantifying can enhance the reproducibility of the binding operation of the cargo package, thereby improving the accuracy of the binding belt tension relaxation model.

Analysis of Therbligs is used to analyze and observe the operation of packing binding. Eight basic actions (Transport Empty, Transport Loaded, grasp, assemble, use, Disassemble, Release Load, Inspect) are selected to describe the whole binding process. On this basis, the operation process is divided into six phases: pre-tightening, pre-loading, step loading, applying safety buckle tension, ratchet unloading and removing ratchet wheel, as shown in Figure 3.

![Figure 3. Loading process of binding belts](image)

The six-phase Analysis of Therbligs table is shown in Table 1.

| basic actions    | phases                      |
|------------------|-----------------------------|
|                  | pre-tightening | pre-loading | step loading | applying safety buckle tension | ratchet unloading | removing ratchet wheel |
| Transport Empty  | √              | √           | √            | √                                | √               | √                        |
| Transport Loaded | √              | √           | ×            | √                                | ×               | ×                        |
| Grasp            | √              | √           | ×            | √                                | √               | ×                        |
| Assemble         | √              | √           | ×            | √                                | ×               | ×                        |
| Use            | √ | × | √ | × | × | × |
|---------------|---|---|---|---|---|---|
| Disassemble   | × | × | × | × | × | √ |
| Release Load  | √ | √ | √ | √ | √ | √ |
| Inspect       | × | √ | √ | √ | × | × |

a: √ indicates the actions required.
b: × indicates the actions not required.

Through the analysis of each phase, the standard binding process of six-stage binding belt is formulated:

1) Pre-tightening: tighten the belt safety buckle and the belt, the key action is to make it fit with the package;
2) Pre-loading: the ratchet loading device is assembled through safety buckles at two ends of the binding belt, and pre-loading is carried out through the ratchet. The key action is to preload the ratchet force $F_{10}$ to 70 N (the ratchet force is measured by a tension sensor connected in series in the ratchet loading device, as shown in Figure 2), and straighten the belt to make it tightly close to the package;
3) Step loading: pulling the ratchet wheel to load the binding belt, limiting that only one ratchet tooth can be rotated at a time, then straightening the binding belt to make the binding belt fit with the cargo package; Repeat until the ratchet force reaches the predetermined value.
4) Applying safety buckle tension: hold the binding belt lead and tighten slowly while observing whether the ratchet force $F_{11}$ falls to the specified range ($F_{11}$), and then stop.
5) Ratchet unloading: press the ratchet loading device buckle to unload the ratchet force.
6) Remove the ratchet: remove the ratchet hook installed in the belt buckle and remove the ratchet loading device.

3.3. Binding order
According to the working conditions, in order to facilitate the operation, four belts are bound in turn according to the order of D2, D4, D1, D3.

4. Data analysis and modeling

4.1. Analysis of modeling method
It is difficult to find a mature mathematical model to guide due to the elastic deformation, plastic deformation and structural slip, fracture, initial tension and binding state of the binding belt. Therefore, it is an easy and effective method to obtain the tension relaxation model of the binding belt by testing and measuring the data of the tension variation for sufficient time and then, fitting the data with polynomial.

Firstly, bind four belts according to the standard binding process and the binding sequence. The initial binding belt tension $F_{31}$ can be obtained by measurement; Then, the tension measurements of the four belts are synchronously started, and a set of data is collected every second for a total of 16 hours continuously; Repeat the above test three times, and record the data as test 1, test 2 and test 3, respectively; Finally, based on the principle of least square method, polynomial is used to fit the tension relaxation model.

4.2. Data filtering
Before fitting the data, in order to remove the noise, the FFT filtering method is adopted to smooth the acquired binding tension data. The effect of FFT filtering is shown in Figure 4.
4.3. Tension relaxation model

Because the value of the tension is nonlinear, the relaxation model is established by polynomial fitting method based on least square method[13][14][15].

4.3.1. Determine the number of polynomial fits.

The tension data of the binding belt D2 are fitted by quadratic, cubic, quartic and quintic polynomials, respectively, and the results are shown in Figure 5.

Figure 4. effect of FFT filtering

Figure 5. comparation of four polynomials
Compared with the four fitting results, it can be seen that the quadratic and cubic polynomial fitting is different from the measured values in the early stage, and the quadratic polynomial fitting curve is increasing at the end time, which is inconsistent with the relaxation of the binding belt to reduce the tension. The tail of the cubic fitting curve shows a divergence trend at the end time, and the error with the measured values is large. Compared with the quadratic, cubic, the fitting curve of the quartic polynomial is basically coincident with the measured values point, and the tail of the curve is consistent with the trend of the measured values, which is a curve with higher fitting degree. The fitting degree of quintic polynomials fitting curve is slightly higher than that of the quartic polynomials fitting curve, but considering the complexity of fitting and the accuracy requirement of the relaxation model, the quartic polynomials is finally selected to fit the binding belt tension relaxation model.

4.3.2. Numerical fitting of tension of binding belt.
The data of the four binding belts in test 1 was fitted by using the quartic polynomial, and the results are shown in Figure 6.

![Figure 6. quartic polynomial of four binding belts](image)

As can be seen from Figure 6, after 16 hours of relaxation, the tension of the binding belts tends to be substantially stable. The corresponding fitting function relationship is shown in Table 2.

| number | quartic polynomial formulation | correction determining coefficients |
|--------|--------------------------------|------------------------------------|
| D1     | $F_{3t}=-177+0.00369t-1.14\times10^{-7}t^2+1.68\times10^{-12}t^3-9.56\times10^{-18}t^4$ | 0.99705 |
| D2     | $F_{3t}=-177+0.00374t-1.15\times10^{-7}t^2+1.75\times10^{-12}t^3-1.01\times10^{-17}t^4$ | 0.99861 |
| D3     | $F_{3t}=-204+0.00504t-1.91\times10^{-7}t^2+3.35\times10^{-12}t^3-2.13\times10^{-17}t^4$ | 0.99095 |
| D4     | $F_{3t}=-197+0.00394t-1.26\times10^{-7}t^2+1.97\times10^{-12}t^3-1.17\times10^{-17}t^4$ | 0.99752 |
As can be seen from Table 2, the correction determining coefficients of four binding belts are all greater than 0.99, indicating that the fitting degree of the $F_{3t}$ tension relaxation model is very high, and the binding belt tension after relaxation at a certain time can be predicted in a small error.

Similarly, based on the data of test 2 and test 3, two other sets of tension relaxation fitting curves can be obtained, as shown in Table 3 and Table 4.

Table 3. Fitting curve of $F_{3t}$ relaxation model in test 2

| number | quartic polynomial formulation | correction determining coefficients |
|--------|-------------------------------|-----------------------------------|
| D1     | $F_{3t} = -185 + 0.00308t - 28 \times 10^{-3}t^2 + 1.06 \times 10^{-12}t^3 - 5.26 \times 10^{-18}t^4$ | 0.99484 |
| D2     | $F_{3t} = -173 + 0.00244t - 24 \times 10^{-4}t^2 + 8.06 \times 10^{-13}t^3 - 4.00 \times 10^{-18}t^4$ | 0.99870 |
| D3     | $F_{3t} = -208 + 0.00410t - 4.0 \times 10^{-7}t^2 + 2.1 \times 10^{-12}t^3 - 1.26 \times 10^{-17}t^4$ | 0.99146 |
| D4     | $F_{3t} = -171 + 0.00242t - 6.08 \times 10^{-8}t^2 + 7.43 \times 10^{-13}t^3 - 3.51 \times 10^{-18}t^4$ | 0.99742 |

Table 4. Fitting curve of $F_{3t}$ relaxation model in test 3

| number | quartic polynomial formulation | correction determining coefficients |
|--------|-------------------------------|-----------------------------------|
| D1     | $F_{3t} = -179 + 0.00228t - 27 \times 10^{-4}t^2 + 3.87 \times 10^{-13}t^3 - 1.65 \times 10^{-18}t^4$ | 0.99772 |
| D2     | $F_{3t} = -186 + 0.00201t - 4.6 \times 10^{-7}t^2 + 9.99 \times 10^{-13}t^3 - 1.05 \times 10^{-18}t^4$ | 0.99897 |
| D3     | $F_{3t} = -212 + 0.00276t - 8.5 \times 10^{-9}t^2 + 2.13 \times 10^{-12}t^3 - 7.53 \times 10^{-18}t^4$ | 0.99603 |
| D4     | $F_{3t} = -193 + 0.00249t - 3.2 \times 10^{-8}t^2 + 5.77 \times 10^{-13}t^3 - 2.69 \times 10^{-18}t^4$ | 0.99772 |

Compared with the function model of three tests in Table 2, 3 and 4, the tension relaxation model of the four binding belts have a completely uniform form, and the coefficients of the fitting equations are in high degree. Therefore, in order to facilitate the coupling model well in cargo binding, the coefficients of the fitting function obtained by three experiments of each binding belt are summed and averaged, and the unified quartic polynomial fitting equation is obtained after the adjustment, as shown in Table 5.

Table 5. Final fitting curve of $F_{3t}$ relaxation model

| number | quartic polynomial formulation |
|--------|-------------------------------|
| D1     | $F_{3t} = B + 0.00302t - 8.8 \times 10^{-4}t^2 + 1.043 \times 10^{-12}t^3 - 0.553 \times 10^{-17}t^4$ |
| D2     | $F_{3t} = B + 0.00273t - 3.46 \times 10^{-7}t^2 + 0.953 \times 10^{-13}t^3 - 0.507 \times 10^{-18}t^4$ |
| D3     | $F_{3t} = B + 0.00367t - 7.85 \times 10^{-9}t^2 + 2.263 \times 10^{-12}t^3 - 1.380 \times 10^{-17}t^4$ |
| D4     | $F_{3t} = B + 0.00295t - 5.32 \times 10^{-8}t^2 + 5.77 \times 10^{-13}t^3 - 2.69 \times 10^{-18}t^4$ |

Among them, $B$ is a constant term, $B=67.5928-0.61565 \times F_{31}$, $F_{31}$ is the initial value of the tension relaxation for the binding belts.

4.4. Checking of relaxation model

After checking and calculating the binding belt tension of the modeling data (relaxation time less than 16 hours) coverage through the relaxation model shown in Table 5, a scatter plot comparing the calculated $F_{3t}$ and measured values $F_{3t}$ for each binding belt is obtained, as shown in Figure 7.
As can be seen from Figure 7, the calculated values are in good agreement with the measured values, and the majority of the error is less than 5%. The results show that the F3 relaxation model can be applied to the prediction of the tension relaxation of the binding belt at the site of cargo package binding.

5. Conclusions
In this paper, we analyze the tension relaxation of the binding belt, establish the tension relaxation model of the binding belt and achieve the prediction of the tension relaxation of the binding belt.

1) Based on the Analysis of Therbligs, the package binding process is divided into six stages: pre-tightening, pre-loading, step loading, applying safety buckle tension, ratchet unloading and removing ratchet wheel. A standard binding process is developed to enhance the reproducibility of the binding operation of the package, thus improving the accuracy of the tension relaxation model of the binding belt.
2) A cargo package binding test platform was built, and a large number of tension data were obtained by the tension sensors connected in series at the end of the binding belts.

3) Based on the least square polynomial data fitting, the tension relaxation model of four binding bands in package binding is established.

4) The tension relaxation model of the binding belt is verified, and the calculated value of the binding belt tension $F_3t$ is in good agreement with the measured value, and the error is mostly less than 5%.

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