Failure analysis of composite tube hinge and optimization design

Bowen Li, Hongling Ye, Yang Zhang
College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing 100124, China
E-mail: yehongl@bjut.edu.cn

Abstract. Composite materials with intriguing mechanical properties are introduced into special deployable structure. The tube hinge in this research is investigated, which has a base tube structure with one slot. However, due to large rotation and large nonlinearity, the composite tube hinge has material failure, thus leading to deployment failure. To overcome the problem, Hashin failure criterion is used for checking the extent to which the material is damaged in folding processes. The optimal model is established base on response surface methodology, which aimed at maximizing the strain energy and minimizing the peak moment to ensure full deployment stably. The failure index during folding processes are subjected (less than 1) to avoid material damage. The length of slot $L$, width of slot $D$, diameter $R$ and thickness $T$ of tube hinge are chosen as the design variables. Using the non-dominated sorting genetic algorithm, the optimum parameters are obtained by solving the multi-objective optimal model. The proposed method has significance on designing novel deployable structures with high stability and reliability.

Keywords. Tube hinges; mechanical damage properties; multi-objective optimization

1. Introduction and background
Space deploying structure is a brand-new aerospace structure product with the development of aviation industry, is the core device of deploying structure. The uncontrollable accident of the space deploying structure in the course of its work will lead to huge economic losses and failure of aerospace mission. Therefore, it is very important to research the reliability of deploying structure.

At present, the novel structure is a thin-walled flexible hinges, it can use the accumulation of elastic strain energy to achieve the automatic expansion of the structure without the need for other power units. After the expansion, the hinge can rely on their own stiffness to provide locking force, which no additional locking device is required. The thin-walled flexible hinge is divided into tape spring and tube hinge from the structure.

The tape spring was proposed by Pellegrino, who analyzed the deploying and locking ability of the structure by theory and experimental methods[1-2]. Then Seffen et al. obtained the mechanical properties of single hinge folding and deploying process by theoretical, experimental and numerical simulation methods[3-4]. In the aspect of hinge optimization design, Ye et al. developed an optimal design approach of tape-spring hinge under a pure bending load in deployable space structures[5].

In the tube hinges aspect, due to the particularity of its structure, the main forms of composite materials are used at present. Compared with metal materials, composites have high specific strength and specific stiffness and many potential advantages. Soykasap et al. studied the deploying behavior of...
composite hinge by experimental and numerical simulation methods, proved the feasibility of applying composites material [6]. Yee et al. analyzed the folding moment of a carbon fiber composites hinge, and gives the analytical expression of the rotational moment [7]. But because the fiber belongs to the elastic brittle material, it is easy to failure in the process of large deformation, which may cause damage to the composites. In order to ensure the stability of tube hinge folding process and the locking ability after expansion, to minimize the damage of composite material deformation, to deal with the damage mechanism and mechanical behavior of composite tube hinge bending and folding in depth study. Pellegrino et al. derives the general analytical expression of the longitudinal folding radius of the tape spring and the peak fiber strain [8]. Mallikarachchi et al. using the maximum strain failure criterion to analyze the failure of the tube hinge [9-11].

Although some scholars have studied and analyzed the mechanical properties of the hinge folding process of composite tubes hinges, there are still few research and optimization designs for the mechanical properties of composite tube hinges considering damage. This study aimed to investigate folding failure behaviors of composite tube hinge and optimization design. When the tube hinge snaps through, the moment decreases quickly and reaches to a peak moment. When the tube hinge is closely fold completely, the moment remains approximately constant which is called as steady moment. In order to obtain the best mechanical properties in case of material damage, an optimal model is established base on response surface methodology, which aimed at maximizing strain energy and minimizing the peak moment to ensure full deployment stably. The failure index during folding processes are subjected (less than 1) to avoid material damage. The length of slot L, width of slot W and thickness T of tube hinge are chosen as the design variables. Using the non-dominated sorting genetic algorithm, the optimum parameters are obtained by solving the multi-objective optimal model.

2. The mechanical properties analysis of tube hinge

2.1. Geometric model and material properties

Tube Hinge is a thin-walled, open cylindrical shell structure, the geometric model is shown in Fig. 1. Its geometric parameters include total length M, outer diameter D, be fixed width a, slot length L, slot width W, thickness t. Create a cylindrical coordinate system with R direction along the tube hinge horizontal radial., T direction counterclockwise around tube hinge, Z direction along the tube hinge axial.

![Fig. 1. Geometrical model](image)

| Table 1. Geometrical parameter of tube spring |
|---------------------------------------------|
| t (mm) | L (mm) | W (mm) | M (mm) | D (mm) | a (mm) |
|-------|-------|-------|-------|-------|-------|
| 0.1   | 140   | 30    | 400   | 40    | 20    |

The composite tube hinge is designed as a two-layer carbon fiber layer with angle of -45°/45°. The material selection is T300-1k/913 uni-directional laminate, material properties are shown in Table 2.

![Table 2. Material properties of tube spring](image)

2.2. Finite Element Model and numerical Simulations

2.2.1. Finite Element
In this paper, in order to simulate the folding process of tube hinge, two reference nodes A and B at the center of fixed sections, are connected to the fixed sections through rigid body. The bending angle of the tube hinge is the sum of the rotational angle of the two reference nodes, which rotation equal angular with value of 86° to achieve pure bending. The dynamic explicit solver, general contact and smooth step are used for quasi-static analysis to avoid solving non-convergence problems. Because the damage calculation has a great influence on the mesh. The tube hinge has divided in the Abaqus software, which ensures the shell element with four corner nodes (S4R), which an approximate element size of 3 mm. The partitioned model consists of 2873 nodes and 2761 elements.

2.2.2. The mechanical properties analysis
Folding simulations of tube hinge involve significant nonlinear processes. The process is considered to be done under quasi-static folding and performed using Abaqus/Explicit solver. The quasi-static behavior is maintained by ensuring that the kinetic energy to internal energy ratio be less than 1%. Fig. 2 show the deformation and mises distribution in the fully folded configuration. It can be obviously observed from the Mises stress distribution that the middle of the folding in the tube hinge is the area with the maximum stress.

![Fig. 2. Deformation and Mises stress distribution of optimal design](image)

Fig. 3 shows the bending moment-time map of the tube hinge, which can be roughly divided into four stages: the rapid increase of the bending moment, the sharp decline after the buckling point, the stabilization stage, and the slow rise after the tube hinge itself contact.

![Fig. 3. Variation curves of moment with time](image)

![Fig. 4. Variation curves energy with time](image)

Fig. 4 shows the curve of internal energy in the process of tube hinge folding. The strain energy increases with time, increases to a certain value at a faster rate, and then the decreases rapidly due to the occurrence of buckling, and when the tube hinge reaches the new equilibrium state again, the strain energy increases steadily with the smaller rate than the beginning of the time. Then because the tube hinge contact, change the stress state, strain energy increase rate and increase at a larger rate.

The energy variation for the tube hinge during quasi-static folding. The kinetic energy is lower than 10 % of the strain energy, which means that the simulation process is quasi-static. The energy balance curve remains zero before the self-contact of the tube hinge, slowly increases after contact, and the tube hinge outputs energy externally. This may be due to friction internal energy after tube hinge folding contact itself.

2.2.3. Failure analysis
Using the Hashin failure criterion to determine the damage of the tube hinge folding, the failure index is also changing gradually due to the change of the deformation time of the tube hinge. Fig. 5 shows the
failure index with time change graph. Fig. 6 shows the maximum damage distribution. FC, FT, MC and MT represent fiber compression, fiber stretching, matrix compression, matrix tensile damage respectively.

![Image](failure_index_with_time.png)

**Fig. 5.** Failure index with time

![Image](failure_distribution.png)

**Fig. 6.** Failure distribution

### 3. Parametric effects analysis

The factors affecting the mechanical properties of tube hinge damage are material parameters and geometric parameters. In this paper, the influence of the geometric parameters of the tube hinge on the material damage of the bending process is analyzed without considering the influence of the material parameters. Specifically, the parameters of the three geometric parameters of the slot length, slot width and thickness of the tube hinge are analyzed, and the parameter design is shown in Table 3.

| Group | Length of slot (mm) | Width of slot (mm) | Thickness (mm) |
|-------|---------------------|--------------------|----------------|
| 1     | 80-140 (10)         | 30                 | 0.1            |
| 2     | 140                 | 20-30 (2)          | 0.1            |
| 3     | 140                 | 30                 | 0.1-0.3 (0.05) |

As can be seen from Fig. 7(a), with the increase of thickness, the failure index of four damage forms of tube hinge structure are monotonically increasing, and the main damage is matrix tensile damage, and the influence on the tensile damage of matrix is the greatest. When the thickness is less than 0.2mm, the growth rate of the damage factor is small, and when the thickness exceeds 0.2mm, the damage factor increases at a larger rate.

As can be seen from Fig. 7(b), with the increase of length of slot, the failure index of four kinds of damage forms of tube hinge structure are monotonically decreasing. The main damage form of tube hinge is matrix tensile damage, and the effect on the tensile damage of matrix is the greatest. When the length of slot is less than 120mm, the reduction rate is larger, and when the length of slot exceeds 120mm, the damage factor falls to a smaller value and decreases slowly.

As can be seen from Fig. 7(c), with the increase of width of slot, the failure index of four kinds of damage forms of tube hinge structure are monotonically decreasing, and the change rate is stable.

![Image](parametric_effects.png)

**Fig. 7.** Parametric effects on failure index of tube hinge
4. Optimal design of tube hinge

4.1. Establishment of optimal model
During the folding process, the three key geometric parameters have effects on the failure index to some different degrees. The optimal design will be studied to find an optimal geometry to get the best mechanical property. Therefore, in the case of composite material damage, it aims at maximum strain energy and minimum peak moment during the tube hinge folding, failure index during folding processes are subjected (less than 1). The optimal model is established as follows:

\[
\begin{align*}
\text{find} & \quad x \in E^* \\
\text{max} & \quad SE \\
\text{min} & \quad PM \\
\text{s.t.} & \quad FI(x) \leq 1 \\
& \quad \underline{x}_i \leq x_i \leq \bar{x}_i \quad (i = 1, \ldots, n)
\end{align*}
\]

Where \( x = [x_1, x_2, x_3] \) denotes design variables, \( SE \) and \( PM \) are objective functions, \( FI(x) \) is constrain function. \( \underline{x}_i, \bar{x}_i \) are the lower and upper limit design variables.

4.2. Response surface models explicit objective function and constraint function
RSM used for obtaining the relationship between the input and output of complex system. According to the design area, the section factorial design is employed in this study, obtain the initial point obtain 22 test sample points. And then, the responses of the maximum strain energy, peak moment and failure index are obtained. The results of 22 design points are listed in Table 4.

| No. | \( t \text{(mm)} \) | \( L \text{(mm)} \) | \( W \text{(mm)} \) | \( PM \text{(NM)} \) | \( SE \text{(J)} \) | \( FI \) |
|-----|----------------|----------------|----------------|----------------|----------------|-----|
| 1   | 0.1            | 120            | 30             | 0.361052       | 0.112501       | 2.237 |
| 2   | 0.1            | 160            | 22             | 0.412134       | 0.148613       | 1.409 |
| 3   | 0.1            | 160            | 26             | 0.386673       | 0.084446       | 1.076 |
| 4   | 0.1            | 160            | 30             | 0.350895       | 0.073938       | 0.567 |
| 5   | 0.1            | 200            | 22             | 0.405241       | 0.139031       | 1.263 |
| 6   | 0.1            | 200            | 26             | 0.381442       | 0.067778       | 0.731 |
| 7   | 0.1            | 200            | 30             | 0.344652       | 0.070233       | 0.453 |
| 8   | 0.1            | 160            | 28             | 0.371927       | 0.076366       | 0.987 |
| 9   | 0.1            | 180            | 30             | 0.347733       | 0.075429       | 1.192 |
| 10  | 0.12           | 172            | 30             | 0.419668       | 0.097737       | 0.569 |
| 11  | 0.12           | 160            | 30             | 0.423962       | 0.098281       | 0.737 |
| 12  | 0.12           | 180            | 28             | 0.442322       | 0.101737       | 0.782 |
| 13  | 0.13           | 193            | 26             | 0.515064       | 0.141768       | 1.361 |
| 14  | 0.14           | 140            | 30             | 0.501827       | 0.158231       | 2.567 |
| 15  | 0.14           | 180            | 26             | 0.538354       | 0.160653       | 1.412 |
| 16  | 0.15           | 120            | 30             | 0.678814       | 0.249395       | 4.892 |
| 17  | 0.15           | 160            | 30             | 0.531503       | 0.172049       | 1.325 |
| 18  | 0.15           | 200            | 26             | 0.574395       | 0.193486       | 0.971 |
| 19  | 0.15           | 200            | 30             | 0.519978       | 0.130672       | 0.697 |
| 20  | 0.15           | 157            | 28             | 0.561598       | 0.204192       | 1.982 |
| 21  | 0.16           | 165            | 29             | 0.581994       | 0.241055       | 1.062 |
| 22  | 0.16           | 120            | 30             | 0.586524       | 0.202637       | 2.086 |
The polynomial expressions of objective function and constraint function are fitted by MATLAB software to realize the manifestation of constraint and objective function, and then inspection of fitting accuracy. The Curve fitting of the target and constraint function is:

$$\tilde{f}(t,L,W) = \sum_{i=0}^{k-1} \alpha_i^t (t,L,W)$$

(2)

In order to ensure the fitting accuracy, the three polynomial function is selected, the expression is:

$$\tilde{f}(t,L,W) = \alpha_0^t + \alpha_1^t t + \alpha_2^t t^2 + \alpha_3^t t^3 + \alpha_4^t L + \alpha_5^t L^2 + \alpha_6^t L^3 + \alpha_7^t LW + \alpha_8^t LW^2$$

$$+\alpha_9^t W + \alpha_{10} t + \alpha_{11} t W + \alpha_{12} L + \alpha_{13} L W + \alpha_{14} W^2 + \alpha_{15} t + \alpha_{16} t W + \alpha_{17}$$

(3)

Where $\alpha_0, \ldots, \alpha_{17}$ is coefficient.

Finally the three polynomial function expression of objective functions obtained as follows:

$$PM(t,L,W) = 2111.1031t^3 + 6.3641t^2L + 66.1178t^2W + 0.0006tL^2 + 0.0029tLW + 0.1343tW^2$$

$$-0.0001t^2W - 0.0002W^3 - 3812.2084t^3 - 1.8906tL - 24.6597tW + 0.0028L^2 + 0.0214$$

$$-0.0007W^2 + 998.8674t - 0.6925L - 0.4732W + 6.1846$$

(4)

$$SE(t,L,W) = 1964.3111t^3 + 10.1772t^2L + 90.7833t^2W + 0.0003tL^2 - 0.0106tLW - 0.1304tW^2$$

$$-0.0001t^2W - 0.0002W^3 - 5098.4016t^3 - 2.1238tL - 13.5408tW$$

$$-0.0036t^2L + 0.0264L^2 + 0.0217W^2 + 1018.9405t - 0.8914L - 2.0826W + 30.8769$$

(5)

Where $PM$ presents the peak moment, $SE$ presents the maximum strain energy.

The three polynomial function expression of constrain function obtained as follows:

$$FI(t,L,W) = -1675.47t^3 + 131.1194t^2L + 1419.3868t^2W + 0.0067tL^2 + 0.0223tLW + 0.9958tW^2$$

$$-0.0004L^3 - 0.00124tLW + 0.0004tL^2W - 0.0037tW^3 - 63003.2t^2 - 36.1967tL - 415.103tW$$

$$+0.0572t^2 + 0.4225L + 0.1449W + 17025.54t - 14.1607tL - 16.0455NW + 316.3278$$

(6)

Where $FI$ is the maximum failure index during the folding process that should be less than 1.

4.3. Precision test of response surface fitting

In order to ensure the accuracy and applicability of the response surface model, the precision of response surface fitting for objective function and constraint function should be tested. If the fitting precision could not satisfy the required one, it is necessary to add the design points. The accuracy of the responses should be evaluated with the use of several criteria, complex correlation coefficient ($R^2$), modified complex correlation coefficient ($R^2_{adj}$) and root mean square error (RMSE).

RMSE is the mean of the square root of the error between the predicted value and the real value. The smaller the RSME, the higher accuracy of response surface fitting. $R^2$ is a value changes between $[0, 1]$, and it closer to 1, the less the effect of the error is. $R^2$ can describe the fitting degree of the response surface, but it has a flaw, that is, its value increases with the increase of the number of independent variables in the regression equation. In order to overcome the defects of $R^2$, it needs to be corrected. $R^2_{adj}$ the effect of the number of parameters k is considered. When the number of parameters increases, the $R^2_{adj}$ does not increase. Thus, the larger $R^2$ and $R^2_{adj}$ are, the smaller RMSE, the better the Response Surface fitting is.

The complex correlation coefficient ($R^2$) of the peak moment response surface model and modified complex correlation coefficient ($R^2_{adj}$) are 0.9999 and 0.9998. The complex correlation coefficient ($R^2$) and modified complex correlation coefficient ($R^2_{adj}$) of the maximum stress energy response surface model are 0.9999 and 0.9999. The complex correlation coefficient ($R^2$) and modified complex correlation coefficient ($R^2_{adj}$) of the maximum failure index response surface model are 0.9944 and 0.9938. The values of RMSE of peak moment, maximum stress energy and failure index are 0.0111,
0.0136 and 0.0707. These three accuracy indicators suggest highly accurate fitted functions. Thus the accuracy of the two response surface models is satisfied.

4.4. Multi-objective optimal solution
By solving the multi-objective optimal model, a set of feasible solutions can be obtained to represent the feasible solutions, and it can be found that the feasible solutions are distributed within a envelope line. The curve is called the Pareto frontier, and when there are multiple targets, when a solution is optimal on a certain target, it is not optimal on the other target because of the conflict between the targets and the phenomenon that cannot be compared. There is no better solution for the corresponding individual than the Pareto frontier solution. Because the solution in the Pareto frontier may become the optimal solution, the designer can choose the most satisfactory solution of the optimal design from the Pareto solution according to the intention and the importance of each goal.

To complete optimal, the peak moment, the strain energy are chosen according actual engineering requirements. The more strain energy to ensure full deployment, the less peak moment to avoid excessive shock and overshoot during the end of deployment.

Because the fitting curve cannot same as the real situation. There is a huge gap in the judgment result when the failure index is near 1. So the constraint condition cannot choose the boundary of composite material damage ($FI=1$). Thus a safety factor is set, which value is equal to 1.4. Therefore, safety factor reduce the effect of error on the result, the final failure index should be less than $1/1.4=0.7$. NSGA-II is employed to find the optimal solutions with a population size of 200, generation number of 1000. The Pareto fronts of feasible solutions is shown in Fig. 8.

![Fig. 8. Pareto fronts of PM and SE for the tube hinge with FI<0.7](image)

From the Fig. 8, it is revealed that the strain energy and peak moment are taken as target, and when the peak moment decreases, the strain energy decreases too. The peak moment and strain energy are correlated with the failure index, which is less than 0.7. We have obtained the Pareto frontier, that is, the range of changes that have been obtained from the two target solutions. In selecting the optimal solution, two targets need to be weighed, so it is necessary to increase the information to narrow the range of the target according to the actual application, so as to select the optimal solution.

5. Conclusions
The material damage of composite tube hinge is analysed using numerical method. Then the optimal design is obtained using the response surface methodology. The results are as follow:
(1) The tube hinge self-contact has a great influence on moment, strain energy and failure index. If the tube hinge can avoid self-contact, the damage can be reduced.
(2) When the tube hinge is in the folding process, the main damage mode is matrix damage, which is manifested as matrix tensile damage. The location of the damage is mainly distributed in the buckling
position on both sides of the slot. The damage factor increases with the increase of thickness, decreases with the increase of slot length and slot width. 

(3) The optimal design is obtained by using the validated numerical model and response surface methodology. The strain energy, peak moment and failure index surrogate model of tube hinge are established. An improved non-sorted genetic algorithm is used to solve the optimal model, and the Pareto front of multi-objective optimization solution is obtained.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (11872080, 11172013), Beijing Natural Science Foundation (3192005) and Beijing Education Committee Development Project (SQKM201610005001).

References
[1] Seffen K and Pellegrino S 1997 *Cambridge University Department of Engineering Report.*
[2] Seffen K A and Pellegrino S 1999 *Proceedings of the Royal Society A Mathematical Physical & Engineering Sciences J* 455 pp 1003-1048.
[3] Seffen K A, You Z and Pellegrino S 2000 *International Journal of Mechanical Sciences* 42 pp 2055-2073.
[4] Seffen K A 2001 *Journal of Applied Mechanics* 68 pp 369-375.
[5] Ye H, Yang Z and Yang Q 2017 *Structural & Multidisciplinary Optimization* 56 pp 973-989.
[6] Ömer S 2009 *Composite Structures* 89 pp 374-381.
[7] Yee J C and Pellegrino S. 2004 Structural Dynamics & Materials Conference.
[8] Yee J C and Pellegrino S 2005 *Journal of Aerospace Engineering* 18 pp 224-231.
[9] Mallikarachchi H.M.Y.C. and Pellegrino S 2011 *Journal of Spacecraft & Rockets* 48 pp 187-198.
[10] Mallikarachchi H.M.Y.C. and Pellegrino S 2009 *Structural Dynamics & Materials Conference.*
[11] Mallikarachchi H.M.Y.C. and Pellegrino S. 2013 *Structural Dynamics & Materials Conference.*