ICAS 2021 SHANGHAI
International Council of the Aeronautical Sciences
32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

A METHOD FOR CALCULATING TORSION ANGLE OF FLEXIBLE RETICULAR TUBE AT DIFFERENT POSITIONS

Deng yangchen[1,3,5], Yang Yu[2], He Yuqing[3], Sun Cong[1,4], Qiu Fusheng[5]

[1]Shenyang Aircraft Design and Research Institute, Shenyang, Liaoning, PRC

[2]Aircraft Strength Research Institute, Xian, Shan-xi, PRC

[3]Shenyang Institute of Automation, State Key Laboratory of Robotics, Shenyang, Liaoning, PRC

[4]Chinese Aeronautical Establishment, Beijing, PRC

[5]Shenyang Aerospace University, Shenyang, Liaoning, PRC

Abstract

In order to explore the torsion deformation of the flexible reticular tube beam (FRTB), this paper firstly proposed the concept and operation steps of cumulative recursive method (CRM), and utilized this strategy to carry out the mechanical modeling and mathematical derivation for FRTB, and obtained the analytical formula on torsion angle of one piece of FRTB. Secondly, the constitutive relation of the mechanical response of one piece of FRTB was constructed. Thirdly, the torsion angle of every piece of FRTB was deduced through the strategy and approach of CRM. Two numerical examples showed that the proposed method was feasible and effective, and it was found that the torsion angle distribution shape of FRTB along the axial direction was stable and unchanged for its deformation characteristic. Finally, four conclusions and the future works to be explored in scheme were also provided.

Keywords: Morphing Structure, Flexible & Elastic Structure, Cumulative Recursive Method, Flexible Reticular Tube Beam, Torsion

1.Introduction

The morphing structure has broken through the configuration of the traditional aircraft, which can maintain well in maneuverability and agility, as well as increase a range or endurance during cruise, so the study of the variable and flexible wing of an aircraft is especially both important and rudimentary. A large number of researches have shown that flexible wings can also improve the aerodynamic & acoustic as well as stealth characteristics of an aircraft while reducing the total weight of an aircraft. Through the control of the flexible wing, the rolling of a plane can also be achieved, moreover, the suppression of the wing flutter as well as the reduction of the gust and maneuverable load are also achieved. Flexible torsion is an effective way of achieving the deformation of the wing, which is usually to use shape memory alloy or piezoelectric for driving the torsion of the wing. However, there are some certain defects in both methods, such as needing high temperature and offering fewer deformations, respectively, which difficultly make the wing turn enough required angle. Theoretical research has displayed that when a plane is flying, the lift of the wing is distributed in ellipse along the direction of the span, which can obtain the minimum induced drag, and this is the most beneficial to the flight range or endurance during cruise. To make the rotation angle of the wing have the ability with arbitrary distribution along span direction, or to realize other purpose, some Japanese scholars [1] firstly did an exploration on such a challenge work, then a French scholar [2] joined this ‘cold topic’ in experimental work on double cylindrical tube. And both of them got fruits of twist-morphing structure with open-section member [1,2]. Later, Deng YC et al [3,4] continued to do it from flexible & elastic structure point of view independently in China and pointed out the above work would be on the key status in one branch of morphing aircraft. Based on the previously mentioned researches, this paper continually studies the flexible driven beam for leading edge of a wing structure. Once the wings have flexible driven beams, an aircraft has the ability to adapt a variety of flight conditions more efficiently.

It was said that in the period of 1960s or 1970s, there had been an argument about improvement in the performance of a second generation fighter in China, so called ‘the Argument by Fang & Gu’. At the time, so as to improve the range at high subsonic cruise of the plane with large sweepback of the wing, the leading-edge of the wing along the span-wise should be turned downward a few degrees in advance was proposed, but it would led to reduce the aircraft's maneuverability and agility. In short, the previous method was unable to meet the performance of cruise range and maneuverability for dog-fighting, simultaneously. But here, the research on the flexible and elastic structure will be the basic study and effective solution to such types of above problems.

2. The Application Theory of FRTB Established

Here, the flexible driven beam is composed of many unit structures which are netlike or reticular. The shape, length, angle and thickness as well as width of each part in every unit has an effect to the torsion angle of this kind of flexible & elastic structure, so constructing the mechanical modeling of the structure is necessary for obtaining the relationship between these above mentioned parameters and the function of torsion angle.

The structure of FRTB should be simplified, so as to study the mechanical properties of flexible reticular structures and facilitate mathematical derivation, and the basic assumptions are as follows: (1) All the structural materials used are isotropy; (2) The structure is ideal, whose structural response conforms to linear and elastic hypothesis; (3) In the process of deformation, this structure does not consider tension deformation, only considering bending and shearing deformation; (4) The rings in the structure regard as rigidity. On the basis of these assumptions, the structure of FRTB on mechanical modeling and deformation derivation will be carried out.

In this paper, the problem of torsion deformation of the FRTB was studied, although it was a typical geometric large deformation, but it was not difficult to find that the deformation had obvious large deformation with small strain characteristics. In order to solve this kind of problem, the paper put forward the ‘cumulative recursive method’ (CRM). The definition of CRM was to decompose the large torsion angle of structure into two parts, corresponding to elastic torsion and rigid rotation, respectively. The following would give the usage principle of CRM in detail at Section 4.

2.1 Mechanics modeling of the FRTB

When the uniform hollow tube beam is twisted, the torsion angle of each station is a constant, but it cannot realize the different angle in different stations along the axial direction. Meanwhile, when torsion acts on the tube beam which is composed of flexible mesh structure, the torsion angle of different position can be obviously different, and of course, it means that the angle distribution can be designed as required. In order to obtain the greater torsion deformation for a leading or trailing edge of an aircraft wing, and meet a required torsion angle distribution, a type of FRTB was set forth here, and up till now it might be a feasible choice for this challenge work.

As shown in figure 1, in this paper every piece of FRTB was composed of three parts corresponding to ‘diamond-shaped’, ‘straight bar shaped’ and ‘toroidal shaped’ (in below figures, they were called ‘rigid rings’) components, respectively. The first two components were jointly to bear the torque and had the ability to provide various torsion angles at different stations of rigid rings. Rigid rings had two main functions, 1) to transform the torque into concentrated forces acting on the ‘straight bar shaped’ components which connect the rigid ring, 2) to prevent the FRTB from instability in the process of torsion deformation.

In order to facilitate the structural response of the FRTB, the structure of figure 1 was expanded into a piece of plane, as demonstrated in figure 2.

The common characteristics of the three parts previously mentioned in figure 1 and figure 2 were extracted, and several parameters were selected to describe these characteristics in accordance with the principle of mechanics, so as to construct the basic model for analysis of mechanics, which was called ‘basic unit’, where, α was the half angle of the ‘diamond shaped’ part and its components’ lengths were ‘a’ & ‘L’, respectively. As well as its width and thickness of the components were ‘b’ & ‘t’, respectively, as shown in figure 3. Furthermore, it was easy to see the

FRTB consisting of several basic units above mentioned in figure 3, and the authors supposed that the number of ‘basic unit’ along axis and vertical/tangent direction of the FRTB were M and N, respectively, as illustrated in figure 2.

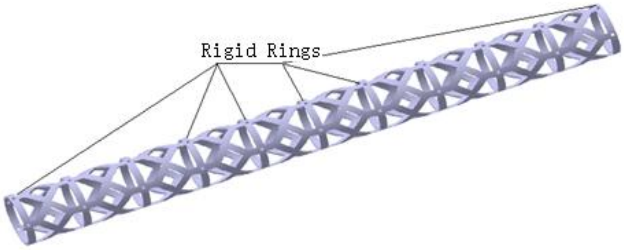

Figure 1 – Structure layout of the FRTB

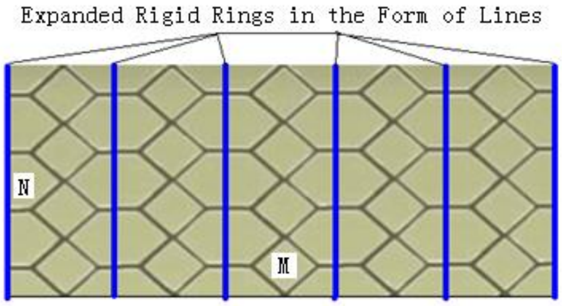

Figure 2 – A plane of the expanded FRTB

Following was a concept of torsion deformation of this kind of FRTB. The concept was usually defined in some papers [1-4] by the angle relative to the constraint station section. The torsion angle defined in this way was not only related to the torsion moment, but also to the distance of the station acting on load. But here, we gave another definition, which meant the torsion angle of the section was just relative to itself torsion moment, and had nothing with the distance of the station.

2.2 Based on the torsion deformation of the above construction model

Using the rigid ring, the torque of the FRTB was transformed into a number of tangential forces along the tangent direction of every rigid ring, and having the expression (1) as below.

$$T = N * F * R \tag{1}$$

Where, T indicated the torque of the FRTB, N stood for the number of basic units along the tangent direction of the FRTB; F represented the shear-force along the tangent direction of the FRTB, R indicated the radius of the FRTB. The description of the above mentioned parameters was shown in figure 4.

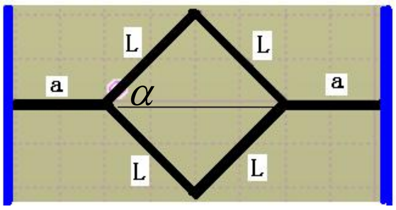

Figure 3 – Feature description of basic unit

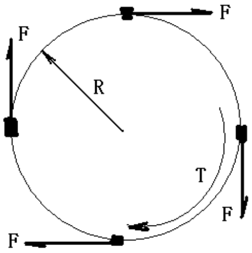

Figure 4 – Load transformation of FRTB section

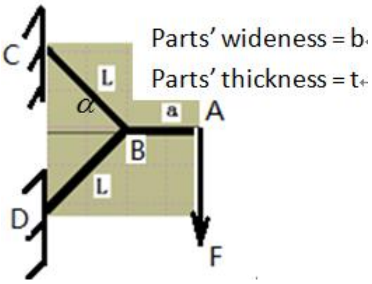

Figure 5 – Model to solve basic unit

The geometric relationship between figure 3 and figure 4 could be obtained in expression (2) as below.

$$R = N * L * sin\alpha/\pi \tag{2}$$

Out of formula (1) and (2), Expression (3) could be deduced easily as below.

$$F = \pi T/(N^2 * L * sin\alpha) \tag{3}$$

Where, the parameters in formula (2) and formula (3) were defined previously as demonstrated in figure 3 and figure 4. In order to solve the torsion deformation of the FRTB in figure 1, the procedure here started firstly with the deformation of the basic unit in figure 3, and its simplified mechanical model was pictured in figure 5. Then, the curvature of the FRTB was deduced and calculated. From the circular equation $X^2 + Y^2 = N^2 \cdot L^2 \cdot \sin^2\alpha / \pi^2$ and the basic curvature formula $K = Y'' / \left(1 + Y'^2\right)^{1.5}$ of the FRTB in figure 1, it was not difficult to deduce and gave the curvature expression $K = \pi / N \cdot L \cdot \sin\alpha$ of the model in figure 5. Allowing for the engineering background of the practical problem, according to the specific parameter values of the following calculation example, and substituting them into the curvature formula, the authors could get K = 0.0429, which showed that the curvature of the FRTB studied in this paper was very small. Therefore, the influence of small curvature could be omitted here and considered in subsequent derivation in other paper.

According to the coordinate of deformation, the mechanical solution of the model in figure 5 was deduced in expression (4) as below.

$$\Delta_A = \frac{Fa^3}{3EI} + tan\left(\frac{FaL}{8EI}\right) \times (a + Lcos\alpha) + \frac{3FaL^2cos\alpha}{8EI} + \frac{FLsin^2\alpha}{Ebt} \tag{4}$$

Where, E was Young's modulus, $I = {tb^3}/_{12}$, and as before, the meaning of other parameters was explained and given in figure 3 and figure 4.

Furthermore, the rotation angle of the rigid ring at point A in figure 5 could be determined in expression (5) (which could be regarded as relative to itself or relative to the constraint points C and D) as following.

$$\varphi_A = \frac{\pi\Delta_A}{NLsin\alpha} \tag{5}$$

Substituting formula (3) and $I = {tb^3}/_{12}$ into formula (4) and substituting the results of formula (4) into formula (5), then expression (6) could be deduced as below.

$$\varphi_A = \frac{\frac{4\pi^2Ta^3}{N^2Lsin\alpha Eb^3t} + \pi tan\left(\frac{3\pi Ta}{2N^2sin\alpha Eb^3t}\right) \times (a + Lcos\alpha) + \frac{9\pi^2TaL}{2N^2tan\alpha Eb^3t} + \frac{\pi^2Tsin\alpha}{N^2Ebt}}{NLsin\alpha} \tag{6}$$

It was not difficult to find that the relative twist angle between the two rigid rings in figure 3 (corresponding to the two adjacent rigid rings in figure 1) was twice as large as φ_A, that was the expression (7) as below.

$$\varphi_r = 2\varphi_A = \frac{2\pi\Delta_A}{NLsin\alpha} \tag{7}$$

Out of figure 1, figure 3 and figure 5, it could be seen that the two adjacent rigid rings twisted φ_A with respect to the symmetry plane CD, but only in opposite directions. Therefore, the relative twist angle of the two adjacent rigid rings should be φ_r logically and reasonably.

From the design point of view, the 'straight bar shaped' component length was set as 'a'. And for FRTB all components' width and thickness were set as 'b' and 't' respectively. The length of the 'diamond shaped' member was set as one parameter 'L', and the half included angle was set as 'α'. Meanwhile, all these parameters could take different values between different two rigid rings, so that it not only considered low-cost manufacturing, but also expanded the design space and was convenient for design. Allowing for the perspective of low-cost manufacturing, the wall thickness of't' of the whole FRTB was set as a constant.

It was easy to see the FRTB of figure 1 had a total number of (M+1) rigid rings. From the above deduction and demonstration, it could be found that the relative torsion angle of two adjacent rigid rings was $\varphi_{ri} \quad i = 1 \ldots M$, where φ_{ri} was displayed in expression (8).

$$\varphi_{ri} = 2\,\frac{\frac{4\pi^2Ta_i^3}{N^2Lsin\alpha Eb_i^3t} + \pi tan\left(\frac{3\pi Ta_i}{2N^2sin\alpha Eb_i^3t}\right) \times (a_i + Lcos\alpha) + \frac{9\pi^2Ta_iL}{2N^2tan\alpha Eb_i^3t} + \frac{\pi^2Tsin\alpha}{N^2Eb_it}}{NLsin\alpha} \tag{8}$$

Facing to the calculation of torsion angles at different stations, the paper set forth the concept and applied the principle of CRM. CRM was proposed for the geometrically nonlinear mechanical problem of 'small strain with large displacement'. The strategy and procedure were to decompose 'large displacement' into 'elastic displacement and rigid movement' and to utilize superposition principle to solve it. The characteristic of this method was that if we wanted to solve the torsion angle φ_i at station i, we must first solve the torsion angle φ_{i-1} at station i-1. Moreover, the torsion angle φ_{i-1} had influence on not only the torsion angle φ_i, but also the torsion angle φ_{i+1}, which was the origin of this name coming from, to some extent.

Using CRM and combined with formula (8), the torsion angle at each rigid ring station of the FRTB in figure 1 could be deduced, as illustrated in expression (9).

$$\varphi_j = 2\sum_{i=1}^{j-1} \frac{\frac{4\pi^2 T a_i^3}{N^2 L sin\alpha E b_i^3 t} + \pi tan\left(\frac{3\pi T a_i}{2N^2 sin\alpha E b_i^3 t}\right) \times (a_i + L cos\alpha) + \frac{9\pi^2 T a_i L}{2N^2 tan\alpha E b_i^3 t} + \frac{\pi^2 T sin\alpha}{N^2 E b_i t}}{N L sin\alpha}$$

$$i = 1, \dots M;\ \ j = 2, \dots M + 1 \qquad (9)$$

The meaning of each parameter in formula (9) has been defined in previous paragraphs, where, $\varphi_{j=1} = 0$ was expressed as the constraint end.

3 Examples of the FRTB

Two examples were given here to answer two questions, which were the constitutive relation of the FRTB and a good design-ability of the proposed method.

The provided known parameters' values were illustrated in Table 1. Substituting the parameters' values in table 1 into formula (2), the average diameter of the FRTB could be obtained as $D_{av} = 46.6\text{mm}$. Furthermore, there were Din_dia = 44.6mm, and Dout_dia = 48.6mm, respectively, according to figure 1 and table 1. The FRTB was made of spring steel with modulus $E = 20000\text{kg/mm2}$, and all rigid rings were set 6 mm in width as well for two examples.

Table 1- Known Parameters of FRTB Structure

parameter	a/mm	L/mm	α/rad	t/mm	b/mm	N	M	L_{total}/mm
value	10.35	20.7	π/4	2.0	2.659	5	10	500.0

Example 1

Here, the corresponding parameter values of any 'basic unit' in the whole FRTB were the same, which would not affect the answer to the constitutive relation. The specific meaning of parameters in table 1 was also displayed in figure 1 to figure 3.

Substitute the parameters' values in table 1 into formula (3), and the shear-force could be obtained as F=8.5853T..

Again, substituting the parameters' values in table 1 into formula (4), the relative displacement of adjacent rigid rings of the FRTB could be calculated as below.

$$\Delta = 2\Delta_A = 0.3043\text{T}$$

From formula (6) or formula (7), continually, the relative torsion angles of adjacent rigid rings of the FRTB could be gotten as well.

$$\varphi_r = 0.02618\text{T}$$

When T = 1 kgm, then, there were $\varphi_r = 0.02618\text{rad} = 1.5°$, and meanwhile, F = 8.5853 kg.

Finally, the torsion angle of each rigid ring of the FRTB could be computed out of formula (9), as depicted in table 2 for details.

Table 2- Torsion Angles of FRTB at Different Stations along Axial Direction

Rings' No.	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8	j=9	j=10	j=11
Tube Station (mm)	0	50	100	150	200	250	300	350	400	450	500
Torsion Angle (°)	0.0	1.5	3.0	4.5	6.0	7.5	9.0	10.5	12.0	13.5	15.0

Example 2

This example was used to test whether the algorithm given in this paper was designable or not, among which, the target value of twist angle distributed as ellipse along the axial direction of FRTB was illustrated in Table 3.

Table 3- Target Values of Torsion Angles Distributed Elliptically along the Axial Direction of FRTB

l (mm)	0	50	100	150	200	250	300	350	400	450	500
φ(°)	0.0	.0752	.3031	.6909	1.2523	2.0096	3.0	4.2879	6.0	8.4617	15.0

In order to achieve the design target values in Table 3 of the FRTB, the design task was carried out based on the data in Table 1 and only with the width ‘b’ as the design variable (other parameters’ values were unchanged owing to easy manufacture). Using table 3 and formula (9), taking the torque T = 1.35 kgm, we could get F = 11.59 kg, and the relevant results were in table 4. The design target values in table 3 and the design result values in table 4 could be seen in figure 6, and their relative errors could be seen in table 5, where, the specific error calculation was based on the expression of $\mathrm{Error} = {(\varphi_{\mathrm{target}} - \varphi_{\mathrm{design}})}/{\varphi_{\mathrm{target}}}$.

Table 4- Component-Width and Torsion Angle of Each Rigid Ring along the Axial Direction of FRTB

Rings’ No	1	2	3	4	5	6	7	8	9	10	11
b (mm)	8	5.52	4.62	4.08	3.69	3.37	3.09	2.81	2.49	1.8	
φ(°)	0	.0758	.3037	.6910	1.252	2.010	3.0043	4.293	6.006	8.4651	14.97

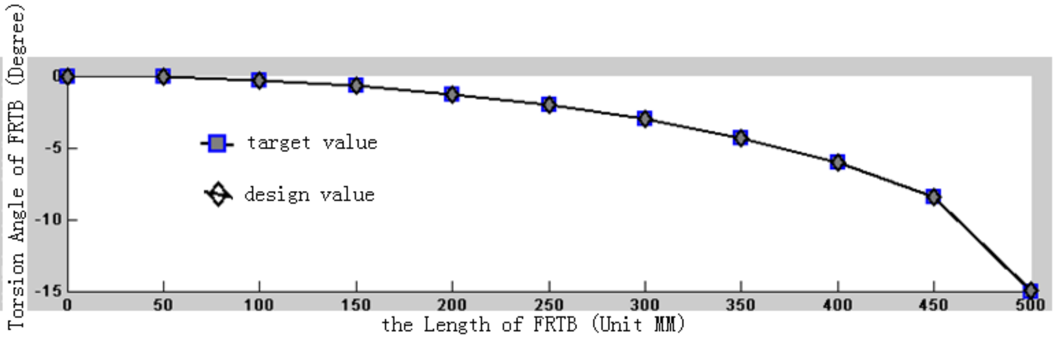

Figure 6 – Target value and design value of torsion angle of ellipse distribution along axial direction of FRTB

Table 5- Relative Error Value of Torsion Angle Distribution along Axial Direction of FRTB

l (mm)	0	50	100	150	200	250	300	350	400	450	500
Error	0%	-0.8%	-.198%	-.015%	0%	-.03%	-.0143%	-.0212%	-.092%	-.04%	.211%

4 Discussions on FRTB

a) For example 1

The data relationship between deformation torsion angle and applied torque at different stations of the FRTB could be seen in table 6 and figure 7, respectively.

Out of table 6 and figure 7, it could be observed that 1) The torsion angle was linearly distributed with the length of the FRTB along axial direction; 2) The torsion angle of the FRTB was linearly related to the applied torque at the same station along the axial direction.

Table 6- Relationship between Torsion Angle and Torque Applied along Axial Distribution of FRTB in Example 1

Station (mm)	0	50	100	150	200	250	300	350	400	450	500	Torque (Kg-m)
Torsion-Angle (°)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	T=1/3
	0.0	1.0	1.5	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	T=2/3
	0.0	1.5	3.0	4.5	6.0	7.5	9.0	10.5	12.0	13.5	15.0	T=1

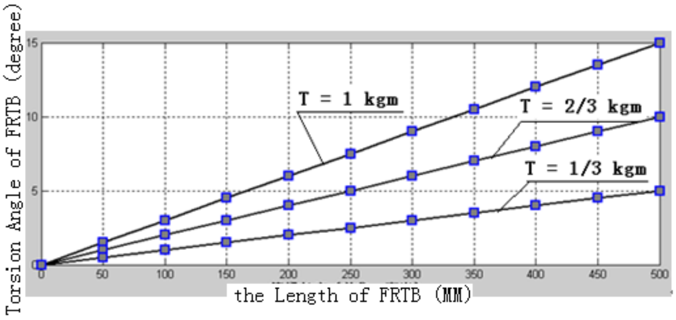

Figure 7 – Different torques and corresponding torsion angles along the axial direction of the FRTB in example 1.

b) For example 2

The data relationship between torsion angle and applied torque at different stations of FRTB could be seen in table 7 and figure 8, respectively.

Out of table 7 and figure 8, it could be observed that 1) The torsion angle and the length of the FRTB along the axial direction had an oval distribution relationship; 2) The torsion angle of the FRTB was linearly related to the applied torque at the same station along the axial direction.

Table 7- Relationship between Torsion Angle and Torque Applied along Axial Distribution of FRTB in Example 2

Station （mm）	0	50	100	150	200	250	300	350	400	450	500	Torque （kgm）
Torsion Angle (°)	0.0	.0253	.1012	.2303	.4174	.6701	1.0014	1.4310	2.0018	2.8217	4.99	T=0.45
	0.0	.0535	.2025	.4607	.8349	1.3401	2.0029	2.8620	4.0037	5.6434	9.98	T=0.90
	0.0	.0758	.3037	.6910	1.2523	2.0102	3.0043	4.2930	6.0055	8.4651	14.97	T=1.35

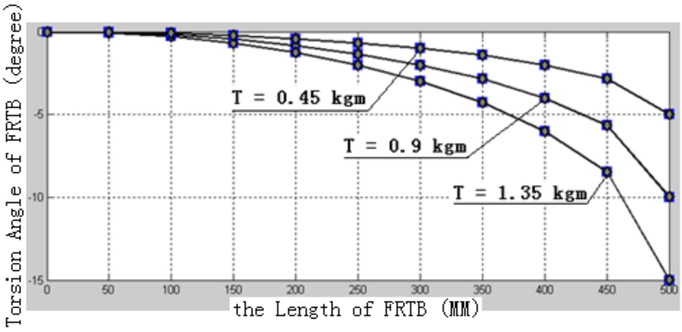

Figure 8 – Different Torque and Corresponding Torsion Angle along the Axial Direction of FRTB in Example 2

c) Phenomena and explanations

The design objective of the scheme of example 1 was to answer the constitutive relation of the FRTB, so the scheme was designed as simple as possible. The technical approach adopted was ‘the torsion angle and the length of the FRTB were linearly distributed along the axial direction’. Meanwhile, the design objective of the scheme of example 2 was to answer if the FRTB structure had a good design-ability or not. Moreover, in combination with the future application background, the technical approach adopted was ‘the torsion angle and the FRTB had an oval distribution relation along the axial length’.

Further study to the above mentioned results expressed that the FRTB proposed in this paper had the ‘inertia’ attribute, which the distribution form of torsion angle remained unchanged during the torque load action. For example, the twist angle distribution curves corresponding to different torques in Example 2 were as following.

$$\text{when } \mathrm{T} = 0.45\text{kgm}\text{, then there was } \frac{\mathrm{x}^2}{500^2} + \frac{\mathrm{y}^2}{5^2} = 1$$

$$\text{when } T = 0.9\text{kgm}, \text{ then there was } \frac{x^2}{500^2} + \frac{y^2}{10^2} = 1$$

$$\text{when } T = 1.35\text{kgm}, \text{ then there was } \frac{x^2}{500^2} + \frac{y^2}{15^2} = 1$$

The shapes of the previously mentioned three curves were shown in figure 8, respectively. Their curve-distributions were always in the form of ellipse and would not change, wherein the physical meaning of the major half axis of ellipse was the length of FRTB. And the physical meaning of the minor half axis of ellipse was the torsion angle at the outer end of the FRTB.

In addition, the following phenomena could be observed from the results of example 1 and example 2 (as shown in figure 7 and figure 8, respectively).

1) At the same station, the torsion angle of the FRTB always had a linear relationship with the applied torque.
2) Along the axial direction of the FRTB the relationship between the torsion angle at different stations and the applied torque was designable, which could be either linear or non-linear. For example, Example 1 gave a linear relationship, while, example 2 offered the nonlinear relation of elliptic distribution.
3) Along the axial direction of the FRTB, the shape characteristics of the center line of the basic unit (figure 3) after torsion deformation were shown in figure 9, wherein, Δ_A was calculated in formula (4).
4) Furthermore, it could be concluded that the method proposed in this paper were able to give the twist angle distribution satisfying the design requirements.
5) The torsion of FRTB studied in this paper could be regarded as a kind of extending Saint Venant torsion with additional design requirements.

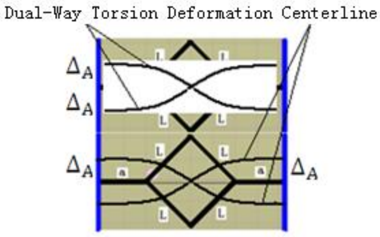

Figure 9 – The Characteristics of Basic Element's Dual-way Torsion Deformation Centerline

From the derivation process of the previous theoretical formulae and specific examples, it could be seen how the CRM decomposed the large displacement of the FRTB into elastic displacement and rigid movement. The torsion angle φ_i obtained here was the rigid movement in φ_{i+1}. Constraining the position of the FRTB at the station of angle of φ_i, the torsion angle at φ_{i+1} position was found to be the elastic displacement in angle of φ_{i+1}. It was precisely such 'accumulation' and 'recurrence' steps that realized the solution of large torsion deformation of this kind of FRTB. Of course, in the solution process, looking at this strategy from the perspective of boundary constraints point of view, it could also be called 'constrained movement method' (CMM), which could also deeply reflect the characteristics of this operation.

5 Conclusions and Prospects

Through the study in this paper, the authors could draw the following four conclusions.

1) The concept of FRTB proposed in theory and the modeling strategy based on the CRM/CMM principle have realized the establishment of the constitutive relation of the FRTB and formed a set of complete design method accordingly.
2) The examples showed that the method was not only feasible but also effective, and could complete the task quickly according to the specific design requirements.
3) It was found that the given FRTB had stable torsion deformation characteristics in mechanical properties.
4) On the whole, the CRM or CMM proposed to study and solve the large deformation problem of the FRTB could reasonably convert large displacement into a combination of elastic displacement and rigid movement, which made this kind of problem skillfully solved.

Finally, a brief plan for the next work step was given. According to the technical scheme of the current examples and the engineering practice point of view, five tasks were currently being planned, 1) The modeling and solution of FRTB were carried out by using CRM/ CMM and linear finite element method; 2) The nonlinear finite element method was used to model and solve the FRTB; 3) Carry out the fabricating of test pieces and demonstration & verification of related experiments will be done; 4) Carry out the comparing and analysis on these simulations corresponding to theoretical calculation, CRM/CMM as well as linear and nonlinear finite element method results; 5) In order to be closer to the actual aircraft engineering problems, the structural responses of FRTB subjected to different torques at various stations along the axial direction would be studied in near future.

Contact Author Email Address

The contact author email address:dengyangchen@sohu.com

Acknowledgement

The fruit work of this paper was jointly funded and supported by the 3rd Shenyang Aircraft Design Research Institute Innovation Fund (No. : SCXJJ180113) and the Liaoning Provincial Natural Science Fund Laboratory Key Project (No. : 2019-KF-01-04) as well as the State Key Laboratory of Robotics in Chinese Academy of Science (No. : 2020-Z02).

Copyright Statement

References

[1] Atsushi ASO. Hiroaki Tanaka. Study on a morphing wing structure using open-section member, 7th Asia-Pacific International Symposium on Aerospace Technology, 25-27 November 2015, Cairns.

[2] Atsushi ASO, Perrey MARCEAU and Hiroaki TANAKA, Experimental Study on Wing Twist-Morphing Structure Using a Double Cylindrical Tube, The 2016 Asia-Pacific International Symposium on Aerospace Technology, October 25-27, 2016, Toyama, Japan.

[3] Deng Yangchen, NIU Xiaokang, SU Dechao; LIANG Shangjun, Aanalysis of a Kind of Flexible Driven Structure for Wings Based on Numerical Simulation, Aircraft Design, 2018, 38(1): 1-6. (In Chinese)

[4] Deng Yangchen, ZHANG Wenbo, CHEN Xianmin, FAN Junling, Study of Modeling on a Kind of Reticulate Tube-Like Flexible Structure, 2018, 38(3): 1-6. (In Chinese)