MULTIDISCIPLINARY EVALUATION OF TRUSS-BRACED WING FOR FUTURE GREEN AIRCRAFT

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Abstract

The truss-braced wing configuration is a promising innovative design for future green aircraft. Some preliminary studies are conducted to explore the full potential of TBW in a multidisciplinary way. A structural model for wing sizing and weight calculation of a TBW is provided. As truss buckling under negative loads is the most critical structural problem, a topology optimization is performed to give a few promising TBW concepts. Different TBW concepts are optimized using full-stress optimization and the calculations reveal the significant influence of the truss on the bending material weight of the wing. The 3-jury configuration can achieve a maximum bending-weight reduction of about 40% and is further evaluated by increasing span while keeping other geometric parameters constant. The results show that with the same wing weight, span of the TBW will be about 18% longer than the cantilever wing so that the induced drag is reduced by about 17%.

1 Introduction

Nowadays more and more attention is being paid to green aircraft development, i.e. aircraft with low fuel consumption and low emissions, which is due to the increasing fuel price and concern over environment, and the limited energy. Industry and NASA are in pursuit of configuration changes that may lead to major performance gains in convenient take-off and landing aircraft [1]. One option towards this pursuit is to employ all-electric alternative propulsion systems [2]. Another is to improve the airframe designs. As the traditional configuration characterized by cantilevered wings has already reached to a maturity level, the designers can hardly make a significant improvement to meet the demand of green aircraft design. Innovative airframe designs have to be explored to achieve a substantial increase in lift-to-drag ratio for a given vehicle weight.

The truss-braced (or strut-braced) wing configuration is a promising innovative design that was proposed by NASA as one of the N+3 (2030-2035) generation aircraft concepts [3]. The idea of TBW configuration was proposed by Pfenninger in the early 1950s [4]. However, the early work focused on structure or aerodynamics discipline separately. As tight coupling exists between structure and aerodynamics, the full potential of TBW configuration needs to be reinvestigated in a multidisciplinary way. Mason et al. have conducted series of work on TBW configuration since 1997 [5], which suggests that multidisciplinary analysis and optimization of TBW configuration has potential of fully exploiting its benefit [6][7].

The benefits of TBW configuration can be explained by the following aspects: First, the truss provides bending load alleviation to the wing, allowing for a decreased thickness to chord ratio, an increased span and usually a reduction of wing weight; second, the thinner wing leads to lower transonic wave drag, and the larger wing span results in reduction of the induced drag. In addition, these favorable features allow for smaller wing sweep, which may unlock the limit of attaining natural laminar flow over traditional transonic wing; third, the engine size can be reduced due to the decreased weight and increased aerodynamic efficiency;

last, the drag reduction means fewer fuel consumption. Thus the TBW configuration is regarded as one of the promising configurations of future green aircraft.

In the design of TBW, buckling of the strut under negative loads is the most critical structural problem, which will be the first barrier when conducting the TBW studies. A single strut with telescoping sleeve mechanism (TSM) [7] and truss plus juries concepts [8] are possible way to solve this problem.

This paper aims to conduct some preliminary work for evaluating the benefit of TBW configuration in a multidisciplinary way considering both aerodynamic and structure. The structure is idealized as an I-beam model that is reasonable for evaluating the bending stiffness of the wing. The presented wing sizing module can be used to calculate the bending material weight of the wing-box. A "bell-shaped" span-wise circulation distribution [9] is applied to provide span-wise aerodynamic loads. The promising truss-system topologies of TBW are explored using topology optimization and then compared with the cantilever wing and compressive inactive SBW, with an attempt to answer the following questions: (1) how much wing weight can be reduced for a given level of aerodynamic performance? (2) For a given weight, how much drag can be reduced due to the increased wing span?

2 Problem Statement

2.1 Truss-braced Wing Modeling

The TBW aircraft is designed similar to A320-200 which flies a range of 5700km at M0.78 with 150 passengers. The wing is of span 34.1m and aspect ratio 9 that is a typical value for the civil airliners.

In the single-strut configuration, buckling of the strut under negative loads is the most critical structural problem when design a strut-braced wing (SBW). A strut with TSM [7] so that it is compressive-inactive and only carries tension loads and can prevent buckling and will be investigated in this paper, as shown in Fig. 1

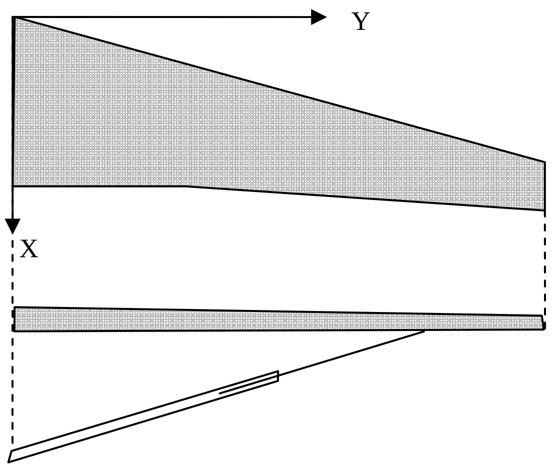


Fig. 1. SBW with TSM

A topology optimization will be performed to give other TBW models for comparison, which will be discussed in the following sections.

2.2 Load Cases

To determine the bending material weight of the SBW, three load cases are considered for structural sizing.

- 2.5 g pull-up maneuver
- -1.0 g pushover
- 1.0g cruise

In the following text it should be noted that, the wing weight for a cantilever wing means the bending material weight, and the wing weight for a TBW means the bending weight plus the truss-members weight.

2.3 I-Beam Model

The structure is idealized as an I-beam model (Fig. 2). This model is made up of web and upper and lower skin panels for carrying bending moments. The drawback of the I-beam model is it cannot carry any torsion moments. As this paper will focus only on the effect of the truss members on the bending stiffness of the wing, the simplification of this structural wing representation is reasonable.

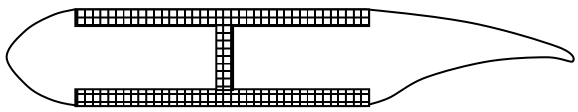


Fig. 2. I-beam model for bending weight calculation

The beam with variable cross sections is shown in Fig. 3. The design variables of the I-beam wing model include thickness of web and upper and lower skin panels of the piecewise wing as well as the cross section area of the truss-system members.

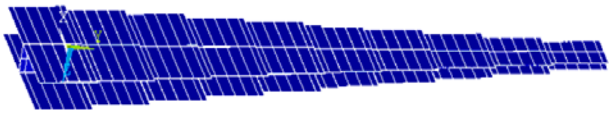


Fig. 3. Beam model with variable cross sections

2.4 Span-wise Lift Distribution

The span-wise lift distribution derived from a “bell shaped” circulation [9] is used to generate the aerodynamic loads. A family of lift distributions can be derived by distorting the elliptical distribution. By applying an exponent to the sine term in the transformation, so called “bell-shaped” circulation distributions can be created (Fig. 4). These were already used by the Horten brothers in most of their designs, beginning in the 1930s.

The span-wise coordinate η is transformed into a polar coordinate θ as:

$$\theta = \arccos(\eta) \text{ or } \sin(\theta) = \sqrt{1-\eta^2} \quad (1)$$

Then the span-wise circulation distribution can be written as

$$\Gamma(\eta) = \frac{\sin(\theta)^n}{\Gamma^*} \quad (2)$$

In Eq.(2) the basic distributions are normalized with the integral value Γ^* in order to produce the same unit lift:

$$\Gamma^* = \int_0^{\pi} \sin(\theta)^n d\theta \quad (3)$$

Typically the exponent n falls into the range between 1 (elliptical distribution) and 5 (heavily bell-shaped distribution).

In order to simplify practical application, the following polynomial approximation for the location of Γ^* is used [8].

$$\begin{aligned}\Gamma^* = {} & 1.959909894358 \\ & -0.478463760929 \cdot n \\ & +0.105689717313 \cdot n^2 \\ & -0.012997921686 \cdot n^3 \\ & -0.000636727578 \cdot n^4\end{aligned} \quad (4)$$

The current study used a bell-shaped distribution of n=2 which is relatively close to the elliptical distribution to generate loads for the I-beam model of wing.

3 Results and Discussion

3.1 Weight Reduction Investigation

3.1.1 Span-wise Position Optimization of Wing-Strut Intersection

This sub-section aims to find the optimal wing-strut intersection span-wise location for attaining maximum wing weight reduction for the single SBW with TSM. It is shown in Fig. 5 that maximum 46% wing weight reduction can be achieved by using SBW when connecting the strut to the wing at about 70% and locating the

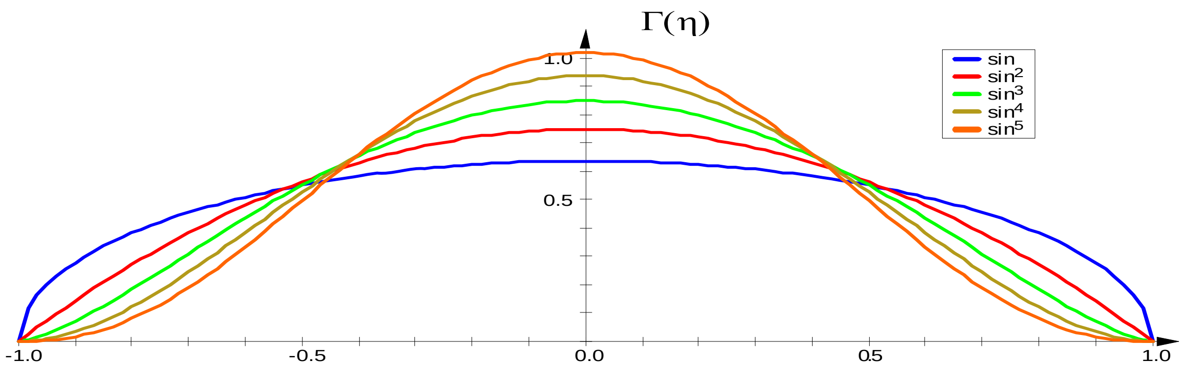


Fig. 4. A family of bell-shaped circulation distributions (normalized for same lift) [9]

engine at 35% span-wise location. The wing weight shown in Fig. 5 indicates the bending material weight.

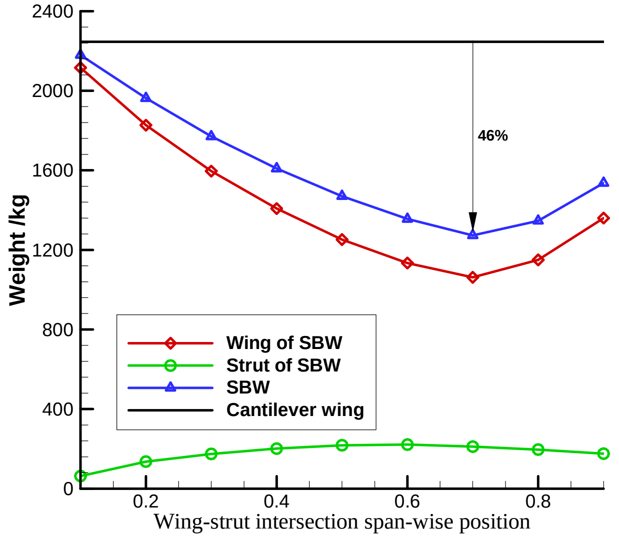


Fig. 5. Weight reduction for different wing-strut intersection

3.1.2 Truss Topology Optimization

This sub-section aims to identify new maximum stiffness topologies that could be used to guide onging multidisciplinary design optimization (MDO) work.

The FEM-based commercial software ANSYS is used for analyzing the structural performance of the I-beam wing structure as well as performing topology optimization and full-stress optimization. There are two options available in the ANSYS topology optimization module, optimality criteria (OC) approach that is the default choice and sequential convex programming (SCP) approach. The OC approach is applicable to problems with volume as constraint only. The SCP approach is applicable to all valid combinations of objective and constraints [10]. OC and SCP are both employed in this work to produce the stiffened configuration of structural material in a given domain for user defined boundary conditions and loads.

The ground-structure, boundary conditions and loading are defined in Fig. 6. Beam 44 of ANAYS finite elements is applied for the I-beam wing and Link 8 is for the truss system.

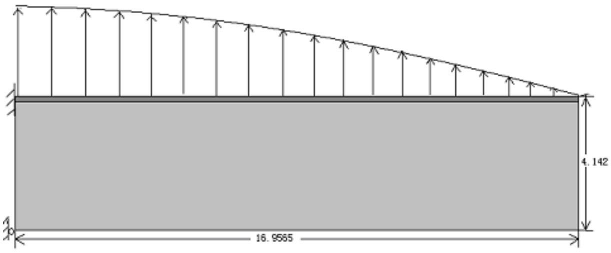


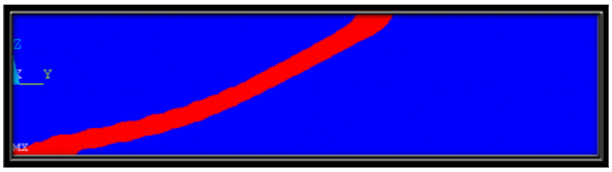
Fig. 6. TBW ground-structure, boundary conditions and loading

The TBW components are assumed to be aluminum alloy, the attributes of which are listed in Table 1.

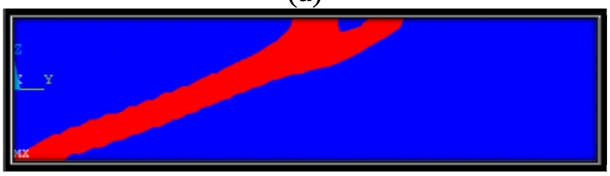
Table 1 Material attributes

Name	Al 7075-0
Elastic modulus /GN/m^2	71.7
Poisson’s ratio	0.33
Density / 10^{3}kg/m^3	2.81
Ultimate tensile strength /MPa	228
Ultimate tensile yield strength /MPa	103
Ultimate shear strength /MPa	152

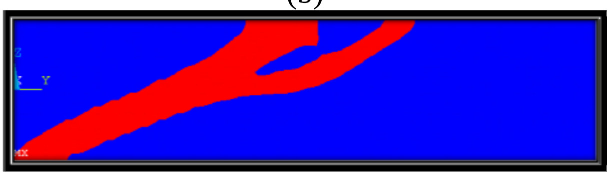
Structures were optimized for total volume fractions (TVF) of 10%, 15%, 20% and 25% of the original domain volume, using OC and SCP approach, respectively, as shown in Fig. 7 and Fig. 8. The response magnitudes using OC and SCP approaches are listed in Table 2 and Table 3, respectively. According to the topologies, three TBW concepts are created and evaluated in the following section.



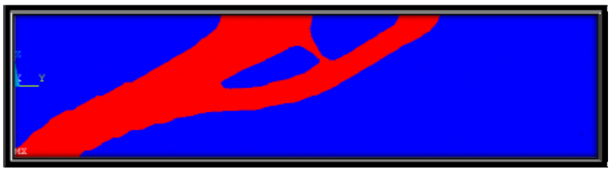
(a)



(b)



(c)

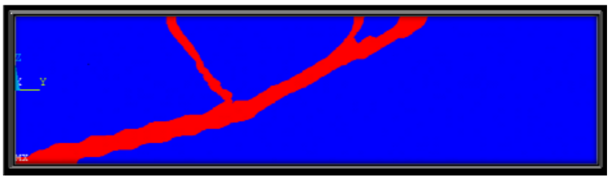


(d)

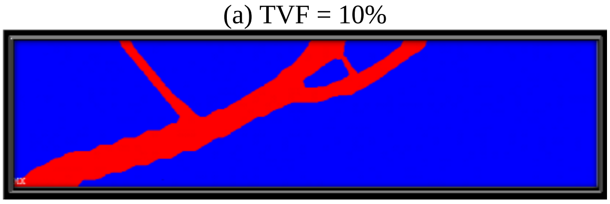
Fig. 7. Truss topology of different TVF (OC)

Table 2 Response of different topology (OC)

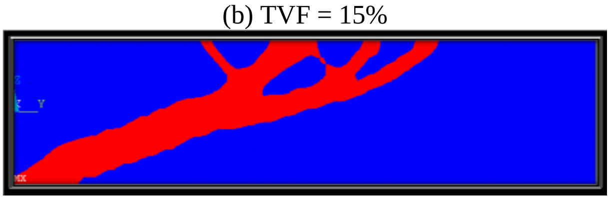
Fig	TVF	Tip deflection	Strain energy	Normalized tip deflection	Normalized strain energy
(a)	10%	56.3	2420	1	1
(b)	15%	47.7	2208	0.85	0.91
(c)	20%	39.7	2002	0.70	0.83
(d)	25%	35.3	1878	0.63	0.78



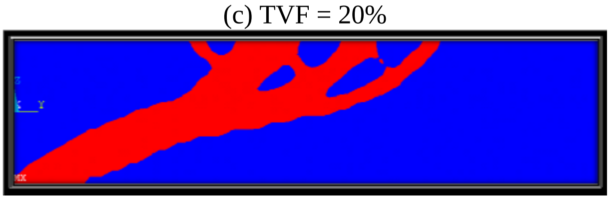
(a) TVF = 10%



(b) TVF = 15%



(c) TVF = 20%



(d) TVF = 25%

Fig. 8. Truss topology of different TVF (SCP)

Table 3 Response of different topology (SCP)

Fig	TVF	Tip deflection	Strain energy	Normalized tip deflection	Normalized strain energy
(a)	10%	62.4	2516	1.00	1.00
(b)	15%	50.3	2373	0.80	0.94
(c)	20%	41.9	2158	0.67	0.86
(d)	25%	35.7	1921	0.57	0.76

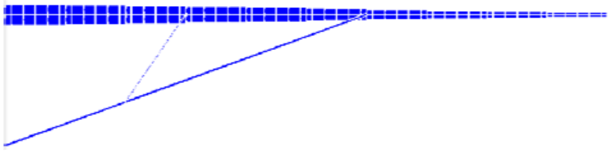
3.1.3 Comparison of Truss-braced Wings

This sub-section aims to make a comparison of the following wing concepts in order to explore the maximum weight-reduction benefit of the TBW:

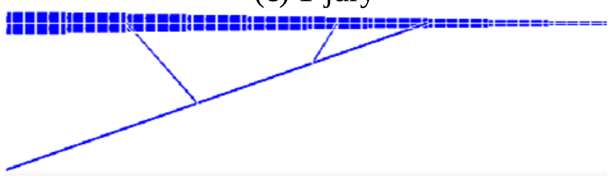
(a) Cantilever wing

(b) SBW with TSM

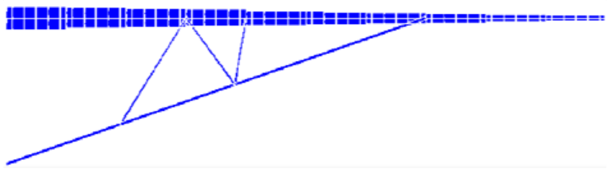
The remains are TBW concepts from topology optimization results in subsection 3.1.2, which include (c) 1-jury, (d) 2-jury and (e) 3-jury TBW configuration (Fig. 9).



(c) 1-jury



(d) 2-jury



(e) 3-jury

Fig. 9. TBW concepts from topology optimization

The full-stress optimization is conducted for sizing these five wing concepts and the comparisons of wing weight and tip deflection under 2.5g-overload are shown in Fig. 10. The results reveal that both (b) SBW with TSM and (e) 3-jury TBW can achieve the maximum weight reduction of about 46%. Furthermore these two configurations have only a small tip deflection under 2.5g-overload. The drawback of the concept (b) is a large tip deflection under negative loads as the wing is more flexible and the strut is not active. In addition, fatigue failure may happen to the strut with TSM if flutter occurs. So the concept (e) is chosen in this paper for the further investigation in the next sub-section.

3.2 Analysis of Aerodynamic Benefit of Truss-braced Wing

As the TBW concept (e) showed a maximum weight reduction in sub-section 3.1.3, some further investigation will be conducted to explore its aerodynamic benefit. The span is increased until the TBW has the same weight with the cantilever wing. It is known that with increase of span, the induced drag will be reduced. Then it can be seen, with the same weight with the cantilever wing, how much induced drag can be reduced by using the TBW. When increasing the span, the wing area is held constant.

Only preliminary study is conducted in which span is increased keeping other geometric parameters constant i.e. wing area, sweep angle and thickness, so that the effect on the total weight of aircraft can be minimized.

Fig. 11 shows the change of wing weight when increasing the span. The green line gives the weight of cantilever wing for comparison. It can be concluded that, with the same wing weight, the span of the TBW will be about 18% longer than the cantilever wing.

A number of methods are available for estimating the induced drag. The most widely used methods are Trefftz plane, Prandtl's lifting -line theory, and the vortex lattice method. In the current study multiple lifting-line theory coded by Prof. Dr. Horstmann of German Aerospace Center (DLR) is used. Fig. 12 shows the change of induced drag with respect to the span. The results show that considerable

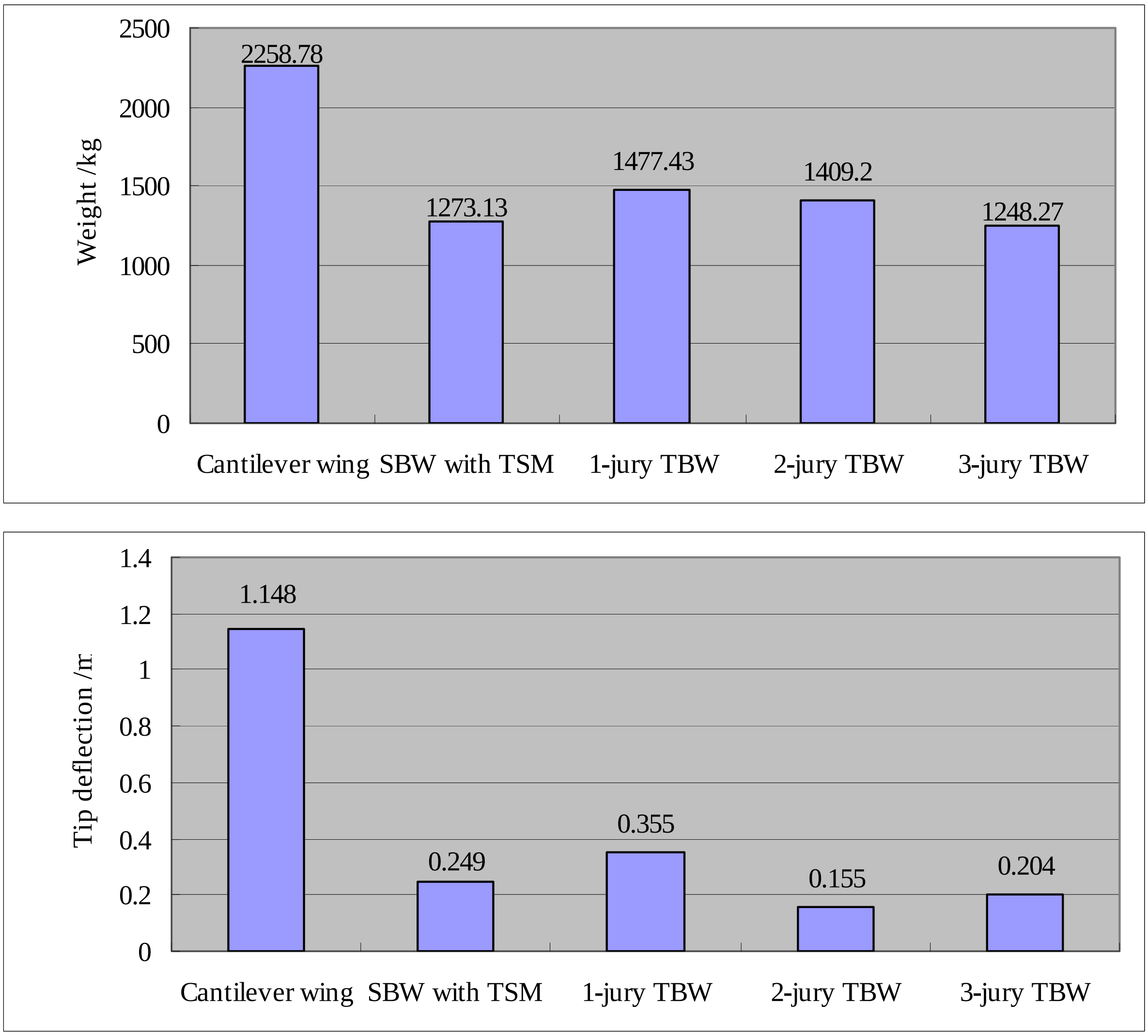


Fig. 10. Comparison of different TBW configurations with cantilever wing

decrease in induced drag can be attained by increasing the span of the wing: if the span is increased by 20%, the induced drag can be reduced by about 31.3%. As the induced drag often contributes nearly half of the wing total drag, it can be concluded that the total drag can be considerably reduced by applying TBW.

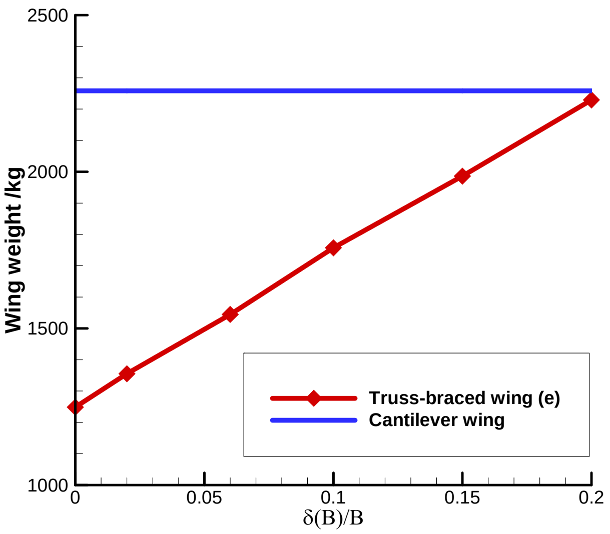


Fig. 11. Effect of span on weight of TBW

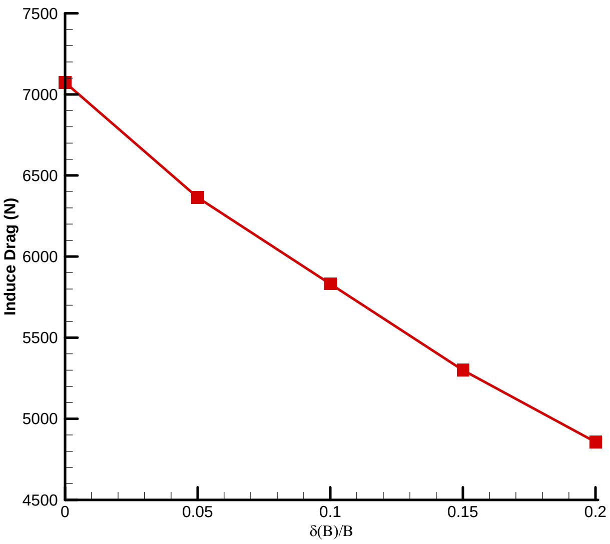


Fig. 12. Effect of span on induced drag

Conclusions

Some preliminary studies on the innovative truss-braced wing are conducted in this paper. The calculations reveal significant bending material weight saving by using truss. It is also shown that the span can be increased without weight penalty and in turn the induced drag can be reduced.

The future work will focus on developing aerodynamic analysis module for TBW, generating box-beam structural model for considering both bending and torsion stiffness of bending material, connecting a MDO chain for an optimized baseline TBW aircraft, consider more design variables for TBW sizing, such as wing-truss intersection locations, wing and truss geometries, etc.

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