Structural optimization of second-stage intertank composite X-shaped truss

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Abstract. An optimization procedure for composite second-stage intertank truss assembly used for connecting the fuel (Liquid Hydrogen, LH₂) tank and the oxidizer (Liquid Oxygen, LO₂) tank is proposed. The typical working conditions of X-shaped truss are 30 tons tensile load and 5.55 tons compressive load in sequence. Parametric geometrical model and finite element model are created in Catia R21 and Abaqus 6.14, respectively. An optimization procedure integrating geometrical model and finite element model has been constructed in Isight 2018, the algorithm of which is multi-islands genetic algorithm. The result shows that the weight of the optimal structure decreased by 26.50% comparing with the initial design.

1. Introduction
The connection adapter is one of the important part in rocket, which used to connect the different parts of rocket such as stages, payloads, fuel tanks and so on. At present, the connection adapter can be divided into two classes by the structural form, shell adapter and truss adapter. The shell adapter including cylindrical and conical adapter which depends on whether the parts have the same diameter or not. The shell adapter has been used in many rockets [1]. A cylindrical interstage adapter was used to connect the common core booster (CCB) and payload in Atlas V heavy-lift vehicle (HLV) series [1]. A conical interstage adapter transition, consists of hand laid-up carbon fiber reinforced polymer (CFRP) skin over an aluminum honeycomb core, was used to connect the CCB and upper stage [1]. Du et al [2] analyzed and manufactured a circular bearing structure subjected compressive load. The circular bearing structure can be integrated molded through flexible-mold assisted resin transfer molding (RTM). The composite lattice structure, one of the shell-like adapter, can also be used as a load-bearing part [3,4]. Vasilie et al [5] analyzed the relationship between buckling loading and geometrical parameters of the composite lattice structure. Zheng et al [6] studied the mechanical properties of the grid lattice cylinders subjected axial compression. The shell adapter can be manufactured by integrated molding. However, the defects during the manufacturing process are difficult to control, which can make such a significant impact on the reliability [7]. The thrust truss adapter assembled by robs and joints can avoid this problem because robs and joints can be manufactured respectively. What’s more, a payload truss adapter consists of composite tubes was adopted to connect the payload and the end of the Centaur’s forward adapter in Atlas V [1]. For composite truss adapter, connection is one of the main problem. The stress of the connection region between load-bearing robs and the frame of parts to be connected is quite complex. Generally, metallic end fitting was used to increase the reliability. However, the weight of the connection adapter increases because of the metallic end fitting.
Refer to the intertank truss assembly used in Delta IV to connect the fuel (Liquid Hydrogen, LH$_2$) tank and oxidizer (Liquid Oxygen, LO$_2$) tank assembled in second-stage rocket, a new composite truss adapter is designed to carry 30 tons tensile load and 5.55 tons compressive load. Unlike the general truss adapter which have metallic joint [8], the body and joint of the X-shaped truss are integral. The joint of the X-shaped truss connects the frame of fuel/oxidizer tank by bolts while the straight section gradually changes to the joint through transition section. This paper is structured as follows. Section 2 introduces the material and its mechanical properties used for X-shaped truss, the geometrical and optimization models. Section 3 presents the analysis of the results while Section 4 is the conclusion of this study.

2. Materials and methods

2.1. Materials and mechanical properties

The material of X-shaped truss is T800/602 epoxy plain-weave composite. The X-shape truss consists of two hat stringers (inner/outer hat stringer) and one flat plate, which can be manufactured in the following steps: 1) Two rigid female molds were manufactured for two hat stringers respectively. Rigid female and male molds were prepared for flat plate. 2) Layups of the plain-weave prepreg layers. The hat stringers were sealed by vacuum bag. 3) Curing in the autoclave at 80℃ for 1 hour and 125℃ for 6 hours subsequently. The curing pressure is 0.6 MPa. 4) These three parts were demoulded and then glued together.

We simplified the mechanical properties of T800/602 epoxy plain-weave composite as in-plane isotropic mechanical properties to decrease the difficulty of the finite element model and increase the optimization efficiency. The mechanical properties are listed in Table 1.

| Engineering constants | Value   | Strength properties | Value |
|-----------------------|---------|---------------------|-------|
| $E_{11}$/GPa          | 70.75   | $X_t$/MPa           | 900   |
| $E_{22}$/GPa          | 70.75   | $Y_t$/MPa           | 900   |
| $G_{12}$/GPa          | 3.787   | $X_c$/MPa           | 700   |
| $G_{13}=G_{23}$/GPa   | 2.931   | $Y_c$/MPa           | 700   |
| $v_{12}$              | 0.08    | $S$/MPa             | 90    |

2.2. Geometrical model

Figure 1. The structure of the intertank truss assembly and fuel/oxidizer tank.

Figure 2. X-shaped truss.
2.2.1. Structural features. The fuel (LH$_2$) tank and oxidizer (LO$_2$) tank assembled in a certain type of second-stage rocket are connected by an intertank truss assembly (Figure 1), which consists of 12 identical X-shaped trusses in circle arrangement. X-shaped truss is symmetrical with SYM plane, which can be divided into four parts: joint, transition, straight section and intersection, according to structural features (figure 2).

The X-shaped truss connect the frame of the fuel/oxidizer tank by bolts in the joint. The joint has eight bolt holes (figure 3). The cross section of the straight section is shown in figure 4. The main role of the flat plate is to carry the tensile and compress load while the hat stringers can improve the stability of X-shaped truss under compressive load. The hat stringer include one flange portion and two legs. The transition section (figure 5) was used to implement the gentle transition between the joint and straight section which are not in the same plane. The hat stringer in straight section gradually reduces the protruding height and increases the width to the joint section through the transition section. The arms of the X-shaped truss converged and intersected in the intersection (figure 6). To decrease the stress concentration, the intersection should be as smooth as possible.

2.2.2. Geometrical parameters. The geometrical model with high-precision is the key phases in numerical analysis [8]. We developed the parametric geometrical model in Catia R21. To describe X-shaped truss completely, a set of geometrical parameters needed to be defined.

- Joint. The height and width of the joint are 96 mm and 256 mm respectively. The bolt holes whose radius is 7 mm have been designed in a staggered arrangement in two rows. The relative position of these bolt holes is shown in figure 3. The dimensions of joint section are

![Figure 3. The dimensions of the joint.](image)

![Figure 4. Structure and geometrical parameters of the cross-section of the straight section.](image)

![Figure 5. Structure and geometrical parameters of the transition section.](image)

![Figure 6. Structure and geometrical parameters of the intersection.](image)
provided by design department, which are predefined dimensions.

- **Straight section.** The cross section of the straight section (figure 4) is symmetrical with SYM1 plane and SYM2 plane. Table 2 lists all of the geometrical parameters of straight section. The cross section of the straight section has seven parameters, six of them are independent. Five variables are needed to define the cross-section’s dimension: the thickness $T_1$, the draft angle $\beta$, the width of the leg $E$, the height and width of the flange portion, $P$ and $J$ respectively. In addition, the flat plate includes two variables: the thickness and the width, $T_0$ and $Q$ respectively. The relationship between the parameters $Q$, $E$, $J$, $P$ and $\beta$:

\[ Q = J + 2(E + P \cdot \tan(\beta)) \]  

Table 2. Parameters of the geometrical model.

| Region      | Symbol | Explanation                        |
|-------------|--------|------------------------------------|
| Straight section | $E$    | The width of the leg               |
|             | $J$    | The width of the flange portion    |
|             | $P$    | The height of the hat stringer     |
|             | $Q$    | The width of the flat plate        |
|             | $\beta$| The draft angle of the hat stringer|
|             | $T_1$  | The thickness of the hat stringer  |
|             | $T_0$  | The thickness of the flat plate    |
| Transition  | $K_u$  | The length of the upper transition section |
|             | $K_d$  | The length of the lower transition section |
| Intersection| $R_1$  | The radius of the fillet on the left and right sides |
|             | $R_2$  | The radius of the fillet on the upper and lower sides |

- **Transition.** As shown in figure 5, the length of transition section is measured by the length of central axis $K$. The central axis of the transition section intersects with the joint at the midpoint of the joint’s upper edge which means the width of the joint $W$ is two times of $S_1$.

\[ W = 2S_1 \]  

The width of flange portion $S_0$ in the connection part closed to the joint is half of the width of the joint $W$.

\[ W = 2S_0 \]  

- **Intersection.** The fillet radius of intersection in the same side are equal. $R_1$ indicate the radius of fillet on the left and right sides while $R_2$ indicate the radius of fillet on the upper and lower sides (figure 6).

2.3. **Finite element model**

Abaqus is used in many fields, such as statics [9] and dynamics [10,11]. The elements’ types used in the finite element model are S4R and S3R. The element size is 5 mm. The finite element model has about 40,000 S4R elements and 1000 S3R elements. The certain number of the elements depend on the geometrical parameters. The two hat stringers were bound to flat plate by tie constraints. We developed the finite element model using the half of the X-shaped truss to reduce the amount of computation. The CPU time of each iteration is about 400 seconds. Symmetry constraints was applied to the symmetrical plane. The edges of each bolt hole are coupled to the center of the hole to simulate the effect of the bolt. All of the node on the edges of each bolt hole have the same kinematic behavior in all directions as the center of the hole. The center of the bolts in the lower joint are full clamped and a fixed displacement in normal direction of the joint surface was applied to the upper joint. The concentrate force was applied to the center of the hole (figure 7). According to the rocket launching
process, the tensile and compressive load of the X-shaped truss are 300 kN and 55.5 kN respectively. We assume that the loads on each bolt are the same. The load on each bolt can be evaluated as

\[
\text{The load of the single bolt} = \frac{\text{Total load of X-shaped truss}}{\text{The number of bolts} \times 2}
\]  

Therefore, the forces on each bolt are 18.75 kN tensile load and 3.47 kN compress load, separately.

![Figure 7. Boundary conditions of the finite element model.](image)

### 2.4. Optimization model

**2.4.1. Definition.** Ten parameters including geometrical parameters and thickness of the shell are chosen as the optimization variables: \(E, J, P, \beta, T_0, T_1, R_1, R_2, K_u\) and \(K_d\). We set the initial values and ranges as shown in Table 3. The objective of the optimization is the mass of the X-shaped truss. The constraints can be summarized as follows: 1) The maximum of the principal strain (TENSILE_E_MAX) under the tensile load. 2) The damage factors calculated by Hashin’s criterion: HSNFTCRT (Hashin's fiber tensile damage initiation criterion), HSNFCCRT (Hashin's fiber compressive damage initiation criterion), HSNMTCRT (Hashin's matrix tensile damage initiation criterion), HSNMCCRT (Hashin's matrix compressive damage initiation criterion). 3) The external load (PRESS_F_MAX) under compressive load. Table 4 lists the initial value and the boundary value of each constraint.

| Region       | Parameters | Lower bound | Initial value | Upper bound | Optimal solution |
|--------------|------------|-------------|---------------|-------------|------------------|
| Straight section | \(E (\text{mm})\) | 25 | 30 | 60 | 53.61 |
|              | \(J (\text{mm})\) | 55 | 60 | 90 | 64.14 |
|              | \(P (\text{mm})\) | 10 | 20 | 45 | 12.30 |
|              | \(\beta (\text{deg})\) | 5 | 10 | 20 | 18.66 |
|              | \(T_0 (\text{mm})\) | 5 | 8 | 12 | 7.55 |
|              | \(T_1 (\text{mm})\) | 1 | 5 | 6 | 2.69 |
| Transition   | \(K_u (\text{mm})\) | 130 | 150 | 250 | 205.0 |
|              | \(K_d (\text{mm})\) | 130 | 150 | 210 | 143.0 |
| Intersection | \(R_1 (\text{mm})\) | 250 | 400 | 600 | 295.24 |
|              | \(R_2 (\text{mm})\) | 40 | 50 | 80 | 45.99 |
Table 4. The constraints of optimization.

| Parameters          | Lower bound | Initial value | Upper bound | Optimal solution |
|---------------------|-------------|---------------|-------------|------------------|
| TENSILE_E_MAX       | \           | 0.00787       | 0.006       | 0.00598          |
| HSNFTCRT            | \           | 0.382         | 1           | 0.098            |
| HSNFCCRT            | \           | 0.014         | 1           | 0.053            |
| HSNMTCRT            | \           | 0.182         | 1           | 0.166            |
| HSNMCCRT            | \           | 0.038         | 1           | 0.119            |
| PRESS_F_MAX         | 27750.0N    | 134008.0N     | \           | 43263.2N         |

2.4.2. Optimization flow. The optimization flow was constructed in Isight (figure 8). Parameters of geometrical model are correlated with the written parameter file in Isight using data exchanger component GEO_DATA. The simcode component UPDATA_GEO updates the geometrical model based on the parameters in GEO_DATA. The finite element model developed in Abaqus using python script is written in data exchanger component FEM_DATA. The finite element model will be submitted after the update of geometrical model and finite element model. The component of READ_RES will extract the results that read by RES_DATA. The optimization algorithm, objective and constraints can be set in optimization component Optimization1. Optimization1 will point out the new direction of the optimization based on the result obtained in last step.

2.4.3. Optimization algorithm. The problem can be summarized as an optimization problem with multiple constraints, multiple variables and single objective. The common algorithms used in such problems include response surface method (RSM) [12,13], genetic algorithm (GA) [14] and multi-island genetic algorithm (MIGA) [13,15]. The MIGA is an improved version of the GA. The population divided into several islands. Then the same operations as GA was performed separately. The migration of population from one island to another island will improve the species diversity, which can promote the global convergence. The migration between the islands depend on the rate of migration and the interval of migration. Thus, we use MIGA to search the optimal design. Table 5 shows the parameters of MIGA.

Table 5. The parameters of MIGA.

| Parameters          | Value |
|---------------------|-------|
| Sub-population size | 10    |
| Number of islands   | 5     |
| Number of generations | 20  |
| Rate of crossover   | 0.01  |
| Rate of mutation    | 0.01  |
| Interval of migration | 5    |

3. Results and discussions

3.1. Design variables
The optimal design is obtained after 1000 iterations through MIGA (figure 9). The blue spots and
orange triangle respectively indicate whether the design satisfies the constraints or not. The green square indicates the optimal solution. The optimal results of design variables were listed in Table 3. None of the values of the optimal design is equal to the boundary value, which means the ranges of the variables are reasonable. For the initial design, the tensile strain does not satisfy the constraint. The buckling loading, however, is about 5 times as much as the constraint boundary value. The optimal design increases the load bearing capacity under tensile load by increasing the value of the E, J, β. As can be seen in the figure 10, these three variables are negatively correlated with the maximum of the principal strain (TENSILE_E_MAX). What’s more, the P value was decreased, which is positively correlated with mass and the buckling loading (PRESS_F_MAX). Although the decrease in P value will induce the decrease in buckling loading, it can save the mass. Furthermore, the optimal design decreases the thickness of the hat stringers and flat plate to reduce the mass.

**Figure 9.** The iteration process.

**Figure 10.** Correlation table.

### 3.2. Responses

The response values of the optimal design are shown in Table 4. For optimal design, the strain value is very close to the boundary value and the other constraints are not, which means the strain constraint is a key constraint. The maximum strain of each part is smaller than the strain constraint. The regions with large strain are the intersection and the connection between straight section and transition section (figure 11). Comparing to the initial design, the buckling load of the optimal design decreased by 66.71%, but it still meets the constraint.

**Figure 11.** Strain contours under tensile load. (a) Outer hat stringer (b) Flat plate (c) Inner hat stringer.
3.3. Objective

The mass of the initial design and the optimal design (half of the X-shaped truss) is 7.838 Kg and 6.220 Kg, respectively. All of the variables except $R_1$ are positively correlated with mass. Although the decrease of the $R_1$ and the increase of the J induces the increase of the mass, which can reduce the strain under tensile load significantly. The decrease of the mass, largely because of the decrease of the thickness of the flat plate.

4. Conclusions

An optimization procedure of composite truss adapter was developed, integrating 3D CAD application and finite element analysis software to implement the automation of the geometric modelling and finite element analyzing. An optimal geometrical model of the X-shape truss subjected to multiple constraints with the minimum request of mass was obtained, which can be used as a reference in manufacturing. Based on the compare between initial design and the optimal design, it has been shown that the required carrying capacity in compressive load is easy to achieve. The main role of the optimization is to increase the load bearing capacity under tensile load. Also, it found that the tensile resistance can be significantly enhanced by widening the arm of the X-shaped truss. The optimal design can deliver up to 26.50% mass savings in comparison with initial design.

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