Mechanical Response of Combined Thin-Walled Boxes under Influence of Complex Mechanical Loading Conditions - FEM Analysis

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Abstract. The subject of the analysis are thin-walled aluminum boxes connected by mechanical fasteners only or with the addition of cohesive layer. The analyzed elements have a great potential in the construction of aircraft engines as well as in other applications where thin-walled components are used. Cohesive connections, are now increasingly used in construction of structural components. Therefore, this paper presents results and comparison of selected thin-walled structure connected with mechanical connectors and cohesive layers. The main objective in this paper was to perform FEM analysis and to determine mechanical response of the selected thin-walled structure with different types of connections under quasi-static load. Aluminum boxes were subjected to a complex load, such as bending and twisting. The numerical model includes 2 damage processes in the: (1) aluminum, and (2) fasteners. This allowed us to determine locations of the most stressed, and most exposed to damage areas inside of the whole thin-walled box. The obtained results also allow to determine degree of usefulness of cohesive joints in the construction of the thin-walled structures under influence of quasi-static loads.

1. Introduction
Thin-walled box sections are commonly used in many fields of technology, such as aerospace industry, automotive industry, naval industry, civil engineering etc. These types of local structural elements connection and high level of energy absorption during load is very important for the whole engineering structures [1]. There are many joining techniques of thin-walled components, such as adhesion [2, 3], welding and spot welding [4-6], clinching [7-10], riveting [11], and combinations of the aforementioned [12-19], are used most frequently. The interesting types of connections are thin-walled beams and columns, e.g. [20-23].

This paper is focused on the influence of an adhesive layer on the equivalent stiffness and strength of the analyzed thin-walled aluminum boxes (figure 1) subjected to complex mechanical loading. The thin-walled FEM model is made of two aluminum parts. We considered 2 types of the boxes connected by:

\begin{itemize}
  \item mechanical connectors only - the first case,
  \item hybrid connection consisting of the mechanical connectors and adhesive layers - the second case.
\end{itemize}

After analyzing several different numerical models it turned out that the most effective is to simplify 3-D exact geometry of the aluminium box with mechanical clips by replacing them with mechanical
connectors, i.e. the "connector" type of joining available in the ABAQUS program, figures 1-3. Both boxes were subjected to complex mechanical loading i.e. bending and twisting, figure 4.

**Figure 1.** Geometries of the 2 parts forming of the thin-walled box

**Figure 2.** Details of the exact 3-D model of the thin-walled box

**Figure 3.** Simplification of the exact 3-D model with application of "connector" type of joining
2. Numerical model
The numerical analysis was performed using the finite element method (FEA) with ABAQUS Explicit code. The complex numerical model consists of three types of elements:

- the 2 basic parts of the thin-walled made of aluminum 7075,
- 4 mechanical clips (figure 2) or their simplified version by 4 "connectors" (figure 3),
- cohesive layer created by adhesive Loctite 9514.

All of above components were modeled by various type of materials with different damage degradation processes. Geometry simplification of the 4 mechanical clips by corresponding mechanical connectors significantly accelerated calculation time and allowed getting the similar results with high level of accuracy.

2.1. Ductile damage model – aluminum
To describe aluminum parts of the boxes an elastic-plastic model with damage was used, e.g. [12-19, 25], figure 5. The damage parameter $D$ starts to gradually increase from initial value 0, for equivalent fracture strain $\varepsilon_{pl0}$, to ended value 1, for equivalent fracture strain $\varepsilon_{plf}$ at the time of complete damage.

![Figure 4](image)

**Figure 4.** Experimental stand with the simplified box and complex scheme of applied loads

![Figure 5](image)

**Figure 5.** Ductile damage model (DDM) of the elasto-plastic material

The model assumes that the equivalent plastic strain $\varepsilon_{pl0}$ at the onset of damage is a function of stress triaxiality $\eta$ and an equivalent plastic strain rate $\dot{\varepsilon}_{pl0}$. Stress triaxiality parameter is equal to $\eta = -p / q$, where $p$ is pressure stress, and $q$ is equivalent von Mises stress.
The criterion for damage initiation is met when:

\[ \omega_D = \int 0 \leq \frac{d \varepsilon^{pl}}{\varepsilon_0^{pl}(\eta / \varepsilon_0^{pl})} = 1, \]  

(1)

where \( \omega_D \) is a state variable that increases monotonically with the plastic deformations. When the \( \varepsilon_0^{pl} \) point is exceeded, damage develops. State of stress \( \sigma \) is a function of the damage parameter \( D \) and stress due to undamaged response \( \sigma_0 \), and it is equal to:

\[ \sigma = (1 - D) \sigma_0 . \]  

(2)

The current value of the Young’s modulus \( E \) is:

\[ E = (1 - D) E_0 , \]  

(3)

where \( E_0 \) is the initial value of the Young's modulus.

Material parameters of aluminum used in FEM analysis are shown in Table 1.

### Table 1. Material parameters of aluminum

| Parameter     | Value   |
|---------------|---------|
| Mass density  | 2700 kg/m³ |
| Young’s modulus | 69.6 GPa  |
| Poisson ratio | 0.34 |
| Yield point   | 470 MPa |
| Fracture energy | 22 mJ |

#### 2.2. Model of mechanical connector [25]

In order to simplify the 3-D thin-walled box the mechanical connector constitutive model (force-displacement characteristics) were determined with the FEA for the exact model subjected to different load cases. The FEA analyzes for: pulling, shearing and bending were made with the 3-D solid model, shown in figure 2. The basic strength characteristics of the connector model are collected in Table 2.

### Table 2. Strength parameters of the connector

| Parameter     | Value   |
|---------------|---------|
| Pulling       | 423 N   |
| Shearing      | 920 N   |
| Bending       | 645 Nm  |
| Max. pull     | 1920 N  |
| Max. shearing | 2250 N  |
| Max. bending  | 5740 Nm |

To describe the constitutive behavior of the connector we adopted the *Cartesian + Cardan* type of joining. This combination allows determination of the joint properties for shifts in each direction and rotation for each axis. There is also the possibility of a detailed description of the connector in the strength context with regard to the elastic part, the plastic part and the damage process (figure 6). The description of the connectors work is limited to determining of the force-displacement relation.

![Figure 6. Constitutive behavior of the connectors](image-url)
After elaboration the new connector model we created the simplified thin-walled box presented in figure 3, which was subsequently subjected to the complex state loading, figure 4.

2.3. Adhesive interface connection along edges of the parts 1 and 2
To describe the adhesive connection (figure 3), the surface-based cohesive behavior was used, e.g. [12-19, 25-35]. Negligibly small interface thickness using the traction-separation constitutive model (figure 7) was introduced between the 2 parts of the thin-walled box.

![Figure 7. Traction-separation model for adhesive interface connection.](image)

The cohesive behavior was modeled as a linear elastic traction-separation with damage. Figure 7 shown this model, were: \( \delta \) is contact separation, \( t \) is contact stress (traction), and \( G_c \) is fracture energy. Traction is the function of contact force \( F \) and current area at each contact point \( A \).

\[
t = \frac{F}{A} \tag{4}
\]

The lower indices in \( \delta_n \), \( \delta_s \) and \( \delta_t \) determine the direction: \( n \) - normal, \( s \) - shear 1, \( t \) - shear 2. Damage initiation occurs when the maximum stress criterion is satisfied:

\[
\text{MAX} \left\{ \frac{t_n}{t_n^{\max}}, \frac{t_s}{t_s^{\max}}, \frac{t_t}{t_t^{\max}} \right\} = 1 \tag{5}
\]

In this cohesive model damage evolution describes the degradation of the adhesive stiffness, and it is based on fracture energy \( G_c \). Table 3 contains adhesive parameters adopted in the numerical model.

| Table 3. Strength parameters of adhesive layer |
|-----------------------------------------------|
| Mass density \([\text{kg/m}^3]\) | Young’s modulus \([\text{GPa}]\) | Tensile strength \([\text{MPa}]\) | Shear strength \([\text{MPa}]\) | Fracture energy \([\text{mJ}]\) |
| Loctite 9514 | 1440 | 1.46 | 44 | 45 | 0.9 |

3. Results
The numerical analyzes carried out allow to assess assumptions correctness in formulation of the simplified model. Figure 8 shows the distribution of forces versus displacement for the exact and simplified models. The force distributions show that the convergence is very good and a small difference occurs only in the maximum force values. However, the difference in time of calculations is huge, because the process of counting in the exact 3-D model is more than 40 times longer than in case of the simplified model.

By comparing the force distributions in figure 9, the influence of the adhesive layer on the quality of the joint can be clearly seen. A greater increase in stiffness in the hybrid connection is clearly visible in the initial loading stage. After exceeding the critical failure stresses in the cohesive connection model, the adhesive layer is totally damaged. Then the stiffness of the entire box is reduced and the system
connected only by the mechanical connectors. For the analyzed model, the damage to the adhesive layer occurred at the displacement level of 6 mm.

Figure 8. Force-displacement diagram. The simplified and the 3-D exact solid model.

Figure 9. Force-displacement diagram. Two kinds of connection.

4. Conclusions

Summarizing, the following conclusion can be formulated:

- A simplified model of the complex shaped clips and boxes strongly accelerate the calculation time.
- The obtained results for the simplified model do not differ qualitatively from the results of the exact 3-D model.
- Simplified solutions give the opportunity to analyze the work of more complex and larger structures with low equipment costs.
- The application of the additional adhesive layer increases the stiffness of the element in the initial phase of the work of the thin-wall structure. But after failure of the adhesive interface, the structure response is the same for both cases. The use of the adhesive joint is justified in the initial deformation stage of the entire element.
5. References

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