Composite Fittings

Shear clips

Attachment clips

Lugs

Large special purpose fitting
Fittings - General

- A fitting connects at least two other parts
- It (hopefully) transfers load effectively at the junction
- Loads are usually transmitted in multiple directions
- Fittings are typically small compared to the parts they connect
- There are some “generic” fittings such as:
  - tension and shear clips
  - lugs
  - bathtub fittings
- Design of fittings is very challenging
Tension Clips

- analyze web for mat’f failure
- analyze web for bolt bearing (attachment to adjacent structure)
- analyze corner for delamination
- analyze flange for pull-through
- analyze flange for mat’f failure (include moment $M_1$)
- large deflection analysis for flange

Close-up edge of horizontal flange of clip with applied loads

c.g. of triangular contact stresses causing $M_1$
Tension clips - example

all clips have the same weight
• analyze corner under shear
• include additional shear stress due to torsion
• important point: amount of torque transmitted is a function of stiffness of back-up structure
Shear clips – transmitted moment

A stiff back-up structure minimizes moment or torque transmitted.

![Graph showing the relationship between clip moment and moment in the backup structure with varying bending stiffness and gussets.](image)
Lugs – axial loading

Net section failure

Shearout, (shear failure ahead of pin hole along loading plane) and net section failure combined

Bearing, (hole elongates and material ahead of pin fails) and net section failure combined

Delamination
Composite lugs under axial loads: Analytical predictions versus test results
Lugs – transverse loading

Lug free-body diagram

Equivalent beam model

\[ L = D + \frac{h}{2} \]
Composite lugs under transverse loads: Analytical predictions versus test results

- Predictions are within 9% of test results for quasi-isotropic lugs with mixtures of tape and fabric plies
Lugs – Oblique loading

- first, solve the two separate problems:
  - lug under axial loading $F \cos \phi$
  - lug under transverse loading $F \sin \phi$
- then apply interaction formula:

\[
\left( \frac{F \cos \phi}{F_a} \right)^{1.6} + \left( \frac{F \sin \phi}{F_{tr}} \right)^{1.6} = 1
\]

$F_a$ and $F_{tr}$ are the individual failure loads under axial or transverse load respectively.
Composite lugs under oblique loads: Analytical predictions versus test results

Graph showing the relationship between $F_{\sin\phi}/F_{tr}$ and $F_{\cos\phi}/F_{a}$ with test results represented by black dots and the analytical prediction by an interaction curve.
Design tools

• **Bruhn, E.F., “Analysis and Design of Flight Vehicle Structures”**
  
  — excellent overview of all types of considerations in the design and analysis of aircraft
  
  — isotropic materials but many methods can be (have been) extended to composites

• **Niu, M.C-Y, and Niu, M., “Composite Airframe Structures”**
  
  — a lot of information, design guidelines, curves and equations BUT not all very accurate (use with care)
Design tools

• Young, W.C., and Budynas R.G., “Roark’s Formulas for Stress and Strain”
  – excellent tabular solutions for various structural configurations (plates, beams, pressure vessels, etc)
  – isotropic only but some results can be (have been) extended to composites

• ESDU
  – design data sheets and software
  – large variety of problems including composites
  – validated design curves and computer programs
  – be extra careful to make sure you use what is applicable to your case
  – www.esdu.com
Application 4 – Composite panel under pressure and use of ESDU data sheets

- simply supported plate
- determine out-of-plane deflection $w$ using a linear solution and compare to ESDU (hence the English units in this problem)
- discuss differences between solutions; can linear solution be used in design?
- what exactly does simply-supported mean in this case?
Application 4 – Panel under pressure; linear solution

• assume the out-of-plane displacement \( w \) is given by

\[
w = \sum \sum A_{mn} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b}
\]

satisfies the requirement \( w=0 \) all around the panel edges; \( A_{mn} \) are unknown coefficients

• the governing equation for \( D_{16} = D_{26} = B_{ij} = 0 \) was given in section 5.2.2:

\[
\frac{D_{11}}{\partial x^4} + 2(D_{12} + 2D_{66}) \frac{\partial^4 w}{\partial x^2 \partial y^2} + D_{22} \frac{\partial^4 w}{\partial y^4} = p_z + N_x \frac{\partial^2 w}{\partial x^2} + N_y \frac{\partial^2 w}{\partial y^2} + 2N_x \frac{\partial^2 w}{\partial x \partial y} -
\]

\[
p_x \frac{\partial w}{\partial x} - p_y \frac{\partial w}{\partial y}
\]

with \( p_z = p_o = 20 \) psi
Application 4 – Panel under pressure; linear solution

• expand \( p_o \) in a double Fourier series:

\[
p_o = \sum \sum B_{mn} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b}
\]

B_{mn} are unknown coefficients

• determine \( B_{mn} \) by standard approach for obtaining Fourier coefficients:

\[
\int_0^a \int_0^b p_o \sin \frac{q\pi x}{a} \sin \frac{r\pi y}{b} \, dydx = \int_0^a \int_0^b B_{mn} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} \sin \frac{q\pi x}{a} \sin \frac{r\pi y}{b} \, dydx
\]

integrals are non-zero only when \( m=q \) and \( n=r \) with \( m,n \)

• performing the integrations

\[
B_{mn} = \frac{16 p_o}{\pi^2 mn}
\]
Application 4 – Panel under pressure; linear solution

• substituting in the governing equation for \( w \):

\[
\sum \sum \left[ D_{11} \left( \frac{m \pi}{a} \right)^4 + 2(D_{12} + 2D_{66}) \frac{m^2 n^2 \pi^4}{a^2 b^2} + D_{22} \frac{n^4 \pi^4}{b^4} \right] A_{mn} \sin \frac{m \pi x}{a} \sin \frac{n \pi y}{b} = \sum \sum \frac{16 p_o}{\pi^2 mn} \sin \frac{m \pi x}{a} \sin \frac{n \pi y}{b}
\]

• matching term by term, can solve for \( A_{mn} \)

\[
A_{mn} = \frac{16 p_o}{\pi^2 mn} \frac{D_{11} \left( \frac{m \pi}{a} \right)^4 + 2(D_{12} + 2D_{66}) \frac{m^2 n^2 \pi^4}{a^2 b^2} + D_{22} \frac{n^4 \pi^4}{b^4}}
\]
Application 4 – Panel under pressure; linear solution

- at the center of the plate the deflection $\delta$ can be determined:

$$
\delta = \sum \sum \frac{16p_o}{\pi^2 mn} \frac{1}{D_{11}} \left( \frac{m\pi}{a} \right)^4 + 2(D_{12} + 2D_{66}) \frac{m^2 n^2 \pi^4}{a^2 b^2} + D_{22} \frac{n^4 \pi^4}{b^4} \sin \frac{m\pi}{2} \sin \frac{n\pi}{2}
$$

(m,n odd)
Application 4 – Panel under pressure; linear solution comparison to ESDU

• ESDU item 93011 provides a large deflection moderate rotation solution with specific results for:

\[ a = b = 50 \text{ in} \quad t = 0.5 \text{ in} \]
\[ D_{11} = D_{22} = 0.347 \times 10^6 \text{ lbf in} \]
\[ D_{12} = 0.11 \times 10^6 \text{ lbf in} \]
\[ D_{33} = 0.12 \times 10^6 \text{ lbf in} \]
\[ A_{11} = A_{22} = 16.7 \times 10^6 \text{ lbf/in} \]
\[ A_{12} = 5.27 \times 10^6 \text{ lbf/in} \]
\[ A_{33} = 5.7 \times 10^6 \text{ lbf/in} \]

• applying our solution to this problem,

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<th>p_0 (psi)</th>
<th>\delta (in)</th>
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Application 4 – Panel under pressure (comparison to ESDU)

**PLATE DATA**

\[
\begin{align*}
a &= b = 50 \text{ in} & t &= 0.5 \text{ in} \\
D_{11} &= D_{22} = 0.347 \times 10^6 \text{ lb/in}^2 \\
D_{12} &= 0.11 \times 10^6 \text{ lb/in}^2 & D_{33} &= 0.12 \times 10^6 \text{ lb/in}^2 \\
A_{11} &= A_{22} = 16.7 \times 10^6 \text{ lb/in}^2 \\
A_{12} &= 5.27 \times 10^6 \text{ lb/in}^2 & A_{33} &= 5.7 \times 10^6 \text{ lb/in}^2
\end{align*}
\]

**Legend:**

- Free to rotate or move in-plane
- No rotation, free to move in-plane
- No rotation, no in-plane displacement
- Present solution

**Graph:**

- Pressure vs. Displacement curve

**Note:**

- The graph illustrates the relationship between pressure and displacement for different boundary conditions.

**Analysis:**

- The plate data includes material properties and dimensions.
- The graph compares different boundary conditions, such as free rotation, fixed rotation, and fixed displacement.
Application 4 – Panel under pressure  
(comparison to ESDU)

• the linear solution is (very) close to the ESDU solution up to $p_o \approx 10$ psi

• compared to ESDU, the linear solution is conservative for $p_o > 10$ psi (i.e. it predicts larger deflections and larger moments); therefore, it can be used for design provided the added conservatism is acceptable

• the (present) linear solution which satisfies only $w=0$ at the panel edges coincides, in the linear portion, with the non-linear solution that has the edges free to rotate and free to move in-plane
“Good” design practices and Design Rules of Thumb

• collect and summarize the design rules we saw so far

• add a few more that have been shown to generate robust designs\(^{(1)}\)

• this does not mean that any and all of these rules of thumb cannot be relaxed for specific cases (e.g. X-29)

(1) see also: Beckwith, SW, “Designing with Composites: Suggested “Best Practices” Rules”, SAMPE Journal, 45, 2009, pp. 36-37
Layup (stacking sequence)-related

• layup is symmetric (B matrix=0)
  – eliminates in-plane and out-of-plane coupling that may cause unwanted loading or deflections

• layup is balanced (A_{16}=A_{26}=0)
  – eliminates stretching-shearing coupling

• no bending-twisting coupling terms (D_{16}=D_{26}=0)
  – eliminates additional (undesirable) loading
  – very hard to do if the layup is NOT anti-symmetric, or does not consist exclusively of plain weave fabric and 0, 90 uni-directional tape plies\(^{(1)}\)

Layup (stacking sequence)-related

• 10% rule: at least 10% of the fibers must be oriented in any of the principal directions 0, +45, -45, and 90 to protect against secondary loading cases

• minimize effect of micro-cracking\(^{(1)}\): no more than 4 uni-directional plies of the same orientation next to each other in a layup; (4 assumes ply thickness of 0.15 mm)

\( (2) \) Microcrack resistant fiber reinforced resin matrix composite laminates, US patent 4820567

\( (2) \) Timmerman, JF, Hayes, BS, Seferis JC, “Cure Temperature Effects on Cryogenic Microcracking of Polymeric Composite Materials”, Polymer Composites, 24, 2003, pp 132-139

\( (2) \) Microcracks lead to delaminations under static and (especially) fatigue loads
Loading and performance-related

• bending stiffness improvement: place 0 degree plies away from the mid-plane to increase bending stiffness (e.g. increase column buckling load)

• panel buckling and crippling improvement: place 45/-45 degree plies away from mid-plane

• skin thickness/ fastener diameter ratio <1/3 to minimize fastener bending

• skin thickness to countersunk depth >3/2 for countersunk fasteners to avoid pulling fastener through the skin under out-of-plane loads

\[
D > 3 \min (t_1, t_2)
\]

\[
t_f < 2t/3
\]
Loading and performance-related

- +45/-45 (or even better (±45) fabric) plies on the outside for improved damage **resistance**

- skin layup is dominated by 45/-45 plies for improved performance under shear

- stiffener layup (in the flanges) is dominated by 0 degree plies for improved axial strength (however, note combination of 45/-45 plies AND 0 plies for improved crippling performance!)

- at least 40% +45/-45 plies in regions with fasteners (to facilitate load transfer around the fastener)
Robust design - related

- minimum fastener spacing = 4-5D
- minimum edge distance = 2.5D + 1.3 mm

avoid interaction and stress enhancement between fasteners and edge
Robust design - related

• plydrop rules to minimize stresses
  – avoid external plydrops
  – drop plies symmetrically with respect to mid-plane
  – drop plies as close to mid-plane as possible
  – do not drop more than 0.5 mm thickness of plies at the same location
  – successive plydrop spacing=at least 10-15h where h is the highest drop height
Plydrop rules

- Too many plydrops at the same location
- Adjacent plydrops too close to each other
- External plydrops

Good design

$\text{d} \geq 15h$
Environmental effects-related

- minimum gauge: for lightly loaded structure, the minimum thickness should be 0.5-0.6 mm to keep moisture from seeping into the structure; otherwise, protective coating will be required
Manufacturing-related

- minimum flange width
  - \(2.5D + 1.3 + 2.5D + 1.3 = 5D + 2.6\text{mm}\) for fastener installation
  - 12.7 mm (lightly loaded) 19 mm (highly loaded) when co-cured

- minimum web height: 17-18\text{mm} for ease of handling
- no 90 degree uni-directional plies around a corner

bridging (concave tool)
pinching (fibers do not conform to tight radius of convex tool)
Design for robustness and producibility

- Move 0 plies away from mid-plane
- Improve flange crippling with $(\pm 45)$
- Change to $(\pm 45)$ fabric

1. 18 mm (min)
2. $2 \times 12.7 = 25.4$ mm (min)
3. $12h_1$
4. $10h_2$

UD or roving material
Design for robustness and producibility

Qualitatively discuss how best to connect the three parts considering the loading shown.
Fitting example

**bolted ("black aluminum")**
- expensive (installing fasteners)
- heavy (splice and angles may end up thicker than necessary for bearing load requirements plus weight of metallic fasteners)

**bonded**
- bondline thickness control?
- reliable inspection?
- lower weight, maybe lower cost

3-D preform co-cured w/ 3 parts
- low recurring cost through integration
- high tooling cost (RTM, VARTM...)
- weight? (RTM has lower allowables)
The “magic” preform

- continuous fibers in all three directions for better load transfer
- very challenging to make (3-D weave? braid?...)
- “crimped” fibers => reduced strength
- additional reinforcements: stitching, z-pinning,...


Black Aluminum versus Efficient Composite Design

• Black Aluminum
  – quasi-isotropic laminates
  – built-up structure (fasteners, bolts, rivets)
  – rules of metal design effective (fitting factors, ...)

• Efficient Composite Design
  – stacking sequence suited to loading (subject to some rules such as symmetric, 10% ??)
  – co-cured structure (no fasteners)
  – abandon metal mentality
    • manuf. risk
    • ease of repair?