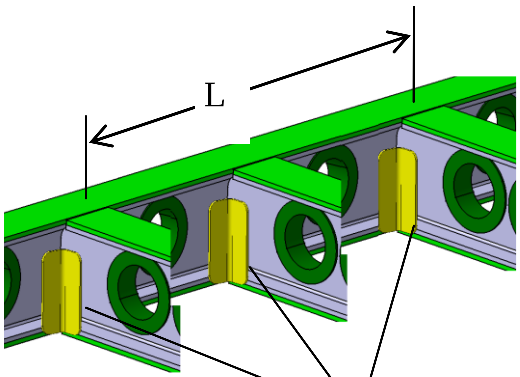
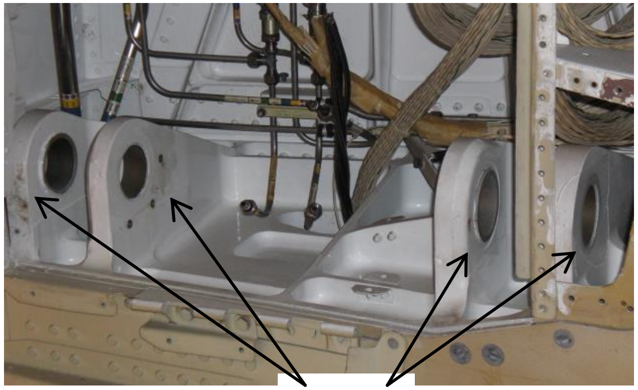
Composite Fittings



Shear clips



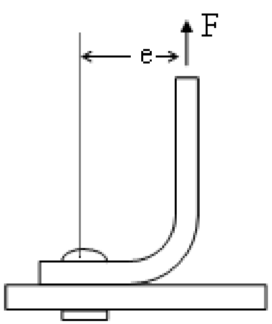
Lugs

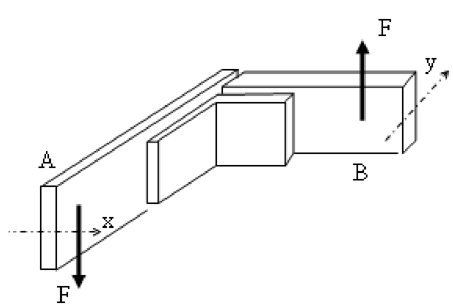
Attachment clips

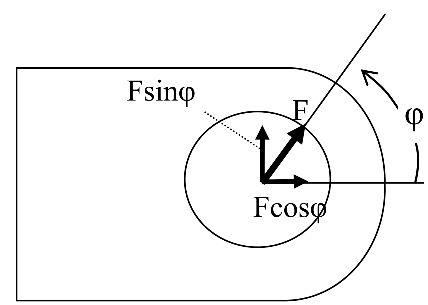
Large special purpose fitting

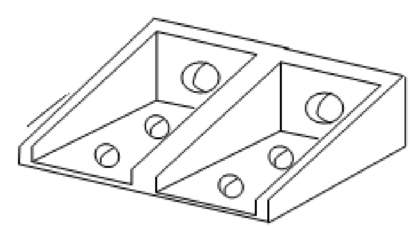
Fittings - General

- 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

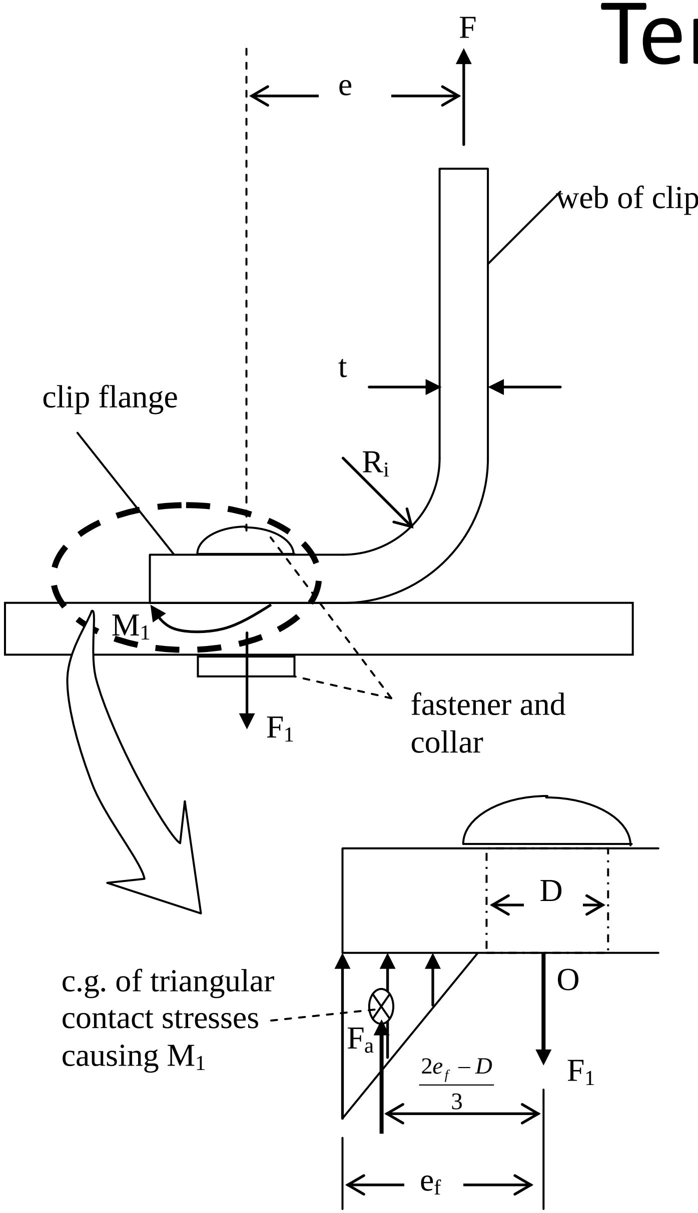








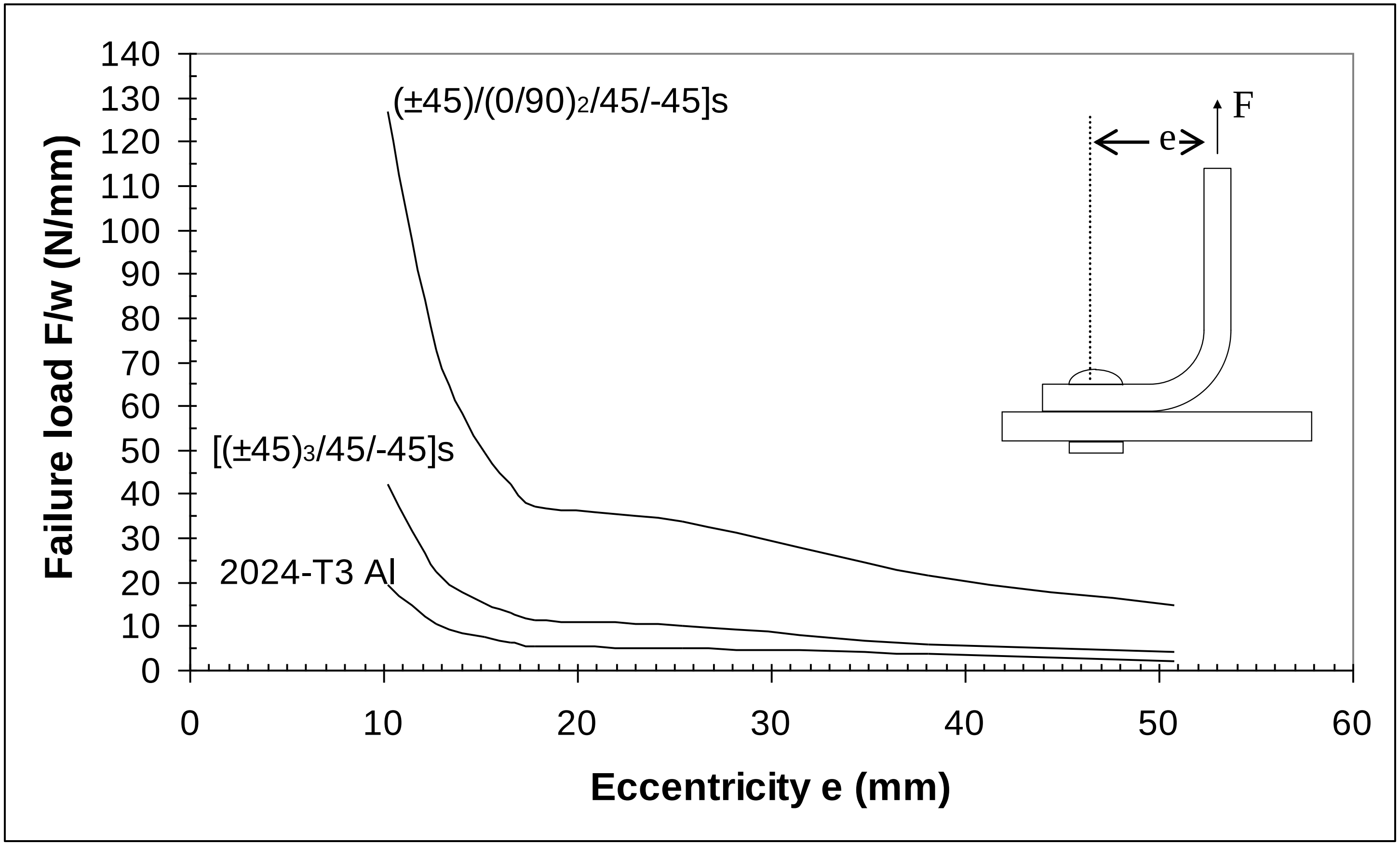
Tension Clips



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

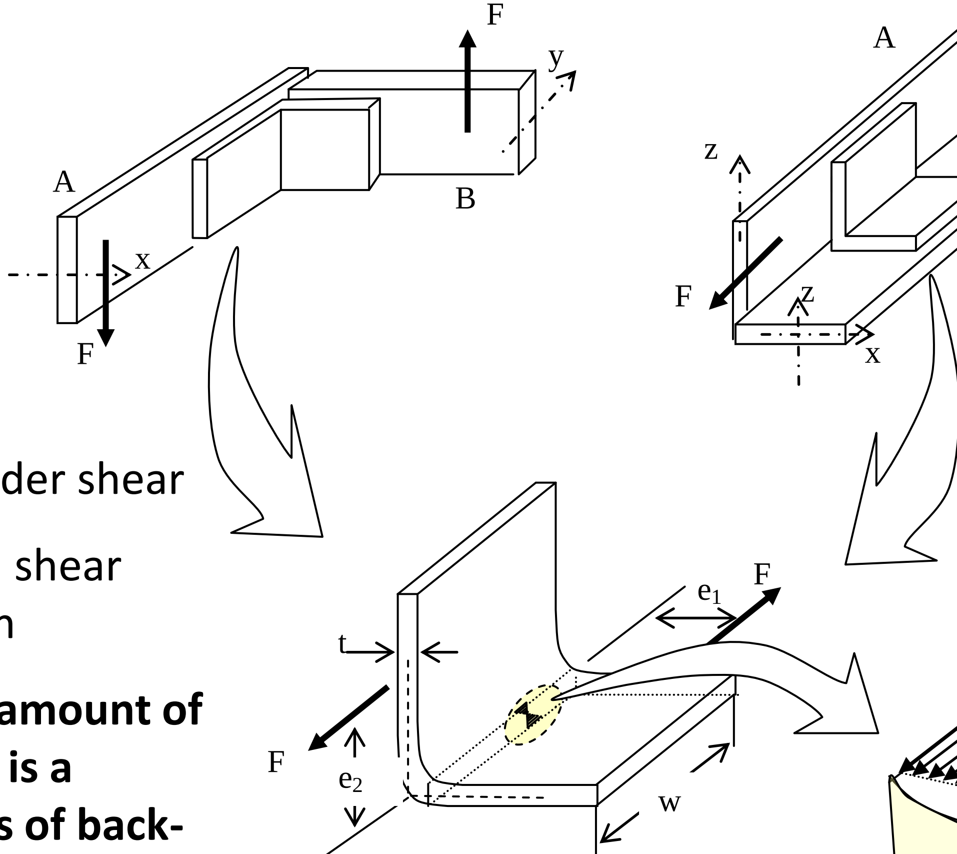
- analyze web for mat’f failure
- analyze web for bolt bearing (attacment to adjacent structure)
- analyze corner for delamination
- analyze flange for pull-through
- analyze flange for mat’f falure (include moment M_1)
- large deflection analysis for flange

Tension clips - example

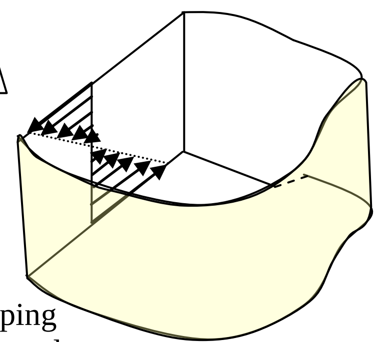


all clips have the same weight

Shear clips

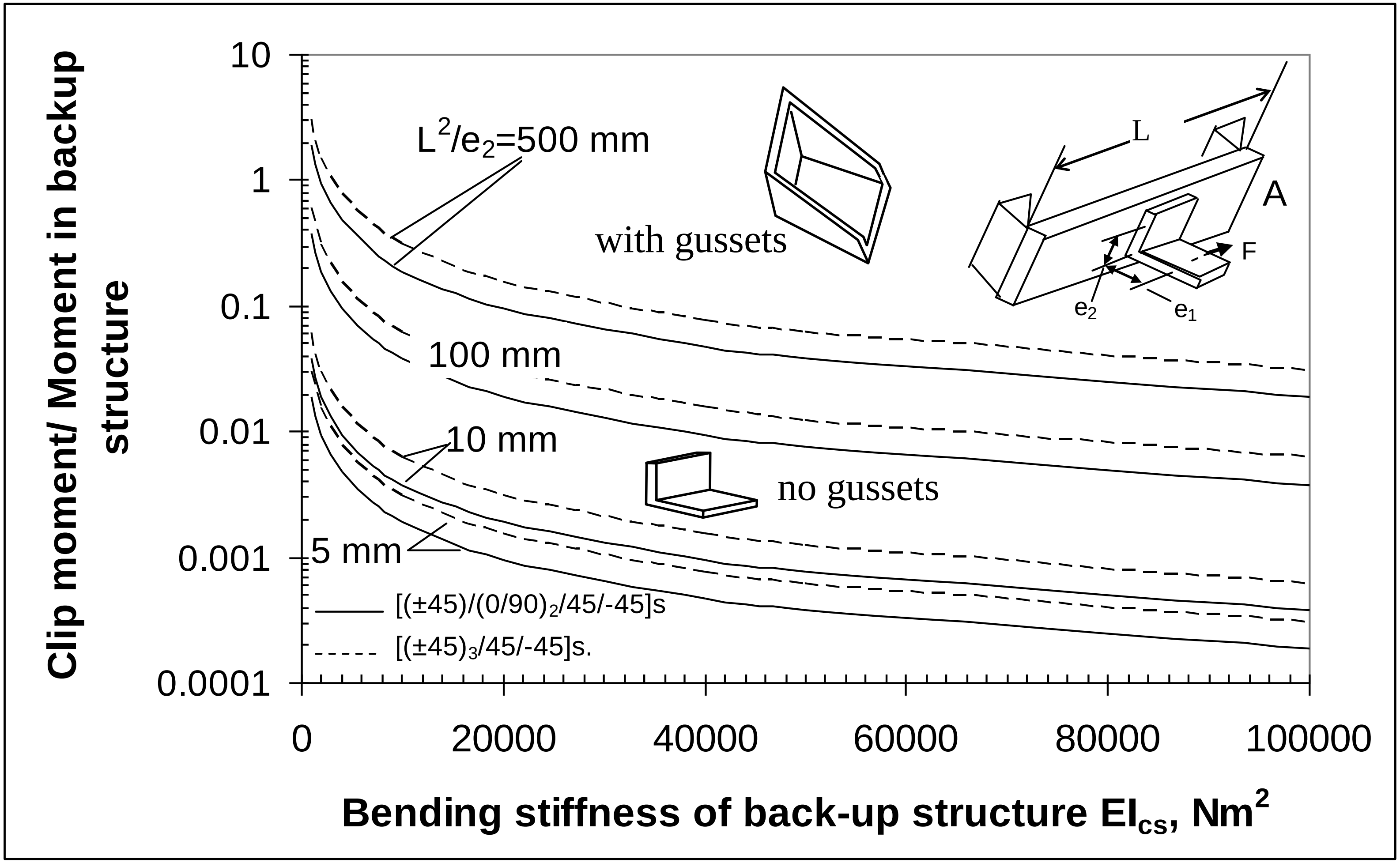


- analyze corner under shear
- include additional shear stress due to torsion
- **important point: amount of torque transmitted is a function of stiffness of back-up structure**



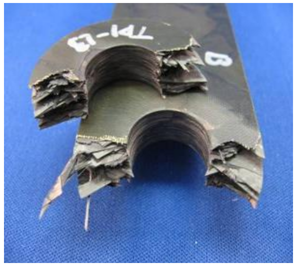
shear stress developing at the root of horizontal flange due to torque Fe_2

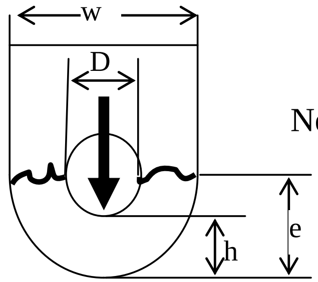
Shear clips – transmitted moment



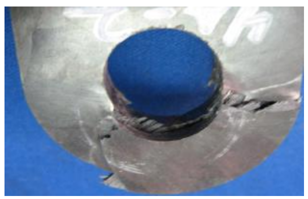
stiff back-up structure minimizes moment or torque transmitted

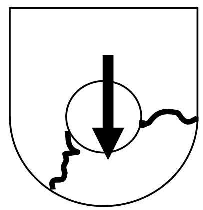
Lugs – axial loading



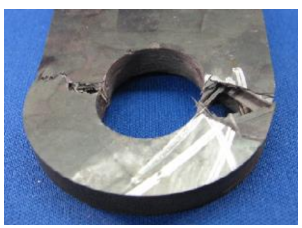


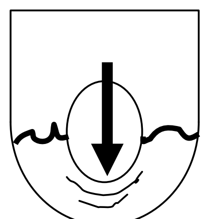
Net section failure





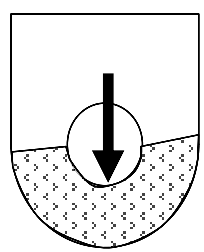
Shearout, (shear failure ahead of pin hole along loading plane) and net section failure combined





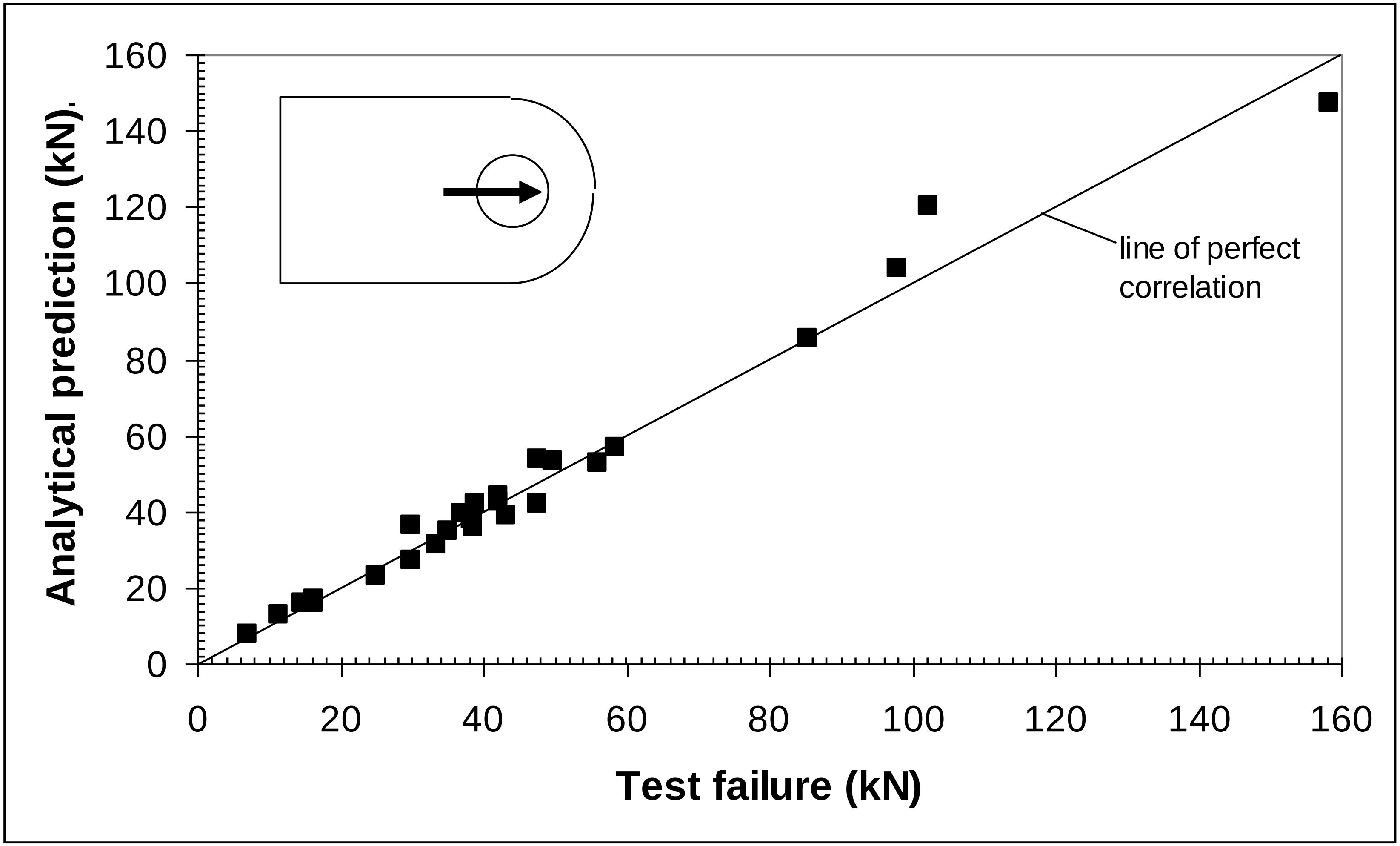
Bearing, (hole elongates and material ahead of pin fails) and net section failure combined

delamination

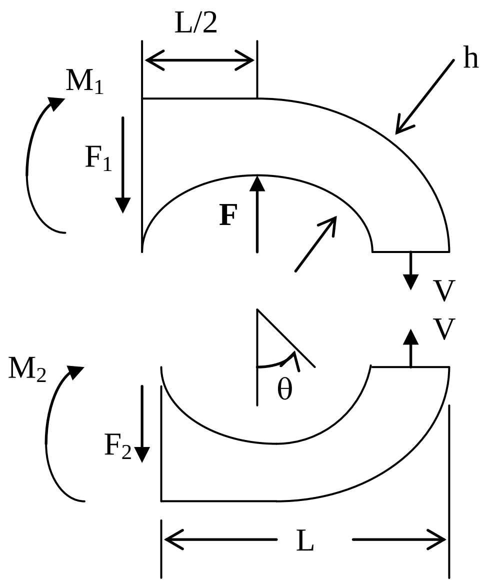


Delamination

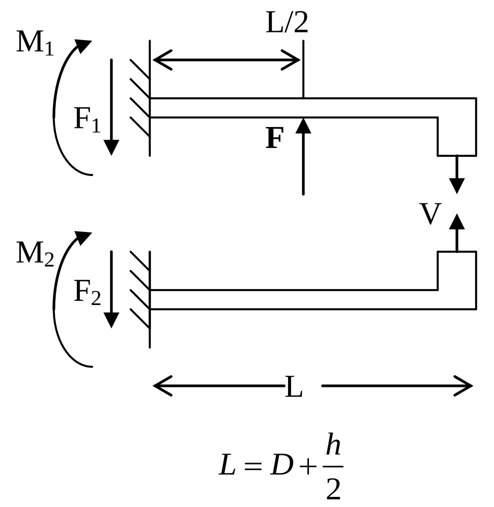
Composite lugs under axial loads: Analytical predictions versus test results



Lugs – transverse loading



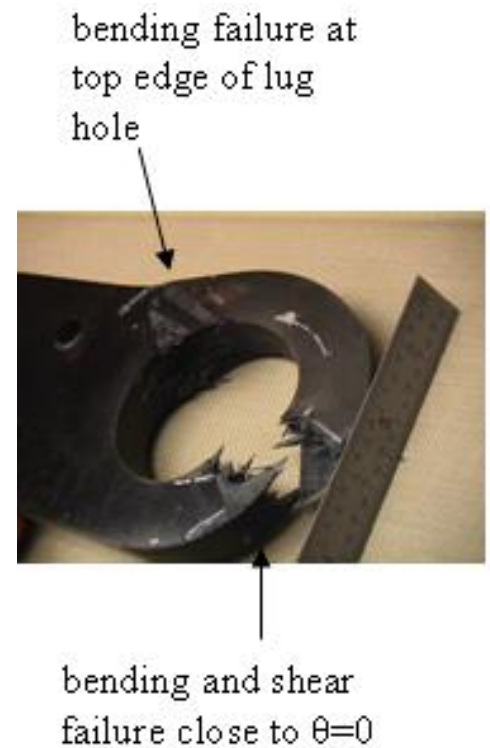
Lug free-body diagram



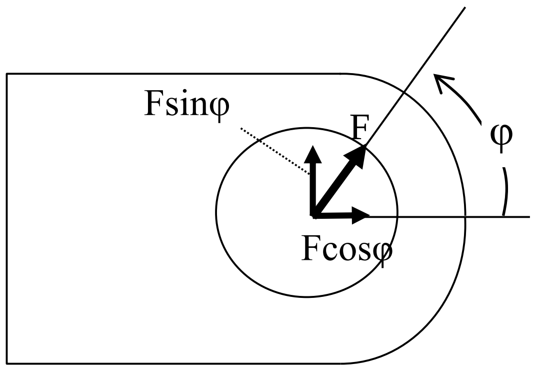
Equivalent beam model

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

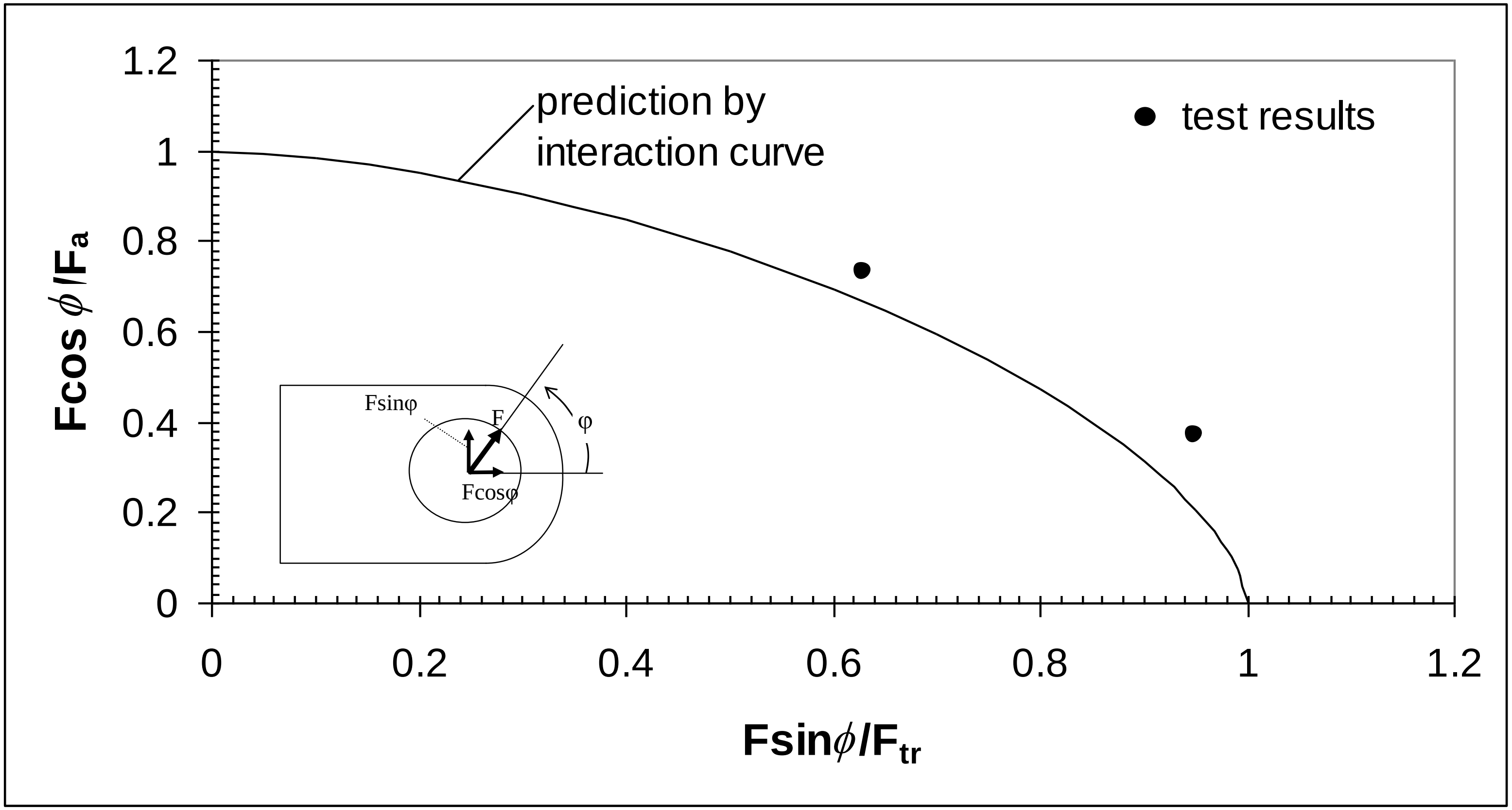


- first, solve the two separate problems:
  - lug under axial loading Fcosφ
  - lug under transverse loading Fsinφ
- then apply interaction formula:

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

F_a and F_{tr} are the individual failure loads unde axial or transverse load respectively

Composite lugs under oblique loads: Analytical predictions versus test results



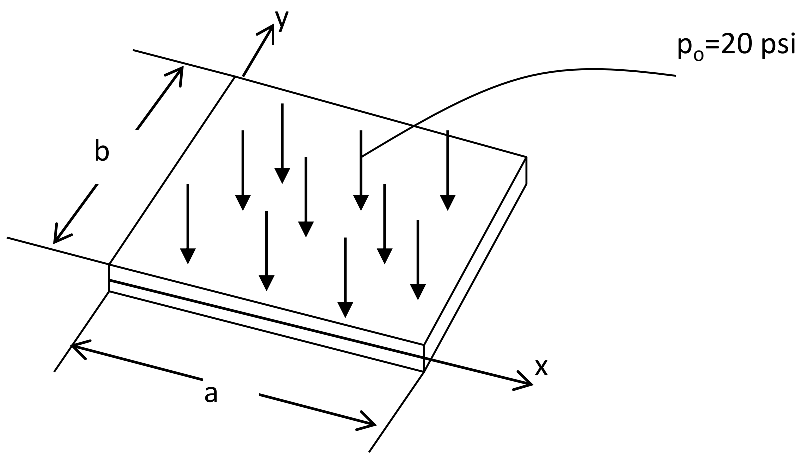
Design tools

- **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



overpressure case of a fuselage panel

- 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:

$$D_{11}\frac{\partial^4 w}{\partial x^4} + 2(D_{12}+2D_{66})\frac{\partial^4 w}{\partial x^2 \partial y^2} + D_{22}\frac{\partial^4 w}{\partial y^4} = p_z + \cancel{N_x \frac{\partial^2 w}{\partial x^2}} + \cancel{N_y \frac{\partial^2 w}{\partial y^2}} + \cancel{2N_{xy}\frac{\partial^2 w}{\partial x \partial y}} - \cancel{p_x \frac{\partial w}{\partial x}} - \cancel{p_y \frac{\partial w}{\partial y}}$$

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:

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

integrals are non-zero only when m=q and n=r with m,n odd

- 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:

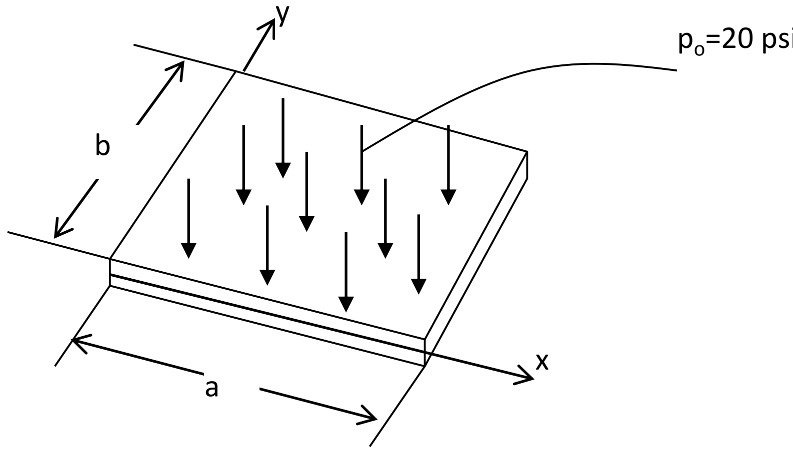
$$\sum\sum\left[D_{11}\left(\frac{m\pi}{a}\right)^4+2\left(D_{12}+2D_{66}\right)\frac{m^2n^2\pi^4}{a^2b^2}+D_{22}\frac{n^4\pi^4}{b^4}\right]A_{mn}\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}=$$

$$=\sum\sum\frac{16p_o}{\pi^2 mn}\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}$$

- matching term by term, can solve for A_{mn}

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

Application 4 – Panel under pressure; linear solution



• at the center of the plate the deflection δ can be determined:

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

Application 4 – Panel under pressure; linear solution comparison to ESDU

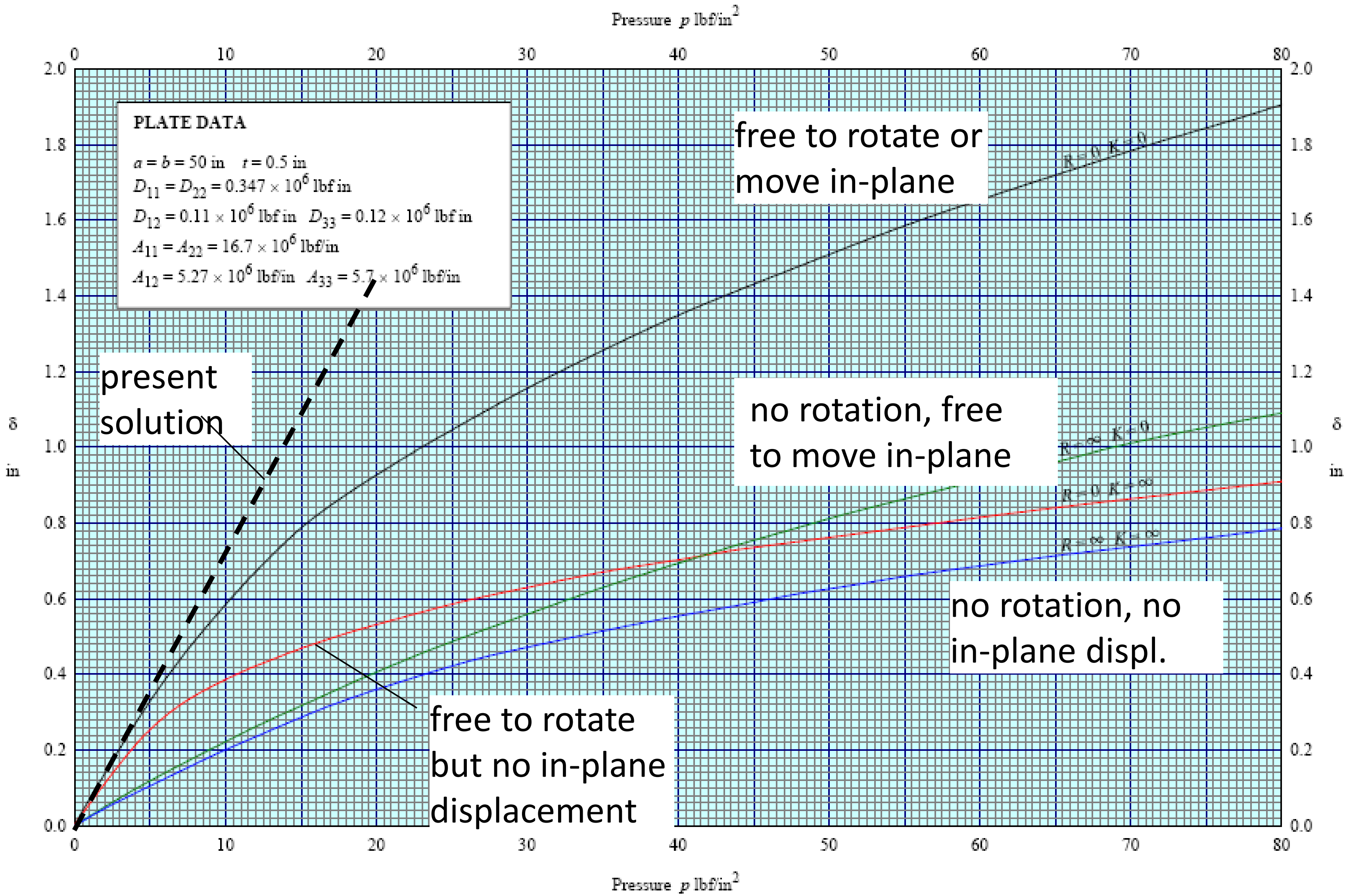
- ESDU item 93011 provides a large deflection moderate rotation solution with specific results for

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

- applying our solution to this problem,

po (psi)	δ (in)
0	0
2	0.146
4	0.261
6	0.437
10	0.728
15	1.0927
20	1.457
25	1.821

Application 4 – Panel under pressure (comparison to ESDU)



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)

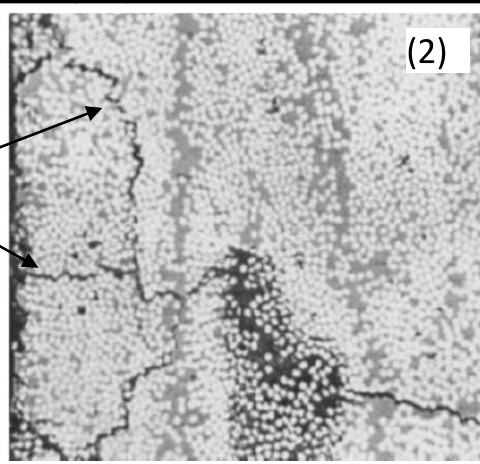
(1) Caprino, F., Crivelli Visconti, I., "A Note on Specially Orthotropic Laminates", JCM, 16, 1982, pp 395-399

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)

micro-cracks



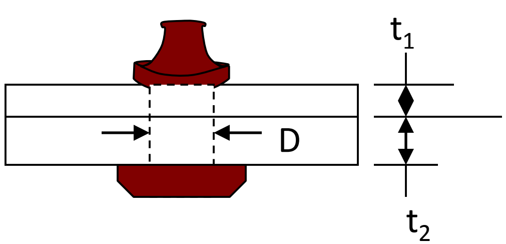
micro-cracks lead to delaminations under static and (especially) fatigue loads

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

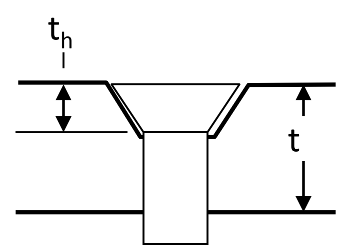
(2) Timmerman, JF, Hayes, BS, Seferis JC, “Cure Temperature Effects on Cryogenic Microcracking of Polymeric Composite Materials”, Polymer Composites, 24, 2003, pp 132-139

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



$D>3\ \min(t_1,t_2)$



$t_f<2t/3$

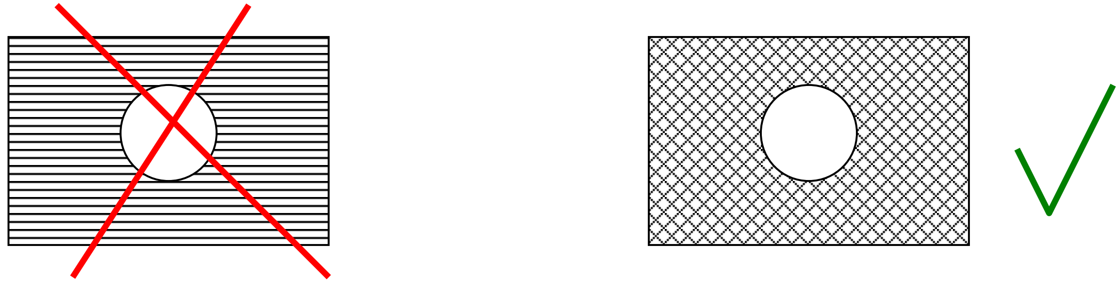
Loading and performance-related

- +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!)

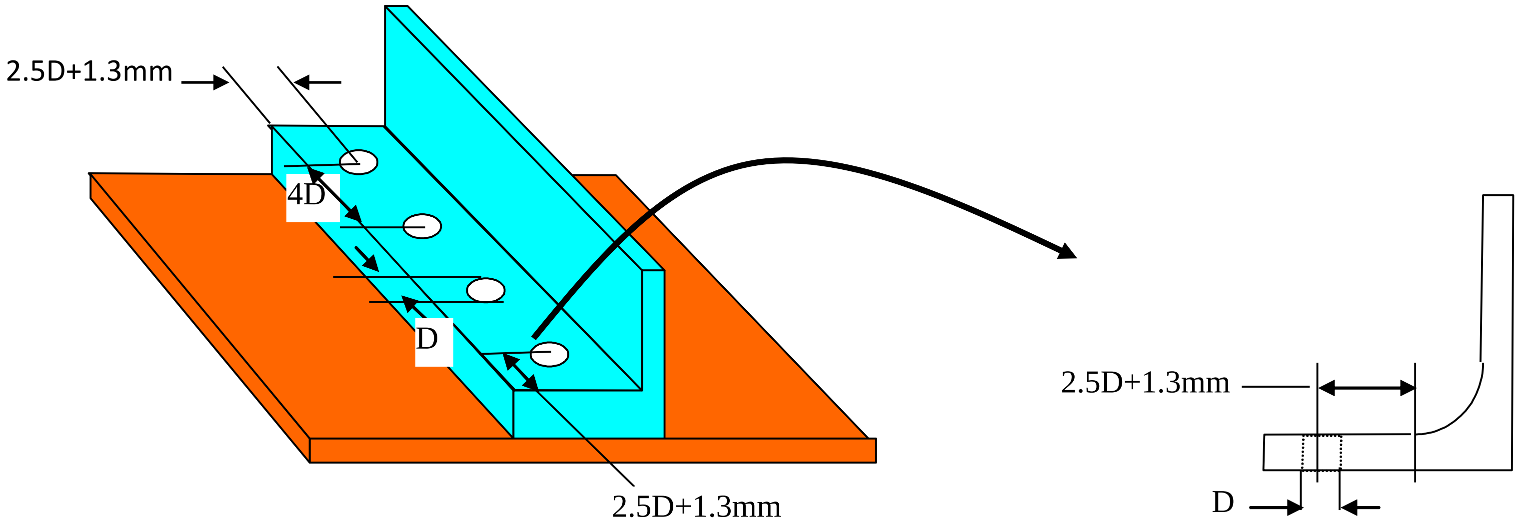
- at least 40% +45/-45 plies in regions with fasteners (to facilitate load transfer around the fastener)



Robust design - related

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

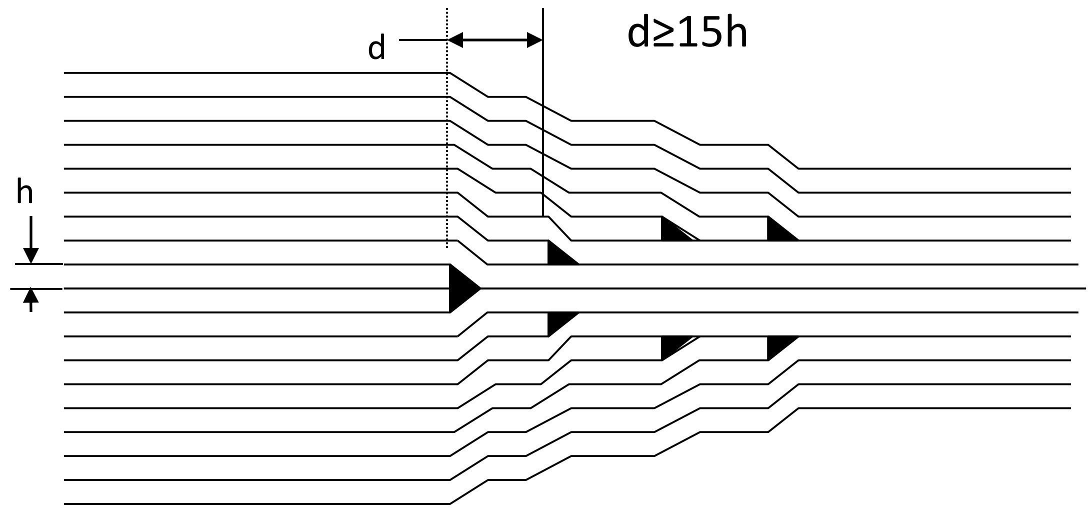
avoid interaction and stress enhancement between fasteners and fasteners and edge



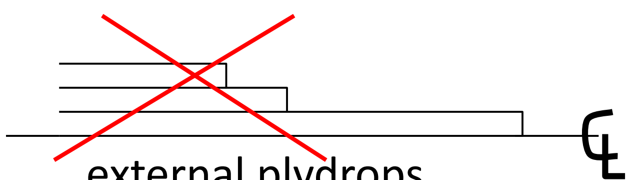
Robust design - related

- 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

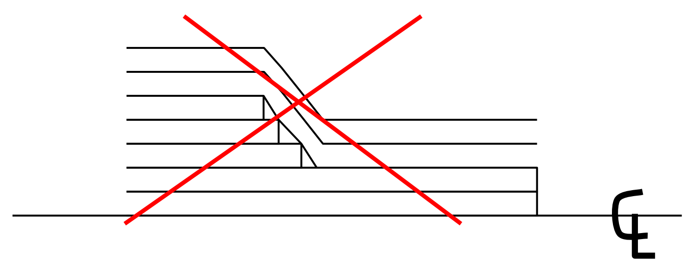
Plydrop rules



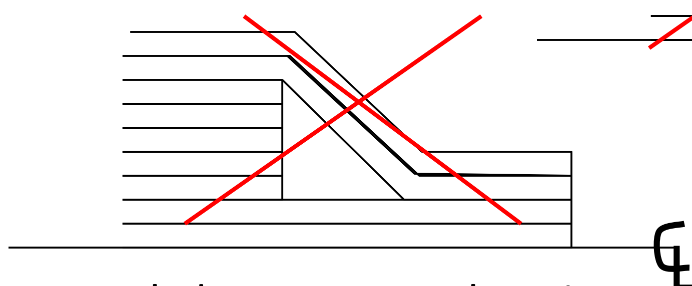
Good design



external plydrops



adjacent plydrops too close to each other



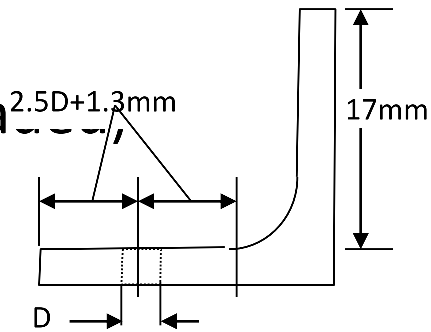
too many plydrops at same location

Environmental effects-related

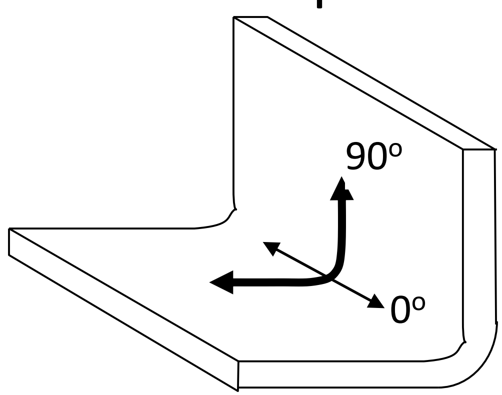
- minimum gauge: for lightly loaded structure, the minimum thickness should be 0.5-0.6 mm to keep moisture from seeping into the structure; otherwise, protective coating will be required

Manufacturing-related

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



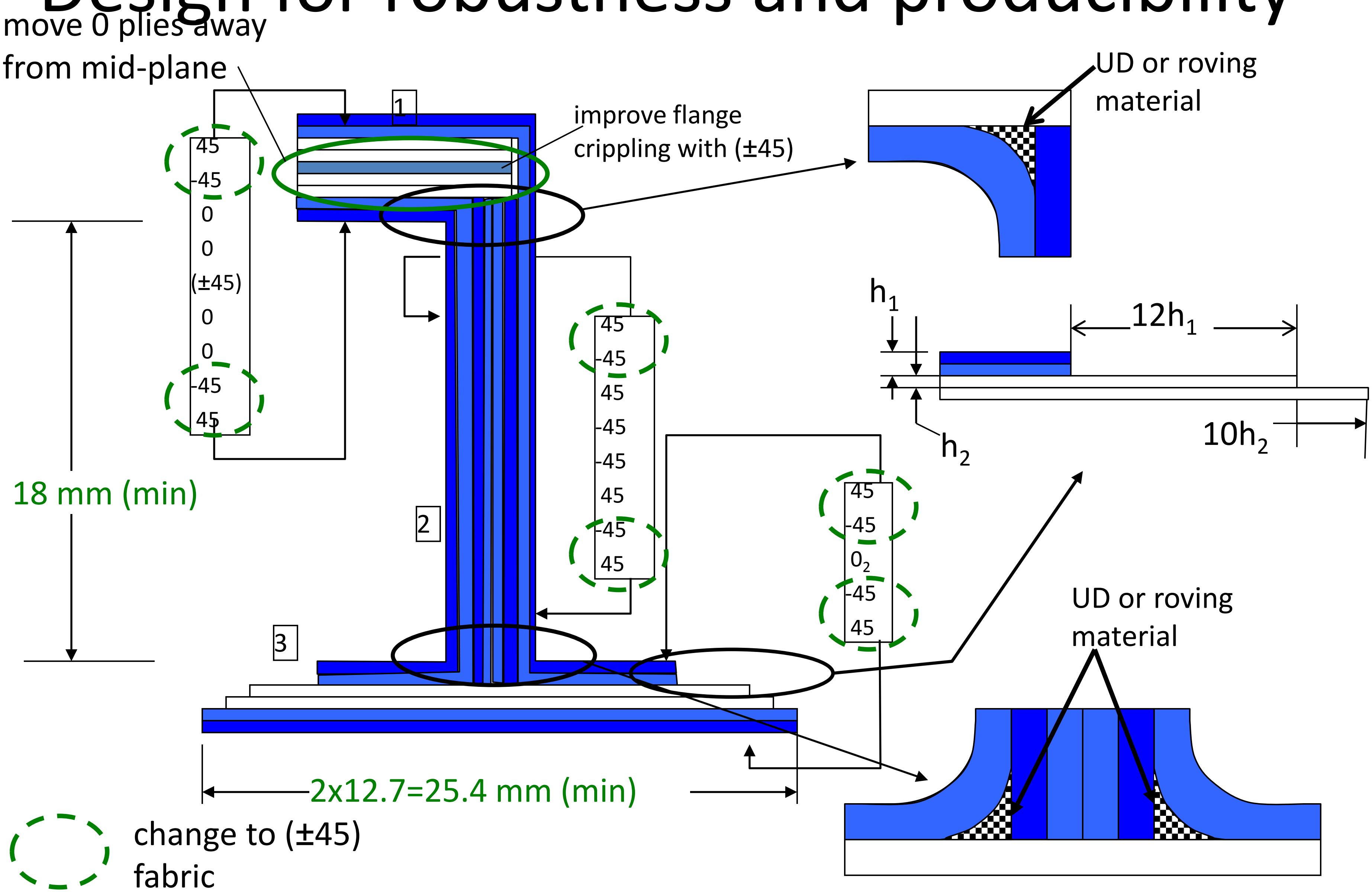
- minimum web height: 17-18mm for ease of handling
- no 90 degree uni-directional plies around a corner



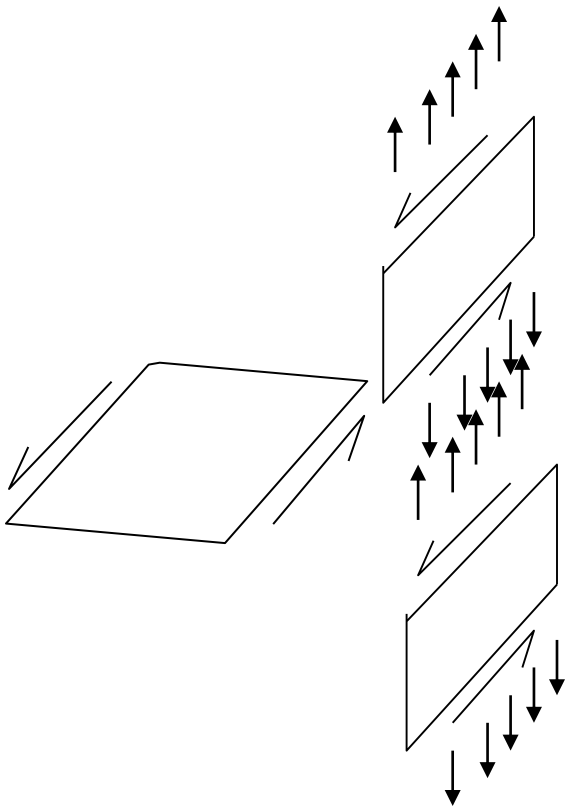
bridging (concave tool)

pinching (fibers do not conform to tight radius of convex tool)

Design for robustness and producibility

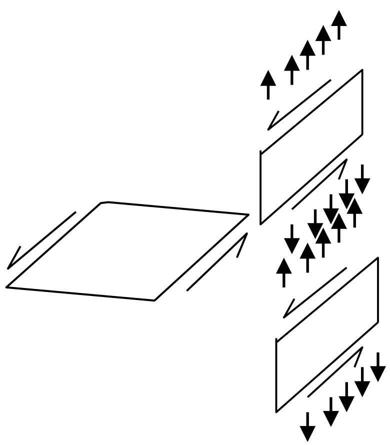


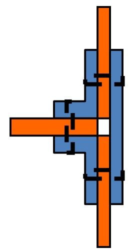
Design for robustness and producibility



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

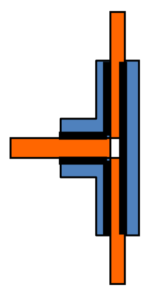
Fitting example





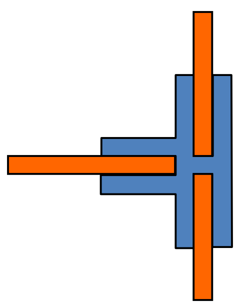
bolted (“black aluminum”)

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



bonded

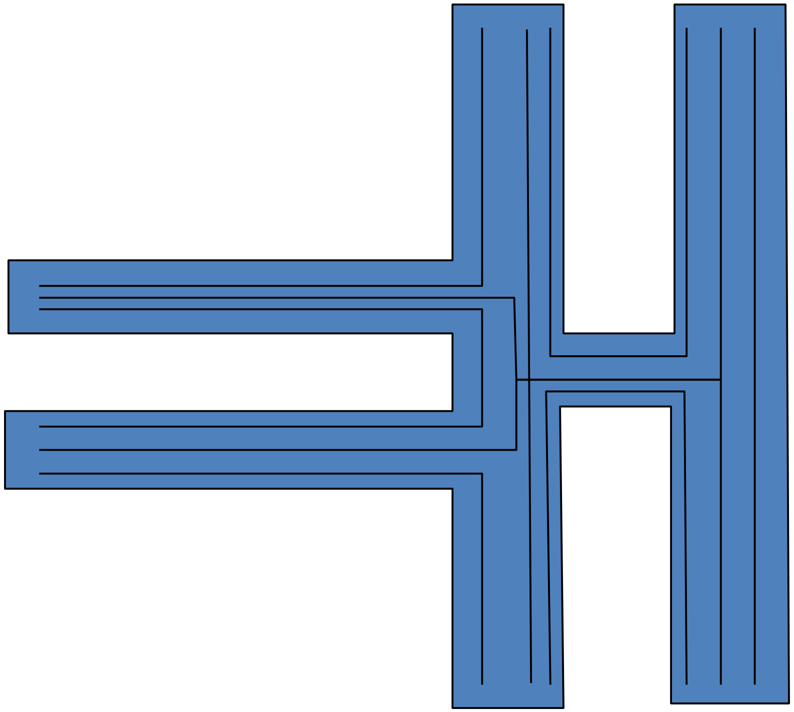
- bondline thickness control?
- reliable inspection?
- lower weight, maybe lower cost



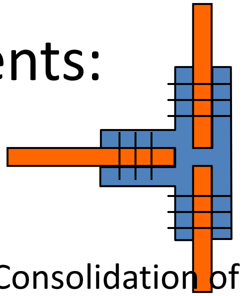
3-D preform co-cured w/ 3 parts

- 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,…



see: (1) Suarez, J., and Dastin, S., “Comparison of Resin Film Infusion, Resin Transfer Molding and Consolidation of Textile Preforms for Primary Aircraft Structure”, 2nd NASA Advanced Composites Technology Conference, Lake Tahoe, NV, 1991, pp.353-386

(2) Adams, LT, Barrie, RE, Leger, CA, and Skolnik, DZ, “Braided/RTM Fuselage Frame Development”, 5th NASA Adv. Composites Technology Conf, Seattle WA, 1994, pp. 615-634

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)
    - manuf. risk
    - ease of repair ?
  - abandon metal mentality