DESN2000 MECH Workshop

Week 3 – Axiomatic Design and Fasteners

Class overview

- **Design Parameters** (10 min)
- **Axiomatic Design** (20 min)
- **Fasteners** (30 min)
- **Project Time!** (50 min)
- **Summary** (5 min)

Design Parameters

Design Parameters	Axiomatic Design	Fasteners	Project Time!	Summary
10 min	20 min	30 min	65 min	5 min
All	All	All	Groups	All

Design Parameters – Recall

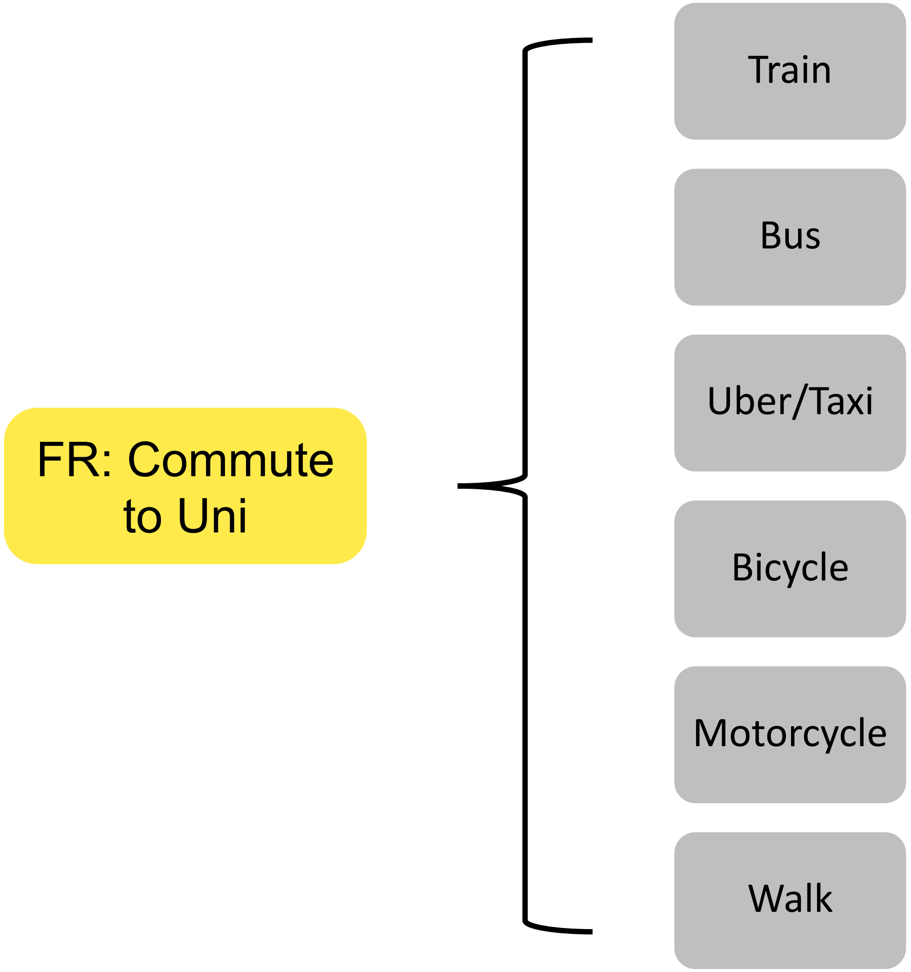
FUNCTIONAL REQUIREMENTS

HOW TO ACHIEVE CUSTOMER NEEDS

DESIGN PARAMETERS

HOW TO FULFIL FUNCTIONAL REQUIREMENTS

Design Parameters – Recall



- **Tip:** To help in creating a diverse range of concepts, try to come up with multiple potential DPs for each individual FR you create.

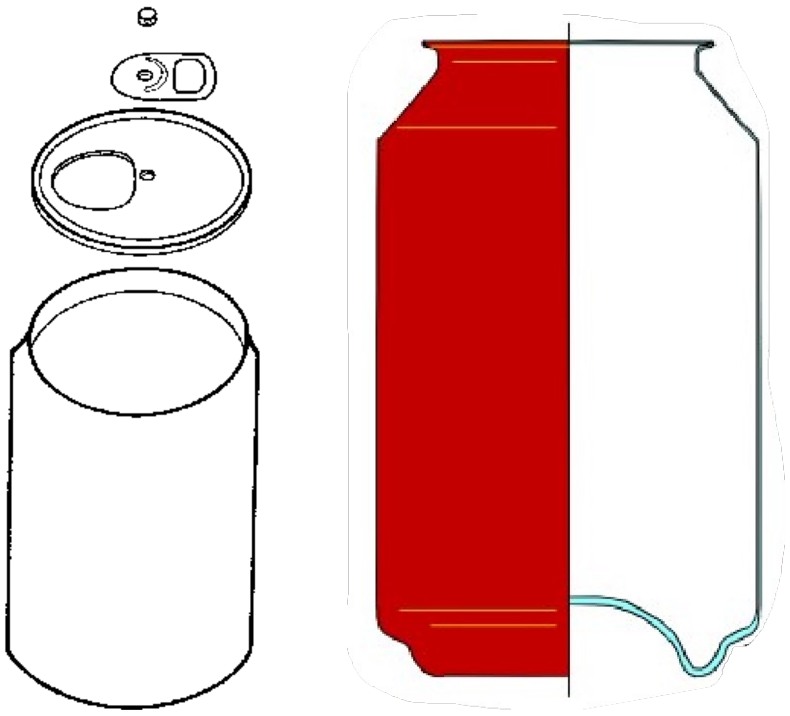
- **Note:** When you create each concept however, you should only map one DP to each FR.

Design Parameters – Recall

Also…

Design Parameters don't always have to be different types of physical components!

- ❑ Example: Aluminium soda can



FR	DP
Withstand axial pressure	Curvature of base of can
Withstand radial pressure	Thickness of wall material

- ❑ Sometimes they can be physical dimensions or other numerical parameters.

Axiomatic Design: Independence Axiom

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Independence Axiom

"Each Functional Requirement should be satisfied by only one Design Parameter."

- Main goal: To evaluate and simplify your design concepts, by minimising the number of coupled FRs.
- How to determine:
  - Create Independence Axiom matrix
  - FR left side, DP right side
  - X if DP fulfils a given FR across a row, 0 for if DP does not fulfil FR.

$$\begin{matrix} \boldsymbol{FR_1} \\ \boldsymbol{FR_2} \\ \boldsymbol{FR_3} \end{matrix} = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix} \begin{matrix} \boldsymbol{DP_1} \\ \boldsymbol{DP_2} \\ \boldsymbol{DP_3} \end{matrix}$$

$$\begin{matrix} \boldsymbol{FR_1} \\ \boldsymbol{FR_2} \\ \boldsymbol{FR_3} \end{matrix} = \begin{vmatrix} \boldsymbol{X} & 0 & 0 \\ 0 & \boldsymbol{X} & 0 \\ 0 & 0 & \boldsymbol{X} \end{vmatrix} \begin{matrix} \boldsymbol{DP_1} \\ \boldsymbol{DP_2} \\ \boldsymbol{DP_3} \end{matrix}$$

Independence Axiom

- How to evaluate your matrices

$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & O & X \end{bmatrix} \bullet \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \end{Bmatrix}$$

Uncoupled Concepts **(always best)**

Independent of orders of decisions

$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & X & X \end{bmatrix} \bullet \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \end{Bmatrix}$$

Decoupled Concepts **(acceptable)**

Specific decision orders must be maintained

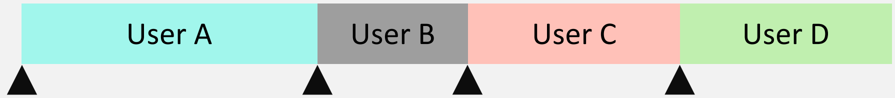
$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \end{Bmatrix} = \begin{bmatrix} X & O & X \\ O & X & X \\ X & X & X \end{bmatrix} \bullet \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \end{Bmatrix}$$

Coupled Concepts **(always bad)**

Impossible to manage decision orders

Independence Axiom

❑ <u>A coupled matrix is fixable! (sometimes)</u>



❑ <u>FRs for peer evaluation tool</u>

- FR_1: Adjust user A score
- FR_2: Adjust user B score
- FR_3: Adjust user C score
- FR_4: Adjust user D score

❑ <u>DPs for peer evaluation tool</u>

- DP_1: Slider 1
- DP_2: Slider 2
- DP_3: Slider 3
- DP_4: Slider 4

$$\begin{array}{c} FR_3 \\ FR_1 \\ FR_2 \\ FR_4 \end{array} = \left|\begin{array}{cccc} 0 & X & X & 0 \\ X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ 0 & 0 & X & X \end{array}\right| \begin{array}{c} DP_3 \\ DP_1 \\ DP_2 \\ DP_4 \end{array}$$

❑ There is coupling present! What could we do to fix it?

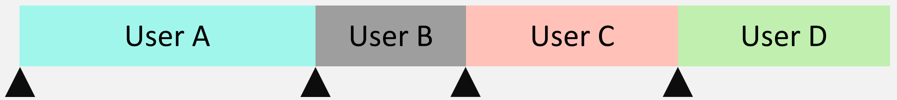
Independence Axiom

❑ <u>A coupled matrix is fixable! (sometimes)</u>

$$\begin{Bmatrix} FR_3 \\ FR_1 \\ FR_2 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} 0 & X & X & 0 \\ X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ 0 & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_3 \\ DP_1 \\ DP_2 \\ DP_4 \end{Bmatrix}$$

$$\Downarrow$$

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ 0 & X & X & 0 \\ 0 & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix}$$



❑ We can reduce the effect of coupling by introducing order. By adjusting the sliders from left to right (1 to 4), then the results of the users further down the track are not affected by the sliders that we are using at any one point.

❑ Keep in mind that not every matrix can be fixed by order. Sometimes there is too much coupling, and you may need to remove the influence certain design parameters have to functional requirements (i.e., reduce the number of FR a given DP fulfils) to fix the coupling issue.

Fasteners

Design Parameters	Axiomatic Design	Fasteners	Project Time!	Summary
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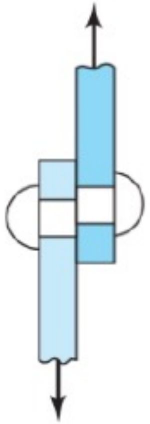
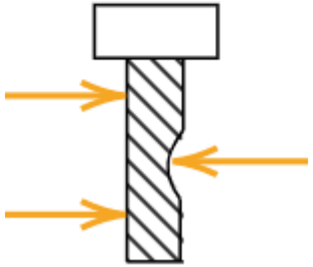
Fasteners

❑ <u>How much do you need to know and how does it apply to assessments?</u>

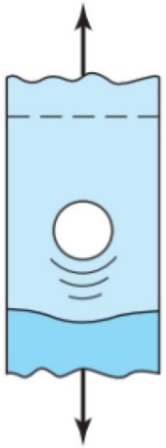
In your final report, you can choose to perform a technical analysis of the fasteners you use on an aspect of your device. One way to do this is to analyse the loading cases your fasteners will experience in your final design concept and predict the failure mode which they might experience. You can then use this to then justify your choice of fasteners, how many and where they are placed.



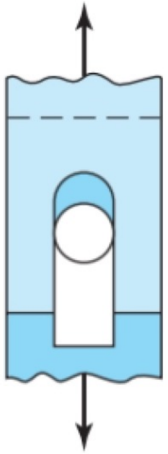
Bolt shear failure



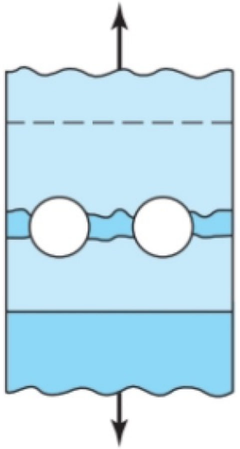
Bolt bearing failure



Bearing failure of members



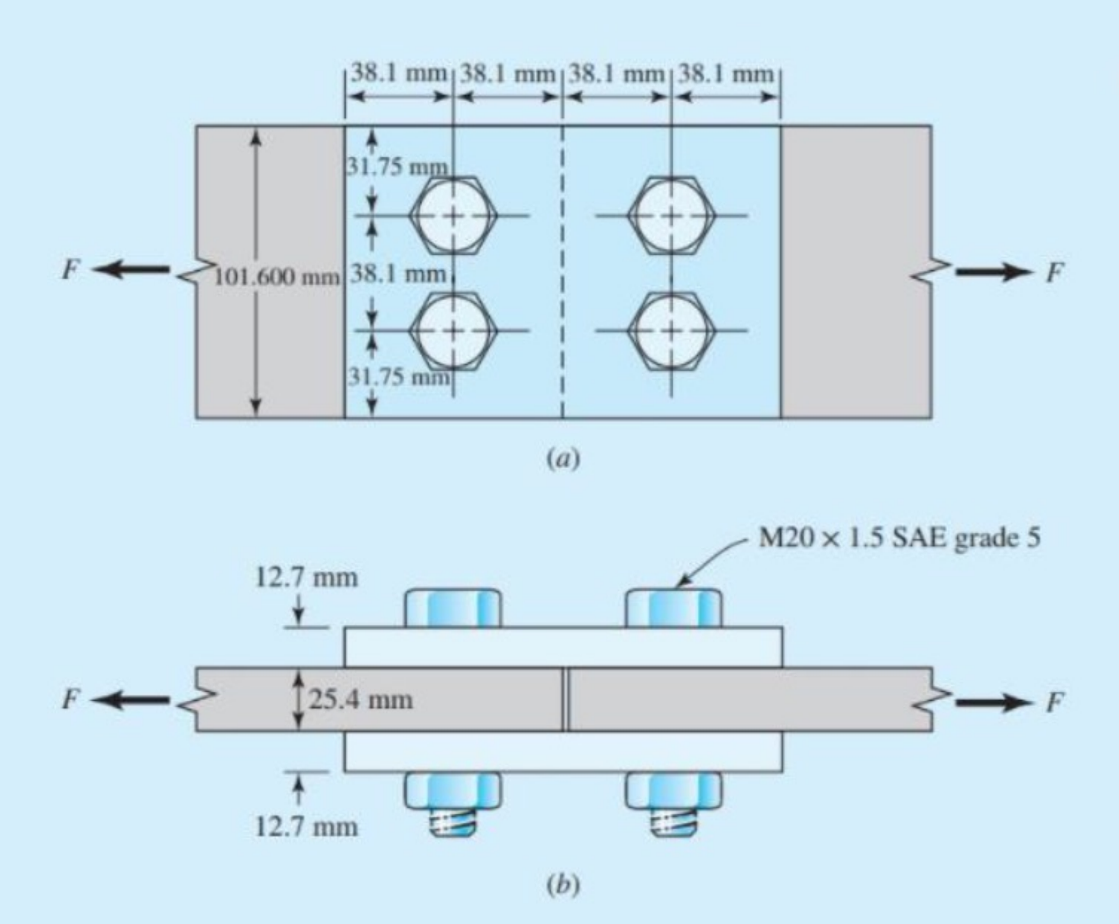
Edge shearing of members



Tensile failure of members

Fasteners – example

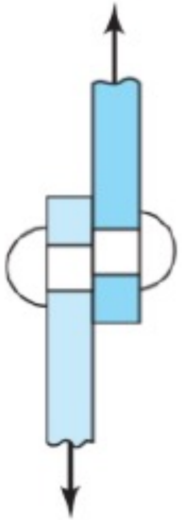
Two 25.4 by 101.6 mm 1018 cold-rolled steel bars are butt-spliced with two 12.7 by 101.6 mm 1018 cold-rolled splice plates using four M20 × 1.5 mm grade 5 bolts as depicted in Figure 8–26. For a design factor of $n_d = 1.5$ estimate the static load F that can be carried if the bolts lose preload.



Goal: Determine the maximum load which can be carried.

Method: Evaluate the joint for all failure modes and find the mode which requires the lowest force.

Scenario 1 – Bolt shear failure



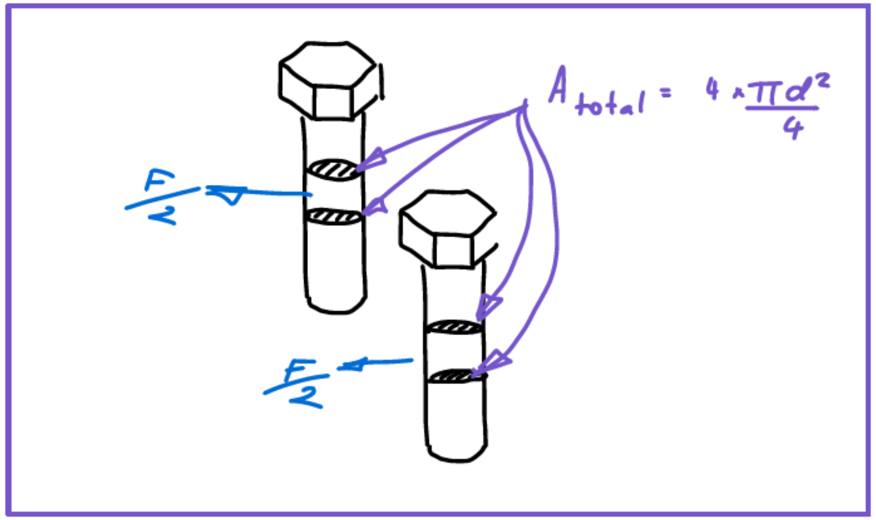
We can use what we prepared earlier,

$$F = A(0.577)\frac{S_y}{n_d},$$

S_y= yield strength (MPa), n_d = safety factor (1.5 in this example). d = bolt major diameter $(20\ mm)$. $A = 4\frac{\pi d^2}{4}$. Thus,

$$F = 0.577\pi d^2\frac{S_y}{n_d}$$

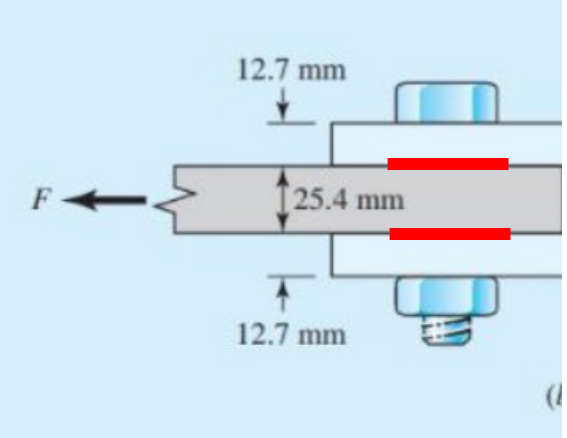
$$= 0.577\pi(20)^2\frac{660}{1.5} = \mathbf{319.04\ kN}$$



How A was obtained. We multiply the shank cross sectional area by 4 as there are 4 shear planes the fasteners experience.

Two 25.4 by 101.6 mm 1018 cold-rolled steel bars are butt-spliced with two 12.7 by 101.6 mm 1018 cold-rolled splice plates using four M20 × 1.5 mm grade 5 bolts as depicted in Figure 8–26. For a design factor of n_d = 1.5 estimate the static load F that can be carried if the bolts lose preload.

From Table A–20, minimum strengths of S_y = 370 MPa and S_{ut} = 440 MPa are found for the members, and from Table 8–11 minimum strengths of S_p = 600 MPa, S_y = 660 MPa, and S_{ut} = 830 MPa for the bolts are found.



Before we start

The fundamental source of all equations you will use in this example, comes from your previous mechanical courses. For tensile stress,

$$\boxed{\text{Factor of Safety } (n_d) = \frac{\sigma_{failure}}{\sigma_{applied}}}$$

- $\boldsymbol{\sigma_{applied}}$ is the **load you intend for your joint to carry**. It will be **determined by you the designer and your research**.
- $\boldsymbol{\sigma_{failure}}$ is the **maximum stress the part will experience**. This is determined by rearranging the formula to make $\sigma_{failure}$ the subject and use the n_d set by the engineering standard relevant to your project.
- Later in material selection, you will need to make sure that $\sigma_{failure}$ falls within the capabilities of your chosen material.

We want to **relate factor of safety and the material properties** to the **load that the joint will experience**. We know that in general, $\sigma = \frac{F}{A}$.

In the example, $\sigma_{failure} = S_y$, a material's yield strength. Thus, by substituting,

$$n_d = \frac{S_y}{F/A}$$

Rearranging to make F (the applied load) the subject,

$$F = A\frac{S_y}{n_d}$$

We will use various versions of this in our analysis

Before we start

You can use the same procedure to relate loading to material properties and factor of safety for shear stress. Just replace σ with τ.

$$\text{Factor of Safety } (n_d) = \frac{\tau_{failure}}{\tau_{applied}}$$

- ❑ We know that in general, $\tau = \frac{F}{A}$. Thus,

$$n_d = \frac{\tau_{failure}}{F/A}$$

Rearranging to make F the subject,

$$F = A\frac{\tau_{failure}}{n_d}$$

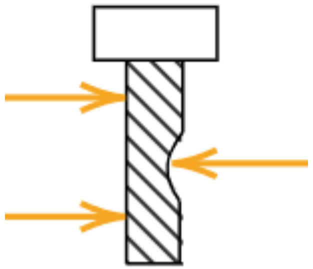
However, most material data for fasteners and materials in general, are given in terms of tensile stress. However, there is an easy way to relate tensile and shear stress. The following relationship (Von Mises Criterion) can be used to approximately convert between the two.

$$\tau = 0.577\sigma$$

Since yield stress (S_y) in a materials data sheet is given in terms of tensile stress, we can re-write $F = A\frac{\tau_{failure}}{n_d}$ as,

$$\boxed{F = A(0.577)\frac{S_y}{n_d}}$$

Scenario 2 – Bolt bearing failure



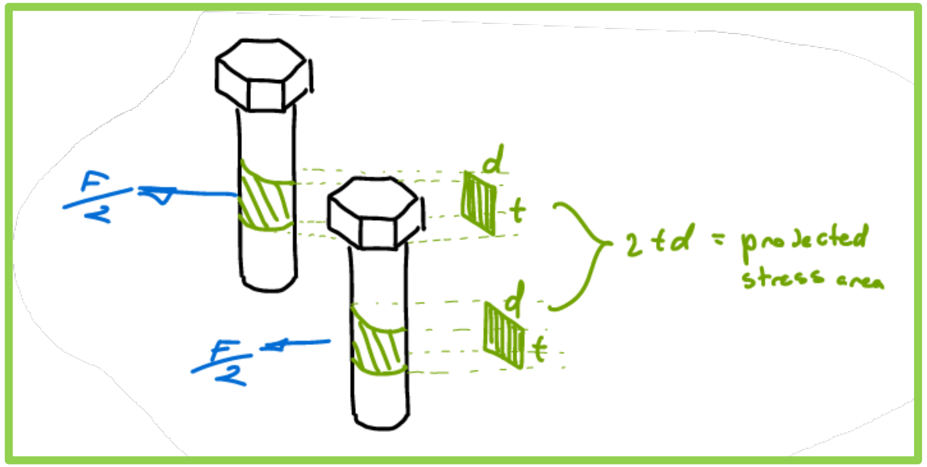
For bearing stress, we can use the original equation we created,

$$F = A\frac{S_y}{n_d},$$

Where $\mathrm{A} = 2td$. d = bolt major diameter $(20\ mm)$ and t = material thickness $(25.4\ mm)$. Substituting,

$$F = \frac{2tdS_y}{n_d}$$

$$= \frac{2(25.4)(20)(660)}{1.5} = \boldsymbol{447.04\ kN}$$



How d and t were obtained.

Two 25.4 by 101.6 mm 1018 cold-rolled steel bars are butt-spliced with two 12.7 by 101.6 mm 1018 cold-rolled splice plates using four M20 × 1.5 mm grade 5 bolts as depicted in Figure 8–26. For a design factor of $n_d = 1.5$ estimate the static load F that can be carried if the bolts lose preload.

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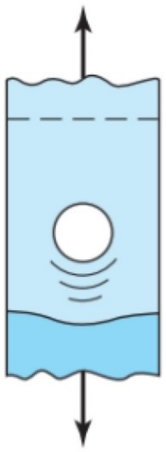
Scenario 3 – Bearing failure of members



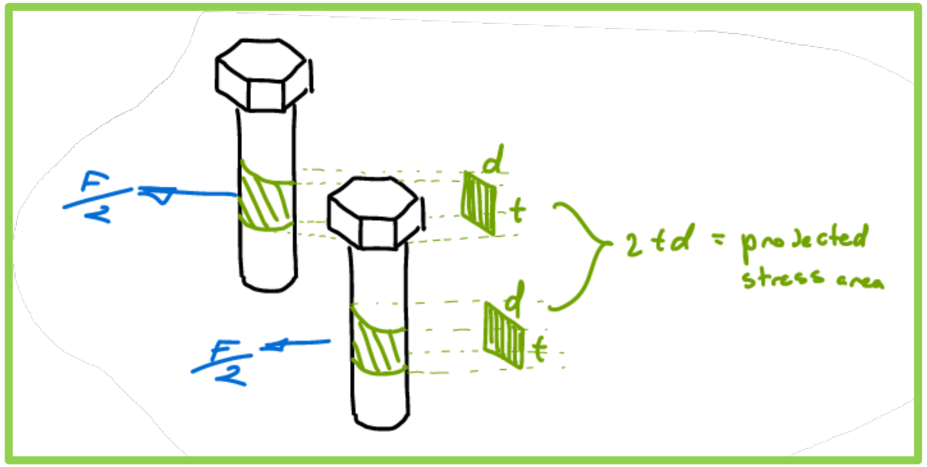
Another bearing analysis, so the same approach as before.

$$F = A\frac{S_y}{n_d},$$

$\mathrm{A} = 2td$ as before, however, $S_y = S_{y,member}$ because we are interested in how the supporting member themselves fail. Thus,

$$F = \frac{2tdS_{y,member}}{n_d}$$

$$= \frac{2(25.4)(20)(370)}{1.5} = \mathbf{250.61\ kN}$$



How d and t were obtained. They are identical to the bolt dimensions as in the context of the material, d and t are also the cross-sectional dimensions of the bolt hole.

Two 25.4 by 101.6 mm 1018 cold-rolled steel bars are butt-spliced with two 12.7 by 101.6 mm 1018 cold-rolled splice plates using four M20 × 1.5 mm grade 5 bolts as depicted in Figure 8–26. For a design factor of $n_d = 1.5$ estimate the static load F that can be carried if the bolts lose preload.

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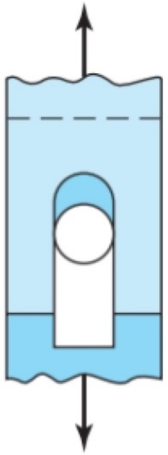
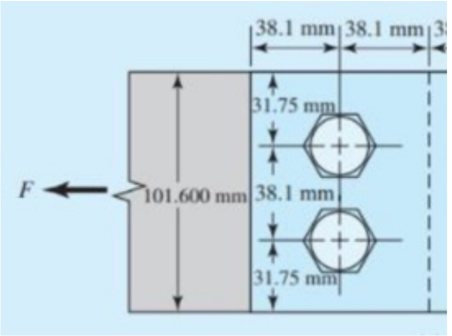
Scenario 4 – Edge shearing of members





We are back to shear analysis, therefore,

$$F = A(0.577)\frac{S_y}{n_d},$$

Where $A = 4at$. a $= 28.1\ mm$ and $t =$ material thickness $(25.4\ mm)$. Hence,

$$F = \frac{4at(0.577)S_{y,members}}{n_d}$$

$$= \frac{4(28.1)(25.4)(0.577)(370)}{1.5} = \mathbf{406.34\ kN}$$

Two 25.4 by 101.6 mm 1018 cold-rolled steel bars are butt-spliced with two 12.7 by 101.6 mm 1018 cold-rolled splice plates using four M20 × 1.5 mm grade 5 bolts as depicted in Figure 8–26. For a design factor of $n_d = 1.5$ estimate the static load F that can be carried if the bolts lose preload.

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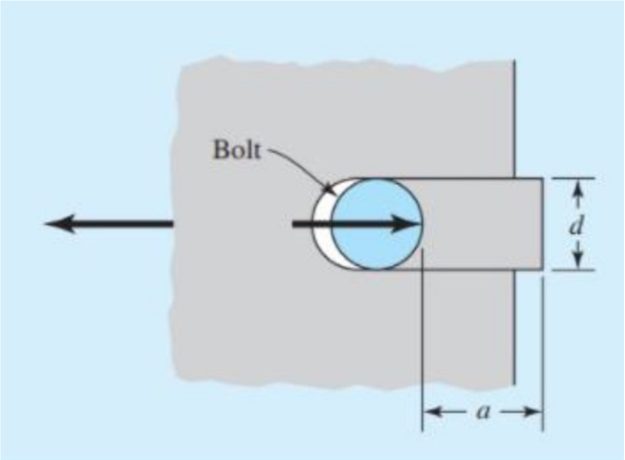
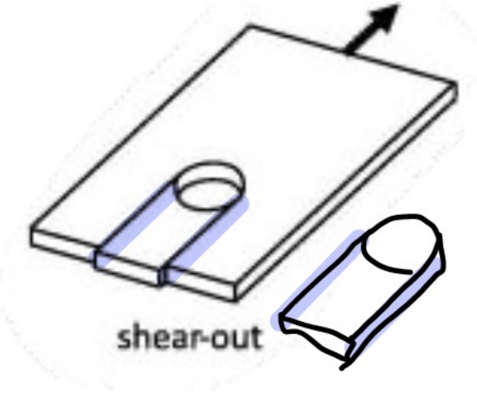


a is the distance from the hole edge to material edge. We subtract bolt radius from the centre to edge distance.

$$38.1 - 10 = 28.1\ mm$$



We use $4at$ because there are two bolt holes, each of which has 2 shear planes (purple).

Determining final answer

Compare the required force for failure and identify the one with the lowest magnitude.

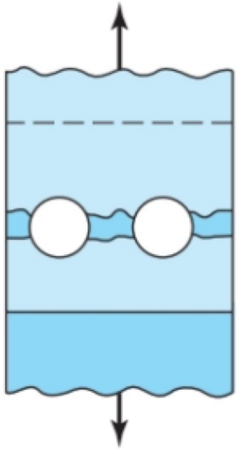
Thus, in this case we see that the limiting failure mode is bearing failure of members, which occurs at $\mathbf{250.61}\ \boldsymbol{kN}$.

Final answer: the maximum load which can be carried is $\mathbf{250.61}\ \boldsymbol{kN}$, beyond which failure by bearing failure of members will occur.

Failure Mode	**Required Force** $(\boldsymbol{kN})$
Bolt shear failure	319.04
Bolt bearing failure	447.04
Bearing failure of members	$\mathbf{250.61}$
Edge shearing of members	406.34
Tensile failure of members	448.60

- Tip: You can instead make another parameter such as S_y or other geometric variables if you know the load that the joint must carry the subject. This will allow you to calculate the minimum yield strength, thickness, bolt size, etc. you need for your joint to work.

Scenario 5 – Tensile failure of members



Same as the other tensile cases,

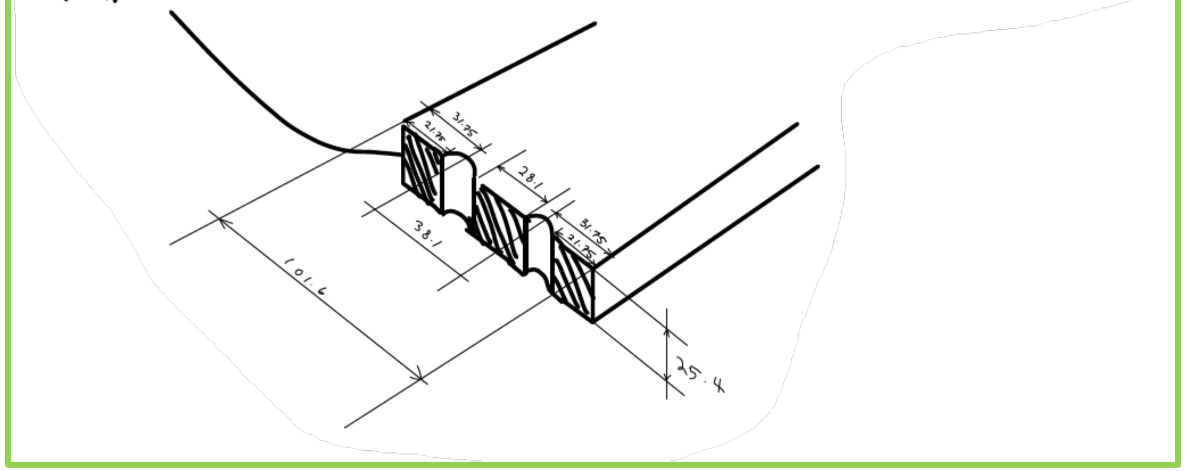
$$F = A\frac{S_y}{n_d},$$

Where $\mathrm{A} = 1818.64\,mm^2$, and $S_y = S_{y,member}$. Thus,

$$F = A\frac{S_{y,members}}{n_d}$$

$$= 1818.64\frac{370}{1.5} = \boldsymbol{448.60\ kN}$$

$A_{total} = 2 \times 21.75 \times 25.4 + 28.1 \times 25.4 = 1818.64\,mm^2$



A is the cross-sectional area of the member, along the predicted failure path.

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Project Time!

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Summary

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Summary

Today we covered:

- ❑ Axiomatic design methods
- ❑ Fasteners
- ❑ Assignment reminders
  - Presentation slides due date: **Sunday Week 3**
  - Presentation day: **during MECH workshop in Week 4**

Next week:

- ❑ Presentations!
- ❑ Planning User testing