AS3020: Aerospace Structures

Module 4: Bending of Beam-Like Structures

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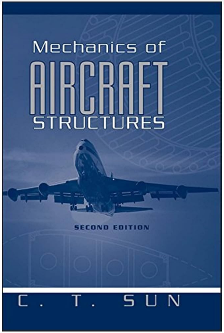
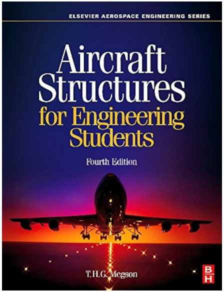
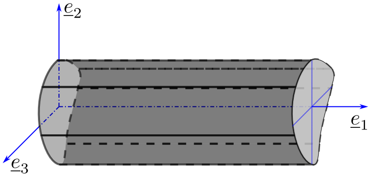


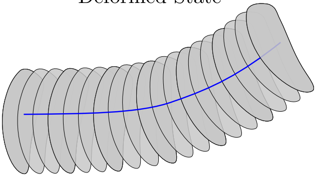
Chapters 4-5 in Sun [1]



Chapters 16-20 in Megson [2]

1. Unsymmetrical Bending





- Displacement Field

$$u_1 = -X_2\theta_3 + X_3\theta_2, \quad u_2 = v, \quad u_3 = w.$$

- Zero shear $\implies \theta_3 = v', \quad \theta_2 = -w'$
- Direct stress

$$\sigma_{11} = E_y \begin{bmatrix} X_3 & -X_2 \end{bmatrix} \begin{bmatrix} \theta_2' \\ \theta_3' \end{bmatrix}$$
$$= \frac{\begin{bmatrix} X_3 & -X_2 \end{bmatrix}}{I_{22}I_{33} - I_{23}^2} \begin{bmatrix} I_{33}M_2 + I_{23}M_3 \\ I_{23}M_2 + I_{22}M_3 \end{bmatrix}$$

- Equilibrium Considerations:

$$M_{2,1} = V_3, \qquad V_{2,1} + F_2 = 0$$
$$M_{3,1} = -V_2, \quad V_{3,1} + F_3 = 0.$$

1.1. Equations of Motion in Terms of Displacement

Unsymmetrical Bending

- The moments are related to σ_{11} through (note the signs)

$$M_3 = -\int X_2 \sigma_{11} dA, \quad M_2 = \int X_3 \sigma_{11} dA.$$

- Since $M_{2,1} = V_3$ and $M_{3,1} = -V_2$ (from equilibrium considerations), we can write the above as

$$\begin{bmatrix} V_2 \\ V_3 \end{bmatrix} = \int \begin{bmatrix} X_2 \\ X_3 \end{bmatrix} \sigma_{11,1} dA.$$

- Invoking force equilibrium ($V_{2,1} = -F_2$, $V_{3,1} = -F_3$) we have,

$$\begin{aligned} -\begin{bmatrix} F_2 \\ F_3 \end{bmatrix} = \int \begin{bmatrix} X_2 \\ X_3 \end{bmatrix} \sigma_{11,11} dA &= E_y \int \begin{bmatrix} X_2 \\ X_3 \end{bmatrix} \begin{bmatrix} -X_2 & X_3 \end{bmatrix} \begin{bmatrix} \theta_3''' \\ \theta_2''' \end{bmatrix} dA \\ &= -E_y \int \begin{bmatrix} X_2 \\ X_3 \end{bmatrix} \begin{bmatrix} X_2 & X_3 \end{bmatrix} \begin{bmatrix} v'''' \\ w'''' \end{bmatrix} dA \end{aligned}$$

1.1. Equations of Motion in Terms of Displacement

Unsymmetrical Bending

- Since deflections v, w do not depend on the section, the above simplifies to,

$$E_y \underbrace{\begin{bmatrix} \int X_2^2 dA & \int X_2 X_3 dA \\ \int X_2 X_3 dA & \int X_3^2 dA \end{bmatrix}}_{\mathbb{I}} \underbrace{\begin{bmatrix} v'''' \\ w'''' \end{bmatrix}}_{\underset{\sim}{u}''''} - \underbrace{\begin{bmatrix} F_2 \\ F_3 \end{bmatrix}}_{\underset{\sim}{F}} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

  which, in array-matrix notation is written as,

$$E_y \mathbb{I} \underset{\sim}{u}'''' - \underset{\sim}{F} = \underset{\sim}{0}.$$

- We have introduced the array $\underset{\sim}{u} = \begin{bmatrix} v & w \end{bmatrix}^T$ here.
- The above is a fourth order differential equation in terms of the deflections that governs the unsymmetrical bending.

2. Shear Stress and Flow in Sections

- If shear strain is assumed zero, can we still have shear stress?
- We posit: $\gamma_{12} = 0$, $\gamma_{13} = 0$, $\gamma_{23} = 0$. As point quantities, the shear stresses may still be small ($\tau_{12} = G\sigma_{12}$).
- But the **integral quantities** are taken to be finite:

$$\int \sigma_{12} dA = V_2, \qquad \int \sigma_{13} dA = V_3,$$
$$\int \sigma_{12} dX_3 = q_2, \qquad \int \sigma_{13} dX_2 = q_3.$$

- Invoking plane stress assumption at the section, the governing equation is,

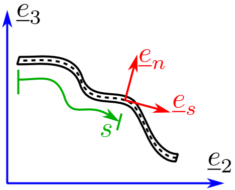
$$\sigma_{11,1} + \sigma_{1s,s} = 0.$$

- Integrating the above from $s = 0$ to s, we get the **Shear flow formula**:

$$q(s) - q_0 = -\frac{\begin{bmatrix}\int_0^s tX_3 ds & -\int_0^s tX_2 ds\end{bmatrix}}{I_{22}I_{33} - I_{23}^2} \begin{bmatrix} I_{33}V_3 - I_{23}V_2 \\ I_{23}V_3 - I_{22}V_2 \end{bmatrix}$$

2. Shear Stress and Flow in Sections

Thin Section: Plane Stress Assumption



- We define the above section-local coordinate system and transform the elasticity equations to $\sigma_{11,1} + \sigma_{1n,n} + \sigma_{1s,s} = 0$. Applying **plane stress** assumption (for thin sections) drops the σ_{1n} term, leading to:

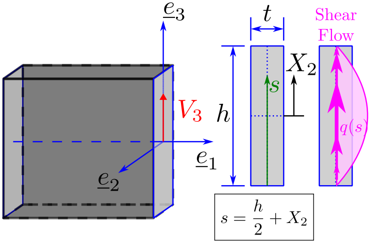
$$\sigma_{11,1} + \sigma_{1s,s} = 0 \implies t\sigma_{11,1} + q_{,s} = 0,$$

  where we have integrated along the $\underline{e}_n$ direction once.
- Following through with the integral along $\underline{e}_s$, this leads to the **shear flow formula**

$$q(s) - q_0 = -\frac{\begin{bmatrix}\int_0^s tX_3 ds & -\int_0^s tX_2 ds\end{bmatrix}}{I_{22}I_{33} - I_{23}^2} \begin{bmatrix} I_{33}V_3 - I_{23}V_2 \\ I_{23}V_3 - I_{22}V_2 \end{bmatrix}$$

2. Shear Stress and Flow in Sections

- Consider the rectangular section with height h and thickness t:



$$q(s) = -\frac{V_3}{I_{22}} \int_0^s t X_3 ds = -\frac{tV_3}{I_{22}} \int_{-\frac{h}{2}}^{X_3} X_3 dX_2$$

$$= -\frac{tV_3}{2I_{22}} (X_2^2 - \frac{h^2}{4})$$

- Remember that V_3 is NOT any externally **applied force**. It is merely **the resultant of all the shear stresses in the section**.
- So V_3 and $q(s)$ point in the same direction in this example. It is incorrect to think that $q(s)$ is balancing out V_3.

2. Shear Stress and Flow in Sections

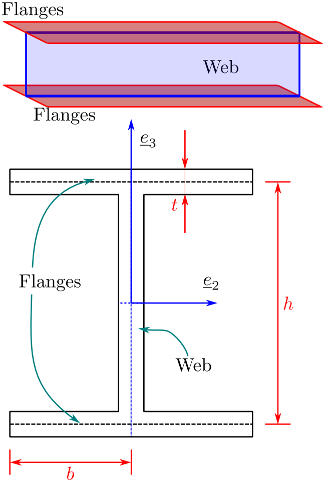
The "I" section

- Consider the shear distribution through an I-section as shown here
- The shear distribution looks like it is "flowing", with more "flow" occurring in the thin vertical web and less in the flanges.
- The second moment of area I_{22} sums up as,

$$I_{22} = \overbrace{\frac{h^3 t}{12}}^{web} + 2 \times \overbrace{\left(\frac{2bt^3}{12} + 2bt \times \frac{h^2}{4}\right)}^{flange} \approx (\frac{h^3}{12} + bh^2)t.$$

- I_{33} sums up as,

$$I_{33} = \underbrace{\frac{ht^3}{12}}_{web} + 2 \times \overbrace{\left(\frac{2b^3 t}{3}\right)}^{flange} \approx \underbrace{\frac{4b^3 t}{3}}_{\approx 0 \text{ for small b}}.$$

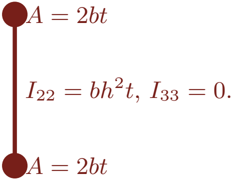


2. Shear Stress and Flow in Sections

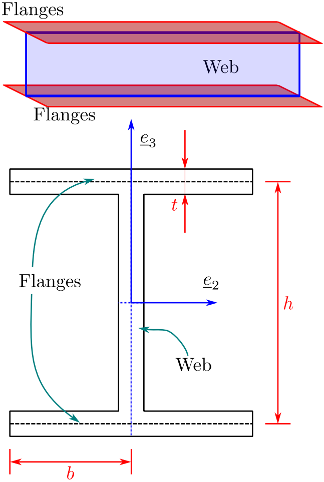
The “I” section

Idealization

- Both I_{22} and I_{33} are dominated by flange contributions, implying that **bending is supported primarily by the flanges.**
- This motivates the following idealization for the I-section:



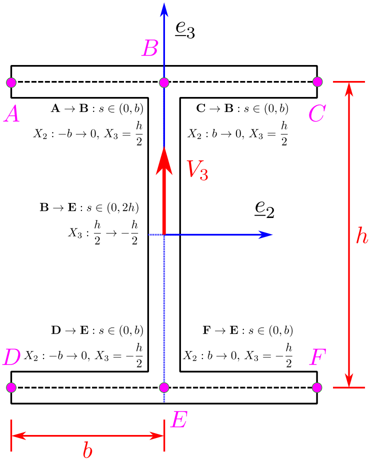
- The lumped area elements denoted are sometimes referred to as **“Booms”** in the section.
- Thickness in the web (denoted) is taken to be zero for bending-stress calculations.



2. Shear Stress and Flow in Sections

The "I" section

- Let us consider the case with $V_2 = 0$, $V_3 \neq 0$.
- The segments $A \to B$, $C \to B$, $D \to E$, and $F \to E$ are exposed in their free ends, simplifying the shear flow integral ($q = 0$ at free ends).



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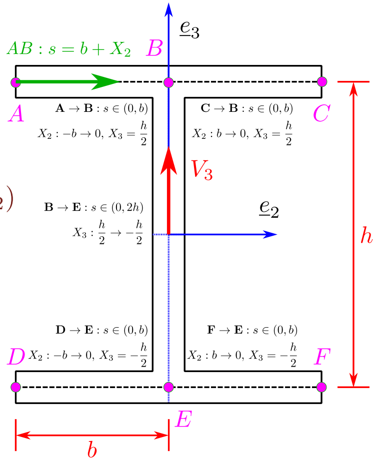
$$\mathbf{A} \rightarrow \mathbf{B} \ : \ q_{AB}(s) \equiv q_{AB}(X_2) =$$

$$-\frac{tV_3}{I_{22}} \int_0^s \cancelto{\frac{h}{2}}{X_3} ds = -\frac{htV_3}{2I_{22}}(b + X_2)$$



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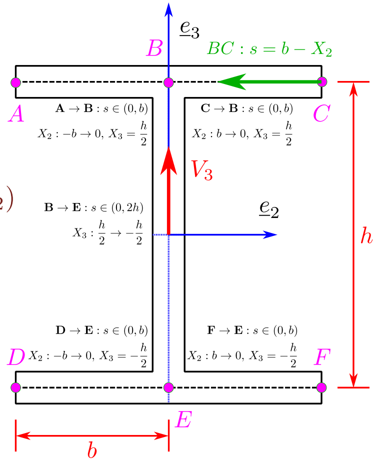

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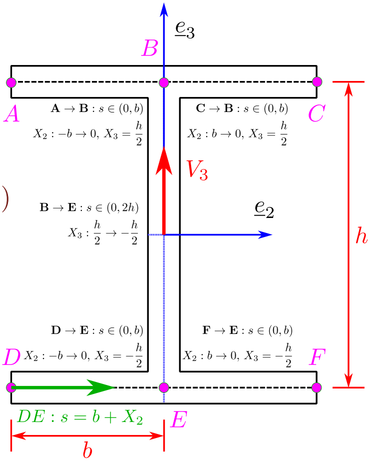
$$\mathbf{D} \to \mathbf{E} \; : \; q_{DE}(X_2) = \frac{htV_3}{2I_{22}}(b + X_2)$$



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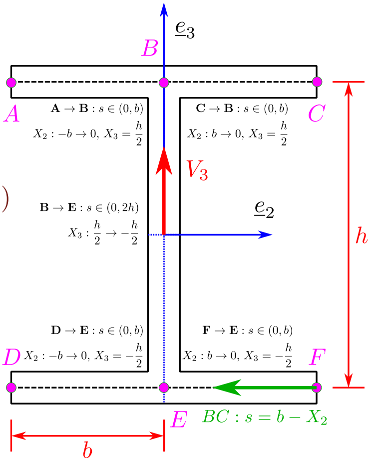
$$\mathbf{F} \to \mathbf{E} \;:\; q_{FE}(X_2) = \frac{htV_3}{2I_{22}}(b - X_2)$$



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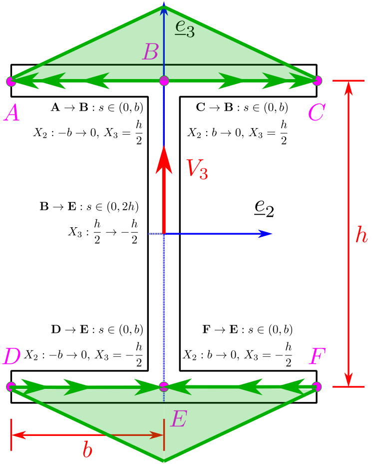
- In summary we have linear relationships at the flanges.



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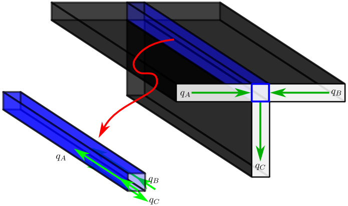
- In summary we have linear relationships at the flanges.
- Before looking at the web ($B \to E$), we have to observe the balance at the “T” junction.

Balance at the T-junction



$\sum F = q_A + qB - qC = 0 => q_C = q_A + q_B$

2. Shear Stress and Flow in Sections

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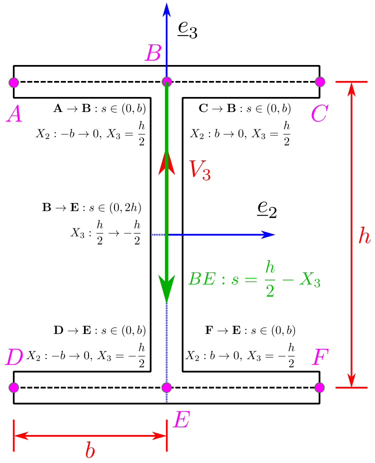
- The segments $A \to B$, $C \to B$, $D \to E$, and $F \to E$ are exposed in their free ends, simplifying the shear flow integral ($q = 0$ at free ends).
- On $\mathbf{B} \to \mathbf{E}$, we have $q_{BE}(0) = q_{AB}(0) + q_{CB}(0) = -\frac{bhtV_3}{I_{22}}$.
- The integration evaluates as,

$$q_{BE}(X_3) = -\frac{bhtV_3}{I_{22}} + \frac{tV_3}{2I_{22}}(X_3^2 - \frac{h^2}{4})$$
$$= -\frac{htV_3}{I_{22}}(b + \frac{h}{8}) + \frac{tV_3}{2I_{22}}X_3^2.$$



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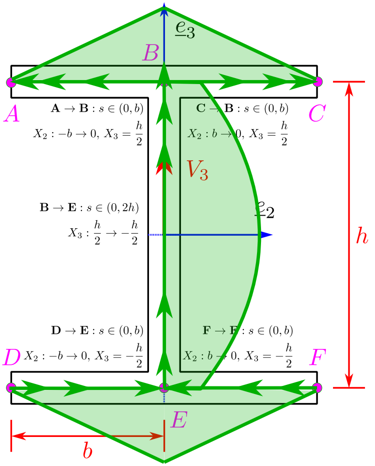
$$= -\frac{htV_3}{I_{22}}(b + \frac{h}{8}) + \frac{tV_3}{2I_{22}}X_3^2.$$

- We now have the complete shear flow in the section.



2. Shear Stress and Flow in Sections

The “I” section: Order of Magnitude Analysis

- Let us consider the “total” shear forces experienced by each member.
- **Flange AB**

$$V_{AB} = -\frac{htV_3}{2I_{22}}\int_{-b}^{0}(b+X_2)dX_2 = -\frac{b^2htV_3}{4I_{22}}$$

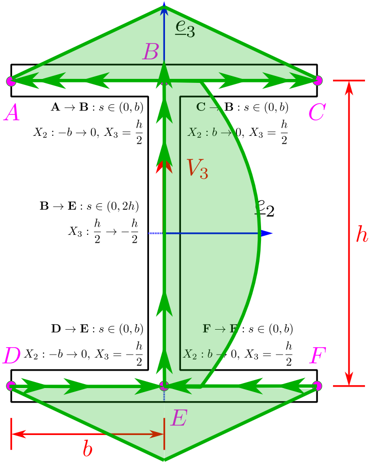
- **Web BE**

$$V_{BE} = \frac{h^2(h+12b)tV_3}{12I_{22}} = V_3$$

- For $b=\frac{h}{2}$, we have,

$$V_{AB} = -\frac{h^3tV_3}{16I_{22}} \approx -\frac{V_3}{8}$$

$$V_{BE} = V_3$$



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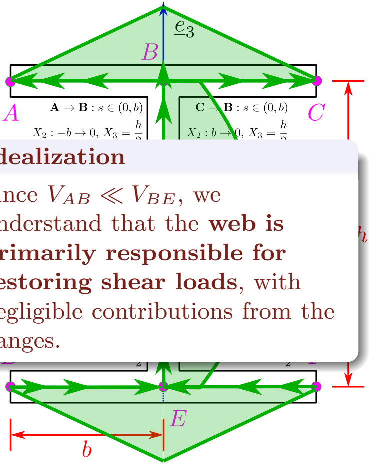


Idealization

Since $V_{AB} \ll V_{BE}$, we understand that the **web is primarily responsible for restoring shear loads**, with negligible contributions from the flanges.

2. Shear Stress and Flow in Sections

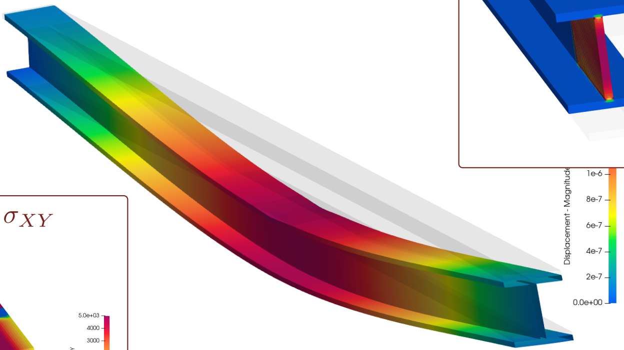
An "I" section beam subjected to 3-point bending: Finite Element Results

Code_Aster on the Salome Platform

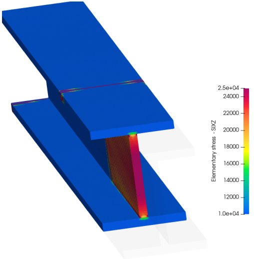
Free and Open Source (FOSS) FE solver that comes with a fully functional frontend (Salome)! Please Do Explore!

2. Shear Stress and Flow in Sections

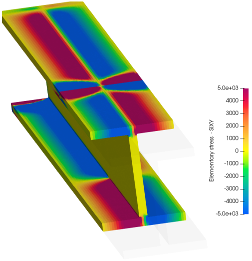
An “I” section beam subjected to 3-point bending: Finite Element Results



Stress σ_{XZ}

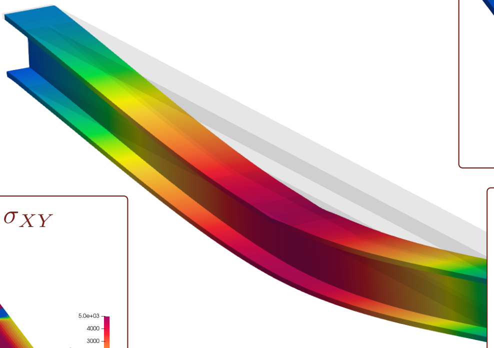


Stress σ_{XY}



2. Shear Stress and Flow in Sections

An "I" section beam subjected to 3-point bending: Finite Element Results



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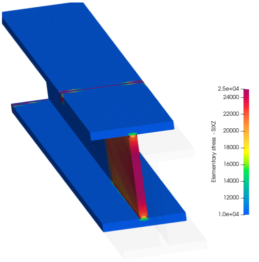

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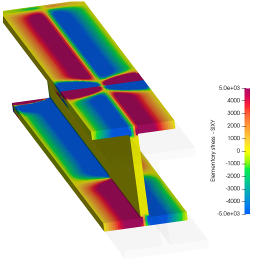
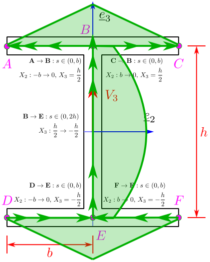


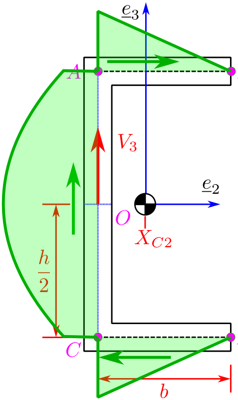
Shear Flow



2.1. Shear Center

Shear Stress and Flow in Sections

- Shear Center is the point of shear load such that $\sum m_1 = 0$. Although in a lot of symmetric sections this is coincident with the centroid, **this is NOT always the case**.
- Consider the "C" section beam:



$$\boxed{I_{22} \approxeq \frac{(h^3 + 6bh^2)t}{12}} + \mathcal{O}(t^2)$$

$$q_{BA}(X_2) = -\frac{htV_3}{2I_{22}}(b - X_2)$$

$$q_{AC}(X_3) = -\frac{htV_3}{2I_{22}}\left(b + \frac{h}{4}\right) + \frac{tV_3}{2I_{22}}X_3^2$$

$$q_{CD}(X_2) = -\frac{htV_3}{2I_{22}}(b - X_2)$$

$$\boxed{M_1 = \oint pqds = -\frac{b^2h^2tV_3}{4I_{22}} := V_3\xi_s}$$

$$\boxed{\xi_s \approxeq -\frac{3b^2}{h+6b} + \mathcal{O}(t)}$$

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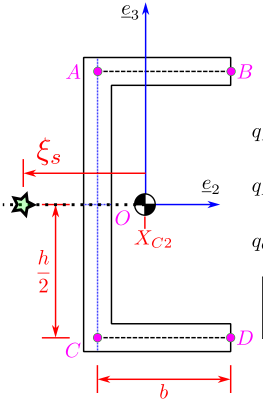


$$\boxed{I_{22} \approxeq \frac{(h^3 + 6bh^2)t}{12}} + \mathcal{O}(t^2)$$

$$q_{BA}(X_2) = -\frac{htV_3}{2I_{22}}(b - X_2)$$

$$q_{AC}(X_3) = -\frac{htV_3}{2I_{22}}\left(b + \frac{h}{4}\right) + \frac{tV_3}{2I_{22}}X_3^2$$

$$q_{CD}(X_2) = -\frac{htV_3}{2I_{22}}(b - X_2)$$

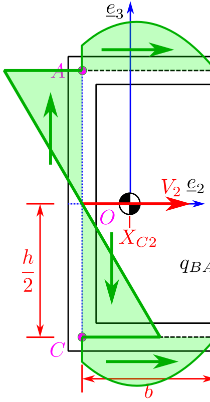
$$\boxed{M_1 = \oint pq ds = -\frac{b^2h^2tV_3}{4I_{22}} := V_3\xi_s}$$

$$\boxed{\xi_s \approxeq -\frac{3b^2}{h+6b} + \mathcal{O}(t)}$$

2.1. Shear Center

Shear Stress and Flow in Sections

- Shear Center is the point of shear load such that $\sum m_1 = 0$. Although in a lot of symmetric sections this is coincident with the centroid, **this is NOT always the case**.
- Consider the "C" section beam:



$$XC_2 = \frac{(bt)\frac{b}{2} \times 2}{2bt + ht} = \frac{b}{2 + h/b}$$

$$q(s) - q(0) = -\frac{tV_2}{I_{33}} \int_0^s X_2 ds$$

Shear Flow

$$q_{BA}(X_2) = \frac{tV_2}{2I_{33}} \frac{(X_2^2(h+2b)^2 - b^2(h+b)^2)}{(h+2b)^2}$$

$$q_{AC}(X_3) = -\frac{tb^2V_2}{(2b+h)I_{33}} X_3$$

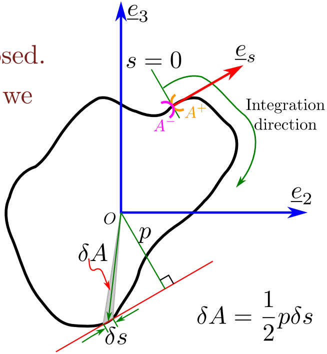
$$q_{CD}(X_2) = -q_{BA}(X_2)$$

2.2. Closed Sections

Shear Stress and Flow in Sections

- The shear-flow integral formula makes no reference to whether the section is open or closed.
- Considering the generic closed section shown, we start the integral at some **arbitrary** point A, denoting the point right before it as A^-. The integral is then written as,

$$q(s) - q_{A^-} = \underbrace{-\int_0^s t\sigma_{11,1} ds}_{q_b(s)}.$$

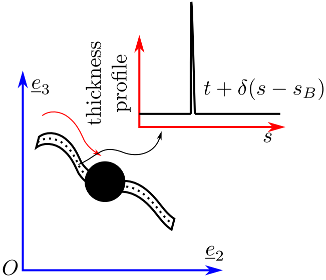


- When no twisting is expected at the section, the moment along $\underline{e}_1$ about O has to be zero. This is computed as,

$$\int_{A^-}^{A^+} dM_1 = \oint pq(s)ds = q_{A^-} \overbrace{\oint pq(s)ds}^{2A} + \oint pq_b(s)ds \implies \boxed{q_{A^-} = -\frac{1}{2A}\oint pq_b(s)ds}.$$

3. Stringer-Web Idealization

- A stringer, when looked at from a section, looks like a feature with a sudden increase in thickness.
- Consider the r^{th} "Boom" to be located at (X_{r_2}, X_{r_3}), with area A_r.



- So the shear flow integral can be generalized to,

$$q(s) - q(0) = -\frac{\begin{bmatrix} t\int_0^s X_3 ds + \sum_r A_r X_{r_3} & -t\int_0^s X_2 ds - \sum_r A_r X_{r_2} \end{bmatrix}}{I_{22}I_{33} - I_{23}^2} \begin{bmatrix} I_{33}V_3 - I_{23}V_2 \\ I_{23}V_3 - I_{22}V_2 \end{bmatrix}$$

- When thickness t is negligible in comparison to the boom sections, this further simplifies to,

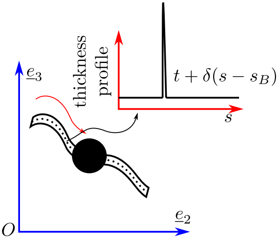
$$q(s) - q(0) = -\frac{\begin{bmatrix} \sum_r A_r X_{r_3} & -\sum_r A_r X_{r_2} \end{bmatrix}}{I_{22}I_{33} - I_{23}^2} \begin{bmatrix} I_{33}V_3 - I_{23}V_2 \\ I_{23}V_3 - I_{22}V_2 \end{bmatrix}$$

3. Stringer-Web Idealization

- Considering the integral right across the boom, we have,

$$q^+ - q^- = -\frac{\begin{bmatrix} A_r X_{r_3} & -A_r X_{r_2} \end{bmatrix}}{I_{22}I_{33} - I_{23}^2} \begin{bmatrix} I_{33}V_3 - I_{23}V_2 \\ I_{23}V_3 - I_{22}V_2 \end{bmatrix}.$$

- For the sections without a boom, there is **no change in the shear flow**.
- Therefore, the shear flow is constant in the webs that join two booms.



General Design Principle

- As a general principle, the stringers/booms are added to support bending.
- The web thicknesses are chosen to ensure the shear stresses don't exceed failure threshold (we should like to have $t = 0$ to minimize weight!).

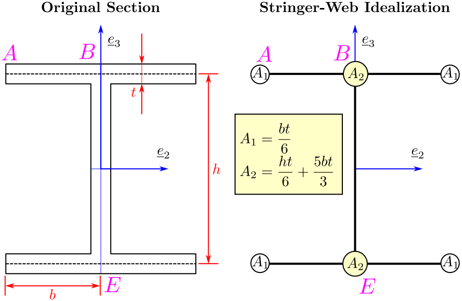
3. Stringer-Web Idealization

Idealization of the I-Section

- We idealize the I-section by lumping area elements A_1 and A_2. A_1 and A_2 are estimated by matching the second area moments:

$$\overbrace{4\times\left(\frac{A_1h^2}{4}\right)+2\times\left(\frac{A_2h^2}{4}\right)}^{I_{22,ideal}} = \overbrace{\left(\frac{h^3}{12}+bh^2\right)t+\mathcal{O}(t^2)}^{I_{22,orig}}$$

$$\overbrace{4\times(A_1b^2)}^{I_{33,ideal}} = \overbrace{\frac{4b^3t}{3}+\mathcal{O}(t^2)}^{I_{33,ideal}}$$



- The total sectional area of the original section is $ht + 4bt$.
- The total area of the new section (assuming the web thickness is drastically reduced) is $4A_1 + 2A_2 = \frac{ht}{3} + 4bt$, which is a **slight reduction**.
- Looking at this from a manufacturing standpoint, this shows that **a web-stringer construction can achieve similar bending stiffness with lesser material expenditure**.

3. Stringer-Web Idealization

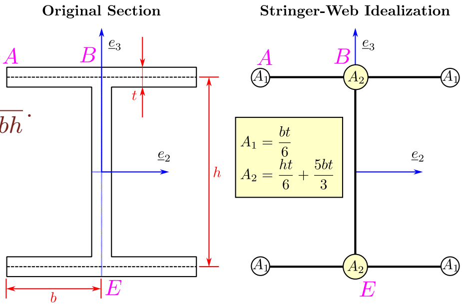
Idealization of the I-Section: Shear Flow Comparisons

- For the idealized section AB, the shear flow is given by,

$$q_{AB,ideal} = -\frac{V_3}{I_{22,ideal}} A_1 \frac{h}{2} = -\frac{V_3 b}{h^2 + 12bh}.$$

The average flow for the original section is,

$$q_{AB,avg} = \frac{1}{b}\left(-\frac{b^2 ht V_3}{4I_{22}}\right) = \frac{3V_3 b}{h^2 + 12bh}.$$



- On BE, the idealized flow is

$$q_{BE,ideal} = 2q_{AB,ideal} - \frac{V_3}{I_{22,ideal}} A_2 \frac{h}{2} = -\frac{V_3}{h},$$

which is the same for the original section also.

- In the stringer-web section, therefore, the flanges carry lesser average shear than the original section, and the web carries the same shear.

4. Shear Lag

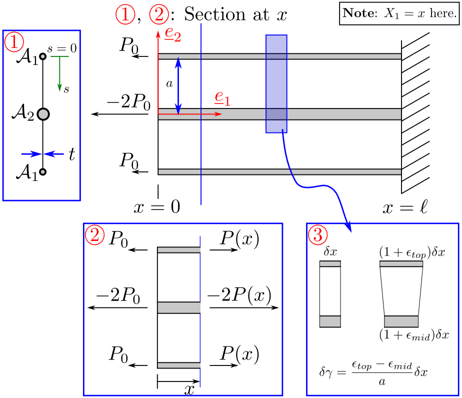
Example from Sun [1] (Section 3.1)

- We already saw the St. Venant's principle. Can we say something more specific about "how fast" the end effects start getting smoothed out in the stress field? Consider:

- Applying equilibrium on the section at some $X_1 = x$ ① leads to top and bottom booms experiencing $\boxed{\int_{\mathcal{A}_1} \sigma_{11} dA = P(x)}$, and the central boom, $\boxed{\int_{\mathcal{A}_2} \sigma_{11} dA = -2P(x)}$.

- Shear flow in top web is given as

$$q_{top} = -\sigma_{11,1}\mathcal{A}_1 = -P_{,1}$$
$$\text{or, } -t\sigma_{12} = -P_{,1}.$$



4. Shear Lag

Example from Sun [1] (Section 3.1)

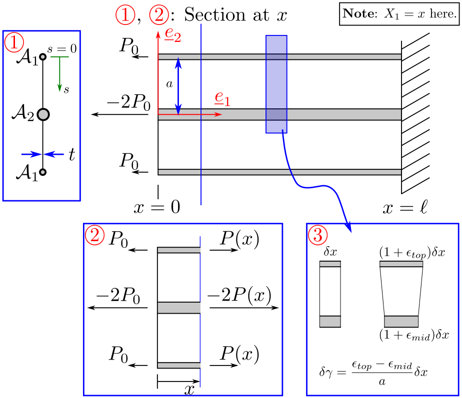
- Considering the shear differential in an infinitesimal section (3) we have,

$$\frac{\partial \gamma_{12}}{\partial x} = \frac{1}{a}(\epsilon_{top} - \epsilon_{mid})$$
$$= \frac{1}{E_y a}\left(\frac{P(x)}{\mathcal{A}_1} - \frac{-2P(x)}{\mathcal{A}_2}\right)$$

- Since $\gamma_{12} = \frac{1}{G}\sigma_{12}$, this becomes,

$$\sigma_{12,1} = \frac{G}{E_y a}\left(\frac{1}{\mathcal{A}_1} + \frac{2}{\mathcal{A}_2}\right)P(x).$$

- Using the force balance relationship $\boxed{\sigma_{12} = \frac{1}{t}P_{,1}}$ also



$$\Longrightarrow \boxed{P_{,11} = \frac{Gt}{E_y a}\left(\frac{1}{\mathcal{A}_1} + \frac{2}{\mathcal{A}_2}\right)P}$$

4. Shear Lag

Example from Sun [1] (Section 3.1)

- The equation governing the **boom restoring axial force** is of the form

$$P_{,11} - \lambda^2 P = 0, \qquad \lambda = \sqrt{\frac{Gt}{E_y a}\left(\frac{1}{\mathcal{A}_1} + \frac{2}{\mathcal{A}_2}\right)}.$$

- This is solved by

$$P(X_1) = C_1 e^{-\lambda X_1} + C_2 e^{\lambda X_1}.$$

- Solving it over $X_1 \in (0, \infty)$, it is easy to see that C_2 must be 0 for $P(X_1)$ to be bounded. So we have an **exponentially decaying** restoring force on the booms:

$$P(X_1) = P_0 e^{-\lambda X_1}.$$

- Substituting for σ_{12} we have (for the top web),

$$\sigma_{12} = -\frac{\lambda P_0}{t} e^{-\lambda X_1},$$

which also decays exponentially in X_1.

4. Shear Lag: Decay Rate

Example from Sun [1] (Section 3.1)

- The shear lag factor λ controls how quickly the effects "diffuse out".
  - Large λ implies "fast" diffusion and potentially high concentration around the ends..
  - Small λ implies "slow" diffusion and potentially low concentrations.
- In general for stringer-web structures,

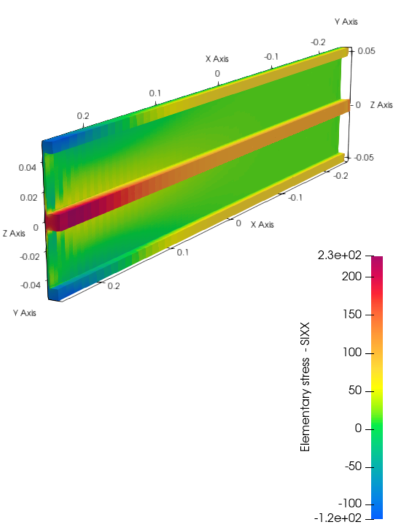
$$\lambda \propto \sqrt{\frac{G}{E_y}}.$$

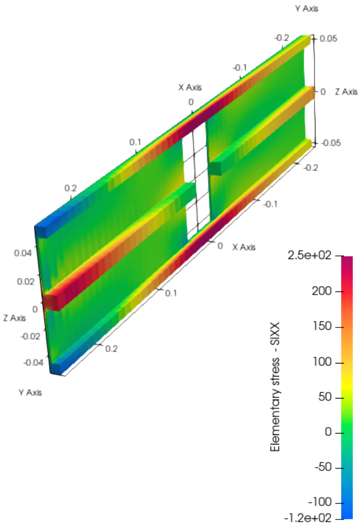
  - $\uparrow G$ (stiffer web), $\uparrow \lambda$ ("faster" diffusion).
  - $\uparrow E_y$ (stiffer boom), $\downarrow \lambda$ ("slower" diffusion).

The terms "faster" and "slower" are used in the sense that "slower" implies that the stress distribution needs a longer axial distance to get averaged out (vise versa for "faster").

4. Shear Lag

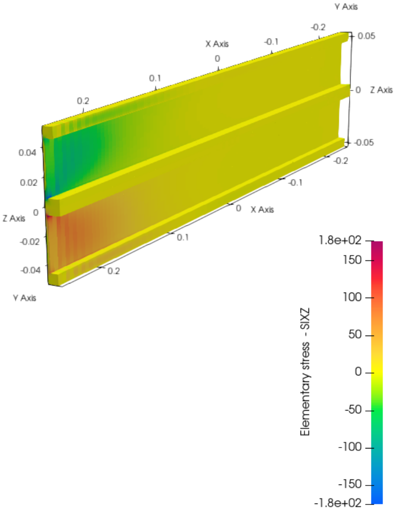
Example from Sun [1] (Section 3.1): FE Results

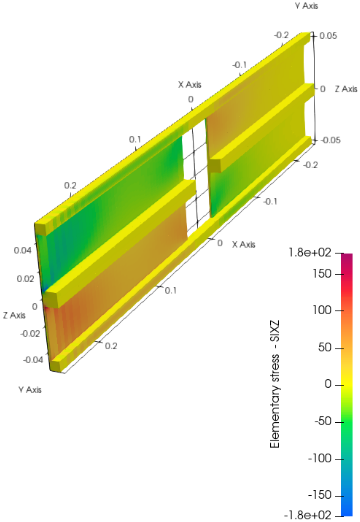




4. Shear Lag

Example from Sun [1] (Section 3.1): FE Results





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[1] C. T. Sun. Mechanics of Aircraft Structures, 2nd edition. Hoboken, N.J: Wiley, June 2006. ISBN: 978-0-471-69966-8 (cit. on pp. 2, 33–38).

[2] T. H. G. Megson. Aircraft Structures for Engineering Students, Elsevier, 2013. ISBN: 978-0-08-096905-3 (cit. on p. 2).