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Course Description

Designing Members for Torsion

February 12, 2015

This webinar will present an introduction to the general topic of torsion in structural members, including descriptions of St. Venant and warping resistance. Tools and methods for calculating twist and torsional demand stresses will be discussed. In addition to member behavior, the specific topic of Steel Lintel Design for Large Openings in Bearing Wall Buildings will also be addressed.

Learning Objectives

- Become familiar with the general topic of torsion in structural members.
- Gain an understanding of the principles of torsion such as St. Venant and warping resistance.
- Gain an understanding of the tools and methods for calculating twist and torsional demand stresses in structural members.
- Become familiar with the design of steel lintels by working through a design example.

There's always a solution in steel.

Designing Members for Torsion

written and presented by
Daniel Linzell, Ph.D., P.E., F.ASCE
Professor
University of Nebraska, Lincoln

structural STEEL

Designing Members for Torsion
(It's NOT a 4-LETTER WORD!!)

Daniel Linzell
University of Nebraska, Lincoln

Steel Design Guide Series 9

Torsional Analysis of Structural Steel Members

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Acknowledgements

- Cristopher Moen, Virginia Tech
- AISC – Charlie Carter, Brent Leu
- Lou Geschwindner, Penn State University
- Paul Seaburg, Penn State, University of Nebraska
- Walt Schneider, Penn State University

VirginiaTech Invent the Future

PENNSTATE

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Overview – The “T” Word

- Background
  - What is it? Why do we care?
- A Few Fundamentals (BUT NOT MUCH THEORY)
  - How can shear “flow”?
  - What is the shear center?
  - There are different types of torsion? Huh? Why? What are they?
- What Do I Do with This Info?
  - Design
  - Analysis
- Where Do I Go for More Help?
  - Texts, guides and specs
- The REAL Reason Why You’re Here – EXAMPLE

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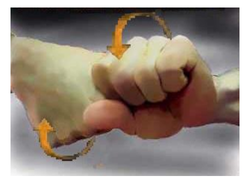
Background - Torsion

- What is it?
  - From Wikipedia

    In solid mechanics, torsion is the twisting of an object due to an applied torque, therefore is expressed in N·m or ft·lbf. In sections perpendicular to the torque axis, the resultant shear stress in this section is perpendicular to the radius.
  - Real world examples



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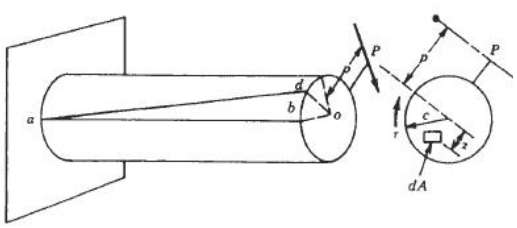
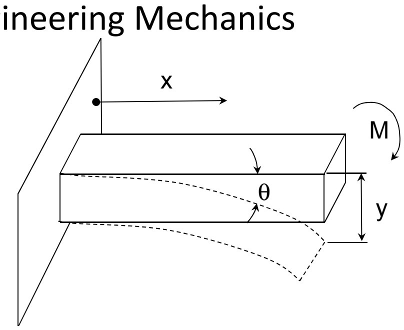
Background - Torsion

- From Your Undergrad Engineering Mechanics Class – "Pure Torsion"





$$\theta = \frac{TL}{GJ} \quad \Longleftrightarrow \quad \frac{d\theta}{dx} = \frac{M}{EI}$$

Torsion *Bending*

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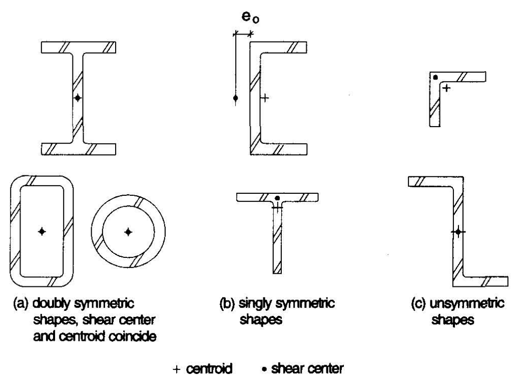
Background - Torsion

- From Your Undergrad Engineering Mechanics Class?
  - How many cantilevered, solid round bars are used in steel building structural elements? Not many – most are like those shown. Consequences?



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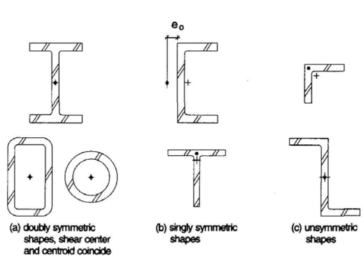
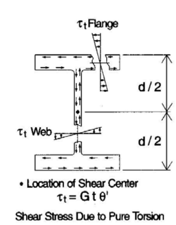
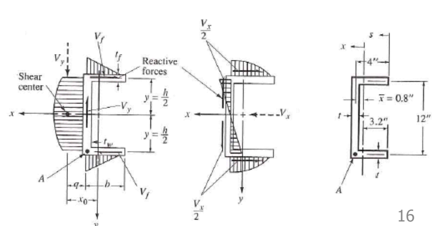
Background - Torsion

- From Your Undergrad Engineering Mechanics Class?
  - Consequences? New worries with these sections – shear flow, shear center, determining J.







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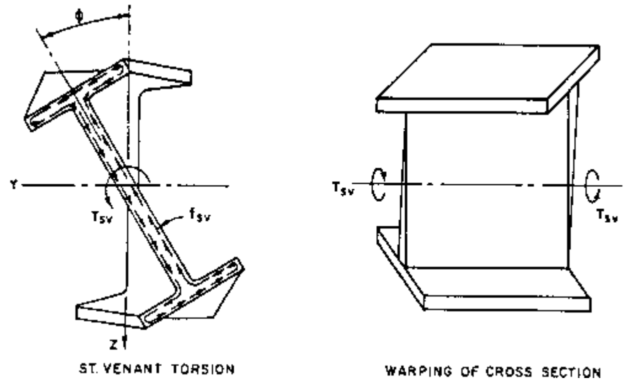
Background - Torsion

- From Your Undergrad Engineering Mechanics Class?
  - More consequences?
    - Pure (St. Venant's) vs. Warping Torsion.



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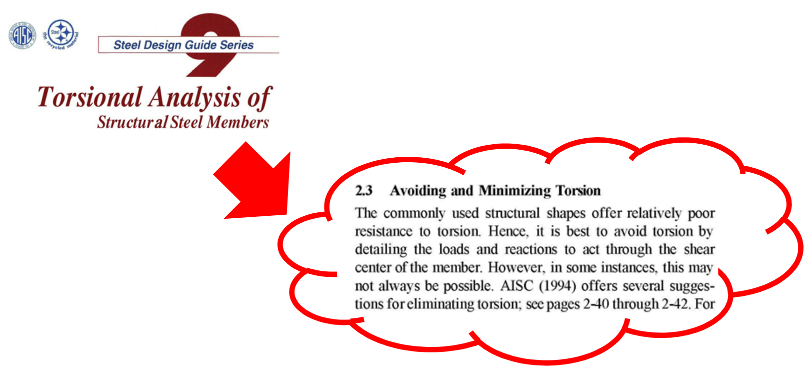
Background - Torsion

- Why Do We Care?
  - Even Though Publications We Use Say/Show This:



2.3 Avoiding and Minimizing Torsion

The commonly used structural shapes offer relatively poor resistance to torsion. Hence, it is best to avoid torsion by detailing the loads and reactions to act through the shear center of the member. However, in some instances, this may not always be possible. AISC (1994) offers several sugges-tions for eliminating torsion; see pages 2-40 through 2-42. For

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Background - Torsion

- Why Do We Care?
  - We Run Into Situations Like This:

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Background - Torsion

- Why Do We Care?
  - AND too much twist can be a bad thing

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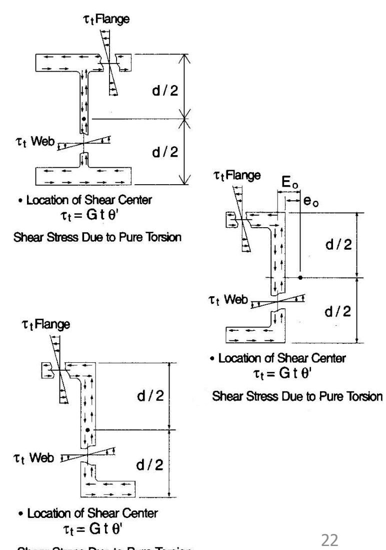
A Few Fundamentals

- Terms You May (or May Not) Know
  - Shear Flow
    - Again, Wiki:

      The gradient of a shear stress force through the body (in solid mechanics)

      The flow induced by such a force gradient (in a fluid)
  - Both definitions applicable?



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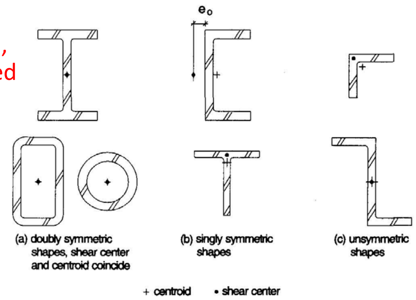
A Few Fundamentals

- Terms You May (or May Not) Know
  - Shear Center (Wiki!!)

    "An imaginary point on a section, where a shear force can be applied without inducing any torsion"

  - Sometimes coincides with centroid (center of area)
  - How establish? Look @ "twist equilibrium" in-plane. No twist occurs due to in-plane shears that develop due to flexure – location where they cancel each other out is shear center.



A Few Fundamentals

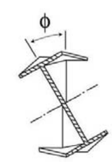
- Terms You May (or May Not) Know (NO WIKI!!)
  - Pure (St. Venant's) Torsion

    Planar rotation of a structural element. Generates in-plane shear stresses.

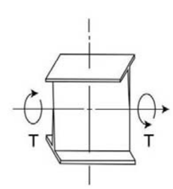
  - Warping Torsion

    Tendency of portions of structural element to move out of plane. If out of plane movement not prevented, no stresses developed. If prevented, generates BOTH in-plane shear stresses and stresses normal to plane.

ALL THIN WALLED SECTIONS WANT TO WARP!! DIFFERENCES RELATE TO HOW MUCH. CAN IT BE IGNORED?



Rotated Cross Section

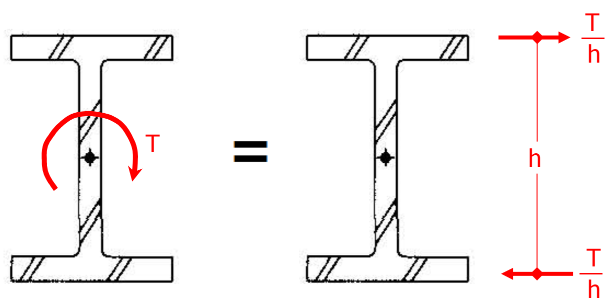


Warped Section

A Few Fundamentals

- Warping Torsion

Can also be seen as a force couple to each flange



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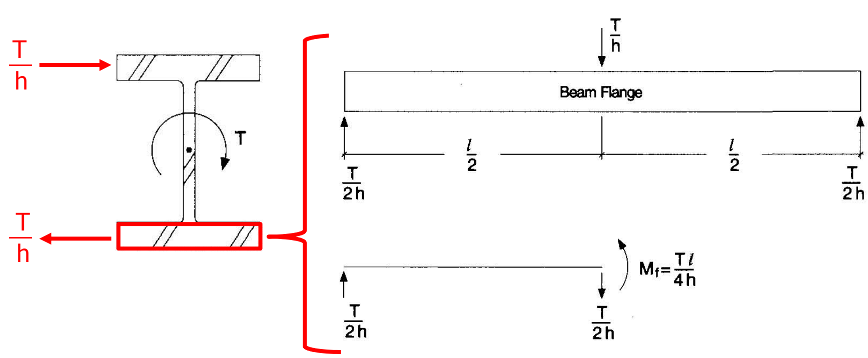
A Few Fundamentals

- Warping Torsion

Now lets look at the bottom flange



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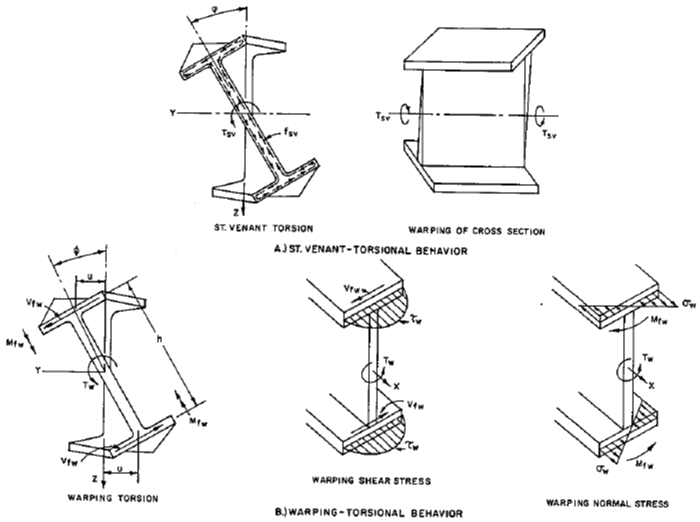
A Few Fundamentals



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Overview – The "T" Word

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What Do I Do? Design

- AISC Manual – Art. H3.2 for HSS
  - HSS Subject to Combined Torsion, Shear, Flexure and Axial Force. INTERACTION approach w/ Eqn. H3-6:

$$\left(\frac{P_r}{P_c}+\frac{M_r}{M_c}\right)+\left(\frac{V_r}{V_c}+\frac{T_r}{T_c}\right)^2 \leq 1.0$$

  - $T_r < 0.2 * T_c$, ignore torsion.
  - T_c prescribed in Eqns. H3-2a or H3-2b.

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What Do I Do? Design

- AISC Manual – Art. H3.3 for non-HSS
  - Non-HSS Members Subjected to Torsion and Combined Stress. Following STRESS LIMITS Apply.
  - Yielding under normal stress (Eqn. H3-7):

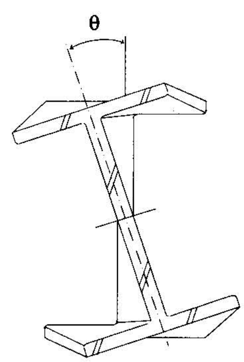
$$F_n = F_y$$

  - Shear yielding (Eqn. H3-8):

$$F_n = 0.6F_y$$

  - Buckling (Eqn. H3-9):

$$F_n = F_{cr}$$



Rotated Cross Section

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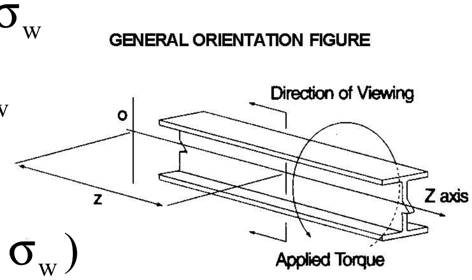
What Do I Do? Analysis

- AISC DG9 – Cumulative Stress from Superposition, using Proper Signs

$$f_n = \sigma_a \pm \sigma_{bx} \pm \sigma_{by} \pm \sigma_w$$

$$f_v = \tau_{bx} \pm \tau_{by} \pm \tau_t \pm \tau_w$$



I-Shapes:

$$f_n = \sigma_a \pm (\sigma_{bx} + \sigma_{by} + \sigma_w)$$

$$f_v = \tau_{bx} + \tau_{by} + \tau_t + \tau_w$$

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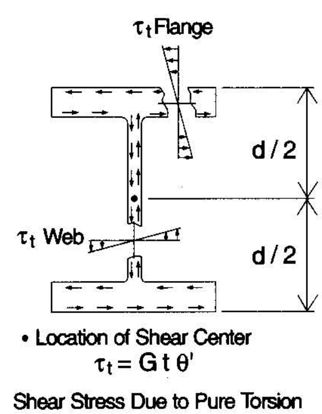
What Do I Do? Analysis

- Determine All Contributors to Stress States
  - Shear
    - St. Venant's Torsion

$$\tau_t = Gt\theta'$$

G = shear modulus
t = element thickness
θ' = Rate of change of θ



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What Do I Do? Analysis

- Determine All Contributors to Stress States
  - Shear
    - Warping Torsion

$$\tau_{ws} = \frac{-ES_{ws}\theta'''}{t}$$

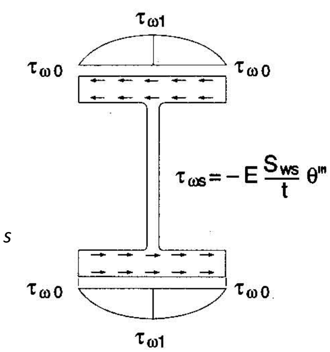
E = elastic modulus

S_{ws} = warping statical moment at s

= $hb_f^2 t_f/16$

t = element thickness

θ''' = 3rd derivative of θ



Shear Stress Due to Warping

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What Do I Do? Analysis

- Determine All Contributors to Stress States
  - Normal
    - Warping Torsion

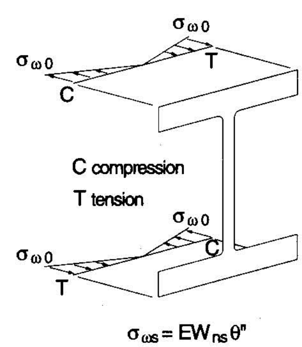
$$\sigma_{ws} = EW_{ns}\theta''$$

E = elastic modulus

W_{ws} = normalized warping function at s

= $hb_f/4$

θ'' = 2nd derivative of θ



Normal Stress Due to Warping

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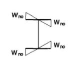
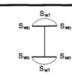
What Do I Do? Analysis

Appendix A
TORSIONAL PROPERTIES



W-, M-, S-, and HP-Shapes



	Torsional Properties					Statical Moments	
	J	C_w	a	W_{no}	S_{w1}	Q_f	Q_w
Shape	in.^{4}	in.^{6}	in.	in.^{2}	in.^{4}	in.^{3}	in.^{3}
W44×335	74.4	536,000	137	168	1,190	282	811
262	37.7	406,000	167	165	922	225	636
230	24.9	346,000	190	164	789	194	551
278	64.7	192,000	87.6	115	622	192	596
264	56.1	181,000	91.3	114	589	184	566
235	41.3	161,000	101	113	530	168	506
211	30.4	140,000	109	112	468	151	453
183	19.6	119,000	125	111	402	134	391
167	14.0	99,300	136	111	336	113	346
149	9.60	79,600	147	110	270	92.0	299
W36×848	1,270	1,620,000	57.5	172	3,530	674	1,910
798	1,070	1,480,000	59.8	169	3,270	634	1,790
650	600	1,090,000	68.6	162	2,520	513	1,420
527	330	816,000	80.0	156	1,960	415	1,130
439	195	637,000	92.0	152	1,570	344	928
393	143	554,000	100	150	1,390	309	830
359	109	493,000	108	148	1,240	281	757
328	84.5	441,000	116	146	1,130	258	691
300	64.2	398,000	127	146	1,020	235	628
280	52.6	366,000	134	145	944	219	585
260	41.5	330,000	143	144	858	200	538
245	34.6	306,000	151	143	799	187	505
230	28.6	282,000	160	143	740	175	472

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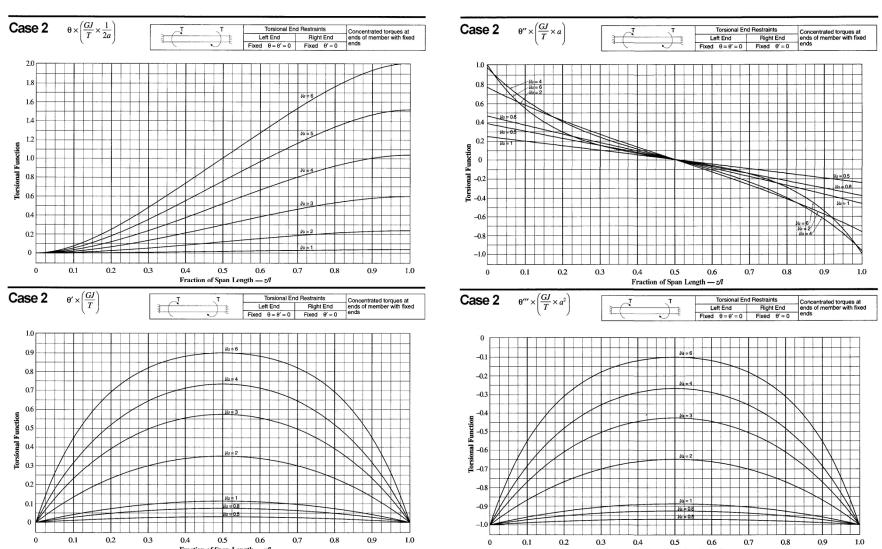

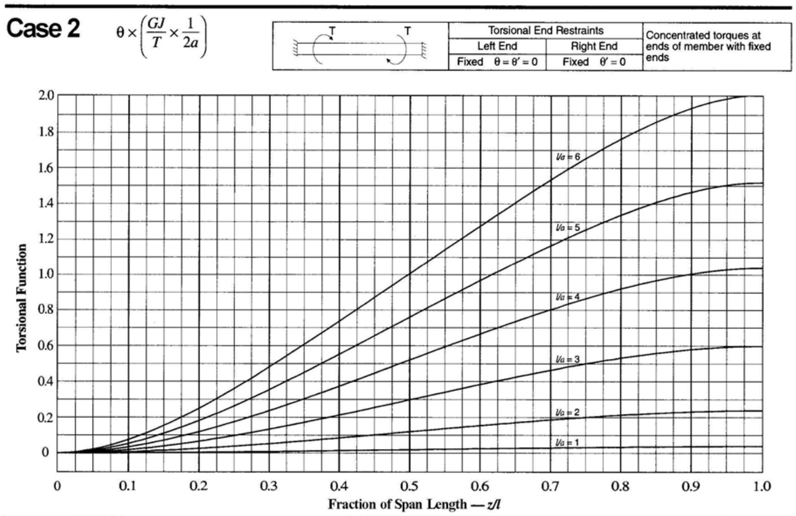

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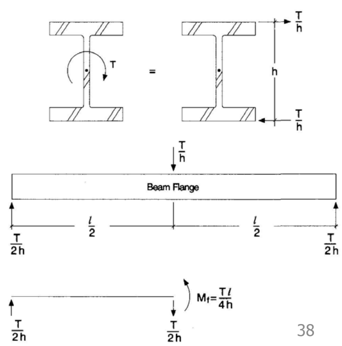
What Do I Do? Analysis

- Approximations to St. Venant's, Warping Stresses – DG9 and others
  - Warping – Torque resolved into flange forces. Those forces on flange "beam" generate shear and bending stresses – approximate using beam theory (DG 9).

$$\tau_w = \frac{1.5V_f}{b_f t_f}$$

$$\sigma_w = \frac{M_f}{S_f}$$



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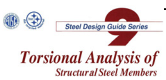
Where Do I Go for More Help?

- Buildings
  - Seaburg, P.A. and Carter, C. J. AISC Steel Design Guide Series #9, Torsional Analysis of Structural Steel Members, American Institute of Steel Construction, 2003.
  - Steel Construction Manual, 14th Ed., American Institute of Steel Construction, 2011.



- Bridges
  - AASHTO/NSBA G 13.1 – Guidelines for Steel Girder Bridge Analysis (2011), http://www.aisc.org/contentNSBA.aspx?id=20130
  - AISC/NSBA Steel Bridge Design Handbook, http://www.aisc.org/contentNSBA.aspx?id=20244
- General
  - Salmon, C.G., Johnson, J.E. and Malhas, F.A., Steel Structures – Design and Behavior, 5th Ed., Pearson Prentice Hall, 2009.
  - Young, W. and Budynas, R., Roark's Formulas for Stress and Strain, 7th Ed., McGraw Hill, 2001.
  - Your undergrad mechanics textbook
  - Your undergrad steel design textbook

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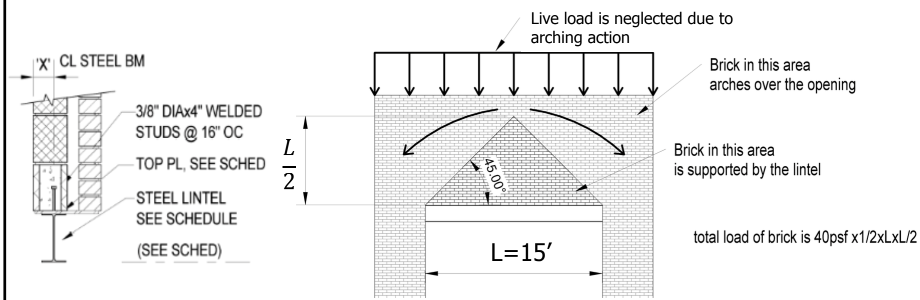
Example

Steel lintel beam spanning opening in a bearing wall building



Thanks to Jake Lamb at OWPR, Inc.
http://www.owpr.com/

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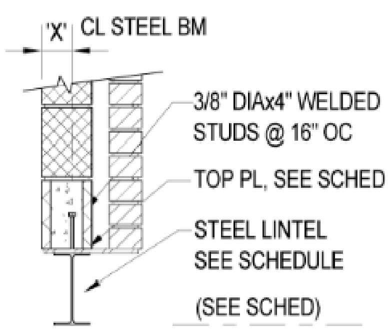
Design approach including torsion…

Steel lintel beam spanning opening in a bearing wall building



(a) Define structural system – span, boundary conditions, materials

(b) Find member demand shear V, moment M, torsion T, and axial force P

(c) Calculate angle of twist θ and its derivatives

(d) Check $M+T+P$ normal stresses

(e) Check $V+T$ shear stresses

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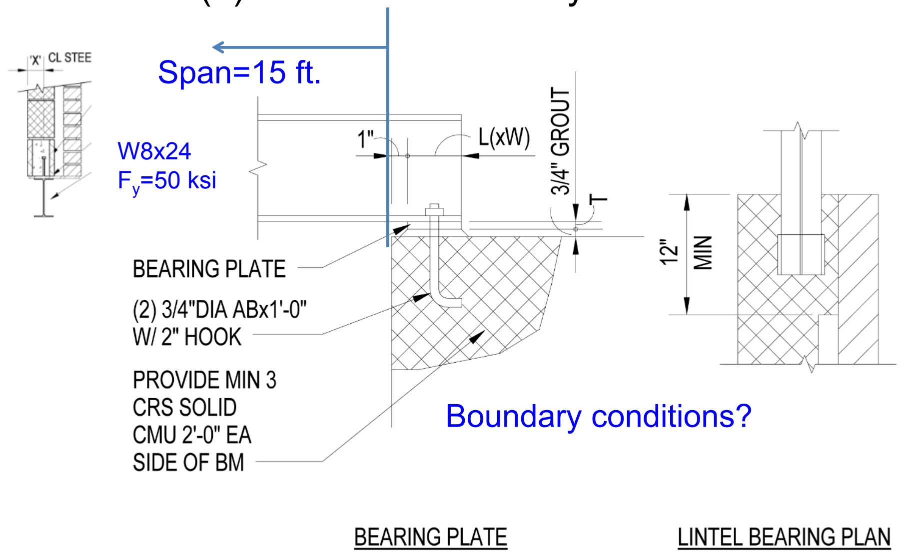
Example
(a) Define structural system



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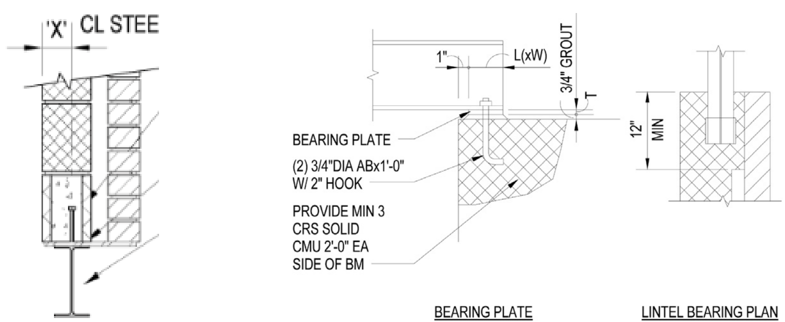
Example
(a) Define structural system



Assume lintel is carrying loads but *__is not composite__* with masonry above.

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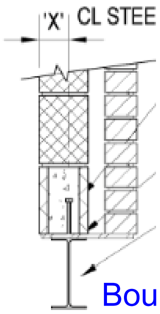
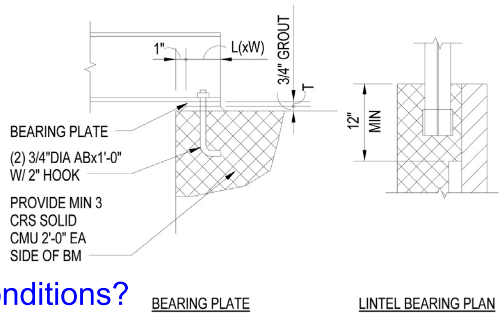
Example
(a) Define structural system

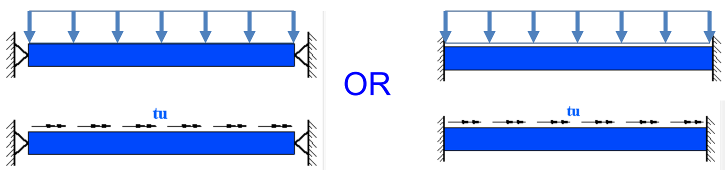




Boundary conditions?

Moment

Torsion



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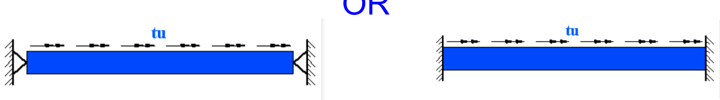
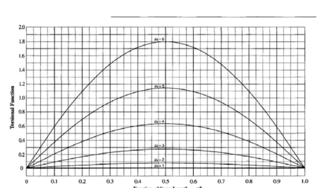
Example
(a) Define structural system

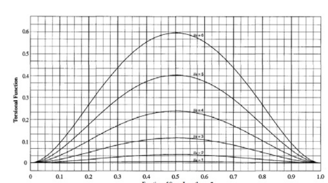
Boundary conditions?

Torsion





θ

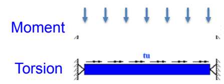


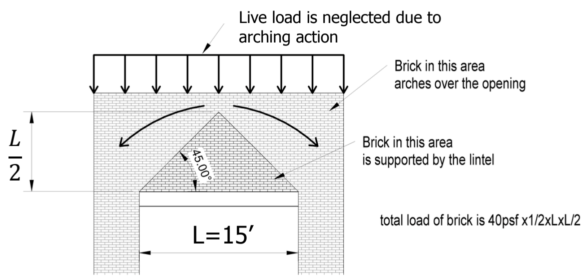
Twist fixed
Warping free

Twist fixed
Warping fixed

46

Example
(b) Find member demand shear *V*, moment *M*, torsion *T*, and axial force *P*





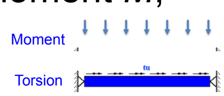
For simplicity, we will approximate the triangular load as a uniform load
Therefore we need w_{facade}, $w_{masonry}$

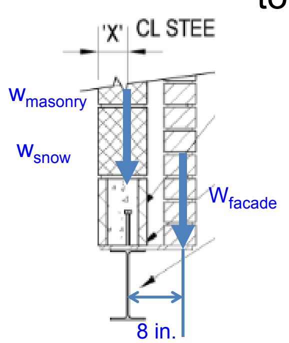
p_{facade}=40 lb/ft^2 $$w_{facade} = 40psf\left(\frac{15'^2}{4}\right)\left(\frac{1}{15'}\right) = 150\ plf$$

$p_{masonry}$=60 lb/ft^2 $$w_{masonry} = 60psf\left(\frac{15'^2}{4}\right)\left(\frac{1}{15'}\right) = 225\ plf$$

47

Example
(b) Find member demand shear *V*, moment *M*, torsion *T*, and axial force *P*





LRFD – factored loads!

$$U = 1.4D$$

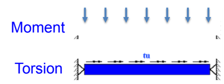
$$V_u = 1.4(150\ plf + 225\ plf)\left(\frac{15'}{2}\right) = 3.9\ kips$$

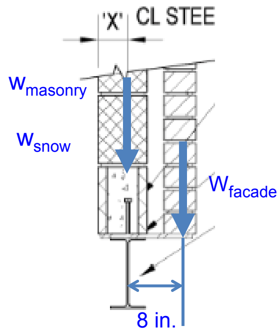
$$M_u = 1.4(150\ plf + 225\ plf)\left(\frac{15^2}{8}\right) = 14.8\ kip * ft$$

48

Example

(b) Find member demand shear *V*, moment *M*, torsion *T*, and axial force *P*



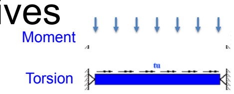


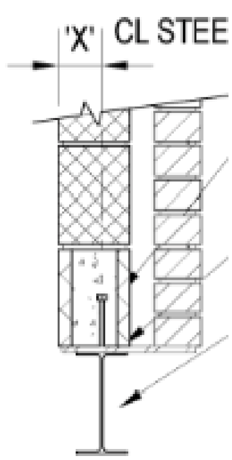
$$t_u = 1.4(150\ plf)\left(\frac{8''}{12}\right) = 0.14\ \frac{kip * ft}{ft}$$

49

Example

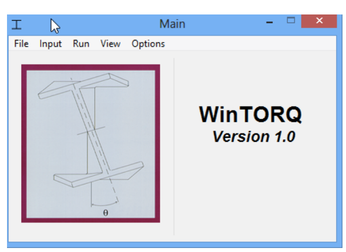
(c) Calculate angle of twist, derivatives





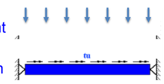
But there is software to help, for example WinTORQ!

http://www.steeltools.org/resources/viewdocument/?DocumentKey=45f39369-2ac2-4a33-a131-7e727afc8cab



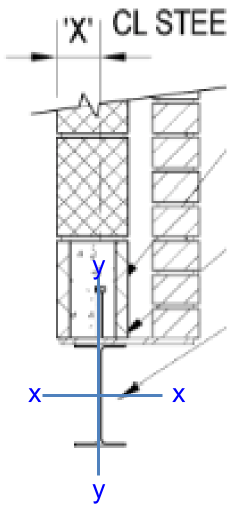
50

Example
(d) Check normal stresses *P*+*M*+*T*



Demand stresses (bending)

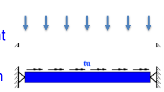
$$f_n = \sigma_a \pm (\sigma_{bx} + \sigma_{by} + \sigma_w)$$



$$\sigma_{bx} = \frac{Mc}{I} = \frac{14.8\ kip * ft(12''/') \frac{7.93''}{2}}{82.7\ in^4} = 8.5\ ksi$$

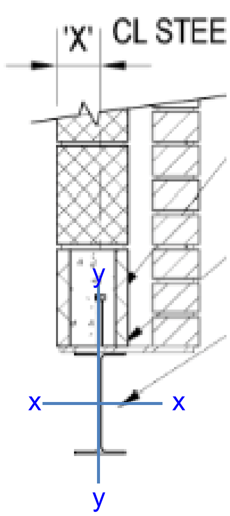
51

Example
(d) Check normal stresses *P*+*M*+*T*

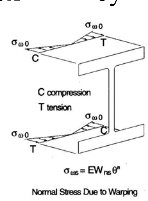


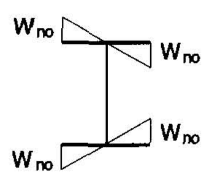
Demand stresses (torsion)

$$f_n = \sigma_a \pm (\sigma_{bx} + \sigma_{by} + \sigma_w)$$

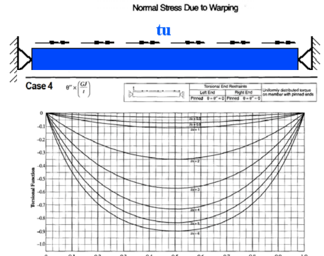


$$\sigma_w = EW_{no}\theta''$$





Torsion

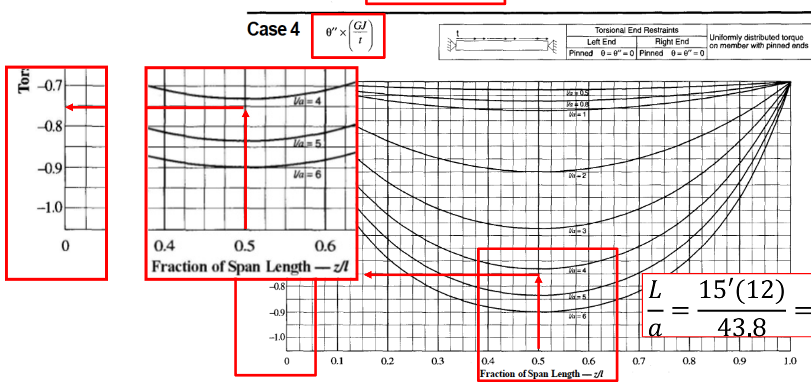


θ''

52

Example
(d) Check normal stresses *P+M+T*

$$\theta'' \times \left(\frac{GJ}{t}\right)$$

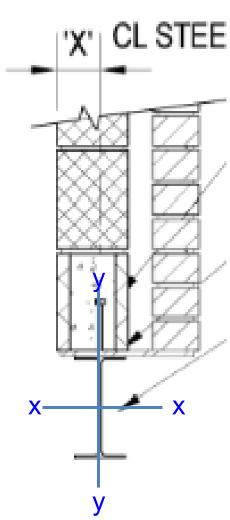


$$\frac{L}{a} = \frac{15'(12)}{43.8} = 4.11$$

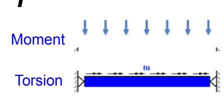
$$-0.75 = \theta''\left(\frac{11200^{ksi} x 0.35^{in^4}}{0.14\frac{kip*in}{in}}\right) \qquad \theta'' = -2.68E-5 \text{ rad/in}^2$$

53

Example
(d) Check normal stresses *P+M+T*



Demand stresses (torsion)



$$f_n = \sigma_a \pm (\sigma_{bx} + \sigma_{by} + \sigma_w)$$

$$\theta'' = 2.08E-5\ \frac{rad}{in^2}$$

$$\sigma_w = EW_{no}\theta''$$

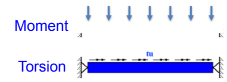
$$\sigma_w = 29000\ ksi\ (12.2\ in^2)\left(2.68E-5\ \frac{rad}{in^2}\right)$$

$$= 9.5\ ksi$$

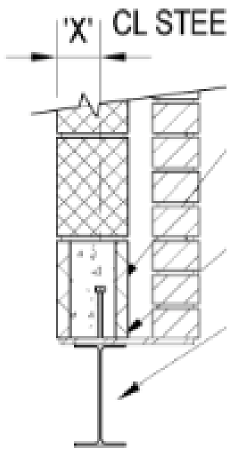
$$f_n = 0 \pm (8.5\ ksi + 0 + 9.5\ ksi) = 18.0\ ksi$$

54

Example
(d) Check normal stresses *P+M+T*



Beam capacity…



Yielding under normal stress (Eqn. H3-7):

$$F_n = F_y$$

Buckling (Eqn. H3-9):

$$F_n = F_{cr}$$

Take the minimum F_n from Eq. H3-7 and H3-9!

$$f_n \le \phi_T F_n$$

Compare capacity to demand

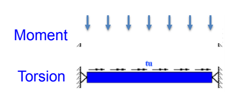
$$F_n = F_y = 50\ ksi$$

φF_n=0.9(50 ksi) = 45 ksi

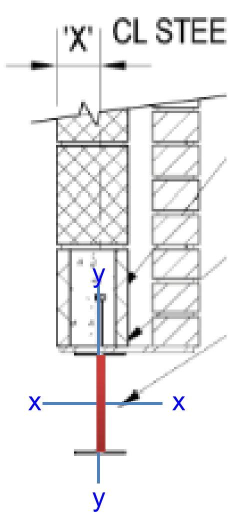
f_n = 18.0 ksi $\le \varphi F_n$ = 45.0 ksi **OK**

55

Example
(e) Check shear stresses *V+T*



Demand stresses (in web)



$$f_v = \tau_{bx} + \tau_{by} + \tau_t + \tau_w$$

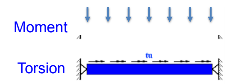
$$\tau_{by} = \frac{V_u Q_w}{I_x t_w}$$

Direct shear

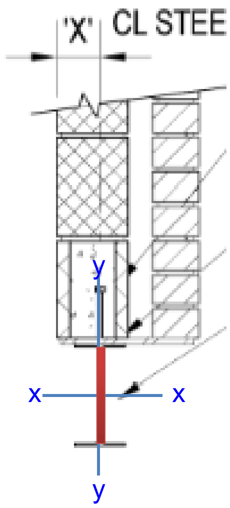
$$\tau_{by} = \frac{3.9\ kip\ (11.6\ in^3)}{82.7\ in^4\ (0.245\ in)} = 2.23\ ksi$$

56

Example
(e) Check shear stresses *V+T*

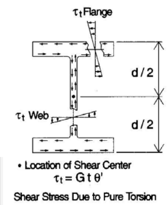


Demand stresses (in web)

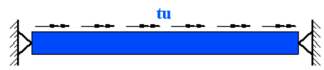


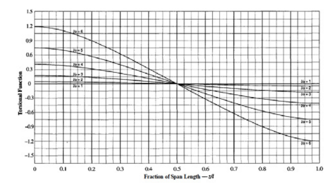
$$f_v = \tau_{bx} + \tau_{by} + \tau_t + \tau_w$$

$$\tau_t = G t_w \theta'$$ Shear stresses from St. Venant torsion



Torsion

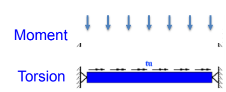




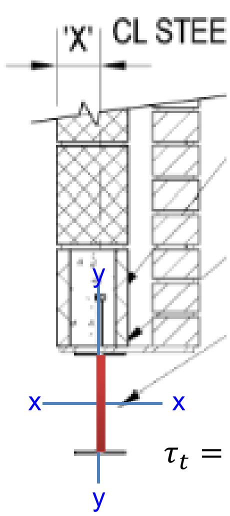
θ'

57

Example
(e) Check shear stresses *V+T*



Demand stresses (in web)



$$f_v = \tau_{bx} + \tau_{by} + \tau_t + \tau_w$$

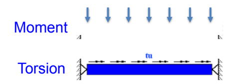
$$\tau_t = G t_w \theta'$$ Shear stresses from St. Venant torsion

$$\theta' = 1.70E - 3\ \frac{rad}{in}$$

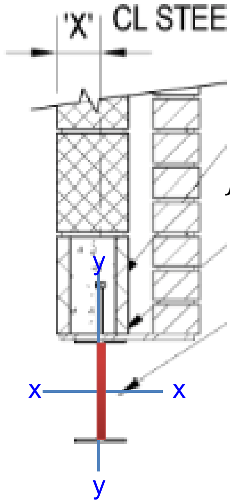
$$\tau_t = 11200\ ksi\ (0.245\ in)\left(1.70E - 3\ \frac{rad}{in}\right) = 4.67\ ksi$$

58

Example
(e) Check shear stresses *V+T*



Demand stresses (in web)

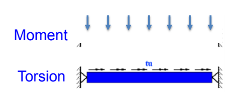


$$f_v = \tau_{bx} + \tau_{by} + \tau_t + \tau_w$$

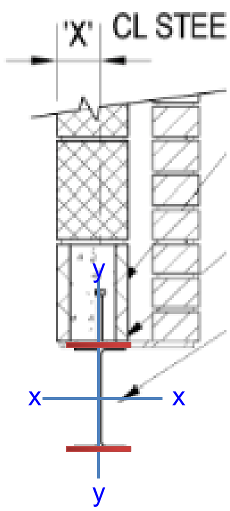
$$f_v = 2.23\ ksi + 0 + 4.67\ ksi + 0 = 6.90\ ksi$$

59

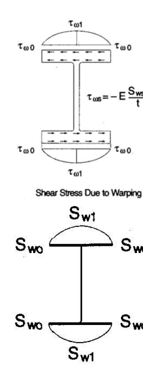
Example
(e) Check shear stresses *V+T*



Demand stresses (in flange)

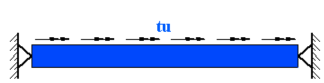


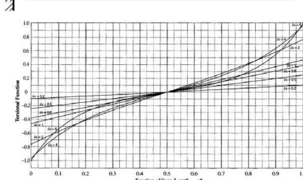
$$f_v = \tau_{bx} + \tau_{by} + \tau_t + \tau_w$$



$$\tau_{ws} = \frac{-ES_{ws}\theta'''}{t_f}$$ Shear stresses from warping torsion

Torsion

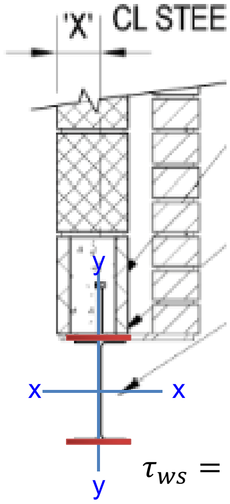


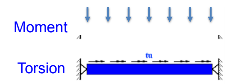


θ'''

60

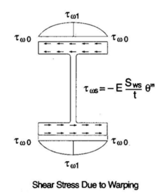
Example
(e) Check shear stresses *V*+*T*





Demand stresses (in flange)

$$f_v = \tau_{bx} + \tau_{by} + \tau_t + \tau_w$$



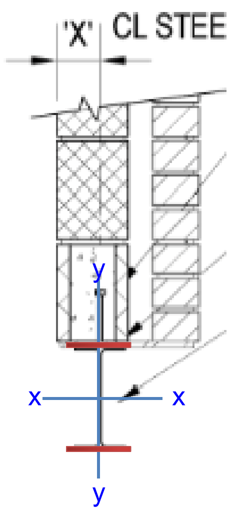
$$\tau_{ws} = \frac{-ES_{ws}\theta'''}{t_f}$$ Shear stresses from warping torsion

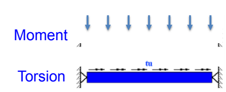
$$\theta''' = 7.90E-7\ \frac{rad}{in^2}$$

$$\tau_{ws} = \frac{-29000\ ksi(7.94 in^4)\ (7.90E-7\ \frac{rad}{in^2})}{0.4\ in} = 0.45\ ksi$$

61

Example
(e) Check shear stresses *V*+*T*

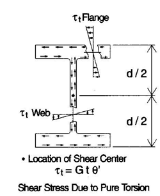




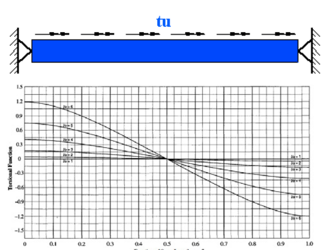
Demand stresses (in flange)

$$f_v = \tau_{bx} + \tau_{by} + \tau_t + \tau_w$$

$$\tau_t = Gt_f\theta'$$ Shear stresses from St. Venant torsion



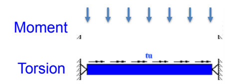
Torsion



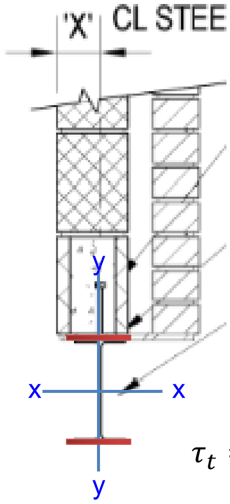
θ'

62

Example
(e) Check shear stresses *V*+*T*



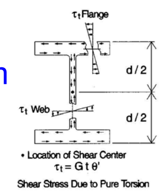
Demand stresses (in flange)



$$f_v = \tau_{bx} + \tau_{by} + \tau_t + \tau_w$$

$$\tau_t = G t_f \theta'$$

Shear stresses from St. Venant torsion

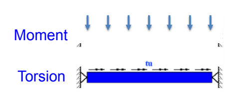


$$\theta' = 1.70E-3\,\frac{rad}{in}$$

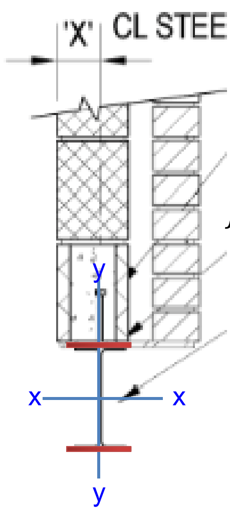
$$\tau_t = 11200\,ksi(0.4\,in)\left(1.70E-3\,\frac{rad}{in}\right) = 7.62\,ksi$$

63

Example
(e) Check shear stresses *V*+*T*



Demand stresses (in flange)

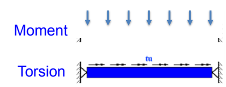


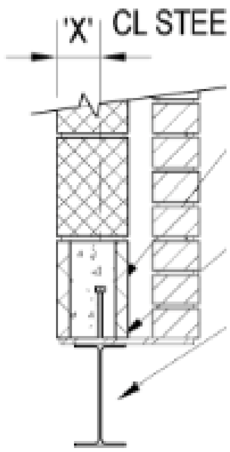
$$f_v = \tau_{bx} + \tau_{by} + \tau_t + \tau_w$$

$$f_v = 0 + 0 + 7.62\,ksi + 0.46\,ksi = 8.08\,ksi$$

64

Example
(e) Check shear stresses $V+T$





Web/flange capacity…

Yielding under normal stress (Eqn. H3-7):

$$F_n = 0.6F_y$$

$$f_v \le \phi_T F_n$$ Compare capacity to demand

$F_v = 0.6F_y = 30\ ksi$

$\varphi F_v = 0.9(30\ \text{ksi}) = 27\ \text{ksi}$

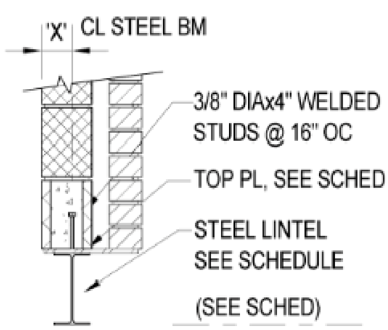
$F_v = 8.08\ \text{ksi (flange)} \le \varphi F_v = 27.0\ \text{ksi}$

OK

65

Design approach including torsion…

Steel lintel beam spanning opening in a bearing wall building



(a) Define structural system – span, boundary conditions, materials

(b) Find member demand shear V, moment M, torsion T, and axial force P

(c) Calculate angle of twist θ and its derivatives

(d) Check $M+T+P$ normal stresses

(e) Check $V+T$ shear stresses

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