High-Strength Bolts: The Basics

- Fundamentals and Behavior
- Specification Requirements (AISC)

Role of the Structural Engineer…

- Selection of suitable bolt types and grades
- Design of the fasteners
- Responsibility for installation
- Responsibility for inspection

ASTM A307 Bolts

- often a good choice when loads are static
- strength level inferior to high-strength bolts (60 ksi tensile ult.)
- pretension indeterminate

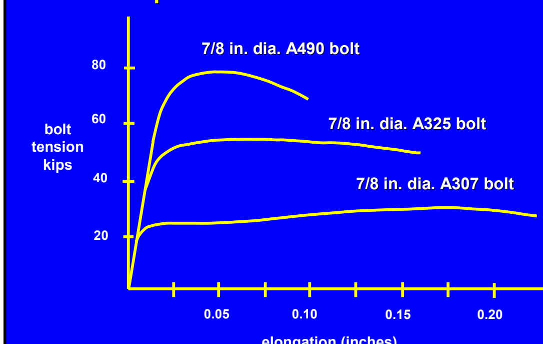
ASTM A325 Bolts

- Type 1 or Type 3 (weathering steel)
- ASTM Spec. ←→ RCSC Spec.
- Minimum tensile strength: 120 ksi
- Pretension can be induced if desired

ASTM A490 Bolts

- Types 1 or Type 3 (weathering steel)
- Minimum tensile strength: 150 ksi, (maximum 170 ksi)
- ASTM Spec. ←→ RCSC Spec.
- Pretension can be induced if desired

Comparison of Bolts: Direct Tension



Comments…

- Note: we quote the ultimate tensile strength of the bolt
  - this is the benchmark for strength statements (e.g. shear strength is some fraction of ultimate tensile strength)
- What about yield strength?
- What is "proof load"

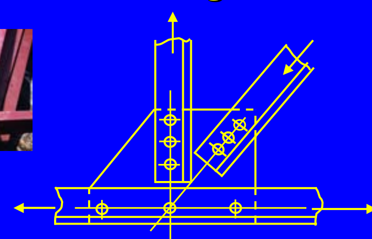
…comments cont'd

- Nuts: ASTM A563
- Washers: if needed, ASTM F436
- Bolt – nut – washer sets implied so far, but other configurations available

Loading of Bolts

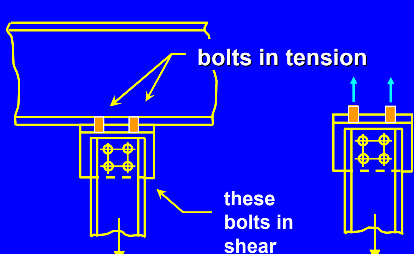
- Shear
  - load transfer by shear in bolt <u>and</u> bearing in connected material <u>OR</u>
  - load transfer by friction (followed by shear and bearing)
- Tension
- Combined Tension and Shear

Shear Loading

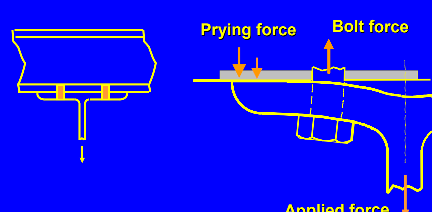


Truss Joint

Bolts Loaded in Tension

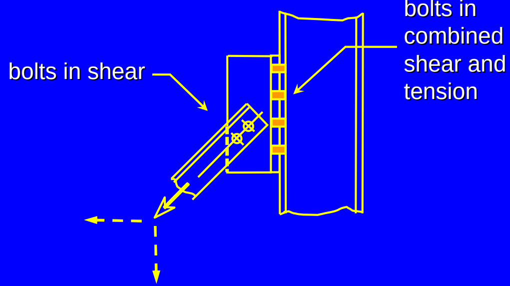


Bolts in Tension – prying

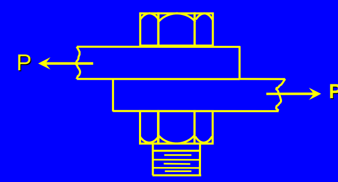


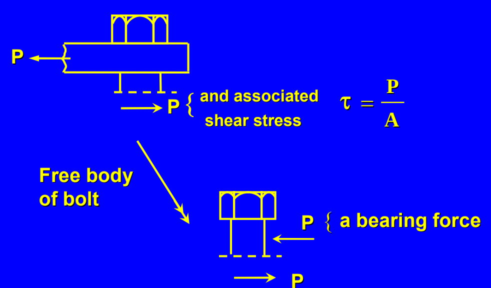
High-strength bolts in tension can be a source of problems!

Bolts in combined tension and shear

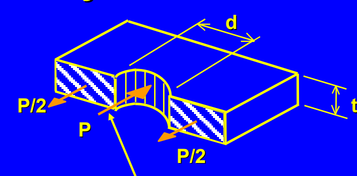


Consider a simple joint —





Finally…



note that this force is equal and opposite to the bearing force shown previously

In the example, we identified…

- force in the bolt (a shear force)
- force that the bolt imposed on the plate (a bearing force)
- force in the plate itself (a tensile force)
- force transfer could also be by friction: not included in this illustration

AISC Standard 2005

- Parallel LRFD and ASD rules
- LRFD uses a resistance factor, Ø
- ASD uses a safety factor, Ω
- Loads as appropriate:
  - factored loads for LRFD
  - non-factored loads for ASD

AISC Standard cont'd

LRFD: req'd strength LRFD $\leq \phi R_n$

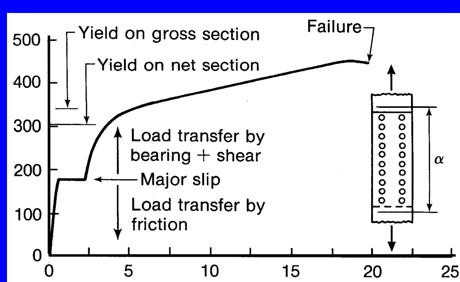
ASD: req'd strength ASD $\leq R_n / \Omega$

Installation —

- Snug-tight only
- Pretensioned
  - Calibrated wrench
  - Turn-of-nut
  - Other means:
    - ✓ Tension control bolts
    - ✓ Load-indicator washers

Behavior of a large joint (shear splice) —

average bolt shear MPa



deformation over α, mm

Bolts in Shear: Issues

- Shear strength of bolt (single shear or double shear, threads in shear plane?)
- Bearing capacity of bolt (never governs)
- Bearing capacity of plate
- Tensile (comp.) capacity of plate

Slip in bolted joints…

- Can be as much as two hole clearances
- Some bolts will already be in bearing at start of loading
- Both laboratory tests and field measurements indicate that slip is more like 1/2 hole clearance

Bolts in shear-type connection:

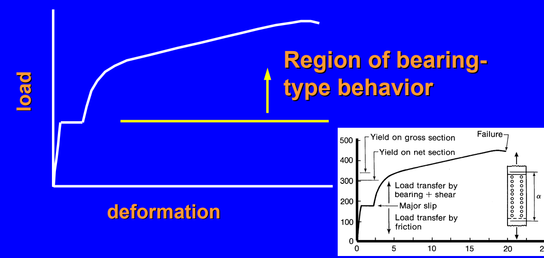
Specifications distinguish between:

- bearing type connections
- slip-critical connections
- Note: a slip-critical joint (service loads) must also be checked as a bearing joint (factored loads)

Bearing-type connections:

- Issues
  - bolt shear strength
  - bearing capacity connected material
  - member strength
- Shear strength of bolts is <u>not dependent</u> on presence or absence of pretension. (How come?)

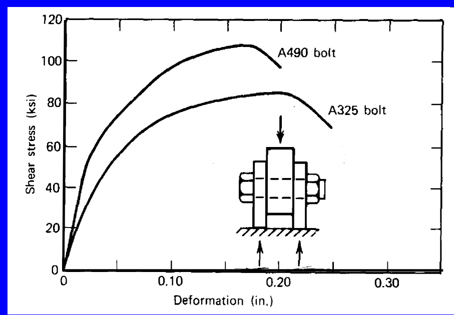
Bolts in bearing-type connections…



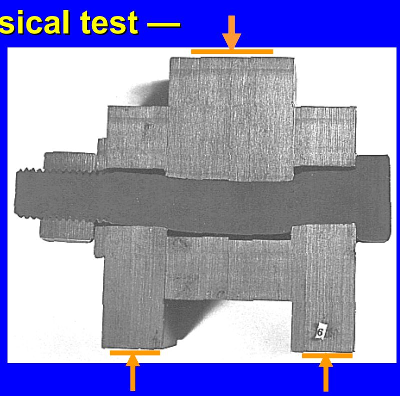
Bolt Shear Strength

- Bolt shear strength ≈ 62% of bolt ultimate tensile strength (theory + tests)
  - Design rule takes 80% of this value
  - Threads in shear plane?
  - Long joint effect: another discount applied.

Individual bolt in shear

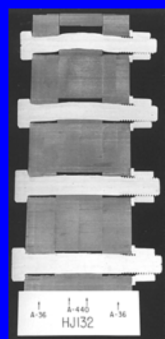


Physical test —



Uneven loading of bolts –

(End four bolts of 13)



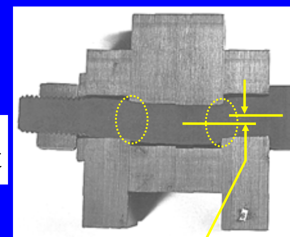
Bolt Pretension v. Shear

- The bolt pretension is attained as a result of small axial elongations introduced as nut is turned on
- These small elongations are relieved as shear deformations and shear yielding take place
- Confirmed by both bolt tension measurements and shear strength tests
- So, bolt shear strength NOT dependent on pretension in the bolt.

Back to bolt in shear —

Shear strength of single bolt (tests) —

$$\tau = 0.62\ \sigma_{u\ bolt}$$



Shear deformation

Bolts in Shear — AISC

$$\phi R_n = \phi\ F_v\ A_b$$

$$\phi R_n = \text{design shear strength}$$

$$F_v = \text{nominal shear strength, ksi}$$

nominal shear strength …

$$\phi = 0.75$$

$$F_v = 80\%\ (0.62 \times F_u) = 0.50\ F_u$$

Thus…

$$\text{A325 bolts}: \ F_v = 0.50 \times 120 \text{ ksi} = 60 \text{ ksi}$$

$$\text{A490 bolts}: \ F_v = 0.50 \times 150 \text{ ksi} = 75 \text{ ksi}$$

— these are the values given in Table J3.2 of the Specification for the thread excluded case. For threads included, the tabulated values are 80% of the above.

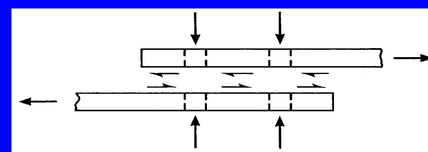
Comments…

- The discount for length (use of 80%) is conservative
- If joint length > 50 in., a further 20% reduction
- The ø – value used for this case (0.75) is also conservative.

Let's return now to slip-critical connections…

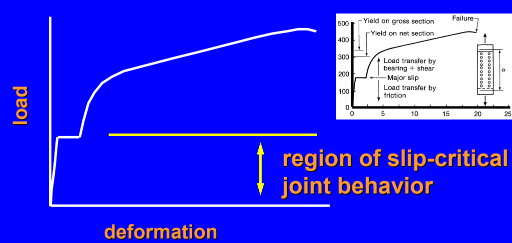
Slip-Critical Connection

Clamping force from bolts (bolt pretension)



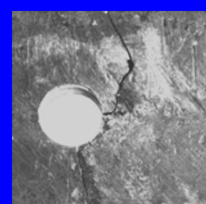
Load at which slip takes place will be a function of …?

Bolts in slip-critical connections…



Slip-critical joints specified when…

- Load is repetitive and changes from tension to compression (fatigue by fretting could occur.)
- Change in geometry of structure would affect its performance.
- Certain other cases.
- Comment: for buildings, slip-critical joints should be the exception, not the rule (but, see also seismic rules)



Slip-critical criteria:

- Choice:
  - a serviceability limit state (no slip under the service loads) OR
  - a strength limit state (no slip under the factored loads). Note: AISC 2005 differs from 1999.

Which one do we use?

- No slip at service loads: e.g. fatigue loading
- No slip at factored loads: e.g. long-span flat roof truss (ponding could result as factored loads attained)

First principles, slip resistance is —

$$P = k_s \, n \, \Sigma T_i$$

k_s = slip coefficient (μ)

n = number of slip planes (usually 1 or 2)

T_i = clamping force (i.e., bolt pretension)

Design slip resistance, AISC

$$\phi R_n = \mu D_u h_{sc} T_b N_s$$

slip coefficient

clamping force

no. slip planes

…terms ϕ, h_{sc} and D_u need to be defined

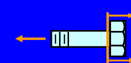
and the modifiers …

h_{sc} = modifier re hole condition
e.g., oversize hole, slotted hole etc.

$D_u = 1.13$, ratio of installed bolt tension to specified minimum bolt tension

ϕ = resistance factor
$= 1.0$ no slip at service loads ($\beta = 1.4$)
$= 0.85$ no slip at factored loads ($\beta = 1.5$)

Bolts in Tension



- Capacity of a bolt in tension: product of the ultimate tensile strength of the bolt and the tensile stress area of the bolt (i.e. F_u A_{st})
- Specifications directly reflect this calculated capacity (…to come)
- Force in bolt must reflect any prying action affect

Bolts in Tension – some comments

- Preference: avoid joints that put bolts into tension, especially if fatigue is an issue
- Use A325 bolts rather than A490 bolts
- Minimize the prying action

Question…

- pretensioned bolt in a connection
- apply external tension force to the connection
- do the bolt pretension and the external tension add?

Bolt tension + external tension

1. Pretension the bolt → tension in the bolt, compression in the plates
2. Add external tension force on connection →
   - Bolt tension increases
   - Compression between plates decreases

Examine equilibrium and compatibility…

And the result is…

- The bolt force does increase, but not by very much (≅ 7%)
- This increase is accommodated within the design rule.

AISC rule, bolts in tension—

$$\phi R_n = \phi \; F_{nt} \; A_b$$

A_b → bolt area for nominal diameter

F_{nt} → nominal tensile strength

ϕR_n = design tensile strength

What is nominal tensile strength, F_{nt} ?

$$P_{ult} = F_u \, A_{st} = F_u \, (0.75 A_b)$$

Adjusted area

$$\text{or,} \quad P_{ult} = 0.75 \, F_u \, A_b$$

Call this F_{nt}

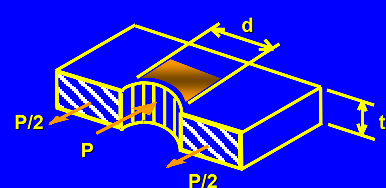
So, the AISC rule for bolts in tension…

$$\phi R_n = \phi \; F_{nt} \; A_b$$

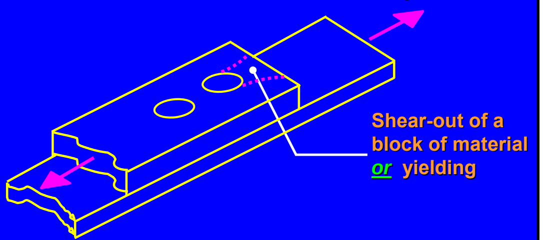
where F_{nt} = 0.75 F_u as tabulated in the Specification

As we now know, the 0.75 really has nothing to do with F_u

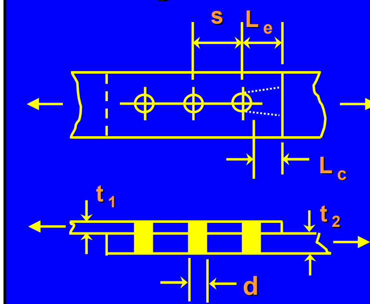
Returning to shear splice joints, we still have to deal with the bearing capacity of the connected material.



Bearing capacity (of connected material)



Bearing stresses at bolt holes…



Needed:

1. shear-out rule
2. yield rule (deformation)

Shear-out rule…

Shear - out is $2\,(\tau_{ult} \times L_c \times t)$

or, $R_n = 2\,(\,0.75\,\sigma_u \times L_c \times t)$

and AISC rule is: $R_n = 1.5\,F_u\,L_c\,t$

Plate bearing…

from tests: $\dfrac{\sigma_b}{\sigma_u^{pl}} = \dfrac{L_e}{d}$

and, some arithmetic gives $R_n = \sigma_b\,d\,t = \sigma_u^{pl}\left(\dfrac{L_e}{d}\right) d\,t$

valid for $L_e \geq 3\,d$

Plate bearing…

Making the substitution and using

$F_u \equiv \sigma_u^{pl}$

$R_n = 3\,d\,t\,F_u$

Finally, the AISC rule for plate bearing capacity is …

$R_n = 1.5\,F_u\,L_c t \;\leq\; 3.0\,d\,t\,F_u$

(with a ϕ-value still to be inserted)

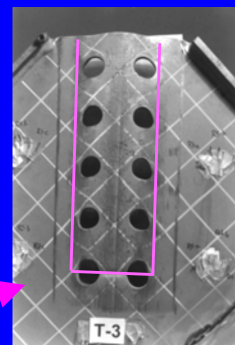
Further note re bearing…

When deformation a consideration, use

$$R_n = 1.2\, F_u\, L_c t \quad \le 2.4\, d\, t\, F_u$$

Why this difference, and when do we use the latter?

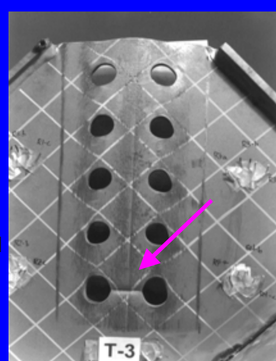
Block shear rupture



Failure (ult. load) is by tensile fracture at location shown, regardless of geometric proportions.

Shear yield along vertical planes.

Failure is controlled by *ductility* – not strength.



Basics…

$$T_r + V_r = \phi\, A_{nt}\, F_u \; + \; 0.60\, \phi\, A_{gv}\, F_y$$

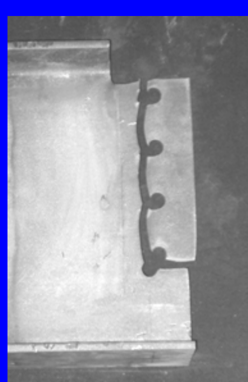
where A_{nt} = net area in tension

and A_{gv} = gross area in shear

tension fracture — shear yield

There are some other requirements, including specific case of coped beams.

An example of shear + tension failure in a coped beam…

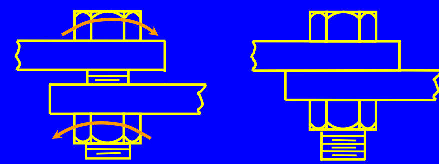


Back to installation…

Bearing-Type Connections—Installation of Bolts

- Bolts can be installed to "snug-tight condition — ordinary effort of worker using a spud wrench. (Pretension unknown, but usually small)

Installation —



– bring parts together, continue turning nut, bolt elongates, tension develops in bolt, and clamped parts compress

Calibrated Wrench Installation

- Reliable relationship between torque and resultant bolt tension?
  NO ! (and is forbidden by RCSC)
- Establish relationship by calibration of the installing wrench.

Hydraulic calibrator –

Calibrated wrench, cont'd

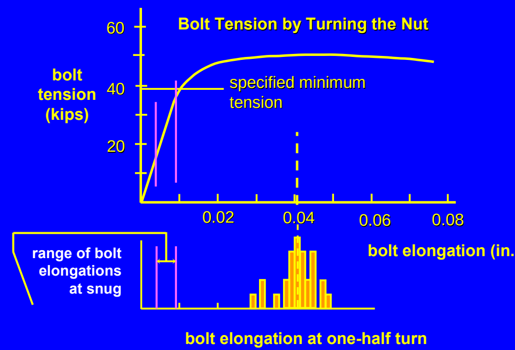
- Adjust wrench to stall or cut out at desired level of bolt pretension
- Target value of pretension (RCSC) is 1.05 times specified min. value
- Calibrate using at least three bolts
- Calibration is unique to bolt lot, length, diameter, grade of bolt
- Washers must be used

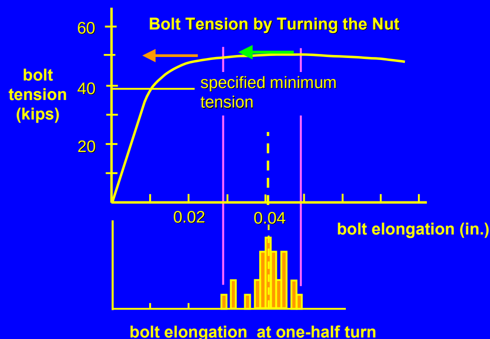
Turn-of-Nut Installation

- Run nut down, bring parts into close contact
- Work from stiffer regions to edges
- Establish "snug-tight" condition (first impact of impact wrench or full effort of worker using a spud wrench)
- Apply additional one-half turn (or other value, depending on bolt length)

Does this definition of snug-tight seem a little vague?

How influential is "snug-tight?"





Inspection of Installation

- Principles:
  - Determination of the bolt pretension after installation is not practical
  - Understand the requirements e.g., are pretensioned bolts required?
  - Monitor the installation on the site
  - Proper storage of bolts is required

Inspection of Installation

- Is bolt tension required? — if not, why inspect for it !
- Know what calibration process is required and monitor it on the job site
- Observe the work in progress on a regular basis

Inspection of installation:

Consider the following AISC cases —

1. Bolts need be snug-tight only
2. Bolts are pretensioned (but not a slip-critical joint)
3. Slip-critical joint

Snug tight only….

- Bearing-type connections
- Bolts in tension (A325 only)
  - only when no fatigue or vibration (bolt could loosen)

Inspection – snug tight

- Bolts, nuts, and washers (if any) must meet the requirements of the specifications
- Hole types (e.g., slotted, oversize) must meet specified requirements
- Contact surfaces are reasonably clean
- Parts are in close contact after bolts snugged
- All material within bolt grip must be steel

Inspection: if pretensioned bolts required…

- All of requirements for snug-tight case
- Observe the pre-installation verification process
  - turn of nut, or;
  - calibrated wrench, or;
  - other (direct tension washers, tension-control bolts)
- Calibration process done minimum once per day
- Calibration process done any time conditions change

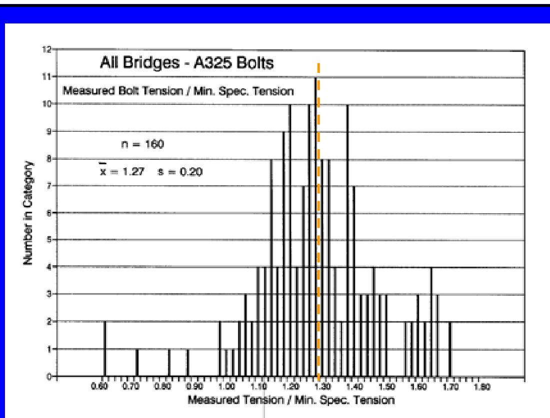
Inspection: for slip-critical joints

- All of the above, plus
- Condition of faying surfaces, holes, etc.
- In addition to observing the calibration process, the inspection must ensure that the same process is applied to the field joints

An inspected joint (turn-of-nut)

and some other comments…

- Pretension values greater than those specified are not cause for rejection.
- Rotation tests are useful for short-grip bolts or coated fasteners (requirement is in ASTM A325 spec. and is for galvanized bolts)



Actual pretensions, cont'd

- For A325 bolts, turn-of-nut:
  - Average tensile strength exceeds spec. min. tensile by about 1.18
  - Average pretension force is 80% of actual tensile
  - Result is that actual bolt tension is about 35% greater than specified bolt tension

Actual pretensions, cont'd

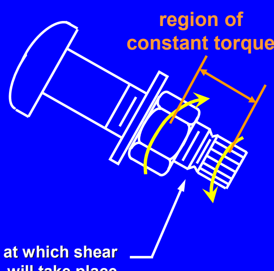
- A325, ½ turn-of-nut: 35% increase
- A490, ½ turn-of-nut: 26% increase
- A325 and A490, calibrated wrench: 13% increase
- etc. for other cases

Note: these increased pretensions are embodied in the specification rules

Some other options for bolts —

Tension Control Bolts

ASTM F1852, F2280



Tension control bolts….

- NOTE: evidence that tips have sheared off is not in itself evidence that desired pretension is present
- Consider limits:
  - Friction conditions are very high…
  - Friction conditions are very low…
- Hence, calibration is essential!

Tension-Control Bolts

- Advantages
  - Installation is from one side
  - Electric wrench is used
  - Installation is quiet
- Disadvantages
  - More expensive
  - Pre-installation calibration required

Direct tension indicators—

Direct Tension Indicators

- Protrusions formed in special washer
- Protrusions compress as force in bolt is developed
- Use feeler gage to measure gap (or refusal)
- User must verify the process (like calibrated wrench)

ASTM 959

Reliability of these...

- Calibration required
- Reliability same as calibrated wrench
- Tension-control bolt is torque-dependent
- Load-indicating washer is elongation-dependent

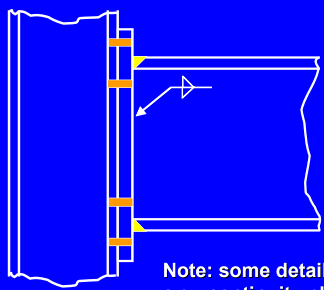
Some additional topics …

- Details, other topics
  - washers (but not today!)
  - slotted or oversize holes (but not today!)
  - seismic design

Seismic design of connections

- Analyze structure in order to compute the forces
  - Use FEMA 350 and/or AISC Seismic Design Spec.
- With forces now known, design connectors
- Advisable to use pre-qualified configurations

Pre-qualified bolted connections



Note: some details not shown, e.g., continuity plates

All-bolted connection

…bolted joints, seismic design

- All bolts pretensioned
- Faying surfaces as per slip-critical
- Use bearing values for bolts
  - moderate quakes: no slip
  - major quakes: slip will occur and bolts go into bearing
- Normal holes or short slotted only (perpendicular)
- No bolts + welds in same faying surface

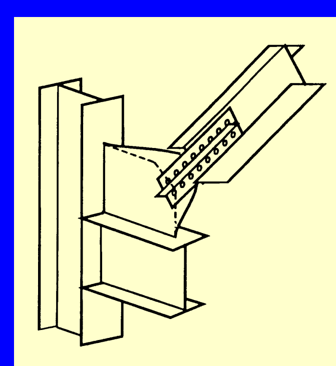
Seismic design, cont'd

- Non-ductile limit state in either member or connection must not govern.
- Calculate bolt shear strength as per bearing type but use 2.4 d t F_u bearing rule
- Must use expected yield and ultimate strengths, not the specified values

$$\text{e.g. A36 plate: use } 1.3\,\sigma_{y\ \text{spec.}}$$

It all started with rivets….

Design example: gusset plate connection



Determine ultimate load for this gusset plate (which is one that was tested)

F_y = 39.9 ksi

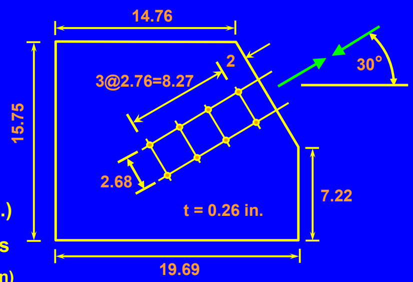
F_u = 69.0 ksi

7/8 A325 bolts

(holes 15/16 in.)

$P_{u\ test}$ =164 kips

(compression)



Set out the issues…

- Brace force in tension–
  - slip load of bolts (no slip at service load)
  - shear load of bolts
  - bearing capacity of plate
  - block shear

Continuing…

- Brace force in compression
  - slip capacity of bolts (already checked for load in tension)
  - shear capacity of bolts (already checked for load in tension)
  - bearing capacity of plate (already checked)
  - block shear (doesn't apply)
  - capacity of gusset plate in compression (New)

Slip load (calculate at factored load level)

$$R_n = \mu\ D_u\ h_{sc}\ T_m\ N_s \quad \text{(per bolt)}$$

$\mu = 0.35$ (clean mill scale) $\quad h_{sc} = 1.0$ (std. holes)

$A_b = \pi\, d^2/4 = 0.60\ \text{in.}^2$ (7/8 in.dia.)

$F_u = 120$ ksi (A325 bolts)

$n = 8$ bolts $\quad N_s = 2$ slip planes $\quad \phi = 1.0$

$$T_m = \text{spec. min. bolt pretension} = (0.75 \times A_b)(F_u)70\%$$
$$= 0.75 \times 0.60\ \text{in.}^2 \times 120\ \text{ksi} \times 70\% = 37.88\ \text{kips}$$

Slip load calculation cont'd.

$$R_n = \mu\ D_u\ h_{sc}\ T_m\ N_s \quad \text{(per bolt)}$$

$$= 0.35 \times 1.13 \times 1.0 \times 37.88\ \text{kip} \times 2\ \text{slip planes}$$
$$= 29.96\ \text{kips/bolt}$$

or, for 8 bolts, 240 kips

Finally, $\phi R_n = 1.0 \times 240\ \text{kips} = 240\ \text{kips}$

Shear resistance of bolts

$$\phi R_n = \phi\ F_v\ A_b$$

Use ø =1.0 so that we can compare this load with the test load, assume threads in shear plane, no joint length effect

$$F_v = 80\%\,[0.62 \times 120\ \text{ksi}] = 60\ \text{ksi}$$

$\phi R_n = 1.0 \times 60\ \text{ksi} \times 0.60\ \text{in.}^2 = 36.0$ kips (per bolt)

or, for 8 bolts, 2 shear planes, threads in shear plane

$= (36.0 \times 8 \times 2)\text{kips} \times 0.80 = 461$ kips

Bearing resistance (use ϕ = 1.0)

$$R_n = 1.5\, F_u\, L_c t \quad \le 3.0\, d\, t\, F_u$$

$$3\, d\, t\, F_u =$$
$$3 \times 7/8 \text{ in.} \times 0.26 \text{ in.} \times 69.0 \text{ ksi} = 47.1 \text{ k/bolt}$$

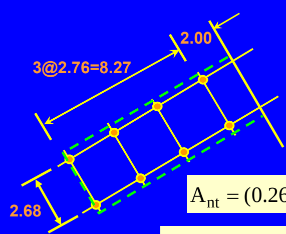
$$1.5\, L_c\, t\, F_u =$$
$$1.5 \times 1.53 \text{ in.} \times 0.26 \text{ in.} \times 69.0 \text{ ksi} = 41.2 \text{ k}$$

Bearing resistance…

…the governing value is 41.2 kips/bolt and, for 8 bolts—

Bearing resistance is 330 kips

Block shear



$$A_{nt} = (0.26)(2.68 - 15/16) = 0.45 \text{ in.}^2$$

$$A_{gv} = (8.27 + 2.00)2 \times 0.26 = 5.34 \text{ in.}^2$$

$$T_r + V_r = \phi\, A_{nt}\, F_u + 0.60\, \phi\, A_{gv}\, F_y$$

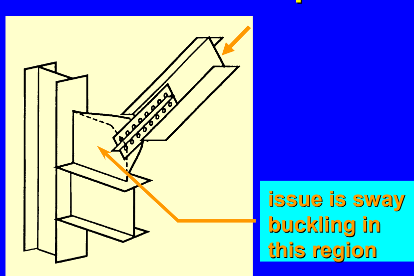
Block shear, cont'd

$$T_r = 0.45 \text{ in.}^2 \times 69.0 \text{ ksi} = 31.0 \text{ kips}$$

$$V_r = 0.60 \times 5.34 \text{ in.}^2 \times 39.9 \text{ ksi} = 127.8 \text{ kips}$$

and the total block shear resistance (unfactored) is 158.8 kips

Brace force in compression:

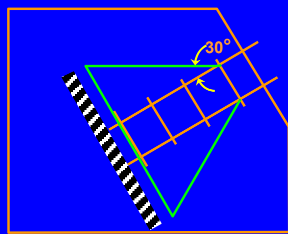


Checking the buckling…

- Whitmore method (checks yield)
- Thornton method (checks buckling)
- Modified Thornton method (checks buckling)

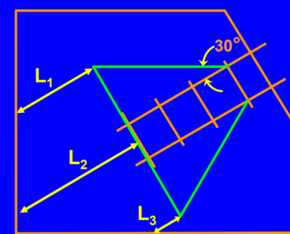
Whitmore method….

- Use beam formulae to check perceived critical sections
- Use 30º , as shown to check yielding at location shown.
- Does not predict ultimate capacity very well, usually conservative but sometimes non-conservative



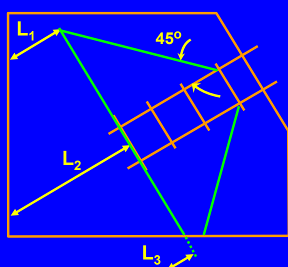
Thornton method…

- Use longest (or average) of L_1, L_2, L_3 to compute a buckling load on a unit width column, then apply this to the total width.
- Use k = 0.65 in the column formulae



Thornton method, <u>modified</u>

As per Thornton method but spread load out at 45º

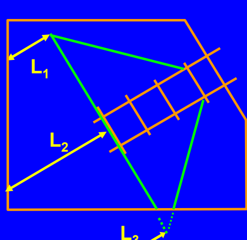


Yam & Cheng gusset plate tests (U of A, 13 tests)

	$\frac{P_u}{P_W}$	$\frac{P_u}{P_T}$	$\frac{P_u}{P_{T'}}$
mean	1.33	1.67	1.06
std. dev.	0.26	0.12	0.08

we'll use this method

Calculations for buckling capacity:



Using scale dwg. L_2 = 9.65 in.

Width of the 45º base is 19.2 in.

$$\phi_c P_n = \phi_c A_g F_{cr} \quad (\text{use } \phi_c = 1.0)$$

$$F_{cr} = (0.658^{F_y/F_e}) F_y \qquad \text{use } k = 0.65$$

Consider a 1 in. wide strip that is 9.65 in. long

$$r = \sqrt{\frac{I}{A}} = \sqrt{\frac{\frac{1}{12} \times 1 \times 0.26^3}{0.26 \times 1}} = 0.0751 \text{ in.}$$

and then completing the calculations, P_n = 6.91 kips (on a 1 in. wide strip)

And applying this to the total width…

P_u = (6.91 k/in.) (19.2 in.) = 132 kips

and the test ultimate load on this particular specimen was 164 kips

so, P_u / $P_{T'}$ = 1.23

(The corresponding ratios for Whitmore and Thornton for this specimen were 1.31 and 1.80)

Summary of our calculations

Brace Force	slip load	bolt shear	plate bearing	block shear	buckling	test load
Tension	226	461	330	159	—	—
Compress.	—	—	—	—	132	164

Some references —

Load and Resistance Factor Design Specification for Structural Joints Using ASTM A325 or A490 Bolts, Research Council on Structural Connections, 2004 (RCSC)

(free download available at boltcouncil.org)

References, cont'd.

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- Bickford, John H., "An Introduction to the Design and Behavior of Bolted Joints," Second Edition, Marcel Dekker Inc., New York, 1990
- G.L. Kulak, *A Bolting Primer for Structural Engineers*, AISC Design Guide 17, Chicago, 2002