Steel Connections
Design Issues

Dr. Seshu Adluri
Introduction

Steel Connections

- Unlike concrete, connections in steel structures need special design
- Bolts, Rivets and Welds are typical connectors
Joining Structural elements

- Mechanical fastenings
- Mechanically formed joints
- Welding
- Adhesive bonding
MECHANICAL FASTENINGS

- Rivets
- Bolting
- Stud Welding
- Powder-Actuated Fastenings
- Threaded Fasteners & Nails
- Expansion Bolts
- Adhesive-held fasteners
- Mechanically formed joints
Rivets

- Old style connectors
- Permanent, need field heating and head forming
- Safety issues
- Tension on cooling is not estimated accurately
- Load distribution is not as good as that for bolts
Rivets

Installation Process
- Heat Rivet
- Insert in Hole
- "Hammer" to produce a second head
- Cool - Expands to form a tight joint

Seldom Used any more
- Labor Intensive
- Less Expensive Alternatives
Pins

- Rarely used compared to bolts and welds
- Special projects only
Bolts
Bolts
Bolts

- **Carbon Steel Bolts** - Normal strength (A307)
  - Similar to ordinary machine bolts
  - Lower Strength, low load/shear connectors

- **High Strength Bolts** - (A325, A325M, A490, A490M etc.)
  - Heat treated for greater strength
  - Higher shear resistance
  - Can also be used in Friction Connections
  - Can be used with or without washers

- **Bolt function**
  - Snug tight bolts (allow slippage)
  - Pre-tensioned bolts (slip critical)
  - Both have the same ultimate strength

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Material behaviour

Fig. 1.1 Stress vs. Strain of Coupons taken from Bolts and Rivets
Material behaviour

Fig. 1.2 Comparison of Bolt Types: Direct Tension
Bolts

- Snug tight bolts (allow slippage)
  - Easy to install (till about the first impact using the pneumatic wrench). No inspection for tension
  - 10-20% of tension strength

- Pre-tensioned bolts (slip critical –no slip)
  - Costly to install, need inspection
  - Repeated loadings, bridges, communication towers, load reversals, impact, cranes, direct tension, etc.
  - Safety against twist-off, all bolts yield

- Both have the same ultimate strength
Pre-tensioned Bolts

Installation

- Turn of the nut method (Table 8 –CSA-S16)
  - 1/3 turn for \( L_b < 4d_b \)
  - 1/2 turn for \( 4d_b < L_b < 8d_b \) (or 200 mm)
  - 2/3 turn for longer bolts

- Tension indicator washers (ASTM F959) Cl. 23.8.3
- Torque wrench
- Strain gauges, etc.
- Bolt tension as per Table 7, CSA-S16
Pretension effect

Bolt Tension in Joint at Snug and at One-Half Turn of Nut
Pretension effect

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Tension controlled bolts

- Wrench grips both the nut & bolt
- When required torch reached,
  - End twists off
  - A plunger inside discharges the splined end
- Ease of installation & consistency
Bolt dimensions

- Standard dimensions, thread lengths, bolt lengths for different grips
  - Handbook p.6-152 to 6-156
  - Gauge dist. P.6-162

<table>
<thead>
<tr>
<th>Nominal Bolt Size</th>
<th>Length Added To Grip</th>
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</thead>
<tbody>
<tr>
<td>5/8”</td>
<td>7/8”</td>
</tr>
<tr>
<td>3/4”</td>
<td>1”</td>
</tr>
<tr>
<td>7/8”</td>
<td>1 1/8”</td>
</tr>
<tr>
<td>1”</td>
<td>1 1/4”</td>
</tr>
</tbody>
</table>
Bolts

- Tension indicator washers

Note: See Section 5, for general requirements for the use of washers.

Proper use and orientation of ASTM F959 direct-tension indicator.
Tension indicator Wash

- ASTM F959 washers (Cl. 23.8.3)
Tension indicator Washers

- Washer with Protrusions (Gap)
- Protrusions flatten as Bolt is tightened
- Visually inspected to ensure that protrusions are flat (gap closed)

Load indicating washers

Principle of tightening with a load indicator washer
Tension indicator Washers

- Load Indicator Washers with a Visible Dye that squirts out when the washer has sufficiently flattened
Pre-tension effect on shear force on the joint

Load transfer

Hardened washer

Frictional action

Clearance holes

Load transmission in a shear connection through friction
Load vs. Elongation

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Pre-tension effect

Load $F$(kN)

Slip of bolt A

HSFG bolts, $t = 6.5$mm (plate bearing failure)

Untensioned bolts, $t = 6.5$mm (plate bearing failure)

The displacement due to clearance holes is not indicated.

Comparison of load/deformation response for a lap joint.
Pre-tension effect on tension force on the joint

- As the applied tension on the joint increases, the bolt elongates a little and eventually elongates enough (to the length before tightening. At that point, the bolt pretension effect disappears and the joint will behave as if the pretension had never been there. If the joint is unloaded at that point, the clamping effect due to pretension will return.

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Bolts BIBLE!

- “Guide to Design Criteria for Bolted and Riveted Joints” by Geoffrey L. Kulak, John W. Fisher & John H. A. Struij at:

- RCSC: Research Council on Structural Connections
  - Specification for Structural Joints Using ASTM A325 or A490 Bolts
    - [http://www.boltcouncil.org/index.html](http://www.boltcouncil.org/index.html)
## Bolt Heads

- **Required Markings**

<table>
<thead>
<tr>
<th>Bolt / Nut</th>
<th>Type 1</th>
<th>Type 3</th>
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</thead>
<tbody>
<tr>
<td>ASTM A325 bolt</td>
<td><img src="image1" alt="Required Markings" /></td>
<td><img src="image2" alt="Required Markings" /></td>
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<tr>
<td></td>
<td>Three radial line 120° apart are optional</td>
<td>Three radial line 120° apart are optional</td>
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<tr>
<td>ASTM F1852 bolt</td>
<td><img src="image3" alt="Required Markings" /></td>
<td><img src="image4" alt="Required Markings" /></td>
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<td>ASTM A490 bolt</td>
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<td></td>
<td><img src="image7" alt="Required Markings" /></td>
<td><img src="image8" alt="Required Markings" /></td>
</tr>
<tr>
<td></td>
<td>Arcs indicate grade C</td>
<td>Arcs with &quot;3&quot; indicate grade C3</td>
</tr>
<tr>
<td>ASTM A563 nut</td>
<td><img src="image9" alt="Required Markings" /></td>
<td><img src="image10" alt="Required Markings" /></td>
</tr>
<tr>
<td></td>
<td>Grade mark DH</td>
<td>Grade mark DH3</td>
</tr>
</tbody>
</table>

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Typical Bolted Joints
Typical Bolted Joints

Lap Splice

Eccentric Joint

Truss Joint

Standard Beam Connection

Bolted Joint Configurations
Typical Bolted Joints

Examples of Bolts in Tension

Bolts in Combined Shear and Tension
Typical Bolted Joints
Typical Bolted Joints

- **Standard beam connection**
- **Unstiffened seat connection**
- **End plate connection**
- **Structural T-connection**
- **Flange plate connection**
- **Diagonal brace connection**
Bearing type bolts in Shear

(a) Single Shear

(b) Double Shear
Bearing type Bolted Joints

Fig. 1.6 (a)

Fig. 1.6 (b) (and associated shear stress, $\tau = P/A$)

Fig. 1.6 (c) a bearing force

Fig. 1.6 (d) $P/2$

associated average bearing stress: $\sigma = P/A = P/(t \times d)$

note that this force is equal and opposite to the bearing force shown in (c)

Bolt Forces and Bearing in Plate
Bolts in Shear
Bolt bearing effect
Bolts in tension failure
Bolt block tear out effect

Tension + Shear Block in a Gusset Plate
Shear lag effect

Shear Lag in Angle Connection

Shear Lag in Gusset Plate Connection

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Design for bolts

Cl. 13.12

- **Shear:** \[ V_r = 0.6\phi_b n m A_b F_{u-bolt} > V_f, \quad \phi_b = 0.8 \] (Cl. 13.12.1.2)

- **Bearing:** \[ B_r = 3\phi_{br} t d_b n F_{u-plate} > V_f, \quad \phi_{br} = 0.8 \] (Cl. 13.12.1.2)

- **Tension:** \[ T_r = 0.75\phi_b A_b F_{u-bolt} > T_f, \quad \phi_b = 0.8 \] (Cl. 13.12.1.3)

- **Slip resistance** (Cl. 13.12.2.2):
  - \[ V_s = 0.53 c_1 K_s mn A_b F_{u-bolt} > V \] (table 3 – CSA-S16)

Combined:
\[
\left( \frac{V_f}{V_r} \right)^2 + \left( \frac{T_f}{T_r} \right)^2 \leq 1 \\
\frac{V}{V_s} + 1.9 \frac{T}{n A_b F_u} \leq 1
\]
Design for bolts, Spacing, etc.

- If threads are intercepted in shear, reduce A to 70%
- spacing: $2.7d_b$ (usually $3d_b$) Cl. 22.3.1
- Min. Edge dist.: Table 6 (based on $d_b$ & edge type)
- Max. Edge dist.: 12t or 150mm
- End distance: Table 6 or 1.5 $d_b$
- Bolt hole diam.: $d_b + 2mm$ (or 1/16”)
- Eff. hole diam.: hole diam.+2mm (for punched holes)
- $d_h = d_b + 4mm$ (punched holes); $d_h = d_b + 2mm$ (drilled holes)
- Installation and inspection: Cl. 23, Washers: Cl. 23.5
It’s cheesy cartoon time!

Bolt Power!

She has the hex bolt power!

He has the other kind!

Together, bolt and nut can keep the structure intact!

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Eccentric bolted connection

\[ L = \text{Moment/Load} \]

Equivalent eccentric load

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Eccentric bolted connection

Rotation effect only

Direct shear effect only
Eccentric bolted connection

Resultant of both rotation and direct shear effects
Bolts – Prying action

Schematic of joint deformation.
Bolts – Prying action
Prying effect

Fig. 6.4 Tee-Stub Connection

Fig. 6.5 Tee-Stub in Deformed Condition

Prying Action Nomenclature
Bolts – Prying action

- Use procedure in the Handbook (no code clauses)
Bolts – Prying action

Figure 6  Model of the transfer of tensile forces - example

Figure 8  The flange strength determines the strength of the connection

e bolt strength determines the strength of the connection
Welds

MIG (Metal Inert Gas) welding

Flux core welding
Tungsten inert gas arc welding
(TIG, GTAW)

- Tungsten electrode
- Contact tip
- Cold (filler) wire
- Arc
- Gas shield
- Weld pool
- Weld metal
- Workpiece
- Power supply
- Filler rod
- Noszzle
- Shielding gas
- Arc
- Shielding Gas Nozzle
- Contact Tube
- Consumable
- Tungsten Electrode

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Automated Welding

Plasma Welding & Cutting

Tungsten Inert Gas Arc Welding (TIG)

laser welding wire feed system

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Welds

Weld failure under electron microscope

Figure 14: Single-sided welding
Types of welds

- Fillet Welds
- Butt Welds
- Lap Welds
- Corner Welds
- Edge Weld
Fillet welds

\[ \text{Throat} = w \times \cos 45^\circ = w \times 0.707 \]
Fillet welds

Figure 12 Lap joint

Figure 9 Stresses in the parent material giving $\sigma_\perp$ and $\tau_\perp$ in the throat

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Butt Welds

Figure 1 Transfer of axial forces with butt welds
Welding symbols
Welding symbols

**ARROW SIDE**

**OTHER SIDE**

**BOTH SIDES**

- **means all-around**

- **means field weld**

*Tail section designating arc welding.*
Welding symbols

- Near side (arrow side)
- Other side
- Both sides
- Weld all around
- E70 reference
- Field weld
Welding symbols

<table>
<thead>
<tr>
<th>WELD SYMBOLS</th>
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<tbody>
<tr>
<td>SQUARE BUTT WELD</td>
</tr>
<tr>
<td>SINGLE V BUTT WELD</td>
</tr>
<tr>
<td>SINGLE BEVEL BUTT WELD</td>
</tr>
<tr>
<td>SINGLE-U BUTT WELD</td>
</tr>
<tr>
<td>SINGLE-J BUTT WELD</td>
</tr>
<tr>
<td>BACKING RUN</td>
</tr>
<tr>
<td>FILLER WELD</td>
</tr>
<tr>
<td>PLUG WELD</td>
</tr>
<tr>
<td>SPOT WELD</td>
</tr>
</tbody>
</table>

Information above reference line identifies weld on same side as symbolic representation.
Information below reference line identifies weld on opposite side to symbolic representation.

1) Dimension referring to cross section of weld
2) Weld Symbol
3) Supplementary symbol
4) Number of weld elements x length of weld element
5) Symbol for staggered intermittent weld
6) Distance between weld elements
7) Welding process reference
8) Welding class
Design of Welds Cl. 13.13

Groove Welds $\phi_w = 0.67$
- Base metal: $V_r = 0.67\phi_w A_m F_u$
- Weld metal: $V_r = 0.67\phi_w A_w X_u$

Fillet Welds $\phi_w = 0.67$
- Base metal: $V_r = 0.67\phi_w A_m F_u$
- Weld metal: $V_r = 0.67\phi_w A_w X_u (1 + 0.5\sin^{1.5}\theta) M_w$

Flare bevel weld in OWSJ:
- $V_r = 0.67\phi_w A_w F_u$
  - $A_w = 0.5 w_r L$

$M_w = \frac{0.85 + \theta_1/600}{0.85 + \theta_2/600}$
governs if $\theta > 45^\circ$ for 350W
Weld sizes, etc

Groove Welds
- Min. groove depths for different situations applicable

Fillet Welds
- Max. size:
  - $D_{\text{max}} = t - 2 \text{ mm}$, if $t > 6 \text{ mm}$
  - $D_{\text{max}} = t$, if $t \leq 6 \text{ mm}$
- $D_{\text{max}} = 0.75t$ for the rounded edges of rolled sections
- Min. size:
  - $D_{\text{min}} = 5 \text{ mm}$, if $t_{\text{max}} \leq 12 \text{ mm}$
  - $D_{\text{min}} = 6 \text{ mm}$, if $12 \text{ mm} \leq t_{\text{max}} \leq 20 \text{ mm}$
  - $D_{\text{min}} = 8 \text{ mm}$, if $20 \text{ mm} \leq t_{\text{max}}$
- Min length $L_{\text{min}} = \max (4D, 40 \text{ mm})$
- Lap Joints: min. lap length $L_{\text{lap}} = 5t_{\text{min}}$ or $25 \text{ mm}$
Problems in Weld placement

- Incomplete Fusion
- Underfill
- Incomplete Joint Penetration
- Undercut
- Overlap

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Problems in Weld placement

Alignment not very good
Problems in Weld placement

- Undercut
- Incomplete Penetration
- Excessive Gap
- Lack of Fusion
- “Wagon Tracks”/Slag Inclusion
- Cracks
- Longitudinal Cracks
- Transverse Crack
- Porosity
- Convexity
- Concavity

COMBATTING DISTORTION

- Pre Setting (weld pull parts into line)
- “Pressing” To counteract shrinkage pull in heavy welds from one side
- Counter back to back or on to “Strong Backs”
References

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