



Fundamentals of Structural Design

Part of Steel Structures

Civil Engineering for Bachelors
133FSTD

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Syllabus of lectures

1. Introduction, history of steel structures, the applications and some representative structures, production of steel
2. Steel products, material properties and testing, steel grades
- ➔ 3. Manufacturing of steel structures, welding, mechanical fasteners
4. Safety of structures, limit state design, codes and specifications for the design
5. Tension, compression, buckling
6. Classification of cross sections, bending, shear, serviceability limit states
7. Buckling of webs, lateral-torsional stability, torsion, combination of internal forces
8. Fatigue
9. Design of bolted and welded connections
10. Steel-concrete composite structures
11. Fire and corrosion resistance, protection of steel structures, life cycle assessment

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Scope of the lecture

- ➔ Manufacturing of steel structures
- Transport and assembling of steel structures
- Welding
- Mechanical fasteners
- Video Steel fabrication

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Manufacturing of structures

- Design of steel structures, co-operation of
 - Architect
 - Civil Engineer
 - Other specialists
- Manufacturing of steel structures (workshops)
 - The structure is completely manufactured and prepared in the factory } including the corrosion protection = painted) to limit the work done on site and reduce the assembling time
- Transport to the site
- Assembly

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Production in workshop

Certificates to prove the ability to produce steel structures are necessary

The factory consists of several parts:

- deposit of material - steel plates, structural sections, needs to be sorted according to steel grade, etc.
- splitting
 - thermal cutting is the most common and universal method
 - scissoring is used for simple shapes made from plates and sheets
 - sawing is used when precise surface is required
- machining shop
 - drilling bolt holes, etc
- welding shop
- workshop assembly
- painting shop
 - surface treatment to remove rust, dust, miles, etc
 - painting
 - hot dip galvanizing is made by specialized company
- deposit of products ready to be transported to the site



The workshop

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Thermal cutting

- Oxy-fuel
 - Mobile cutting machines for manual cutting
 - Stable cutting machines – convenient to make complex shaped parts (from steel plates)
 - Magnetic or rolling head, or optical copying head following the template or drawing
 - Modern machines are numerically controlled (CNC machines)
 - Multiflame torch cutting automats are used for increased productivity
- Plasma
- Laser

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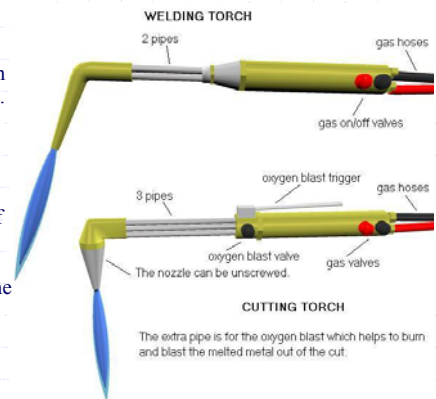
Manual oxy-fuel cutting

A cutting torch is used to cut materials. It is similar to a welding torch, but can be identified by the oxygen blast valve.

Acetylene, propylene, hydrogen, butane, propane and butane/propane mixes are used as fuel for the cutting torch. They are delivered in pressurized cylinders. The acetylene flame temperature can reach up to 3500 °C.

The metal is first heated by the flame until it is cherry red. Once this temperature is attained, oxygen is supplied to the heated part by pressing the "oxygen-blast valve". This oxygen reacts with the metal, forming iron oxide and producing heat. It is this heat that continues the cutting process. The cutting torch only heats the metal to start the process; further heat is provided by the burning metal.

The melting point of the iron oxide is around half that of the metal. As the metal burns, it immediately turns to liquid iron oxide and flows away from the cutting zone. However, some of the iron oxide remains on the workpiece, forming a hard "slag" which can be removed by gentle tapping and/or grinding.



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Manual oxy-fuel cutting



Compressed gas cylinders containing oxygen and acetylene gas



Edge of steel plate after oxy-fuel cutting



Manual oxy-fuel cutting

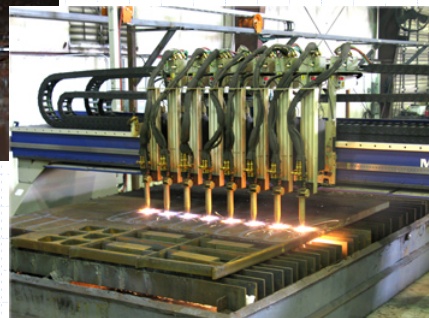
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Automatic oxy-fuel cutting



Automatic oxy-fuel cutting



Multi-torch oxy-fuel cutting

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Automatic oxy-fuel cutting



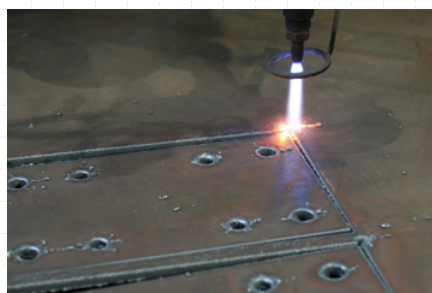
Preparation of edge for butt weld of thick plate by oxy-fuel cutting

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Plasma cutting

In this process, an inert gas (in some units, compressed air) is blown at high speed out of a nozzle; at the same time an electrical arc is formed through that gas from the nozzle to the surface being cut, turning some of that gas to plasma. The plasma is sufficiently hot to melt the metal being cut and moves sufficiently fast to blow molten metal away from the cut. It produces a cleaner edge than flame cutting.



Automatic plasma cutting

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Laser cutting

Laser cutting works by directing the output of a high-power laser, by computer, at the material to be cut. The material then either melts, burns, vaporizes away, or is blown away by a jet of gas, leaving an edge with a high-quality surface finish.

Can be used for many materials.

For steel, the melt and blow method is used. It uses high-pressure gas to blow molten material from the cutting area, greatly decreasing the power requirement. First the material is heated to melting point then a gas jet blows the molten material out of the kerf avoiding the need to raise the temperature of the material any further.

Flying optics lasers feature a stationary table and a cutting head (with laser beam) that moves over the workpiece in both of the horizontal dimensions.



Industrial 4kW laser with flying optics system

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Drilling

To produce holes for rivets and bolts

Made by pedestal drilling machines

Drills need to be cooled by liquid or air

Multi-spindle drilling machines are used to make groups of bolt holes

Numerically controlled machines (CNC) are used in modern workshops



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Punching

To produce holes for rivets and bolts

It is faster and cheaper than drilling, however, the material at the vicinity of the bolt hole is damaged (deformed, micro-cracks may exist)

This is not acceptable for some structures (i.e. when fatigue resistance needs to be checked)

Good quality hole can be obtained by punching it approx. 2 mm smaller and then reaming it to the final diameter, this way the same quality as from drilling is reached

Holes in sheets up to thickness 25 mm can be punched

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Scope of the lecture

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Transport to the site

transport on the road

- the most common method of transport
- fast, takes the parts directly to the site, no need for re-loading
- standard length up to 12 m
- large elements can be transported at special conditions (special routes, road closed during the transport for other traffic, care should be taken about the load carrying capacity of the bridges, etc.) - complicated, expensive

transport on the railway

- size and weight is limited by strict rules of the railway traffic
- usually need for reloading to trucks for transport to the site

transport on the ship

- limitations: ports should be close to the factory and the site, otherwise must be combined with other types of transport
- unlimited size and weight
- care should be taken when passing under bridges

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Transport on the road



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Transport on the road



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Transport on the road



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Transport on the railway



Transport on railway



Heavy transport on railway, capacity of the car is 120 t

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Transport on the ship



Transport of the Neckar Bridge on ship

The middle part of the bridge was pre-assembled from smaller parts in a port, loaded and transported on a ship, lifted to its final position and welded to the parts assembled in advance



Assembling the Neckar Bridge Zwingenberg, Germany



Transport on the ship



Lifting of the structure by floating crane



Assembling of steel structures on site

Usually done by specialized company

Project of assembling of the structure needs to be made

- draft of storage space
- method of transport of parts to the site
- schedule of delivery of the structural elements
- resistance of the structure in the partially erected stage (stages) needs to be considered
- parts of the structure can be pre-assembled from simple elements before the erection
- schedule of works on pre-assembly platform
- details on erection of the elements
- arrangement of welding
- schedule of using cranes (lifting capacity, the height and distance they reach)
- finalizing the corrosion protection
- etc.

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Assembling of steel structures on site

preferably **bolted** assembly connections

assembly documentation

assembly is made by specialized company

pre-assembly – options:

- assembly element = transported element
convenient when the elements are short, simple shape,
easy to transport (beams, columns)
- assembly element made of more transport elements
used when the assembly element is too long or has a
complicated shape therefore the transport of the assembly
element would be complicated or even impossible



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Assembling of steel structures on site



Assembling the structure of multi-storey building - connecting the secondary beams

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Scope of the lecture

Manufacturing of steel structures

Transport and assembling of steel structures

→ Welding

Mechanical fasteners

Video Steel fabrication

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Connections

Welding ↔ Workshop
Bolting ↔ Assembly

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Welding

is used to join steel parts. This is done by melting the workpieces and adding a filler material to form a pool of molten material that cools to become a strong joint

Types of welding

- forge welding – used by blacksmiths, now is a historical method
 - oxy-fuel welding – method similar to oxy-fuel cutting, it is **not allowed** for welding of structural steel elements
 - **electric arc welding** – mainly used for welding of structural elements
 - electric resistance welding – used in industry mainly for welding thin steel sheets, for example car body has several thousand spot welds made by industrial robots
 - laser beam welding
 - friction stir welding
 - and others
- } these are mainly used in industrial applications

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Electric arc welding

This process uses a welding power supply to create and maintain an electric arc between an electrode and the base material to melt the steel at the welding point.

This arc produces extreme temperatures in excess of 3,000°C.

It is used either direct (DC) or alternating (AC) current

It is made with consumable (steel) or non-consumable (tungsten) electrodes.

The welding region needs to be protected by inert or semi-inert gas, known as a shielding gas.

Filler material is sometimes used to protect the weld as well.

There are many types of electric arc welding technologies:

- manual metal arc welding (MMA)
- submerged arc welding (SAW)
- metal active gas welding (MAG)
- metal inert gas welding (MIG)
- tungsten inert gas welding (TIG)
- and maybe some others or modification of these, used in industry

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Manual metal arc welding (MMA)

- Electric current is used to strike an arc between the base material and consumable steel electrode, which is covered with a flux that protects the weld area from oxidation and contamination by producing carbon dioxide (CO₂) gas during the welding process.
- Electrodes are steel wires of diameter 1 to 8 mm, length 450 mm
- Weld times are rather slow, since the consumable electrodes must be frequently replaced and because slag (the residue from the flux) must be chipped away after welding.
- Welding is allowed to persons with an official exam after certificate to the person is issued.



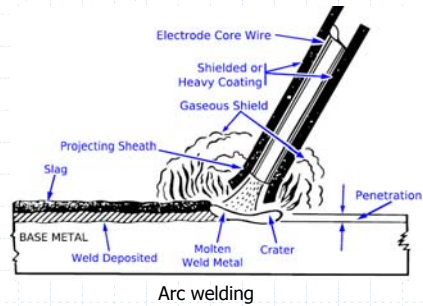
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Manual metal arc welding (MMA)

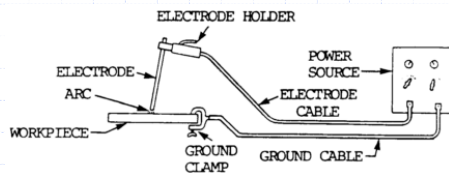
As the electrode melts, the flux covering disintegrates, giving off shielding gases that protect the weld area from oxygen and other atmospheric gases. In addition, the flux provides molten slag which covers the filler metal as it travels from the electrode to the weld pool.

Once part of the weld pool, the slag floats to the surface and protects the weld from contamination as it solidifies.

The slag, the residue from the flux, must be chipped away after welding.



Arc welding



The main components of arc welding equipment



Accessories and safety equipment for arc welding

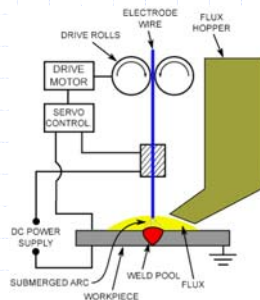
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Submerged arc welding (SAW)

Submerged arc welding is a common arc welding process, normally operating in the automatic or mechanized mode.

The molten steel and the arc zone are protected from atmospheric contamination by being "submerged" under a blanket of granular fusible flux. When molten, the flux becomes conductive, and provides a current path between the electrode and the work. This thick layer of flux completely covers the molten metal. The slag must be removed after welding.

The process is normally limited to the flat or horizontal-fillet welding positions and long straight welds (welding of I sections, for example).



Submerged arc welding



Submerged arc welding

The flux powder is supplied on the left hand side, then follow three wire guns (electrodes) and finally a vacuum cleaner to remove excessive flux

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Gas metal arc welding (MIG, MAG)

Welding process in which an electric arc forms between electrode and the steel workpieces, which heats them, causing them to melt and join. Along with the wire electrode, a shielding gas feeds through the welding gun, which shields the process from contaminants in the air.

The process can be semi-automatic or automatic.

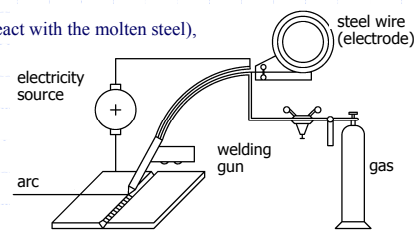
Steel wire is used as the electrode, which is fed automatically through the torch.

Leads to higher speed than manual arc welding when the electrode needs to be replaced periodically.

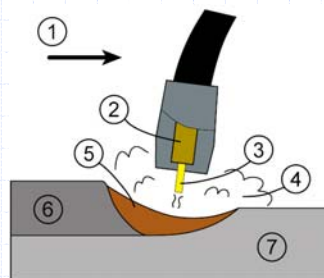
It is difficult to use it outdoors as wind blows out the gas.

- metal active gas (MAG) welding
 - carbon dioxide (CO_2) is used which reacts with molten steel, cheap
- metal inert gas (MIG) welding
 - argon is used to protect the weld (inert gas does not react with the molten steel), more expensive than CO_2 .
 - it is used mainly for welding stainless steel and aluminium

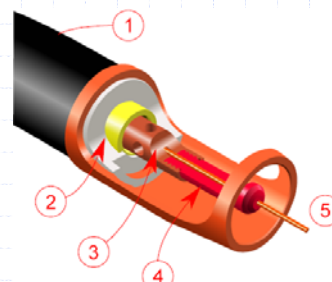
Mixture of gases ($\text{Ar} + \text{CO}_2$) is often used



Gas metal arc welding (MIG, MAG)



Gas metal arc welding
 (1) Direction of travel, (2) Contact tube,
 (3) Electrode, (4) Shielding gas, (5)
 Molten weld metal, (6) Solidified weld
 metal, (7) Workpiece



Gas metal arc welding
 torch nozzle (cutaway image)
 (1) Torch handle, (2) Molded phenolic dielectric
 (shown in white) and threaded metal nut
 insert (yellow), (3) Shielding gas diffuser,
 (4) Contact tip, (5) Nozzle output face

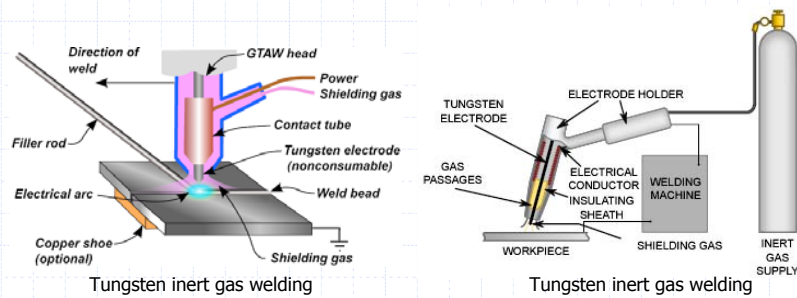
Tungsten inert gas welding (TIG)

It is similar to MAG/MIG welding, but the electrode is made from tungsten. It is non-consumable, steel wire is added as filler metal.

Inert gas (argon, helium or mixture of these) is used to protect the weld from the atmosphere.

It is used to weld thin sections of stainless steel and non-ferrous metals such as aluminum, magnesium, and copper alloys.

Can produce high-quality welds when performed by skilled operators.



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Stud welding

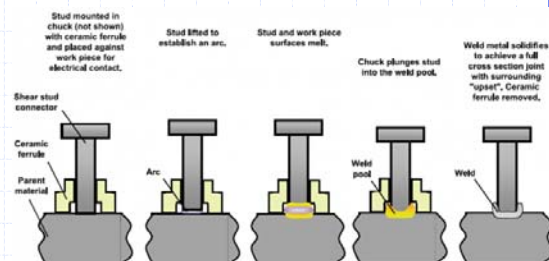
For shear connectors of composite steel concrete structures

Very strong source of the electricity is required

Electric arc + applied pressure

Quality can be verified by bending of some studs by about 15°

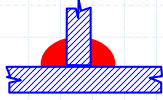
It is possible to weld through the zinc coated sheet to the flange of beam



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Types of welds

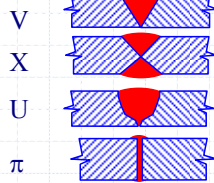
Fillet welds



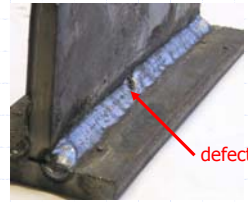
Butt welds



Types of butt welds



The shape of the butt weld is designed by weld specialist



Fillet weld



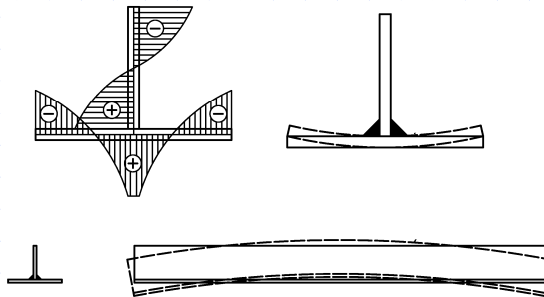
Butt weld

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Residual stresses and deformations

Are caused by non-uniform heating and cooling

Can be avoided or at least limited by welding process



Residual stresses and deformation of welded T section element

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Check of welds, crack detection

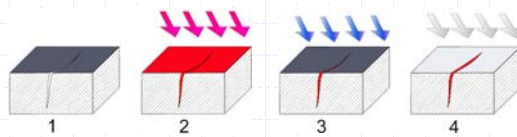
The typical welding defects are:

- lack of fusion of the weld to the base metal
- cracks or porosity inside the weld
- variations in weld density
- slag embedded in the weld

There are many methods for testing of weld quality

The method used depends on application, more precise (and more expensive) methods are used to test welds on pressurized gas, oil and water pipes, bridges, nuclear power stations, etc.

- Visual inspection
- Non destructive methods
 - Liquid penetrant
 - Magnetic particles
 - Ultrasonic
 - Radiographic
 - X rays
 - Gamma rays



Testing weld for surface cracks by liquid penetrant method
1. Section of material with a surface-breaking crack that is not visible to the naked eye. 2. Penetrant is applied to the surface. 3. Excess penetrant is removed. 4. Developer is applied, rendering the crack visible

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Scope of the lecture

Manufacturing of steel structures

Transport and assembling of steel structures

Welding

➔ Mechanical fasteners

Video Steel fabrication

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Mechanical Fasteners

Rivets

Bolts (standard bolts)

Pins

Fasteners for cold-formed profiles

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Riveting is now history

Now, it is used only for historical structures, it is replaced by bolts and welding

Exhibition can be seen on 3rd floor of Eiffel's tower

Can still be seen on many old structures, also in Prague:

railway bridge across Vltava near Vyšehrad

roof on railway station Hlavní nádraží

tower on Petřín

and more

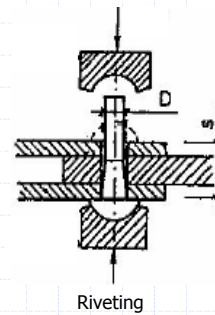


Riveted connection on Petřín tower

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Riveting

- Assembling
 - Must be heated to white colour
 - The other head is created by pneumatic hammer (max. clamping length of rivet $s = 4,5 d$)
- Function (after cooling)
 - Fully filled hole (before riveting, the rivet diameter is 1 mm smaller than diameter of the hole)
 - Pre-stressing connected sheets after cooling
 - No slip in the connection
- Made from steel corresponding to connected material
 - Rivet are made from steel with lower strength (when they need to be replaced they can be easily cut off)
- Rivet head
 - Semi-spherical (most common)
 - Countersink head



Rivets with semi-spherical head

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Bolts

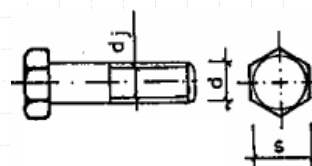
hexagonal head and cylindrical shaft
metric thread - „M“ ... M20

hexagonal nuts
washers, usually one (below the nut), but two are required for pre-stressed (slip-resistant) bolts

common diameter of bolts for steel structures:
 $d = (12), 16, 20, 24, (27), (30)$ mm
larger diameter is often used for anchor bolts

bolt grades 4.6, 5.6, 8.8, 10.9

bolt grade 10.9
 $f_{ub} = 10 \cdot 100 = 1000$ MPa
 $f_{yb} = 0,9 \cdot f_{ub} = 900$ MPa

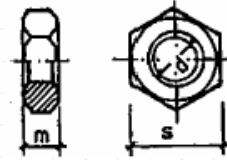


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Nuts

Three types according to height

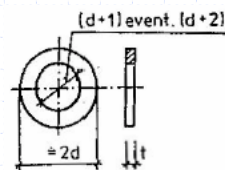
- Normal (height approx. $0,8d$)
- High (height $1,2d$ up to $2d$)
used for bolts loaded by high tensile forces
- Low (height $0,4d$)
to prevent loosening of the nuts



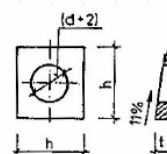
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Washers

- Bellow the part that rotates during the tightening
 - To distribute the compression force of the nut to larger area
 - To eliminate grinding of steel surface during the tightening the bolt
 - To eliminate ramming of edges of the hole
 - To secure bolt against loosening (secure washer)
- Dimensions
 - Inner diameter = bolt diameter + 1 ($d+1$) mm
 - Outer diameter approx. $2d$
- Quenched washers for slip-resistant connections
- Wedge washers for hot rolled I and U sections with slope flanges



Washer



Wedge washer

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Pins

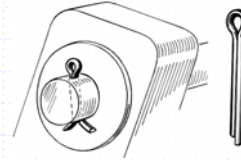
Free rotation of connected parts is ensured

Large diameter

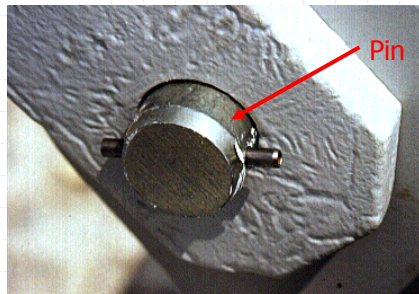
Locked to secure it in place

- By nuts
- By split pin
- By special covers

Rather expensive solution



Pinned connection secured with split pin and washer



Pinned connection



Pinned connection

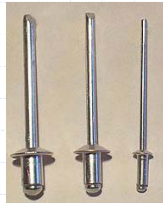
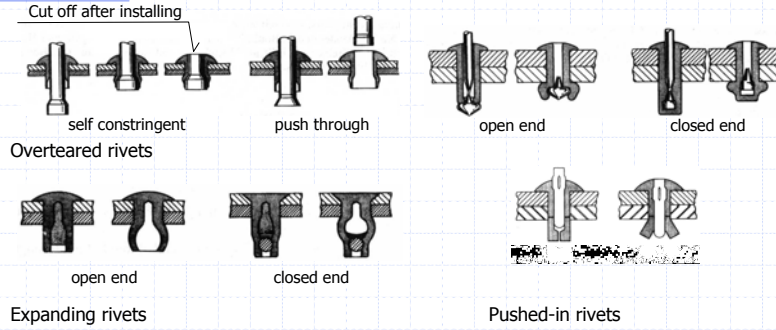
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Mechanical fasteners for cold-formed sections

- Bolts
standard bolts used for steel structures
- Blind rivets
- Screws
- Cartridge fired nails
- Clinching

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Blind rivets

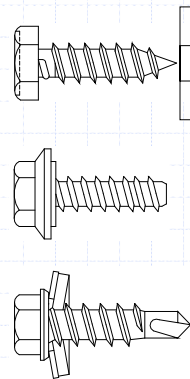
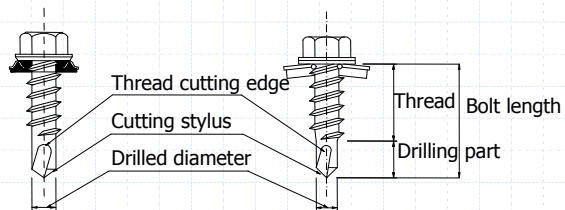


Variable size of blind rivets

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Screws (for steel sheets)

- Self drilling screws
to drill the hole and cut the thread
- Self tapping screws
to cut the thread in pre-drilled hole cutting

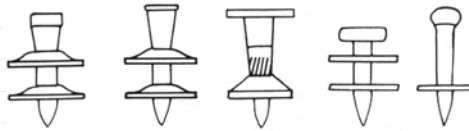


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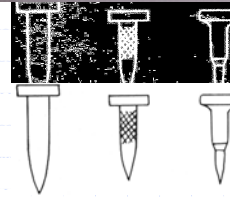
Cartridge fired nails

Driven into material by pressure

- induced by the explosion of cartridge
- induced by compressed air



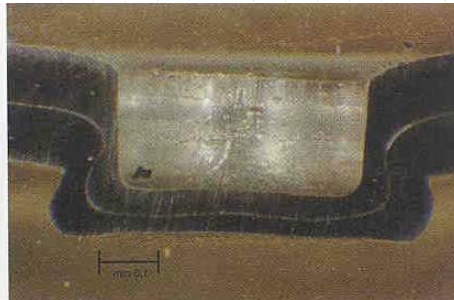
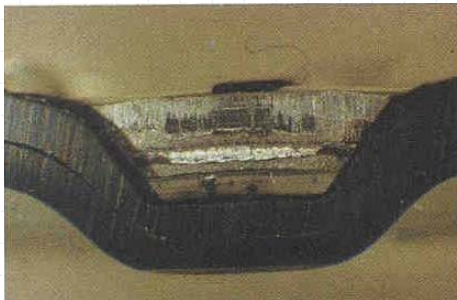
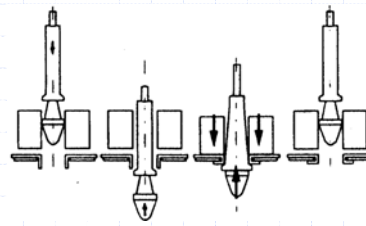
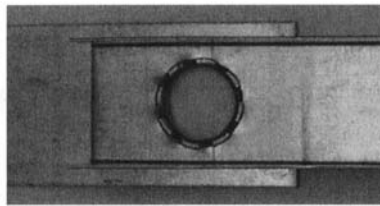
Nails driven by cartridge explosion



Nails driven by compressed air

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Clinching (metalworking)



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Scope of the lecture

Manufacturing of steel structures

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Welding

Mechanical fasteners

➔ Video Steel fabrication

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Thank you for your attention

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