Structural Steels
and Their Weldability

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Contents

■ Historical Review of Steels
  Iron and Steel
■ Structural Steels
  Mechanical Properties
  Chemical Composition of Steels
  Weldability
    Cracks
    Lamellar Tearing

Historical Review of Steels

Iron and Steel

Iron

Fe Ductile Material, Tensile Strength=200-300MPa

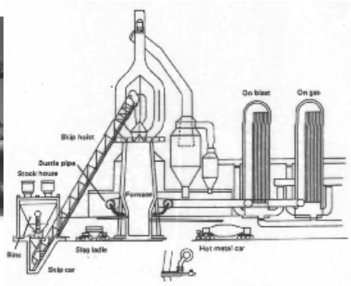
Steel

Removal of Impurities

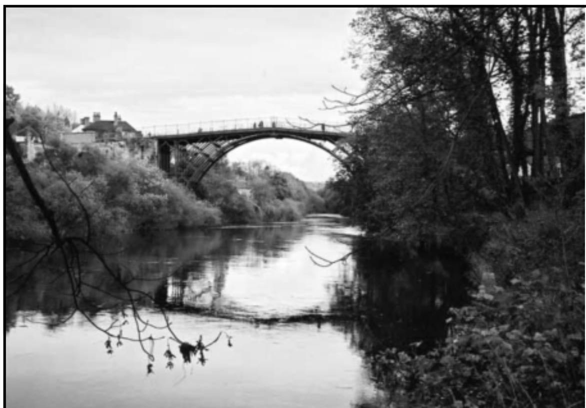
Fe + Additional Alloy Metals
(C+Mn+Si+Cr+...)

Improved Properties

Production of Iron

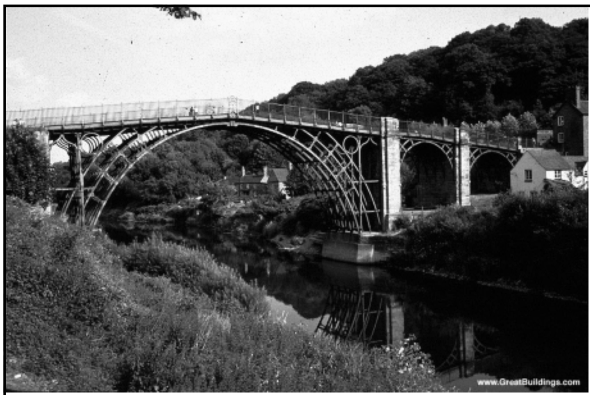


Pig Iron and Slag



Iron Bridge (1779, UK) The First Iron Bridge

Iron Bridge (1779, UK)

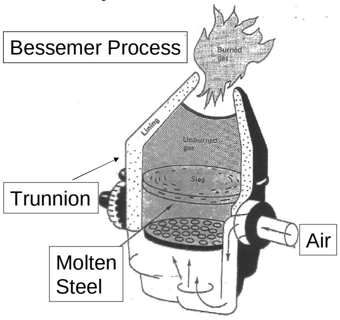


Coalbrookdale Bridge UK 1779 SPAN=30.5m

7

Production of Steels

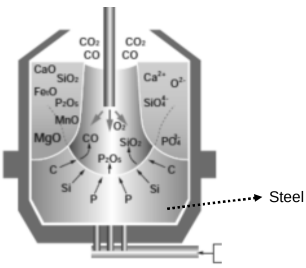
Impurities in pig iron are removed
by oxidation in a vessel called a converter



Pig Iron C:2.5-4.5%

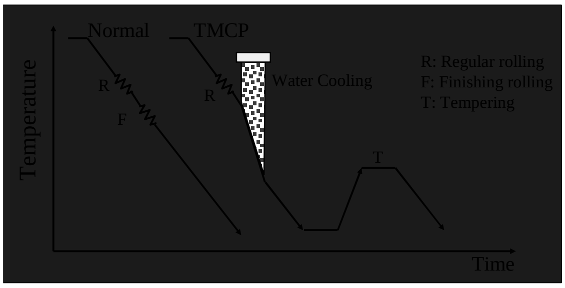
⇨ Cast Iron 8

Converter



9

Temperature Control during Rolling



Normalizing Quenching

Annealing Tempering

10

TMCP (Temperature Mechanical Control Process)

Temperature Control during Rolling

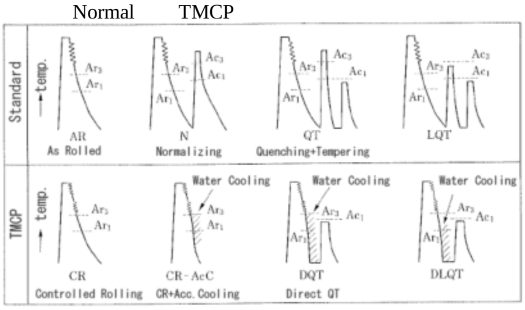
Normal TMCP

- Normalizing : heated to austenite temperature (A_3+20-30 degree) keep it for a while, cool down in the air. Finer and even crystallization, improve ductility and toughness
- Annealing : Heat up products to appropriate temperature and cool down slowly. To soften steel, release residual stress
- Quenching : Heat steel to A_3 or A_1+30-50 ° keep it for a while, and cool down quickly, Hardness of steel is dependent on quantity of martensite
- Tempering : Improve the property of steel after quenching by heating the steel below A1 point. QT steel is processed in quenching and tempering.
- TMCP (Temperature Mechanical Control Process)
  Cooling speed is controlled during rolling. Fine crystal, higher strength with lower carbon equivalent content. (good weldability) It is possible to lower the yielding ratio (ratio of yield strength to tensile strength)

11

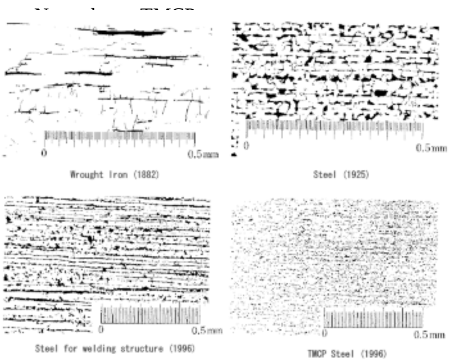
TMC Process

Normal TMCP



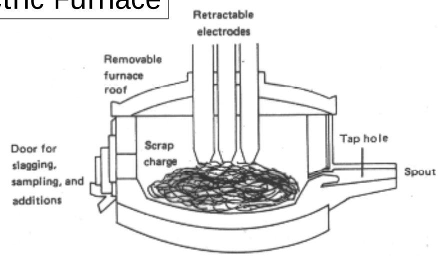
12

Granular size

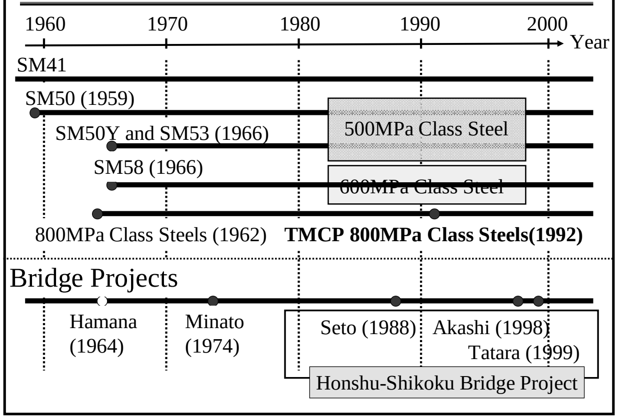


Recycling Steels from Scrap

Electric Furnace



Development of Structural Steels in Japan



Effects of Impurities and Alloy Metals

Chemical Composition   Example: JIS-SM490YB,SM570Q

	C	Si	Mn	P	S	Cu	Ni	Cr	V
SM490YB	0.14	0.46	1.56	0.020	0.005	0.01	0.01	0.02	0.04
SM570Q	0.14	0.23	1.44	0.012	0.005				

Carbon, C

Very Influential Element

Carbon acts as Hardener and Strengthener, but reduces the Ductility

Silicon, Si

Less 0.2%: Slight Effects on Strength and Ductility
0.3-0.4%: Elastic Limit and Strength are Raised

Effects of Impurities and Alloy Metals

Nickel, Ni

Nickel-Chromium Steels have a very high tensile strength with considerable toughness and ductility, improves corrosion resistance

Stainless Steels

Chromium, Cr

Same as Ni, hardening Agent, Intense Hardness after quenching with very high strength
Chromium improves corrosion resistance

Copper, Cu

Increases the resistance of steels to atmospheric corrosion

Weathering Steels

increase strength and hardness but decrease ductility

Effects of Impurities and Alloy Metals

Sulfur, S

Less than 0.1% : No appreciable effects
It has a very injurious effects upon the hot metal,
Lessening its malleability and weldability

Phosphorus, P

The Most undesirable impurity
It decrease toughness, ductility, and weldability
It Improves Corrosion Resistance

Manganese, Mn

Improves the strength of carbon steel, decrease ductility

Mechanical Properties of Steels

Governed by Chemical Composition

	Mn	Si	P	S	Ni	Cr	Cu
Strength	○	○				○	○
Ductility	×						×
Toughness			×		○		
Hardness	○					○	○
Corrosion Resistance			○		◎	◎	○
Weldability	△		×	×		△	

19

Steels

Iron ⇨ Steel

Chemical Composition

Improvement of Mechanical Properties
- High Strength
- High Ductility
- Mass Production
- High Quality

Steels:
Tensile Strength: 400, 500, …., 800MPa

Cables:
….., 1100, ….., 1600, 1800 MPa

20

Weld Cracks

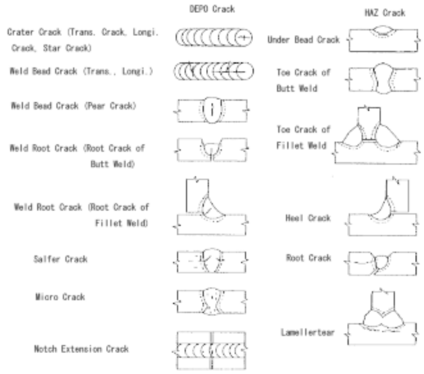
Hot Cracks

Cold Cracks

Lamellar Tearing

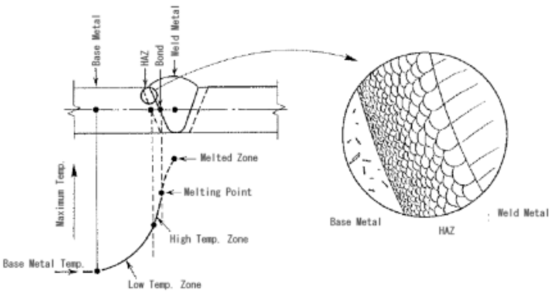
21

Weld Cracks



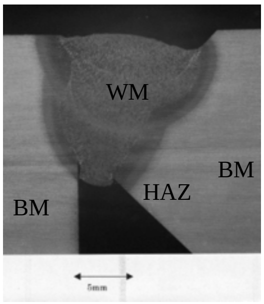
22

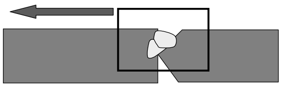
Micro structure of weld metal



23

HAZ in Welded Joints





K-Groove Butt-Welding

Heat Cycle and Microstructure Change

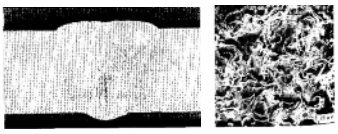
24

Hot Cracks

Cracks occur near melting temperature during welding or after welding

Hot Cracks can be eliminated by designing the material composition of weld metal and base metal.

$$HCS = \frac{C(S + P + {Si}/{25} + {Ni}/{100})}{3Mn + Cr + Mo + V} \times 10^3 < 4$$



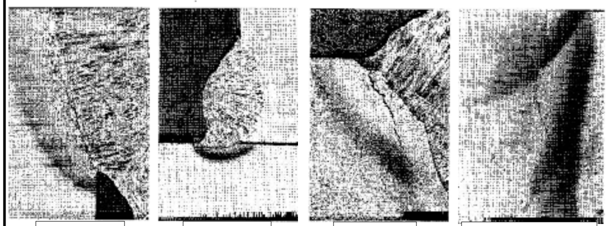
Cracks occurred during solidification

25

Cold Cracks

Generally, Tran-granular cracks

Short time cracking: during cooling process
Delayed cracking: after some time lapse at room temperature
Hydrogen is responsible for cold cracks



HAZ (Heat Affected Zone)

Resistance Performance of HAZ against Cold Crack

Carbon Equivalent

$$C_{eq} = C + \frac{Mn}{6} + \frac{Si}{24} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{14}\left(+ \frac{Cu}{13}\right)$$

$$P_{CM} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B$$

IIW

$$CE_{IIW} = C + \frac{Mn}{6} + \frac{Cu + Ni}{15} + \frac{Cr + Mo + V}{5}$$

27

Prevention of Cold Cracks

Use of Low C_{eq} or P_{CM} steel

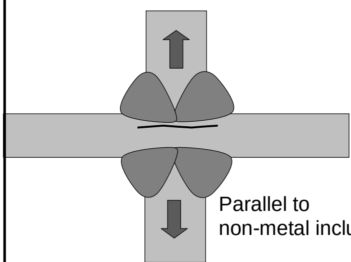
Use of Low Hydrogen Processes

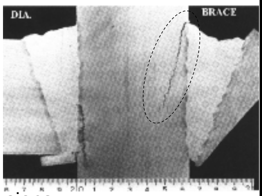
Preheating

Reduce Joint Restraint

28

Lamellar Tearing



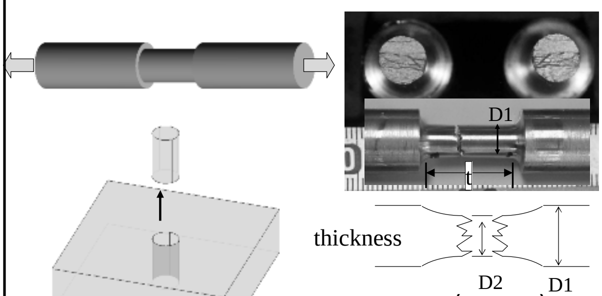


High Constraint Condition
Large Deposited Weld
Ductility in Plate Thickness Direction

29

Z-tension tests

- Φz: Reduction of Area in Thickness Direction (Z-Direction) Tension tests

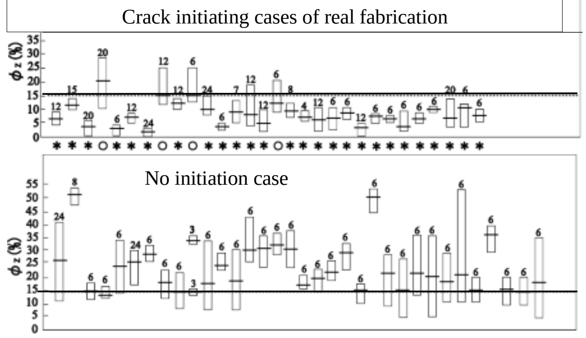


$$\phi_z = \frac{\left(D_1^2 - D_2^2\right)}{\left(D_1\right)^2}$$

30

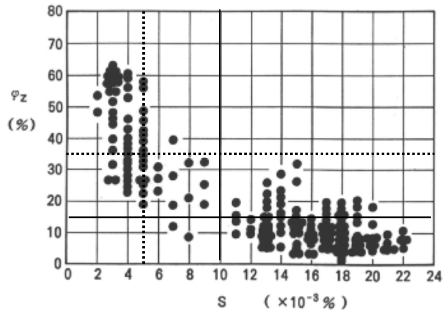
Lamellar tearing and φz

- ϕ_z<15%, High risk of Lamellar tearing



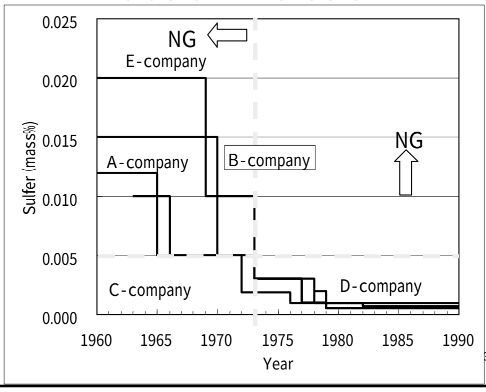
Φz and Sulfur Inclusion in Steels

- If S>0.01% then many of the z-tension test results are ϕ_z<15%.



32

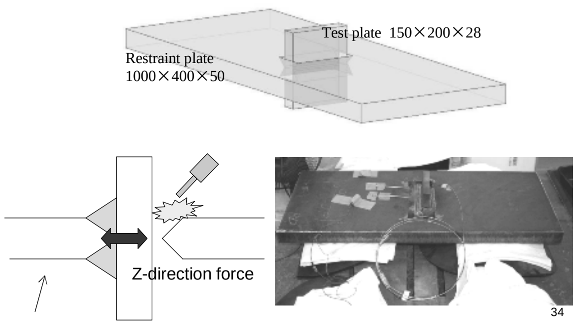
Historical Review of Sulfur Inclusion in Steels



33

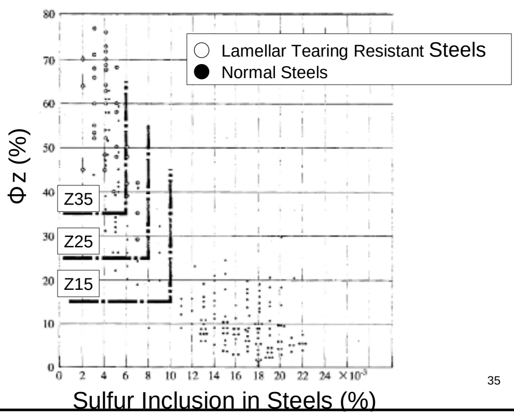
Z-Window Welding Tests

To Evaluate the possibility of Lamellar Tearing



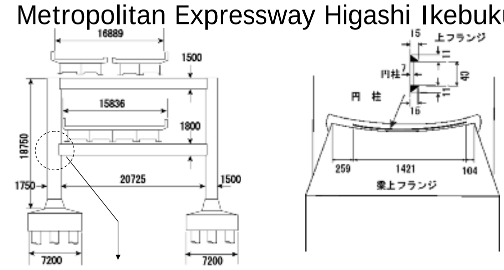
34

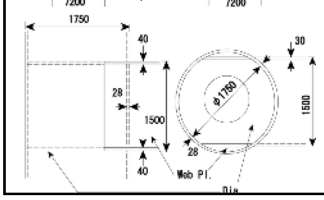
Lamellar Tearing Resistant Steels



35

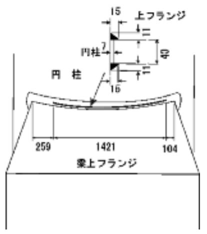
Metropolitan Expressway Higashi Ikebukuro

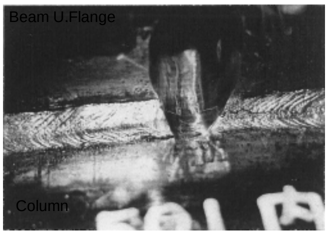




36

Fatigue Crack (Inside of the Pier)

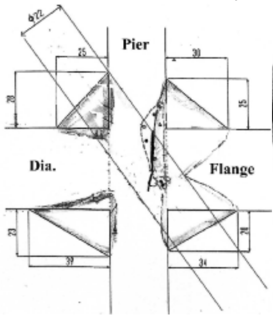


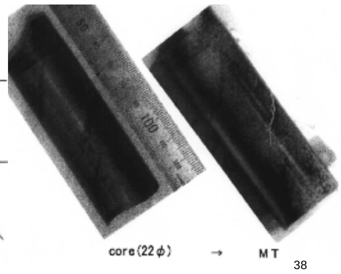


37

Material property(1)

- To check the result of UT, a core sample was taken from welded section. Crack due to lamellar tearing was found in the pier column.



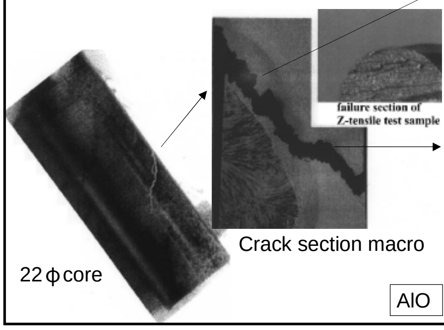


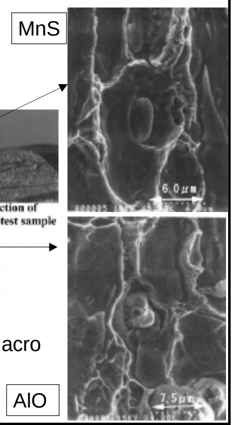
Core position&UT result

38

Material property(2)

- Crack was initiated from HAZ, MnS was found on surface of the crack. → Lamellar tear





Material property(3)

- Sulfur level is not so high, compared to contemporary steels
- Some samples show very low RAZ.

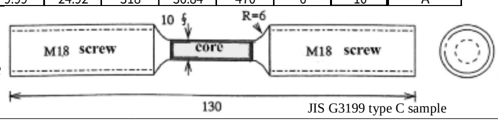
Chemical compositions

sample No.	chemical compositin(mass %)										parameters	
	C	Si	Mn	P	S	Ni	Cu	Cr	Mo	V	Ceq	Pcm
No.1	0.16	0.29	1.36	0.012	0.012	0.017	0.04	0.018	0.012	0.003	0.406	0.242
No.2	0.17	0.29	1.36	0.012	0.01	0.017	0.04	0.018	0.012	0.003	0.416	0.252
No.3	0.17	0.29	1.35	0.012	0.009	0.016	0.04	0.017	0.012	0.003	0.414	0.251

Z-direction tensile test result

sample No.	diameter (mm)	0.2% load		tensile stress		elongation (%)	RAZ (%)	break point
		Load(kN)	N/mm2	Load(kN)	N/mm2			
No.1a	9.99	26.81	342	27.89	356	3	0.2	connection
No.1b	9.99	28.34	362	39.78	508	12	8	A
No.1c	9.99	27.57	352	40.13	512	10	12	A
No.2a	10.00	26.49	337	39.41	502	18	20	A
No.2b	10.00	26.39	336	40.16	511	10	19	A
No.2c	9.99	24.92	318	36.84	470	6	10	A

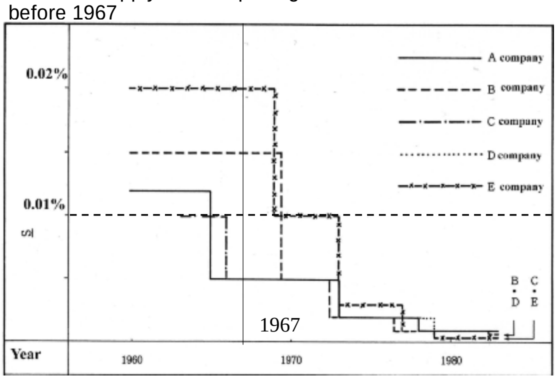
Bolt hole core sample



JIS G3199 type C sample

History of Sulfur Inclusion in Steel

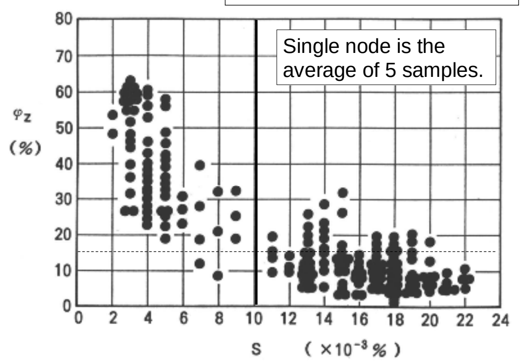
- Difficult to Apply Weld Repairing to Piers constructed before 1967



Sulfur and RAZ

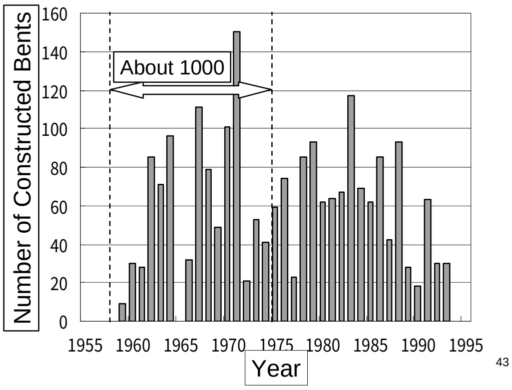
- RAZ is strongly related, but not determined only by sulfur.

Production data from Hirohata works.



42

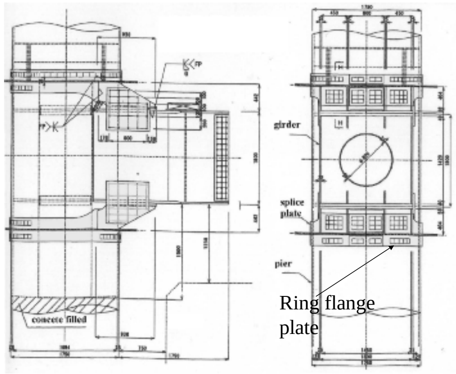
Construction Year and Number of Constructed Steel Bents in MEX



43

Support members for welding

- Decreasing the traffic stress by more than 50%.



44