A Design Study in Steel Castings

Cast High Strength Steel Connectors for Building Structures

Design Study Outline

Key Words *= metal casting, steel, connector, ASTM 958, Cast Connex, SFSA,*

Start the Design Study !

Acknowledgment --

The metalcasting design studies are a joint effort of the Steel Founders' Society of America and the American Foundry Society. Project funding was provided by the American Metalcasting Consortium Project, which is sponsored by the Defense Logistics Agency, Attn: DLSC-T, Ft. Belvoir, VA, 22060-6221

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A Design Study in Steel - **Cast Connex Steel Construction Connector**

Steel Connector -- Application

Concentrically braced frames are widely used in steel structures because of the increased stiffness, low cost, and ease of construction, compared to other lateral reinforcement systems.

- The diagonal bracing members of braced frames are often hollow structural sections (HSS) because of their compression load efficiency and their aesthetic appearance.
- These HSS connectors are either field-welded or field-bolted.
- HSS members come in a wide range of section sizes and geometries.

Diagonal Steel HSS Bracing

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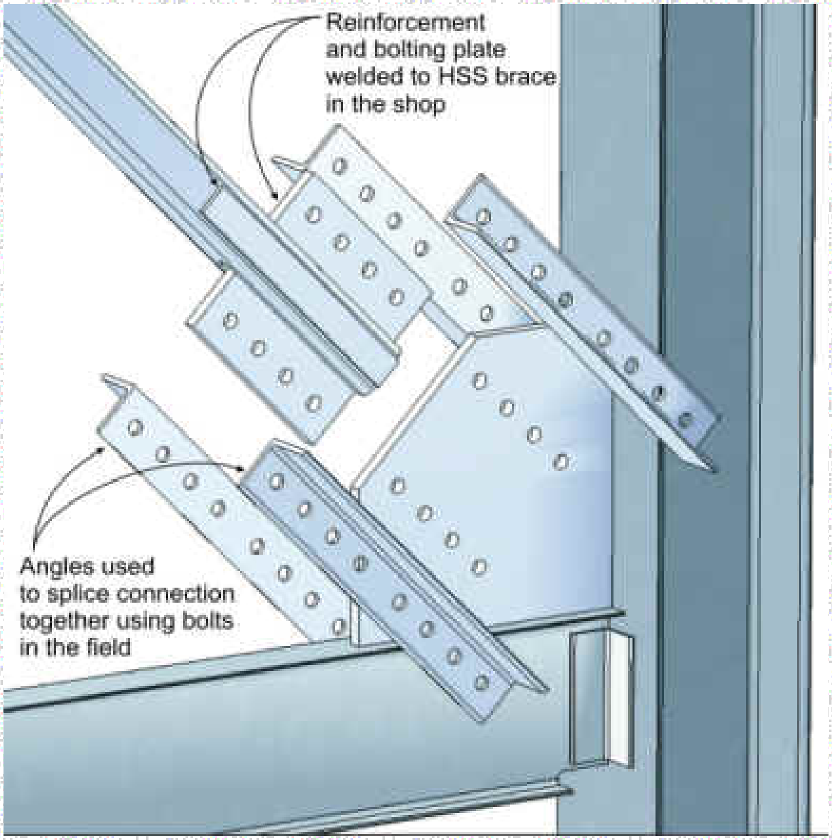
Steel Connector -- Application



Gusset-Connector-Brace System

Rectangular hollow section (RHS) brace members are easily mill- fabricated and are connected to the steel frame through tailored reinforced gusset- connector-brace systems.

- **But the RHS braces suffer from reduced ductility, lower notch toughness, and lower compression strength because of residual stresses and stress concentrations in the section corners.**

Circular hollow section (CHS) members avoid this corner effect, but pose different connection challenges.

A structural connector in building construction has to meet stringent building code requirements and should be easy to design for a range of structural forces and configurations, have low production cost, and provide simple field fabrication.

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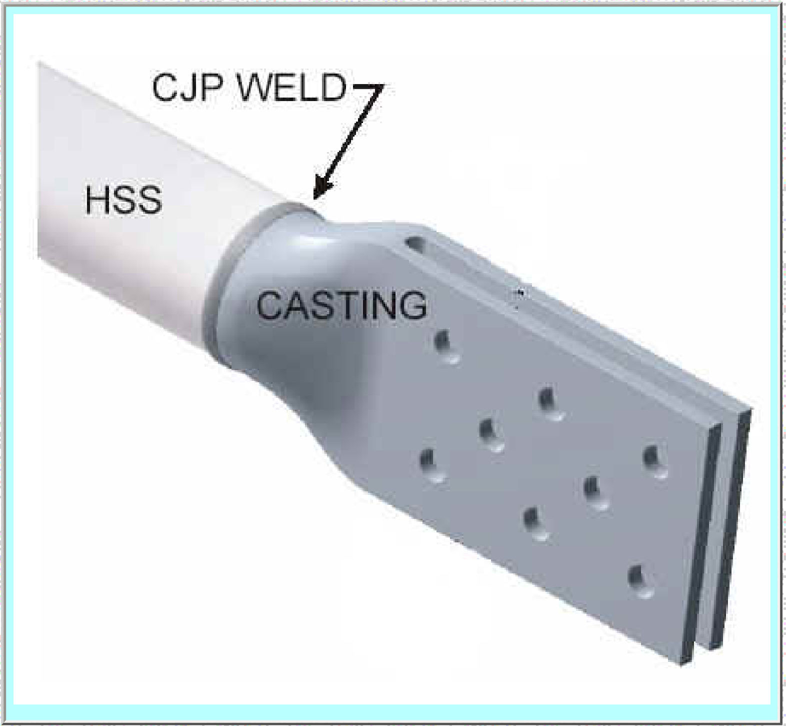
Steel Connector -- Description

Cast Connex Corporation of Toronto, Canada has developed a new connector design for CHS members that uses a high strength cast steel connector.

The connector meets structural requirements for strength and provides design, production, assembly, and cost benefits.



The steel connector casting consists of solid round section transitioning into two flat plates which are bolted to the gusset plate.

- **Bolt attachment to a single gusset plate accommodates simple fabrication, construction, and site erection.**
- **The bolt connection eliminates the need for field welding with its inherent variability.**

The heavy end of the connector is tapered to accept hollow round braces of different wall thickness for complete joint penetration (CJP) welding.

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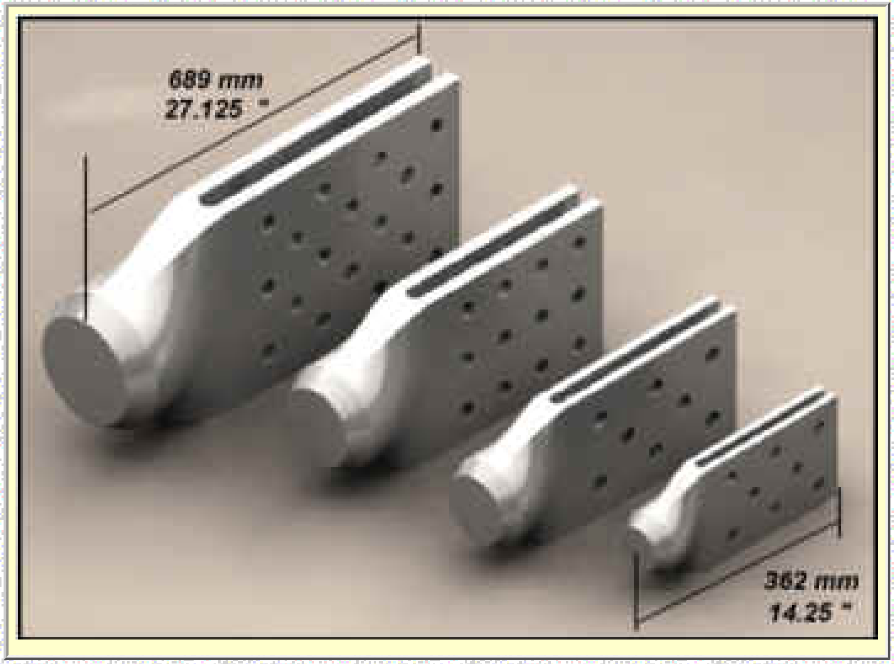
Steel Connector -- Description

- Cast Connex offers the steel connector in four sizes for connection to different outer diameter braces (OD = 4", 5.5625", 6.625", and 8.625").
- The four connectors range in size from (14" x 7") to (27" x 14") with weights from 41 lbs to 320 lbs.



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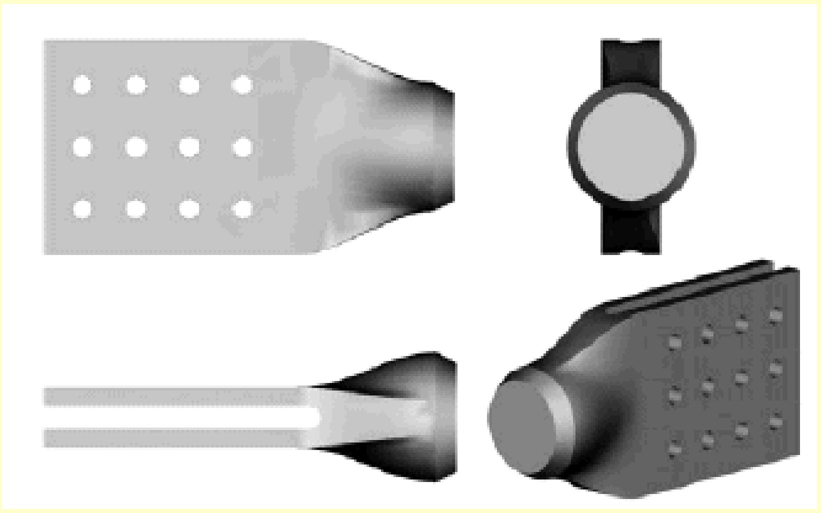
Connector Performance Requirements

A structural connector in building construction has to meet stringent building code requirements.



Steel Connector

The mechanical strength requirements were-

- **Ultimate tensile strength = 550 MPa (80 ksi),**
- **Tensile yield strength = 345 MPa (50 ksi)**
- **Percent elongation = 22% in 50 mm**
- **Reduction in area = 35%.**

The steel must have Charpy Impact strength of 27 J at -20C. The steel connector must be weldable and the finished weld must have Charpy impact strength of 27 J at -30C.

The surface finish requirement is 450 RMS

The quality assurance requirements were also extensive, covering both casting process parameters and comprehensive mechanical testing and non-destructive evaluation of castings.

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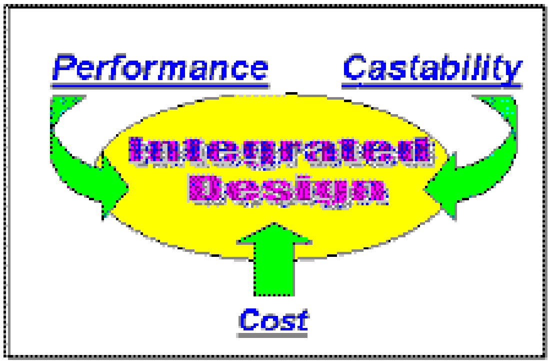
A Design Study in Steel - **Cast Connex Steel Construction Connector**

The Casting Design Issues

Cast Connex selected the Pacific Steel Casting Company of Berkeley, CA to produce the castings.



The casting design team *(the Cast Connex design engineers and the Pacific Steel casting engineers)* focused on three imperatives.

- ***Design for Performance***
- ***Design for Production/Castability***
- ***Design for Cost***

Critical Casting Design Issues **--The requirements for performance, casting production, and cost are closely interconnected. Three casting design issues played a major role in meeting the three design imperatives.**

- **Select a *steel alloy* that meets the mechanical requirements and reliably produces these four different size castings in a sound condition.**
- **Select a *molding method* that produces the required dimensional tolerances and surface finish in a cost-effective manner.**
- **Develop a *casting and mold design* that produces flaw-free within-tolerance connectors at the best cost.**

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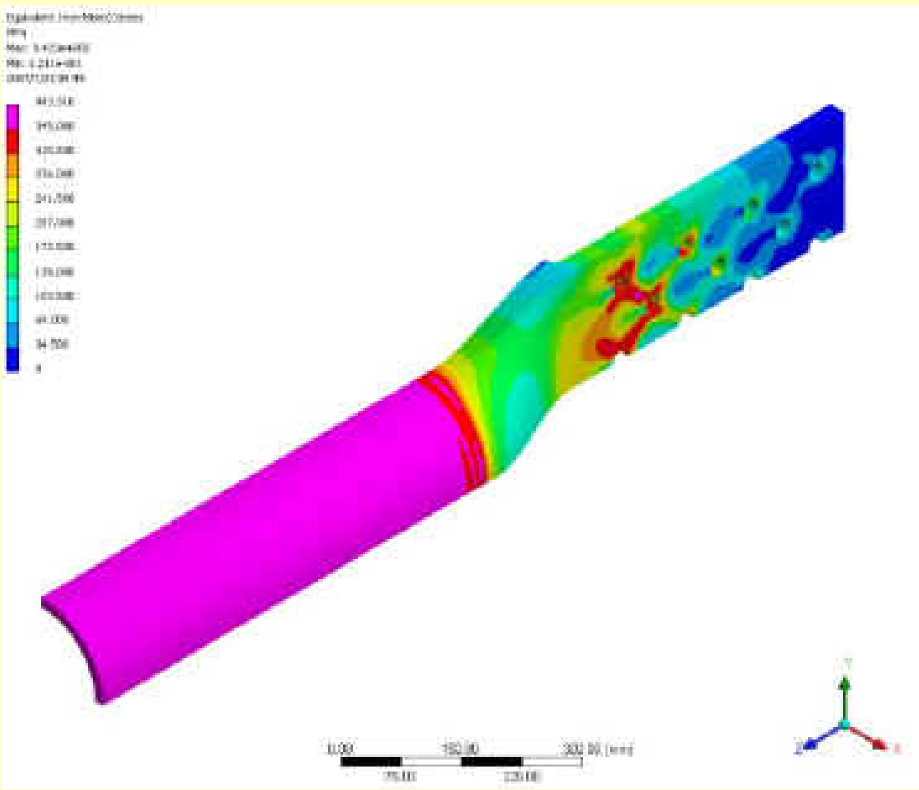
A Design Study in Steel - **Cast Connex Steel Construction Connector**

Finite Element Analysis



Finite Element Analysis of the Connector

- **Cast Connex design engineers used finite element analysis (FEA) to design the transition section between the cylinder section and the two plate fins.**
- **FEA verified the smooth blending of the cylinder into the fins, avoiding stress concentrations and maintaining stresses below the material yield strength.**

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A Design Study in Steel - **Cast Connex Steel Construction Connector**

Steel Alloy Selection

Cast Connex design engineers originally considered three different steel casting alloys, as specified by ASTM standards.

ASTM A27 Grade 70-40 ***Carbon Steel Casting for General Application***
Composition = 0.25 C max, 1.20 Mn Max, 0.80 Si Max, 0.06 S Max, 0.05 P Max
ASTM A148 - Grade 80-50 ***High Strength SteelCastings for Structural Purposes***
Composition = C, Mn, Si, S per agreement; 0.06 S Max, 0.05 P Max
ASTM A958 - Grade 8620, Class 80/50 ***Steel Castings with Tensile and Chemical Requirements Similar to Wrought Grades***
Composition = Min/Max Specified for C, Mn, Si, Ni, Cr, Mo; Max for S and P.

The three specifications gave the following properties for the three alloys.

	Performance Requirement	A27 Grade 70-40	A148 Grade 80-50	A958 Grade 8620
Minimum Ultimate Tensile Strength	80 ksi	70 ksi min	80 ksi min	80 ksi min
Minimum Yield Strength	50 ksi	40 ksi min	50 ksi min	50 ksi min
Minimum Elongation	22%	22% min	22% min	22% min
Minimum Reduction of Area	35%	30% min	35% min	35% min
Chemistry Control	Very Tight	Max Values Specified,	Max Values for S and P	Max/Min Values for all
Heat Treatment Spec. and Control	Very Tight	Not Specified	Not Specified	Specified

Given the mechanical property and process control requirements for the connector,
Choose the best alloy - A27, A148, OR A958.

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Choose an alloy above

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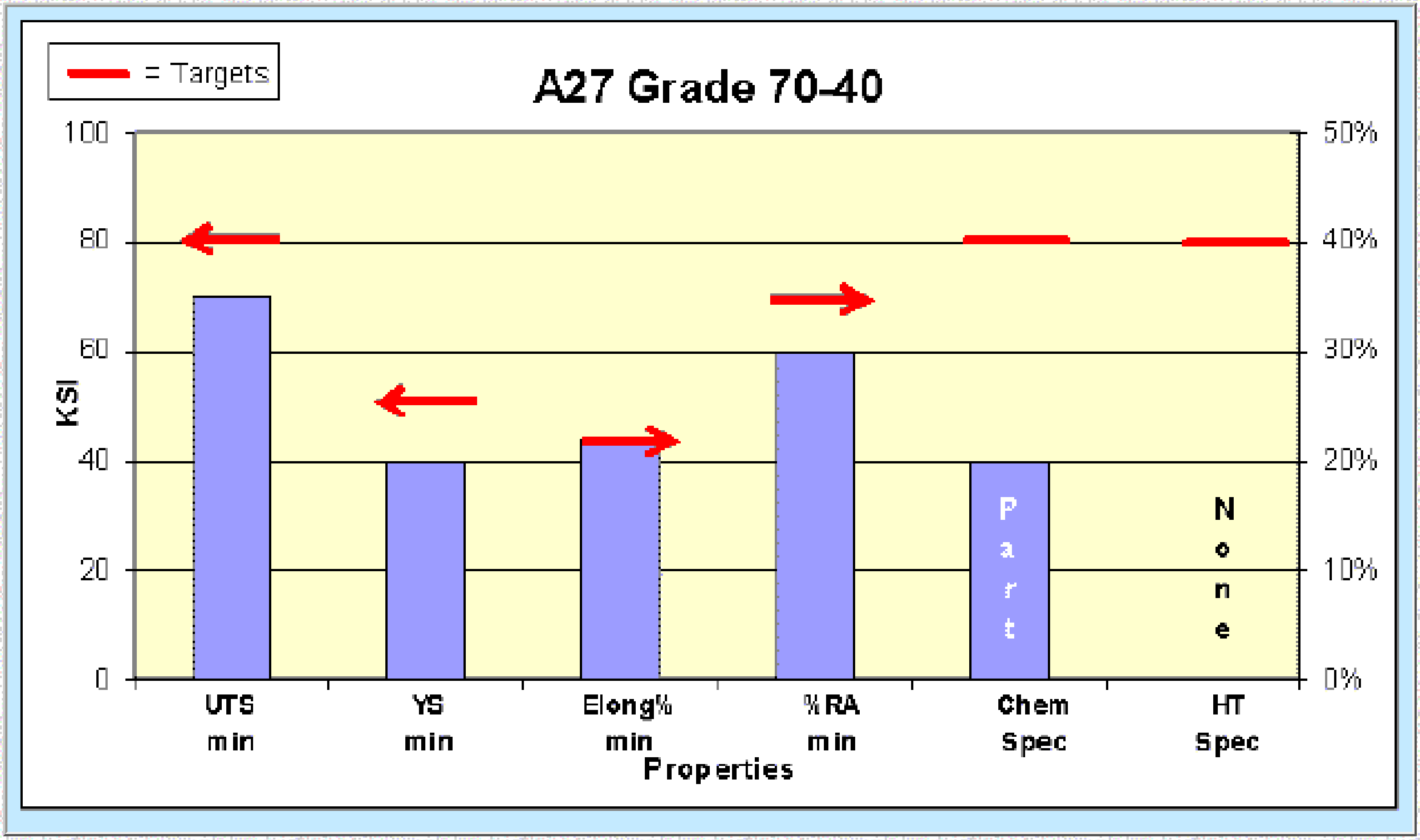
A27 Grade 70-40 Steel Alloy



The A27 Grade 70-40 is the strongest grade of A27, but it does not meet the mechanical property requirements for the steel connector.

- **The ultimate tensile strength of 70 ksi is below the 80 ksi design goal.**
- **The tensile yield strength of 40 ksi is below the 50 ksi design goal.**
- **The elongation meets the 22% requirement, but the reduction in area value fails to meet the 35% target.**

In addition, the chemistry and heat treat specifications are not tight enough to permit precise control of the alloy for this demanding application.

The A27 alloy does not meet the mechanical property requirements for the steel connector.

The A27 is not the best choice.

Go Back for Another Alloy!

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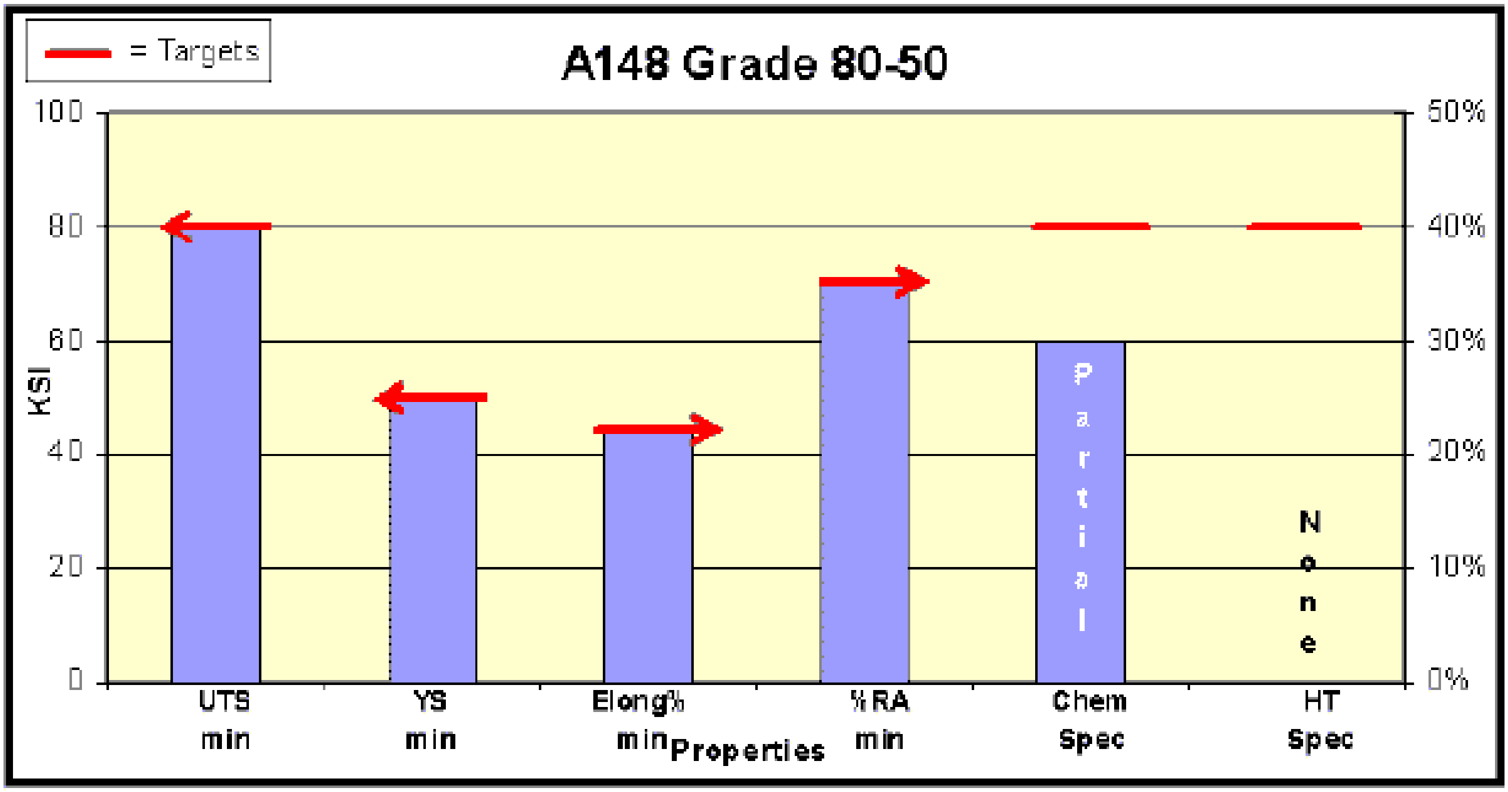
A148 Grade 80-50 Steel Alloy



The A148 Grade 80-50 meets all the mechanical property requirements for the steel connector -

-- Ultimate tensile strength (80 ksi), -- Tensile yield strength (50 ksi)
-- Elongation (22%) -- Reduction in area (35%)

But the broad chemistry and open heat treat specifications are not tight enough to permit precise control of the alloy for this demanding application.

The A148 alloy does not have a detailed specification for chemistry or heat-treatment.

The A148 alloy is not the best choice.

Go Back for Another Alloy!

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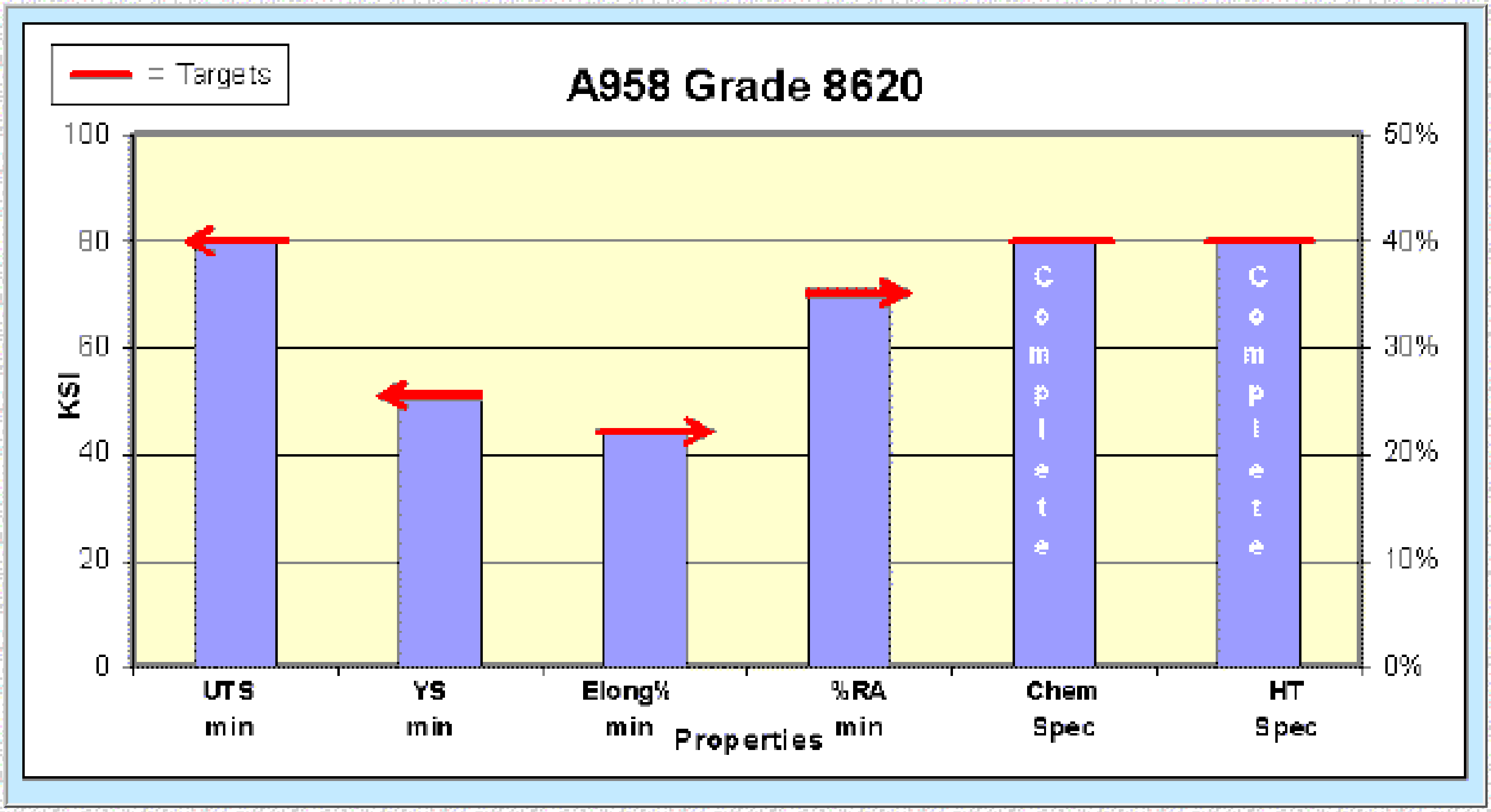
A958 Grade 8620 Steel Alloy



The A958 Grade 8620 meets all the mechanical property requirements for the steel connector -

-- Ultimate tensile strength (80 ksi) **-- Tensile yield strength (50 ksi),**
-- Elongation (22%) **-- Reduction in area (35%) .**

The full max/min specification for chemistry ***(C = 0.18/0.23, Mn =0.60/1.0, Si 0.30/0.60, P Max = 0.35, S Max = 0.04, Ni = 0.4/0.7, Cr = 0.4/0.60, Mo = 0.15/0.25)*** **and the full specification for heat treatment** ***(Austenitize at 1650F, air quench, Temper at 1150C)*** **ensure that the casting will meet specifications.**

The A958 Grade 8620 alloy will meet the mechanical property requirements and will be well specified for chemistry and heat treatment..

The A958 Grade 8620 is the best choice.

Go on to the next casting design issue.

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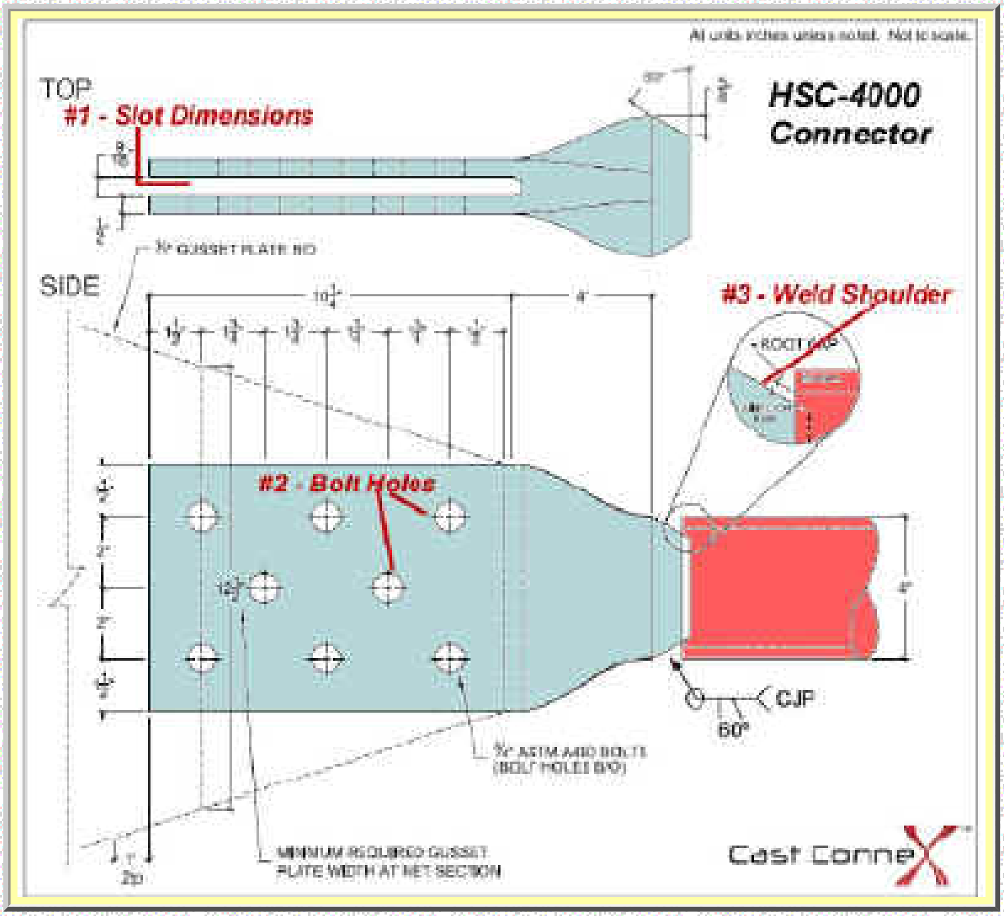
Critical Features and Tolerances

The three most critical dimensional features in the connector are:



1. **The uniformity and the +/- tolerance of the center slot opening.** ***Too narrow, the gusset won't fit into the slot; too wide and the bolted plates won't have surface contact with the gusset.***
2. **The position, alignment, and the diameter of the bolt holes on the two plates.**
3. **The angle, depth, and uniformity of the weld shoulder on the cylinder.**

The dimensional tolerances for the castings are specified by the ISO 8062 Grade CT8. (*The a grade specifies the tolerances per the basic casting dimension.)*

Dimension (mm/in) - Up to --	1" / 25 mm	4" / 100 mm	10"/ 250 mm	25" / 630 mm
+/- Tolerance (mm/in) Grade CT 8	0.05" / 1.2 mm	0.06" / 1.6 mm	0.09" / 2 mm	0.1"/ 2.6 mm

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Molding Method

One of the first casting decisions is the choice of a molding method, which will affect the surface finish and the dimensional tolerances of the finished casting.

Cast Connex and Pacific Steel engineers considered two types of molding methods for the steel connector.

GREEN SAND MOLD

Moist, clay-bonded sand is tightly packed around a wood or metal pattern in mold boxes to form a rigid mold cavity. The two pattern halves are removed, and the mold is assembled with or without cores.

NO-BAKE SAND MOLD

Chemically bonded sand is packed around a wood or metal pattern in mold boxes. At room temperature, the sand mold become rigid. Pattern halves are removed and the mold is assembled with or without cores.

Sand Mold (Green and No-Bake)

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The Molding Process

Each of the two molding methods has relative capabilities, advantages, and costs, as shown in the table below.

	Target	Green Sand	No-Bake Sand
As-cast dimensional +/- tolerance across 100 mm (4")	ISO8062 CT-8 1.6 / 0.06	Typical = 1.6 / 0.06	Typical = 1.4 / 0.05
As-cast dimensional +/- tolerance across 630 mm (25")	ISO8062 CT-8 2.6 / 0.1	Typical = 3.0 /0.12	Typical = 2.0 / 0.08
Nominal surface finish (RMS)	450	400-900	300-900
Minimum Section Thickness (mm / ")	12.5/ 0.50	6 / 0.25	5 / 0.19
Intricacy of Detail	Fair	Fair	Good
Tool/Pattern Cost	Low	Low	Low
Mold Material Cost	Low	Low	Medium

Given the as-cast tolerance and finish requirements, the level of detail, and the low cost issue, choose an appropriate molding method for the LARGER 27" LONG CONNECTOR --

GREEN SAND, NO-BAKE SAND

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Green Sand Molding


Metal Pouring into Sand Mold

- **Green sand molding can meet the baseline requirements for the connector for surface finish, detail level, and cost.**
- **But for the longer 27" heavy connector, green sand molding has a larger dimensional tolerance (3.0 mm) than the target tolerance of 2.6 mm.**

Green sand molding is not the best choice.

Go back and select another process

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No-Bake Sand Molding


Metal Pouring into the Sand Mold

- **No-bake sand molding can meet the baseline requirements for the connector for surface finish, detail level, and cost. It actually has slightly better numbers than green sand for surface finish.**
- **The key issue is that no-bake sand molding can hold tighter dimensional tolerances at larger dimensions than green sand. It meets the target tolerance of 2.6 mm for the larger dimension.**

No-bake sand molding is the best choice for the larger connector.

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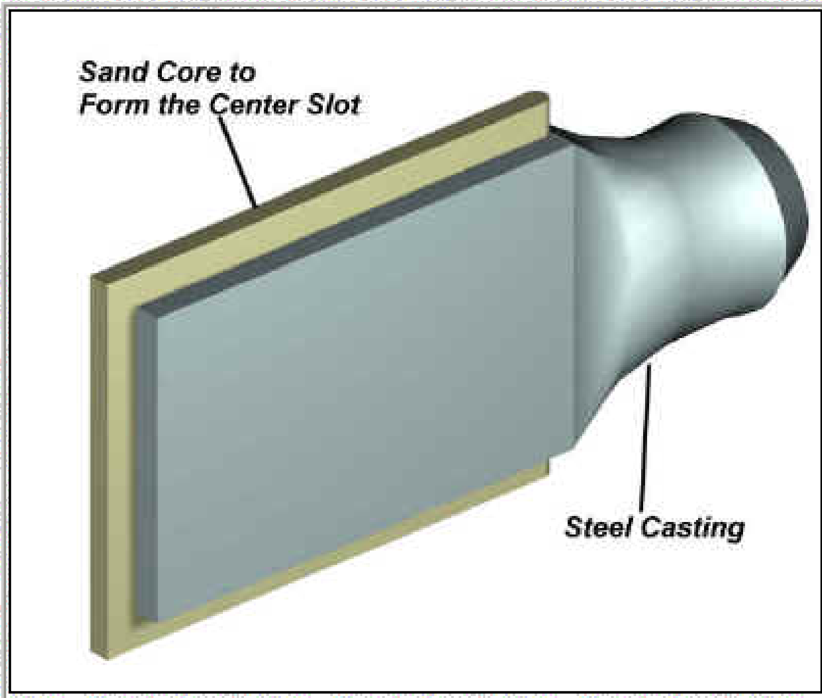
A Design Study in Steel - **Cast Connex Steel Construction Connector**

The Center Slot

The center slot of the connector is a key feature in the connector, because the gusset has to fit cleanly but tightly into the slot for the field assembly.

One advantage of casting over other fabrication methods is that complex, deep features such as the slot can be produced as a near-net shape in the casting.



For the connector, the center slot was formed with a sand core in the mold.

- **Cores are preformed sand shapes inserted into the mold to produce interior and exterior features in the casting.**

Using a core to form the slot offers a clear cost advantage over the extensive machining that would be required to cut out the deep slot in the connectors *(10" and 18" deep cuts for the smallest and largest connectors).*

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Orientation in the Mold

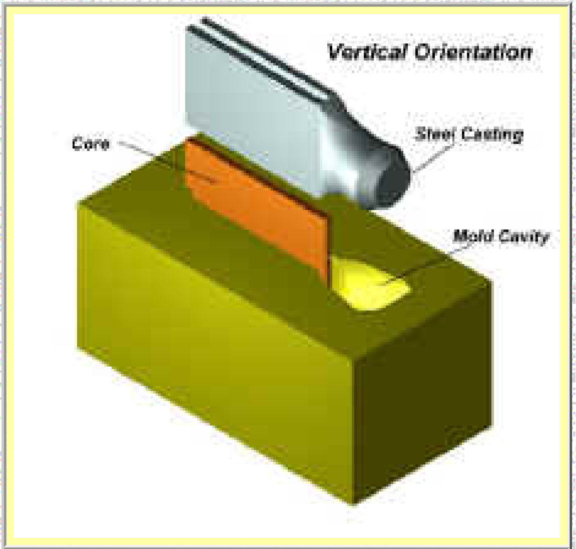
In mold design, the orientation of the part in the mold is an important factor in producing a sound casting.

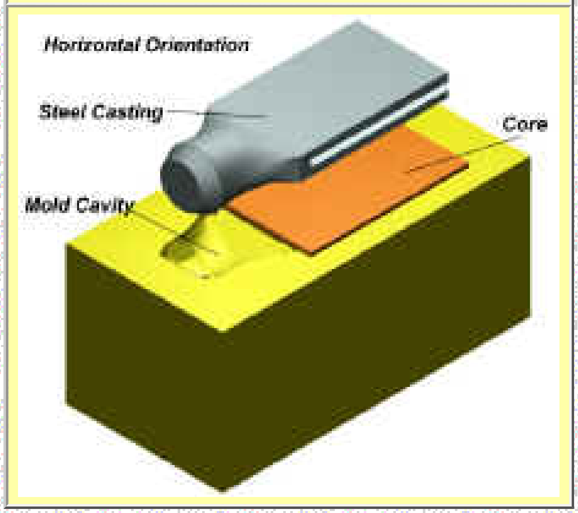
The part should be oriented in the mold, so that --

- **Metal flow is uniform and even in the different sections of the casting.**
- **The core can be securely positioned in the mold.**

The foundry engineer has two options for orienting the connector in the mold

- **Option A - Vertical Orientation**
- **Option B - Horizontal Orientation**





Which orientation will produce uniform metal flow and give the most secure core position? Vertical or Horizontal?

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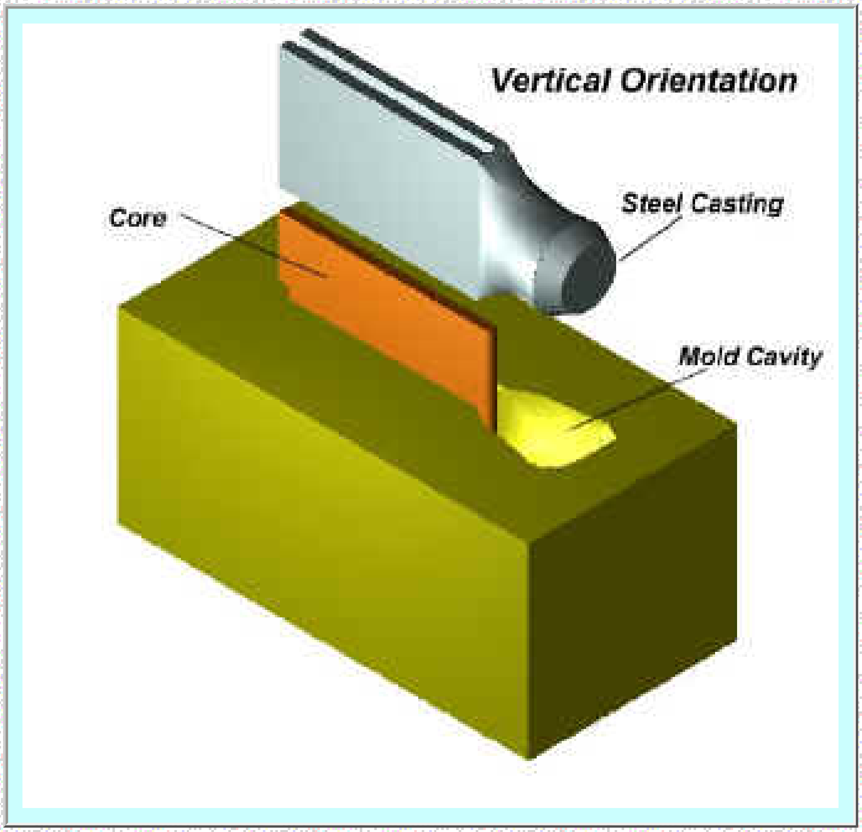

Option A -- Vertical

In the vertical orientation, metal flow will be uniform with the two vertical plate sections filling evenly together.

The center core is also oriented vertically, securely seated in core prints (seating slots) in the top and bottom molds.

A vertical orientation is best for producing a flaw-free casting.

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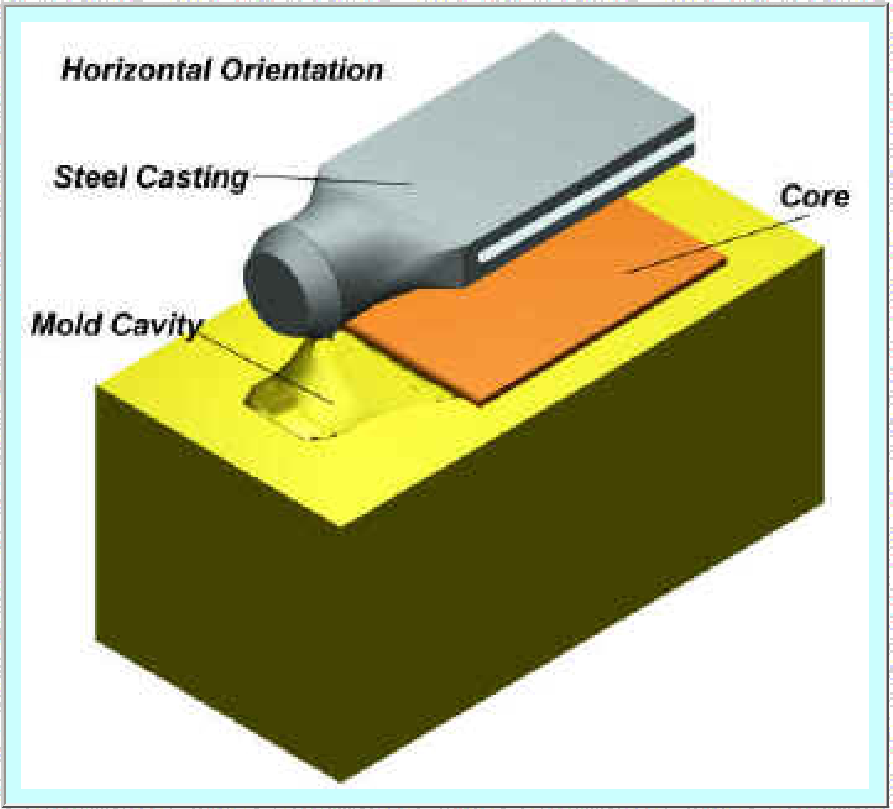

Option B -- Horizontal

In the horizontal orientation, metal flow will first into the lower plate and then into the top plate, producing non-uniform flow and fill into the two plate sections.

In addition, the core forming the center slot will be oriented horizontally and will tend to "float" in the melt, producing variation in the slot geometry.

The horizontal orientation is not a good approach for producing a flaw-free casting.

Go back and select another approach.

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Bolt Holes

One of the advantages of casting is that detailed features can be produced in a near-net shape configuration in the casting process. This capability can reduce or even eliminate expensive machining steps.

- **One of the design choices for the connector is whether and how to produce the bolt holes in the connector plates.**
- **Bolt holes can be rough and finish drilled into the finished casting**
- **Or they can be produced in the castings with features on the sand core and then finish drilled after casting.**

- ***The deciding factor was the fact that there are no standard bolt hole configurations for these structural connectors.***
- ***In actual use each structural designer chooses the bolt size, count, and configuration based on the structural loads he has to work with.***
- ***With that in mind, it was decided to produce the connector without bolt holes and let the field engineers drill the holes they need for their design.***

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Controlling Solidification

When metal solidifies it shrinks. If a heavy section of a casting is isolated from molten metal, there is no molten metal to "back fill" that shrinkage.

It is common casting practice to use a "riser" as a reservoir of molten metal from which the casting "back fills" as it shrinks during solidification.

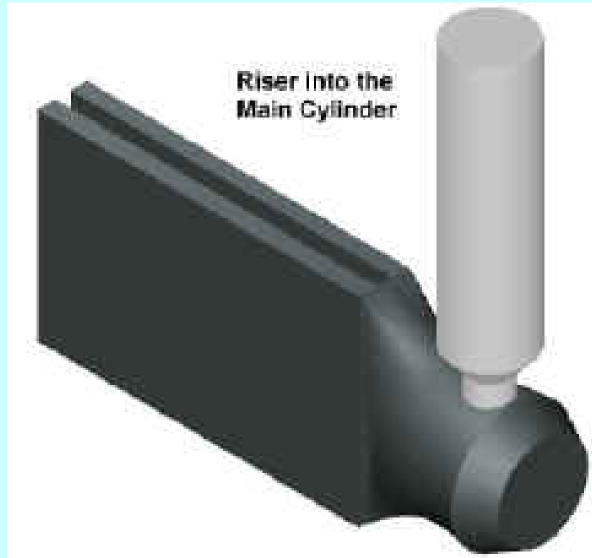
A riser, being the last section to solidify, acts as a "trap" for the solidification shrinkage.

Risers are commonly positioned to feed into the heaviest sections of a casting which will be the last sections to solidify, because they have the greatest thermal mass.

Two approaches were considered for controlling solidification in the connector:

- Approach A -- A riser feeding into the main cylinder.
- Approach B -- A riser feeding into the two plates.

Choose the riser design
(Approach A or Approach B)
which will be more effective in reducing solidification shrinkage in the body of the casting.



Approach A- Riser on the Cylinder

Approach B - Riser on the Plates

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Select an approach

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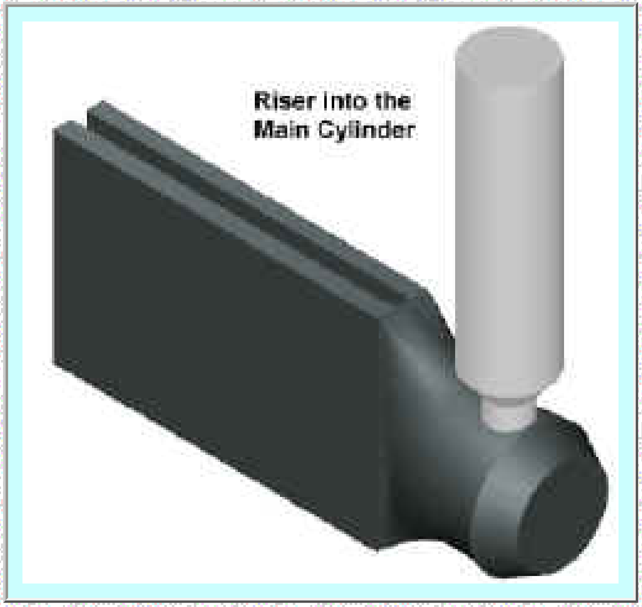

Option A -- Riser on the Main Cylinder

The main cylinder of the connector is the heaviest mass in the body and will be the last section to freeze/solidify, well after the two thinner plates have solidified.

The best position for the riser is into the main cylinder, to feed molten metal into that slow-cooling section.

A riser on the cylinder is best location for producing a flaw-free casting.

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Option B -- Riser on the Two Plates

The two plates on the connector are relatively thin and have lower mass, compared to the thicker cylinder. Those two plates will freeze/ solidify first, well before the main cylinder.

A riser on the two plates will not provide molten metal to the heaviest cylinder section which will freeze last and where solidification shrinkage will likely occur.

The riser on the plates is not a good approach for producing flaw-free casting.

Go back and select another approach.

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The Casting Process

The steel connectors are cast in a four step process.

Metal Pouring into the Assembled Mold

1. The molten steel (2850F) is poured into the assembled sand mold and allowed to cool and solidify in the mold.

2. After cooling, the casting is removed and "shaken out" of the sand mold.

3. The risers are cut off and the riser stubs and flash lines are ground smooth.

4. The casting is shot-blasted for surface appearance.

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Heat Treating

Heat treatment of the connectors was a critical process step to produce the required microstructure, mechanical properties, and Charpy Impact values.

The castings were heat treated per the ASTM A958 specification (a 1700F austenitizing, water quench, and an 1150F temper cycle).

Pacific Steel Heat Treat Furnace

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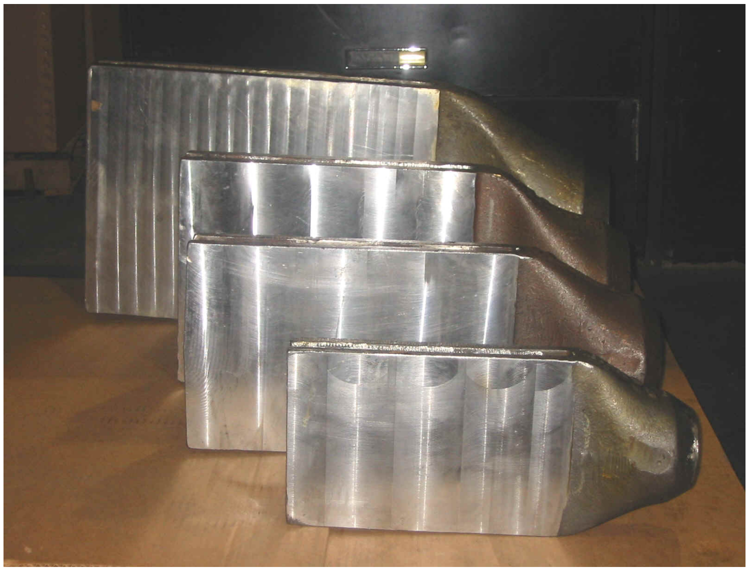
Machining

One feature is finish machined on each connector.

The outside faces of the two plates are milled to a required flatness and thickness.

The bolt holes and the weld shoulder in the connectors are machined by the end users to match their bolt pattern and connection configuration in their structural design.



Cast Connectors Machined and Ready for Shipment

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Quality Assurance

Quality assurance for these structural components is driven both by building codes and specifications and by design requirements.

Testing and inspection include -

- **Tensile tests and Charpy V-notch tests on test blocks from each heat**
- **Visual examination per ASTM A802**
- **Magnetic particle examination per ASTM A903**
- **Ultrasonic examination per ASTM A609**

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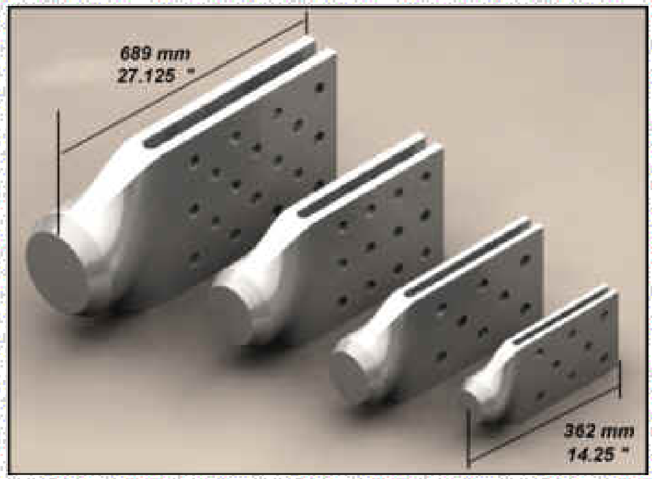
Lessons Learned

Cast Connex and Pacific Steel Castings engineers worked together in a collaborative design and process optimization effort.



Major lessons learned were:

- **Close collaboration and communication between designer and foundry are essential for rapid, effective design development, process optimization, and quality control management.**

- **Casting process optimization in the first item stage was critical for production verification and quality assurance. Solidification modeling was an important tool in effective and timely design.**

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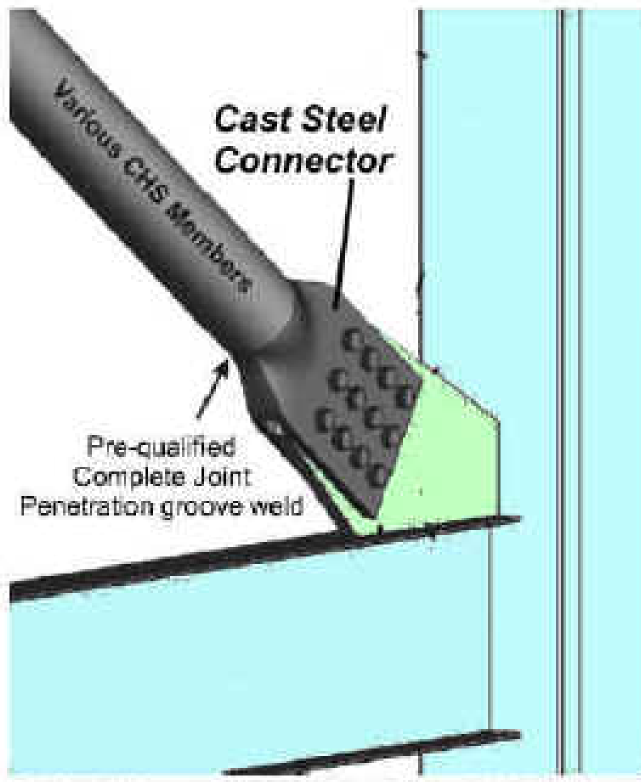
A Design Study in Steel - **Cast Connex Steel Construction Connector**

Summary

Cast High Strength Steel Connectors for Building Structures



The steel casting connector offers the following design and engineering benefits.

- **A mechanical design with integrated features, reduced stress concentrations, and isotropic properties.**
- **A functional design with reduced detailing and fabrication time, well-controlled welding methods, and simplified assembly with straight-forward field bolting.**
- **A standardized design with wide application to different load requirements that eliminates the need for one-off design of connectors.**

For further information on Cast Connex steel connectors, contact --
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