APPLYING STEEL CASTINGS IN STRUCTURES

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ABSTRACT

Steel castings have the potential to provide new opportunities for reducing cost, improving performance, and facilitating unique structures. Steel castings are currently used for high performance and critical applications in the railroad, construction, mining, and pump/valve industries. Recent research has shown steel castings can be used in seismic applications for building construction and perform well beyond testing requirements. Steel castings provide open geometry, manufacturing flexibility, equivalent mechanical properties to wrought material, and good weldability. Steel Founders' Society of America (SFSA) and American Institute of Steel Construction (AISC) have partnered with Robert Fleischman at the University of Arizona to develop casting applications for building construction through National Science Foundation sponsorship.

BACKGROUND

Steel castings are not commonly used in building construction. In the past, castings have been used in the building industry and for bridges. There are occasional uses but the ordinary application of steel castings to create steel structures that are pervasive in industrial equipment are absent from building construction. Steel castings are used in safety critical applications and in harsh demanding environment to carry significant loads. They are commonly welded into a fabricated structure. Castings give users unlimited potential for steel geometry. In industrial equipment, steel castings are used as connectors to perform demanding tasks while holding the other structural elements together. The use of steel castings as connectors in building construction can be an attractive option to improve the performance of the connection while lowering the total cost of the structure.

Connections are a critical feature of building construction. While the connectors are rarely more than 5% of the total weight, they are typically 60% of the cost. Moment and special bracing connections are especially difficult and costly. The cost for steel construction in 2001 was 25% material, 33% shop, 28% erector, and 14% other. Labor related costs exceed 60% of the cost of construction (Geschwindner, 2002). Modular cast connectors could reduce labor and erection costs, improve performance, decrease erection time, easily transfer loads from one shape beam or column to another, enhance reliability of the connection, and reduce engineering and detailing costs. In seismic applications, they could improve the safety and reliability of the structure cost-effectively. For special architectural features, they could provide innovative and attractive transitions between shapes or unique designs.

Good connections must:
1. support the loads
2. satisfy the code and specification requirements
3. perform safely and economically
4. be simple and repetitive
5. fabricate and erect with ease
6. minimize the labor required

The most common problems with connections include:
1. fit up and access at the site
2. failure to clearly satisfy the code requirements
3. incorrect interpretation of drawings
4. lack of needed information on the drawing, e.g. loads
5. poor match between member sizes
6. high cost of fabrication and erection

(Merrell, 2002)

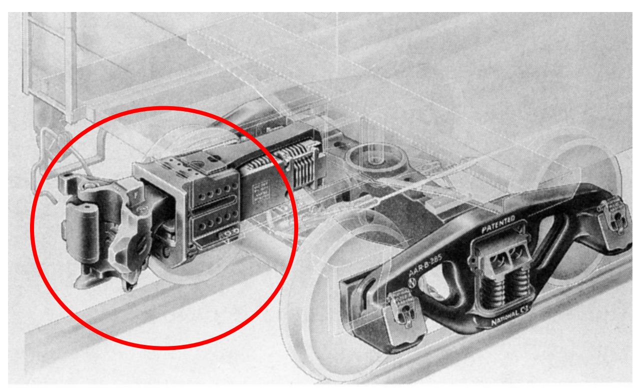

Figure 1: Standard railcar coupler

Castings are capable of meeting the requirements of good connectors. The most common application of steel castings is couplers for the railroad industry, Figure 1. As an example of the severe requirement, the electric utilities use large dedicated trains to move coal from the Powder River Basin to the Midwest. These trains are commonly made up of 120 freight cars that each weigh 286,000 pounds, for a total train weight of over 13,000 tons. This train is powered by two sets of 12,000 horsepower locomotives for a total of 24,000 horsepower. These trains cross the Rocky Mountains in the dead of winter at temperatures well below freezing on tracks that are remote and may have rocks or other debris on the track. This whole system of 13,000 tons and 24,000 horsepower is connected in the center by one set of steel castings in the form of a coupler. The example of a railroad coupler illustrates that steel castings can clearly meet the requirements listed for a good connection. They are capable of safe, economical, reliable, simple, repetitive performance.

If connections are a problem, and steel castings offer an answer, why are castings not being used? The American Institute of Steel Construction (AISC) and the Steel Founders' Society of America (SFSA) have formed a joint task committee to explore the possibilities of using steel castings in steel building construction. Most of the problems in using steel castings in building applications seem to be related to a lack of understanding. Steel foundries do not understand the requirements or needs of the building construction industry. Designers, fabricators and erectors do not understand the use of castings. A brief overview of steel casting use, method of manufacturing, properties, and purchase requirements may be useful.

APPLICATIONS

Steel castings are used broadly in industrial equipment as connectors. The example of a railroad coupler already discussed is a good example. The railroad industry uses steel castings extensively for the trucks, wheels, and corners. Fifth wheels for large over the road trucks are steel cast connectors. Caterpillar aggressively used steel castings in its 797 mine haul truck, Figure 2. The truck can carry 360 tons and has a diesel engine that provides 3400 hp (Caterpillar, 2003). Caterpillar used steel castings to make the entire load-bearing frame for improved durability and resistance to impact loads. Whether as connectors for structural components or power transmission parts, steel castings are commonly used in industrial equipment (SFSA, 1995).

Figure 2: Caterpillar 797 truck

One example that may be easier to relate to steel structures is the use of steel castings for valves and fittings. Steel castings can have complex internal passages, which is a unique capability compared to other manufacturing processes. This is why castings are used for blocks or heads in automotive engine applications. In fittings for piping, castings not only provide a flow path, they are a structural connector of pipe, a hollow structural shape. The structural design for fittings is seen as straight forward since the fitting is a successful structural component as long as it outlives the pipe. The cast steel fitting cross section is maintained larger than the pipe cross-section and this assures that the pipe will fail first.

The reason steel castings are attractive as connectors is the freedom of design. Any shape that can be imagined can be cast. Frequently, a casting cannot be made effectively not because the design was too aggressive but because it was too timid. Often a fabrication design that is inadequate is sent to the foundry to see if it can be made as a casting. This normally causes manufacturing problems. And changing the manufacturing process will not overcome inherent performance characteristics of a design. Cast parts are best manufactured when designed for the casting process. One reason that castings are seen as problems is because the foundry is often asked to make poor designs successful and so the lead-time is long and the cost is high. Good casting design allows weight to be reduced, cost to be lowered and performance to be improved.

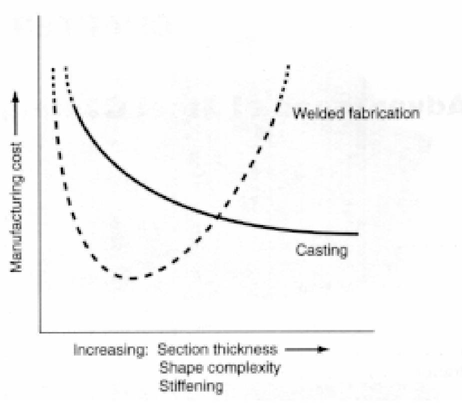

Figure 3: Cost of Casting v. Fabrication

Steel castings are expensive sources of steel but cheap suppliers of geometry. Good applications of steel castings are details that have many parts with high fabrication costs, poor material utilization and performance limits based on section size or geometry limits. Figure 3 illustrates the cost trade-off of a casting compared to a fabrication. The flexibility of casting allows material to be placed where needed and material to be removed where it is not needed. Castings like big sweeping curves, non-uniform sections, and complex geometry.

One structural example of the use of steel castings to give shape and performance in a steel structure is their use as nodes in offshore oil platforms, Figure 4. The casting is designed to perform in a demanding environment of high stress and corrosive atmosphere, it weighs 20% less than a fabricated connection, and moves the welds to the Hollow Structural Sections (HSS) elements outside the high load regions of the structure to prevent failure of a welded joint in a high stress region. The steel cast nodes are designed so the pipes drive the loads into the casting. The casting geometry and section size are tailored to survive the requirements of the application (Marston, 1991). Similar to welding procedures that rely on the same principles of metal solidification as castings, casting procedures call out testing requirements to ensure mechanical performance. First article tests typically call out x-ray and magnetic particle inspection to ensure the quality level of the casting. Therefore, ensuring quality and performance of a casting is very similar to that of a weldment.

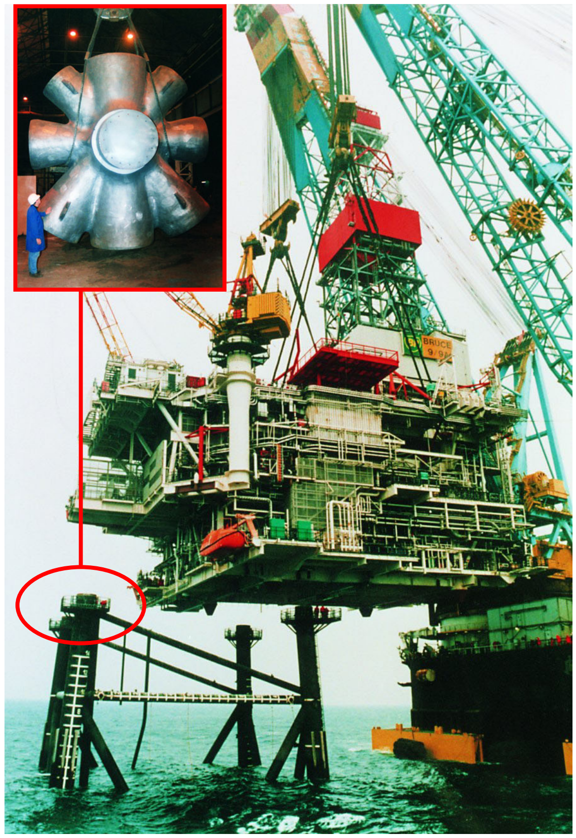

Figure 4: Cast node and offshore oil platform

PROCESS

All steel is cast. Traditional integrated mills melted ore in blast furnaces, converting blast furnace iron to steel and cast steel ingots. The ingots are rolled into plate or bar and then finally rolled into the desired structural shape. Mini-mills melt steel scrap in electric furnaces and then continuously cast the steel into bars that are directly rolled into the structural shape. Foundries melt steel scrap in electric furnaces like mini-mills but cast the steel directly to shape in molds.

Molds are made of sand held together by a binder. Molds were traditionally made of sand with clay and water as a binder but now the use of organic polymers to hold the sand together. The desired shape is first made as a pattern of wood, metal or plastic. The pattern is made oversize to compensate for the change in size of the metal cooling to room temperature. The pattern forms the mold cavity that holds the molten steel during solidification and cooling. Most molds are made in two halves, the top half is called a cope and the bottom is called the drag. The joint between the cope and drag is called the parting line. The pattern must be removed from the mold at the parting line without damage to the pattern or mold. This requires draft of about 1° on the pattern tooling, Figure 5. Draft is required in all split manufacturing methods like casting or forging. Sometimes reorientation of the shape in the mold can avoid the need for draft on some surfaces, for example an offset parting on an "L" bracket.

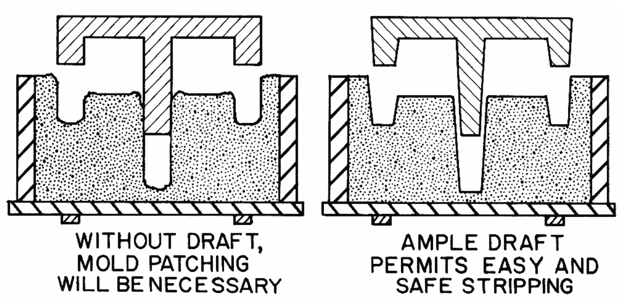

Figure 5: Proper drafting of mold

Making loose pieces of sand called cores can create features that cannot be made in the mold by the pattern, Figure 6. The use of cores in molds allows castings to be made hollow or with features that cannot be formed in the mold. Cores add cost in manufacturing, reduce the ability of the casting to hold tolerances, but may be necessary to form key features that provide the geometry designed. A design may be modified to reduce the number of cores by consolidating features, using offset parting lines or through changes in component design.

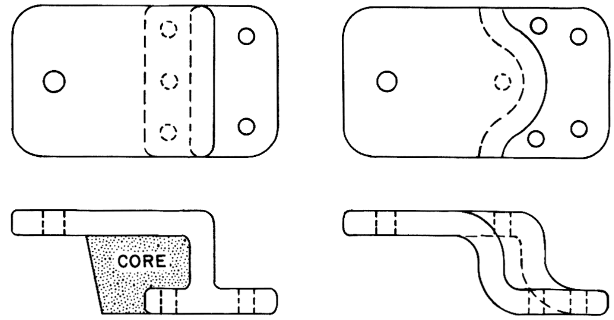

Figure 6: Casting design for core reduction

The top half of the mold must be held in position or it will float when the liquid steel is poured into the mold and the steel will run out at the parting line. The cores used to form features must also be held in place to locate the feature on the casting and to prevent the core from floating before the liquid steel solidifies. Often the core is made long to extend into the mold and the pattern is modified to create a pocket to hold the core. This pocket is called a core print and allows the foundry to remove the spent sand of the core from the casting, locates and holds the core, and allows the core feature to be inspected.

In addition to using sand to make a mold, a ceramic shell can also be utilized for the production of casting steel. This process is referred to as investment (or lost-wax) casting. A positive, or replica of the part, is made of wax. This is then dipped in a ceramic slurry several times to build up a shell. The shell is then dried and the wax is melted out in an autoclave. The cavity is now ready to be filled with molten steel. After the steel solidifies, the ceramic shell is broken away from the casting. This process is typically used for smaller parts with finer detail, ones that require no draft, and those that have complex geometries that would otherwise require extensive coring.

The mold has a flow path for the liquid steel to allow it to fill the mold cavity without damage to the mold shape or metal quality. This flow path is called a gating system. The sprue allows the liquid steel to drop into the lower parts of the mold and then gates and runners transfer the steel to the mold cavity. A typical sand mold with associated terminology is shown in Figure 7.

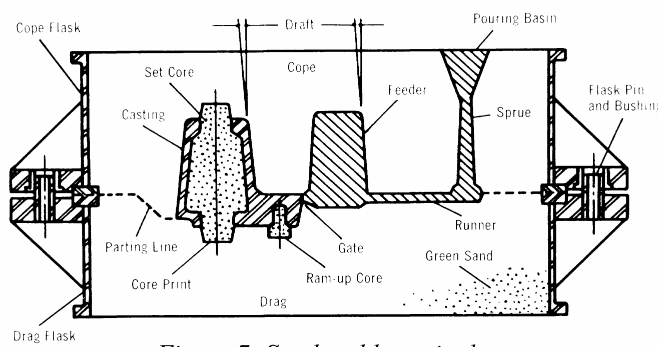

Figure 7: Sand mold terminology

When steel solidifies it shrinks. The mold must include risers to make the casting sound. A casting geometry with an isolated heavy section such as a flange or boss would have a shrinkage cavity in the center. Risers are placed on heavy sections of the casting to overcome the shrinkage in the part and hold it in the riser. It may be necessary or desirable to add taper to a section or reorient a heavy section to make sure the casting is sound, Figure 8. Castings are evaluated for soundness during design using computer simulation much like how finite element analysis is used to evaluate structures for service performance. Optimizing the design and rigging for casting the part through directional solidification will decrease cost.

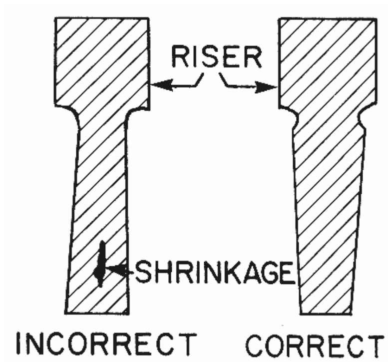

Figure 8: Directional solidification

After solidification, the casting is removed from the mold and shot blasted to remove the sand from the surface and internal cavities. The gating system and risers are cut off. The casting is heat treated to the properties desired. The casting is inspected to ensure it meets the requirements of the purchaser. Additional information on the casting process can be found in Appendix A.

MATERIAL

Many believe that cast steel is brittle because the cast iron that is commonly used in automotive and household goods, like cookware, easily cracks. However, the properties of steel are very different from iron. Steel castings can meet or exceed the ductility, toughness, or weldability of rolled steels. Technically, all steel is cast. Designers generally think of design requirements in terms of strength, but the design is commonly constrained by modulus, fatigue, toughness or ductility. Increasing the strength of steel normally reduces the ductility, toughness, and weldability. It is often more desirable in steel casting design to use a lower strength grade and increase the section size or modify the shape. The design freedom makes castings an attractive way to obtain the best fabrication and material performance and the needed component stiffness and strength.

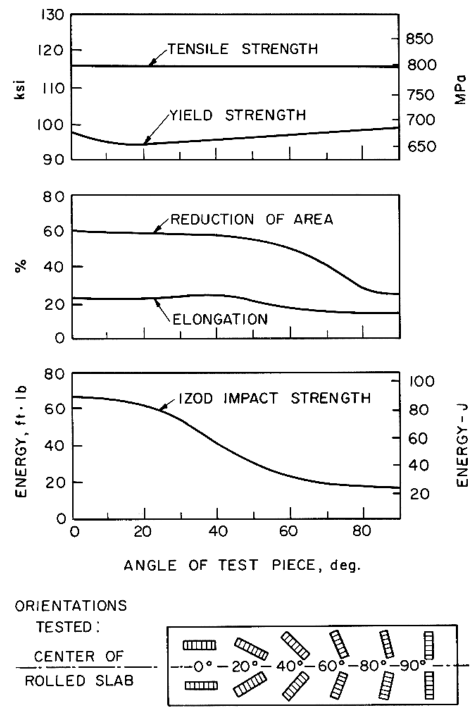

Figure 9: Orientation properties

Rolled sections of steel have their structure elongated in the direction of rolling. The strength and ductility is improved in that direction but they are reduced across the rolling direction, Figure 9. The lack of a rolling direction in steel castings gives them uniform properties in all directions. Rolling steel cold can also strengthen the steel but reduces ductility and toughness. Cast steel grades achieve the same trade off by alloying and heat treatment.

Steel castings are used in demanding applications that are safety critical, highly specified, and performance demanding. A railroad coupler is a good example of a common application that is critical. Castings are used in high-pressure service in nuclear power plants. The use of steel castings in pressure containing systems is common and specified in the ASME Boiler and Pressure Vessel Code.

One aspect of the ASME code is the requirement that suppliers develop and demonstrate a weld procedure including welded properties for the components and materials they supply. The cast carbon steels that would be used in building construction are already well known and established in the Code, including their design requirements and welded properties.

REQUIREMENTS

The biggest advantage in quality that forged or rolled shapes have over steel castings is their ability to begin with a simple optimal casting. The ingot or bar can be easily inspected prior to rolling or forging. The use of casting processes to make uniquely designed shapes requires inspection that is correlated to the casting process, part design, and performance requirements. Often the purchaser of steel castings uses nondestructive examination, mechanical testing, and engineering analysis to ensure the desired reliability.

Steel casting producers routinely test each heat of steel to make sure it meets the mechanical properties required in the material specification. The heat is also analyzed chemically to certify that it meets the standard. Other specialized tests can be required like low temperature impact testing when service performance requirements dictate. The dominant material used in building construction is carbon steel because of its reliable properties, low cost and ease of fabrication. One common grade used for building construction in rolled sections is ASTM Specifications A36. The use of steel castings is permitted in building construction using material from either ASTM A27 grade 65-35 or ASTM A148 grade 80-50 (AISC, 1998). The properties of carbon steel depend on the composition and heat treatment. Because designers use yield strength as a basic property in design, often material is ordered to higher strength without considering the advantage in castings of using a lower strength material with optimum ductility and weldability. Since the load-carrying cross-section can be increased to accommodate lower strengths, the casting can be supplied in the highest ductility with strength levels that are compatible with the rolled structural shapes. This use of cast carbon steel in its optimal condition makes sure that the casting will perform safely and reliably and that excessive loads will cause failure to occur first in the rolled section familiar to the designer. The use of ASTM A27 grade 65-35 in the normalized and tempered condition will give a strong ductile weldable steel.

Cast steel alloys are available in a wide range of options. One can increase different performance characteristics such as corrosion resistance and wear resistance through alloying and heat treatment. Mechanical properties such as strength and elongation can likewise be adjusted. ASTM A216 grade WCB offers a good option to balance strength, weldability, ductility, and cost (yield strength of 36 ksi and elongation of 22%). If a 50 ksi steel is the only factor in material selection, ASTM A954 grade SC8620 class 80/50 can be utilized (yield strength 50 ksi and elongation of 22%). For corrosion resistant applications, ASTM A743 grade CF-8M (similar to wrought 316) is a good option (yield strength 30 ksi and elongation of 30%). Since mechanical properties of a part are based on material and geometry, it is possible to design a cast steel connector with lower material yield strength than the wrought sections it connects by utilizing the geometry available through casting. This provides the added benefit of making the casting more ductile and more weldable than the wrought material. This practice is commonly used to design the casting to out live the wrought material it joins.

Traditionally, nondestructive testing has been used to certify casting quality. Soundness is verified through the use of radiographic inspection. Surface quality is evaluated using magnetic particle inspection. More recently, the use of computer simulation of solidification of the casting integrated with finite element analysis of its performance has been used to design optimal casting configurations. The development of these tools allows the designer to ensure that critical areas of the part meet requirements while ensuring the most economical means of manufacturing the whole part. Additional information covering the purchase of steel castings can be found in Appendix A. Casting design tutorials are available on the web at http://www.sfsa.org/tutorials/index.html.

DESIGN

There are six key factors in casting design (Gwyn). These factors are based on physics and govern the castings service performance, manufacturability, and cost. Understanding and utilizing these six casting factors in addition to the freedom of geometry results in cast components that excel in their applications. The first four factors are related to casting properties and include fluid life, solidification shrinkage type and volume, inclusion formation tendency, and pouring temperature. The other two factors are related to structural characteristics and include section modulus and modulus of elasticity.

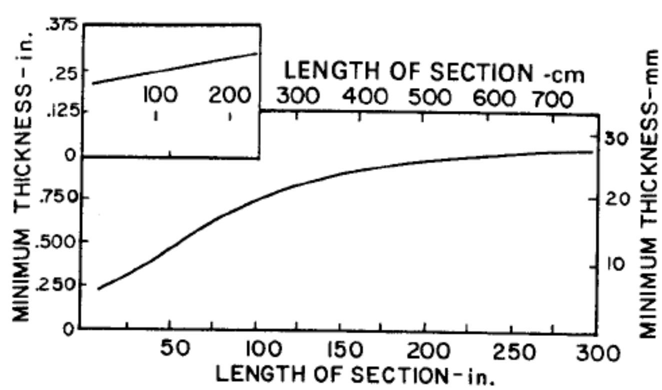

Figure 10: Minimum Thickness v. Length of Section

Fluid life refers to the dynamic change in property of the molten metal as it enters the mold. As the metal enters the mold it transfers heat, forms a skin of solidified metal, and reduces in fluidity. The characteristic is not only governed by pouring temperature but also chemistry of the alloy. Fluid life impacts the minimum section thickness, details such as lettering on surface, and transition geometry. Section thickness is governed both by the material cast and the length of section. Figure 10 shows the relationship for cast steel. Carbon and low alloy steels tend to have lower fluid life. Thus, details of the part are placed in the drag half of the mold where the liquid metal enters and is at its hottest. Cast letters on steel castings need to be larger. Softer transitions, large radii and good taper, are also utilized to maximize fluid life. This has the added benefit of having geometry that can more readily handle loads and reduces stress concentration points.

The two major forms of shrinkage in making a casting occur when the liquid changes to a solid and when the solid cools to room temperature. Both of these forms of shrinkage must be accounted for in order to achieve dimensionally accurate parts. The shrinkage in volume as the solid cools is referred to as "patternmakers contraction". The way the mold and cores are designed largely influence this. Steel shrinks at approximately ¼ inch per foot. Risers, or reservoirs of liquid metal, are required in the casting process to feed the shrinkage that would otherwise lead to shrinkage cavities in the casting. Steel has a larger amount of shrinkage and directional solidification. Directional solidification refers to the fact that steel will solidify from the further point first and work its way back to the point of origin. Therefore, if good risers and taper are incorporated into the mold design, steel castings can have good internal soundness. Geometry plays a role in solidification due to its effect on heat transfer. Thus, geometry can be used to improve solidification in a part.

Nonmetallic inclusions form from reoxidation during the melting and pouring process, and from components of refractory. Figure 11 shows steel being melted in an electric arc furnace. Nonmetallic inclusions form when air is entrained in the molten metal as it enters the mold or when the steel is moved from the furnace to pouring ladle. The oxygen in the air chemically reacts and precipitates out of the metal as an inclusion. Inclusions from refractory come from the material that is used to line the furnace or transfer vessels for pouring the steel. Steel has a moderate tendency to form inclusions. It is also important to make certain the metal enters the mold in with minimum turbulence. Turbulence in the liquid metal causes more air to be entrained and results in additional inclusions. Good gating design along with smooth casting geometry reduce turbulence. Inclusions can be minimized through good foundry practices.

Figure 11: Electric Arc Furnace Melting Steel

Pouring temperature is simply the temperature of the liquid metal when it is poured into the mold. Higher melting point metals like steel are more aggressive on refractories and start to approach the limit of the sand mold materials. Steel is typically poured at temperatures a little under 3000F. Heat transfer impacts how the part will solidify.

Design engineers typically design parts based on allowable stress and deflection. Both the stress and deflection capabilities of a part are governed by the geometry. Bending stress, torsional shear, and deflection calculations are all based on the area moment of inertia of the cross section. Therefore, utilizing clever geometry can yield a part that is capable of meeting specified mechanical requirements. Designing cross sections as I-beams or C-channels utilize geometry to increase strength and reduce deflection. Figure 12 shows how different cross sections provide different maximum stresses for a sample part. Note, that the "omega" cross section design handles stresses second best to the solid shape. It is easy to cast omega geometry versus trying to create this as a fabrication, utilizing this geometry reduces both weight and cost. Steel is a very robust material and doesn't necessarily require a lot of geometry to help make the part perform at the desired level. However, one can make use of steel's excellent mechanical performance by making innovative cast parts that can absorb shocks or severe loading.

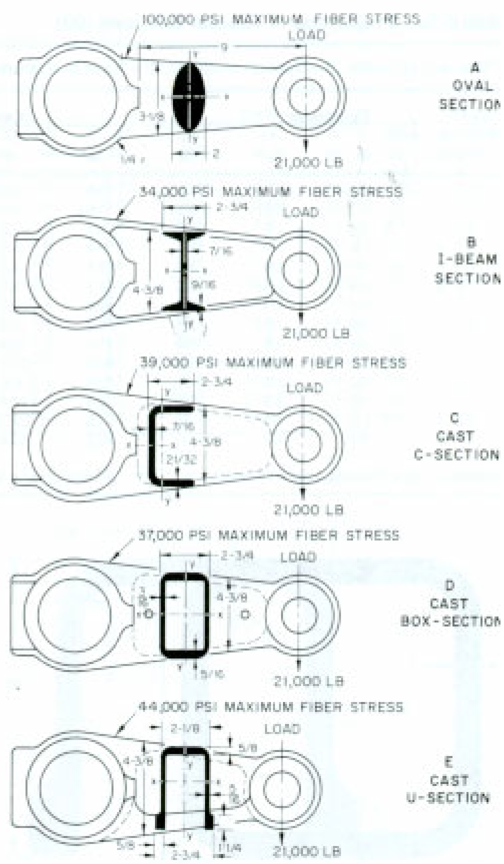

Figure 12: Cross Section Impact on Stress

The modulus of elasticity is based solely on the material itself. It is based on the type of alloy and its metallurgy. Heat treatment does not affect modulus; it does affect the yield strength. Steels have a modulus around 30 x 10^6 psi, which puts them near the top compared to other metals. The larger the modulus the smaller the deflection of a part.

From the six casting design factors, some general rules of thumb can be deduced. First, if isolated heavy sections are required to meet form/fit/function, then these sections will need to be fed. Figure 13 shows isotherms or the areas that would be last to solidify and therefore could have shrinkage cavities. The formation of isotherms also demonstrates how it is desirable to have these areas in the risers as these are not part of the final part and are removed. Junctions within a casting should be designed not to add mass. Figure 14 shows how to design junctions in castings. If a junction is required, tapering the section, adding feeding to the section, or dimpling the area can all be leveraged to ensure a sound casting. Changing section thickness in a casting is best handled with smooth, easy transitions. As seen in Figure 15, adding taper and having a large radius help to accomplish this. Reducing the number of undercuts and other sections that would require cores helps to minimize cost. Specifying as-cast tolerances when allowable is also important for minimizing cost. Related to this, considering what other post-processing will be required and how it will be fixtured also influences final cost of the part. Working directly and concurrently with a foundry will ensure a part is optimized for both casting and the end use.

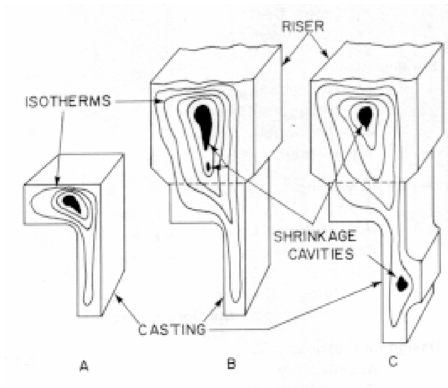

Figure 13: Isotherm Locations

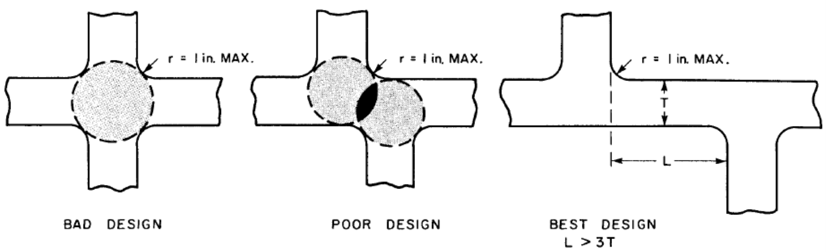

Figure 14: Cast Junction Design

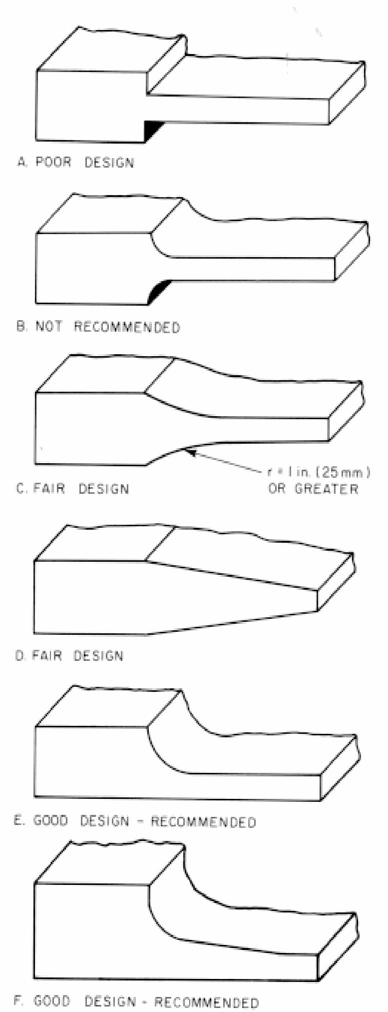

Figure 15: Transition Geometry

CONSTRUCTION

Steel castings have been shown to be capable of demanding service in building construction. One example is the development of a modular connection by the ATLSS program at LeHigh, Figure 16. A self-aligning beam to column connection was designed to improve safety and productivity in erection. This self-aligning connection used a wedge shaped extension on the beam that slid into a wedge shaped slot on the column. The manufacture of the complex wedge and slot was accomplished with steel castings. The ATLSS connection was subjected to full-scale mechanical performance tests. When loaded beyond the design requirement, it finally deformed plastically and did not fail catastrophically. Additional information on the test and the results can be found in the reference (Fleischman, 1993).

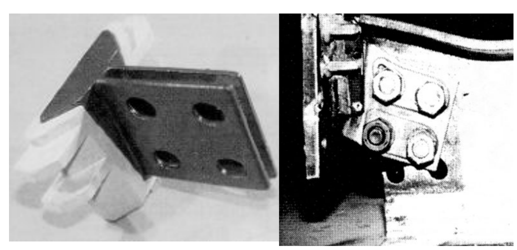

Figure 16: ATLSS connector and test

A gusseted reinforced "L" bracket was designed as a carbon steel casting and was tested for earthquake retrofitting of damaged and undamaged structures in California, Figure 17. The connection was designed by ICF Kaiser to be installed where welds had failed by bolting it to the bottom of the beam column connection. A prototype was cast, tested, and approved by the State of California. The test demonstrated that the cast connector would survive the maximum load required. Additional information on the test and the results can be found in the reference (Bleiman).

Figure 17: ICF Kaiser bolted connection and test

An example of steel casting advantages for high performance complex connections is shown in some recent work by Robert Fleischman at the University of Arizona for designing seismic connectors (Fleischman, 2002). Since castings can have non-uniform walls and contain complex features, they can be designed to locate the strain deformation of a loaded structure. A cast modular node was produced that looks nominally like a reinforced welded connection. In reality, the casting process allows the intersection of the beam and column to be increased and the column and panel section tailored to absorb the deformation with little transferred load to the beam or column. The welds can be made outside of the node and high stress region. This Panel Zone part, as-cast and after test, is shown in Figure 18. The Panel Zone part is designed with a weaker panel section that facilitates energy dissipation. The challenge is to limit the plastic deformation of the panel section otherwise curvature or kinking with occur in the columns. "Dog bone" features were incorporated into the part to allow for deflection within the node and at controlled locations. Cast geometry efficiently provides the functionality of the part. A graph of the FEMA cyclic test is shown in Figure 19.

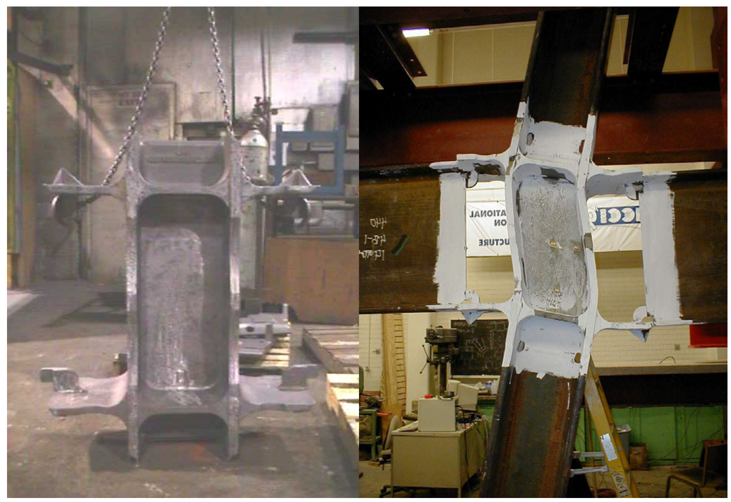

Figure 18: Panel Zone seismic connector and test

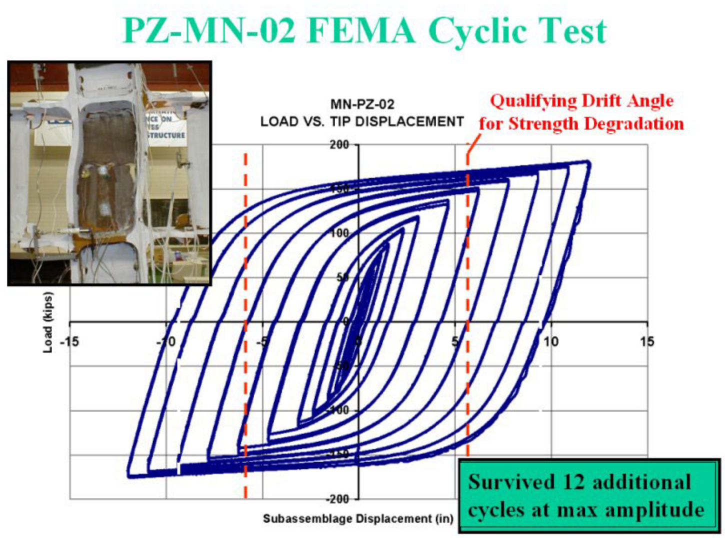

Figure 19: Panel Zone FEMA test results

A cast Modular Connector (MC) was also developed and evaluated using finite element modeling and casting solidification simulation to provide an effective design. The casting prototype for the cast modular node is shown in Figure 20. A full size test subassembly was fabricated and subjected to the Federal Emergency Management Agency (FEMA) – 350 cyclic test protocol. The cast modular node exceeded the requirement greatly as can be seen in Figure 21. Note, after being taken to failure, which was well beyond test requirements, the casting failed in a ductile manner. The MC design allows for the cast connector to absorb energy and has a higher capable load strength compared to a standard connection with a bigger bolt because it mitigates prying forces. As with the PZ part, “dog bone” geometry is used to control the location and amount of yielding.

Other regions of the world are already using cast components to achieve unique structures. Dave Eckmann of OWP&P Architects provided two examples. Figure 22 shows a cast node for tubular HSS that is welded into a structure. A complex cast base is shown in Figure 23. Castings for both tubes and nodes were used to make the lattice structure that support the Bush Lane House in London, Figure 24. In this case, castings made from a stainless steel provide a corrosion resistant structure. The freedom of manufacturing different sized cast components based upon the location of use provided a cost savings compared to fabrication. There have also been a few applications in the United States. The Crystal Cathedral in California used cast nodes for their weldability and mechanical properties.

Figure 20: Cast modular connector

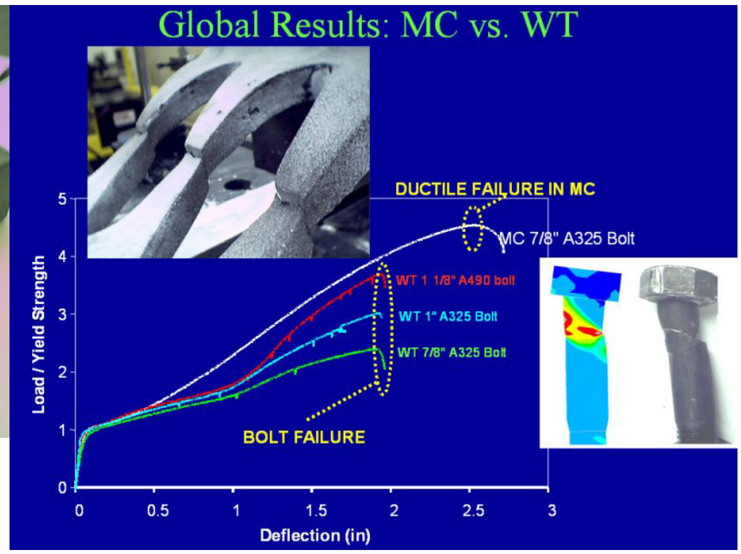

Figure 21: Test results for modular connector

Figure 22: Stuttgart Stadium

Figure 23: Stuttgart Tower

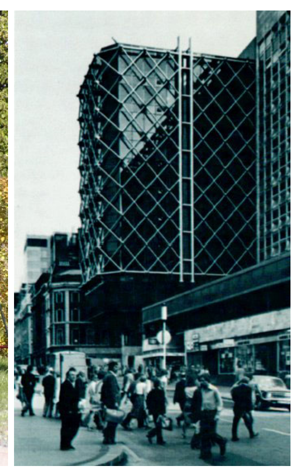

Figure 24: Bush Lane

The AISC/SFSA task committee has started to compile potential applications for castings in building construction. Identified applications include: HSS to W shape connectors, HSS nodes, W shape nodes, steel frame to concrete core connectors, plane or space truss connectors, column bases, seismic details, bridge splices, roof davits, details for blast/impact resistant structures, turnbuckles, clevises, pin connections, and cable clamps. Additional parts and architectural applications will continue to be reviewed.

CONCLUSION

Steel casting may provide new opportunities for lower cost, improved performance, and unique designs. The ability to make complex shapes repetitively can allow the design of modular connectors that are reasonable in cost, and reduce shop and erection costs. The ability to tailor geometry, customize steel properties, and integrate castings by welding allows improved performance. The freedom of geometry, size and complexity allows the designers flexibility that is unprecedented. Steel castings offer architectural and structural flexibility that will challenge building designers' imagination.

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APPENDIX A

Overview

When making inquiries or ordering parts, all pertinent information must be stated on both the inquiry and order. This information should include all of the following components.

1. Casting shape – either by drawing or pattern. Drawings should include dimensional tolerances, indications of surfaces to be machined, and datum points for locating. If only a pattern is provided, then the dimensions of the casting are as predicted by the pattern.
2. Material specification and grade (e.g. ASTM A 27/A 27M – 95 Grade 60-30 Class 1).
3. Number of parts.
4. Supplementary requirements (e.g. ASTM A 781/A 781M – 95 S2 Radiographic Examination).
    a. Test methods (e.g. ASTM E 94)
    b. Acceptance criteria (e.g. ASTM E 186 severity level 2, or MSS SP-54-1995).
5. Any other information that might contribute to the production and use of the part.

To produce a part by any manufacturing process it is necessary to know the design of the part, the material to be used and the testing required. These three elements are discussed in detail in the following sections.

Background

To obtain the highest quality product, the part should be designed to take advantage of the flexibility of the casting process. The foundry must have either the part drawing or pattern equipment and know the number of parts to be made. To take advantage of the casting process, the foundry should also know which surfaces are to be machined and where datum points are located. Reasonable dimensional tolerances must be indicated where a drawing is provided. Tolerances are normally decided by agreement between the foundry and customer. SFSA Supplement 3 represents a common staring point for such agreements. Supplement 3 is not a specification and care should be taken to reach agreement on what tolerances are required. Close cooperation between the customers' design engineers and the foundry's casting engineers is essential, to optimize the casting design, in terms of cost and performance. Additional guidelines for casting design are given in "Steel Castings Handbook" and Supplement 1,3, and 4 of the "Steel Castings Handbook".

Minimum Section Thickness

The rigidity of a section often governs the minimum thickness to which a section can be designed. There are cases however when a very thin section will suffice, depending upon strength and rigidity calculations, and when castability becomes the governing factor. In these cases it is necessary that a limit of minimum section thickness be adopted in order for the molten steel to completely fill the mold cavity.

Molten steel cools rapidly as it enters a mold. In a thin section close to the gate, which delivers the hot metal, the mold will fill readily. At a distance from the gate, the metal may be too cold to fill the same thin section. A minimum thickness of 0.25" (6 mm) is suggested for design use when conventional steel casting techniques are employed. Wall thickness of 0.060" (1.5 mm) and sections tapering down to 0.030" (0.76 mm) are common for investment castings.

Draft

Draft is the amount of taper or the angle, which must be allowed on all vertical faces of a pattern to permit its removal from the sand mold without tearing the mold walls. Draft should be added to the design dimensions but metal thickness must be maintained.

Regardless of the type of pattern equipment used, draft must be considered in all casting designs. Draft can be eliminated by the use of cores; however, this adds significant costs. In cases where the amount of draft may affect the subsequent use of the casting, the drawing should specify whether this draft is to be added to or subtracted from the casting dimensions as given.

The necessary amount of draft depends upon the size of the casting, the method of production, and whether molding is by hand or machine. Machine molding will require a minimum amount of draft. Interior surfaces in green sand molding usually require more draft than exterior surfaces. The amount of draft recommended under normal conditions is about 3/16 inch per foot (approximately 1.5 degrees), and this allowance would normally be added to design dimensions.

Parting Line

Parting parallel to one plane facilitates the production of the pattern as well as the production of the mold. Patterns with straight parting lines, parting lines parallel to a single plane, can be produced more easily and at lower cost than patterns with irregular parting lines.

Casting shapes that are symmetrical about one centerline or plane readily suggest the parting line. Such casting design simplifies molding and coring, and should be used wherever possible. They should always be made as "split patterns" which require a minimum of handwork in the mold, improve casting finish, and reduce costs.

Cores

A core is a separate unit from the mold and is used to create openings and cavities that cannot be made by the pattern alone. Every attempt should be made by the designer to eliminate or reduce the number of cores needed for a particular design to reduce the final cost of the casting. The minimum diameter of a core that can be successfully used in steel castings is dependent upon three factors; the thickness of the metal section surrounding the core, the length of the core, and the special precautions and procedures used by the foundry.

The adverse thermal conditions to which the core is subjected increase in severity as the metal thickness surrounding the core increases and the core diameter decreases. These increasing amounts of heat from the heavy section must be dissipated through the core. As the severity of the thermal condition increases, the cleaning of the castings and core removal becomes much more difficult and expensive.

The thickness of the metal section surrounding the core and the length of the core affect the bending stresses induced in the core by buoyancy forces and therefore the ability of the foundry to obtain the tolerances required. If the size of the core is large enough, rods can often be used to strengthen the core. Naturally, as the metal thickness and the core length increase, the amount of reinforcement required to resist the bending stresses also increases. Therefore, the minimum diameter core must also increase to accommodate the extra reinforcing required.

The cost of removing cores from casting cavities may become prohibitive when the areas to be cleaned are inaccessible. The casting design should provide for openings sufficiently large enough to permit ready access for the removal of the core.

Internal Soundness/Directional Solidification

Steel castings begin to solidify at the mold wall, forming a continuously thickening envelope as heat is dissipated through the mold-metal interface. The volumetric contraction which occurs within a cross section of a solidifying cast member must be compensated by liquid feed metal from an adjoining heavier section, or from a riser which serves as a feed metal reservoir and which is placed adjacent to, or on top of, the heavier section.

The lack of sufficient feed metal to compensate for volumetric contraction at the time of solidification is the cause of shrinkage cavities. They are found in sections that, owing to design, must be fed through thinner sections. The thinner sections solidify too quickly to permit liquid feed metal to pass from the riser to the thicker sections.

Machining

In the final analysis, the foundry's casting engineer is responsible for giving the designer a cast product that is capable of being transformed by machining to meet the specific requirements intended for the function of the part. To accomplish this goal a close relationship must be maintained between the customer's engineering and purchasing staff and the casting producer. Jointly, and with a cooperative approach, the following points must be considered.

1. The molding process, its advantages and its limitations.
2. Machining stock allowance to assure clean up on all machined surfaces.
3. Design in relation to clamping and fixturing devices to be used during machining.
4. Selection of material specification and heat treatment.
5. Quality of parts to be produced.

Layout

It is imperative that every casting design when first produced be checked to determine whether all machining requirements called for on the drawings may be attained. This may be best accomplished by having a complete layout of the sample casting to make sure that adequate stock allowance for machining exists on all surfaces requiring machining. For many designs of simple configuration that can be measured with a simple rule, a complete layout of the casting may not be necessary. In other cases, where the machining dimensions are more complicated, it may be advisable that the casting be checked more completely, calling for target points and the scribing of lines to indicate all machined surfaces.