For those who understand cast steel, it offers an interesting and useful structural option; here is what you need to know to take advantage of this alternative.

Steel Castings for AESS and Beyond

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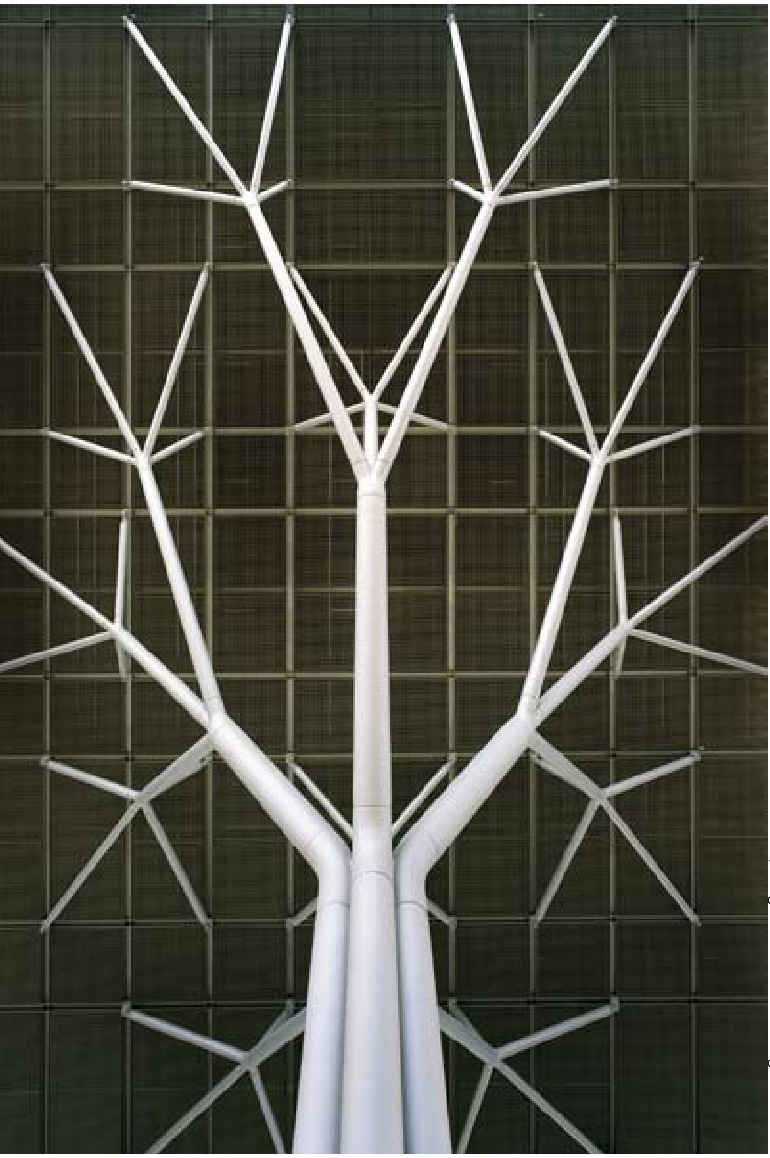

Architekten von Gerkan, Marg and Partner and Juergen Schmidt

ACROSS NORTH AMERICA, one of the hottest new trends in steel construction is the use of steel castings—and not just tiny "spider" fixtures for glass, nor fittings for cable or rod systems. We're talking heavily loaded, yet sleek and streamlined steel castings that are being implemented in the primary structural systems of buildings from Boston to San Francisco. And although castings are proven solution providers for fatigue-critical connections and for complex, heavily loaded structural connections in both static and seismic load carrying applications, steel castings are getting a lot more *exposure* these days in architecturally exposed structural steel (AESS).

The reason for the increased use of castings, particularly in AESS, has a lot to do with the ability of castings to provide smooth, tapering and curving geometries in structural steel—geometries that would otherwise be difficult, if even possible to achieve at all, using conventional steel fabrication. Architects in particular are frequently eager to implement cast steel components in their AESS constructions, and engineers and steel fabricators should not shy away.

Steel castings can be integrated seamlessly into any steel frame, providing curving, smooth transitional geometries between attaching structural elements and causing the finished construction to appear as if it were constructed as a single, monolithic form. Or, the cast elements can be cast with reveals or emphasized through shaping to highlight the node and draw the eye to the detail. Castings can be used to mate between various materials (like steel to timber), various structural steel shapes, or to solve complex engineering challenges. From elegant off-the-shelf clevis-type connectors for hollow structural section (HSS) columns, struts, ties or braces, to earthquake-resistant brackets and brace connectors, to custom nodes that can weigh anywhere from tens to thousands of pounds, the possibilities are virtually endless.

In this roof-supporting structure in Terminal 3 of the Stuttgart Airport, the cast steel nodes include a recessed reveal that highlights the nodes.

When Should Steel Castings Be Considered?

There isn't a single rule of thumb that can be applied in determining the suitability of custom castings in a given project. As with all special structural and architectural solutions, the benefits should be weighed against the costs in each circumstance. The costs associated with casting manufacturing stem from the structural engineering and shaping of the component, casting process engineering (gating and tooling design), the manufacturing of casting tooling, machining and machining tooling (where machining is required), and ultimately the production of the components and their integration into the structural steel frame. While conventional structural steel connections also require engineering, detailing and fabrication, the additional cost of tooling and specialty engineering means that engineers shouldn't expect customized castings to be suitable in every situation. Nevertheless, there are many circumstances where the use of steel castings will be less costly than conventionally fabricated connections, or where the premium that may be required to cast connections rather than fabricate will be well worth the benefits, which can include improved connection stiffness, strength, fatigue resistance, aesthetics, LEED credits for 100% recycled content, and simplified fit up, fabrication, erection and more.

In general, castings may be appropriate in any of the following circumstances. The suitability of castings is increased in situations where more than one of these conditions applies:

- ➤ Complex connections (i.e., with incoming members at different angles).
- ➤ Connections subject to very high loading, where large welds are required but would be difficult to apply and inspect.
- ➤ Architecturally exposed joints, particularly for HSS connections.
- ➤ Fatigue critical connections.
- ➤ Repetitive details.

Material Properties

The foremost misconception regarding steel castings is that they are brittle. This is not the case—cast *steel* is not cast *iron*. All steel, even hot-rolled or cold-formed structural steel shapes, starts its life as cast steel. The main difference between standard structural steel shapes and steel castings is that hot-rolled or cold-formed products attain their yield strength through the rolling or forming processes, whereas steel castings are heat treated to attain the desired mechanical properties. In practice, this means that steel castings are isotropic and have no residual stresses—this is not the case with rolled shapes—and steel castings are just as ductile as rolled steel products, and can be more ductile. In a normalized condition, low alloy steel castings can be readily produced with yield strengths in the range of 30 to 40 ksi. With quenching and tempering, yield strengths of 50 ksi and greater can be attained. In Europe, a process called secondary heat-treatment is now being used to attain yield strengths as high as 150 ksi in castings to be used in special structural applications, like for rope heads in cable stayed bridges.

Another misconception is that steel castings are not weldable. Again, this comes from incorrectly drawn parallels to cast iron. Cast steel grades can be selected for any number of mechanical properties, including weldability. For example, AISC 360-10 lists ASTM A216 Grade WCB with Supplementary Requirement S11 as a cast steel grade useful for steel structures. For that specification and grade, the supplementary requirement sets the maximum carbon equivalent for the material at 0.50, which provides adequate

Stahlbau, courtesy of John Wiley and Sons

▲ Cast steel node for fatigue-critical wind turbine support structure.

▼ Steel castings used to integrate AESS and timber members.

Fast+Epp and Structure Craft, Nic Lehoux

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Other examples of steel castings used to integrate AESS and timber members.

Fast+Epp and Structure Craft

Cast steel rockers in the Beijing Poly Plaza simultaneously support the world's largest cable-net glass wall and a suspended eight-story museum, which protrudes through the glass wall. The cast steel rocker effectively works like a pulley, decoupling the cables from the building's lateral system.

weldability. That said, it should be noted that there are currently no cast steel grades listed as prequalified base metals in AWS D1.1, and as a result, welding procedure specifications must be qualified whenever castings are to be welded. Preheating is required for welds applied to very thick castings and good welding practices for quenched and tempered materials should be employed when quenched and tempered cast steel grades are specified.

Structural Design, Design Documentation and Specifications

The AISC *Specification* references steel castings and lists one cast steel grade that is useful for steel structures, although there are many other cast steel grades that are suitable for structural use. The commentary on the *Specification* notes that non-destructive testing should be considered for cast steel products, and suggests that users reference the Steel Founders' Society of America's *Steel Castings Handbook* for design information. In sum, although castings are referenced in the *Specification*, there is very little guidance provided on the adequate design and non-destructive examination of steel castings for structural applications.

What's more, if you've ever called a foundry for design support, you probably quickly learned that most steel foundries don't engage in casting design. That's because foundries are typically staffed with metallurgists and process engineers, not structural engineers, and they are most used to interacting with mechanical engineers who have been taught how to design castings simultaneously for both their end use and for casting manufacturing. However, there are firms that specialize in the structural design and supply of steel castings for use in steel structures (like AISC member Cast ConneX, for example), and more engineering firms are building the in-house expertise required to design steel castings.

Considering and Using Castings

The most common mistake made by structural engineers venturing into the design of steel castings for the first time is to try to convert a design for a fabricated connection directly into a casting—the design of steel castings is as much of an art as is the design and detailing of fabricated structural steel connections. Custom steel castings should be designed simultaneously for their end use and for casting manufacturing. While most geometric forms can be cast, the highest quality and most economical castings are those that can be molded with the fewest parting lines, those requiring the fewest cores, and those designed to promote directional solidification or that include other provisions for feeding liquid metal into the part as it solidifies.

In practice, modern steel casting design is almost exclusively done in 3D with the aid of solid modeling software. In addition to 3D models, casting design drawings showing standard views and critical sections of the part must be produced to communicate critical dimensions and allowable tolerances.

Casting drawings are not standard structural drawings—they must show more information than typically called out on a steel framing plan, elevation or detail. Today, the 3D models of the part are often directly used for the CNC-production of casting tooling.

For each project, specifications must be developed which cover all aspects of casting manufacturing, including but not limited to: cast steel process requirements, steel grade (including chemistry, heat treatment, and mechanical properties like material strength and toughness), non-destructive examination requirements, surface finish, tolerances and machining requirements. Note that being overly prescriptive or setting requirements that conflict (like a very high yield strength with a very low carbon equivalent requirement, for example) may result in unnecessarily expensive cast components; this is where interaction with the foundry is critical.

In terms of non-destructive testing, "first article" components (the first parts cast from a new mold) need be more heavily scrutinized than production components. Modern steel foundries use highly sophisticated simulation software to design and optimize the gating and feeding of new cast steel components, and correlation between the predicted and actual soundness of cast parts is quite good. Regardless, first article components are typically radiographically tested to prove the gating design, and production com-

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▲ A 1:20 scale 3D print of the 35,000-lb cast steel node developed by AISC member Cast ConneX for the 70-ft-tall AESS Delta Frame structures for the proposed Queen Richmond Centre West, Toronto, Ontario.

◄ Off-the-shelf, clevis-type HSS connectors were used at the New Jersey Air National Guard Operation and Training Facility. The Universal Pin Connectors from Cast ConneX are offered in outside diameters from 4 in. to 16 in. and come with all of the associated hardware, including stainless steel cap plates, cap screws, and washers and the carbon steel, load bearing pin.

ponents are typically subjected to visual examination and magnetic particle and ultrasonic testing to identify surface and subsurface defects that exceed acceptable standards. The acceptance level for the various non-destructive test methods should be commensurate with the level of stress in the various regions of the component—lowly stressed regions of a casting need not be as heavily scrutinized as, say, thinner extremities where attaching elements impart higher stresses. Again, engineering judgement is a key to specifying cost effective, high-quality cast steel structural parts.

Surface quality is another issue that should be addressed in specifications for AESS castings. Generally speaking, the as-cast surface finish of a casting has the appearance of an orange peel, with varying degrees of uniformity and roughness based on the casting process. Whether the as-cast surface is suitable or whether additional surface finishing is appropriate for AESS castings is based on a number of factors, including casting process, steel coating (single-coat paint, multi-coat or high-build systems, intumescent coatings, etc.), in-situ viewing distance and AESS category.

Structural Analysis

Given the geometric forms that casting manufacturing allows, typical design equations for steel connections rarely apply to castings. As a result, structural analysis of cast steel nodes or connections often necessitates the use of numerical finite element (FE) analysis to determine the 3D stresses and strains that develop in the steel casting under the application of various load combinations. There are a number of software applications capable of carrying out FE stress analysis; however, very careful consideration must be given to boundary conditions, loading assumptions, element type, meshing method, mesh density, and analysis type when generating and running the FE analysis model. FE software will always generate output provided that equilibrium can be achieved in the model; the output is meaningless, however, if the user has made inappropriate assumptions in their numerical model.

For example, because applied loading is also a boundary condition, modelling the cast element in complete isolation may impose unrealistic strain distributions. In so doing, users may miss undesirable phenomena like shear-lag, which may be present at critical welded joints between the casting and the other structural steel elements. As always, paired with careful modeling and analysis must come sound engineering judgement. A final note on FE analysis is that it is well established that the results of such analyses are sensitive to mesh density and element type, particularly in the vicinity of elevated stress gradients, so the use of sensitivity analyses is recommended when relying on FE results to confirm the adequacy of a casting design.

Bringing it all together

The importance of coordination between the various design professionals and between the designers and steel contractor is well established, and the lines of communication are continually being improved, particularly through the use of BIM platforms. Most BIM software packages, including Revit, Tekla, and SDS/2 for example, offer the ability to import a wide range of file types and can thus accommodate the incorporation of the 3D model of the cast steel elements directly into the architectural and/or steel detailing models. Additionally, most of the 3D solid modeling applications suitable for the shaping of complex 3D forms (like CATIA, SolidWorks, and Rhinoceros, for example) support online viewing portals or email-friendly visualization applications that offer the ability to easily share and collaborate on the visually critical exterior shaping of the casting.

Another tool that can be used to better convey the architectural consequence of various design options is rapid prototyping, more commonly referred to as 3D printing. This offers the ability to quickly (and now fairly cost effectively) produce scale models of either the full AESS construction or of simply the cast steel element. These tools help produce better integrated designs, which is important when incorporating steel castings in AESS, where the castings must be everything to everyone—structurally adequate, architecturally appropriate, readily integrated with conventional structural elements, economical and castable. MSC