ABSTRACT: Cast steel nodes have been used for some time in offshore steel structures and recently there has been a resurgence of interest in steel castings for onshore tubular structures. This has taken place principally in Europe, where cast nodes have now gained acceptance in road and railway bridges that are susceptible to fatigue. In North America, the potential for revival of steel castings in onshore construction has just been realized. Tubular structures, in particular, are an ideal application and castings can provide viable solutions to tubular connection design problems, particularly under seismic and fatigue loadings. A summary of Canadian experience with cast steel nodes is given, including descriptions of both an in-progress project involving cast steel nodes used for a tree-like roof supporting structure at the University of Guelph, Ontario as well as current research being carried out at the University of Toronto on cast steel connectors for tubular hollow sections which are subjected to cyclic inelastic loading.

1 INTRODUCTION

Steel castings are rarely used in conventional building construction in North America. Even in Europe, significant use of castings is typically reserved for high profile buildings where the desire for architectural flair is the driving force behind the building’s design. Castings have had greater success in the European bridge industry, where castings can be found in many pedestrian, highway, and railroad bridges, particularly where hollow structural sections (HSS) have been used (Veselcic et al. 2003). In the offshore construction industry, castings have been used extensively since the early 1980s, where they represent an enormous improvement to welded connections in tubular steel offshore platforms.

There is justification for the successful use of castings in these situations - the casting process allows for almost any shape to be manufactured and, unlike wrought steel, cast steel is isotropic in strength and toughness. This makes the use of castings ideal in fatigue critical applications, particularly when regions of geometric complexity coincide with the heat-affected zone of a weld. In these cases, the use of a cast steel node relocates the weld to a region of lower stress and improves transitional geometry, both of which significantly reduce stress concentrations and greatly improve the fatigue life of the connection (Lomax 1982).

The manufacture of unique cast steel connections is typically cost prohibitive; cost savings realized from the use of castings are primarily derived from savings in fabrication cost for highly complex geometry and in high repetition. Thus, it has been shown that the use of castings in typical onshore tubular structures should be restricted to those situations where aesthetics are a main concern (Glijnis et al. 2003). However, it is still believed that the use of castings can provide cost savings in structures where a complex connection is repeated a number of times. Further, when a connection is subjected to cyclic inelastic loading, the use of a cast steel seismic fuse can provide improved energy dissipation (Fleischman et al. 2004).

2 CANADIAN EXPERIENCE WITH STEEL CASTINGS

2.1 CDP Capital Centre, Montréal, Québec

Canadian experience with steel castings in building construction is limited. It is believed that only one Canadian building structure, the CDP Capital Centre located in Montréal, Québec, features significant use of structural castings. Completed in 2003, this building’s eight-storey open atrium features a glass façade that is supported by tubular steel trusses. The trusses incorporate cast steel nodes (Figure 1) that were cast at the foundry Métallurgie Castech Inc., Thetford Mines, Québec.
With this limited experience, Canadian structural engineers are hesitant to specify steel castings in building construction. Many engineers wrongly assume that cast steel exhibits the same brittle response as cast iron. There is also the misconception that all castings exhibit critical defects and are unsafe for structural use. While defects can occur during casting solidification, modern software packages allow the foundry to simulate fluid flow and solidification of the molten steel within the casting mould. This enables the foundry to greatly reduce the likelihood of developing a defect within the casting. Many Canadian structural engineers are unaware of the modern foundry’s capability of producing sound and reliable castings that can be produced to conform to a wide range of standards for mechanical properties.

2.2 New Science Complex at the University of Guelph, Ontario

Construction of the New Science Complex (Phase 2) at the University of Guelph began in March 2005. Designed by Robbie/Young & Wright Architects, the Science Complex will provide new laboratory and research space for chemical and biological sciences. Completion of the project is set for spring 2007.

The complex includes an open atrium featuring a glass roof supported by a single tree-like structure, a rendering of which is shown in Figure 2. The tree is approximately 25 m in height and will be fabricated using HSS welded to cast steel nodes at the tree’s branching points. Each cast steel node is approximately 1 metre in height and depth and weighs up to 1.1 tons.

The steel fabricator, Walters Inc. (Hamilton, Ontario, Canada), was responsible for the design of the connections. Although aesthetics were the driving force behind the decision to use cast steel nodes rather than weld-fabricated connections, machining the nodes from stock steel as well as using laminated profiled plates were options that were also considered but were ruled out due to excessive cost.

Design of the nodes began with the creation of suitable and aesthetically pleasing exterior geometry. Connector wall thickness was then optimized to ensure a safe but also economical design using finite element stress analysis. Stress analysis was carried out using the finite element software package CATIA ME2. Due to the complexity of the shape, free meshing using tetrahedral elements was employed. In addition to the branching point, 300 mm long flanges, representing short lengths of the attached hollow structural sections, were included in the model to ensure realistic load transfer into the casting (Figure 3).

Boundary conditions for the finite element model consisted of fixing the end of the lower trunk-flange and equally distributing the applied loads from each upper branch to the ends of the respective branch flanges. Loading of the cast node was based on both design loads as provided by the structural engineer as well as the condition that the node be stronger than the connected HSS to ensure member rather
than "connection" failure. As all stresses had to remain below or just reach yield stress, linear elastic stress analysis was sufficient.

Initial wall thickness for each node was chosen based on the results of the finite element stress analysis. As is typical in the design of castings, solidification analysis carried out by the foundry revealed a need to increase the initial wall thickness toward the base of each of the nodes to facilitate directional solidification. Final node wall thickness varied from 25.4 mm (top branching point) to 63.5 mm (bottom branching point).

German foundry Friedrich Wilhelms-Hütte GmbH, Mülheim an der Ruhr was selected to produce the cast steel nodes. Friedrich Wilhelms-Hütte has great experience with structural castings, providing high fabrication standards and offering a wide range of material and structural testing of their products. Test procedures included non-destructive testing (visual, ultrasonic, liquid penetrant, and magnetic particle examination) as well as tensile, bending, and notch toughness (Charpy) testing of the cast material.

Walters Inc. specified a cast material based on ASTM A27 (2005a) Grade 70/40, slightly modified to improve the material’s weldability (lower carbon and silicon content were specified to eliminate the need for weld preheating). Ultimately, the material utilized for the castings was G20Mn 5 N according to EN 10213-3 (CEN 1996). For a thickness up to 50 mm, G20Mn 5 N has a specified minimum yield strength of 300 MPa and an ultimate strength of 500 MPa, which is similar to the prescribed strength of typical HSS in Canada. The actual yield and ultimate strengths of the casting are 401 MPa and 580 MPa respectively, as indicated by the foundry’s tensile testing of coupons cast from the same heat as that of the nodes. The measured notch toughness of the cast material was 117 J at room temperature.
3 NEW RESEARCH: CAST STEEL SEISMIC CONNECTORS FOR TUBULAR BRACES

3.1 Background

Concentrically braced frames (CBF) are an efficient means of providing lateral support in low- and medium-rise steel structures. By specifying simple shear connections throughout the structure, fabrication cost and erection time are both greatly reduced in comparison to other structural systems. The nature of the bracing system, typically consisting of several diagonal braces located intermittently throughout the structure, allows for great design versatility and erection simplicity. Design flexibility is further increased by the variety of concentric brace configurations that are at the designer’s disposal.

The diagonal brace members of a CBF are subjected to either compression or tensile forces with the application of lateral load on the structure, which can be induced by wind pressure or ground motion. Typical bracing members include but are not limited to angles, double angles, rectangular (RHS) and circular (CHS) hollow sections. HSS are a particularly popular selection for lateral bracing members because of their efficiency in carrying compressive loads, their improved aesthetic appearance, and because of the wide range of section sizes that are available.

In the event of a design level earthquake, brace members experience cyclic inelastic loading, repeatedly yielding in tension and buckling in compression, thereby dissipating seismic energy. Recent seismic events have shown the susceptibility of slotted tube to gusset connections to brittle connection failure (Tremblay et al. 1996). Initially, CHS were considered best suited for seismic brace applications due to their improved inelastic response over RHS tubes owing to the reduced degree of cold working involved in their manufacture. However, connection issues relating to net section fracture at gusset connections led to the increased use of RHS braces for reasons associated with ease of connection reinforcement. Thus, modern CBFs feature RHS braces with connections that are significantly reinforced; as a result, these tube connections are expensive and unsightly, with performance being sacrificed to accommodate connection reinforcement (Figure 6).

New research at the University of Toronto is focused on the use of cast steel connectors for tubular brace elements subjected to cyclic inelastic loading. For this application, a casting provides an efficient connection between a single gusset plate that is connected to the building structure and a CHS brace member as shown in Figure 6.

Figure 6. (a) Modern seismic RHS brace connection (Photo courtesy of Professor R. Tremblay, École Polytechnique de Montréal, Canada) (b) Proposed cast steel connector for CHS braces

3.2 Benefits of using a cast steel seismic connector for tubular braces

The geometric freedom that casting manufacturing offers allows the design of a connector that is able to develop loads in excess of the yield capacity of the brace. The casting can then be designed to use a full-penetration weld to connect to a range of CHS members of variable wall thickness but constant outer diameter. Thus, the cast connector is an improvement to the weld-fabricated slotted tube to gusset connection as unreinforced CHS brace members can be used without risk of net section fracture during a seismic event. Further, as a single connector type can be utilized throughout an entire structure (as brace wall thickness can be varied to achieve the required lateral storey strength), and for both static and dynamically loaded braces, the connectors can be mass-produced, greatly reducing the manufacturing cost per cast connector. Another advantage to using a pre-engineered cast steel connector is that the fabricator need not individually design every tube-to-gusset connection as is required when specifying typical weld-fabricated connections.

3.3 Design of a cast steel seismic connector

Design of the cast connector had to satisfy all of the requirements for dynamically loaded connections set out in CSA (2001a). Further, in typical concentrically braced frames designed for seismic applications, the brace members themselves are the energy absorbing elements. Therefore, according to the principles of capacity design, the cast connector had to be designed to remain elastic during the formation of the following energy absorbing mechanisms:
1. tensile yielding of the brace member,
2. elastic buckling of the brace, or
3. plastic hinging of the brace at midspan due to overall or local inelastic buckling.

Plastic hinges at the brace ends were designed to form in the gusset plates welded to the building connection region during brace buckling. This limits the bending demand put on the connector during brace buckling and allows for the control of the buckling direction of the brace.

3.4 Selection of a cast steel alloy for the connector

Design of the connector first required the selection of a suitable cast steel alloy. Although the current Canadian structural steel design specification (CSA, 2001a) references only two standards for cast steel (ASTM A27, 2005a, and ASTM A148, 2005b), there are many other ASTM standards for cast steel which are suitable for structural use. ASTM A958 (2000) is a specification for carbon and low-alloy steel casting grades having a chemical composition similar to that of a standard wrought steel grade, with each casting grade being heat treated such that the cast steel’s tensile properties conform to those of a specific wrought steel grade. Since the cast connector is to be welded to HSS brace members having mechanical properties similar to ASTM A572 (2004) Grade 50, the connector was made according to ASTM A958 Grade SC8620 Class 80/50. According to the ASTM specification, this casting material provides a minimum yield stress of 345 MPa, a minimum ultimate tensile strength of 550 MPa, and a minimum elongation in 50 mm of 22% with a reduction of area of 35%. ASTM A958 was selected over ASTM A27 or ASTM A148 because A27 and A148 are general specifications that allow the foundry to make a variety of cast materials that comply with the specification but may not be most suitable for structural use due to other properties (i.e. weldability or ductility), whereas A958 is a more stringent standard, therefore ensuring a higher quality casting.

It was requested of the foundry that tensile tests be carried out for each heat and that the cast steel have a minimum Charpy V-Notch (CVN) impact test value of 27 J at −20°C. To ensure the casting was sound, it was subject to the following acceptance criteria: visual examination per ASTM A802 (2001) Level I, non-destructive examination per ASTM A903 (2003) Level III, and ultrasonic examination per ASTM A609 (2002) Level 3. Welding between the CHS brace and the cast connector did not require any special provisions for preheating or weld preparation. Welding was carried out in accordance with CSA W59 (2003). CSA (2001a) stipulates that for dynamically loaded connections weld filler material must have a CVN test value of 27 J at −30°C as certified in accordance with CSA W48 (2001b). The quality of the weld was also confirmed using visual examination and ultrasonic testing.

3.5 3-dimensional modelling and finite element stress analysis of the cast steel connector

Once a cast material grade had been selected, the connector was designed first in 2-dimensions and finally in 3-dimensions using SolidWorks 2005. As previously mentioned, both connecting ends of the casting were designed according to CSA requirements for dynamically loaded connections and to ensure elastic behaviour during yielding or buckling of the brace. Transitional geometry between the boundaries was simply created by inserting smooth curves (splines) over a transitional length of approximately one tube diameter. As a result, finite element analysis was required to verify that the connector would not yield in the transitional region of the casting during inelastic deformation of the connected brace.

Finite element (FE) analysis was carried out using ANSYS Workbench v. 9.0. Only one-eighth of a full brace assembly was modelled, with symmetry boundary conditions used to emulate the remaining assembly. Solid bodies were meshed with higher order 3-D 10-node tetrahedral solid elements (SOLID187) using mapped face meshing. These elements have quadratic displacement behaviour and are best suited for modelling solid bodies that are curved or have irregular boundaries (Moaveni, 1999). Non-linear analysis was carried out by applying incremental displacements to the bearing faces of the bolt holes. In reality, the bolts are pretensioned resulting in load transfer through distributed frictional stresses between the cast tabs and the gusset plate, however, application of displacement in this manner adequately emulated static displacement-control loading of the connection assembly and also produced conservatively large stress concentrations at the bolt holes. Non-linear material properties were considered and geometrical non-linearities and shape change during loading were taken into account by allowing large deformations. Reduced integration was used for the formulation of the local stiffness matrix of each element, thereby preventing volumetric mesh locking of the elements within the solid bodies of the model. Figure 7 shows the finite element model of the connector, full penetration groove weld, and brace segment.

Finite element analysis confirmed that when the brace assembly was loaded, inelastic deformations were localized in the brace member up to the probable yield capacity of the brace as shown in Figure 8.

The initial design was forwarded to Canada Alloy Casting Company (CAC), the foundry partner retained for this project, in the form of drawings and a 3-dimensional solid model in stereolithography.
(*.STL) file format. The drawings indicated surfaces to be machined and stipulated that critical cast dimensions have dimensional tolerance in accordance with ISO 8062 (1994) Grade 8, with all other cast dimensions to have a dimensional tolerance corresponding to ISO 8062 Grade 10. CAC suggested several design changes to improve the castability of the connector. The changes were adopted, with an increase in connector weight of approximately 18-percent. The final connector geometry is shown in Figure 9. The connectors were cast using the sand casting process. Figure 10 shows one-half of the positive pattern CAC developed to form the sand mould later used for casting.

3.6 Conclusions

Pseudo-dynamic and static testing of tubular brace assemblies, including gusset plates and cast connectors, as well as an investigation on the difference between the stipulated material properties and the casting’s actual mechanical properties, are ongoing. This research will confirm that the use of cast steel connectors is a viable, elegant, and cost effective solution for connecting to dynamically loaded HSS braces.

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