STRUCTURAL STEEL CASTINGS

SCI Steel Knowledge

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ACHIEVE HIGH QUALITY, GEOMETRICALLY COMPLEX AND PRECISE STEEL COMPONENTS

Structural Engineers can leverage cast steel structural components to provide significant performance advantages over joints produced via conventional steel fabrication when any of the following advantages can be leveraged:

Material optimization

Cast steel structural components can be designed to offer material savings over their fabricated counterparts.

Casting manufacturing enables structural forms that are more directly informed by the forces to which they will be subjected.

Enhanced strength and stiffness

Castings are well-suited for arduously loaded structural connections, where elevated strength or stiffness may be required.

Cast steel is isotropic, ideal for use in connections that are subjected to complex stress states. In the design stage the stiffness of cast joints can be accurately predicted and tuned.

Improved fatigue life

With cast steel nodes, weld access, fatigue performance, and service life are greatly improved as compared with conventionally fabricated connections.

Simplified fabrication

When steel castings are used to replace complex fabrications, they improve quality; they can be used to eliminate complex or heavy weldments and can therefore offer risk reduction to contractors and their clients.

Improved constructability

Castings reduce risk in the field and can provide total installed cost savings.

Cast steel components provide precision and accuracy at a level that is unachievable via conventional fabrication, improve site fit-up, and reduce rework costs and the associated delays. Castings can be designed to eliminate the need for field welding.

Aesthetics

Castings enhance the aesthetic appeal of architecturally exposed structural steel in projects of any size and budget.

Designers can leverage casting manufacturing to achieve geometries that are not possible with conventional fabrication techniques. Craftsmanship requirements in fabrication are greatly reduced when utilizing cast steel connections.

The MSG Sphere at The Venetian features over 10,000 standardised and bespoke CAST CONNEX products.

CAST CONNEX® is the industry leader in the structural engineering, design and supply of cast steel structural components for use in construction of buildings and bridges.

Our areas of expertise include industrial design and 3-dimensional modeling, finite element stress analysis, steel connection design, casting detailing, steel casting manufacturing and technologies, destructive structural testing of full-scale cast steel components and structural assemblages, performance based casting and non-destructive examination specification writing.

Our **standardised products** include pre-engineered connectors that are available off the shelf and we offer design-build services for **bespoke components**. All of our products are designed for use with AISC, EN, and CSA standards.

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STRUCTURAL STEEL CASTINGS

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STRUCTURAL STEEL CASTINGS

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SUMMARY

Castings are a highly versatile way of producing components of complex shape, or of producing shapes which are difficult to fabricate from wrought steel. In some situations, a casting is the only way of practically achieving both the structural load carrying capacity and the aesthetic requirements for architecturally exposed structural steel connections.

Castings can be streamlined for minimum stress concentration, minimum weight, and maximum strength. Tight tolerances can be achieved, and the single piece construction leads to greater structural rigidity and avoidance of misalignments and tolerance errors. Castings can be produced in a range of surface finishes; it is easier achieving a higher standard of finish than with a fabrication. The benefit a casting offers in terms of minimum use and waste of material is increasingly important in our low embodied carbon world.

This publication gives guidance on the properties, specification and procurement of carbon steel and stainless steel structural castings. The relevant requirements in current European product, design and fabrication standards are interpreted. The guide emphasises that the specification of the appropriate level of quality of the casting is very important and requires close liaison between the foundry and the design and construction team.

Case studies of recent projects using structural steel castings are presented.

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INTRODUCTION

Over five millennia, the casting process has been used to create a final or near-final shape directly by pouring liquid into a mould and allowing it to solidify. Since early civilisations, metal casting has provided a means to make art, tools and weapons and over the last 200 years, castings have been used in building structures for components such as columns and haunches. Since the latter decades of the 20th century, steel castings have become increasingly common in modern structural applications.

The desirable qualities of high strength, ductility and toughness, along with developments in analysis and manufacturing processes, led to the introduction of structural steel castings for offshore applications in the early 1980s. Cast steel nodes offered an effective solution for the often complex, multi-planar tubular joints required to withstand the wind and wave loading to which offshore platforms are subjected.

In the years since, further developments in technical capabilities – design, analysis, production and quality control processes – have seen the introduction of steel castings into onshore structures. They are used extensively for end terminations and connections for solid bar and tubular members in long spanning structures such as exhibition halls, airport passenger terminals, and in the roof structures of stadia. Castings are also utilised in structures where fatigue life is a concern such as pedestrian, road, and railway bridges, giving much better performance than welded connections. Smaller castings are used ubiquitously for tie rods, cable clamps, and glass facade brackets.

1.1 Why use steel castings in construction

There are many benefits to using steel castings, relative to equivalent fabricated components, and numerous scenarios where a casting is the only practical solution to an engineering challenge. The following paragraphs discuss just a few of the more general advantages of using steel castings; project-specific benefits can also be wide-ranging. It should be noted that it is likely that custom castings (those that are designed and manufactured specifically for the project in which they are employed) will require longer lead times than equivalent fabricated components, and that they may cost more. However, their use can simplify downstream activities such as erection, which can lead to overall cost and time savings.

Design versatility and flexibility – Custom castings can be engineered to achieve connections of all manner of highly complex member arrangements, whether the members are planar or multi-planar. Members of different cross-sections can readily be connected in a material-efficient manner, and connections between members of differing materials can be elegantly accommodated.

Optimal shaping – Smooth geometries and gentle transitions can be incorporated to streamline the flow of stresses through the component, eliminating notches, abrupt changes in section and sharp fillets, thereby avoiding or reducing stress concentrations and improving design life in fatigue critical applications. Whereas fabricated connections may be susceptible to coating system failure due to multiple sharp edges and re-entrant corners, the generous radii and gentle geometric transitions of castings reduce the susceptibility to vulnerabilities in the coating system.

Maximising strength/weight & stiffness/weight ratios – Material can be added where it is most needed for resistance to bending, tensile and compressive forces whilst ensuring adequate stiffness in all necessary directions. At the same time, efficiency can be achieved by removing material where it is not required to minimise weight without compromising the structural performance of the component.

Simplification of fabrication & erection – Castings are monolithic components, hence reducing fabrication complexity and welding requirements. Welds are moved away from high-stress concentration regions (improving fatigue performance) into regions with improved access to simplify welding procedures, whether on site or in the factory. Geometries at interfaces with members can be prepared to facilitate welding and erection aids can be incorporated directly into the casting.

Close dimensional tolerances – Component patterns can be created using computer numerical control (CNC) processes and post-casting CNC machining of critical features can provide machine-level precision in the finished geometry. This high level of quality assurance facilitates simplified, reduced-risk, site assembly.

Control of properties – Careful control of the steel chemical composition along with post-casting heat treatment mean a wide range of mechanical properties are achievable. Unlike rolled steel products with anisotropic properties (due to higher, strain hardened yield strength or reduced ductility in one direction compared with the other), the casting process produces steel geometries with isotropic mechanical properties, which can be useful in components subjected to complex loading/ stress states.

Minimised material waste – Casting uses material efficiently, for example the shape can be optimised with redundant metal removed. Steel castings are themselves produced from recycled scrap steel.

Economies of scale – With fabricated assemblies, the same process needs to be repeated for each assembly using similar materials and labour, however multiple castings can be made at one time delivering significant economies of scale. Likewise, it is quicker to produce multiple castings than multiple complex fabrications.

With these advantages in mind, a casting may be a cost-effective design solution for:

- large quantities of repetitive components,
- end terminations for changes in section of members, e.g. round steel bar to connection plates,
- pinned connections,
- complicated tubular connections with incoming members at different angles,
- connections subject to very high forces, where large welds would be difficult to inspect and test, and expensive to repair,
- tapered sections, or where thick sections are required adjacent to thin sections,
- thick plate details where isotropic material properties are required,
- visibly exposed connections where aesthetics are important,
- fatigue-sensitive joints.

1.2 What is a casting?

A steel casting is a component formed by pouring liquid metal (reprocessed from scrap steel, with a very small addition of virgin alloys) into a mould containing a cavity of the desired shape. Upon cooling and solidification of the metal, the mould is removed, and the steel component cleaned. Heat treatment and subsequent finishing is then performed to achieve the desired properties or finish to the casting. Appendix B gives more information about the manufacturing process for steel castings.

Castings can be produced as one-off or small-batch components (as is often the case for custom castings, designed for specific applications in specific projects) or produced by the thousands (such as for standardised 'off-the-shelf' components).

Most steel products used in construction are wrought (i.e., they have undergone hot and/or cold rolling). Many of the material compositions used for castings are quite similar to those of standard wrought metals. However, the mechanical properties of cast metals are not necessarily identical to those of wrought metals of corresponding composition - properties such as yield stress and ductility of wrought steels are more closely related to the thickness of the material, whereas those of cast steels have less thickness-dependency well beyond the available thickness of wrought steel shapes and plate.

Structural cast steels can be obtained with equivalent strength and toughness to grade S355J2 to BS EN 10025 steel. More highly alloyed cast steels are also available with higher strengths and toughness. Section 3.1 covers the product standards, alloys and properties of structural castings. Whereas the cross-section of a casting can be chosen with the design loads in mind to give optimum strength and stiffness properties, design with rolled sections is limited by the available standard sizes.

The mechanical properties achievable with steel castings are generally comparable with those of hot rolled structural steels. Similarly, the quality, integrity and consistency of castings are comparable with fabricated steel.

Cast steels are no more difficult to weld than the corresponding wrought steels providing the chemical composition and heat treatment are correctly considered.

Traditionally, castings were limited by the time and cost of tooling; however, with additive manufacturing it is possible to make casting tooling or moulds, which makes it possible to make a one-off casting in a short time.

1.3 Examples of structural steel castings

1.3.1 Custom castings

'Custom' castings are designed for specific applications in specific projects. They could be produced as a one-off product or in small-batches, or even in thousands specific to a project.

Steel castings were used for the connections of the tubular branches of the tree-like columns used to support the roof at Terminals 1, 2 and 3, Stuttgart Airport (Figure 1.1). Profiling and welding these complex tubular connections would have been a very fabrication-intensive activity. Member optimization was made possible by the geometric flexibility afforded by casting manufacturing to accommodate multiple member outer diameters and varying wall thicknesses in one joint.

Figure 1.1 Terminal 1, Stuttgart Airport, Germany

Fifteen tonne cast steel nodes were used in the construction of the three 24 m tall concrete-filled steel ‘delta frames’ which support an 11 storey building above two historic 4 and 5 storey high Toronto buildings (Figure 1.2).

Cast steel nodes are used to connect the supporting members to the columns at the new elevated passenger transport system at Frankfurt Airport (Figure 1.3).

Super duplex stainless steel cast nodes were used in David Hammons’ permanent sculptural installation *Day’s End* in the Hudson River near Chelsea Piers and the Whitney Museum of American Art in New York (Figure 1.4). The skeletal stainless steel structure is 15 m tall and 114 m long and mimics the shape of a warehouse formerly occupying the site.

Figure 1.2 Cast steel nodes at Queen Richmond Centre West, Toronto

Figure 1.3
Cast steel nodes, new passenger transport system, Frankfurt Airport, Germany

Figure 1.4
Stainless steel cast nodes, Day's End by David Hammons

1.3.2 Standardised castings

The casting process can prove to be a cost-effective way of manufacturing connections in commonly used shapes and sizes which are difficult to fabricate. Standardised cast connections with proven strength capacities are usually available as proprietary products, obtainable 'off-the-shelf' from some manufacturers. Typical delivery times are around a month. Examples include fork-end connectors for hollow sections and tension rods, tee connections for portal frame structures, and girder clamps.

Some standardised castings are covered by a European Technical Assessment (ETA). An ETA provides an independent Europe-wide procedure for assessing the essential performance characteristics of non-standard construction products. The ETA offers manufacturers a voluntary route to CE marking when the product is not or not fully covered by harmonised standard under the Construction Products Regulation. ETAs can be found on the EOTA website by searching for the ETA number. Following the departure of the UK from the European Union, UKCA marking and designated standards have been introduced, which are UK equivalents to CE marking and harmonised standards respectively. UKTAs (UK Technical Assessments) are the UK equivalent to ETAs.

Fork-end connectors for hollow sections

Standardised fork-end castings provide end connections for compression struts, column bases, truss web members, or anywhere a load bearing true-pin connection is desired. They are designed to connect to commonly used sizes of circular hollow sections (CHS) and may be ideal in architecturally exposed structural steel (AESS) applications. They provide smooth transitional geometry that is otherwise unachievable using standard fabrication practices, simplifying the design, detailing, and fabrication and significantly improving the aesthetic value of the finished assembly.

Figure 1.5 CAST CONNEX® Universal Pin Connector™ at a CHS brace member end with cast stainless steel cable fork ends in the foreground in the Whitney Museum in New York, NY

Conical tapers

Cast conical tapers are hollow, cast structural steel elements that are designed to connect to the end of CHS, typically those acting in compression, for use in architecturally exposed structural steel applications, such as for columns in a building atrium. They are often combined with a fork-end connector, providing a more slender overall appearance to the member. The taper also enables a smaller connector to be used.

Conventional fabrication of hollow conical steel tapers is difficult as it involves cold or hot forming/bending flat plate into a conical shape and welding. By contrast, cast conical tapers are produced to tight tolerances and can be connected to the end of the CHS by one simple circumferential weld. Once assembled, the welded joints can be ground smooth to create an elegant finished structural element.

Figure 1.6 CAST CONNEX® Architectural Taper™ at a CHS column end (left); CAST CONNEX® Universal Pin Connector™ + Architectural Taper™ at CHS member ends (right)

Tie rod or cable connectors

Tension systems are widely used in roof structures, vertical glazing, bracing and truss structures, and bridges. The connectors are typically steel fork end connectors or spades with pinned connections and a machined internal thread which allows connection to a threaded rod. Smaller sizes tend to be machined, and larger sizes cast (typically M12 - M160 are available as standardised castings) (Figure 1.7). The fork-end connectors and spades are connected by double shear pin connections to corresponding steel gusset plates or anchor discs. The use of threads allows the systems to be adjusted in length which is useful for in-situ adjustment.

Figure 1.7 Tie rod

Figure 1.8 shows the high strength tie bar system used as the tension elements in the trusses at Cannon Place in London.

Figure 1.8 Tension system at Cannon Place, London

Bolted splices

Cast steel bolted splices that enable unobtrusive field bolted connections in CHS are also commercially available. They are designed such that the bolted connection is within the outer diameter of the member. The splice can be sheathed using thin-gauge cover plates for concealment. These splices are typically available to fit CHS in diameters from 127 mm upwards. The connectors include weld preps so that they can be easily welded to the end of a CHS of any typical wall thickness.

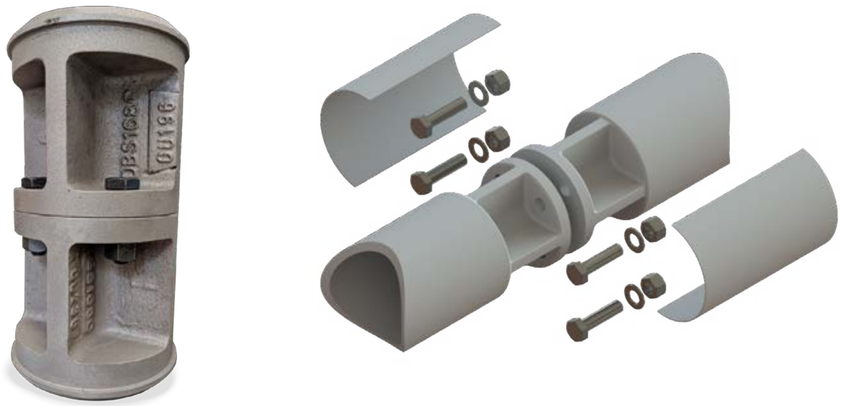

Figure 1.9 CAST CONNEX® Diablo Bolted Splice™

Fork-end connectors for timber elements

Cast steel fork-end fittings designed to connect to the ends of heavy timber or glue-laminated structural elements loaded in predominately tension or compression are also commercially available. They are used in architecturally exposed applications.

Figure 1.10
CAST CONNEX®
Timber End
Connectors™

1.4 Scope of this publication

This publication provides guidance on procurement, design and manufacture of a structural casting. The guidance covers carbon steel and stainless steel castings for use in buildings and bridges, both project-specific ‘custom’ components and off-the shelf ‘standardised’ connections. Case studies demonstrate examples of steel castings in recent projects.

“Publication P445” in references page *Steelwork Joint Design - Process and Information*[1] focuses on the design and manufacture of joints between structural members using fabricated assemblies of gusset plates, splice plates, stiffeners, bolting and welding.

PROCUREMENT OF CUSTOM CASTINGS

2.1 Introduction

The specification, design and production of structural steel castings requires specialist knowledge and experience. If custom castings are being considered for a project, all parties involved need to have the necessary knowledge and experience in casting design and delivery.

The foundry is responsible for the manufacture of the casting, producing a component to the requirements of the casting production specification in an economical and efficient way. The responsibility falls to the other parties in the project to ensure that the specification states their requirements clearly, and that these requirements are appropriate for the casting being considered.

The supply of structural castings usually falls entirely within the structural steelwork contract (i.e., the steelwork contractor is responsible for purchasing the castings).

This publication presents two procurement options, depending on the capabilities of the parties involved in the project. The first of these involves the steelwork contractor engaging a third party 'casting designer-supplier' to design and supply the casting. This is SCI's recommended option for those with little to no experience in specifying and procuring structural castings.

The second option is the 'traditional' arrangement with the steelwork contractor working directly with a foundry. Casting design (including structural design, 3D modelling and detailing, shop drawings, and development of a casting production specification) is undertaken by the steelwork contractor and foundry, with support from the lead structural engineer and architect.

Adopting the second option limits the number of foundries available to the steelwork contractor as many highly capable foundries will not assume responsibility for the structural design and resulting performance of the castings that they manufacture.

The contractual and functional relationships for these procurement options are shown in Figure 2.1 and Figure 2.2 with further guidance in the following sections. Note that the diagrams are specific to the procurement of castings and other relationships may exist between these parties for other aspects of the project.

It is strongly recommended that there is early engagement with the casting designer-supplier (or foundry, for the traditional procurement option) to ensure that a well-defined casting production specification is developed as early as possible, allowing for accurate tenders and sufficient time for delivery of the required quantity and quality of castings. This also allows the design team to understand the possibilities and limitations of castings.

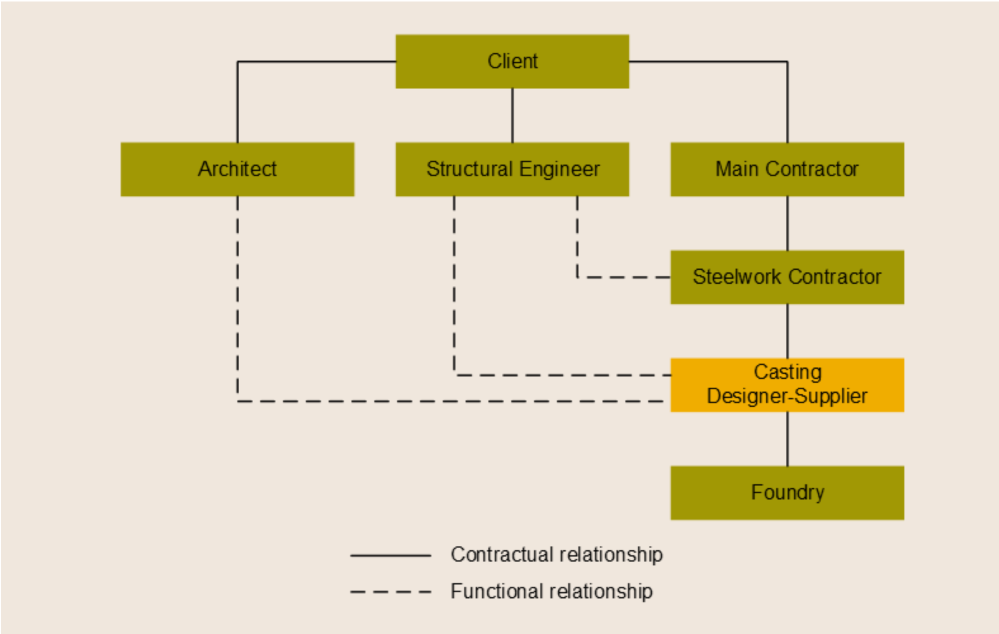

Figure 2.1 Contractual and functional relationships for procurement using a casting designer-supplier

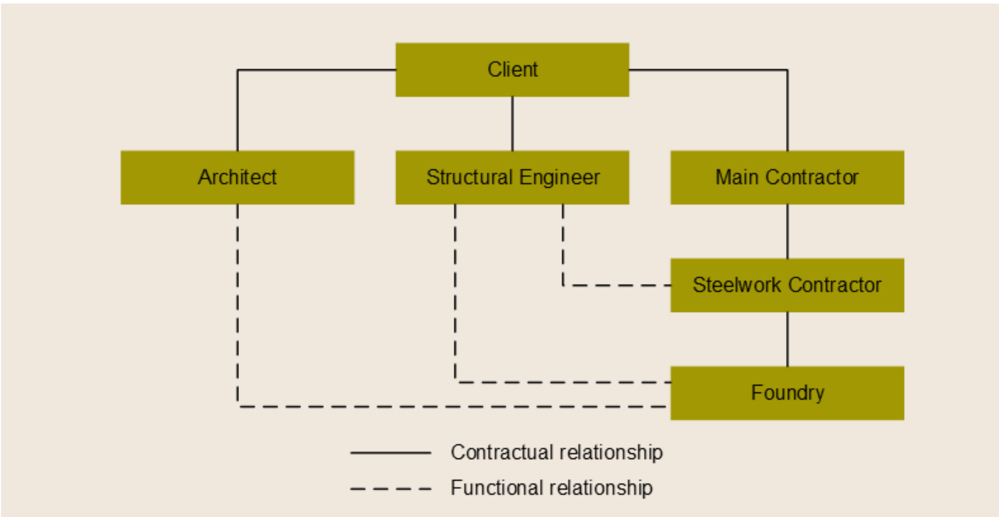

Figure 2.2 Contractual and functional relationships for the traditional procurement option

2.2 Procurement using a casting designer-supplier

2.2.1 Overview

This procurement option involves a third party organisation with specialist expertise in the design and production of structural steel castings and experience working with foundries. The lead structural engineer, architect, and steelwork contractor do not require in-depth knowledge and experience of structural steel castings. The ideal casting designer-supplier also has extensive understanding and capabilities in structural engineering, industrial design, steel connection design, structural steel detailing, fabrication, and erection, and is therefore capable of developing casting designs that add significant value to the construction project.

The casting designer-supplier will typically be contracted to the steelwork contractor and take on most or all the responsibility for designing and delivering the casting(s). The casting designer-supplier provides expert guidance at all stages of the process, from conceptual design, detailed design, casting production and quality control, including the dimensional accuracy, quality of surface finish and NDT programme. The casting designer-supplier offers services that are not commonly performed by structural engineering or steelwork contractors, including 3D modelling and finite element stress analysis of cast elements, casting design and detailing, NDT specification, and, for some projects, the organisation of destructive structural testing of full-scale components and assemblages.

Depending on the casting designer-supplier, initial design guidance and casting design conceptualisation may be provided to the structural engineer/architect free of charge, prior to tendering for the contract for the casting supply. This early involvement leads to a better definition of the scope and performance requirements of the casting(s), with the advantage of tendering for the complete design based on a well-defined specification.

Table 2.1 outlines the key documents required in the procurement process, explaining the purpose of the documents, who prepares them, and who they are written for.

The **Performance Requirements Report** forms part of the tender documents for the casting designer-supplier.

The **Casting Design Report** is submitted for approval by the steelwork contractor, architect and lead structural engineer after tender. Approval must be received before manufacturing begins.

The **Production Specification** is prepared after the casting designer-supplier is engaged.

Information transfer requirements are discussed in the following sub-sections and summarised in Figure 2.3.

Performance Requirements Report			
Written by	**Written for**	**Purpose**	**Scope**
Architect & lead structural engineer	Casting designer-supplier, as part of the tender documents	The casting designer-supplier uses this information to develop the casting design and pricing. Information in this report will influence the details of the Production Specification.	1. Drawings showing external dimensions, including details of all adjoining members 2. Configuration of connections to adjoining members (e.g. identification of welded versus bolted connections) 3. Key architectural features, including surface finish 4. Characteristic actions and design combinations 5. Minimum service temperature (to determine impact energy requirements) 6. Design basis (e.g., design in accordance with BS EN 1993 and execution in accordance with BS EN 1090-2) 7. Project Schedule
Casting Design Report			
Written by	**Written for**	**Purpose**	**Scope**
Casting designer-supplier	Architect, lead structural engineer and steelwork contractor	This report is submitted to evidence the completeness of the design to meet the Performance Requirements Report and for coordination with the steelwork contractor.	1. Shop drawings detailing dimensions and number of castings required. Connection details, and any other input information and design assumptions 2. Alloy and heat treatment (i.e., mechanical properties) in accordance with BS EN 10340 3. Summary of NDE: techniques, scope, acceptance levels, and method for verifying mechanical properties 4. Summary of the overall design approach (usually a combination of code-based formulae and FEA) 5. FEA modelling assumptions (boundary conditions, element type, mesh density, etc.) 6. Validation/verification of the FEA model 7. Description of the framework used for the interpretation of FEA results, with consideration of loading regime (static, dynamic) and performance requirements (fatigue, fracture, etc) 8. Engineering calculations for any code-based analysis 9. FEA results summary and analysis
Production Specification			
Written by	**Written for**	**Purpose**	**Scope**
Casting designer-supplier	Foundry	The foundry follows the parameters of the Production Specification to develop their manufacturing plan and pricing.	1. Shop drawings detailing dimensions and number of castings required 2. Alloy and heat treatment (i.e., mechanical properties) in accordance with BS EN 10340 3. Method for verifying mechanical properties 4. NDE: techniques, scope, and acceptance levels 5. Method for rectification of defects 6. Project Schedule

Table 2.1
Key documents required for procuring a casting

2.2.2 Information transfer between lead structural engineer and casting designer-supplier

The following list highlights some of the key items of information the lead structural engineer will need to provide to the casting designer-supplier:

- Geometry of the centrelines of members framing into the node being considered, with details of horizontal and vertical extents of the proposed casting from the nodal point and/or any angles as appropriate.
- Dimensions of key structural elements such as size and thicknesses of connecting members, shape and thickness of any integrated base or cap plates, and any other structural features to be incorporated.
- Axial forces, shear forces and bending moments at the junctions between the cast component and the structural members both in-plane and out-of-plane (if applicable). For initial design these may be the maximum values of these actions whilst for subsequent detailed design, equilibrated load combinations will be required.

Information may be provided in documentation or drawings as appropriate.

During design, consideration should be given to the stiffness of the cast steel node such that it fits with the global structural model assumptions chosen by the lead structural engineer.

2.2.3 Information transfer between architect and casting designer-supplier

The architect is often the party to suggest that a structural casting is used on a project, principally with a particular architectural vision or structural concept in mind. Discussion should take place between the architect and the casting designer-supplier to decide on:

- Required surface finish. The architect will probably be responsible for specifying any finishes for aesthetics, or coatings for corrosion and fire protection. The casting designer-supplier will be able to advise on the necessary casting surface finish to achieve the architect's requirements and/or permit the successful application of the desired coating.
- Any shaping requirements, curvatures, radii etc. that define the form of the casting to achieve the architectural vision for the structural system.

2.2.4 Information transfer between steelwork contractor and casting designer-supplier

As cast components will be connecting to steel elements within the steelwork contractor's work package, it is essential that a close working relationship is formed between the steelwork contractor and the casting designer-supplier.

Key information to transfer between these parties is as follows:

- In the case of bolted connections, the connection geometry and tolerances will need to be agreed to ensure correct transfer of forces and accurate fit-up. Bolt geometries (spacing, pitch, etc.), hole sizes, location of mating surfaces (such as offsets of lapped plates) will all require agreement for the design of the casting.
- When a cast node is welded to a hot finished section, the steelwork contractor will need to know the chemical composition of the cast steel in order to prepare appropriate weld procedures. Any particular details to facilitate a welded connection, such as edge preparation, should be clearly defined by the steelwork contractor.

The casting designer-supplier shares the shop drawings and/or 3D digital models of the casting prepared for the foundry with the steelwork contractor, who may also distribute them to the architect and lead structural engineer. This enables the castings to be directly incorporated into the detailing/BIM software model of the whole steel structure.

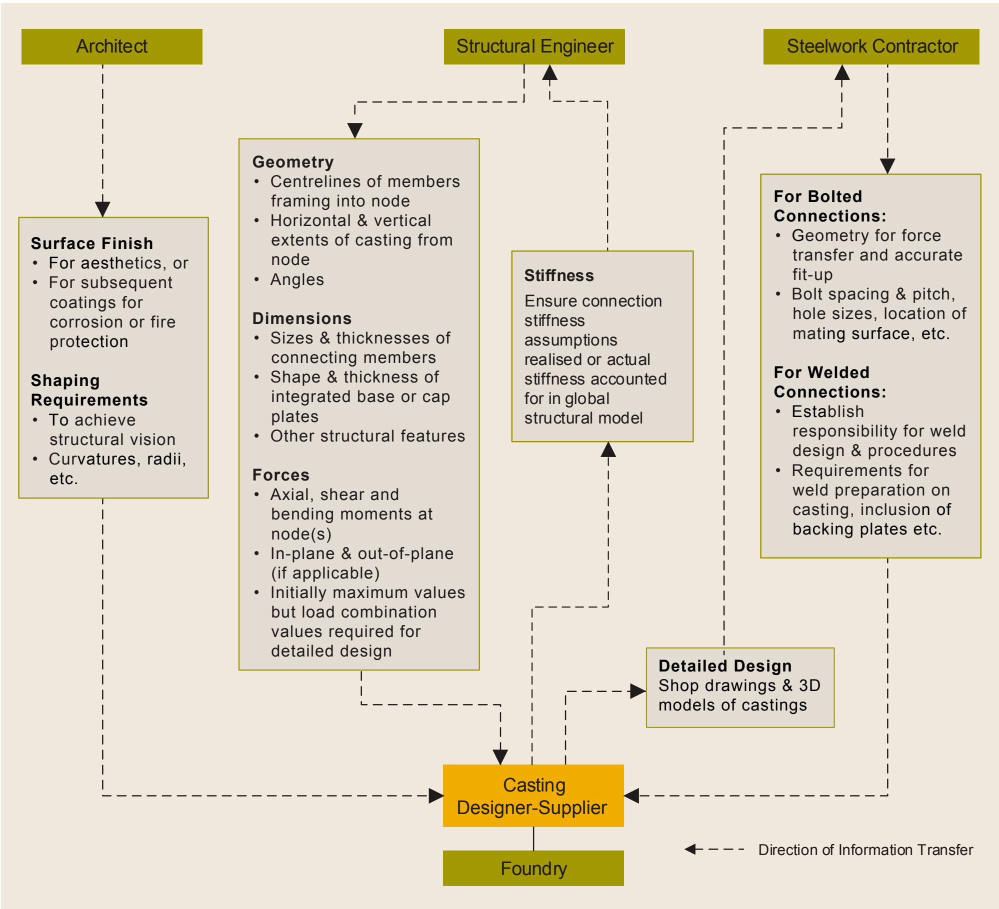

Figure 2.3
Information transfer using a casting designer-supplier

2.3 Traditional procurement option

This procurement option is the path that has typically been used in the past: the cast component will be developed with cooperation between the lead structural engineer, the architect, and the steelwork contractor, with input and production by an appointed foundry. The relationships between the parties are shown in Figure 2.2.

With no single entity providing overall coordination of the casting development activities, it is important for all parties involved to understand the role they play in producing and using a successful casting.

Early discussions should be held between all parties so that the implications of the various processes, design decisions and desired quality requirements are fully understood, taking account of programme and cost.

The foundry will be able to advise on the method of casting production and type of pattern required to produce the desired surface finish and dimensional accuracy, as well as helping the other parties understand the problems that may need to be overcome and the challenges in forming certain shapes. This is crucial to understand early in the process as the method of manufacture has a significant impact on cost and lead times.

The foundry will also advise on the inspection and testing methods within their capabilities. The lead structural engineer will need to define the non-destructive examination (NDE) and non-destructive testing (NDT) programme and other elements of the production specification, including shop drawings or models.

PROPERTIES OF CAST ALLOYS

3.1 Product standards

BS EN 10340 *Steel Castings for Structural Uses*[2] is the UK designated standard for steel castings for structural use, and it covers both carbon steel and stainless steel castings. Castings supplied to this standard are able to be CE/UKCA marked. By this, the manufacturer declares the product conforms to BS EN 10340, meeting any specified threshold values required by that Standard as well as confirming the conformity assessment procedures have been complied with.

BS EN 10340 is to be read in conjunction with, and provides additional conditions to, BS EN 1559-1[3] and BS EN 1559-2[4] which cover the requirements for all types of castings. The European structural steelwork execution standard, BS EN 1090-2[5], refers to these three standards when it covers steel castings.

Steel grades suitable for use in structural castings are listed in BS EN 10340, covering both carbon and stainless steels. These grades exhibit a variety of mechanical and physical properties, making them suitable for different strength applications, sub-zero conditions, heat- and corrosion-resistant service, wear and abrasion resistance, and magnetic or non-magnetic applications.

Although BS EN 10340 gives properties for specific grades, in some cases it may be more appropriate for a foundry to develop a new, specific grade exactly suited to a given application. As foundries typically melt in small volumes, a tailored alloy composition is more feasible with a casting than with a rolled steel product which is made in higher volumes and tends to be limited to commercial grades, or require substantial lead-time for specialty compositions.

Neither the First Generation edition of BS EN 1993-1-1[6] nor the Second Generation edition[7] reference a product standard for steel castings. However, the UK National Annex to the First Generation BS EN 1993-1-1[8] states:

"Steel castings and forgings may be used for components in bearings, junctions and other similar parts. Castings should conform to BS EN 10293 *Steel Castings - Steel Castings for General Engineering Uses*[9]. Further guidance on steel castings is given in *Castings in Construction*[10]."

It is expected that the UK National Annex to the Second Generation BS EN 1993-1-1 will reference BS EN 10340 and this design guide.

Like BS EN 10340, BS EN 10293 should be read in conjunction with BS EN 1559-1 and BS EN 1559-2. Covering alloys for steel castings suitable for a range of applications (such as machinery, railroad, automotive industries etc.), it permits the use of a wider range of steel grades than those permitted for structural purposes (as listed in BS EN 10340). Care should be taken to ensure castings with a structural function are specified in a grade listed in BS EN 10340. It should be noted that BS EN 10293 is not a UK designated standard for construction products. BS EN 10293 replaces BS 3100[11], which is now withdrawn.

The Second Generation edition of BS EN 1993-1-11 *Design of steel structures: Tension components* references BS EN 10340 as the product standard for use in Group A tension elements. Group A covers tension rod systems made of steel or stainless steel, reinforcing steel or prestressing steel, including fork-end connectors.

The parallel standard to BS EN 10293 for stainless steel castings is BS EN 10283[12] and it includes martensitic, precipitation hardening, austenitic and austenitic-ferritic (duplex) alloys.

The properties of the alloys in BS EN 10340 are given in Table 3.1 and Table 3.2.

In accordance with the steel alloy naming system in BS EN 10027-1[13], the letter ‘G’ in the alloy name designates it is a steel suitable for casting.

- For **structural steels**, the G is followed by an S which designates a structural steel. The number after the S is the minimum specified yield strength in MPa.
- For **non-alloy steels**, the G is followed by a number which is the specified average carbon % content multiplied by 100. The chemical symbols of special additional elements are then given followed by a number which is 4, 10, 100 or 1000 x the average content of that element (for example, the multiplier is 4 for manganese and chromium, and 10 for molybdenum and vanadium).
- For **stainless steels**, the G is followed by X. The number after the X is 100 x specified average carbon % content. Following that, the chemical symbols for the alloying elements that characterise the steel are given. Numbers separated by hyphens represent the average % of these alloying elements, rounded to the nearest integer.

For example:

- GS240 is a steel casting alloy with a minimum specified yield strength of 240 MPa
- G17Mn5 is a steel casting alloy with an average carbon content of 0.17% and an average manganese content of 1-1.6%
- GX2CrNi19-11 is a stainless steel casting alloy with an average carbon content of 0.02%, chromium content of 19% and nickel content of 11%.

When specifying the required grade for a casting, if a minimum impact energy at a particular service temperature is required, this should be clearly stated in the Performance Requirements Report for the casting. For grades in Table 3.1 with multiple impact testing values at different temperatures, the impact test will be conducted at room temperature unless specified otherwise.

The 0.2% proof stresses and impact testing energies are all presented as minimum requirements for the particular grade in the listed maximum thickness.

As indicated in Table 3.1, cast steel is usually subjected to heat treatments (annealing, normalising, annealing and normalising or quenching and tempering) in order to produce the necessary property requirements.

					Tensile Testing		Impact Testing	
Name	Number	Steel Type	Heat Treatment[3]	Thickness (mm)	0.2% Proof Stress (N/mm^2)	Ultimate Strength (N/mm^2)	Energy (J)	Temp. (°C)
GS200	1.0449	Structural steel	N	≤ 100	200	380 to 530	35	20
GS240	1.0455	Structural steel	N	≤ 100	240	450 to 600	31	20
G17Mn5	1.1131	Non-Alloy steel[1]	QT	≤ 50	240	450 to 600	27	-40
							70	20
G20Mn5	1.6220	Alloy steel[2]	N	≤ 30	300	480 to 620	27	-30
							50	20
			QT	≤ 100	300	500 to 650	27	-40
							60	20
G24Mn6	1.1118	Non-Alloy steel[1]	QT1	≤ 50	550	700 to 800	27	-20
			QT2	≤ 100	500	650 to 800	27	-30
			QT3	≤ 150	400	600 to 800	27	-30
G10MnMoV6-3	1.5410	Alloy steel[2]	QT1	≤ 50	380	500 to 650	27	-20
							60	20
				≤ 100	350	480 to 630	60	20
				≤ 150	330	480 to 630	60	20
				≤ 250	330	450 to 600	60	20
			QT2	≤ 50	500	600 to 750	27	-20
				≤ 100	400	550 to 700	60	20
				≤ 150	380	500 to 650	60	20
				≤ 250	350	460 to 610	60	20
			QT3	≤ 100	400	520 to 650	27	-20
							60	20
G18NiMoCr3-6	1.6759	Alloy steel[2]	QT1	≤ 80	700	830 to 980	27	-40
			QT2	≤ 150	630	780 to 930	27	-40

Notes:
1 Structural, pressure vessel and engineering steel with C<0.5%
2 Structural, pressure vessel and engineering steel
3 N = normalizing, QT = Quenching + Tempering

Table 3.1 Mechanical properties of carbon steels in BS EN 10340 Table 2

There are seven carbon steel casting alloys in BS EN 10340, with G17Mn5 and G20Mn5 being the most widely used alloys for structural castings, with the former being more weldable due to its lower carbon content.

GS200 has similar mechanical properties to S235

GS240 has similar mechanical properties to S275.

G17Mn5 has similar strengths and elongations to GS240 and S275, with specified Charpy notch toughness values at -40°C.

The strength of **G20Mn5** lies between S275 and S355, with specified Charpy notch toughness values at -30°C (+N) and -40°C (+QT).

G24Mn6 is a higher strength steel casting, with mechanical properties similar to S500 and with specified Charpy notch toughness values at -20°C (QT1) and -30°C (QT2/3).

G10MnMoV6-3 is a higher strength steel casting with mechanical properties between S355 and S460 and specified Charpy notch toughness values at -20°C (QT1).

G18NiMoCr3-6 is the highest strength steel casting in BS EN 10340 with mechanical properties similar to S690.

Stainless steel castings should be considered where an exposed metallic surface finish is required, or if superior corrosion resistance with minimum maintenance is needed.

GX2CrNi19-11 (equivalent to the wrought alloy S30403) is a basic chromium-nickel low carbon stainless steel and is suitable for rural, urban and light industrial sites.

GX2CrNiMo19-11-2 (equivalent to the wrought alloy S31603) is a chromium-nickel-molybdenum low carbon stainless steel, the presence of molybdenum greatly improving the overall corrosion resistance and especially pitting resistance. It performs well in marine and industrial sites.

GX2CrNiMoN25-6-3 (equivalent to the wrought alloy S32205) is an extremely corrosion resistant duplex grade, suitable for use in marine and other aggressive environments.

Table 3.2 Mechanical properties of stainless steels in BS EN 10340 Table 2

Name	Number	Stainless steel family	Heat Treatment[1]	Thickness (mm)	Tensile Testing: 0.2% Proof Stress (N/mm^2)	Tensile Testing: Ultimate Strength (N/mm^2)	Impact Testing: Energy (J)	Impact Testing: Temp. (°C)
GX4CrNi13-4	1.4317	Martensitic	QT	≤ 300	570	760 to 960	50	20
GX4CrNiMo16-5-1	1.4405	Martensitic	QT	≤ 300	540	760 to 960	60	20
GX2CrNi19-11	1.4309	Austenitic	AT	≤ 150	185	440 to 640	80	20
GX2CrNiMo19-11-2	1.4409	Austenitic	AT	≤ 150	195	440 to 640	80	20
GX2CrNiMoN25-6-3	1.4468	Duplex	AT	≤ 150	480	650 to 850	50	20

Notes:
1 QT = Quenching + Tempering, AT = Solution Annealing

In terms of ASTM standards, ASTM A958/A958M covers steel castings suitable for structural applications which are similar to standard wrought grades[14]. Alloy SC8620 Class 80/50 is a similar alloy steel to BS EN 10340 G20Mn5+QT and G24Mn6 + QT.

ASTM A351/A351M[15] and A890/A890M[16] specify stainless steel castings. ASTM A351/A351M steel alloy CF8 has a similar composition to S30400 austenitic stainless steel. ASTM A890 4A has a similar composition to S31803 duplex stainless steel.

3.2 Weldability for joining

Cast steels, whether carbon or stainless, have similar welding characteristics to wrought steels with comparable carbon equivalent values (CEV). It is advisable to consult with the casting designer-supplier or foundry to discuss the potential range of CEV that would be expected for the specific grade under consideration, or any supplemental requirements, such as a maximum CEV.

The mechanical properties of welds joining cast steel to cast steel and of welds joining cast steel to wrought steel are close to those of similar welds joining wrought steel to wrought steel, providing the materials are of similar composition.

Welds undertaken by the steelwork contractor to join the casting to adjacent wrought steel members should be treated according to the typical requirements for structural welds.

3.3 Machinability

Machining is used in casting manufacture after heat treatment for features that require more precise dimensional precision than could be achieved in the as-cast configuration, or where castings are to be mechanically joined to other sections, for example by threading. CNC machining methods are widely used and result in improved accuracy, increased production speeds, enhanced safety, increased efficiency, and cost savings compared to manual machining methods.

Carbon and stainless steel castings can all be readily machined. However, macroscopic sand, slag and refractory inclusions that can occur in castings may reduce machinability. The NDE and NDT programme and subsequent casting production welding are used to control casting quality and can be defined to ensure desired machinability.

Preparing the surface of a sand-moulded casting wears a cutting tool rapidly, possibly because of adherence of abrasive mould materials to the casting. However, once the surface is removed, the machinability is no different to that of a wrought metal of similar composition and in a similar condition of heat treatment.

Particular care is required in machining stainless steels because of their tendency to work harden. Cutting lubricants are essential.

CASTING DESIGN AND SPECIFICATION

4.1 Structural analysis

As with any other structural component, stresses are induced in a cast component by the permanent and variable loads applied to the structure. In line with typical practice for fabricated connections, structural analysis is usually performed to verify the adequacy of the component at the ultimate limit state (ULS).

The level of complexity required in the structural analysis of the component is likely to be proportional to the complexity of the component. For simple geometries with simple loading (for example, fork-end connectors with in-plane forces only), it may be sufficient to use hand techniques to determine loads, which can then be compared with resistances calculated using BS EN 1993-1-1[6] and BS EN 1993-1-8[17] , taking appropriate section properties from the critical cross-sections of the casting (such as shear areas, net areas for tension, elastic section moduli, etc).

For more complex connections, such as 3D nodal joints, components with changes in thickness, and components subject to fatigue, more sophisticated analysis will be required to predict stress distributions, deformations and stiffnesses of the cast component accurately. Finite element techniques are regularly used. Experimental testing of the component may also be performed.

Sometimes the shape and size of a structural casting are governed by aesthetic and architectural requirements rather than functional, structural requirements, in which case the casting may only be lightly stressed. In these cases, a rigorous structural analysis may be unnecessary.

The design of a casting should take due consideration of:

- structural response to ensure it has sufficient resistance to carry the design loads from the incoming members, and is at least as stiff as what was assumed in the global structural model,
- architectural requirements, e.g. incorporation of reveals or other aesthetic demands,
- constructability aides e.g. lifting lugs,
- connection to incoming members,
- castability concerns with respect to manufacturing of the casting,
- ther project performance requirements (e.g. fire resistance).

Guidance on design for castability is given in Appendix B.9.

4.1.1 Design by codes

As described in Section 3.1, there are no design rules in BS EN 1993-1-1 and BS EN 1993-1-8 that apply specifically to steel castings, but the rules typically used to verify the cross-sectional resistance of other structural components can also be applied to (simple) structural castings.

The Second Generation edition of BS EN 1993-1-11 *Design of steel structures: Tension components* references BS EN 10340 (Section 3.1).

4.1.2 Design by Finite Element Analysis

For more structurally complicated cast connections, such as multi-planar nodal connections, finite element analysis (FEA) can be used to predict stresses, deformations and stiffnesses of the cast component, efficiently and accurately.

An FEA model of a casting is likely to make use of 'solid' elements, with a mesh density sufficient to accurately capture the geometry and expected behaviour of the casting, as indicated by a sensitivity analysis. The boundary conditions applied in the model will vary depending on the circumstances of the design. Figure 4.1 shows the FEA model and structural analysis for one of the exosphere castings in the MSG Sphere at The Venetian (a case study for this project is given in Annex A.2).

The use of advanced FEA enables topology optimisation whereby the design of a connection can be optimised by extracting redundant material and then refining the shape for castability.

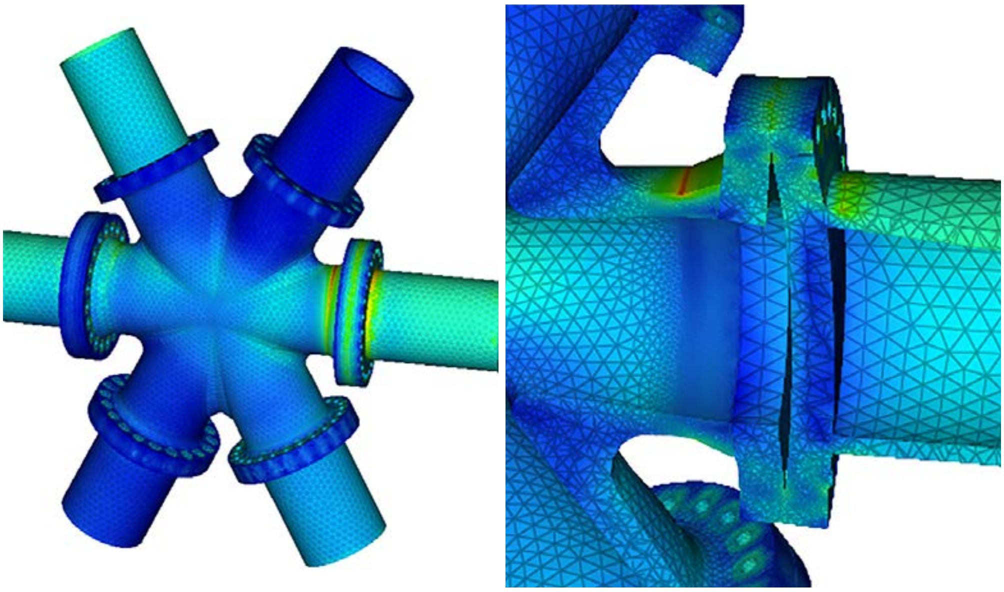

Figure 4.1 Finite element modelling of the exosphere steel castings enabled their dimensions to be optimised for strength and stiffness

4.2 Fire resistance

Cast steel can be fire protected in the same fashion as wrought steel. For example, thin film intumescent coating can be applied to carbon steel castings to enhance fire resistance.

The fire resistance of a casting can also be improved by filling it with unreinforced concrete or grout whereby the concrete acts as a heat sink in the event of a fire. A performance-based fire engineering analysis would need to be carried out to determine the structural response of the composite section in fire. Likewise, as wall thicknesses are easily manipulated in casting manufacturing, with a performance-based analysis, cast steel elements may be designed to have increased sections for adequate design capacity ratio at elevated temperatures, precluding the need for additional fire protection. The case study in Appendix A.3 describes how filling the cast steel column bases at the Charlotte International Airport with concrete provided a 2-hour fire resistance rating without the need for intumescent coating of the casting.

4.3 As-cast dimensional tolerances

Consideration of geometric tolerances is important in the detailed design of steel castings for incorporation into structural steelwork. The achievable dimensional tolerances of as-cast features of cast metal parts are affected by the alloy, casting design, pattern equipment, moulding process, quantity of castings required, and the size of the part or feature.

General tolerances for metal alloy castings are specified by BS EN ISO 8062-3[18] which uses a system of fifteen Dimensional Casting Tolerance Grades (DCTG) relating to tolerances corresponding to a series of basic casting dimensions, from DCTG 1 (the tightest tolerances) to DCTG 15 (the most generous tolerances). Features for which the general tolerances are not suitable, e.g. bolt holes, should be machined, with machining capable of delivering part dimensions accurate to within a fraction of a millimetre.

4.4 Surface finish

A wide variety of surface finishes can be achieved depending on the casting process and finishing techniques employed, from the surface being prepared for the application of a coating (such as for fire or corrosion protection) or being polished to achieve a decorative finish.

As with dimensional accuracy, surface finish is dependent on the alloy being cast, the size of component, the type of mould, the method of finishing, etc. Moulds with fine impenetrable surfaces give the smoothest surface, for example castings made in plaster, investment or ceramic moulds have smoother surfaces than those from conventional sand moulds. Smooth castings are likely to be more expensive than those with a rougher finish. In sand castings, the type of sand used has a significant effect on the surface quality of the casting.

Surface finish requirements should be discussed between the relevant parties early in the contract. While surface finish may not affect the structural performance of the casting (the exception to this statement is for castings subjected to fatigue loading), it can be a very important consideration for the end-user.

Very smooth surface finishes should only be specified for critical faces of a casting as they can add considerable cost; the highest standards of surface finish may not always be achievable all over the casting.

Surface finish of castings is specified using visual or tactile replicas of a standard range of actual cast surfaces. The use of tactile comparators is better than simply referring to photographs because the depth of surface irregularities can be compared more accurately. There are three specifications in common use:

ANSI/MSS SP-55-11 *Quality Standard for Steel Castings for Valves, Flanges, Fittings, and Other Piping Components - Visual Method for Evaluation of Surface Irregularities*[19]
The specification consists mainly of photographs of different types of surface conditions. It is widely used throughout the casting industry. MSS-SP-55 has one acceptance level which should be achievable on all sand castings. This level is midway between ASTM A802 levels II and III.

ASTM A802 *Standard practice for steel castings, surface acceptance standards, visual examination*[20]
This standard gives four different acceptance levels, all based on the CTI comparators.

CTI (formerly known as SCRATA) *Comparators for the Definition of Surface Quality of Steel Castings*[21]
These are tactile comparators; acceptance levels are given. The replica plates represent various features found on steel castings, such as surface texture, gas porosity and non-metallic inclusions.

Further guidance on acceptance levels of finish is given in Section 5.3.

4.5 Surface treatment

Just as with wrought steel products, surfaces of steel castings can be treated or coatings applied in order to provide protection against corrosion, fire, wear, galling, etc. Most often, steel castings are supplied to the steelwork contractor in the bare steel condition such that the castings may be readily welded into structural steel subassemblies at the fabrication shop and subsequently coated along with the adjoining steel framing.

Whether wrought or cast steel, the most important factor influencing the life of a paint coating is the proper preparation of the surface to be painted. When paint has lifted off a surface, it is usually due to chemical or electrolytic action underneath, caused by some contaminant which was not removed. In large components where descaling is difficult, an etch primer or phosphate primer can be used. In applying such a primer, metal reacts with it to form an insoluble complex phosphate. Primers may be applied by dipping, spraying or brushing. Polymer binders are contained in the primer, which seal the coating and form suitable pre-treatment surfaces for subsequent painting.

Heat tint forms on the surface of carbon and stainless steels after heat treatment or welding due to interference colours being set up by the thickening oxide layer. Although not a concern for carbon steel components because they are invariably painted, heat tint in stainless steels is undesirable. Even if discolouration is aesthetically acceptable, there is some uncertainty regarding whether its removal is necessary to maintain corrosion resistance. It does not seem generally important to remove heat tint for service in atmospheric conditions where the steel offers a good margin on resistance to that required for the particular environment. Removal of heat tint can be costly; if required, a pickling and passivation procedure should be followed. Local heat tint can be removed by polishing.

Surface finish is also important for carrying out various non-destructive tests and influences the ability to interpret results obtained from Magnetic particle inspection (MT) and Ultrasonic inspection (UT); further information is given in Section 5.3.

FOUNDRY QUALITY CONTROL, INSPECTION AND TESTING

This chapter describes foundry quality control, verification of mechanical properties and non-destructive testing. Inspection and testing should always be focused on those features which are relevant to the service use of the casting. This applies both to the methods specified, the acceptance level, and whether certain types of inspection can be restricted to specific parts of the casting. The significance of the casting within the overall structure should also be considered when planning the inspection programme. The shape and size of some castings are determined by aesthetic and not functional considerations, and so although a member is critical to the integrity of the structure, it may be subject to such low stresses that extensive inspection is unnecessary.

Poor quality control at a foundry can have serious consequences. It is essential to confirm that the mechanical properties indicated on the material test certificate issued by the foundry are representative of the actual cast component. Further information can be found in CROSS reports[22],[23],[24].

Serial numbers cast into each component provide traceability to all NDT and material test reports.

5.1 Foundry quality control

Foundries require third party accreditation in order to manufacture castings which are UKCA/CE marked to BS EN 10340. Using a foundry which is accredited to ISO 14001, ISO 45001 and ISO 9001 is also highly recommended. To be accredited to EN 10340, a foundry will need to implement a certified Factory Production Control system in accordance with the Construction Product Regulations, which involves maintenance and calibration of equipment, frequent checking to ensure product conformity, management of non-conforming products, procedures for controlling the quality of welds etc. Inspection and auditing of a foundry should be regularly carried out by a competent person with knowledge of the casting process to ensure all the necessary quality procedures are being carried out in accordance with the FPC system. Foundries can also be approved for manufacturing by organisations such as Lloyds Register, Det Norske Veritas and TÜV.

5.2 Verification of mechanical properties

For steel castings, BS EN 1090-2 requires Type 3.1 inspection documents according to BS EN 10204. These documents give strength, Charpy notch toughness, chemical composition etc. According to Table 1 of BS EN 1090-2, Type 2.2 inspection documents are also acceptable if the specified minimum yield strength of the casting is not greater than 355 MPa and specified impact energy is tested at a temperature of 20 °C.

As with all structural steelwork, it is good practice to check the adequacy, completeness and authenticity of all certification of steel castings, particularly when safety-critical items are involved.

BS EN 10340 requires that the mechanical properties of a casting (tensile strength, elongation, impact and hardness tests) be verified on test blocks (samples) 'of relevant thickness' (as described in 8.4.1 of BS EN 1559-2:2014) up to a thickness of 150 mm. The test blocks can be separately cast, cast side-by-side, cast on or cut from the casting. To remove test bars from the casting itself is impractical because it would destroy the usefulness of the component or require costly weld repairs to replace the material removed for testing purposes. Production specifications may call for full scale testing of a production casting when deemed appropriate.

The properties of test bars can only give approximations of the properties of the finished castings. For example, the cooling rate for small individually cast blocks is normally greater than for heavy wall castings. Both corrosion resistance and tensile properties are sensitive to cooling rate. Furthermore, the response to heat treatment can be different because of differences in cross-section or thickness. For this reason, separately cast test bars with cross-sections significantly different from those of the casting do not provide an adequate check on mechanical properties for structural applications, although they are probably sufficient for architectural details and castings which are subject to low stresses.

These difficulties can be overcome to a certain extent by testing coupons cut from test blocks which are larger than normal and that have cooling rates more representative of those experienced by the piece being produced. BS EN 1559-2 permits the geometry of the test blocks to be:

$t \times t$, where t is the relevant wall thickness, or

$t \times 3t \times 3t$, when the relevant wall thickness is greater than 56 mm.

It is generally preferable, however, for the mechanical properties of the casting to be verified by test blocks connected to the casting (known as a keel block). In cases where it is impractical for test blocks to be cast onto the castings themselves (as is the case for smaller castings), the test blocks should accompany the castings they represent during heat treatment. If the heat treatment of the test block does not replicate the heat treatment of the cast part, there will be a discrepancy between the mechanical properties of the test block and those of the cast part.

An alternative approach is to cast a prototype alongside some separate test blocks, all manufactured according to the proposed production method. Samples can then be cut from the prototype and mechanically tested along with test bars cut from the test blocks. This approach will give an indication of how closely the mechanical properties of the test blocks predict those of the actual casting. For safety critical components, e.g. bridge hanger connectors, random production pieces can be selected and test pieces cut from these.

The frequency of testing for mechanical properties required by BS EN 1090-2 is a minimum of once per melt. However, if multiple heat treatments are conducted per melt, each heat treatment batch should have a separate test block to represent the castings in that batch, as described above.

5.3 Non-destructive examination and testing (NDE and NDT)

Several NDE and NDT techniques may be executed by foundries to comply with the production specification. The requirements of the production specification should be selected to ensure a product is fit for service for the requirements of the project (as detailed in the performance requirements report). However, it is worth noting that neither BS EN 1559-2 or BS EN 10340 give any recommendations for NDE/NDT protocol stating that "*The castings shall be subjected to non-destructive examinations under conditions agreed at the time of enquiry and order*". As NDE/NDT can increase the costs of a casting considerably it is therefore important that for structural castings this is considered early in the design phase and acceptance levels set with reference to BS EN 1090. For especially critical components or those of higher Execution Class, more frequent and/or more onerous NDT than that specified in BS EN 1090-2 may be applicable.

BS EN 1090 Part 2, 5.4 includes requirements for testing and acceptance criteria "unless otherwise specified." Expertise is required to assess if the requirements of 5.4 are adequate to produce a component fit for the structural purpose intended and if not the NDE/NDT requirements should be amended.

Overly conservative specification, for example a blanket requirement for elimination of all types of defects from every area of the casting, is inappropriate and impractical. The choice of inspection method and acceptance level should be based on an evaluation of the part configuration and stress distribution under anticipated service conditions and the Execution Class of the structure or component. Many castings (or areas of castings) are not subject to high stresses and overly onerous acceptance criteria for surface flaws (unless the surface is clearly visible within short range and architecturally important) or sub-surface indications should not be specified.

The term defect in the context of steel castings is easy to misunderstand. All components, whether fabricated or cast, contain defects (blemishes, flaws, indications, etc.). Action is only needed if they exceed the determined acceptance level, i.e. if they are 'nonconformities'. For fabricated steelwork, an example of a nonconformity would be a defect which exceeds the geometrical tolerances.

The same acceptance levels need not apply to all areas of a casting, or to all types of defect. Some types of defect are more detrimental than others, depending on the nature of the stress to which the casting is subject in service. However, it is important to ensure that the areas of a casting which are to be welded to other structural members are of suitable soundness for welding.

For castings which are very highly stressed or critical to the integrity of the structure, thorough testing of a prototype, or First Article, may be carried out to investigate whether the proposed programme of examination can identify all the critical defects. This will usually lead to a reduction in examination and testing requirements for factory production control procedures. Fracture mechanics methods may be used to justify the selection of a given NDE acceptance level/sensitivity as well as to investigate whether a casting containing defects larger than the maximum permitted size is fit for purpose.

As no single method of NDT can survey all defect situations, NDT techniques are often used in a complementary manner, e.g. magnetic particle inspection will show a surface crack while ultrasonics will measure its depth, or ultrasonics may reveal a defect and radiography will show its identity. Expertise is needed to identify where defects are likely to occur in a given cast part in order for an economic and achievable NDT programme to be developed.

5.3.1 Surface inspection methods

Visual inspection (VT)

Visual inspection is generally carried out with the unaided eye in good lighting. Surface imperfections such as sand inclusions and cold laps can be detected visually, but pinhole porosity, cracks and hot tears cannot. See also Section 4.4.

Magnetic particle inspection (MT)

MT is an inexpensive, simple, yet sensitive method of detecting cracks which reach the surface or near to the surface of a casting. During MT, the casting is first magnetised to produce magnetic lines of force in the material. Fine iron particles are then applied either in dry powder form or in a liquid medium. The particles accumulate at discontinuities, such as cracks, because the magnetic flux is distorted and 'leaks' in these regions. Surfaces are then visually inspected with the fine iron particles bringing attention to surface or near surface discontinuities. The particles may be coated with fluorescent dye to make them easier to see.

MT is only applicable to magnetic materials; austenitic stainless steels are non-magnetic and therefore cannot be inspected using this method.

Penetrant inspection (PT)

PT is a sensitive and inexpensive method of detecting defects open to the surface. It is based upon capillary action, where low surface tension fluid penetrates into clean and dry surface-breaking discontinuities. Surplus liquid is then removed from the surface and a developer draws the dye out of the flaws so they become visible.

PT can be used on all steels, but it is generally only used on non- or slightly magnetic steels such as austenitic or duplex stainless steels.

5.3.2 Sub-surface inspection methods

Ultrasonic testing (UT)

Ultrasonic testing can be used to identify cracks and linear discontinuities as well as pores, voids, and inclusions larger than 3 mm within the body of a casting. Ultrasonic impulses are sent into the casting from special probes. Attenuation and echoes of the impulses are monitored to determine the presence and location of defects. UT by manual methods depends on the skill of the operator for correct calibration, application and interpretation of the displayed signals in order to estimate the nature and size of the defects. Nevertheless, it is often used as a rapid and economical check of casting soundness.

UT is applicable to carbon steel castings greater than 40-80 mm in thickness, depending on the microstructure and grain size of the steel. There are no standards for UT of austenitic stainless steel castings and duplex stainless steel castings as in some circumstances the microstructure and grain size can be larger, or of the same order as the ultrasonic wavelength. It may be possible to generate material specific test blocks and equipment calibration to apply UT in bespoke circumstances.

Radiographic testing (RT)

Radiographic testing can be used to identify volumetric indications within steel castings. This method involves placing a film immediately behind the casting with a source of radiation directed towards the casting from the other side. The source may be gamma or X-rays. The wavelength of the radiation is sufficiently short to allow a proportion of the radiation to pass through the metal to reach the film. The amount of radiation absorbed depends on the thickness and density of the metal - differences in the thickness of the metal due to the presence of flaws will lead to a difference in exposure on the film. The maximum thickness that can be practically inspected is dependent on the radiation source; most facilities cannot examine steel parts with thicknesses in excess of 120 mm.

It is important to note that any flaws which do not affect the density or path length through the metal will not be detected. Hence, radiography is good at identifying volumetric non-planar flaws such as porosity as well as planar flaws which are aligned parallel to the direction of the radiation beam and are not closed tightly together. However, planar flaws that are aligned perpendicular to the radiation beam or closed tight, such as hairline cracks, cannot be detected via RT.

5.4 NDT specification requirements

5.4.1 Typical NDT specification requirements

Table 5.1 gives the relevant European standards for NDT of steel castings. The standards covering testing conditions give acceptance criteria expressed in terms of severity levels with corresponding maximum permissible discontinuities. Discontinuities include gas porosity, cracks, hot tears, inserts, blowholes, non-metallic inclusions, and shrinkage. In all cases the severity level with the lowest number is the strictest.

Table 5.1
NDT for steel casting

Name	Visual VT	Liquid penetrant DT	Magnetic particle MT	Ultrasonic UT	Radiographic RT
General principles	BS EN 10318[25]	BS EN ISO 3452-1[26]	BS EN ISO 9934-1[27]	BS EN ISO 16810[28]	BS EN ISO 5579[29] BS EN ISO 19232-1[30] BS EN 14784-1[31]
Testing conditions and severity levels	BS EN 1370[32]	BS EN 1371-1[33] BS EN 1371-2[34]	BS EN 1369[35]	BS EN 12680-1[36] BS EN 12680-2[37]	BS EN 12681[38]

For every NDT, the following should always be carefully specified:

i. The type of test and the relevant standard
ii. The acceptance level (severity level)
iii. The area of casting to be tested (location and extent, for example 100% coverage of all accessible areas, or fillets, changes in section and weld areas)
iv. The percentage and/or frequency of castings to be inspected (for example every casting, or one in every 5 castings)

While good part design and foundry process engineering can reduce the likelihood of defects, some types of defects are somewhat random (e.g., sand inclusions or gas porosity) and therefore cannot be eliminated without inspection and upgrade. As such, if a part is not tested, it cannot be assumed to be of identical soundness in every respect to another identically produced part.

Conversely, some types of defects are very heavily correlated to certain aspects of foundry process engineering (e.g., shrinkage porosity is the result of inadequate part feeding). This is why “first article” castings are more typically subjected to RT than are production parts (because if the first article casting did not exhibit shrinkage porosity, the feeder/gating system for the part has been “proven” and so, all other things being equal, the production parts are unlikely to exhibit shrinkage porosity).

The severity levels for different NDT techniques are as follows:

Visual inspection (BS EN 1370): Severity levels for the dimensions of surface discontinuities range from VD1 to VD8. Surface discontinuities can also be classified by the CTI visual tactile comparators[21], and are ranked in four severity levels from VC1 to VC4.

Penetrant inspection (BS EN 1371-1): discontinuities can be non-linear (isolated (SP) or clustered (CP)), linear (LP) or aligned (AP). There are eight severity levels for SP 01 to SP5, six severity levels from CP 01 to CP 3 and nine levels for LP/AP 001 to LP/AP 7.

Magnetic particle inspection (BS EN 1369): Discontinuities are categorised as non-linear indications (SM) and linear and aligned indications (LM and AM). Seven severity levels are applied to non-linear indications (SM 001 to SM5). Nine severity levels are applied to linear and aligned indications (LM 001 to LM7, AM 001 to AM7).

Ultrasonic inspection (BS EN 12680-1): Metrics such as number of discontinuities in a 100 mm x 100 mm frame and maximum value of dimension in through-wall direction of discontinuities are used to categorise the severity levels. There are five severity levels 1 to 5.

Radiographic testing (BS EN 12681): Discontinuities are categorised according to reference radiographs given in ASTM E186[39], ASTM E280[40] and ASTM E446[41]. There are five severity levels 1 to 5.

5.4.2 BS EN 1090-2

Unless otherwise specified, BS EN 1090-2 clause 5.4 requires the properties of delivered castings to be evaluated by the following tests:

a. 100 % visual inspection;
b. the following destructive tests on items taken at random during production. The execution specification shall specify whether the items shall be destructive product samples (i.e. cut from the casting), extension pieces (i.e. cast on) or separate items cast simultaneously:
    1. tensile and elongation tests (one unit per melt);
    2. impact tests (three units per melt);
    3. reduction of area test (one unit per melt if relevant);
    4. chemical analysis (one unit per melt);
    5. microscopic examination of cross-sections (one unit per melt).

c. the following non-destructive tests on items taken at random from each manufacturing lot:
    6. MT or PT of surface-breaking discontinuities on 10 % of each manufacturing lot, and;
    7. UT or RT to detect sub-surface discontinuities on 10 % of each manufacturing lot.

Note: This very low frequency of MT/PT testing would only be suitable for very high volume components, where incremental process improvements would have been made to ensure quality, i.e., this frequency of testing would be completely inappropriate for most custom designed cast components for use in structural applications where MT/PT testing of every casting would often be appropriate. It may also be unsuitable for some structures where 'off-the-shelf' castings play a critical role in load transfer, such as hangers for bridges which typically would be classified as Execution Class 4 and so a higher level inspection regime may be warranted, for example as stated in the model specification for structural tension assemblies published by the BCSA[42] .

As discussed above, test bars should be subjected to the same heat treatment as the castings they are meant to represent, and this requirement is not stated in clause 5.4.

For steel castings, RT is commonly reserved for the first article casting. RT is only used for production parts at a reduced frequency or for special applications where other test methods cannot be relied upon to identify defects in critical regions of production components due to some geometric or other constraint.

Unless otherwise specified, BS EN 1090-2 defines the following acceptance levels for cast steel components:

- SM2 and LM3/AM3 to BS EN 1369 for MT;
- Severity level 2 to BS EN 12680-1 for UT;
- Severity level 3 to BS EN 12681-1 for RT.

As mentioned in Section 5.3, the same acceptance levels need not apply to all areas of a casting.

Fracture mechanics methods may be used to justify the selection of acceptance levels.

5.4.3 Manual of Contract Documents for Highway Works

The Manual of Contract Documents for Highway Works, Volume 1 *Specification for Highway Works*, Series 1800 *Structural Steelwork* requires that steel castings shall be verified by the constructor in accordance with the specific testing requirements and acceptance levels given in Table 18/3 and reproduced below as Table 5.2.

The Quantified Service Category (QSC) characterises a detail, component or structure (or part thereof) in terms of the circumstances of its use within specified limits of static and cyclic stressing. The number of each QSC corresponds to the reference value of fatigue strength in N/mm^2 at 2 million cycles. This is the same numbering system as used for detail categories in BS EN 1993-1-9.

As mentioned above, the same acceptance levels need not apply to all areas of a casting.

BS EN 1090-2:2018, 5.4	Testing requirement	Quantified Service Category (QSC)				
		F56	F71	F90	F112	F140
a) Visual inspection	% of lot	100				
b) Destructive tests	Test piece type	Product sample				
c) Non-destructive tests	6) MT% of lot	20	100	100	100	100
	7) UT% of lot	20	50	100	100	100
	7) RT% of lot	20	20	50	100	100
Acceptance level	MT severity level SM	2	2	1	NP[1]	NP[1]
	MT severity level LM/AM	3	2	1	NP[1]	NP[1]
	UT severity level	2	1	1	NP[1]	NP[1]
	RT severity level SM[2]	3	2	1	NP[1]	NP[1]

[1] NP = no indications permitted
[2] In accordance with BS EN 12681

Table 5.2 Specific testing requirements and acceptance levels for steel castings

5.5 Foundry production welding

As part of the production process, the foundry will remove any defects which exceed the agreed acceptance level. For small defects close to the surface, this may be done by grinding and/or blending. More significant flaws can be removed by cutting out with an arc-air lance. The cavity can then be filled with sound metal by welding using a consumable that ensures compatibility with the original cast material. Once the defect is removed, the area is typically ground flush and re-examined by the methods and to the acceptance level specified.

After welding, castings may then undergo post weld heat treatment to eliminate residual stresses introduced by welding operations, or to optimise mechanical properties. Welding may not be required if small defects have been removed by machining operations, providing the design intent of the casting is not compromised. Not all production welding will need post weld heat treatment, however, it is necessary with some alloys to reduce the hardness of the heat affected zone.

Foundry production welding should comply with the same criteria for NDE as the relevant part of the casting and should be carried out according to a qualified welding procedure (EN ISO 11970[43]). Guidance on the development of foundry production welding procedures for castings can be found in BS EN 1011[44] and BS 4570[45]. Manual metal arc (MMA) methods with coated electrodes are widely used. Low hydrogen electrodes, shielding gases such as CO_2 and argon, and submerged arc and electro-slag methods are also suitable. Welding should have no adverse effects on the integrity of castings because it is carried out under controlled shop conditions using qualified procedures and qualified welders, with welded areas reinspected by qualified inspectors.

SUSTAINABILITY ISSUES

Limiting embodied carbon is becoming as important as controlling cost and safety, although it should be noted that it is only a subset of a range of environmental impacts which, in turn, is one of the three pillars of sustainable development alongside social and economic considerations.

The bulk of carbon emissions from foundries arises from the production of the substantial amount of energy required to melt the scrap steel. Foundries can be considered as recycling facilities in their own rights since almost all the material melted is recycled steel scrap. The remaining emissions come from energy used in generating compressed air, managing cooling water, managing the sand, dies and moulds, and machining and heat treatment operations.

The UK foundry industry has achieved significant energy and carbon reductions since 2011. This has been achieved through energy efficiency improvements and switching to electric induction furnaces. If the electrical energy comes from renewable sources, such as a wind or solar installation on site, then the carbon footprint is further reduced. Recycling of sand used in the sand-casting process means that most of the sand used is now recycled.

Most foundries by necessity are very familiar with keeping energy costs under control, however, a system accredited to ISO 50001[46] is of value since it follows a framework of measurement, review and continuous improvement following a logical policy strategy. Accreditation provides additional motivations since the system and the necessity for reporting against set targets, is audited annually.

It is expected that an Environmental Product Declaration (EPD) for a steel component cast in a UK or EU foundry would be similar to that for a UK or EU rolled steel component manufactured via the electric arc furnace route.

Casting can be considered as a ‘near-net shape’ manufacturing process as it optimizes material usage, minimizes fabrication efforts (for example welding consumables are not needed) and can cut down on the time of erection. These all contribute to lowered embodied carbon.

Castings are less susceptible to coating system performance failure because they have generous radii and gentle geometric transitions. This reduced susceptibility to failure also means lower embodied carbon through reduction in maintenance. Castings can also provide significantly enhanced service life to fatigue critical structures wherein cast steel nodes are used in lieu of conventionally fabricated connections.

The following advances in technology have also led to greater production and design efficiency, and the lower use of resources:

- 3D modelling and casting simulation software enables the foundry to influence the design process at a much earlier stage and identify design modifications or how to combine multiple assemblies into a single, more efficient casting that reduces weight, materials, and cost.
- Digital casting simulations make it possible to identify casting issues or potential defects before a pattern has been made. This cuts down the number of pattern modifications needed and reduces time and resources in producing cast prototypes/first articles.
- Rapid prototypes using additive technology (3D Printing) reduce the need for patterns to be made in the traditional way. 3D scanning of existing components to enable reverse engineering also enhances efficiency.

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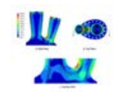

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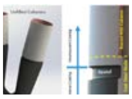

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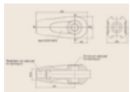

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Figure B.4;
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APPENDIX A
CASE STUDIES

A.1 Western Concourse, King's Cross Station, London

Client:	Network Rail
Architect:	John McAslan + Partners
Structural Engineer:	Arup
Main Contractor:	Vinci Construction
Steelwork Contractor:	Seele
Foundry:	Guivisa
Year of completion:	2012

King's Cross Station is a major rail terminus located on the edge of Central London. It is a Grade I listed historic structure and one of the busiest stations in the United Kingdom, serving as the southern terminus of the East Coast Main Line; one of Britain's major railways connecting London with cities including Leeds, Newcastle, and Edinburgh.

The station, originally designed by civil engineer and architect Lewis Cubitt, opened in 1852 with two platforms. It was expanded and redeveloped over the years to eventually include 11 platforms but by the end of the 20th century the station needed upgrading and restoration.

The £550m redevelopment project began in 2008 and was completed in 2012, in time for the start of the London 2012 Summer Olympics. The centrepiece of the project was a new western concourse positioned next to, but required to be structurally separate from, the historic listed buildings of the original station.

The roof of the concourse rises to a height of 20 m and spans 150 m. The 1,200 tonne roof is formed of a steel diagrid shell structure spanning between a central 'funnel' structure and 16 equally spaced perimeter 'tree' columns, each carrying a horizontal load of about 600 tonne. The funnel structure and tree columns are formed of steel structural hollow sections, with a mix of circular and rectangular sections forming the majority of the diagrid roof. The 4.5 m tall tree columns are elliptical in section and taper upwards towards a multiplanar node casting which connects the branches to the trunk, with each casting weighing 1.5 tonnes. The finish of each casting is the texture of the sand that was used in the casting.

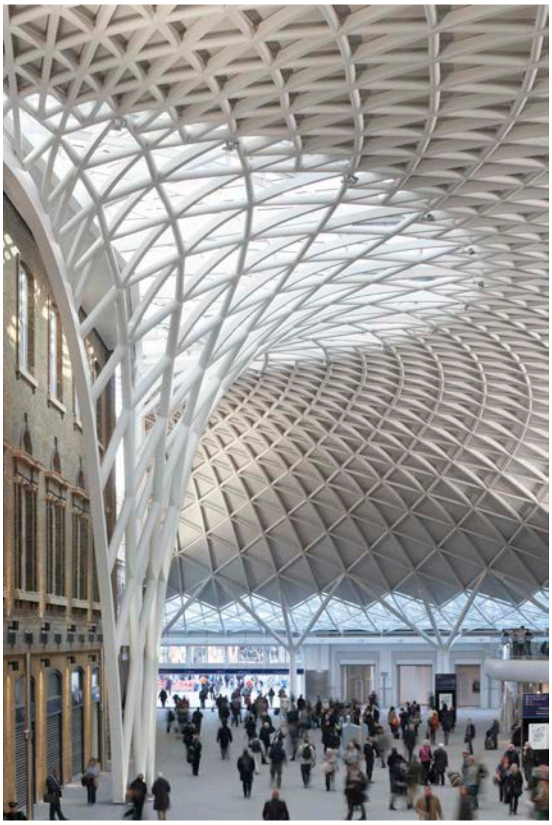


Figure A.1 Completed Western Concourse showing the funnel and perimeter columns

Figure A.2 Steel castings at the fabrication shop

Figure A.3
Cast nodes connect the ‘branches’ to the ‘trunk’columns

A.2 MSG Sphere at The Venetian, Las Vegas

Client:	Madison Square Garden Company
Architect:	Populous
Structural Engineer:	Severud Consulting Engineers
Main Contractor:	AECOM Hunt, Madison Square Garden Company
Steelwork Contractor:	W&W | AFCO Steel
Foundry:	CAST CONNEX
Year of completion:	2023

The MSG Sphere at The Venetian is a music and entertainment arena near the Las Vegas Strip, USA. At almost 160 m in diameter, the steel exosphere structure is the largest spherical structure in the world. The primary function of the exosphere structure is to provide support for the nearly 54,000 m^2 LED screen.

The structure of the exosphere consists of circular hollow sections, ranging in diameter from 324 mm to 610 mm, connected in a triangulated grid arrangement by cast steel nodes. This arrangement of members means that a typical node connects six hollow section members, each orientated slightly out of plane to achieve the gentle curvature of the large sphere.

Altogether, 368 cast steel nodes were required, in 21 different designs. Finite element modelling of the exosphere steel castings enabled their dimensions to be optimised for strength and stiffness (Figure 4.1). The weights of these individual nodes ranged from 1.4 to 6.5 tonnes, leading to a total weight of almost 1180 tonnes for the structural nodes alone. Additional 'off-the-shelf' standardised cast field-bolted splice components were utilised in the tubular structure forming the secondary trellis covering the primary exosphere.

A comparison between the casting and a fabricated equivalent for a typical node with six incoming members showed significant reductions in weight, number of bolts and surface area to be coated. These comparisons are shown in Table A.1. As well as these reductions, the cast nodes have CNC-machined flanges and bolt holes, ensuring high accuracy in spatial location and angles compared to the fabricated equivalent which would have been subject to mill tolerances and distortion due to the heat of welding, which was a major concern.

Table A.1 Comparison between cast and fabricated nodes for a typical node with six incoming members

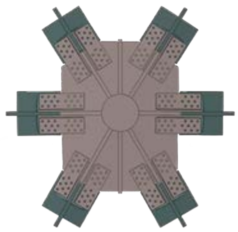
Measure	**Cast node** 	**Fabricated node** 	**Reduction achieved with Casting**
Weight (tonnes)	3.5t cast node + 1.5t for flange plates welded to ends of adjoining pipe members	11.6t for fabricated node, splice plates, and connections at ends of adjoining pipe members	57%
Number of Bolts	104	432	76%
Surface Area (m^2)	8	33	76%

Figure A.4 Cast node (left). 'Up' indicators were cast into the nodes to aid rapid assembly (right)

Figure A.5
Cast nodes on site ready to be installed

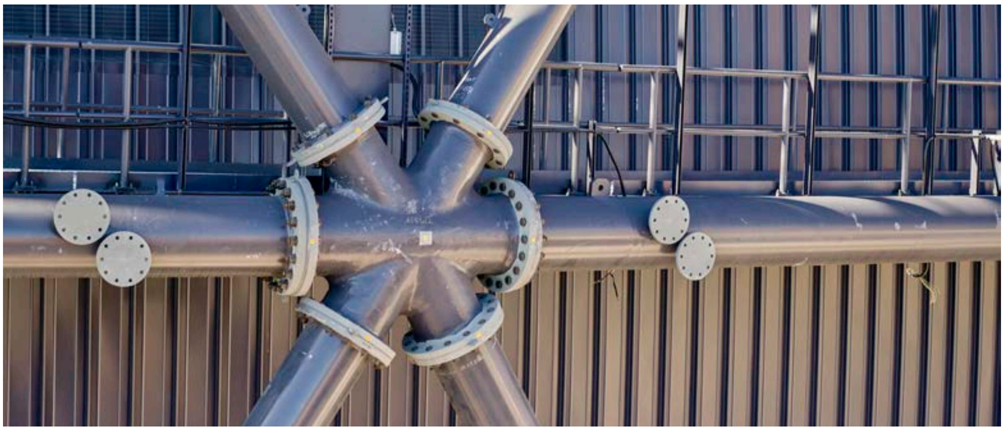


Figure A.6
Close-up of cast node in MSG exosphere

Figure A.7
MSG exosphere

A.3 Concourse A Expansion, Charlotte Douglas International Airport

Client:	Charlotte Douglas International Airport
Architect:	Perkins&Will and C Design
Structural Engineer:	Stewart
Main Contractor:	Turner Rogers Joint Venture
Steelwork Contractor:	CMC Structural (now SC Steel)
Foundry:	CAST CONNEX
Year of completion:	2018

As part of the expansion of Charlotte Douglas International Airport, a hybrid three-storey concourse structure was built consisting of a structural concrete podium with a structural steel mezzanine and roof. Exposed V-shaped steel columns (500 mm and 400 mm circular hollow sections) support the roof trusses and the lateral supports to the glass walls and were connected at the base by custom cast steel nodes (Figure A.8). The nodes each weigh over 1.8 tonnes and transfer wind, seismic, and blast loading through an elevated concrete slab to concrete columns below. Castings were chosen rather than fabricated connections because the connections were architecturally exposed, complex, heavily loaded, and a high degree of fixity with tight tolerances were required. It would have been very difficult to achieve the complex curvatures and freeform geometries with a conventionally fabricated connection to the tight dimensional tolerances and high quality surface finish requirements.

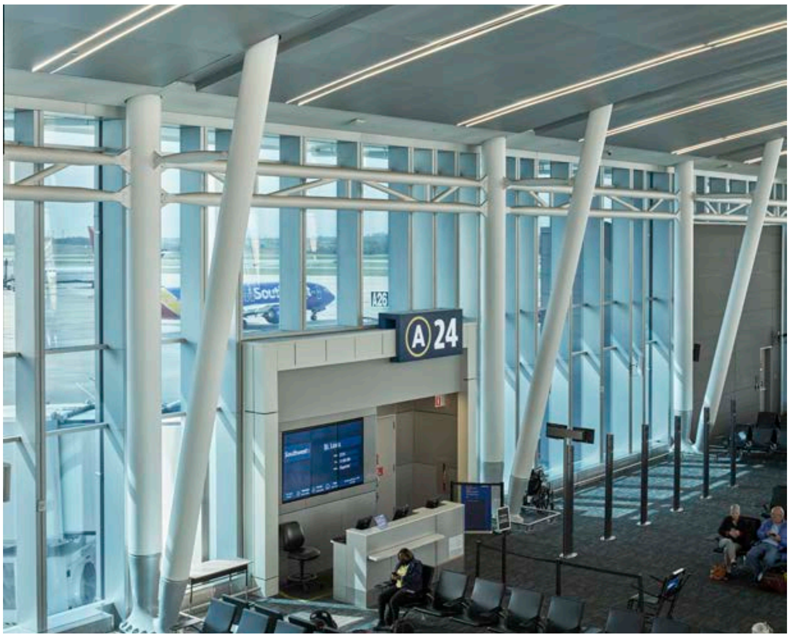


Figure A.8 Columns and cast steel bases in Concourse A, Charlotte Douglas International Airport

The design of the cast steel bases was developed through a collaboration between the architect, structural engineer, and casting designer-supplier (Figure A.9). The design process involved a number of iterations, considering fabrication and erection as well as optimising architectural and structural performance.

The alloy used for the casting was Grade SC8620 Class 80/50 specified in accordance with ASTM A958.

Figure A.9 Collaborative conceptual design development of the cast steel base

The detailed design was carried out using finite element methods with a model that included coupling constraints, contact boundary conditions, and non-linear material models to sufficiently capture the interaction between the steel columns, cast steel base, anchor rods, and reinforced concrete structure below the base (Figure A.10).

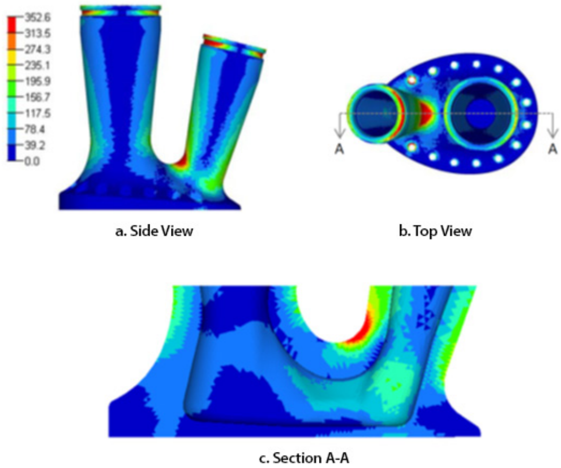


Figure A.10 Finite element analysis of cast steel base

A two hour fire resistance rating was required for the columns and cast steel bases. However, the architect wanted to avoid the use of intumescent paint on the castings as an intumescent painted finish is unlikely to be smooth, will collect dust and debris, and may be more susceptible to erosion (chipping off) in highly trafficked areas than a standard painted coating. Using a performance-based fire engineering analysis, two hour fire resistance was achieved by increasing the wall thickness of the casting and filling it with concrete.

Figure A.11
The cast base achieved two hour fire resistance by increasing the wall thickness and infilling with concrete

Because the cast steel bases were required to comply with very tight dimensional tolerances, close coordination was needed with the contractor responsible for the concrete placement to ensure the anchor rods were installed accurately to align with the precise cast steel connection. (Accuracy can be achieved through the use of steel templates (like modular cages) which hold the rods in their correct position/spacing relative to one another. A template also ensures that the rods remain aligned/straight during concrete placement.

The openings in the casting to accept the anchor rods were CNC milled and the casting designer-supplier developed a template for the concrete contractor to use to assist coordination between trades and simplify construction activities.

Figure A.12
CNC machining of casting to facilitate fit-up with incoming columns

Figure A.13
Cast steel base in-situ

CAST CONNEX's 'Off-the-shelf' standardised cast steel Architectural Taper™ and Universal Pin Connector™ (220 mm and 168 mm diameter) were also used in the frames and trusses of the concourse to connect lateral bracing in the long span roof at the top of the columns and in the bracing orthogonal to the frames (Figure A.8 and Figure A.14). The use of castings for these components eliminated complicated fabrication and potential fit-up difficulties with fabricated components. Additionally, savings were realized in design as the designer could refer to tabulated connection capacities, and 2D and 3D CAD files were available to assist in design documentation and detailing of the standardised products.

Figure A.14
Standardised cast steel Architectural Taper and Universal Pin Connectors by CAST CONNEX were used to connect the lateral bracing in the long span roof at the top of the columns and in bracing orthogonal to the frames

A.4 A244 Walton Bridge, Walton-On-Thames, Surrey

Client:	Surrey County Council
Design:	AtkinsRéalis
Main Contractor:	Costain
Steelwork Contractor:	Mabey Bridge
Tie rod manufacturer:	Anker Schroeder ASDO GmbH
Year of completion:	2013

There has been a crossing over the River Thames near London connecting Walton-on-Thames and Shepperton since the mid-1700's. The sixth incarnation of this is an award-winning contemporary steel arch bridge featuring two parallel hexagonal curved steel arches that span 96 m supporting the road deck. These thrust arches give the bridge a distinctive and elegant appearance, with a modern aesthetic that complements the surrounding landscape. The bridge's clean lines and smooth curves make it a visually striking feature along the river, and it has become a significant local landmark. The road deck provides two lanes for vehicles and separate pathways allow pedestrians and cyclists to cross safely.

Figure A.15 Ariel view of the Walton bridge across the River Thames

Overall, Walton Bridge is not only a vital transportation link for the local community but also a visually striking structure that adds to the beauty of the River Thames and its surroundings.

Figure A.16
Cast fork end

The deck is suspended from the arches using Anker Schroeder M100 high strength structural tie rods which are connected using standardised cast steel connectors (i.e. 'off-the-shelf' fork ends/clevis).

The castings were selected for their sleek transition from solid round steel to the deck connection plates, complementing the contemporary aesthetics of the bridge. The castings allowed the tie rods to be free to rotate transversely, top and bottom, with easily formed pinned joints which also aided the construction sequence, allowing the suspension of the deck in stages.

Figure A.17
Detail of tie rod connection and construction sequence

The tie rod size was selected for a ULS load of 3200 kN which allowed for hangers to be replaced one-by-one should the need arise in the future. The cast fork ends were also required to accommodate a 0.5° misalignment and the fatigue requirements for the structure.

The fork ends were cast using the sand mould process with G20Mn5 grade steel to BS EN 10340. From each heat (melt) approximately six castings were produced along with one separately cast test piece as per BS EN 1559-2. The test bar was heat treated with the same batch of castings it represented. Each test bar was of sufficient size to allow three lots of test samples for determining the mechanical properties (yield, tensile, elongation, Charpy). One set was tested by the foundry prior to release of the castings, one set used by the supplier for random checks and one set for future reference should it be required.

As standard 'off-the-shelf' products, each batch of castings followed the minimum NDT requirements of BS EN 1090-2 with some enhancements based on the tie rod manufacturer's experience. Since the castings were being used in a bridge structure for safety critical components, the minimum requirements of BS EN 1090-2 were not felt to be adequate or sufficient by the project engineer, therefore additional project NDT requirements were required as shown in Table A.2.

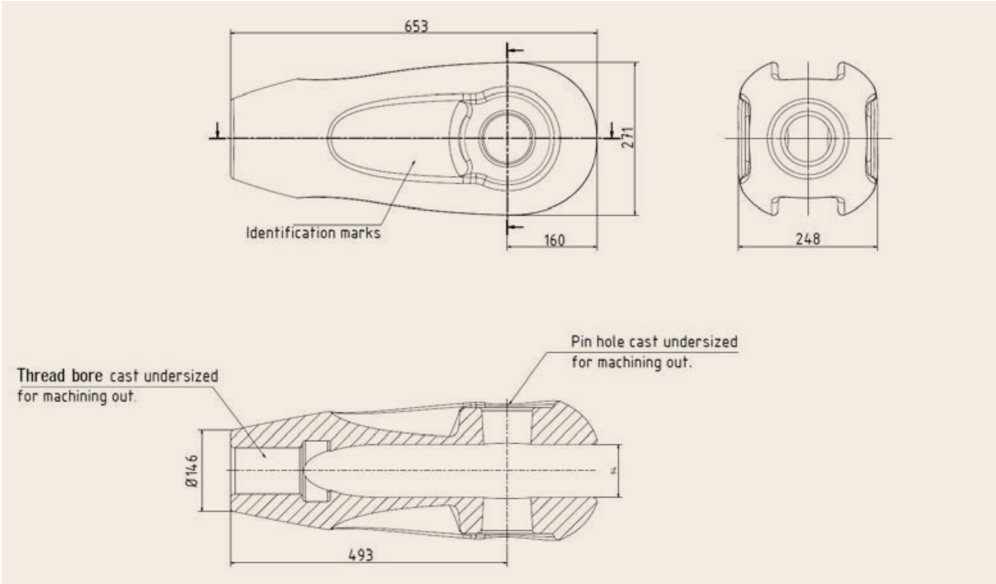


Figure A.18
CAD detail of fork end

Table A.2
NDT levels for castings as safety critical components

	Visual VT	Magnetic particle MT	Ultrasonic UT	Radiographic RT
Testing conditions	BS EN 1370	BS EN 1369	BS EN 12680-1 BS EN 12680-2	BS EN 12681
Acceptance levels		SM2/LM2/AM2	Level 2	Level 2 around pin holes Level 3 other areas
Quantity tested by foundry	100%	10% random	10% random	3% random
Quantity tested by manufacturer	10% random	5% random	5% random	1% random
Additional project requirements	100% before use	100% before use		100% before use

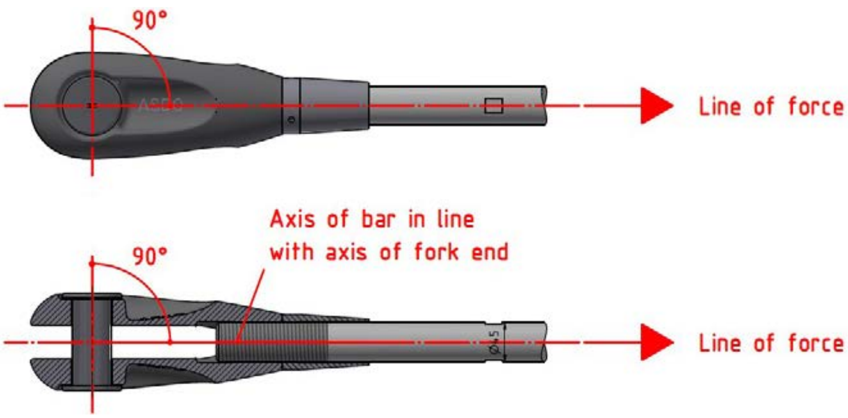


Figure A.19
Alignment of pin and thread with line of force

After casting, the fork ends were CNC machined to form the pin holes and threaded bore to receive the tie rod. It is vital that these are made as accurately as possible and are in line with the load axis of the complete system (Figure A.19). As the sand casting process is not accurate enough to achieve this, the pin holes and thread bore are cast with excess material to allow machining and accurate placement. Previous failures in these types of castings have been due to poor alignment of load bearing surfaces giving rise to additional stresses and bending.

In addition to the NDT tests, a fatigue test and full-scale test to destruction were required for the complete tie rod system. These not only tested the complete system but also the casting design and strength. A further requirement was for the cast fork end connection to be deliberately loaded with a 0.5° misalignment of the connecting lugs to simulate in-service use.

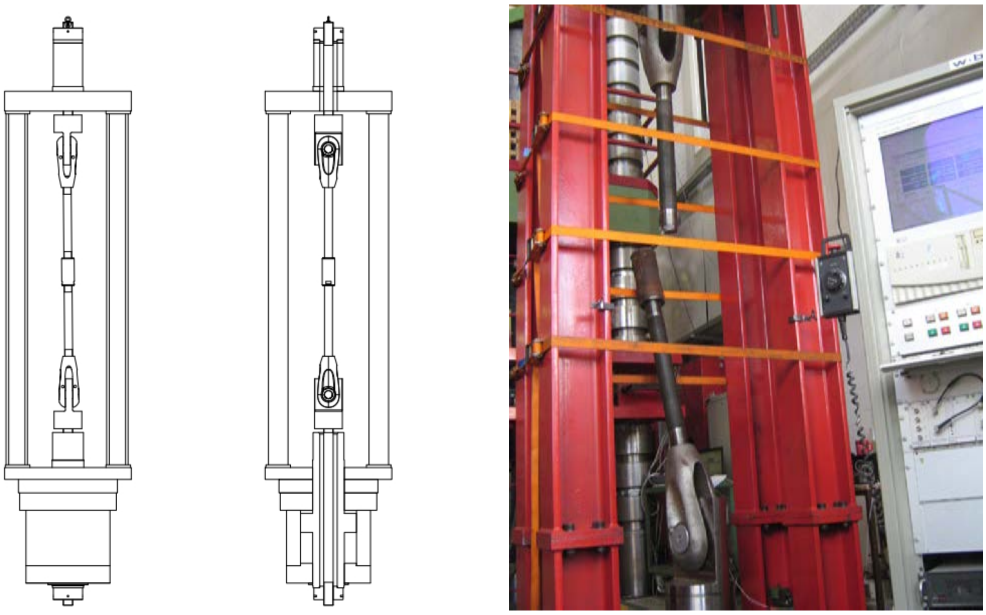


Figure A.20 Fatigue and destructive load test

Random castings were selected from production and a representative hanger system made which could fit into the test rig (Figure A.20). Connection details were fabricated that also incorporated the 0.5° angular misalignment. The whole assembly was then loaded for two million cycles at a stress range equal to 1.25 times the damage equivalent stress range calculated by applying fatigue load model 3 of BS EN 1991-2:2003 *Eurocode 1. Actions on structures - Traffic loads on bridges*. After fatigue testing, the assembly was then subjected to a breaking load test to ensure that the rated load capacity of the system was met. The photograph in Figure A.20 shows that the assembly failed at the bar thread entry to the turnbuckle, demonstrating that the cast connectors more than exceeded the design rating.

Model specifications for structural tie rods (including cast components) can be found in Model *Specification for the Purchase of Structural Tension Assemblies*[42]. More detailed design aspects of the bridge are described in Hendy *et al*, Proceedings of the Institution of Civil Engineers - Bridge Engineering Volume 170 Issue 2, June, 2017.

APPENDIX B CASTING MANUFACTURE

B.1 The casting process

A steel casting is formed by pouring liquid steel into the cavity of a mould which is the shape of the part to be produced. Compared to the final dimensions of the casting, the cavity is oversized to account for shrinkage and contraction of the part during solidification and cooling. The cavity also includes 'rigging' – passageways (gating) for the liquid metal to enter the mould and additional sacrificial reservoirs (feeders) to feed the casting as it solidifies. The foundry designs the mould to provide the desired dimensions and quality.

Moulds are made from a refractory material, usually sand containing a suitable bonding agent. A tool (pattern), the exact shape of the part, creates an impression in the sand. Generally, the mould is made in two halves so that the pattern, which can be reused to make more moulds, can be removed to form the cavity for the liquid steel. To create the internal geometry of the part or other special features, additional pieces, known as cores, are manufactured from sand and placed into the mould like a 3D puzzle so that the final mould cavity represents the part plus rigging. The most suitable method of moulding depends on the size of the cast product, the number required, the desired surface finish, etc.

Once the metal has completely solidified, the casting is taken out of the mould and finished by removing excess metal including the gating and feeders. Typically, castings are heat treated, non-destructively tested, production welded, re-tested, and critical features machined.

The following sections in this Appendix are relevant to sand casting, which is the most common process for structural steel castings. However, other relevant processes for structural applications include:

Investment casting (lost wax casting) is appropriate for mass produced 'off-the-shelf' products and certain highly specialised castings requiring an unusually fine finish, precise detail or close tolerances in the as-cast configuration. It is generally limited to small castings with weights from 0.025 kg to about 20 kg and with section thicknesses in the range of 1 mm to about 75 mm. In this process, a mould is produced by coating (investing) a wax replica of the final casting with a ceramic slurry. The wax replica must be oversized to account for shrinkage/contraction. The wax is then melted or burned out leaving a cavity in the mould of exactly the same shape as the wax pattern.

Centrifugal casting is a technique for making thin-walled cylinders. Tooling or dies for centrifugal casting are commonly made from metal but a protective refractory wash is applied so that the liquid metal does not bond to the die. This casting process rotates the mould during pouring and solidification to make the part geometry oriented around an axis.

B.2 Patterns

Patterns for sand castings are usually made of wood, plastic or metal, based on the expected production runs. Sand casting patterns are generally split, with the two halves mounted on separate plates or boards, one forming the top and one the bottom of the mould. The parting line is the plane or planes along which a mould is split. Parting in one plane facilitates the production of the pattern as well as the making of the mould. Patterns are not a simple positive of the casting because they need to allow for the flow of liquid metal as well as its contraction during cooling and solidification.

Extra feed metal must be placed at strategic locations around the mould during casting to avoid the formation of unwanted cavities within the casting due to shrinkage during solidification. Steel directionally solidifies with solidification fronts propagating towards areas of thermal mass. Sacrificial feed metal reservoirs (feeders) can be used to accommodate shrinkage. After casting, the reservoirs are removed and remelted to make new castings. Patterns should be made with dimensions larger than those required in the finished casting. Typical shrinkage allowances are 2% for carbon steel and 2.5% for stainless steel.

The vertical sides of a pattern usually have a taper or draft to permit removal of the pattern from the mould. Some patterns will include additional features such as chills for promoting directional solidification and cores to create internal part geometry or other features difficult to make such as undercuts.

The choice and design of pattern depends on the number of castings to be produced, the moulding and core process to be used, dimensional tolerances required and size and shape of casting. Investing in a good pattern can lead to considerable cost savings in the long term, e.g., by reducing the cost of machining the cast products.

For replacement work, the original part can be 3D scanned, reverse engineered, and tooling produced.

Nearly all tooling is produced via CNC machining or milling. This enables geometrically accurate patterns and/or prototypes to be manufactured at lower cost and with short lead times. Modifications can also be easily carried out.

For prototypes or low volumes, patterns can be made from materials such as closed-cell extruded polystyrene foam or from additively manufactured plastics.

B.3 Moulds

The prime requirement of a mould is that it must be able to withstand the action of the poured metal and heat from the liquid metal in such a way as to produce the required geometry and mechanical properties in the casting.

No single moulding process will satisfactorily make all types and sizes of castings. Therefore, the process must be carefully selected in order to produce castings which are 'fit-for-purpose', to specified dimensional tolerances and with the desired surface finish.

Most steel castings weighing over 20 kg are produced in sand moulds in which the sand grains are bonded together by a moist clay film or a chemical binder.

It is also possible to use additive manufacturing to directly print sand for moulds and cores, or to CNC machine sand blocks, which enables the production of very complex internal geometry and voids that would be impossible using traditional pattern and moulding methods, though there are size constraints. 3D printing of moulds is most suitable for smaller numbers or one-off castings.

B.4 Computer simulation of the casting process

Many foundries have sophisticated computer modelling software such as MAGMASOFT® for simulating the casting process which enables costs to be cut and production speeded up. The process of mould filling can be simulated to determine the size and shape of runners, gates, and feeders in order to predict solidification times and quickly identify areas within the casting geometry that could give rise to process-related defects. The running system design can then be adjusted to evaluate how different design options might affect defect size and location so they can be controlled or eliminated. Using computer simulation early in the design process can greatly reduce the amount of guesswork involved in specifying cost effective and functionally acceptable casting geometry. This has enabled faster and more accurate simulation of prototype castings facilitating higher quality confidence levels in cast parts underpinned by non-destructive testing validation.

Computer based casting process simulation also facilitates consistency and predictability and makes it possible to properly evaluate the overall design before tools are cut and the design is committed to hardware. When used properly, the result is a substantial reduction in design time and tooling iterations.

Further research and adoption of simulation in casting technology will result in the production of highly accurate 'near-net shapes' requiring little or no secondary mechanical processes.

Figures B.1 to B.4 illustrate the use of simulation software in the production of G20Mn5 steel nodes for the roof of a football stadium in Warsaw, Poland.

Figure B.1 Stadion Narodowy, Warsaw with cast nodes in the roof structure

Figure B.2 Model to develop the geometry of a cast steel node to optimise castability

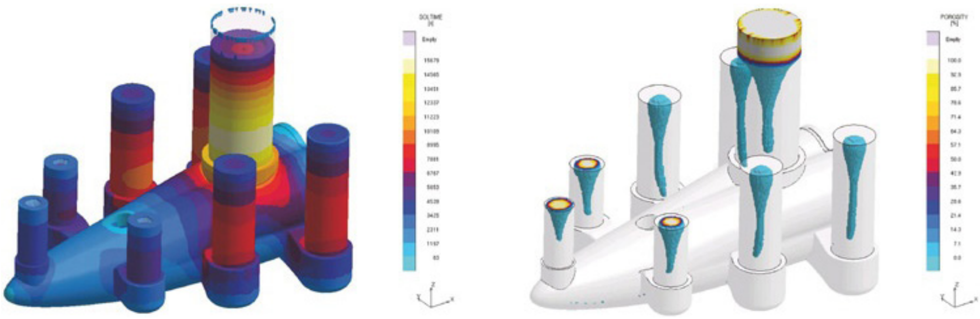


Figure B.3 Hotspot analysis of cast steel node to optimise size and position of feeders (left) and solidification analysis to confirm porosity occurs within the feeders, outside of the part (right)

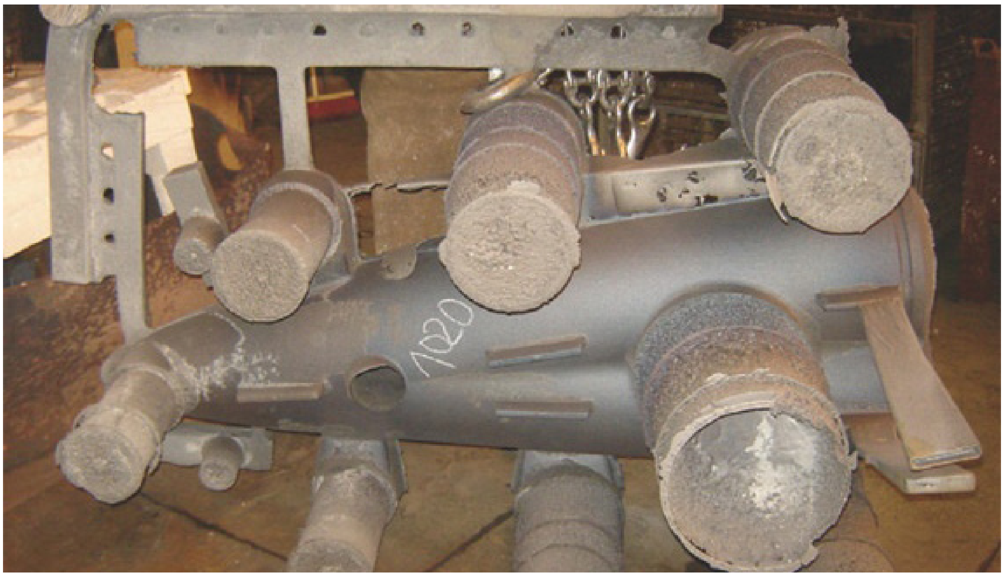


Figure B.4 Cast steel node after shake-out

B.5 Feeding and gating

Feeding is the process of supplying liquid metal to compensate for shrinkage while a casting is solidifying. A feeder is a reservoir of liquid metal from which a casting feeds as it shrinks during solidification. A gating (or runner) system consists of channels, runners and gates in a mould. These are the passageways through which the liquid metal flows before entering the casting cavity. Channels or vents are also required to allow gas to escape. In order to obtain a sound casting without shrinkage cavities, it is desirable that sections remote from the feeder head solidify first and those nearest last. This is called directional solidification and can only occur if the gating system is designed correctly to:

- trap slag in the metal or any oxidation products in the runners so that only clean metal enters the mould,
- allow the metal to flow quickly but without turbulence,
- permit the distribution of metal to form a sound casting,
- prevent undue wear or corrosion of the mould or cores.

As liquid and solidification contraction occurs, the formation of shrinkage cavities is prevented by the addition of liquid metal from feeders. A feeder needs to be large enough to supply the metal which must remain molten until the casting has solidified.

B.6 Melting and pouring

Melting steel requires high energy input to raise the temperature to around 1600 °C to transform the solid scrap steel to a liquid. This is commonly achieved using an Electric Arc Furnace (EAF) or an induction furnace. Furnaces are lined with a refractory material to hold the metal in place.

After melting and alloying in the furnace is complete, which is commonly confirmed by chemical analysis of a sample, the metal is transferred into a vessel, known as a ‘ladle’, from which the moulds are filled. Like the furnace, a ladle is protected from the liquid metal by refractory material. The ladle fills each mould through a point of entry, typically a pour cup or basin, or sprue. Temperature and flow rate are important for making a good casting and are managed through the ladle. After the mould is filled, the metal is allowed to solidify and cool.

The excess steel produced during the casting process is reclaimed and re-used.

B.7 Finishing

Once a casting has been removed from its moulds (this process is called shakeout), it must normally undergo certain finishing processes. The type, number and sequence depend on the composition and quality requirements of the castings and the manufacture route.

Finishing (also called fettling) operations typically involve:

- removal of moulding material (usually by abrasive blast media, chipping or grinding),
- removal of excess metal such as runner systems and any metal which is superfluous to the castings (usually by oxygen/fuel gas cutting, arc-air cutting or grinding).
- removal of defects (usually by arc-air cutting, grinding, and welding),

Accurate moulds and careful pattern design can help to reduce these labour intensive activities.

Finishing operations also involve checking, non-destructive testing and inspection.

B.8 Secondary processing

Heat treatment, for example by annealing, normalising, quenching and tempering, is commonly undertaken to manipulate the crystalline structure of the alloy to modify its mechanical behaviour in a predictable way and obtain the required mechanical properties.

While casting offers the opportunity to achieve ‘near-net shape’, features that require tight tolerances are often machined. For example, column bases or other bearing surfaces may need to be machined flat. It may also be necessary to drill holes in the casting: holes are easier to form accurately in this way rather than by casting them. Bearing holes (e.g. for pins) typically have to be machined after casting to meet tolerances according to BS EN 1090-2, particularly for sand castings.

B.9 Designing for production

Whilst it is possible to cast almost any shape by adopting appropriate techniques, if castings are not designed with production in mind, manufacture will be complex and production costs will be higher. The quality of the final casting may also suffer, it may be heavier than necessary and be less able to satisfy its performance requirements.

In designing a casting for production, the following topics must be considered:

- Fluidity and solidification of the metal,
- Practicalities associated with the production of moulds and cores,
- Finishing requirements

There is much interaction between the various characteristics of the casting. For example, the required thickness for structural performance will determine the frequency of the channels in the mould required to convey the liquid metal which will in turn have an impact on the finishing of the casting. Similarly, the casting function will dictate the mechanical properties, toughness and surface finish; this will in turn determine the level and frequency of testing and appropriate acceptance criteria. All these aspects will have a significant effect on the cost of production of the casting.

The ability of liquid metal to completely fill a mould cavity, reproducing all of its details, is known as the fluidity of the metal; low fluidity of metals limits the minimum section that can be cast. In conjunction with the fluidity of the liquid metal, the minimum thickness that can be cast depends on the characteristics of the mould and the method of mould-filling. For example, section length and surface area, as well as the position of the thinnest section relative to the gating system will influence the minimum section thickness that can be achieved.

It is generally recommended that steel castings have a minimum thickness of no less than 6 mm but this value should be increased if the thin section is longer than approximately 300 mm. Special techniques can permit thinner sections to be cast in certain circumstances, but these will come with higher associated costs. Advice from a suitable foundry should be sought if thin castings are required.

There is no practical upper limit on the section thickness of a casting, but the effect of thickness on achieving any relevant toughness criteria should be considered. The mechanical properties in BS EN 10340 apply up to maximum wall thicknesses given in Table 2 of the standard which are alloy-dependent.

STRUCTURAL STEEL CASTINGS

Castings are a highly versatile way of producing components of complex shape, or of producing shapes which are difficult to fabricate from wrought steel. In some situations, a casting is the only way of practically achieving both the structural load carrying capacity and the aesthetic requirements for architecturally exposed structural steel connections.

Castings can be streamlined for minimum stress concentration, minimum weight, and maximum strength. Tight tolerances can be achieved, and the single piece construction leads to greater structural rigidity and avoidance of misalignments and tolerance errors. The benefit a casting offers in terms of minimum use and waste of material is increasingly important in our low embodied carbon world.

This publication gives guidance on the properties, specification and procurement of carbon steel and stainless steel structural castings. The relevant requirements in current European product, design and fabrication standards are interpreted. The specification of the appropriate level of quality of the casting is very important and requires close liaison between the foundry and the design and construction team.

Complementary titles

P449 | Best practice for designing low embodied carbon steel buildings

P445 | Steelwork joint design – process and information

P413 | Design manual for structural stainless steel

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