Integration of cast simulated mechanical properties into FEA for improved tensile strength evaluation of ductile iron gate valve bodies

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Abstract

Valve production is one of the most cost competitive industries worldwide, and South African valve manufacturers face strong competition, predominantly from China. Simulation software can be used to engineering lighter, more cost effective products to stay ahead of competitors. The casting process affects the properties of the material resulting in a component with local variations in material properties and possibly discontinuities that are not accounted for in a stress analysis. This dissertation aims to investigate how the use of casting process simulation coupled with FEA can improve the accuracy of the stress analysis and identify the FEA input parameters that are most critical to the coupled simulation. This dissertation met these research aims through an extensive study of literature regarding the casting process and casting process simulation and the implementation an experimental investigation. The experimental investigation was carried out on SG42 Ductile Iron test samples and was used to evaluate the accuracy of the coupled simulation approach. It was determined that four casting simulation results (yield strength, young’s modulus, residual stress and porosity) are important to integrate from the casting simulation into the stress analysis to more accurately predict the Factor of Safety of the component. An 18% increase in the accuracy of the stress analysis was observed after integrating the aforementioned properties over a stress analysis with a single material definition, although the increase was mostly due to the integration of yield strength and porosity data. The main conclusion drawn from the research was that integrating casting simulation results into the stress analysis increased the accuracy of the stress analysis. The increase in accuracy significantly reduced the uncertainty regarding the materials strength, and the effect of the discontinuities present and can result in worthwhile cost savings for manufacturers through the reduction of section sizes that compensate for uncertainties in the material. Further research is however required on actual valve bodies to confirm these findings and determine the specific cost reductions achievable.

Keywords: Casting process simulation, ductile iron, casting defects, Finite Element Analysis, Gate valve, integration, stress analysis, Factor of Safety.
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List of Acronyms

**FEM**  Finite Element Method

**FEA**  Finite Element Analysis

**SABS**  South-African Bureau of Standards

**F.S**  Factor of Safety

**CAT**  Computerised Axial Tomography

**UTS**  Ultimate Tensile Stress

**YS**  Yield Stress

**SEM**  Scanning Electron Microscope

**F.S**  Factor of Safety
List of Symbols

$\sigma$  Stress
$F$  Force
$A$  Area
$N$  Newton
Chapter 1

Introduction

1.1 Background

“South African valve manufacturers are facing strong international competition especially in the commodity valves sector as a result of the price-driven flood of imports predominantly from China” (Breytenbach 2014). This drives engineers to design components that meet customer requirements at a minimised cost. Philip (2011, 35) observed that manufacturing these, sometimes complex, parts by metal casting is often the most economical choice due to the nature of the processing method. Subsequently “the correct use of Finite Element Method (FEM) analysis, as well as geometry optimisation methods, have become critical” to engineering lighter, more cost effective products (Olofsson & Svensson 2012b, 1).

A FEM stress analysis is constructed using knowledge of the strength of the material to approximate the response to an applied force. “The input of the correct data regarding
material behaviour in the virtual component is crucial to the accuracy of these predictions” (Olofsson 2014, 2). Furthermore, the stress analysis makes use of geometrical data to construct an elementary stiffness matrix, which is representative of the component geometry. In metal castings, metallurgical variations and discontinuities such as segregation, shrinkage cavities, shrinkage porosity, and gas porosity will cause variations in the material properties. These variations are typically not accounted for in the Finite Element Analysis (FEA) material definitions (Askeland & Phulê 2003, 318-322), and may have a significant impact on the accuracy of the FEM stress analysis.

Casting process simulation software can predict the occurrence of discontinuities, which can subsequently be classified as defects if they fall outside the requirement specification, as they can conduct thermal and fluid dynamic analysis of the casting process (Guo & Samonds 2009, 37). Quantitative predictions of microstructure and engineering properties, such as tensile strength and elongation, are also possible. Practically, this means that the designer can take predicted properties into account when conducting a FEM stress analysis. As variations in mechanical properties can be taken into consideration, the stress analysis can now provide more accurate results.

However, there is some uncertainty regarding the accuracy of casting simulations and errors made during the casting simulations may be more significant, and cause greater errors, than the errors resulting from assuming a single material definition (Olofsson 2014, 46). Simply stated, integration may introduce unnecessary risk into the analysis (Olofsson 2014, 46). It is also unclear which cast simulated properties are essential to integrate.

### 1.2 Problem statement

A single material definition does not accurately represent the mechanical properties of a cast component, this decreases the accuracy of a FEA stress analysis.
1.3 Aim

The overall aim of this study, therefore, was to investigate and implement a method for increasing the accuracy of FEA stress analysis applied to castings, using data obtained from casting simulations as the FEA input parameters.

More specifically, to achieve the above overall aim, this study aims to:

1. Identify which FEA input parameters affect the accuracy of the FEM stress analysis.
2. Provide an overview of how the casting process causes variations in the identified FEA input parameters.
3. Analyse the sensitivity of the FEM stress analysis to variations in the identified FEA input parameters.
4. Evaluate whether casting process simulation can accurately predict variations in these FEA input parameters.
5. Review results from recent studies that implemented integration of these parameters from a casting simulation into a FEA.
6. Integrate the identified input parameters from a casting simulation into an FEA stress analysis, of a ductile iron component.
Chapter 2

Literature survey

2.1 Introduction

This chapter starts by reviewing the fundamentals of mechanical stress, stress analysis and other factors that may influence stress distribution throughout a component.

2.2 Mechanical stress

Mechanics of materials is a branch of engineering that examines the relationships between the mechanical response of a deformable body and the loads acting on it, especially evaluating the resultant internal stresses acting within the body. This subject
also involves computing the deformations and studying the body’s stability when the component is subjected to external forces. The size of the structural members, their deflection and stability, depend not only on internal stress but also on the properties of the materials from which the members are made (Hibbeler 2013).

The relationship between the external loads and the intensity of the internal forces is given by the stress quotient; which gives the intensity of the internal force on a specific plane (area). The definition of average normal stress, denoted \( \sigma \), can be mathematically expressed as follows:

\[
\sigma = \frac{F}{A},
\]

where \( F \) denotes the magnitude of the force applied in Newton (N) and \( A \) the cross-sectional area that the force is applied to in square meter (m\(^2\)). Thus stress has a unit of N/m\(^2\).

### 2.3 Allowable stress

An engineer responsible for the design of a structural member or mechanical element must restrict the stress in the material to a level that will be safe. To ensure safety, it is necessary to choose an allowable stress that restricts the applied load to one that is smaller than the load that the member can safely support. This restriction is required as the design load may be different from actual loadings. The intended measurements of the member may not be exact due to errors in fabrication or assembly. Unknown vibrations or accidental loadings may occur that may not be accounted for in the design. Corrosion, decay or weathering may cause the materials to deteriorate during service. Moreover, some materials, such as wood, concrete, castings and fibre-reinforced composites show high variability in mechanical properties.

One method of allowing for such uncertainties is specifying a Factor of Safety (F.S). The F.S is the ratio of the failure load \( F_{fail} \) to the design load, \( F_{allow} \). Here \( F_{fail} \) is found from experimental testing of the material, and the F.S is selected based on experience.
so that the above-mentioned uncertainties are accounted for when the member is in service. The formula for F.S is as follows:

\[ F.S = \frac{F_{\text{fail}}}{F_{\text{allow}}} \quad (2.2) \]

If the load applied to the member is linearly related to the stress developed within the member (equation 2.1) the following applies:

\[ F.S = \frac{\sigma_{\text{fail}}}{\sigma_{\text{allow}}} \quad (2.3) \]

The failure stress \( \sigma_{\text{fail}} \) is usually defined as the 0.2 % offset Yield Stress (YS) that marks the stress level at which the relationship between the stress \( \sigma \) in the material and the corresponding strain \( \varepsilon \) changes from linear to non-linear as shown in Fig. 2.1 below.

![Stress Strain Curve](image)

*Figure 2.1: The stress strain curve showing the method for determining 0.2% offset Yield Stress.*

Intuitively the chosen F.S of a component design must be greater than 1 in order to avoid the potential for failure. Specific values depend on the type of materials used and the intended purpose of the member. For example, the F.S used in the design of aircraft or space vehicle components may be close to 1 to reduce the need for redundant material and thus keep vehicle weight to a minimum.
Chapter 2

Variations in stiffness

Substituting equation 2.1 into equation 2.3 and solving for $A_{allow}$ illustrates that the cross sectional area (size of the member) is directly proportional to the F.S.

$$A_{allow} = \frac{F.S \cdot F_{allow}}{\sigma_{fail}} \quad (2.4)$$

Thus considering our example of an aircraft or space-vehicle component: Keeping the vehicle weight to a minimum can be achieved by reducing $A_{design}$, this can be achieved in one of three ways:

1. By reducing F.S
2. by reducing $F_{allow}$
3. by increasing $\sigma_{fail}$

Changing the magnitude of the allowable load is seldom an option as is the case with valves, operating pressures and ranges are specified by the application and test conditions are fixed. However, as already discussed material properties may vary, and the material may be stronger than expected in some areas. This situation presents an opportunity for mass reduction. In some cases, as in the design of aircraft components, the F.S may be reduced to keep vehicle weight to a minimum.

2.4 Variations in stiffness

It is important to appreciate how stress distribution throughout a component relates to relative stiffness. If a stiff spring, or stiff load path, is in parallel with a soft spring or soft load path, the stiff path carries more of the load. If a stiff spring or stiff load path is in series with a soft spring or load path, the loads carried are equal, but the stiff spring deflection is smaller than the soft spring deflection (Collins, Busby & Staab 2010, 179).

The importance of these simple concepts cannot be overemphasised because all real components and structures can be represented by combinations of springs in series and parallel. The stiffness is directly proportional to the Modulus of Elasticity or the Shear Modulus which describes the correlation between the force applied and the resulting
deformation of the material (Collins et al. 2010, 180).

In the manufacturing of valve bodies, differential cooling rates may result in sections, or bands of material, with higher stiffness than the surrounding material, which will have a direct effect on the stress distribution when the material is placed under load. Moreover, this effect may lead to unexpected yielding when the component is in service. It is thus important to consider variations in stiffness during the stress analysis to reduce the total uncertainty of the analysis.

Olofsson & Svensson (2012a, 11) have demonstrated that these variations in material properties can cause the FEA analysis to predict the location of maximum stress incorrectly which is a significant problem. The designer may make the wrong design changes or decisions based on this misleading information.

2.5 Valve design

As in most design processes, industrial valve designers analyse the stress levels and stress distributions throughout the component under operating loads using structural simulation. An acceptable Factor of Safety is usually the primary design objective and is used as a measure of design performance.

2.5.1 General principals

In valve design, the Factor of Safety is commonly specified by design codes and engineering handbooks, and are intended to keep a balance between ensuring public and environmental safety and providing a reasonable solution to the design problem. The South-African Bureau of Standards (SABS) design codes for gate valves, SANS 664, do not specify a F.S but rather a physical test that must be passed to achieve certification.

The test requires the valve to maintain a pressure of two times the operating pressure
for a specified period, without any signs of sweating (slow leaking/weeping) or defects of any kind. For these valves to pass the test specification the designer cannot simply select a F.S of 2, as the previously mentioned uncertainties may cause the valve material to fail when subjected to double the design load. The design engineer must, through experience and an understanding of the limitations of the analysis, select an appropriate F.S so that uncertainties are accounted for when the valve undergoes testing.

It follows that if uncertainties can be reduced the F.S required to account for uncertainties may be reduced, resulting in a smaller cross sections/wall thicknesses, and ultimately a lighter valve. As pointed out in the background, Section 1.1, local valve manufacturers are facing strong, price driven international competition. Methods to reduce total cost must be investigated as the cost of raw materials contribute roughly 80% to the total cost. Therefore reducing material by lowering the F.S presents a valuable opportunity.

However, if the F.S is to be reduced, the design engineer must first address the limitations of the stress analysis and lessen the severity of uncertainties so that the valve
may still operate safely with a lowered F.S

2.5.2 Uncertainties in design analysis

As stated it often necessary to guard against uncertainties associated with material properties, the magnitude of external forces, part-to-part dimensional variations and so forth (Totten, Xie & Funatani 2003, 14).

A design must compensate for two types of uncertainties: those that are related to the component, and those that relate to the environment. Environmental uncertainties include all operating conditions such as temperature variations, unplanned corrosion exposure, unknown vibrations, and unexpected loadings. Component related uncertainties include variations in material properties, discontinuities in cross sections (hidden internal cavities) and dimensional errors.

Environmental uncertainties, in the case of the current SABS 664 design codes, are accounted for by a test pressure of two times the normal operating pressure, which affords protection against unknowns in operation. No unexpected environmental uncertainties should occur during certification as the test conditions are carefully controlled. It is therefore not necessary to consider environmental uncertainties in designing a valve to pass certification testing. Under test conditions, the only remaining uncertainties are those inherent to the component.

Component related uncertainties originate from the design and manufacturing stages. They can, therefore, be mitigated through cooperation between these two stages. Valves are commonly manufactured by metal casting, due to the need for manufacturers to do high volume production runs (Philip 2011, 35). Due to the nature of the casting process, valves are particularly vulnerable to component related uncertainties. Castings may have wide variations in properties, contain numerous internal cavities, have significant dimensional errors (although they are easily controllable), and may contain internal residual stresses induced by the manufacturing process. Therefore casting factors are commonly applied, casting factors are arbitrary increases in casting section
thickness applied to compensate for perceived lack of reproducibility of component properties (ASM 1997, 1698). This perception, more often than necessary, results in over designed and unnecessarily heavy sections in cast components.

### 2.6 FEA input parameters critical to stress analysis

The casting process may cause variations material properties and geometry that need to be considered to predict the mechanical response accurately (Reusch & Estrin 1998). Parameters that directly impact the stress analysis results and the F.S calculation as discussed in this chapters are:

1. Deviations in **Cross Sectional Area**.
2. Deviations in **Yield Strength**.
3. Deviations in **Young’s Modulus**.
4. Presence of **Residual Stress**.

Variations may range in severity, from barely detectable to catastrophic, and cause uncertainties in predicted stress levels within the component. If discontinuities in the castings and the resulting effect on the component can be accurately predicted, and integrated into the Finite Element Analysis, component related uncertainties, as discussed in Section 2.5.2, can be significantly reduced. The following section examines the basic process of casting, focussing on how metallurgical variations and defects occur and how parameters critical to the stress analysis are affected. If the uncertainties in the design analysis are to be mitigated, their causes and effects must first be understood.
2.7 Effect of metal casting on mechanical properties

The following Subsections (2.7.1-2.7.3) will discuss the casting process and provides detail on the physical and metallurgical effects that occur in the casting of ductile iron.

2.7.1 The casting process

Metal casting involves pouring molten metal from a melting ladle into a mould cavity of the shape of the component, after that the metal is allowed to cool and solidify. The mould is then broken away or removed exposing the solidified part. This basic principle is universal. Many processes can be used to make metal castings. Processes differ mostly in mould construction and material, the type of pattern used to make the cavity, and the amount of filling pressure, that is used to fill the mould cavity with molten metal (Hwaiyu 2004).

Moulds are produced by forming a refractory material like silica sand to form a cavity or impression of the shape required. The molten metal can then be poured from the melt ladle into the mould cavity. The mould must retain the cavity shape until the molten metal has solidified and cooled sufficiently but must give way at some point to allow for shrinkage of the solidified component (Hwaiyu 2004).

2.7.2 Metallurgy and the effect of cooling rates on the mechanical properties of ductile iron

Ductile cast iron is cast iron in which the graphite is present as tiny spheres or nodules.

In ductile iron, eutectic graphite precipitates from the molten iron during cooling and solidification under stable equilibrium conditions. The separation occurs similar to the manner in which eutectic graphite precipitates in grey cast iron. However, because of additives introduced into the molten iron before casting, the graphite grows as spheres
Chapter 2  

Effect of metal casting on mechanical properties

(Fig. 2.4), rather than as flakes of any of the forms characteristic of grey iron.

Cast iron containing spheroidal graphite is stronger and is more ductile than grey iron or malleable iron. It may be considered a natural composite within which the spheroidal graphite imparts unique properties to ductile iron.

![Figure 2.3: The iron-carbon phase diagram showing the stable iron-graphite equilibria (solid lines) and the metastable iron-cementite reactions (dashed lines), (adapted from Askeland & Phule 2003, 489).](image)

The relatively high strength and ductility of ductile iron give it an advantage over grey or malleable iron in many structural applications. Ductile iron also does not require heat treatment to produce graphite nodules as is the case with malleable iron (Davis 1996, 54).
Effect of composition on properties

The properties of ductile iron first depend on composition. The composition should be uniform within each casting and among all castings poured from the same melt. Many elements influence existing properties, but those of greatest importance are the chemical elements that influence the matrix structure or the shape and distribution of graphite nodules (Davis 1996, 64). The main elements are discussed here shortly.

**Carbon**: Influences the fluidity of the molten iron and the shrinkage characteristic of the cast metal as shown in Fig. 2.5. Excess carbon in suspension, not in solution, reduces fluidity.

Carbon Equivalent (CE) is an empirical value in weight percent, relating the combined effects of different alloying elements used in the making of cast irons to an equivalent amount of carbon. For cast irons CE is calculated by the formula $CE = %C + \frac{%Si}{3}$.
As ductile iron solidifies, the carbon in solution precipitates out and causes an expansion of the liquid metal, which can offset the shrinkage of the iron as it cools from liquid to solid. The size and number of graphite nodules formed during solidification are affected by the amount of carbon, the number of graphite nuclei present, and the inoculation practice. However, in practice, the carbon equivalent is not a major variable as it is maintained close to the eutectic value of 4.3% (Davis 1996, 64).

**Silicon**: Silicon is a powerful graphitising agent, allowing the formation of graphite in the free form, as flakes or nodules, distributed throughout the cast product upon solidification. Within the normal composition limits, increasing amounts of silicon promotes structures that have progressively higher percentages of ferrite. Furthermore, silicon adds to the solution strengthening and hardness of the ferrite matrix. Increasing the amount of ferrite reduces both the yield and tensile strength, but increases ductility and impact resistance. The ferrite envelope surrounding the graphite nodule in pearlitic ductile iron reduces the indicated yield strength but increases ductility, impact strength, and fatigue strength. Silicon reduces the impact strength of ferritic both as cast and sub-critically annealed (Metals Research and Development Foundation 1986).

**Nickel**: is frequently used to increase strength (Fig. 2.6) by promoting the formation of fine pearlite. It also increases hardenability, especially for surface hardening appli-
Magnesium: lowers the sulphur and oxygen contents and causes graphite to form in the shape of spheroids (Gundlach, Loper Jr & Morgenstern 1992).

Manganese: is among the alloying elements used to improve the mechanical properties of ductile iron, manganese acts as a pearlite stabiliser and increases strength, but reduces ductility and machinability (Sponseller et al. 1968). The addition of manganese also increases the risk of inter-celulr carbides.

Copper: is used as a pearlite former for high strength with good toughness and machinability (Sponseller et al. 1968).

Figure 2.6: Plot showing the effect of increased Nickel Content on the 0.1% Yield Stress of four ductile iron alloys (adapted from International Nickel Limited 1974).

Molybdenum: is used to stabilise the microstructure at elevated temperatures. The
amount must be controlled because of its tendency to segregate to the cell boundaries as stable carbides (Sponseller et al. 1968).

Effect of microstructure on properties

**Matrix structure**: The principal factor in determining the different grades of ductile iron in the specifications is the matrix composition. In the as-cast state, the matrix will consist of proportions of pearlite and ferrite. As the concentration of pearlite increases, the strength and hardness of the iron also increase (Fig. 2.7). Ductility and impact properties are principally governed by the proportions of ferrite and pearlite in the matrix (Davis 1996, 66).

![Figure 2.7: Plot showing the relationship between strength and amount of pearlite in irons having varying proportions of graphite in a nodular form (adapted from Fuller et al. 1980).](image)

As the amount of pearlite in the matrix decreases, the maximum absorbed impact energy in the ductile condition increases, and the ductile to brittle transition temperature range decreases. Heat treatments can alter the matrix structure, and those most often carried out are annealing, to produce a fully ferritic matrix, and normalising, to produce a substantially pearlitic matrix. Annealing produces a more ductile matrix
with a lower impact transition temperature than that obtained in as cast ferritic irons (Davis 1996, 66). Heat treatments do however add to manufacturing cost, and as SG42 and similar graded of ductile iron can be achieved without any heat treatment most producers will try to do this.

Normalising produces higher tensile strength with a higher amount of elongation than achieved in a fully pearlitic as-cast irons. In the former case, increased strength and ductility result from homogenisation and a fine pearlitic structure than occurs in the as-cast condition (Davis 1996, 66).

**Graphite Shape:** An increased nodule number, achieved by better inoculation, will tend to increase the amount of ferrite in the as-cast condition and will lead to more rapid annealing with less chance of retained pearlite after a given annealing time. The graphite structure can affect the matrix structure. Shapes that are intermediate between true nodular form and a flake form yield mechanical properties that are inferior to those of ductile iron with a true nodular graphite. The size and uniformity of graphite nodules also influence mechanical properties but to a lesser extent than the graphite shape. Numerous, small nodules are usually accompanied by high tensile properties. Excessive nodules may weaken a casting to such a degree that it may not withstand
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the loads in its intended application (Davis 1996, 65).

All properties related to strength and ductility decrease as the nodularity decreases. Properties relating to failure, such as ultimate tensile strength and fatigue strength, are more easily affected by small amounts of such non-nodular graphite than 0.2\% offset yield strength (Fig. 2.9a). The form of the non-nodular graphite is also important because thin flakes of graphite with sharp edges have a more unfavourable effect on strength properties than compacted forms of graphite with rounded ends. Graphite form also affects modulus of elasticity (Fig. 2.9b). Inoculation has the effect of increasing nodule number, which prevents the formation of carbides and increases ferrite, thus avoiding hard and brittle castings.

![Figure 2.9](image)

(a)  

(b)

Figure 2.9: Plot showing the effect of nodularity on: (a) Tensile and yield strength (adapted from Fuller 1978). (b) Young’s Modulus (adapted from Mullins et al. 1990).
**Carbides:** Carbide content has both a direct and indirect effect on the properties of ductile iron castings. Increasing volume percentage carbides increases the yield strength but decreases the tensile strength of ductile iron castings. This convergence of yield and tensile strengths provides a reduction in ductility with increasing carbide content (Fig. 2.10). The presence of carbides in the matrix also increases the elastic modulus and significantly reduces machinability (Davis 1996, 66).

![Figure 2.10: Plot showing the effect of nodularity and carbide content on (a) tensile and yield strength and (b) Youngs Modulus of pearlitic ductile iron (adapted from Mullins et al. 1990).](image)

**Effect of section size and cooling rate on properties**

As the section thickness decreases, the solidification and cooling rates in the mould increase, which results in a fine grain structure that can be annealed more rapidly. In thinner sections, however, carbides may be present that will increase the hardness, decrease machinability, and lead to brittleness. Producing soft, ductile material in thin sections requires heavy inoculation at a late stage to promote graphite formation through a higher nodule count, because of the rapid cooling.
As the section size increases the number of nodules decreases and micro-segregation becomes more pronounced, resulting in a large nodule size, reduced proportion of as-cast ferrite, and increased resistance to the formation of a ferritic structure upon annealing. In thicker sections, minor elements (especially those that form carbides such as chromium, titanium and vanadium) segregate to form a segregation pattern that reduces ductility, toughness and strength. The effect on proof strength is much less pronounced (Fig. 2.11). It is important for heavy sections to be well inoculated and to be made from a composition that is low in trace elements. (Davis 1996, 66-67)

Figure 2.11: Plot showing the effect of cast section size on the properties of ductile iron (adapted from Davis 1996, 70).

The structure of the matrix is primarily determined by the cooling rate through the
eutectoid temperature range, though the specific effects of cooling rate are modified by the presence of alloying elements. Slow cooling rates prevalent in thick sections promote the transformation to ferrite. If a pearlitic matrix is required, pearlite formers (such as copper) can be added to the molten iron. It is essential that castings be allowed sufficient cooling time in the mould to allow the lamellar pearlite to be tempered to break up the plates partially and be rendered machinable. Insufficient cooling time may produce very fine pearlite, which reduces machinability. As-cast ductile iron anneals itself in the mould. Without a pearlite former, castings with variations in section thickness will have variations in hardness. Bainite and martensite are not found in normally cooled as-cast structures because heat treatment forms them. Rapid cooling of thin structures may produce acicular carbides. (Davis 1996, 67)

2.7.3 Casting defects and their effect on cast properties

The occurrence of a defect resulting from the casting process is always a possibility (Rajkolhe & Khan 2014, 375). All castings have imperfections which break the continuity of the structure, some discontinuities are severe enough to make the casting unfit for service, at this point the discontinuity becomes a defect. The investigation of castings that have failed often reveal defects formed during the casting process, to be the primary cause. Defects originate from complex metallurgical, chemical, and physical reactions that the molten metal undergoes during the process of casting and solidification, and may be difficult to avoid (Wilby & Neale 2012). A casting defect as defined by ASM International (1988, 4) is “a discontinuity whose size, shape, orientation, or location makes it detrimental to the useful service of the of the part in which it occurs”. Defects may remain undetected until failure as they are often contained within the bulk material, and are only detectable by destructive testing or advanced detection such as X-Ray or Computerised Axial Tomography (CAT) scanning (Davis 1996, 308-314). According to Beeley (1972, 180), the general origins of defects lie in three sectors:

1. The casting design,
Defects that can be predicted and eliminated early in the design phase will usually result in significant savings, by the reduction of repair and scrap costs. Adjustments to the method of manufacture may include changing the pouring temperature, melt composition, casting pattern geometry, pouring rate as well as changes to the mould manufacturing process. Craftsmanship errors are often to blame and are difficult to prove, but correction of common craft errors may drastically reduce the occurrence of defects.

The logical classification of casting defects is challenging due to the broad spectrum of causes. Many classifications have been proposed. According to Beeley (1972, 181) a practical grouping by metallurgical origin provides seven types or categories of casting defects:

1. Shaping faults arising in pouring.
2. Inclusions and sand defects.
3. Gas defects.
4. Shrinkage defects due to volume contraction in the liquid state during solidification.
5. Contraction defects occurring mainly or wholly after solidification.
6. Dimensional errors.
7. Compositional errors and segregation.

Note that these groups are not mutually exclusive, some defects may belong to more than one group due to the complexity of their origin.

These defects increase the uncertainty of the stress analysis. The following subsections will briefly examine each type of defect, its origins and the effect that it may have on component performance.
Group 1: Shaping faults arising in pouring

During pouring the flow of molten metal may be intermittent and cause cold laps to form (Fig. 2.12). “Cold laps are caused by molten metal overlapping previously solidified layers with incomplete bonding between the two” (Dorcic & Verma 1988, 325-326).

![Figure 2.12: Photo of a steel casting showing a cold lap and shut (adapted from Beeley 1972, 294).](image)

If the weakly bonded layer intersects a load bearing section of the casting, the defect may result in component failure. Another similar defect is a cold shut; cold shuts are “seams in the casting where two streams of metal have come together but have not fused” (Sully 1988, 294) as shown in Fig. 2.13. Cold laps and shuts result from both low bonding temperatures and poorly designed flow paths respectively.
Cold shuts may pass through a section greatly diminishing or even eliminating the load bearing ability of the section. Cold laps and shuts may also influence the leak tightness of the component because the poorly fused faces may form a pathway through a section. The oxide films found on cold laps are the primary cause of leaks in high-pressure components (Campbell 1993, 281).

**Group 2: Inclusions and sand defects**

Inclusions are non-metallic and sometimes inter-metallic phases that become implanted in the solidified material matrix. There are essentially two groups if inclusions, those indigenous, or innate to the molten metal treatment process, and those exogenous, derived from external sources (Wilby, Neale & Trojan 1988, 88). Indigenous inclusions such as nitrides, sulphides, and oxides evolve from the molten metal upon solidification or contact with the mould material. These inclusions are usually small and evenly distributed (Wilby et al. 1988, 88-97). Exogenous inclusions result from the entrainment of non-metallic materials such as slag, dross, refractories, and trapped mould materials such as sand particles or core pieces (Fig. 2.14). These inclusions are usually grouped together in a corner or below the surface of the casting (Wilbey et al. 1988, 88 and Beeley 1972, 182).
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Figure 2.14: Photo of a casting showing an inclusion defect with irregular cavities possibly containing traces of refractories and/or slag particles (adapted from Investment Casting Institute 1983,45).

All inclusions reduce the load bearing section of the component thus lowering the magnitude of the force required to exceed the yield strength. Sulphur precipitates specifically have a detrimental effect on yield strength; thus it directly affects the materials properties. Inclusions may induce stress concentrations depending on their shape and location as the inclusions are usually poorly fused and seldom load bearing. Inclusions have the largest effect on the effective Ultimate Tensile Stress (UTS) as each inclusion acts as an additional crack nucleation site (Campbell 1993).

Due to the mechanics of ductile failure as described by Campbell (1993, 276), ductility is significantly affected by inclusions because the effective section is reduced (Fig. 2.15). Any inclusions also reduce crack formation time even at loads below the yield strength of the material, thereby significantly affecting fatigue life.
Group 3: Gas defects

Gas porosity is an important casting defect and is generally the result of evolution of dissolved gasses from the molten metal upon solidification due to a decrease in solubility with temperature, or contact with the mould material (Fruehan 1988, 82). Gas porosity takes the form of gas pockets within the casting and generally result in a reduction in the load bearing section and increased stress concentrations around the defect. It is sometimes referred to as gas entrapment. According to Beeley (1972, 193) gas defects can take the form of internal blowholes, surface blows, surface of subcutaneous pinholes or intergranular cavities, and airlocks, depending upon the immediate cause. Gas defects affect the properties of the casting in the same way as inclusions.
and sand defects, the severity of the effect depends only on the number and size of the defects (Campbell 1993, 279).

![Figure 2.16: Photo of a casting showing gas holes caused by green or damp pouring ladle (adapted from Rowley 1988, 16).](image)

**Group 4: Shrinkage defects**

Shrinkage defects when the flow of material is unable to compensate for liquid and solidification contraction. According to Craig, Hornung & McCluhan (1988, 640) shrinkage defects can appear as either isolated or interconnected irregularly shaped voids. These voids are common in castings with varied section thickness, elbows, T’s, and remote volumes that are difficult to feed with molten material. The adverse effects of shrinkage defects are the same as for inclusions, and as with all defects, the effect on the useful service life of the component will depend on the location of the specific defect. Shrinkage defects in non-load bearing sections are often allowed and designed for as they will not affect the performance of the component.
Group 5: Contraction defects

Solid shrinkage occurs while the casting cools from the solidus to ambient temperature. During this phase, the casting cannot be fed by liquid material, and contraction takes place in all linear directions of the casting. If contraction is inhibited by the mould material at high temperatures the strength of the material may be exceeded and hot tearing may occur while the cast material is a relatively brittle form. Contraction hindrance at low temperature can result in cold cracking, plastic deformation, or residual stresses (Beeley 1972, 212-214). These cracks may form through entire sections or occur as large flat inclusions.

Residual stresses are further induced by differential rates of post-solidification cooling, primarily due to varying section thickness but can be alleviated by exposure to
elevated temperatures and slow cooling (Rooy 1988, 762). Severe residual stress may result in cracking upon further processing such as grinding or machining. Residual stresses may be the same direction as the operating load, reducing the useful load bearing strength of the section.

![Figure 2.19: Photos of castings showing hot tears and cold cracks caused by residual stress. (a) Cold crack (Beeley 1972, 289). (b) Hot tear (Investment Casting Institute 1983, 36). (c) Hot tear (Rowley 1988, 37).](image)

**Group 6: Dimensional errors**

As correctly stated by Beeley (1972, 227), casting dimensions are subject to vary within normal limits of the manufacturing method applied. Abnormal variation originates from specific faults in equipment and practice; these faults occur during pattern-making, moulding and casting. Pattern-making errors are less common, and thus most dimensional variations arise during moulding or casting procedures. Beeley (1972, 227) further concludes that the primary causes are mostly misalignment of parts and cores, mould distortion, abnormal contraction and distortion in cooling. When the final shape of the casting varies significantly from the designed parameters due to porosity, cavities or warpage, it follows that the component will not yield as predicted, thus the final as cast shape of the casting must be considered in the analysis.
Group 7: Compositional errors and segregation

“Segregation may be defined as any departure from a uniform distribution of the chemical elements in the alloy” (Campbell 1993, 151). Castings may be segregated on a macroscopic or microscopic level, depending on the process by which segregation occurs.

**Micro-segregation** takes place as dendrites grow into the melt, as secondary arms spread from the main dendrite stem, the solute is rejected, effectively being pushed aside to concentrate in the small regions enclosed by the secondary dendrite arms. Micro-segregation can be caused by various other mechanisms, but the outcome is similar. Fortunately, micro-segregation can usually be significantly reduced by homogenising heat treatment lasting only minutes or hours because of the small distance, generally in the range of 10-100 µm, over which diffusion has to take place to redistribute the alloying elements is sufficiently small (Campbell 1993, 151).

**Macro-segregation** cannot be removed. It occurs over distances ranging from 1-1000 cm, and so cannot be removed by diffusion without geological time-scales being available. Varying cooling rates caused by variations in section thickness of a casting are a major cause of macro-segregation causing substantial variations in mechanical properties. In general therefore whatever macro-segregation occurs has to be lived with.

**Planar front segregation**, a type of macro-segregation caused by directional solidifica-
tion, occurs as the concentration of a solute builds up ahead of the solidification front resulting in varying solute concentration across the casting as shown below. The last liquid to solidify usually having the highest concentration of rejected solutes (ASM International 1988, 10).

![Illustration of directional solidification on a planar front giving rise to segregation as the solute builds up of is swept away by the advancing front (adapted from Campbell 1993, 152).](image)

**Figure 2.21:** Illustration of directional solidification on a planar front giving rise to segregation as the solute builds up of is swept away by the advancing front (adapted from Campbell 1993, 152).

### 2.7.4 Effect of variations in FEA input parameters caused by casting

The relative impact of variations in each input parameter, on the accuracy of the FEA, may provide useful insight into which input parameters are the most important to integrate from the casting simulation to the FEA. This subsection attempts such an analysis based on estimates of the possible deviation of each parameter from the normal, or design value.

In actual castings, the causes of variations are not mutually exclusive, and the magnitude of the variations depend heavily on geometry and casting conditions. Multiple variations may occur at the one point in the casting, having a combined effect on the material properties. It is, therefore, difficult to determine the actual true range of each parameter, as it will depend on the geometry and casting conditions, with this in mind, approximations have been made for the purpose of a sensitivity study.
Each critical FEA input parameter, that has been identified in Section 2.6, and the estimated possible deviation of the parameter is given in Table 2.1 below. Note that the ranges have been approximated from a qualitative study of literature regarding castings and casting defects in general. The estimated ranges are not to be taken as exact values, and are only for the purpose of evaluating the sensitivity of a FEM analysis should the range indicated be the accepted.

<table>
<thead>
<tr>
<th>Critical FEA input parameter</th>
<th>Cause of variation</th>
<th>Possible deviation from normal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross sectional area</td>
<td>Inclusions</td>
<td>0-25 %</td>
</tr>
<tr>
<td></td>
<td>Gas porosity</td>
<td>0-25 %</td>
</tr>
<tr>
<td></td>
<td>Shrinkage porosity</td>
<td>0-50 %</td>
</tr>
<tr>
<td></td>
<td>Hot tears</td>
<td>0-100 %</td>
</tr>
<tr>
<td></td>
<td>Cold cracks</td>
<td>0-100 %</td>
</tr>
<tr>
<td>Yield strength</td>
<td>Cold laps</td>
<td>0-50 %</td>
</tr>
<tr>
<td></td>
<td>Variations in nodularity</td>
<td>0-30 %</td>
</tr>
<tr>
<td></td>
<td>Variations in pearlite content</td>
<td>0-25 %</td>
</tr>
<tr>
<td></td>
<td>Presence of carbides</td>
<td>0-20 %</td>
</tr>
<tr>
<td></td>
<td>Variations in section size</td>
<td>0-30 %</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>Variations in nodularity</td>
<td>0-25 %</td>
</tr>
<tr>
<td>Residual Stress</td>
<td>Contraction effects</td>
<td>0-50 %</td>
</tr>
</tbody>
</table>

*Table 2.1: Possible deviation from normal of critical FEA input parameters due to defects and metallurgical effects (estimated data).*

The average of the possible deviation in Table 2.1 above is used in Table 2.2 below to represent average possible deviation of each critical FEA input parameter. These normalised ranges can then be used to conduct a sensitivity analysis to gain insight into which of the critical properties are the most important to consider.
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Effect of metal casting on mechanical properties

<table>
<thead>
<tr>
<th>Critical FEA input parameter</th>
<th>Average possible deviation from normal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross sectional area</td>
<td>0-60 %</td>
</tr>
<tr>
<td>Yield strength</td>
<td>0-31 %</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>0-25 %</td>
</tr>
<tr>
<td>Residual stress</td>
<td>0-50 %</td>
</tr>
</tbody>
</table>

Table 2.2: Average possible deviation from normal of critical FEA input parameters due to defects and metallurgical effects (estimated data).

**Sensitivity analysis:** Using the average possible deviation ranges given above a sensitivity analysis can be done by normalizing the ranges and plotting the % change in F.S over the normalised range. Fig. 2.22 below shows the effect of the normalised deviation in the critical parameters on the F.S.

![Figure 2.22: Plot showing the sensitivity of F.S to the normalised deviation in critical parameters.](image)

The results of the sensitivity analysis (Fig. 2.22) show that unexpected changes in the cross-sectional area can have the most adverse effect on F.S. It can also be seen that residual stress, if in the opposing direction to the design force, can have the largest positive effect. The effects of Young’s Modulus and Yield Strength are less pronounced.
but are still large enough to cause concern. Both Young’s Modulus and Yield Strength are influenced by nodularity. Thus they may have combined effects that may be more pronounced than displayed here.

The sensitivity plot shows that all four FEA input parameters investigated, if the estimated deviation ranges are to be accepted as realistic, have a significant effect on the F.S. Thus it could be said that variations in all four parameters must be considered in a stress analysis to predict the actual response of the component accurately. The sensitivity analysis confirms that even small variations in these properties (±10%) can have a significant effect on the accuracy of stress predictions. The analysis substantiates the relevance of integrating of cast simulated properties into the stress analysis. The next Section will examine the current capabilities of casting simulation, in particular evaluating the accuracy of the prediction of the identified properties.

2.8 Casting process simulation

Casting process simulation software can conduct thermal and fluid dynamic analysis of the casting process and is now used extensively in the casting industry. Casting simulation can help predict the occurrence of defects and help investigate their causes, resulting in better mould design, riser and runner placement and improves cast quality. Quantitative predictions of microstructure and engineering properties, such as tensile strength and elongation, are now possible through the coupling of simulation solvers with, more traditional, thermal, fluid flow, and stress models. The following subsections will examine the different components of a casting simulation and how accurately the current models are when compared to experimental results.

2.8.1 Accuracy of casting process simulation

A casting process simulation can be broken into three components:
1. Filling and solidification modelling, includes the modelling of liquid flow during pouring and volume contraction and feeding during solidification.
2. Residual stress formation modelling, includes the modelling of thermally induced residual stresses.

There are numerous studies that compare simulations to experimental measurements from actual castings. Through summarizing the results from these studies, the accuracy of simulations can be evaluated.

### 2.8.2 Filling and solidification modelling

Mould filling and metal solidification have been studied extensively over the past 50 years. Most recently Aranda (2015) comprehensively evaluated the accuracy of various casting process simulation software packages through comparisons with experimental results. Specimens were complex automotive engine blocks, of aluminium EN AV 46000, manufactured by High Pressure Die Casting (HPDC). The accuracy of porosity prediction was evaluated. The casting simulations were able to predict the location of all instances of porosity identified by radiographs and sectioning. Additionally simulation results showed high-risk areas that did not show porosity in the experiments; this may indicate that the casting simulation software used is somewhat conservative in comparison to actual castings.
Chapte... Casting process simulation

Figure 2.23: Photos of sectioned castings and the accompanying simulation results displaying the accuracy of shrinkage prediction for different cast iron castings (adapted from Strum & Busch 2011, 54).

Slavkovic, Jugovic, Kozak, Veg, Radisa, Dragicevic & S Popovic (2013) also evaluated the ability of casting simulation software to accurately predict the occurrence of volume defects in an E295 structural steel excavator cutting tooth and high manganese steel (X120Mn12) casting. A high degree of accuracy regarding the prediction of internal defects such as porosity was reported.

Other studies by Sturm & Busch (2011), Han (2013) and Iqbal, Sheikh, Al-Yousef & Younas (2012) again showed excellent agreement with experimental findings. Similarly Carlson & Beckermann (2005) also verified the model for re-oxidation inclusion formation.

2.8.3 Residual stress Modelling

Today, modelling of thermally induced residual stresses has become state-of-the-art. It allows addressing of various quality issues, such as hot tearing, crack susceptibility, residual stress levels and casting distortion (Sturm & Busch 2011). (Monroe &
Beckermann 2004) developed the current commercial residual stress models and were able to achieve good agreement with experimental results in cast iron castings. The model material data has since been improved to account for strain hardening and strain rate dependence during cooling (Monroe & Beckermann 2007). Further improvements have also been made using refined instrumentation to further investigate the distortion and hot tearing of steel castings (Monroe & Beckermann 2006).

Figure 2.24 provides an example where castings did not have any defects after casting but showed cracks when placed under load. Simulation of residual stresses showed that the material around the valve stem hole was under high stress after casting but not high enough to crack the casting during cooling. The crack starting point is depicted on the left and the risk areas for cold cracking are shown on the right and coincide with the actual crack.

![Figure 2.24: Photos of a cracked wheel rim casting and the accompanying simulation results (adapted from Strum & Busch 2011, 57).](image)

### 2.8.4 Solidification Micromodelling

Micromodelling entails the simulation of individual phase formation as a function of metallurgy, melting, and inoculation practice, allowing prediction of microstructure after solidification (nodule count/number of eutectic cells, the amount of grey/white cast iron solidification, amount of austenite/eutectic graphite) (Sturm & Busch 2011).
Through calculation of the further cooling and the local segregation down to the solid state reaction, the local phase distribution of the matrix (ferrite/pearlite distribution, coarseness of pearlite) can be assessed quantitatively. Micromodelling also enables predicting the transition of different graphite morphologies as a function of the applied metallurgy, the alloy composition and the local cooling conditions (Sturm & Busch 2011). To be able to predict the mechanical properties in ductile iron castings, it is necessary to consider the eutectoid transformation (Sturm & Busch 2011). The quantitative knowledge about local phases and microstructure allows the prediction of mechanical properties for the entire casting (tensile strength, hardness, yield strength, elongation and Young’s modulus). (Sturm & Busch 2011)

Heisser & Sturm (2003) developed and extensively verified the current micro models for ductile iron. Overall, the results given by the simulation showed a very close correlation to actual castings allowing accurate derivation of mechanical properties.

Sjögren & Svensson (2007) further developed the model for prediction of Young’s Modulus based on graphite morphology and matrix composition, Sjörgen and Svensson obtained high levels of prediction accuracy (<5%) for cast irons. The model was verified for elastic and plastic deformation behaviour of cast irons (Sjögren 2007).
Chapter 2 Related studies

Figure 2.25: Image of a casting simulation result showing the percentage pearlite in the matrix and a micrograph of the actual casting conforming the result to be in line with the simulation (adapted from Strum & Busch 2011).

2.9 Related studies

Olofsson & Svensson (2012a) evaluated the effects of variations in mechanical properties on stress and strain levels in a ductile iron component. Results showed that variations in mechanical properties significantly affected the predicted response of the component. Olofsson & Svensson further concluded that “a homogeneous material description fails to express the stress-strain distribution caused by the local variations in mechanical behaviour in the component”.

The component studied had variations in section thickness, and the simulation results predicted a Young’s modulus varying between 168-176 GPa through the casting. This variation in stiffness proved to have an influence on the stress flow through the component and resulted in a different location of maximum stress being predicted for the simulation with cast simulated properties than for the stress simulation using a stan-
standard material definition.

*Op. cit.* also examined the effect of residual stress and found that the inclusion of residual stresses contributes significantly to the predicted stress level when the applied load is low, but that local variations in microstructure provide a larger contribution to the predicted stress level when the applied load is high. This effect is presumably observed as the residual stress level was most likely low, a high residual stress level would consequently continue to affect the accuracy of prediction even at high loads.

In their investigation *op. cit.* did however not consider porosity or voids and variations in yield strength. As discussed in Section 2.7.4 this could also have a large effect on the accuracy of the FS predictions that were not addressed in their study. However, *op. cit.* concluded that both local variations in mechanical behaviour and residual stresses must be included to predict the stress and strain levels at all loads accurately.

### 2.10 Summary and recommendations for further research

The casting process causes variations in the properties of the casting. Casting process simulation can predict these variations accurately, which can then be used for stress analysis. This integration should provide more accurate predictions of stress in the component. Integration may also allow further reduction of weight as the need for arbitrary “casting factors” can be mitigated.

The four critical properties related to the mechanical strength that can be affected by the casting process, and have an impact on the stress analysis have been identified to be: Residual stresses, voids and porosity, Young’s Modulus, and Yield Strength. It has already been shown that variations in these properties can be significant enough to notably affect the stress analysis in ductile iron components for the generalised case. Available literature has shown that the properties identified can be accurately predicted through casting process simulation. The casting simulations must, however, be validated as process conditions vary widely among foundries. If the Factor of Safety
can be more accurately predicted the need to compensate for component related uncertainties can be reduced and lighter, more cost effective components can be designed.

Some researchers have investigated the impact of integrating cast simulated properties on the stress analysis, but the effect on the F.S calculation and its accuracy has not been studied. Yield stress, voids and porosity were also not accounted for in the investigations.

Further investigation is therefore required to evaluate the effect of integrating each of the four identified properties to assess whether the uncertainty regarding the accuracy of the F.S calculation can be reduced and to what degree each identified property has an effect.
Chapter 3

Experimental research strategy

3.1 Introduction

This chapter provides a framework for, and describes in detail, the techniques and methods employed during the experimental investigation. Following the recommendations from the literature survey, the objective of the experimental investigation was to evaluate the effect of integrating the cast simulated FEA input parameters identified in Section 2.6 on the accuracy of the Factor of Safety prediction of a FEA simulation.

The analysis specifically considered the impact on Factor of Safety, as this is generally the primary variable considered in the design of valve bodies. The following sub-sections provide detail regarding research strategy and method of investigation followed.
3.2 Research strategy

A baseline or target value was selected to evaluate whether integrating the cast simulated FEA input parameters had a positive or negative effect. As the aim of any simulation is to predict the actual response, the actual response was used as the target value. The data was collected from tensile testing of actual castings.

The accuracy of the two simulation approaches, one with a standard material definition and the other with FEA input parameters integrated from casting simulation, was evaluated against the target values. Thus three sets of data were generated:

1. Tensile test results - From cast samples.
2. Standard simulation results - Using documented material properties.
3. Integrated simulation results - Using cast simulated FEA input parameters.

Comparing the accuracy of the two FEA simulations (Items 2 & 3) to the test results (Item 1) provided insight into the effect of integrating the cast simulated FEA input parameters.

The chapters to follow will review the methods of investigation and the results observed in the experimental investigation of each of the aforementioned data sets.
Chapter 4

Casting simulation and test sample design

4.1 Introduction

The casting simulations and test sample design was done concurrently as information gained from the casting simulation results could be used to alter the design and achieve the desired result. Section 4.2 describes the baseline and final design used after some casting simulations, thereafter Section 4.3 provides detail regarding the set-up of the casting simulations, although the geometry changes throughout the process, the set-up parameters remained the same. Finally the relevant results of the casting simulation are given and discussed.
4.2 Test sample design

Some requirements were established for the design of the test samples in agreement with good research practice and the proposed research strategy:

1. The samples must allow repeatable experiments that can be performed in a controlled setting.
2. The samples must allow experimental testing of a sufficient number of samples to achieve statistical significance of results while minimising cost.
3. The samples must undergo similar casting procedures and heat treatment conditions as would be typical of valve body castings.
4. The design must be representative of ductile iron components such as valve bodies that contain variations in the identified critical FEA input parameters.

The following design decisions were made to satisfy the conditions mentioned above:

1. To maximise repeatability of the physical testing:
   (a) Test samples were designed to be compatible for testing using an MTS Landmark 1000kN automated tensile test rig, this allows precise control of strain rates and accurate measurement of results via calibrated load cells.

2. To enable testing of a sufficient number of samples:
   (a) The test samples were designed to be small and relatively inexpensive.
   (b) Samples were also designed to be cast in batches so that a significant number of samples can be produced at minimum cost.
   (c) Machining operations were to be kept to a minimum.

3. For samples to be representative of valve bodies:
   (a) Test samples were cast at a pouring temperature of 1400°C.
   (b) The casting was shaken out when the highest temperature in the casting fell below 500°C. Thereafter castings were air cooled to room temperature, such as is typical for valve bodies.
(c) In typical valve bodies, the thinnest sections are normally the pipe walls of the valves that can be as thin as 5mm. The thickest sections are the flange connections that can be as thick as 30mm for PN16-DN400 valves which are typically used in water distribution networks. Thus the test samples will range in thickness from 15 to 30mm with steps of 5mm to represent the varying wall thickness found in valve bodies.

(d) To represent areas of valve bodies with high thickness rations, usually the joint between the pipe and flanges sections, a thickened centre has been included, this will represent areas in valves that are prone to shrinkage porosity due to poor feeding.

(e) Residual stress in valve body castings are usually a result of the mould material constricting the contraction during cooling. To represent this, flanges have been added to the top and bottom of the castings that may act in a similar manner during cooling to the flanges of a valve, and may induce residual stress in the test samples.

4. To be representative of valve ductile iron components:

(a) Test samples were cast of SG42, a common South African ductile iron grade frequently used in valves and piping.

The basic test sample design was taken from the Birmingham UK 10 test bar, as named by casting Dispinar & Campbell (2005), and is displayed in Fig. 4.1. The basic design allowed for controlled filling of the samples, maximising the repeatability of the filling process. However, for the samples to be representative of actual valve bodies, geometrical alterations were made following the design decisions listed above.
The following design changes were made and can be seen in Fig. 4.2 below:

1. The vertical cylinders, which will be the test pieces, vary in base diameter from 15 - 30 mm in steps of 5mm.
2. Flanges were added to the top and bottom and were tapered according to the molten metal feed requirements to compensate for solidification shrinkage of the bars.
3. The pouring basin design was changed after some initial casting simulations to provide a smoother flow of liquid metal down the runner.
4. Bars on the left have thick centre bands to represent positive changes in section thickness.
5. Bars on the right have thin centre bands to represent negative changes in section thickness.
6. All sharp corners were rounded to reduce chances of mould breakage and ease of pulling the pattern from the sand mould.
4.3 Casting simulation set-up

Using the geometry shown in Fig. 4.2, a casting simulation was set up in MAGMASoft in order to analyse the filling and solidification of the casting. The simulation was done using the MAGMAIron module of MAGMASoft which is used for the process simulation of cast-iron castings.

**3D model set-up:** The geometry was imported and materials assigned as shown in Fig. 4.3. The inner section of the sand mould was assigned as ‘core’ material to allow for calculation of stress in the sand moulds. The casting was divided into ‘machining allowance’ and ‘castings’ so that a machining step could be applied which may relieve the residual stresses formed during cooling. The inlet was specified to have a radius of 24mm.
Meshing: The mesh was generated for Solver 5 (advanced solver). The mesh generated consisted of 3,577,365 cells of which 397,345 were cavity cells. The solids (sand mould and core) were meshed using a mesh size of 5mm (equidistant). The runner and machining allowance was meshed using a mesh size of 2mm and castings were meshed using a mesh size 1mm, this fine mesh of the castings can be seen quite clearly in Fig. 4.4b.

Material Definitions: The sand mould material was defined as Furan Sand, which was used in the actual moulds. The cast alloy definition used was that of EN-JS1020, the equivalent of SANS SG42. The iron composition data used for the casting simulation is given in Table 4.1.

Heat transfer definitions: For the cast alloy the ‘TempIron’ temperature dependent heat transfer coefficient was selected. For the Furan sand mould the ‘C800’ constant heat transfer coefficient was selected.
Melt treatment: The inoculation practice was selected to be ‘good’ with a treatment yield of 100% and a graphite precipitation level of 5 according to the practice of the foundry and the recommendation of the casting simulation software distributor.

Stress: Stress and contact stress was considered between the core and the cast materials.

Pouring: Pouring height of 30mm was specified through the 24mm diameter inlet with a pouring time of 13 seconds.

Treatment after casting: A shake-out (removal of the casting from the sand mould) was specified to take place when the highest temperature in the casting reached 500°C. A machining operation was also specified to remove the material labelled as ‘machining allowance’.
Addition simulation options: The following additional options were activated: Consider sand permeability, consider surface tension, extended feeding algorithm, consider water content, stable mould model for mould dilation, considered microstructure formation.

<table>
<thead>
<tr>
<th>Element</th>
<th>Concentration [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (Carbon)</td>
<td>3.600</td>
</tr>
<tr>
<td>Si (Silicon)</td>
<td>2.650</td>
</tr>
<tr>
<td>Mn (Manganese)</td>
<td>0.150</td>
</tr>
<tr>
<td>Mg (Magnesium)</td>
<td>0.036</td>
</tr>
<tr>
<td>Cu (Copper)</td>
<td>0.100</td>
</tr>
<tr>
<td>Mo (Molybdenum)</td>
<td>0.007</td>
</tr>
<tr>
<td>Ni (Nickel)</td>
<td>0.029</td>
</tr>
<tr>
<td>P (Phosphorus)</td>
<td>0.016</td>
</tr>
<tr>
<td>S (Sulphur)</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Table 4.1: Chemical composition used for the set-up of the casting simulation for a EN-JS1020 ductile iron.

4.4 Casting simulation results

The casting simulation produced a large amount of data that can be discussed length but only results concerning the FEA input parameters identified in section 2.6 are reviewed.

4.4.1 Porosity formation simulation results

The casting simulation results showed the formation of numerous pores throughout the casting (Fig. 4.5a). Only the pores formed in the centre of samples 1-4 coincided with the machined test samples; this corresponds with the observations from section 5.3.
Figure 4.5: (a) Simulation results showing porosity % of the cast samples. (b) Section view of porosity % of samples 1-8
The result, shown in Fig. 4.5b showed that samples 1 and 2 had significant levels of porosity in the centres of the samples as the design intended. The centre of the porous areas in Samples 1 and 2 were more than 90% empty according to the simulation (Fig. 4.5), but microscopy showed a more connected matrix of small pores. Sample 3 only showed a maximum porosity of 28% and sample 4, showed the lowest porosity of 12%. Porosity in sample 5 was in the clamped section of the test bar and thus had no noticeable effect on the tests. Samples 6-8 showed no porosity in both the simulation and microscopic inspection.

The size of the porous area observed in microscopy also corresponded well with the size of the pores predicted in samples 1 and 2 indicating an excellent agreement between porosity predicted by the simulation and the actual castings.

### 4.4.2 Young’s Modulus

Casting simulation results showed a Young’s modulus ranging from 169.7 - 171.5 GPa (Fig. 4.6). The range is quite small even though the section sizes varied from 15 to 30mm in diameter. The variations in Young’s modulus should not have a large effect on the stress analysis as the standard value of 170 GPa is very close to the mean of the simulation results.

The thin centre samples (Samples 4 and 5) had the highest Young’s modulus due to smaller section sizes which affected cooling rates and subsequently both the graphite and matrix structures.
4.4.3 Yield strength

The mean yield strength of the samples predicted by the casting simulation ranged from 370.5 - 494.3 MPa (Fig. 4.7). This variation is significant and will have a significant effect on the calculation of F.S. The specified yield strength of SG42 ductile iron is only 275 MPa. It is worth noting that even the minimum predicted yield strength is 95 MPa higher than the material specification.

As with the Young’s modulus, the thin centre samples had the highest yield strength. Samples 1 and 8 and Samples 2 and 7 had the same section thickness, but yield strengths of Samples 1 and 2 were much greater than the yield strengths of Samples 7 and 8, this is due to the difference in sequence or pattern of solidification. In samples 1 and 2 solidification initiated at the ends of the samples and propagated inwards whereas the opposite took place for samples 7 and 8.
4.4.4 Residual stress

The residual stress levels predicted in the casting were quite low and were mostly concentrated in the bottom section of the runner (Fig. 4.8). After machining only Sample 5 had significant levels of residual stress (Fig. 4.9). Sample 5 had a maximum equivalent residual stress level of 117.5 MPa but this high stress was isolated to the outer sides of the sample. A section of the sample reveals a low stress intensity through the centre with a maximum of roughly 35 MPa.

The stresses induced were thus low and the addition of plates to the top and bottom of the castings did not significantly constrict the contraction of the sample as intended by the design.
Figure 4.8: Simulation result showing residual stress (Von Misses) in the casting before machining.

Figure 4.9: Simulation result showing residual stress (Von Misses) in each test sample after machining.
Chapter 5

Manufacture and stress-testing of samples

5.1 Manufacture of test samples

The first step in making a casting is making a pattern. A cope and drag type pattern was used. The pattern was used to form the cavity in the sand mould which was filled with molten metal. After casting the sand was broken away, runners and pouring basins removed, and machining operations produced the final test pieces.

Pattern: To compensate for solidification shrinkage, the casting geometry was scaled up by a factor of 0.8%. All vertical faces were drafted with a daft angle of 4°. All sharp edges were given a 2mm fillet as sharp corners may easily cause the sand to crack or break away. Four locating cones were added with a draft angle of 10° to align the cope
and drag upon closing.

The pattern was machined out of Meranti hardwood, the material of choice for many batch foundries. This results in a lightweight pattern that is dimensionally stable and does not absorb moisture. The pattern was machined using a Fanuc m710i robot arm equipped with a router end attachment resulting in a total dimensional accuracy of +/- 0.5mm. Before mould making the patterns were coated with “silver slip”, a graphite lubrication coating that prevents the Furan sand from sticking to the pattern and allowed easy separation of the pattern and mould after the sand has hardened.

![Image showing a 3-D model of the mould assembly including the cope, drag and casting.](image_url)

**Sand moulds:** The moulds are produced by filling the two core boxes with Furan sand, a sand-resin mixture. The sand was carefully compacted to ensure that it was densely packed around the pattern with no voids. The Furan sand took about 1-3 hours to fully harden depending on the ambient temperature.

**Casting:** The castings were manually poured, pouring times varied between 9 and 11 seconds which corresponded reasonably well with the predicted filling time of 13
seconds. The melt temperature before pouring was 1405°C. Innoculant was added immediately before castings and all castings filled completely.

Castings were manufactured at two different foundries. Castings made at Foundry 1 were allowed to cool overnight in the sand mould to room temperature before being demoulded. Castings made at Foundry 2 were allowed to cool for 20-30 minutes before being de-moulded and allowed to air cool to room temperature.

**Machining:** Test pieces were machined using a CNC lathe, machining tolerances used were according to ISO 6892-1:2009. A machined test piece is shown in Fig. 5.3a below. See Appendix for dimensions and a technical drawing of the test pieces.

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Figure 5.2: (a) Photo of the sand mould after removal from the pattern. (b) Photo of a batch of test samples being cast. (c) Photo of the casting removed from the sand mould after solidification.
5.2 Tensile testing

Tensile tests were carried out using an MTS Landmark test rig. The strain rate applied was 0.01mm per second. Specimens were clamped as shown in Fig. 5.3b.

![Figure 5.3: (a) Photo of test pieces after machining the castings. (b) Photo of test pieces clamped for tensile testing.](image)

For each test sample a stress strain graph was produced from which the 0.2% offset yield strength could be determined. The yield was taken as the point of elastic failure. Figure 5.4 provides an example.

![Figure 5.4: Plot of stress (MPa) vs. strain (%) for test sample 4A showing the Young’s Modulus and 0.2% offset yield strength lines.](image)
5.3 Microscopy results

Microscopic investigation was conducted in order to confirm a ferritic matrix material as specified for SG42 was obtained from casting. A nodularity of approximately 99% was observed with nodules being small, numerous and well formed (Fig. 5.5a), which indicates a correct melt composition for SG42 and good inoculation practice before castings.

Figure 5.5: (a) Micrograph of sample 8 at 40x magnification, unetched, showing 99% nodular graphite. (b & c) Micrographs of sample 2 showing porosity, the darker areas around the porosity would be the result of leakage from the pores causing staining (b at 40x magnification and c at 100x magnification.)
Scanning Electron Microscope (SEM) images of the fracture surface of sample 2 revealed a large porous area roughly two-thirds the diameter of the test piece (Fig. 5.6a).

![SEM images](image)

(a) ![SEM images](image) (b)

(c) ![SEM images](image) (d)

Figure 5.6: SEM images of the fracture surface of sample 2 showing (a) a large porous area in the centre of the sample (b) the smooth surface if the pore and the path of fracture. (c) SEM images of a pore coated in a thin film of graphite (d) SEM image of the broken edge of a graphite film showing a layered structure.

Closer inspection revealed how the fracture propagated through the porous area; the fracture also followed a path through the nodules which could act as crack arrestors. Figure 5.6b shows the smooth surface of the pore and some broken out nodules in the path of the fracture. The porous areas were only found on the fracture surfaces of test
samples 1-4.

Most of the pores observed were also covered in a thin film of graphite as shown in Fig. 5.6c, the film has a wrinkled appearance and a layered structure that is can be observed in Fig. 5.6d.

5.4 Stress-testing results and discussion

After collecting the data from the tensile tests, the force at which each physical test sample reached the 0.2% offset yield stress was taken as the yield force. The yield force result was then divided by the design force of 13.825 kN to calculate the experimental F.S for each sample. Six castings were made, two at Foundry 1 and 4 at Foundry 2, resulting in 48 test samples. The mean F.S determined for the two foundries is shown in Fig. 5.7. The results from both foundries showed a F.S larger than 1 for all samples.

![Figure 5.7: Plot of mean experimental F.S for foundries 1 and 2.](image-url)
The difference between test samples was less pronounced for results from Foundry 1, most likely due to the different demolding times. The samples made at Foundry 2 were de-moulded after only 20-30 minutes which increased the effect of differences in section thickness between samples. Results also show that samples 4 and 5 was noticeably stronger at Foundry 2 than at Foundry 1, this can be explained by a larger percentage of pearlite structures in the matrix due to faster cooling rates.
Chapter 6

FEA simulation of stress-testing

6.1 FEA simulation set-up

The tensile test stimulations were conducted using ANSYS Mechanical. This section describes the geometry, material properties and boundary conditions used for the stress analysis using standard material definitions.

Geometry: The test piece geometry was used without any alterations or simplifications as the test piece is quite simple. The test piece geometry is shown in Fig. 6.1.
Material Properties: Material properties were taken from the SANS936:2008 specification for Spheroidal graphite iron castings as the melt was made to this specifications. The values were set as in Table 6.1 according to the material specification:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (Young’s Modulus)</td>
<td>170 GPa %</td>
</tr>
<tr>
<td>YS (Yield Strength)</td>
<td>275 MPa %</td>
</tr>
<tr>
<td>$\nu$ (Poisson’s ratio)</td>
<td>0.275 %</td>
</tr>
</tbody>
</table>

Table 6.1: Table of mechanical properties used for FEA simulation setup.

Meshing: The test pieces were meshed using 20-node hexahedral elements (SOLID186). According to the ANSYS (n.d.) element reference guide: “SOLID186 is a higher order 3-D 20-node solid element that exhibits quadratic displacement behaviour. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The element supports plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyperelastic materials.”
Figure 6.2: Illustration of the cubic element SOLID 186 that was used to mesh the geometry of the test samples for Finite Element Analysis. The 6 faces are labelled 1-6 and the 20 nodes are labelled A-T.

The mesh refinement analysis in fig 6.3 evaluates the change in predicted maximum equivalent stress. The graph shows that even at very coarse mesh settings, results are within less than 1% of each other, with results converging to within 0.04% at around 40 000 elements. This indicates high mesh stability and proves mesh independence even at low element counts.

For the analysis a mesh with an element count of 39 824 elements was used (Fig. 6.4). To further evaluate the quality of the mesh the orthogonal quality was evaluated. An average orthogonal quality of 97.5% indicates a very high quality mesh. Furthermore the minimum value of 85.5% indicates that there are no significantly skewed or warped elements throughout the entire mesh.
Chapter 6  

**FEA simulation set-up**

Figure 6.3: Plot of no. of mesh elements vs. % change in maximum equivalent stress showing mesh independence even at low element counts.

**Loads:** Loads were applied to the ends as in the experimental test set-up (Fig. 6.5a). Frictionless supports were added on the same surfaces to stabilise the model preventing large displacements and model instability as shown in Fig. 6.5b.

**Safety Factor Calculation:** The inverse Factor of safety (1/FS) was calculated by dividing the material Yield Stress by the Equivalent (Von-Mises) stress.
Figure 6.4: 3D Model showing a longitudinal cut-plane of the meshed geometry.

Figure 6.5: 3D Model showing the boundary conditions applied to the stress analysis. (a) Forces applied. (b) Frictionless supports applied.
6.2 Integration of cast simulated FEA input parameters

Results from the casting simulation were integrated into the ANSYS FEA analysis using the MAGMALink module of MAGMASoft. The module allows the FEA mesh created in ANSYS to be laid over the cubic volume mesh results in MAGMA. As the mesh elements do not coincide the MAGMALink module interpolates the results from the MAGMA mesh elements to the FEA mesh elements at the FEA element centre. The following results were exported:

- 0.2% Yield Stress - Scalar
- Young’s Modulus - Scalar
- Porosity (as % empty) - Scalar
- Residual Stress - Tensor

**Integrating Young’s Modulus and Porosity:** Young’s Modulus for each was exported to a text file which specifies the element number and the interpolated scalar value. This data is then incorporated into the ANSYS simulation using a material property input file (.mp), which is read by ANSYS during set-up using the ‘MPREAD’ command. Figure 6.6 provides an example of the exported result.

![Figure 6.6: Screen capture showing an example of scalar values for for elements 1-15 exported using MAGMALink.](image)
For the integration of porosity results a Young’s Modulus modification factor is used as described by Hardin & Beckermann (2007). The Young’s Modulus was modified using the following equation:

\[
E(\phi) = E_0 \left(1 - \frac{\phi}{\phi_0}\right)^n
\]  

(6.1)

Where \(E(\phi)\) is the elastic modulus of the porous material, \(E_0\) is the elastic modulus of the solid material and \(\phi\) is the porosity volume fraction. The term \(\phi_0\) denotes the critical porosity fraction, above this porosity level there is no longer an interconnected solid throughout the volume of material and the material looses all stiffness and load carrying capability, the elastic modulus becomes zero. The variable \(n\) is a power exponent that has been found to vary in measurements between 0.5 and 4 (typically \(n > 1\)), which models the severity of the effect. Experimental data in the reviewed literature show how \(n\) and \(\phi_0\) depend on pore shape and other characteristics of the pores on a microscopic scale (Herakovich & Baxter 1999, Roberts & Garboczi 2000, Rice 2005, Rice 1996). The factors \(\phi_0\) and \(n\) were varied to achieve best fit with experimental data and is discussed in the results section.

The modified elastic modulus was then incorporated into the ANSYS material property input file. Thus the porosity predicted in the casting simulation was modelled as an area with reduced stiffness according to Equation 6.1 above.

**Integrating residual stress:** Residual stresses are exported from MAGMA as 6 component tensors per element. The results were then rearranged into the format of an ANSYS ‘initial state’ file which allows the input of initial stress state conditions for each element. The initial state (.ist) file was then read by ANSYS using the ‘INISTATE, READ’ command.

**Integrating yield stress:** Integrating the predicted Yield Stress as a failure criteria is problematic when using ANSYS, as a maximum of 250 failure criterion are allowed per simulation. To bypass this limit the 39 824 values for Yield Stress, 1 for each element, were imported into an array table from which calculation of F.S could be done. After each simulation was solved, the Equivalent Stress result from ANSYS and the yield stress result from MAGMA was used to calculate the resulting safety factor for
each element, this result was then plotted.

Figure 6.7: Screen capture showing an example of tensor values for elements 1-8 exported using MAGMALink.

Integration interpolation errors:

The import procedures, calculation and plotting of results was automated using a short macro which ensured error free set-up of each simulation.

6.3 FEA simulation results and discussion

Standard FEA simulation: The standard stress analysis result, marked ‘std’ is shown in Fig. 6.8 below. The force applied (13 825 N) resulted in a minimum F.S of 1.0, indicating that the test bar would yield plastically when the force applied exceeded 13 825 N.

Integrated FEA simulations: The same force was then applied to each of the integrated stress analyses, the results are marked 1-8 in Fig. 6.8.

Figure 6.8 shows that the samples with porosity, Samples 1 and 2, had much higher maximum stress values than the standard simulation (about 60 MPa). This result is
expected as there is a smaller cross-sectional area available to carry the load due to the presence of pores. The F.S of Sample 1 and 2 is also affected, but the negative impact of the pore is offset by the increase in YS of the material. The samples therefore still have a higher F.S than the standard simulation result. Porosity integration factors of \( n = 0.5 \) and \( \phi_0 = 1 \) was found the produce the best correlation to the experimental results.

The effect of the residual stress can only be seen in sample 5 as a small discontinuity in stress at the top and bottom right curves of the sample. The location of the discontinuity coincides with the location where the stress was predicted (Fig. 4.9).

For all test samples, the integrated result for 1/F.S differed significantly from the standard simulation result. The minimum F.S for the integrated simulations was 1.19 for Sample 2 compared to 1 for the standard simulation.

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**Figure 6.8: Sectioned contour plots of equivalent stress (left) and 1/Factor of Safety (right) for the each test sample using the standard material definition ‘std’ and the integrated material definition ‘1-8’.”**
To isolate the effect of integrating each critical FEA input parameter, addition simulations were run with only one FEA input parameter integrated at a time. A total of 32 simulations were run. The results are shown in Table 6.2 from which it can be seen that the integration of Yield Strength had the greatest effect among all test sample FEA simulations. Samples 4 and 5, the thin centre samples, were most affected by integrating Yield Strength. The second largest effect was that of integrating porosity, but only in Samples 1 and 2, which had high levels of porosity. Sample 3, which had 28% predicted porosity in a smaller region was almost unaffected. The third largest effect was that of residual stress, which had a 5.5% effect on Sample 5, the effect on the other samples was insignificant. Finally, the integration of Young’s Modulus had almost no effect across all test samples as the range was small and close to the mean for the material.

<table>
<thead>
<tr>
<th>Sample nr</th>
<th>Yield Strength</th>
<th>Residual Stress</th>
<th>Porosity</th>
<th>Young’s Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31.8</td>
<td>-0.28</td>
<td>-20.2</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>31.9</td>
<td>0.04</td>
<td>-20.9</td>
<td>-0.01</td>
</tr>
<tr>
<td>3</td>
<td>32.9</td>
<td>-0.01</td>
<td>-1.2</td>
<td>0.003</td>
</tr>
<tr>
<td>4</td>
<td>37.5</td>
<td>0.1</td>
<td>-0.2</td>
<td>-0.15</td>
</tr>
<tr>
<td>5</td>
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<td>-5.5</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>6</td>
<td>32.0</td>
<td>0.04</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>26.5</td>
<td>-0.001</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>27.0</td>
<td>-0.31</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6.2: Table of results listing the % effect of integrating each FEA input parameter on the change in F.S
6.4 Comparison of simulations vs. physical tests:

A comparison between the experimental and simulation results is shown in Fig. 6.9. The results showed that the integrated simulation predicts the experimental FS more accurately than the standard simulation. The average error of the standard simulation was 24.3% whereas the average error of the integrated simulation was only -4%. The negative average indicates that the integrated simulations generally predicted a higher FS than what was experimentally determined.

![Figure 6.9: Plot of mean with Std.Err of experimental FS vs the FS determined from the standard and integration simulations.](image)

On average the experimental test samples were 33% stronger than the material specification of 275 MPa and the integrated simulation was able to predict this difference within less than 10%. The results show that integrating cast simulated FEA input pa-
rameters increased the accuracy of the stress analysis by a mean of 18% when considering absolute error, which is a significant improvement.

Considering the results, using an integrated simulation in the design of a component could reduce the thickness of sections between 15 and 30%. This reduction in will however be dependent on the geometry and the resulting microstructure of the section. Caution should however be exercised as the integrated simulation produces more accurate, but less conservative results than the standard simulation approach.
Chapter 7

Conclusion and Recommendations

7.1 Introduction

The overall aim of this research was to investigate and implement a method for increasing the accuracy of the FEA stress analysis using coupled stress and castings simulation results. The main findings are discussed below.

7.2 Summary of findings and conclusions

Properties that were identified to directly affect the accuracy of the stress analysis results and the F.S calculation are:

2. Variations in Yield Strength.
3. Variations in Young’s Modulus.
4. Variations in Residual Stress.

A sensitivity study was conducted, and it was found that all four identified FEA input parameters can have a significant effect on the safety factor of the component for estimated severity ranges, it is concluded that variations in all four FEA input parameters must be considered in the stress analysis to predict the stress throughout the casting accurately.

An investigation of recent publications evaluating the different aspects of numerical modelling of casting processes was conducted. The investigation considered the accuracy of filling and solidification modelling, residual stress modelling and solidification micro-modelling. Evidence from literature showed excellent agreement between simulations and experimental results. It is concluded that casting simulation using MAGMASOFT can accurately predict variations in the identified FEA input parameters and that integrating these predicted parameters would not necessarily introduce additional risk into the simulation chain.

Further investigation was required to evaluate the effect of integrating each of the four identified FEA input parameters, to assess whether the accuracy of the F.S calculation can be increased and to what degree each identified parameter has an effect. An experimental investigation was carried out on a casting that could be tested and was as representative of a valve body as possible. The castings were also manufactured at two different foundries to consider the effect of foundry practice. A casting simulation was done using MAGMASOFT, and results were integrated into the stress analysis using ANSYS. The results of the integrated simulations were then compared to that of a simulation set up with a standard material definition. The experimental results were used as a baseline for evaluating the accuracy of the simulations.

The integrated FEA simulations more accurately predicted the Factor of Safety. The reduction in error from the simulation using a standard material definition was roughly 18%. A difference in experimental results between the two foundries was observed,
but the difference does not negate the positive impact that integration could have for either one of the foundries.

In summary it is concluded that integrating casting simulation results into the stress analysis increases the accuracy of the stress analysis, especially when considering Factor of Safety. The increase in accuracy significantly reduces the uncertainty regarding the material of the manufactured component and can result in worthwhile cost savings for manufacturers through the reduction of large section sizes that compensate for uncertainties in the material.

7.3 Recommendations

This study has shown that there is a substantial potential for cost savings in using an integrated simulation methodology but the test samples used were only analogous of valve bodies, and it is thus difficult to say what the true extent of savings would be for actual valve bodies. It is thus recommended that further investigation be done on actual valve bodies under pressure tests as specified by the relevant test specifications.

As each valve body design will have unique properties due to geometry and casting process conditions, results from this investigation cannot simply be extrapolated to all valve bodies; thus the specific valve designs that a manufacturer may want to optimise should be treated individually on a case by case basis.
Bibliography


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## Appendix A

### Results tables

#### A.1 Stress analysis results

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Max Eqv Stress [MPa]</th>
<th>Min F.S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard (std)</td>
<td>278</td>
<td>1.0</td>
</tr>
<tr>
<td>Integrated (1)</td>
<td>337</td>
<td>1.20</td>
</tr>
<tr>
<td>Integrated (2)</td>
<td>340</td>
<td>1.19</td>
</tr>
<tr>
<td>Integrated (3)</td>
<td>281</td>
<td>1.46</td>
</tr>
<tr>
<td>Integrated (4)</td>
<td>279</td>
<td>1.58</td>
</tr>
<tr>
<td>Integrated (5)</td>
<td>301</td>
<td>1.47</td>
</tr>
<tr>
<td>Integrated (6)</td>
<td>278</td>
<td>1.46</td>
</tr>
<tr>
<td>Integrated (7)</td>
<td>278</td>
<td>1.35</td>
</tr>
<tr>
<td>Integrated (8)</td>
<td>279</td>
<td>1.35</td>
</tr>
</tbody>
</table>

*Table A.1: Table of results listing max stress and F.S. for the standard simulation (0-8) and the integrated simulations of each test sample*
A.2  Comparison of stress analysis results

<table>
<thead>
<tr>
<th>Sample nr</th>
<th>Standard Simulation</th>
<th>Integrated Simulation</th>
<th>Tensile Tests Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2</td>
<td>1.24</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.19</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.46</td>
<td>1.31</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.58</td>
<td>1.46</td>
<td></td>
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<td>5</td>
<td>1.47</td>
<td>1.57</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.46</td>
<td>1.31</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.35</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.35</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Mean:</td>
<td>1.38</td>
<td>1.33</td>
<td></td>
</tr>
</tbody>
</table>

Table A.2: Table of results comparing minimum F.S. for the different simulations and the experimental results.

A.3  Yield force of test samples

<table>
<thead>
<tr>
<th>Sample nr</th>
<th>Foundry 1 Casting A</th>
<th>Foundry 1 Casting B</th>
<th>Foundry 2 Casting C</th>
<th>Foundry 2 Casting D</th>
<th>Foundry 2 Casting E</th>
<th>Foundry 2 Casting F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.8</td>
<td>18.7</td>
<td>18.0</td>
<td>17.0</td>
<td>17.3</td>
<td>14.7</td>
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<tr>
<td>2</td>
<td>18.0</td>
<td>18.5</td>
<td>17.4</td>
<td>16.9</td>
<td>15.0</td>
<td>15.3</td>
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<td>3</td>
<td>18.9</td>
<td>19.1</td>
<td>18.2</td>
<td>17.4</td>
<td>18.2</td>
<td>16.9</td>
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<tr>
<td>4</td>
<td>19.6</td>
<td>19.3</td>
<td>21.5</td>
<td>20.4</td>
<td>21.4</td>
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</tr>
<tr>
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<td>19.5</td>
<td>23.0</td>
<td>22.8</td>
<td>22.2</td>
<td>22.7</td>
</tr>
<tr>
<td>6</td>
<td>19.1</td>
<td>19.2</td>
<td>17.9</td>
<td>16.9</td>
<td>18.1</td>
<td>17.3</td>
</tr>
<tr>
<td>7</td>
<td>19.2</td>
<td>19.4</td>
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<td>16.8</td>
<td>15.6</td>
</tr>
<tr>
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<td>19.9</td>
<td>no data</td>
<td>16.7</td>
<td>17.2</td>
<td>no data</td>
</tr>
</tbody>
</table>

Table A.3: Table of results of yield force calculated for each casting.
### A.4 F.S calculated from yield force

<table>
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<tr>
<th>Sample nr.</th>
<th>Foundry 1 Casting A</th>
<th>Foundry 1 Casting B</th>
<th>Foundry 2 Casting C</th>
<th>Foundry 2 Casting D</th>
<th>Foundry 2 Casting E</th>
<th>Foundry 2 Casting F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>1.36</td>
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<td>2</td>
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<td>1.34</td>
<td>1.26</td>
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<td>1.10</td>
</tr>
<tr>
<td>3</td>
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<td>1.38</td>
<td>1.31</td>
<td>1.26</td>
<td>1.31</td>
<td>1.22</td>
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<td>4</td>
<td>1.42</td>
<td>1.40</td>
<td>1.56</td>
<td>1.48</td>
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<td>1.39</td>
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<td>1.64</td>
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<td>1.30</td>
<td>1.22</td>
<td>1.31</td>
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<td>1.39</td>
<td>1.40</td>
<td>1.20</td>
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<td>1.21</td>
<td>1.13</td>
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</table>

*Table A.4: Table of results of F.S calculated from yield force for each casting.*

### A.5 Comparison of %Err of standard and integrated simulations

<table>
<thead>
<tr>
<th>Sample nr</th>
<th>Standard Simulation [%]</th>
<th>Integrated Simulation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.2</td>
<td>3.2</td>
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<td>2</td>
<td>17.9</td>
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<tr>
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<td>-3.8</td>
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</tbody>
</table>

*Table A.5: Table of %Err for each simulation of each sample using the experimental average F.S as a baseline.*
A.6 Detail drawing of test bar

Figure A.1: Detail drawing and dimensions of test bar.