ANALYTICAL AND EXPERIMENTAL STUDY ON THE EFFECT OF DISCONTINUITIES ON CAST STEEL COMPONENT PERFORMANCE

by

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As members of the Master’s Committee, we certify that we have read the thesis prepared by Joseph Moya, titled Analytical and Experimental Study on the Effect of Discontinuities on Cast Steel Component Performance, and recommend that it be accepted as fulfilling the dissertation requirement for the Master’s Degree.

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Final approval and acceptance of this thesis is contingent upon the candidate’s submission of the final copies of the thesis to the Graduate College.

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ABSTRACT

An experimental and analytical study is performed to investigate the effect of different discontinuities on the yield strength, ultimate strength and ductility of steel cast components. Steel plates containing various discontinuities were cast in sand molds, cut to size, and tested in monotonic tension to fracture. Radiographic imaging was used to identify, classify, and rate discontinuities. Three different types of discontinuity and three different ASTM 2868 indication levels were tested. The discontinuities varied in size from 0.46 percent to 9.09 percent of the average gross-section area of the specimens. Specimens rated Level 2 or lower tended to fracture at the minimum section, not at the discontinuity. Specimens with Level 5 indications tended to fracture at the discontinuity. Specimens which fractured at the discontinuity had reduced ductile capacity. Elongation was reduced by Level 5 indications by between 45.7 to 70.0 percent. Ductile fracture predictive models were used in finite-elements analysis to predict component performance. Models used color data from radiography for discontinuity size. Good agreement is obtained between experimental and predicted elongation at fracture. The analytical modeling methods used in this thesis allow for accessible prediction of ductile capacity of a cast component.
1 - INTRODUCTION

1.1 Problem Statement

Components made of cast steel present a variety of desirable traits for the construction of civil structures. Castings can be both structurally efficient and economical. They have desirable material qualities and can be more readily made into complex shapes than can welded or forged components. Despite their good qualities, hot-rolled steels remain the default material in construction. Cast steels are rarely used.

Cast steel components have a variety of uncertainties that are not well understood by most civil-structural engineers. Cast steel components may have discontinuities within them due to the nature of the cast steel production process. These discontinuities lead to worse local strength than a similar, discontinuity free component. If present in significant quantity, discontinuities may lead to failure of the specimen at a load below the design strength.

In addition to the loss of strength due to discontinuities, discontinuities reduce the ductile capacity of a component. Current design procedure uses safety factors that assume a certain level of ductility. This ductility allows for excessive deflection should the component ever be overloaded. The excessive deflection acts as a warning for the general public to evacuate the area prior to a potential catastrophic failure. Any significant reduction in ductility may lead to sudden failure with little warning.

Discontinuities in castings are typically found and rated using non-destructive evaluation, such as radiographic imaging. Current code does not specify the level of discontinuity acceptable in a cast steel component. Design engineers are required to specify acceptable levels by their judgment. Engineers typically act conservatively and require a better rating than may be necessary. An accessible correlation between discontinuity size and performance is needed for engineers to be ready and capable of safely using steel cast components in their structural design.

1.2 Objective

The objective of this thesis work is to examine the effects of discontinuities in cast steels on the performance of cast steel components and to use commercially available finite element analy-
sis to predict the performance of a cast steel component with discontinuities present.

A combination of physical experiments and analytical modeling is used for the examination. Analytical modeling is first used to predict component performance. The evaluation involves correlating the nature (size, shape, location, etc.) of the discontinuities present in a steel component to the component's ductile performance. In the analytical stage, non-linear finite element (FE) analysis is used. The performance is estimated through internal measurements in the FE analysis. Finally, physical experiments are used to verify or further calibrate the methodology.

1.3 Research Scope

The scope of the thesis work investigates the performance of steel castings. The component is intended to remain elastic. The effect on yield and ultimate strength is found by testing. The investigation into the ductile capacity of a component uses both experimental and analytical methods and is intended to determine the inherent factor of safety.

Two cast steel materials of varying strength and ductility are studied in the steel casting evaluation. Multiple discontinuity types and severity are included.
II - BACKGROUND

Before presenting the research, it will be instructive to provide background information on Cast Steel Components (1) and the concept of ductile fracture and relevant predictive models (2).

2.1 Cast Steel

Casting steel is a process in which molten steel is poured into molds. The process begins with the creation of a pattern representing the finished geometry of a component. (Figure 2.1.1 (a)) For limited production, this is often from wood, though for specialized parts that require high geometric accuracy may be made from wax or foam. A mold is then formed around the pattern into which the molten steel will be poured. The most common molding practice today is the process known as green sand. Sand is packed around the mold, either manually or by machine, and is bound together using clay and water. (Figure 2.1.1 (b)) This results in a highly economic and readily recyclable mold. Other molding procedures exist. Ceramics are often used for smaller parts (less than several hundred pounds) which require high accuracy or very fine finish. (Steel Casting Handbook 1995)

Fig. 2.1.1 – A steel casting pattern (Steel Casting Handbook 1995) (a) and a green sand mold (Hawthorn Castings) (b)

Most civil structures use hot rolled steel for main members (columns, beams, etc.) and cold-formed steels for light elements (e.g. metal deck, open web roof joists). Cast steel components are rarely used. However, cast steel can offer many highly desirable qualities in structures. In particular, castings offer the ability to create complex geometries more economically and efficiently than fabricated shapes. Fabricated joints, for example, often involve ill-fitting members
intersecting at different angles and points, requiring complicated cutting and difficult welds. In this situation, castings create a significant advantage in creating the joints between members, particularly for tubular sections in planar and space frames and trusses. Cast steels are underutilized however, to a large extent, due to poor understanding in the engineering world of their behavior and the variability, perceived or real, in their material properties (Hardin 2013).

Cast steels do differ in properties when compared to wrought steels. For instance, cast steels exhibit near-uniform properties in all directions. This uniformity is due to the component being cooled in its finished geometry. Crystallization is not forced into one direction. Hot rolled, and cold-formed steel, however, are shaped by working semi-molten steel with drums into the desired shapes. Wrought components contain plastically elongated inclusions and chemical separations within the steel matrix in a direction. These directionally elongated inclusions lead to differing properties in the directions orthogonal to the working direction. (Elwell 1977) Tensile strength in the orthogonal directions is not significantly affected. However, elongation and fatigue strength are. This reduction in ductile capacity is reflected in steel construction, as certain weld geometries are not allowed, see Fig 2.1.2. (AISC 2014) Cast steels do not have this loss of ductility in a working direction because no working is performed. For parts that are loaded three-dimensionally, this results in more favorable behavior. (Steel Casting Handbook 1995)

Sand molds may result in unique discontinuities such as are not seen in wrought steels. In the case of green sand molding, the model is held together solely by the adhesion of clay and sand and the cohesion of water. Grains of sand may enter the steel matrix during pouring. Such
inclusions change the behavior of the cast steel locally, and if present in high enough amounts, can greatly reduce the strength, stiffness, and ductility of the steel. (Figure 2.1.3)

In addition to sand inclusions, cast steels have a variety of other possible discontinuities that are unique to cast metals. When cast steels cool, the outer edges harden and shrink faster than the interior. As the still molten interior cools, it pulls away from the center towards the already hardened outer edge, resulting in voids at the center of the casting, known as shrinkage porosity. If present in significant enough quantity and concentration, this can greatly reduce the strength and ductility of a cast part.

Yet another possible discontinuity is air inclusion. During the pouring process, air can become trapped within the steel, and, if not separated properly by casting design or by allowing time for bubbles to float out of the casting, can result in trapped gas voids. These voids called gas poros-
ity result in similar mechanical property losses as those due to shrinkage porosity. Other common discontinuities include cracks, tears, inserts, and mottling. (ASTM E2868)

The presence of these discontinuities can be greatly reduced if not eliminated by proper casting design. Limiting local areas of high thickness near thin areas, placing molten steel reservoirs, called gates, in strategic locations, and controlling the cooling process all can limit the presence of shrinkage porosity. Controlling the speed at which the molten steel is poured or adding volume to the casting designed to collect the entrapped gases during pouring can reduce the presence of gas porosity. Any risers, gates, and sinks are typically removed after pouring. (Steel Castings Handbook 1995)

Casting process design may use finite element software to simulate the casting process, from pouring rates to solidification. Areas that will likely result in shrinkage porosity can be found by simulating the cooling process. Steps can then be taken to mitigate the expected porosity, such as cooling surrounding areas to prevent the temperature differentials which create shrinkage porosity. Simulating the pouring procedure can aid in estimating the air entrapped in the steel matrix and can suggest areas that may be effective for sinks in which to trap the air. Common software used for this purpose is MagmaSoft. The steel castings studied in this research were designed by Dr.'s Richard Hardin and Kristoff Beckerman of the University of Iowa using MagmaSoft software.

Yet another difference between cast steels and wrought steels in chemical composition. The cast steel industry has been working for many years with rail companies, aircraft manufactures, and the military, all of whom have material demands quite different from those of steel building designers. Common cast steels, therefore, have chemical compositions that are not proper fits for steel construction. Milder cast steels do exist, one of which was used in this research. These steels may chemically qualify as ASTM wrought steels but often cannot be labeled as such due to the difference in the production process. While this may seem a disadvantage, foundries are quite skilled in producing steels that are effective and meet the customer's needs. A much wider variety of steels exists in the casting industry as compared to the typical hot rolled steel sections.
The identification and classification of discontinuities in steel castings are typically performed using non-destructive testing (NDT) by the foundry which produced the cast components. Multiple techniques are used to locate these discontinuities. Four techniques are commonly used by foundries to identify discontinuities, magnetic particle inspection, liquid dye penetrant, radiography, and ultrasonic testing.

Two low-cost techniques are magnetic particle inspection and liquid dye penetrant. Magnetic particle inspection is typically performed according to ASTM E709 standards. The process involves inducing a magnetic field in a ferromagnetic component, such as a steel casting. This field is created by the introduction of an electric current through the component, or by placing the component near an external magnetic source. The magnetic field is interrupted at locations of discontinuity in the component. The shape of the magnetic field can be seen by placing magnetic particles in a medium called flux. The particles gather at areas of discontinuity. (ASTM E709) Liquid penetrant inspection is performed in accordance with ASTM E165. A liquid penetrating dye is applied evenly to the surface of the inspected component. Surface discontinuities collect the penetrant and are revealed when the pigment is developed chemically. (Figure 2.1.5) Liquid penetrant is limited to identifying discontinuities that reach the surface. (ASTM E165)

![Fig. 2.1.5– A liquid penetrant test using fluorescent fluid](image)
Inspection methods becoming the norm today are radiographic testing (RT) and ultrasound testing. RT uses focused x-rays from a radioactive element to penetrate the steel component. Radiographs are black and white images, with varying levels of black pigment in relation to the resistance of a component to x-ray radiation. (Blair 2009) Thicker sections of steel are more resistant than thinner sections, and therefore are whiter in the radiograph. The discontinuities are visible as more highly exposed (dark) locations on the produced image. Historically, radiographic film has been used as the x-ray sensitive element. Digital radiography, in which no physical film is used, has become commonplace.

RT discontinuity identification and classification procedure requires the inspector to compare the new radiograph with a series of reference radiographs. Current procedure separates indications into one of seven discontinuity types; gas porosity, slag and sand inclusions, shrinkage porosity, cracks, hot tears, and mottling. Gas porosity, slag and sand inclusions, and shrinkage are further divided into levels of severity, with Level 1 being the least severe and Level 5 being the most severe. (ASTM 446) The identified discontinuity in RT is called an indication.
Current RT standards, such as ASTM E2868, are subjective. (Blair 2009) The repeatability of an RT rating is low (Carlson 2001). Only Level 0 for no indication and Level 5 for severe indications were commonly repeated across different rating individuals. Individuals also rated the same RT image differently on different occasions. (Carlson 2001). A more quantitative approach to radiographic rating has been proposed using the ratio between the length of the indication in a direction and the length of the component in the same direction (Blair 2009). (Figure 2.1.7) Yet another, more accurate prediction method is the use of the ratio of the area of the indication and gross-section area of the component. This method of rating relies partially on how dark the indication is in the RT image, K level. This differs from current standards which do not allow K level to be considered in rating a casting (ASTM 446).

Fig. 2.1.7 – Length ratio method as proposed by Blair et, all (2009)
2.2 Ductile Fracture Background

An important failure mode in steel structures is fracture. Unlike other limit states for steel elements, such as yielding or buckling, which reduce strength or stiffness, fracture is to the total loss of load-carrying capacity. For this reason, fracture of critical elements can lead to catastrophic failure of an entire component. Fracture may govern the strength of several structural elements, including bolted connections and welded connections. (AISC 2014)

In engineering, structures are generally designed elastically. Most civil engineering structures remain elastic during their service life. Elastic and elastic-plastic fracture analysis is acceptable for such structures. However, every structure yield at points of stress concentrations, and certain structures, such as special moment frames, are designed to yield during service. Elastic and elastic-plastic analyses are insufficient in such situations.

Two types of fracture are often distinguished from one another, brittle and ductile fracture. Brittle fracture involves transgranular cleavage or the separation of atoms within the material matrix across grains in the steel caused by stress. Brittle fracture is the controlling limit state for components made of non-ductile materials but may occur in ductile steels if stress concentrations at the location of a defect overcome the material strength. This behavior is most commonly modeled using Stress Intensity Factors (K_I), the use of the J-Integral, or Crack-Tip Opening Displacements (CTOD). (Kundu 2008)

Ductile fracture, on the other hand, occurs after the location surrounding the fracture has significantly yielded. The local growth, coalescence, and necking of voids caused by yielding create a discontinuity large enough to initiate fracture of the element. (Hancock 1976)

Ductile fracture inherently depends on the plastic behavior of the underlying material. Plasticity in materials is a shear phenomenon. Materials will only yield in a stress state in which shear is present and if the materials shear strength is less than half the material's tensile strength. (Claisse 2016) Shear stress at a point is generated by the difference between axial stress states orthogonal to each other, as seen in the well-known two-dimensional Moor's circle. Shear will occur once this difference in principle stresses cause shear stress greater than the materials shear strength.
and will occur in the direction of this shear stress. This behavior can be readily observed in ASTM .505 tensile coupons of ductile steel. If the stresses in both directions are equal, no shear stress is present in the reference plane.

Three-dimensional stress states are described using different measures. One such measure is the mean stress of hydrostatic pressure, Equation 2.2.1.

\[ \sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \]  \hspace{1cm} [2.2.1]

where, \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the three principal stresses.

Two commonly used three-dimensional yield criteria exist, Tresca’s Yield Criterion and Von Mise's Yield Criterion. This research uses Von Mise's criterion, Equation 2.2.2.

\[ \sigma_\varepsilon = \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \]  \hspace{1cm} [2.2.2]

Von Mise's stress criterion is the difference in the three principal stresses at a location. As shear at a three-dimensional point may be different in all directions, it is not the same as the shear stress as it was in the two-dimensional case. However, just as in two dimensions, if a stress state creates no difference in the principal stresses, a Von Mise's stress value of zero, the material will not yield, no matter how high the stress gets.

The ratio of these two measures is known as stress triaxiality, \( T \), defined as follows:

\[ T = \frac{\sigma_m}{\sigma_\varepsilon} \]  \hspace{1cm} [2.2.3]

Triaxiality is equal to one third in a state of pure uniaxial tension stress. The value of triaxiality approaches infinity as Von Mise's stress approaches zero when there is no difference in the principal stresses. As previously stated, if no difference exists between three principal stresses at a point, no yielding can occur. Fracture will, therefore, be brittle. Ductile fracture will occur only when a significant volume has yielded in the location of fracture.

Yielding initiates multiple processes that influence ductile fracture. Nucleation of inclusions can cause larger holes and microcracks. Inclusions can also separate from the matrix, creat-
ing cracks. The holes formed by these processes grow by plastic flow. (Hancock 1976) Eventually, these holes may neck and coalesce, leading to failure of the component. In addition to the multiple mechanisms controlling ductile fracture, the fracture is history-dependent. (Rice and Tracey 1969) That is, ductile fracture is not only controlled by the current stress state, as is the case in brittle fracture and initial yielding. Ductile fracture is affected by previous strain history. This is because the current stress and strain state only controls current incremental deformation, with the ductile fracture being controlled by localized necking that occurs over time.

Due to the history-dependent aspect of ductile fracture, the prediction of fracture needs to consider the changing stress state relative to the plastic strain over time. It was proposed based on the work of Rice and Tracey (1969) that a quantity representing the growth of voids was a good predictor of fracture. Fracture would occur when this value, the Void Growth Index (VGI), reached some critical value. This critical value represents the value of this index at which voids would grow large enough to trigger necking between voids. (Kanvinde 2006) This model is mathematically represented as follows:

\[
VGI = \int_{\varepsilon_p,cr}^{\varepsilon_p} \exp \left(-1.5 \frac{\sigma_m}{\sigma_e} \right) d\varepsilon_p \quad > \quad VGI_{cr}
\]

where \(\sigma_m\) is the mean stress, \(\sigma_e\) is the von mises stress, \(d\varepsilon_p\) is the incremental equivalent plastic strain, \(\varepsilon_{p,cr}\) is the critical plastic strain, and \(VGI_{cr}\) is a material parameter representing the critical void ratio. The detailed derivation of the VGI can be found in Rice and Tracey (1969) and Kanvinde and Deierlein (2004). VGI\(_{cr}\) is found for each distinct material by calibration to notched bar tests. The exponent factor of 1.5 used was determined by Rice and Tracey (1969) by theoretical derivation. Other values have been proposed as giving better results. Hancock and Brown (1983) showed that best-fit coefficients were anywhere between 1.1 and 2.3. For this paper, the value of 1.5 is used.

In the VGI equation, stress triaxiality varies can vary over plastic strain history. Should this not be true, as shown to be common by Hancock and Mackenzie (1976), one can simplify this as shown:
\[ \varepsilon_{p_{critical}} = \alpha \exp \left( -1.5 \frac{\sigma_m}{\sigma_y} \right) \]

Where \( \alpha \) is a material constant representative of material toughness. This model is known as the Stress Modified Critical Strain (SMCS) model. \( \alpha \) can be found by calibrating a known stress triaxiality value to a known corresponding \( \varepsilon_{p_{cr}} \). As stress is near uniaxial in small scale tensile coupons, such as the ASTM .505 coupon (ASTM E8), \( \alpha \) can be found by using the maximum true plastic strain from a tensile test and a triaxiality value of 0.33. The SMCS model was shown by Kanvinde and Deierlein (2006) to be nearly as accurate in monotonic loading cases as the history-dependent VGI. The SMCS has the advantage over VGI of only requiring the stress and strain values at a single point in time, rather than requiring integration across time. The application in FEA is simpler. As the castings studied in this paper were loaded monotonically, the SMCS was used for all fracture predictions.

![Fig. 2.2.1 – The Stress Modified Critical Strain Model curve for an ASTM 8630 80/50 steel with 28% elongation.](image-url)
III - INVESTIGATION OF THE PERFORMANCE OF CAST STEELS WITH DISCONTINUITIES

Experimental and analytical work was used to determine the performance of cast steel components with discontinuities in critical regions. The overall purpose of the research into the effect of discontinuities on cast steels is to create a series of guidelines for civil-structural engineers to accept castings for use in structural applications. Three main aspects of structural components that may be affected by the presence of discontinuities are strength, stiffness, and ductility. Loss of strength may cause unexpected failure. Loss of ductility may result in sudden failure if overloading occurs. Loss of stiffness may result in undesirable deflection, even if strength and ductile requirements are met. A casting would be acceptable for use in structural applications if it met all three acceptance criteria, see Figure 3.0.1.

![Graphical representation of acceptance criteria.](image)

Fig 3.0.1 - A graphical representation of acceptance criteria.

The work was composed of two thrusts, testing of cast components and finite element analysis (FEA). Testing focused on cast steel tensile specimens with ultimate strengths of up to 200 kips. The castings from which the specimens were taken were specifically designed to contain different discontinuity types. NDT in the form of radiography was performed by the foundry. Radiography identified and rated the level of indication on each casting. (Section 3.1).
Monotonic tensile testing was performed on the specimens to fracture. (Section 3.2) Testing was broken up into two phases, Phase 1 and Phase 2. Linear voltage displacement transducers (LVDTs) were used to measure deflection in the gage region of the specimen.

FEA was used to predict fracture performance of the specimen. (Section 3.3) Analysis of the radiographic images was performed using commercial imaging software to measure internal discontinuities. Surface discontinuities were measured by silicone rubber castings of the surface. Highly accurate models of each specimen were created using three-dimensional drafting software. The SMCS model was applied to the FE models to predict the load and displacement at which fracture would occur. The result of this analysis was compared with test results.

3.1 CAST SPECIMENS

Testing was separated into two distinct phases, Phase 1 and Phase 2. Each phase had a different steel material and indication type. Phase 1 material was a steel chemically equivalent to A8630 115/95 material. Phase 2 material was chemically equivalent to A8630 80/50. The exact chemical composition of each material is given in Table 3.1.1.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>S</th>
<th>P</th>
<th>Mn</th>
<th>Si</th>
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<th>Ni</th>
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*Table 3.1.1 – The chemical composition of the two study steels*

Specimens were tested in uniaxial tension. Specimens larger than ASTM standards were desired for a more realistic scale between discontinuity and component. The design of test specimens was a collaboration between a foundry industry partner, the research team, and partner Universities. The nominal specimen dimensions are shown in Figure 3.1.2. The specimens were poured in 36-inch plates for the ease of casting by the foundry. The casting process (gating, riser location) design was used to ensure discontinuities in the gage region. Dr.'s Richard Hardin and Cristoph Beckerman at the University of Iowa performed solidification analysis using the commercially available software MagmaSoft. The results of this modeling are shown in Figure 3.1.3 and Figure 3.1.4. Phase 1 castings focused on surface indications. Phase 2 focused on internal
discontinuities such as centerline shrinkage porosity and sand inclusions. The gating systems for each phase were designed to create these discontinuities.

Mechanical properties of each steel were found by tensile testing after the plates were cast. ASTM E8 tensile coupons were machined from each casting and loaded to failure. Mechanical property testing was performed in house for the Phase 1 plates. Phase 2 mechanical testing was performed in a commercial laboratory.

**Fig. 3.1.2** – The Phase 1 casting cross section dimensions

**Fig. 3.1.3** – MagmaSoft solidification analysis, showing inclusions on the surface (Hardin 2018)

**Fig. 3.1.4** – MagmaSoft solidification analysis, indicating shrinkage in the casting (Hardin 2018)
performed by the foundry. The results of each may be seen in Figure 3.1.5. Testing revealed that the Phase 1 material was stronger than anticipated, with a yield strength of 124 kips per square inch (ksi) and an ultimate strength of 142 ksi. Elongation at fracture across two inches for this material was 14%. Such high strength, low ductility material would rarely be used in construction but was useful to show the applicability of the fracture predictive methods in various materials. Phase 2 material was a construction-grade steel, with a yield strength of 55 ksi and an ultimate strength of 88 ksi. Elongation at fracture was found to be 28%. Mechanical properties are summarized in Table 3.1.6.

Digital radiography was performed by the foundry where the specimens were cast, Spokane Industries. The radiographs were taken according to ASTM E2868 standards. The radiographic

![Stress-strain profiles for the Phase 1 material (orange) and the Phase 2 material (blue)](image)

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<th>Fy (ksi)</th>
<th>Fu (ksi)</th>
<th>Elong. (%)</th>
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<td>28.0</td>
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*Table 3.1.6 – Mechanical properties of Phase 1 and Phase 2 material*
image of the single Phase 1 casting is shown in Figure 3.1.7. Four distinct surface discontinuities were identified. Three of these four discontinuities were under one inch in width. One discontinuity was much larger. Each of these indications was rated a level 5, meaning they would almost certainly have been discarded at the foundry. A comparison between the ASTM RT rating and the F rating as described by Blair (2009) for each indication is given in Table 3.1.8. Six specimens were taken from the Phase 1 casting. Three were cut around indications 2, 3, and 4. An additional two specimens were cut from clean sections of the casting and machined with a ball end mill to have surface discontinuities of equal area to indications 2 and 3. Their purpose was to simulate the naturally occurring discontinuity. A third additional specimen was taken from a clean section of the casting as a control specimen. These additional specimens are listed in Table 3.1.8 as 3X-1 (control), 3X-3, and 3X-5 (simulated discontinuity).

![Fig. 3.1.7 – RT image of the Phase 1 casting, with indications numbered left to right.](image)

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<tr>
<td>F Rating</td>
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*Table 3.1.8 – RT image rating using ASTM standards and F system proposed by Blair 2009*
Phase 2 specimens came from seven different castings. The castings were numbered as follows: 1X, 2X, 3X, 4X, 5X, 6X, and 10X. Two specimens were cut from each casting, indicated by the yellow lines each of the following RT images. The RT image of the Phase 2 casting 1X is shown in Figure 3.1.10. Half of the casting had a slightly wrinkled surface. RT found only one internal discontinuity, a level 2 shrinkage indication. The RT image of casting 2X is given in Figure 3.1.11. Casting 2X was created with a section of reduced thickness at the center of the gage region. This can be seen in the radiograph. Four surface indications were found. specimens were taken at the location of indication 2 and 4.

Measurement of surface indications was performed by creating a silicone cast of the casting surface, then measuring the silicone casting with calipers. This method allowed for accurate measurements of surface indications which were larger under the surface than at the surface. One such silicone mold is shown of specimen 3X-6 in Figure 3.1.9. Specimen 1-3X-1 (Phase-Plate-Specimen number) had its surface machined to remove any eccentricity and change in thickness across the gage region to create a near-ideal control specimen.

Fig. 3.1.9 – Silicone Casting of surface indication 3X-6
The RT image of casting 3X is shown in Figure 3.1.12. Level 5 sand and slag inclusions were found through the casting. The RT image of casting 4X is given in Figure 3.1.13. Only one specimen was cut from casting 4X, as indicated by the yellow lines. Level 5 sand inclusions were found within the gage region.
Fig. 3.1.12 – RT image of the Phase 2 casting 3X, showing Level 5 sand/slag inclusions

Fig. 3.1.13 – RT image of the Phase 2 casting 4X, showing Level 5 sand/slag inclusions
The RT image of casting 5X and 6X are shown in Figures 3.1.14 and 3.1.15. Casting 5X contained both minor surface indications and Level 5 sand inclusions. Casting 6X contained level 5 shrinkage porosity.

Fig. 3.1.14 – RT image of the Phase 2 casting 5X, showing Level 5 sand/slag inclusions

Fig. 3.1.15 – RT image of the Phase 2 casting 6X, showing Level 5 shrinkage
Casting 10x's radiograph is shown in Figure 3.1.16. Level 5 shrinkage porosity was found throughout.

**Fig. 3.1.16 – RT image of the Phase 2 casting 10X, showing Level 5 shrinkage**

Measurement of the internal indications was performed utilizing image analysis, according to the methods described by Hardin and Beckermann (2013). The RT image was imported into ADOBE Illustrator, a commercially available image creation and editing software. The image was converted to a true grayscale image having no color values. The image was also converted from Red-Green-Blue (RGB) color space to Cyan-Magenta-Yellow-Black (CMYK) color space. This conversion allowed for the direct measurement of black pigment (K) concentration in the RT image. This black pigment concentration, the K value, were found at various locations of known thickness in the radiograph. A curve was created from this data representing the thickness value related to each K value. An example of this process for specimen 2-5x-1 can be found in Figure 3.1.17. A summary of Phase 2 specimen radiographic findings is shown in Table 3.1.18.
Fig. 3.1.17 – RT image of sand inclusion and related K values and thicknesses.

### Table 3.1.18 – Phase 2 RT image rating using ASTM standards and F system proposed by Blair (2009)

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3.2 Experimental Program

Specimens were tested under monotonic tension to failure. Testing was performed in an MTS testing machine with a 220-kip capacity. A load cell calibrated to 200 kips was used to measure load. The expected ultimate strength of the specimens varied from 142 kips to 176 kips. The expected load required a high strength fixture. A set of high strength clevises was created for the purpose, Figure 3.2.1.

![Fig. 3.2.1 – Fabricated clevis for tensile testing](image)

The loading regimen of the specimens was displacement controlled. A pneumatic actuator was used to apply the load. The displacement of the pneumatic actuator was tracked with an internal LVDT.

Due to the high strength of the Phase 1 material, specimens could not be two square inches as desired. One-inch wide specimens were cut from the casting around the known surface indications. The weaker Phase 2 material allowed for two-square-inch specimens.

Before testing, detailed measurements were taken of the specimens along the gage region. Markings were placed at regular intervals along the specimens to keep track of local deformations along the gage, Figure 3.2.2. A plot of specimen 2-1X-1's gage thickness vs. location along the gage is given in Figure 3.2.3. The thickness measurements begin at the end region and continue seven inches to the opposite end region, including the two radius sections. Note that the location of minimum thickness and, therefore, the minimum gross-section area was at the end of the radius.
This was generally true for each specimen.

The large amount of steel in the fixturing, in addition to the possible slip in the pins and deformation in the end region, lead to diluted gage deformation readings when using the test machine's inbuilt LVDT for deformation measurement. Figure 3.2.4 shows an example of the load vs. displacement of the actuator and the slope of the nominal stiffness of the gage region of the specimen. Note the significant difference. Additional instrumentation was applied to the specimen to better isolate gage deformations. The deformations within the fixturing itself were also tracked to check fixture performance at different levels of load. During Phase 1 testing, a total of nine LVDT's and a string potentiometer (string pot) were applied to the specimen and fixturing, as shown in Figure 3.2.5. In the figure, instrumentation attached only to the fixturing is indicated in blue. Instrumentation directly attached to the test specimen is indicated in black.
Fig. 3.2.4 – Testing machine internal LVDT load vs. displacement (solid) and E/L (dashed)

Fig. 3.2.5 – Instrumentation diagram for Phase 1 testing
The average response of LVDT 7 and 13 are presented in this thesis as the gage region displacement response. These two LVDTs were on opposite sides of the specimen, accounting for any eccentricity in the specimen, or out of plane deflection caused by eccentric discontinuities. These LVDTs were attached to the specimens at the end region by welded on bases, Figure 3.2.6. A specimen with full instrumentation in the testing position is shown in Figure 3.2.7.

Five of the specimens tested in Phase 1 are pictured in Figure 3.2.8(a). An isometric view of the Phase 1 specimen 1-3X-3 is given in Figure 3.2.8(b) for clarity. As can be seen, high strength steel washers were welded onto the end to reinforce them. These reinforcements were necessary due to a smaller than nominally specified end region. This small end region in the Phase 1 specimens made them susceptible to fracture in the end region rather than in the gage. One such fracture can be seen in Figure 3.2.9.

---

**Fig. 3.2.6** – Phase 1 LVDT base  
**Fig. 3.2.7** – Phase 1 Instrumentation

**Fig. 3.2.8** – Phase 1 specimens (a) and isometric view of specimen 1-3X-3
The load in each of the following load-displacement plots is normalized for the average gross-section area of the specimen. The gage response of specimen 1-3X-1 is given in Figure 3.2.10. In the plot, the nominal stiffness of a steel coupon with a five-inch gage is shown by the dashed line. The reason for the discrepancy was deformation in the end region which was not well separated by the Phase 1 instrumentation. The maximum normalized load reached by this discontinuity free specimen was 138.4 kips. The specimen fractured at a measured displacement of 0.4065 inches. This specimen exhibited the longest elongation at fracture of all Phase 1 specimens, 8.13%.
The fracture surface of specimen 1-3X-1 is given in Figure 3.2.11. The fracture surface shows signs of yielding in the location of fracture, as can by its semi-conical shape. The specimen fractured at the gage radius, the location of the minimum cross-sectional area.

![Specimen 1-3X-1 fracture surface (a) and location (b)](image)

**Fig. 3.2.11** – Specimen 1-3X-1 fracture surface (a) and location (b)

A specimen exhibiting similarly high ductility was 1-3X-4. This specimen had the smallest surface indication of the Phase 1 specimens, accounting for only 4.45 percent of the gross-section area. The load-displacement response of the specimen can be found in Figure 3.2.13. The speci-

![Load vs. Displacement of Specimen 1-3X-4](image)

**Fig. 3.2.12** – Load vs. Displacement of Specimen 1-3X-4
men reached a maximum normalized load of 133.7 kips. The displacement at fracture was 0.3103 inches or an elongation of 6.2%. The specimen fractured at the gage radius, similar to specimen 1-3X-1. The fracture location and surface are pictured in Figure 3.1.13. Note that the specimen did not fracture at the discontinuity, but at the same location as the control specimen. This suggests that for small indications, geometry controls over discontinuity.

![Specimen 1-3X-4 fracture surface (a) and location (b)](image)

**Fig. 3.2.13 – Specimen 1-3X-4 fracture surface (a) and location (b)**

Juxtaposed to these two specimens exhibiting high ductility and similar fracture locations is specimen 1-3X-2. As shown in Table 3.1.8, the surface discontinuity accounted for 8.94% of the gross-section area, nearly double that in specimen 1-3X-4. The load-displacement response is given in Figure 3.2.14. The specimen reached a maximum normalized load of 120.8 kips, a loss in ultimate strength of 13% as compared to the control specimen. Ductility was also greatly reduced. The specimen fractured at 0.1520 inches, an elongation at fracture of 3.0%. The fracture surface and location are pictured in Figure 3.2.15. The fracture of specimen 1-3X-2 occurred at the location of the discontinuity.

The response of the two simulated discontinuities in comparison with their natural counterparts is given in Figure 3.2.16(a) and (b). A side by side of their fracture locations is given in
Figure 3.2.17(a) and (b). The simulated discontinuities were conservative, tending to have lower ductility and lower strength than their natural counterparts, even with similar discontinuity areas.

Specimen 1-3X-6 could not be tested as desired due to its large indication. The response is not covered in this thesis.

Several changes were made between Phase 1 testing and Phase 2. Instrumentation for Phase 2 was reduced and bettered. Phase 1 instrumentation took several hours to place on each specimen,
increasing test time significantly. Phase 2 instrumentation consisted of 2 specimen LVDTS, the MTS load cell, and the MTS LVDT. A diagram of the Phase 2 instrumentation is shown in Figure 3.2.18. Metal tabs were tack welded close to the gage region to better isolate the deformation response of the gage, Figure 3.2.19. In addition, the end region was lengthened by 0.5 inches to prevent the issues with the end region experienced in Phase 1 testing. The new specimen dimensions are given in Figure 3.2.20. The new instrumentation and improved gage region lead to better deformation isolation. Specimens were once again tested monotonically. A specimen instrumented and ready for testing is pictured in Figure 3.2.21.
Fig. 3.2.18 – Phase 2 instrumentation diagram

Fig. 3.2.19 – Phase 2 specimen with tack welded steel tabs for LVDT placement.
The load-displacement response of Phase 2 specimen 2-1X-1 is given in Figure 3.2.22. Just as in Phase 1, the load is normalized to the average gross-section area of the gage region. This specimen functioned as the control specimen for Phase 2, as it had no significant discontinuity. The maximum normalized load of the specimen was 85.5 kips. The specimen fractured at a displacement of 0.9646 inches, an elongation of 19.3%. It should be noted here that this elongation should not be compared directly with the elongation of Phase 1, due to the differences in the underlying materials ductile capacity.
The fracture surface of specimen 2-1X-1 is pictured in Figure 3.2.23. The specimen fractured in the gage radius in a highly ductile manner, as can be seen from the highly conical fracture surface.

The load-displacement response of specimen 2-1X-2 is given in Figure 3.2.24. RT of the specimen found Level 2 shrinkage within the gage. This led to significantly decreased ductility. The specimen fractured at a displacement of just 0.5818 inches, a decrease of 39.7% as com-
pared to the control specimen. The specimen also had decreased ultimate strength, 78.1 kips. The ultimate strength of the specimen decreased by 8.7% as compared to the control specimen. The fracture surface reveals a highly brittle fracture, Figure 3.2.25. The fracture, being nearly perfectly perpendicular to the loading direction, was near perfect Mode I fracture in classical fracture mechanics. It shows little evidence of yielding in the fracture location.

Fig. 3.2.24 – Specimen 2-1X-2 load vs. displacement response

Fig. 3.2.25 – Specimen 2-1X-2 fracture surface
The load-displacement response of specimen 2-3X-1 is given in Figure 3.2.26. The specimen was loaded to 120 kips then unloaded, and then loaded again to fracture. The maximum normalized load experienced by the specimen was 88.8 kips, roughly equivalent to the nominal strength of the material. The specimen fractured at a total displacement of 0.6274 inches or an elongation of 12.9%.

![Graph of load-displacement response](image)

**Fig. 3.2.26 – Specimen 2-3X-1 load vs. displacement response**

A final representative load-displacement curve for Phase2 of specimen 2-10X-1 is given in Figure 3.2.27. The specimen contained significant shrinkage porosity, Level 5 according to ASTM standards. The specimen fractured at the location of the porosity at a normalized load of 76.95 kips. The specimen fracture at 0.4200 inches of displacement, or 8.4% elongation, the smallest elongation of any Phase 2 specimen. The fracture surface, Figure 3.2.28, reveals the significant porosity in the gage region of the specimen.

Specimen 2-5X-1 failed in the end region due to a large amount of sand inclusion there. Specimens from casting 6X could not be tested to failure due to their larger than average gross section area, 2.36 square inches, which was too large to fracture safely in the testing machine. The responses for these specimens are left out. All other load-displacement responses can be found in Appendix A.
Figure 3.2.29 compares the elongation at fracture of each specimen with discontinuity size as a percentage of gross area. The orange squares in the plot represent data from Phase 1, the blue circles represent data from Phase 2, and the black diamond represents the elongation of a defect-free ASTM .505 tensile coupon. (ASTM E8) A dashed line divides specimen which fractured at the location of a known discontinuity and specimens which fractured at the minimum section. The lone outlier was specimen 2-1X-2, which fractured much earlier and at a lower strength than its Level 2 shrinkage indication would have suggested.
What may be most striking in the elongation reduction plot is the reduction in elongation of approximately 28% in specimens which did not contain a known discontinuity and specimens which contained a discontinuity yet fractured at a different location. This reduction may be attributed to the high triaxiality at the minimum section, limiting plastic strain at the location of necking and fracture. This reduction in ductile capacity is due to geometry alone, not due to anything which could be deemed a defect. It should also be of note that this reduction in ductile capacity was stronger than several indications labeled as Level 2 by the foundry and that the only specimens which fracture at the discontinuity were rated level 4 or 5 by the radiographer, and would, therefore, be typically scrapped at the foundry. One may conclude that level two indications or lower, outside the critical section, would have minimal effect on the ductile capacity of a component.

The reduction in yield strength and ultimate strength of the specimens vs. area percentage of discontinuity is shown in Figure 3.2.30. As opposed to the clear upwards trend of reduction in elongation, ultimate, and yield strengths were not significantly affected by the presence of discontinuities. Some significant discontinuities contributed little to a reduction in strength at all. A stronger upwards trend is seen in the Phase 1 specimens than in the Phase 2 specimens. This can be attributed to the different steels. As ductile fracture is controlled by the necking of voids in areas of high stress, local plastic strains are the controlling factor of strength, not stress. For a steel such as the ASTM 8630 80/50 used in Phase 2, where the stress-strain curve has a downward slope for
Fig. 3.2.30 - Reduction in yield strength as a percentage (a) and ultimate strength as a percentage (b) vs. discontinuity size.

A significant amount of strain values, a reduction in the plastic strain of up to 30% will still reach the peak stress. A higher strength, lower elongation steel, such as the Phase 1 ASTM 8630 95/115, will have a reduction in strength even with a minor decrease in the plastic strain at failure. A sum-

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</tbody>
</table>

Table 3.2.31-Phase 1 testing summary

<table>
<thead>
<tr>
<th>TYPE</th>
<th>1X-1</th>
<th>1X-2</th>
<th>2X-1</th>
<th>2X-2</th>
<th>3X-1</th>
<th>3X-2</th>
<th>4X-1</th>
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<tbody>
<tr>
<td>AREA %</td>
<td>0</td>
<td>0.46</td>
<td>1.06</td>
<td>9.87</td>
<td>0.813</td>
<td>0.77</td>
<td>5.39</td>
</tr>
<tr>
<td>ASTM E2868</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
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<tr>
<td>F Rating</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>FY Red. (%)</td>
<td>0.48</td>
<td>6.21</td>
<td>-1.62</td>
<td>-</td>
<td>8.13</td>
<td>6.84</td>
<td>15.5</td>
</tr>
<tr>
<td>FU Red. (%)</td>
<td>2.84</td>
<td>11.3</td>
<td>1.29</td>
<td>-</td>
<td>-0.03</td>
<td>-0.18</td>
<td>10.1</td>
</tr>
<tr>
<td>Elong. Red. (%)</td>
<td>31.0</td>
<td>58.5</td>
<td>25</td>
<td>-</td>
<td>26.1</td>
<td>36.1</td>
<td>57.05</td>
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</tbody>
</table>

Table 3.2.32– Phase 2 testing summary
mary of Phase 1 findings can be found in Table 3.2.31. Phase 2 findings are summarized in Table 3.2.32.

Figure 3.2.33 is a plot of ASTM RT rating vs. reduction in yield strength, ultimate strength, and elongation reduction as a percentage of the nominal properties for each material. A general upward trend is seen in each plot. Indication levels zero through two tend to exhibit the lowest reduction in strength and elongation. Indications rated level five can have a much greater effect than the smaller indications. However, some level 5 indications performed nearly as well as level 0 indications. Figure 3.2.30 presents the same data, now in reference to Blairs's F rating. A stronger separation between rating levels is. The trend is still not as clear as the indication area method of Hardin and Beckermann (2013).

<table>
<thead>
<tr>
<th>TYPE</th>
<th>5X-1</th>
<th>5X-2</th>
<th>6X-1</th>
<th>6X-2</th>
<th>10X-1</th>
<th>10X-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA %</td>
<td>5.55</td>
<td>2.45</td>
<td>3.48</td>
<td>8.73</td>
<td>8.09</td>
<td></td>
</tr>
<tr>
<td>ASTM E2868</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
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</tr>
<tr>
<td>F Rating</td>
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<td>4</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>F_y Red. (%)</td>
<td>-</td>
<td>10.6</td>
<td>-</td>
<td>-</td>
<td>14.6</td>
<td>18.2</td>
</tr>
<tr>
<td>F_U Red. (%)</td>
<td>-</td>
<td>10.8</td>
<td>-</td>
<td>-</td>
<td>12.5</td>
<td>2.45</td>
</tr>
<tr>
<td>Elong. Red. (%)</td>
<td>-</td>
<td>26.9</td>
<td>-</td>
<td>-</td>
<td>70.0</td>
<td>59.8</td>
</tr>
</tbody>
</table>

Table 3.2.32 (cont)– Phase 2 testing summary

Fig. 3.2.33 ASTM E2868 rating vs. reduction in yield strength (a), reduction in ultimate strength (b), and elongation (c)
3.3 Finite Element Modeling and Fracture Prediction

Eight specimens from Phase 1 and 2 were simulated using FEA. Table 3.3.1 lists the simulated specimens. The specimens modeled included three different discontinuity types as well as four different ASTM RT levels. The control specimen from each phase was modeled as well.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Discontinuity</th>
<th>ASTM Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3X-1</td>
<td>None</td>
<td>0</td>
</tr>
<tr>
<td>1-3X-3</td>
<td>Surface</td>
<td>5</td>
</tr>
<tr>
<td>1-3X-4</td>
<td>Surface</td>
<td>5</td>
</tr>
<tr>
<td>2-1X-1</td>
<td>None</td>
<td>0</td>
</tr>
<tr>
<td>2-1X-2</td>
<td>Shrinkage</td>
<td>2</td>
</tr>
<tr>
<td>2-2X-1</td>
<td>Surface</td>
<td>1</td>
</tr>
<tr>
<td>2-3X-1</td>
<td>Sand</td>
<td>5</td>
</tr>
<tr>
<td>2-10X-1</td>
<td>Shrinkage</td>
<td>5</td>
</tr>
<tr>
<td>2-10X-2</td>
<td>Shrinkage</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.3.1 - Simulated specimens
As shown in section 3.1, the cast steel specimens did not perfectly match the nominal dimensions. This imperfection is because the specimens were not machined to size. Early in the program, there was a desire to study the effect of the surface finish on the behavior of the casting. The casting had to be left as-is for testing purposes. Any slight variation in dimension had to, therefore, be accepted. The other cause was the purposeful creation of discontinuities. For abundant discontinuities to be present, a poor pouring process had to be designed. This resulted in less than perfect cast specimens. Due to this imperfect geometry, to get accurate fracture prediction, it was necessary to have accurate measurements of the entire specimen. For this purpose, paper tracings were taken of the specimens, Figure 3.3.2. The tracings were scanned and imported into AutoCAD 3D. A line tracing was created of the imported paper tracing. This line tracing was used to create accurate 3D models of the specimen shape. Scaling was performed to ensure accurate dimensions.

![Fig. 3.3.2- Example specimen tracing for exact measurement](image)

Discontinuities were modeled in three dimensions as well. As shown in section 3.1, surface discontinuities were measured using silicone rubber. Internal discontinuities were measured using image analysis. Surface discontinuities were modeled as geometric voids on the surface of the specimen. Some simplification was necessary for the easy of meshing. Figure 3.3.3.

Large sand and slag inclusions, in which the discontinuity is a concentrated whole, could be readily measured by the means of pixel measurements. The indication was also modeled as a single smooth void, Figure 3.3.4. Shrinkage porosity was measured in a similar manner. However, shrinkage is not a single void as are large sand inclusions. Rather, it is a series of small discrete
voids. Porous metals can be modeled by reducing local stiffness, as is discussed by Hardin and Beckerman (2013). However, in this thesis, the porous void group was modeled by a single void, as shown in Figure 3.3.5. As shown by Hancock and Mackenzie (1976), it is the coalescence of voids which leads to failures, and accurate fracture predictions can be made by looking at a group of voids together rather than at the effect of voids individually.

Fig. 3.3.3- Realistically modeled surface discontinuity (a) and simplified discontinuity for ease of meshing (b)

Fig. 3.3.4- Sequence of measuring discontinuity by radiograph to 3D modeling of a specimen with a sand inclusion in AutoCAD.

Fig. 3.3.5- Sequence of measuring discontinuity by radiograph to 3D modeling of a specimen with porosity in AutoCAD.
The three-dimensional models were imported into the commercially available FE software ANSYS. The specimens were meshed using the internal ANSYS meshing algorithm. Due to difficulties in meshing the models in brick elements, caused by the many curved surfaces, the models were meshed with 8-node tetrahedral elements. (ANSYS 2018) An example of this meshing is shown in Figure 3.3.6. Surface to surface contact was modeled in the pins. High accuracy was required in the end region as failure often occurred on specimens near the end region to gage region radius.

**Fig. 3.3.6- Example meshing of a Phase 2 specimen.**

Load was applied to the specimen model by incrementally displacing the pins. Models were solved using the dynamic solver in ANSYS, with a time step of 10 seconds. Material nonlinearity and geometric nonlinearity were used. The material input depended on the specimen which was being modeled. The material inputs for Phase 1 and Phase 2 models can be found in Figure 3.3.7.

**Fig. 3.3.7- True stress-True strain ANSYS material input for Phase 1 specimens (orange) and Phase 2 specimen (blue)**
The SMCS model was applied to the FE model by checking stress triaxiality for each node at a load step. This was used to calculate the critical plastic strain of the SMCS model for each node. The ratio of equivalent plastic strain to critical plastic strain, plastic strain ratio, was calculated for each node. Failure was said to occur at the first load step in which a node reached a plastic

\[ \frac{\varepsilon_p}{\varepsilon_{pl,cr}} = \frac{14.42}{14.43} \]

**Fig. 3.3.8** - A visual representation of the SMCS model application in ANSYS using specimen 2-10X-1

\[ \sigma_m = 80 \text{ ksi} \quad \sigma_y = 121.4 \text{ ksi} \]

\[ T = 0.664 \]

**Fig. 3.3.9** - A visual representation of the SMCS model application in ANSYS using specimen 1-3X-3

\[ \sigma_m = 135 \text{ ksi} \quad \sigma_y = 152.7 \text{ ksi} \]

\[ T = 0.884 \]

\[ \varepsilon_p = 6.78\% \]

\[ \varepsilon_{pl,cr} = 6.72\% \]
strain ratio greater than or equal to 1. A visual breakdown of this process is given in Figure 3.3.9, using specimen 2-10X-1. A second example, using specimen 1-3X-3 with a surface discontinuity can be found in Figure 3.3.10.

For the SMCS to be accurate and for the use of VGI to not be necessary, triaxiality needs to be relatively constant across strain history. This was true for the specimen FE models. A plot of stress triaxiality vs. load step for the critical node of specimen 2-10X-1 is given in Figure 3.3.10 (a). Triaxiality converges on a value after a series of large fluctuations. The high variation in stress triaxiality is before the onset of yielding, indicated in the plot by the red dot. The stress triaxiality quickly converges to a value of approximately 0.66 after yielding. The stress triaxiality remained near-constant during plastic straining. Thus, the use of SMCS is acceptable.

![Graph showing stress triaxiality vs. load step](image)

**Fig. 3.3.10** - Stress triaxiality in the region of failure vs. time in load steps (a) and Triaxiality in the FE specimen 2-10X-1 at the failure load step. (b)

The equivalent plastic strain and critical plastic strain values at the critical node of the specimen 2-10X-1 model are given in Figure 3.3.11. The ratio between the two is provided as well for clarity. The nodal triaxiality value of 0.66 created a relatively stable critical plastic strain value of 14.4%. The critical node reached this plastic strain at load step 175, a simulated gage displacement of 0.447 inches. The actual specimen 2-10X-1 fractured at a gage displacement of 0.42 inches of displacement, and error of 5.29%. The comparison of simulated load-displacement
response and experimental results for specimen 2-10X-1 is given in Figure 3.3.12. Fracture of the experimental specimen and the FE predicted fracture is indicated by the red dots. Similarly good prediction was found in other simulated specimens.

Fig. 3.3.11 - SMCS critical plastic Strain (gray) and equivalent plastic strain (black) at each load step (a) and the ratio between critical plastic strain and equivalent plastic strain (b)

Fig. 3.3.12 - Experimental load-displacement (blue) and FE prediction (dashed) - 2-10X-1

The experimental and simulated load-displacement response of specimen 1-3X-1 is given in Figure 3.3.13. Real fracture and predicted fracture are once again indicated by red dots. The specimen was predicted to fracture at 0.400 inches of displacement. The actual specimen fractured at a displacement of 0.4065 inches, the predicted failure displacement had an error of 1.6%.
The simulated and real load-displacement response of specimen 1-3X-4 is provided in Figure 3.3.14. The actual specimen fractured at a displacement of 0.1415 inches. The specimen was predicted to fracture at a displacement of 0.135 inches, an error of 4.9%.

A comparison of predicted failure and tested failure elongations is shown in Figure 3.3.15. Table 3.3.16 gives the details of each prediction. Five percent and ten percent error lines are given in Figure 3.3.15 as dashed lines alongside a solid black line representing one to one agreement. Six of the eight predictions were within a 10% error. Of these, Phase 2 specimen 1-3X-1 had the
largest error at 6.0%. The others all fell within 5% error, with specimen 1-3X-1 being the closest to correct at 1.6% error. One of the outliers was specimen 2-1X-2. As discussed in section 3.2, this specimen failed earlier than expected for an ASTM E2868 Level 2 discontinuity. An inaccurate prediction was to be expected as the model was based on the RT image. The other outlier was specimen 2-1X-1. The wrinkled surface on the specimen was not modeled. This may be the cause of the greater error here.

![Graph showing predicted vs. measured elongation](image)

**Fig. 3.3.15 - Comparison of predicted and actual deformation at fracture with Phase 1 in orange and Phase 2 in blue**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Discontinuity</th>
<th>ASTM Level</th>
<th>Meas. Def. (in)</th>
<th>Pred. Def. (in)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3X-1</td>
<td>None</td>
<td>0</td>
<td>0.407</td>
<td>0.400</td>
<td>1.60</td>
</tr>
<tr>
<td>1-3X-3</td>
<td>Surface</td>
<td>5</td>
<td>0.153</td>
<td>0.146</td>
<td>4.26</td>
</tr>
<tr>
<td>1-3X-4</td>
<td>Surface</td>
<td>5</td>
<td>0.142</td>
<td>0.135</td>
<td>4.59</td>
</tr>
<tr>
<td>2-1X-1</td>
<td>None</td>
<td>0</td>
<td>0.967</td>
<td>1.20</td>
<td>24.2</td>
</tr>
<tr>
<td>2-1X-2</td>
<td>Shrinkage</td>
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<td>0.582</td>
<td>1.11</td>
<td>90.8</td>
</tr>
<tr>
<td>2-2X-1</td>
<td>Surface</td>
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<td>0.42</td>
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<td>Sand</td>
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<td>1.034</td>
<td>1.10</td>
<td>6.38</td>
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<td>2-10X-1</td>
<td>Shrinkage</td>
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<td>0.420</td>
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<td>Shrinkage</td>
<td>5</td>
<td>0.563</td>
<td>0.587</td>
<td>4.26</td>
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</table>

**Table 3.3.16 - Comparison of predicted and actual deformation at fracture**
IV - CONCLUSIONS

Discontinuities in cast steel can greatly affect the performance of components. The presence of discontinuities in critical sections can reduce the yield strength, ultimate strength, and ductility of a component. Discontinuities are typically found and measured using radiography performed according to ASTM standards. Three common discontinuities found in radiography are rated on a five-level system, with one being the smallest and five being the largest discontinuity.

Level 1 and 2 indications can have little to no effect on the overall performance of a casting. The effect of these small indications did not control over the effect of a slightly reduced cross-section at an area of higher restraint. Imperfections in geometry alone, with or without small discontinuities present can greatly reduce the ductile capacity of a component, as well as the ultimate strength. Discontinuities that are large enough to affect performance are typically scrapped at the foundry.

Current ASTM rating standards do not have a strong correlation with casting performance. In testing, several specimens with Level 5 indications in the gage section performed nearly as well as did discontinuity free specimens. ASTM ratings are based solely on a comparison of an RT image with reference images and are thus largely subjective. Other proposed rating systems, such as the F-rating (Blair 2009), yield better prediction of performance than current standards. However, the best prediction of behavior was found by estimating the thickness of discontinuities by measuring black pigment levels in RT images, following the procedures described by Hardin and Beckermann (2013).

The estimation of discontinuity size by measuring pigment value combined with the Stress Modified Critical Strain model can accurately predict the failure of a cast component. Simulated specimens had an average error in predicted displacement at fracture of 5.37%, excluding outliers. High accuracy has been previously shown (Hardin 2013), but can be applied using relatively simple techniques, such as using three-dimensional voids in an FE model. This three-di-
imensional model method is accessible to structural engineers and therefore may be readily used by specialized companies.
Testing on specimens with more varied geometries and with more realistic discontinuities is planned. Finite element analysis is being used to design the specimen’s geometry and desired discontinuity size. Dr. Richard Hardin and Dr. Cristof Beckermann will once again be aiding the research team by designing casting procedure.

Testing is planned on the ductile behavior and fatigue life of cast steel nodes welded to hot-rolled tubes. 6" round hollow structural section is being welded to cast specimens and will be placed under four-point bending tests. Monotonic, high-cycle fatigue and low-cycle fatigue loading will be applied to the specimens.

Testing is planned on prototype truss node castings. Current plans are to create castings with discontinuities in the non-critical regions of the node to test a real cast node in a structure.

The VGI and SMCS ductile fracture models are being applied to steel seismic connections to investigate their fracture performance.
Phase 1 Specimen Load vs. Displacement Response

1-3X-1

[Graph showing normalized load vs. displacement for 1-3X-1]

1-3X-2

[Graph showing normalized load vs. displacement for 1-3X-2]
1-3X-3

1-3X-4
Phase 2 Specimen Load vs. Displacement Response

1-3X-5

2-1X-1
NOTE: Specimen 2-2X-1 had a gage region of two inches long, rather than the typical 5 inches long as seen in the other specimens.
NOTE: Specimen 2-5X-1 fractured in the end region due to sand inclusion. The load displacement plot does not represent gage strength or ductility.
NOTE: Specimen 2-6X-1 had an ultimate strength of over 200 kips, and could not be tested to failure.
Normalized Load (kip) vs. Displacement (in)
REFERENCES


