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Effect of Shrinkage on Service Performance of Steel Castings

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ABSTRACT

An overview of the objectives and progress made by the “Integrated Design of Steel Castings for Service Performance” research program is presented. The methods being used in the program to predict the structural service performance of steel castings with porosity are reviewed. Structural performance predictions are given for a commercial steel casting applying the methods to known porosity defects detected by radiography. These are compared with measurements. Next, example results are computed for service life throughout an entire casting using a predicted porosity field. The approach being taken to experimentally validate the effect of shrinkage discontinuities is described. Results from this project task; the generation of test specimens having varying degrees of soundness is presented. Future work and project plans are summarized.

1. INTRODUCTION

A primary concern of every steel foundryman is producing the highest quality steel casting despite many constraints placed upon them. Consistently high quality is not easy to achieve. As the reader well knows, it comes through knowledge and expertise in casting, and attention to the casting process details. It also comes at increased time and production costs, and the cost of improving technology. Fortunately the highest level of casting quality is not warranted, nor is it usually required for most commercial steel castings. It is safe to say that in almost all cases, the level of casting quality and soundness required by part designers is not presently based on engineering principles, but their own or their workgroup's experience and practice. These soundness requirements impose many constraints on foundries and limit the market for castings. Because of this, validated engineering methods for analyzing and predicting the structural performance of cast parts with advanced models of the as-cast material could revolutionize the casting industry. Such advanced modeling would take into account the casting process and incorporate porosity into the prediction of part strength and durability, or fatigue life. The development of engineering approaches to analyze, to better understand and predict casting "soundness" quality and its effect on casting structural performance in service, is the focus of this work.

The determination of a steel casting's "soundness" quality is based on non-destructive examination (NDE) techniques; radiography, ultrasonic, eddy current, magnetic particle and dye penetrant testing. The relationship between quality level and the structural performance of the part in service is rather speculative unless the designer requires the part to be the highest class of quality, i.e. entirely sound with no surface imperfections. Part designers have long had their own notions about the significance of levels of quality determined by these NDE methods and their relationship to casting structural performance, and these vary depending on the designer. Sometimes NDE standards are applied as if they were directly related to the casting service performance, which is a misunderstanding or misuse of the standards. In other words, NDE standards are often used as if they were structural performance related standards, when they are actually workmanship standards.

Lacking an engineering approach that considers casting soundness, design engineers may be over specifying the required casting soundness, over designing the casting with excessive safety factors, or may misapply the NDE standards required for the part. Over specifying the casting might result in increased costs, or might result in a part that is not casting friendly, or even the part is deemed not "castable". Over designing the casting results in a heavier casting, and perpetuates the myth that castings cannot be lightweight. Misapplying the NDE standards may result in specifying excellent interior soundness though the part might fail during service from fatigue due to an undetected discontinuity at the casting surface.

2. PROJECT OVERVIEW

As a response to the issues raised above, it is not proposed that steel foundries make more unsound castings, but rather that they and the part designers begin to consider soundness in the part design in a more advanced way. Once designers can relate x-ray standards to part structural

performance, fewer castings will be produced and rejected when not necessary, and likewise, fewer castings will pass radiographic testing when they should not. From this work, engineering guidelines that relate casting soundness to structural performance in service will begin to evolve, and it is envisioned that this work will result in an increase in customer confidence in steel castings and in casting structural performance.

The present work couples casting simulation and finite element stress analysis (FEA or FEM) to predict the load-carrying capacity and durability. In order to begin to use predictive models for durability prediction in the presence of porosity, not only must casting simulation codes be able to predict the location, distribution, and size of shrinkage discontinuities, but also information about its shape. The smooth surface of a gas pore will very likely behave differently than the jagged surface of dendrites associated with a macro-shrinkage produced cavity. Using a stress analysis model that uses the above-mentioned information from a casting simulation, the effect of the shrinkage discontinuities on the structural performance of a cast steel component will be predicted in this study. High-resolution radiography and strength/fatigue tests will be used to validate the model predictions. The integrated casting simulation/stress analysis tool developed in this project will then allow for simultaneous optimization of the casting process parameters (e.g., riser location) and the component geometry (e.g., section thickness) at an early stage in the product definition, as shown schematically in Figure 1. The new predictive methods will be tested on selected commercial steel castings. Improved radiographic inspection standards will be established that take into account the size and location of shrinkage discontinuities on the structural performance of steel castings. New guidelines for the design of steel castings will ultimately result.

This research program, “Integrated Design of Steel Castings for Service Performance”, has ambitious objectives; to validate the analysis methods for casting soundness and structural performance prediction developed through radiographic and mechanical testing, and to ultimately propose new design guidelines and improved inspection standards. At present, this research program is approximately midway through a 42-month planned duration. Expected benefits of the project are:

- Data on the effect of shrinkage discontinuities on the mechanical properties and structural performance of steel castings.
- A validated simulation tool that predicts the location and amount of shrinkage discontinuities and quantitatively evaluates the load-carrying capacity and fatigue durability of a cast component containing the discontinuities.
- Improved capability to design steel castings with non-uniform mechanical properties (allow a discontinuity where it can be tolerated, ensure soundness where needed) and examine the tradeoffs between manufacturing costs and structural performance.
- New design guidelines based on meaningful radiographic inspection standards.

Other outcomes of the project should be improved designer and end user confidence in steel castings, decreased casting weight, increased casting yield, new applications for steel castings, and reduced lead time and cost through fewer design iterations.

3. REVIEW OF PREVIOUS WORK

ASTM radiographic standards are presently used to specify the allowable level (or severity) of shrinkage discontinuities in a steel casting. Therefore, this work investigates the effect of shrinkage discontinuities that are detected using the ASTM radiographic standards for steel castings (ASTM E446, E186 and E280) on the structural performance of carbon and low alloy steel castings. Current ASTM standards for radiographic testing of castings provide only a qualitative basis upon which to accept or reject castings, and the accuracy in the x-ray rating is probably at best only ± 1 x-ray rating grades [1, 2]. Also, under the present ASTM standards, it is entirely possible, for example, for the small defect near the surface to be passed whereas a larger, centerline shrinkage causes rejection of the casting. This example may result in two failures of the desired inspection. Rejection of a casting that should not be rejected, since previous work indicates that a large level of discontinuities located in the center of a casting section may not affect mechanical properties or fatigue structural performance of the component [3 – 6]. Acceptance of a casting that should not be accepted, since a small discontinuity near a surface may have a significant effect on fatigue life [4, 7, 8]. Consequently, the design engineer uses large safety factors, over-specifies the casting making it expensive to produce, or possibly rejects the use of steel castings altogether [9].

Twelve casting strength/performance case studies were conducted [10] that demonstrated internal discontinuities such as shrinkage porosity had little effect on the strength performance of the castings. However, when discontinuities appeared at the surface, or were brought there by machining, there was a drop off in strength, particularly if the surface area was in high stress. It was thought that different results on the importance of internal casting discontinuities might be obtained if dynamic loading was considered instead [4]. In dynamic (fatigue) loading, it was observed that internal discontinuities detected by radiography (considered “unacceptable” by the standards) had little effect on the service life of the steel castings in the study. On the other hand, it was found that surface discontinuities in stress concentration areas had a severe detrimental effect on service life [4]. Another important outcome was that even the most severe surface indications detected using ASTM E-125 magnetic particle inspection appeared to have less an effect on measured endurance properties than suggested by notched fatigue data.

In the area of fatigue of cast metals there is significant research investigating material properties and modeling the durability of castings with discontinuities such as porosity and inclusions. There is little work found in the literature where integration of casting process simulation, or predicting the porosity, and durability modeling are studied concurrently. Life estimation in fatigue analysis is usually considered in two stages [11, p. 231]. The first of these is the “crack initiation” or “crack nucleation” stage, and the second is the “crack growth” stage. Prediction of the duration of the first stage of “life” for a component is usually performed using the strain-life (or ϵ -N) approach [11, pp. 93-117]. This initial stage of life and the strain-life models presented in [11] predict the duration of life to initiate a crack on the order of 1 mm. One may use this concept to determine the crack initiation life in a casting in the presence of porosity by modeling the pore as a notch. Researchers studying aluminum castings have treated pores in castings as notches in order to predict the effect of porosity on crack

initiation life [12], and also the mechanism of crack formation from pores has been investigated recently [13].

The second stage of fatigue life, the “fatigue crack growth” stage, has a very critical role in damage-tolerant design life prediction, particularly in nuclear and aerospace applications. It presumes the presence of a crack, formed either from fatigue or during manufacturing of the part. It is applicable to inclusions and porosity in steel casting. Not surprisingly, it appears to be the most commonly applied method used in the literature for analyzing the life of cast components with porosity. Commonly used models to predict crack growth arise from the concepts of fracture mechanics, in particular linear elastic fracture mechanics (LEFM) [11, pp.122-173]. An excellent overview of the use of fracture mechanics with application to steel castings is given by Jackson [14] from the SCRATA. Quite recently Horstemeyer et al. [15-17] have used crack growth fracture mechanics to map failure, optimize part geometry, and predict fatigue life in aluminum castings in the presence of inclusions, porosity, and microstructural variations. Fatigue life investigations for cast metals with porosity by fracture mechanics approaches are available for a variety of metals and alloys such as titanium [18], nodular cast iron [19], nickel-aluminum bronze [20]. However, interest in cast aluminum alloys appears to predominate the literature [15-17,21-24].

Of immediate interest to the reader is the literature available on steel castings. Modeling and experimental studies on the effect of steel casting defects and porosity on fatigue life using fracture mechanics and crack growth models is well summarized by Jayet-Gendrot et al. [25]. Experimental work on the effect of porosity on the fatigue strength of cast steel reveals that reductions in fatigue strength of 35% and 50% are observed for “sizes” (areas of cavities) of less than and greater than 3 mm², respectively, for cast 13 Cr stainless steel [26]. For low alloy steel, fatigue strength reductions from 8 to 30% were found when shrinkage porosity cavities covered 3 to 7% of the fracture surface [27]. Heuler et al. [28] present a comparison between the measured fatigue life of test specimens containing casting defects (porosity and inclusions) and the fatigue life obtained by modeling the specimen using crack initiation (local strain and strain life concepts) and crack propagation (fracture mechanics) approaches. For the crack growth model, Heuler et al. treated the casting defects as 2-D elliptical cracks having an envelope about the defect, and the defects were considered to be 3-D notches in the crack initiation model. Heuler et al. [28] found that the crack initiation estimate of life was more accurate than the fracture mechanics approach. They found that interpreting the defects as cracks resulted in too conservative an estimate of the fatigue life. Dabayeh and Topper [21] came to a somewhat different conclusion for cast aluminum where the local strain approach gave quite unconservative estimates of fatigue life, and the crack growth method gave good agreement.

Stephens et al. [29] provide benchmark fatigue property data for nominally sound cast steels: SAE 003 normalized and tempered (NT), SAE 0050A NT, low alloy C-Mn normalized, quenched and tempered (NQT), low alloy Mn-Mo (NQT), and AISI 8630 (NQT). The specimens measured were deemed nominally sound, but all five cast steels were reported to contain “the usual inclusions and porosity.” An exception was observed in some 8630 specimens that were observed to have an unusually low reduction in area, but fractographic analysis gave 20% to 30% porosity in those specimens. Property data and model parameter data included in [29] are monotonic stress-strain (σ - ϵ) behavior, cyclic stress-strain (σ' - ϵ') behavior, low cycle fatigue behavior data (provides parameters needed in strain-life models), and fatigue crack propagation behavior data (provides parameters needed

in crack-growth models). Prof. Stephens was asked and agreed to participate in the current project to produce additional fatigue property data for AISI 8630 steel specimens with varying degrees of porosity in them. Using the data in [29] as base-line “sound” material data, measurements will be made for the current project using sound and unsound specimens for comparison with prediction and the measurements made earlier.

4. CURRENT WORK AND RESULTS

An integrated approach involving both numerical and experimental methods is being undertaken to meet the objectives of this research project. Up to this point in the project, work has been performed on the following items with results example calculations provided.

4.1 Computational Models for Casting Simulation and Stress/Durability Analysis

An improved simulation model has been developed to predict the amount and location of shrinkage discontinuities in steel castings. This model has been implemented into a commonly used casting simulation code, MAGMAsoft [30]. This paper [30] is presented at this T&O Conference, and provides all model details along with example results; it will not be discussed further here.

Interfaces between existing (commercial) software and a new computational model have been developed to predict the load-carrying capacity and fatigue durability of steel castings in the presence of shrinkage discontinuities as presented in Figures 2 and 3. An existing model is being employed for static strength based on the porous-metal plasticity theory for stress analysis using FEA in the commercial code ABAQUS (see Figure 2), which is commonly used in the industry. An interface has been developed to transfer the porosity field predicted by MAGMAsoft onto the finite element mesh as outlined in Figure 3 and graphically demonstrated in Figure 4. Using this integrated model and predicted distribution of shrinkage discontinuities and base metal properties, the strength and fatigue life of cast steel products can be predicted.

The approach and methodology used to analyze the casting service performance was developed at the University of Iowa by Prof. Sharif Rahman and his graduate student Dong Wei for this project. Their methods are as outlined in [11] for the two stages of fatigue life discussed earlier in the literature review. The calculations are outlined in Figures 5 and 6 for the crack initiation and fatigue crack growth analyses, respectively. The method used to analyze the static strength is the porous metal plasticity model available in the ABAQUS software. To test the casting structural performance analysis methods, a commercial casting with known documented shrinkage in [4] was chosen for static and fatigue analysis. This casting and simulation mesh are shown in Figure 7. Although the casting rigging and parameters are not given in [4], the internal shrinkage typical of the process is given. A casting rigging which gives the same internal soundness as reported in [4] was determined and used in casting simulations. The static strength testing and simulated results are shown in Figures 8 and 9, where the internal porosity in the casting is simulated using the ABAQUS porous metal plasticity model. There is good agreement up to large displacements in the experimental and simulated results. This casting is

reported in [4] to fail at the location of highest stress in static testing, and the porosity does not play a role. This observation is typical for all castings presented in [4].

Fatigue predictions using the two methods of life prediction with “known” defects taken from x-rays in [4] were conducted as outlined in Figures 10 through 12. Using the x-rays, defects at two surface locations were identified (nodes A and B). At node A, a parameteric study was performed using four sizes of defect 0, 0.25, 0.5, and 1 mm as shown in Figure 10. Note that four internal defects were also identified and analyzed (nodes C, D, E, and F in Figure 10). The fatigue life at each node determined by modeling the part loading as given in [4] in ABAQUS and transferring the stress and strain results to the fatigue calculations. The fatigue crack initiation life is shown in Figure 11, and the crack propagation life is shown in Figure 12. The results showed that using the 0.5 mm diameter defect at the high stress location gives the best agreement with the test results for the crack initiation model, followed by the other surface node and the internal node C. The results change somewhat comparing the crack growth model results in Figure 12, where the surface node B and internal node C are the more conservative and better agreeing results. Following these initial comparisons with known defects, it was determined that neither method for prediction stood out over the other. Although, the model shown in Figure 11 appears to better predict the life at the position of maximum stress (near node A), and the trend in load versus life is somewhat better.

Based on these initial studies, it was determined to first focus on crack initiation life predictions. Methods were developed to automate the calculations on the finite element mesh, and a fully integrated model is demonstrated on an example casting in Figures 13 to 16. The example casting was actually a case study casting that was entirely sound as produced, and any porosity data shown in the plots is purely for demonstration purposes. Porosity was introduced by manipulating the simulations for purposes of demonstrating the modeling. In Figure 13, the stress concentration factor (K_t) field resulting from the porosity is shown. In this case, K_t was determined assuming the porosity to be a distribution of 1 mm diameter pores and standard formulas for holes of uniform spacing were used [31,32]. In general, K_t can be determined by notch shape and loading type/direction, also it depends on location (surface, near surface or deep inside). A more sophisticated approach for determining K_t in the model should be incorporated in the final version. From the K_t field, the fatigue notch field (K_f) may be determined [32] as shown in Figure 14, for the same slice as Figure 13. Using the approach outlined in Figure 5 [11], the strain life for crack initiation can be calculated. For the case of no porosity, K_t and K_f are 1, a life distribution throughout the part such as that shown in Figure 15 results. Considering the porosity, and using the K_t and K_f fields shown in Figure 13 and 14, respectively, a different life distribution results which includes a few additional low life “hot spots” as shown in Figure 16.

4.2 Experimental Validations and Effect of Shrinkage Discontinuities

The computational models for casting simulation and stress/durability prediction will be verified with the experimental data. Although this part of the project is not completed (scheduled for completion in February 2003), here is an update on the progress. Test castings were produced with a range of soundness as can be detect using normal ASTM radiographic standards. Figure 17 shows the castings used to generated the test specimens, and the finished specimen shown in Figure 18 will be machined

out the test blank castings. The test casting blanks and rigging are shown in Figure 19. The predictions of the “feeding percentage” porosity for the specimen castings are shown in Figure 20, while radiographs of the specimens are shown in Figure 21. The shrinkage in the casting is relatively symmetric about the center of the specimen center length, at the disk location. The improved porosity predictor [30] results in a porosity distribution shown in Figure 22; this more closely agrees with the actual porosity. The two “lobed” appearance in some of the predictions is believed to be an artifact from interpolation. Radiographs of as-cast and final machined fatigue test specimens (as shown in Figure 23) were taken. The objective of future work is to validate the shrinkage predictions from casting simulation model using digital analysis of the x-ray images, and use them to characterize the specimen soundness. Mechanical tests are presently being performed to validate the predicted strength and fatigue life from the computational stress/durability model amounts of shrinkage discontinuities. Following validation of computational models, further stress/durability analyses will be performed with the model to evaluate the effect of shrinkage discontinuities on static strength and fatigue properties of cast steel.

4.3 Structural Performance of Mechanical Components and Relationship with Radiographic Standards

Following discussions with DoD and industrial sponsors and collaborators, representative production steel casting components typically used in the industry have been selected for study. Although this work is not scheduled to begin until February 2003, substantial progress has already been made by identification of participant companies, components, and beginning work on them. Harrison Steel Casting Company, Caterpillar, Packer Technologies International Inc., Huron Casting Inc., and Oshkosh Truck Corp. will be participating. The shrinkage distribution will be quantified through casting simulation and x-ray testing. The distribution will then be used as input to the experimentally validated model for stress/durability analysis. Using this methodology, the mechanical performance of the casting will be examined. A limited number of experiments will also be performed to validate the predictions. The integrated casting simulation/stress/durability analysis method will be used to investigate the effects of changes in certain casting process parameters (such as riser locations) and component geometry (such as section thickness) on the service performance of the selected components. The goal is to achieve more optimized casting processes and component designs. A quantitative relationship between service performance and radiographic inspection measures will be established.

5. CONCLUSION

Presently, designers have no quantitative engineering principles to follow for the selection of a desired level of casting quality and, consequently, use overly large safety factors or reject the use of steel castings. The lack of a precise, structural performance-based standard leads to castings that are rejected when not necessary, and castings passing radiographic testing when they should not pass. A method for the analysis of the structural service performance steel castings has been developed, but much work remains to validate and determine its range of applicability. From this work and the modeling tools that will be developed, it is envisioned that engineering guidelines relating casting soundness to structural performance in service can be developed.

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REFERENCES

- [1] Quantrell, R., "Evaluation of the Consistency of Radiographic Grading for Shrinkage Defects," SCRATA Committee Paper, 1981.
- [2] Carlson, K., Ou, S., Hardin, R. and Beckermann, C., "Analysis of ASTM X-Ray Shrinkage Rating for Steel Castings," *2000 SFSA Technical and Operating Conference Proceedings*, 2000.
- [3] Wallace, J. F., et al., *Effect of Shrinkage Porosity on Mechanical Properties of Steel Casting Sections*, Steel Foundry Research Foundation Report, SFRF, 1962.
- [4] Vishnevshy, C., Bertolino, M. and Wallace, J. F., *The Evaluation of Discontinuities in Commercial Steel Castings by Dynamic Loading to Failure in Fatigue*, Steel Foundry Research Foundation Report, SFRF, 1967.
- [5] Wallace, J. F., et al., *The Effect of Internal Shrinkage Discontinuities on the Fatigue and Impact Properties of Cast Steel Sections*, Steel Foundry Research Foundation Report, SFRF, 1969.

- [6] Larson, H. R., et al., "Comparison of X-ray Quality and Tensile Properties on Cast High Strength Steel," *AFS Transactions*, Vol. 100, pp. 676-684, 1959.
- [7] Wallace, J. F., et al., *The Effect of Surface Discontinuities on the Fatigue Properties of Cast Steel Sections*, Steel Foundry Research Foundation Report, SFRF, 1966.
- [8] Wallace, J. F., et al., *Impact Properties of Cast Steel Sections with Surface Discontinuities*, Steel Foundry Research Foundation Report, SFRF, 1967.
- [9] Gwyn, M., "Cost-Effective Casting Design," *Modern Casting*, Vol. 88, No. 5, pp. 32-36, 1998.
- [10] Choi, C., Miller, W., Oberacker, D., Turnbull, G., Wallace, J. and Wright D., *Correlation of Destructive Testing of Steel Castings with Stress Analysis and Mechanical Properties*, Steel Foundry Research Foundation Report, SFRF, 1962.
- [11] Stephens, R.I., Fatemi, A., Stephens, R.R., and Fuchs, H.O., *Metal Fatigue in Engineering*, John Wiley and Sons, 2001.
- [12] Sonsino, C., and Ziese, J., "Fatigue Strength and Applications of Cast Aluminum Alloy with Different Degrees of Porosity", *Int. Journal of Fatigue*, vol. 15(2), pp. 75-84, March, 1993.
- [13] Buffiere, J-Y., Savelli, S., Jouneau, P.H., Maire, e., and Fougères, R., "Experimental Study of Porosity and its Relation to Fatigue Mechanisms of Model Al-Si7-Mg0.3 Cast Al Alloys", *Materials Science and Engineering A316*, pp. 115-126, 2001.
- [14] Jackson, W. J., *Fracture Toughness in Relation to Steel Castings Design and Application*, SFSA, 1978.
- [15] Horstemeyer, M.F., "Mapping Failure by Microstructure-Property Modeling," *JOM*, pp. 24-27, September, 2001.
- [16] Horstemeyer, M.F., Osborne, R.J., and Penrod, D.E., "Microstructure-Property Analysis and Optimization of Control Arm," *AFS Transactions* 02-036.
- [17] McDowell, D.L., Gall, K., Horstemeyer, and Fan, J., "Microstructure-based Fatigue Modeling of Cast A356-T6 Alloy," *Engineering Fracture Mechanics*, article in press, 2002.
- [18] Petty-Galis, J.L., Goolsby, R.D., and Osborn, L.M., "Investigation of Fatigue Behavior of Cast Ti-15V-3Al-3Cr-3Sn," *Microstructure/Property Relationships in Titanium Aluminides and Alloys*, Young-Won and Boyer eds., TMS, pp. 563-578, 1991.

- [19] Mansson, T., and F. Nilsson, "Fatigue Life Estimation of Cast Components", *Int. Journal of Cast Metals Research*, v. 13, pp. 373-378, 2001.
- [20] Taylor, D., and Knott, J.F., "Growth of Fatigue Cracks from Casting defects in Nickel-Aluminum Bronze," *Metals Technology*, Vol. 9, pp. 221-228, 1982.
- [21] Dabayeh, A., and Topper, T. H., "Fatigue of Casting Flaws at a Notch Root under an SAE Service Load History," *Fatigue Fracture Engng. Mater. Struct.*, vol. 23, pp. 993-1006, 2000.
- [22] Dabayeh, A., Berube, A. and Topper, T. H., "An Experimental Study of the Effect of a Flaw at a Notch Root on the Fatigue life of Cast Al 319," *Int. Journal of Fatigue*, vol. 20(7), pp. 517-530, 1998.
- [23] Skallerud, B., Iveland, T. and Harkegard, G., "Fatigue Life Assessment of Aluminum Alloys with Casting Defects," *Engineering Fracture Mechanics*, Vol. 44(6), pp. 857-874, 1993.
- [24] Wang, Q., Apelian, D., and Lados, D., "Fatigue Behavior of A356-T6 Aluminum Cast Alloys. Part I. Effect of Casting Defects," *Journal of Light Metals*, pp. 73-84, 2001.
- [25] Jayet-Gendrot, S., Gilles, P. and Migne, C., "Behavior of Duplex Stainless Steel Casting Defects under Mechanical Loadings," *Fatigue and Fracture: 1997 PVP-Vol. 350*, vol. 1, ASME, pp. 107-116, 1997.
- [26] Kohno M., Makioka M., "Some Studies on the Manufacture of Cast 13 Chrome Stainless Steel Francis Type Runners for Hydraulic Turbines", *AFS Transactions*, vol. 78, pp. 9-16, 1970.
- [27] Chijiwa K., Nakayama T., and Imamura M., "Effect of Casting Defects upon the Endurance Limit of Large Steel Castings," *35e CIF*, pp. 36-1 to 36-12.
- [28] Heuler P., Berger C., Motz J., "Fatigue Behaviour of Steel Castings Containing Near-Surface Defects," *Fatigue Fracture Engng. Mater. Struct.* Vol. 16(1), pp. 115-136, 1992.
- [29] Stephens, R.I., *Fatigue and Fracture Toughness of Five Carbon or Low Alloy Cast Steels at Room or Low Climatic Temperatures*, SFSA Research Report Nos. 94A and 94B, 1982.
- [30] K. Carlson, Z. Lin, R. Hardin and C. Beckermann, "Modeling Of Porosity Formation And Feeding Flow In Steel Casting," 2002 SFSA Technical and Operating Conference Proceedings, 2002.
- [31] Nueber, H., *Kerbspannungstehre*, Springer, Berlin, 1958; In Translation, *Theory of Notch Stresses*, U.S. Office of Technical Services, Washington, D.C., 1961.

[32] Peterson, R.E., *Stress Concentration Factors*, John Wiley and Sons, New York, 1974.

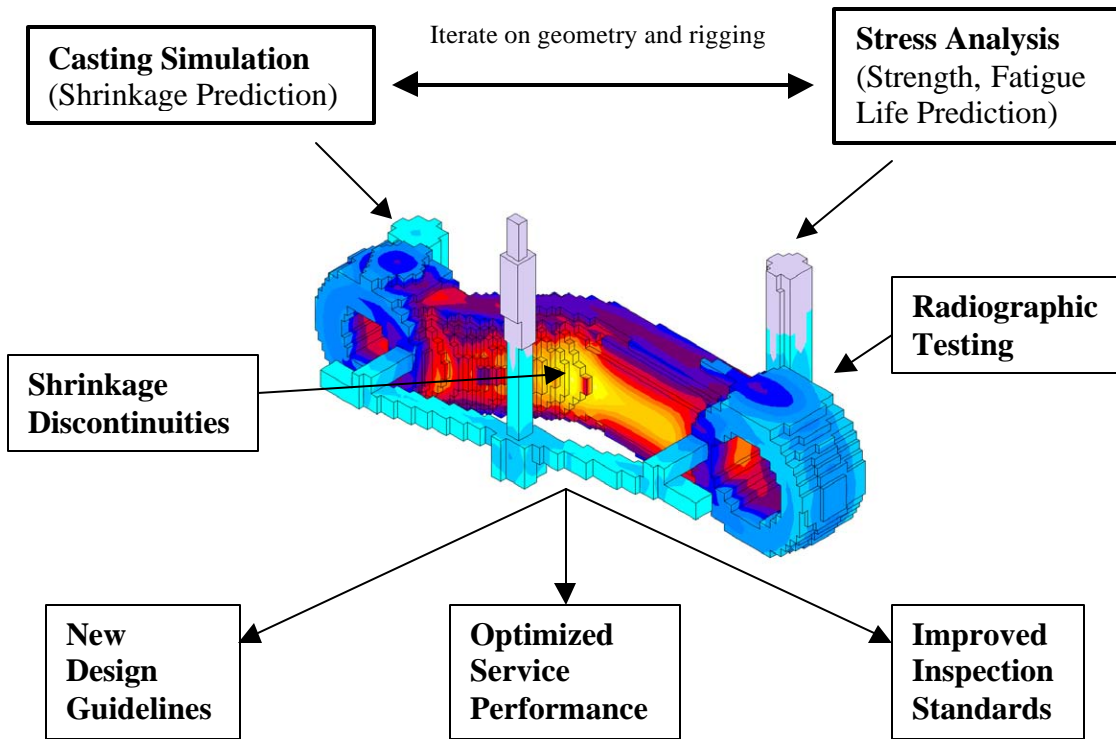


Figure 1: Illustration of Integrated Design of Steel Castings for Service Performance.

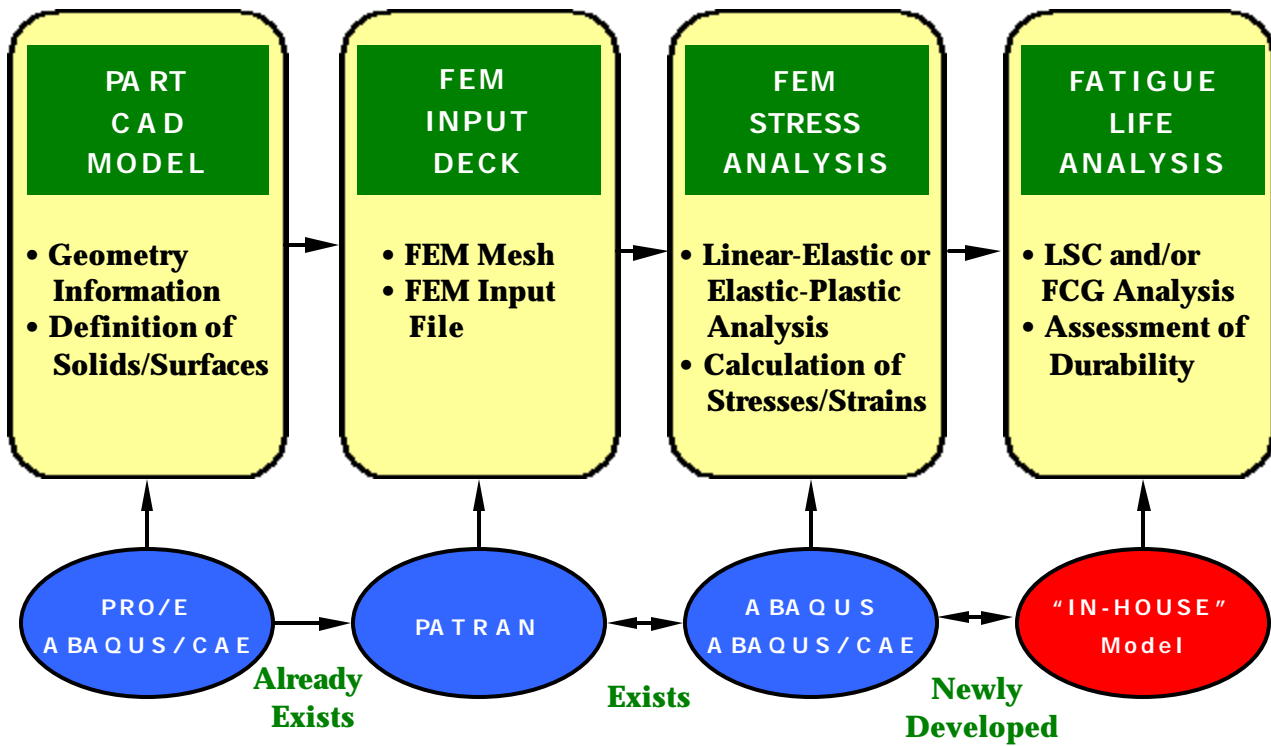


Figure 2: Overview of software used in analysis of service performance

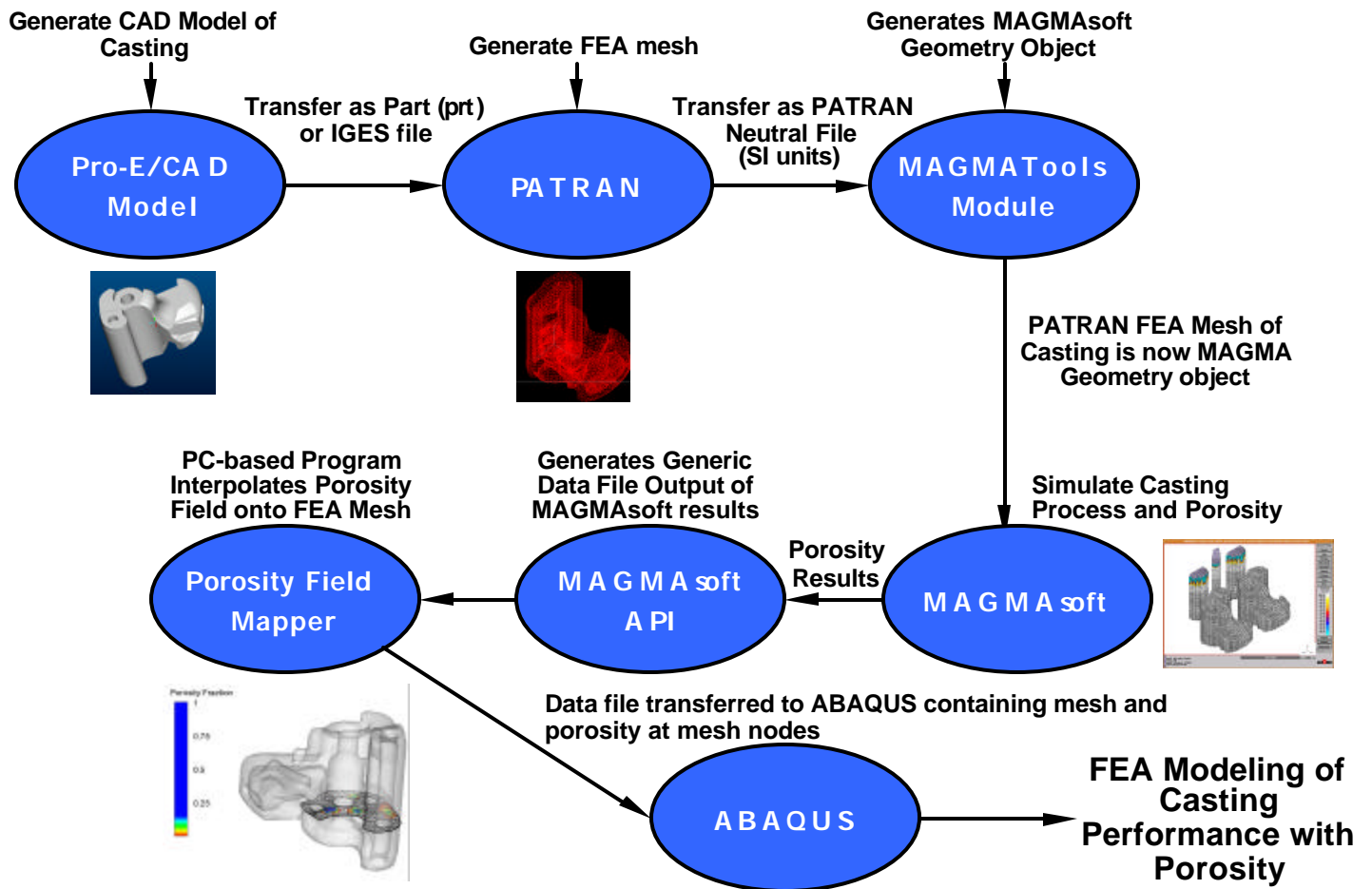


Figure 3: Overview of software and interfaces for integrating casting soundness and service performance prediction

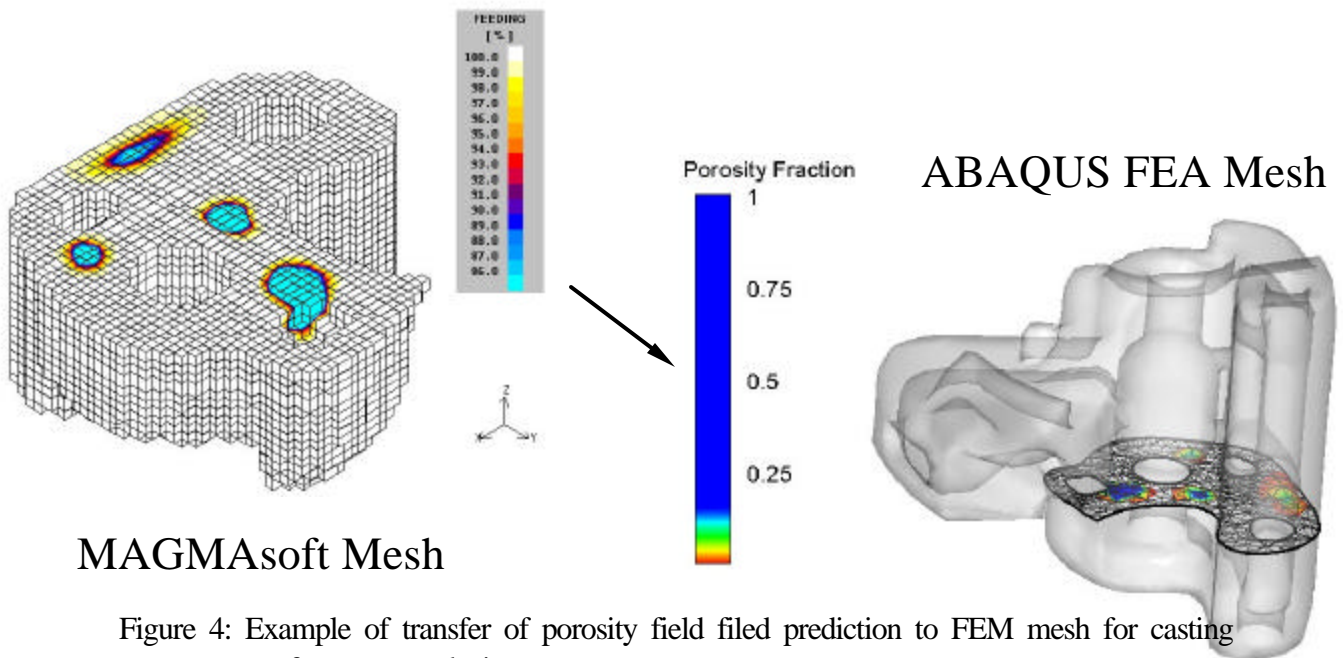


Figure 4: Example of transfer of porosity field filed prediction to FEM mesh for casting performance analysis

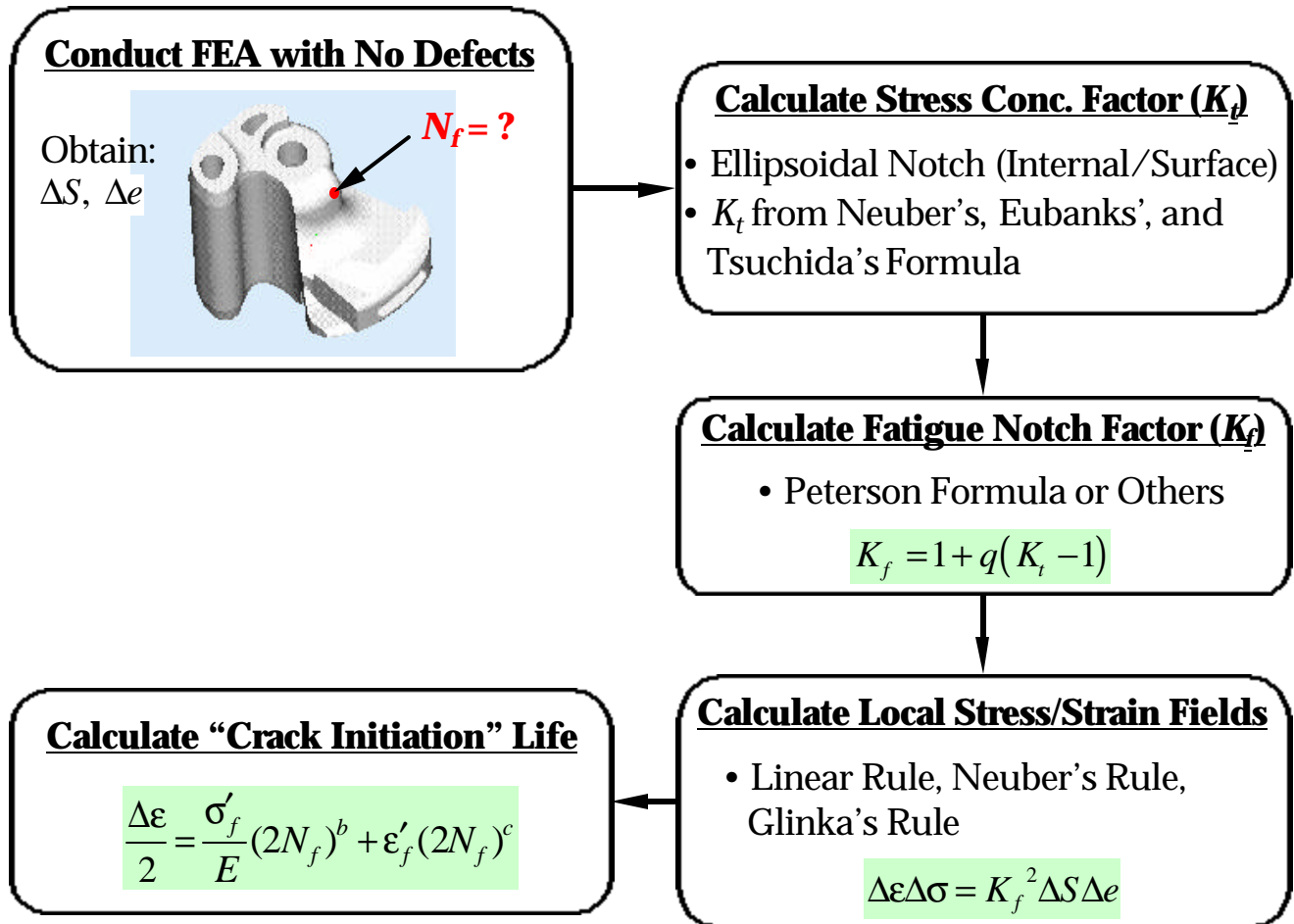


Figure 5: Schematic overview of calculation of method used to predict crack initiation life based on strain-life approach [11]

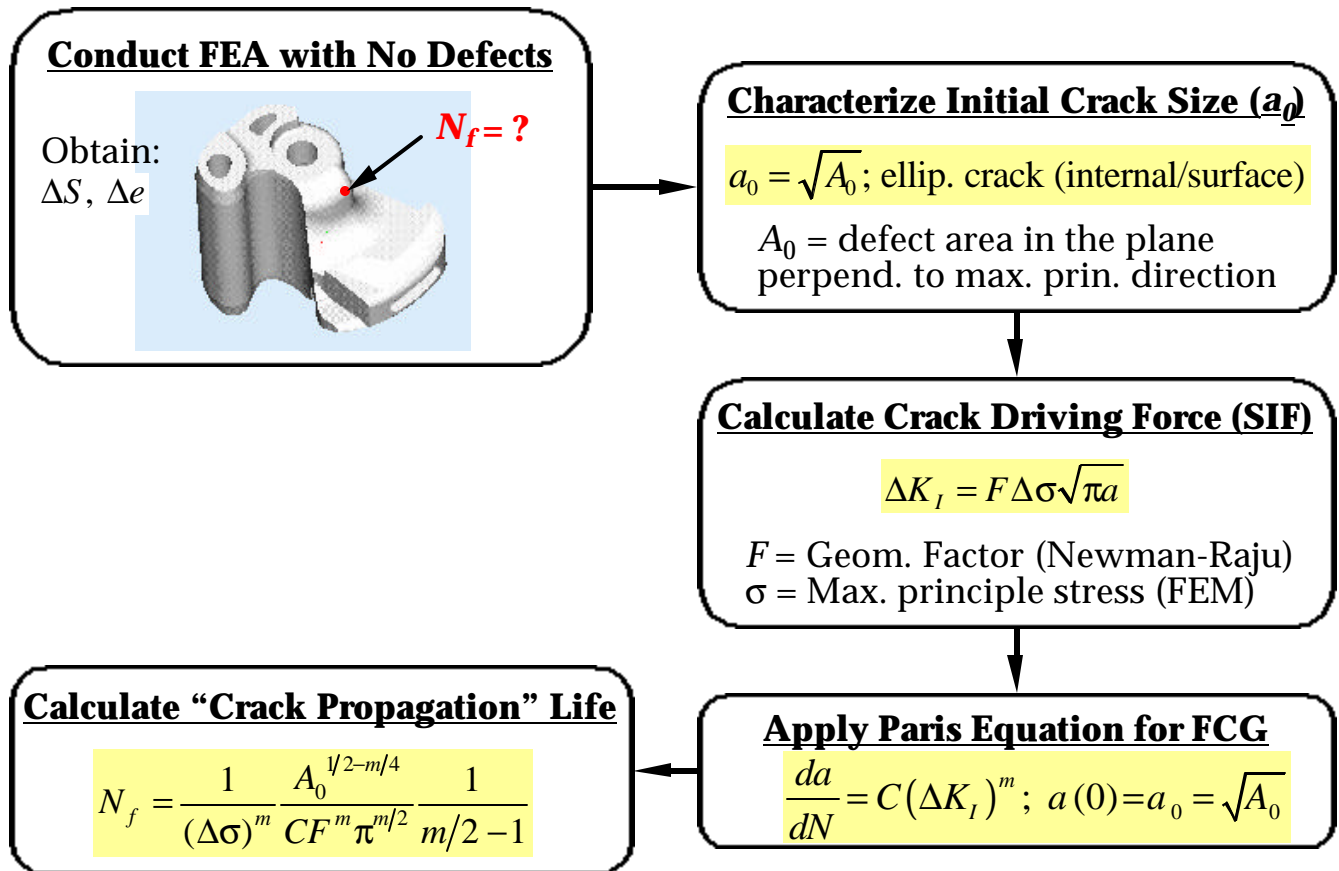


Figure 6: Schematic overview of calculation of method used to predict fatigue crack growth (FSG) of propagation life based on fracture mechanics approach [11]

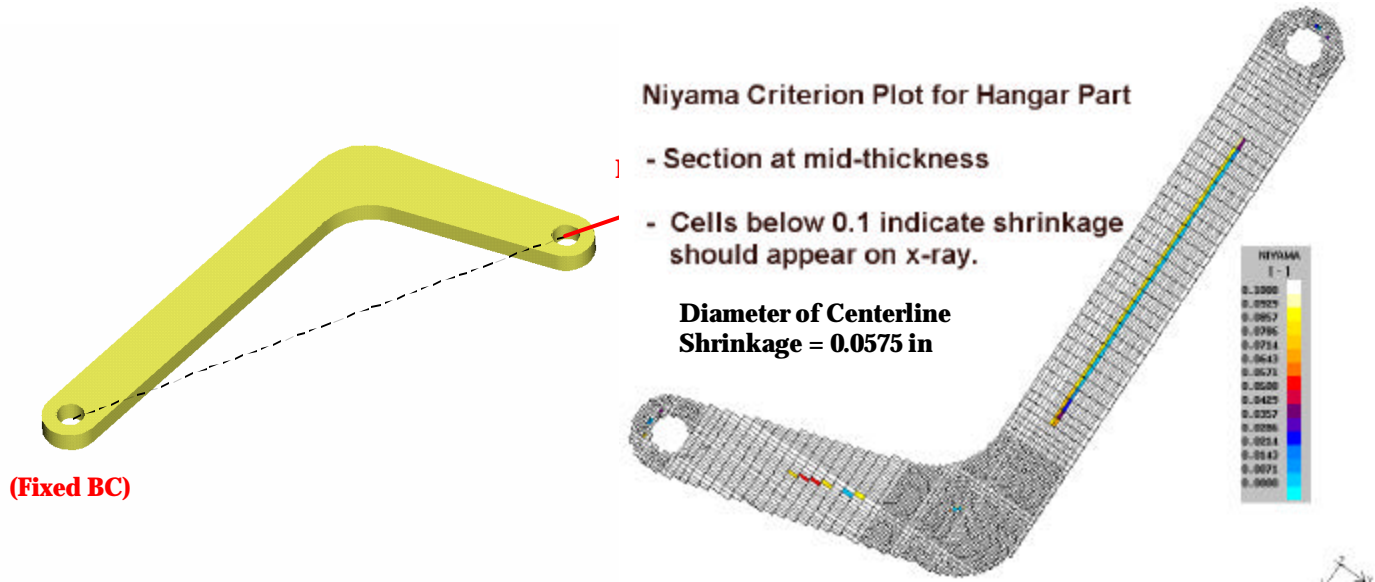


Figure 7: Hanger casting from [4] used to test casting performance prediction methods

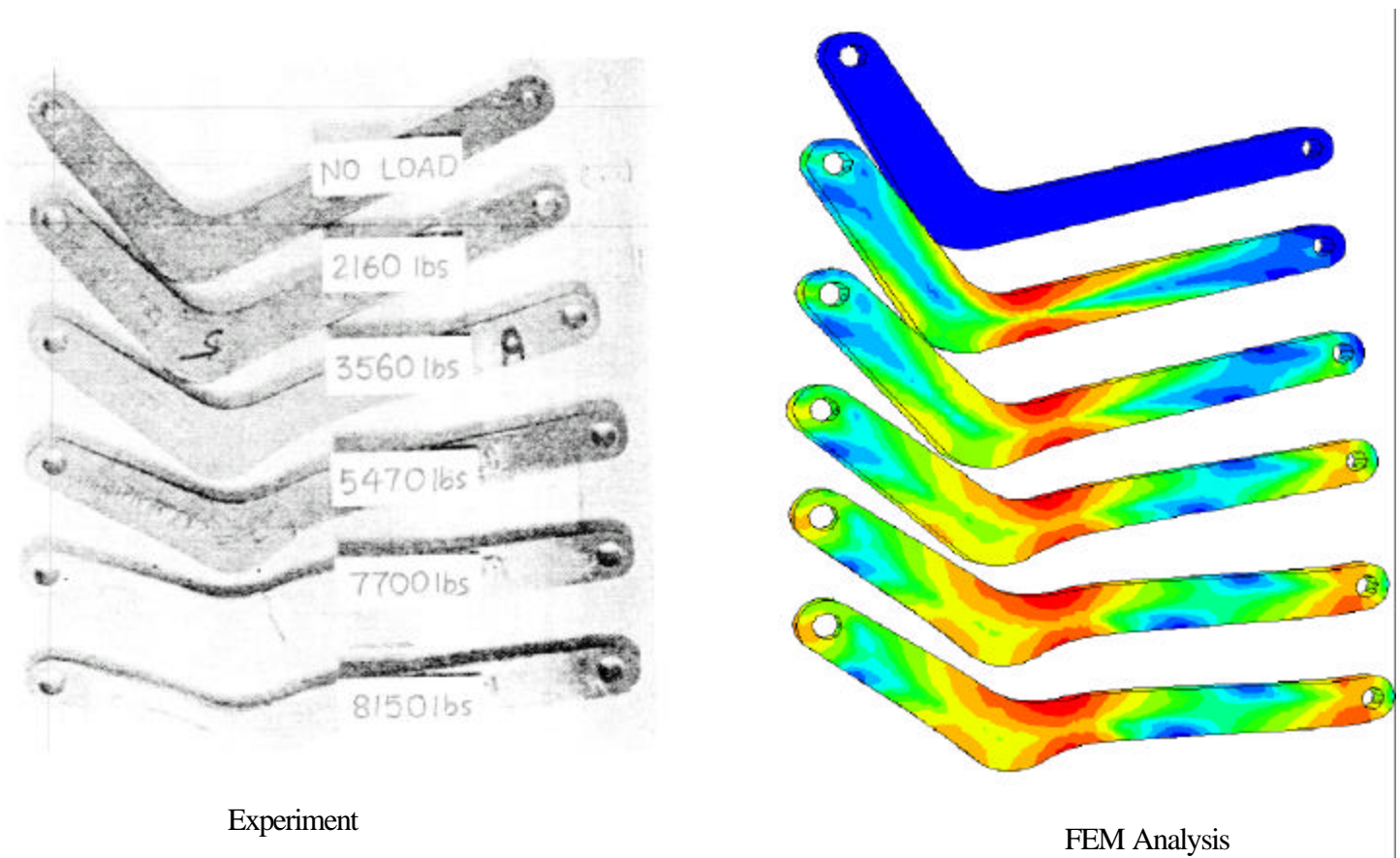


Figure 8: Hanger casting deformed by static strength testing in experiment (above left from [4]) and under the same loads using FEM analysis

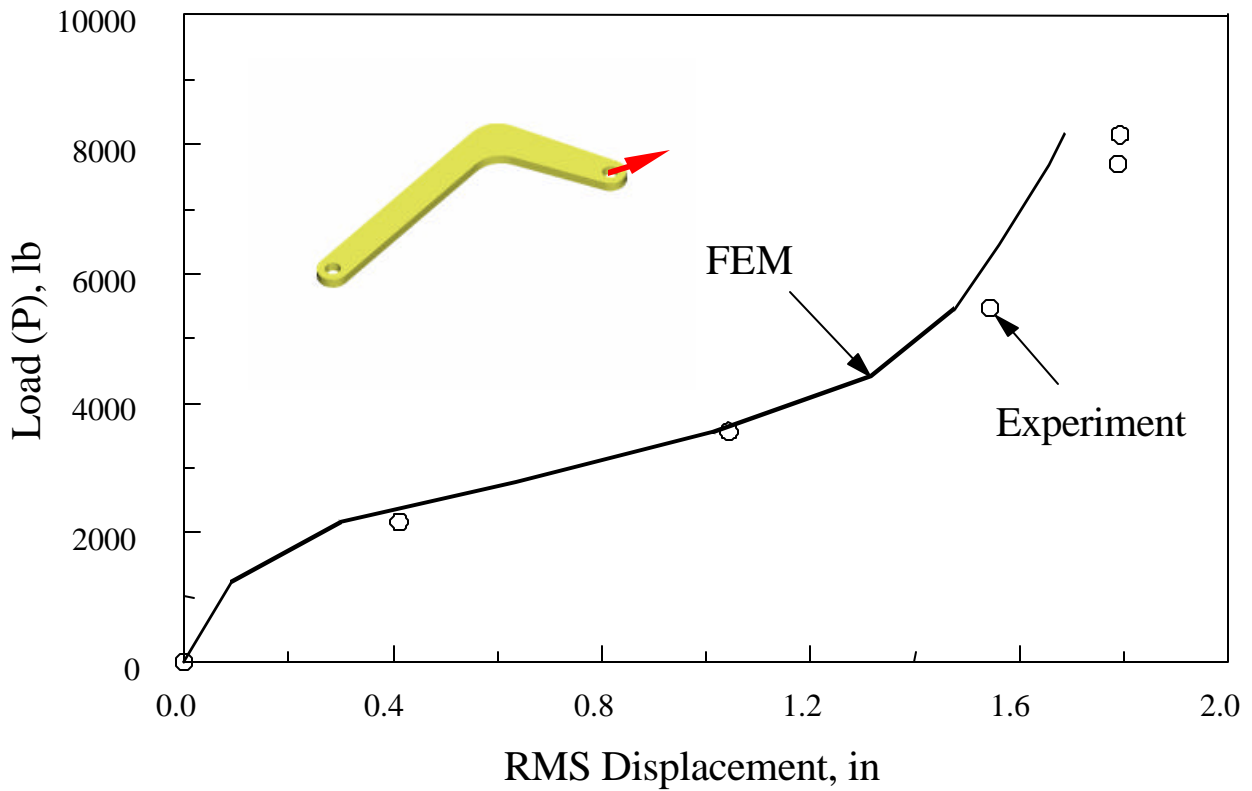
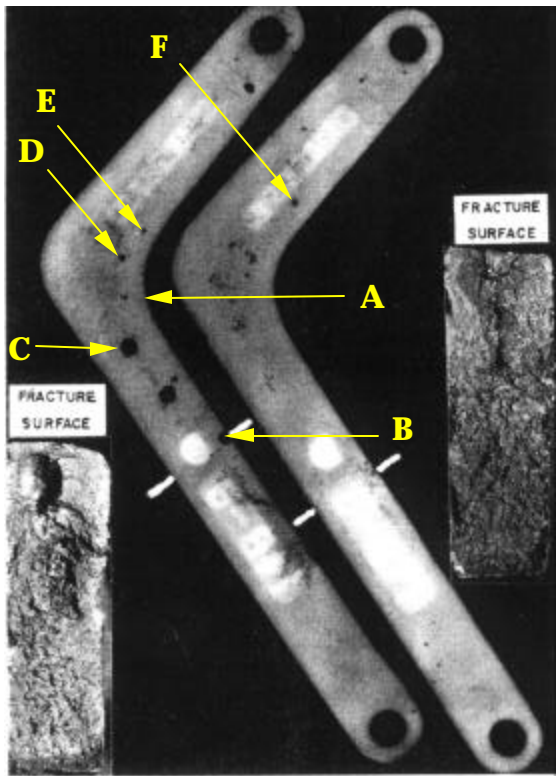


Figure 9: Load vs. displacement results of hanger casting from experiment [4] and from FEM analysis using porous metal plasticity model in ABAQUS



Surface Defect:

Node A: $D_h = 0, 0.25, 0.5, 1 \text{ mm}; a/b = 1$

Node B: $D_h = 5 \text{ mm}; a/b = 1.33$

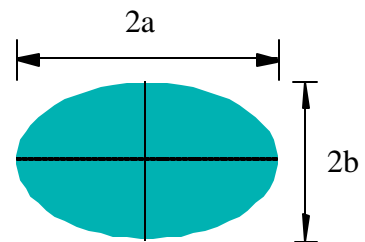
Internal Defect:

Node C: $D_h = 6 \text{ mm}; a/b = 1$

Node D: $D_h = 2.3 \text{ mm}; a/b = 1$

Node E: $D_h = 1.6 \text{ mm}; a/b = 1$

Node F: $D_h = 2.5 \text{ mm}; a/b = 1$



$$D_h = 2a$$

Figure 10: Measured internal shrinkage pores and the defect geometry used to describe them in the fatigue life predictions

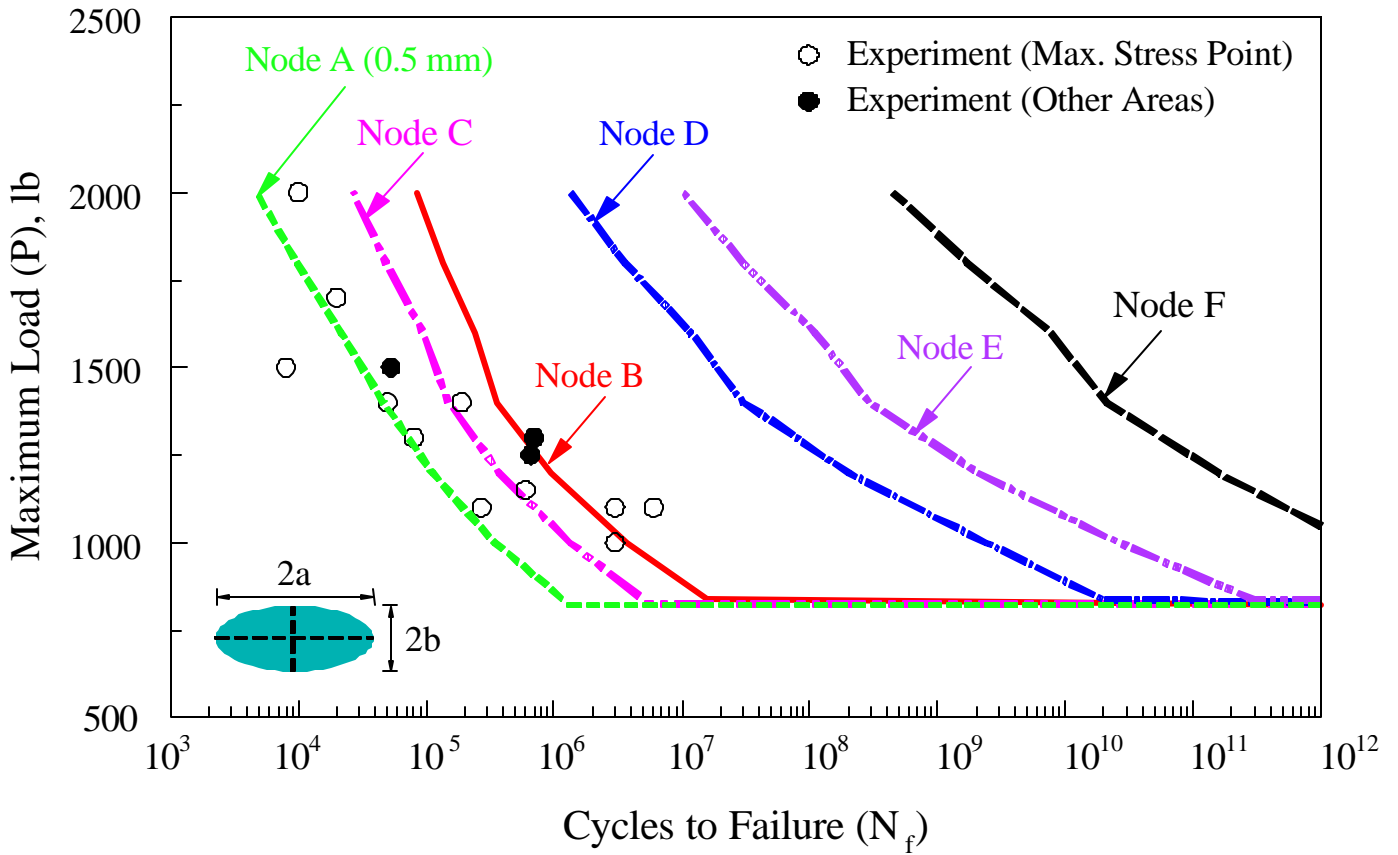


Figure 11: Predicted and measured [4] fatigue life for hanger casting using crack initiation life based on strain-life approach [11], symbols are shown for test results found at the position of maximum stress and at defect locations (other areas)

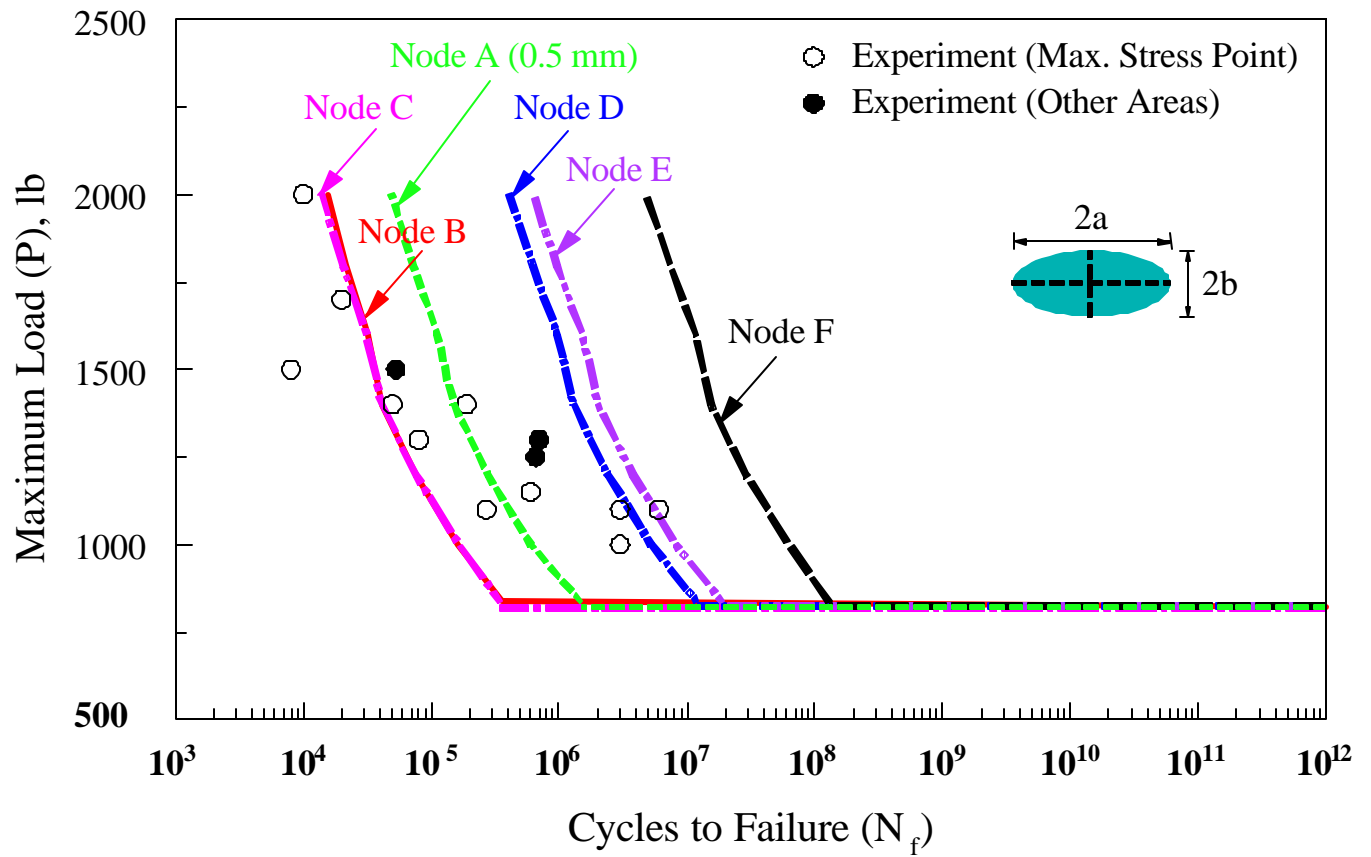


Figure 12: Predicted and measured [4] fatigue life for hanger casting using fatigue crack growth (FCG) life calculation based on fracture mechanics approach [11], symbols are shown for test results found at the position of maximum stress and at defect locations (other areas)

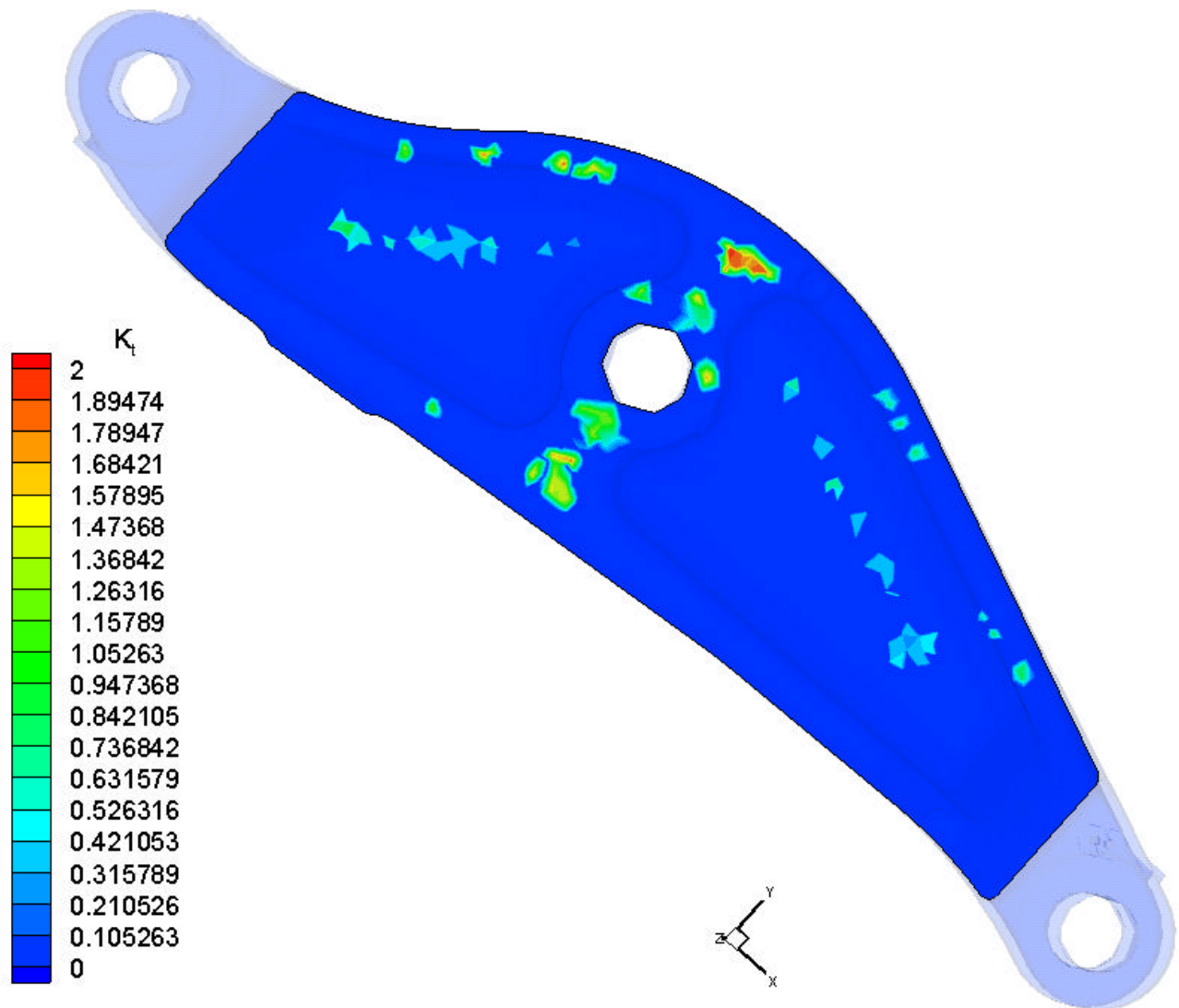


Figure 13: Stress concentration factor field at a slice through an example casting based on the porosity field and a pore characteristic diameter of 1 mm

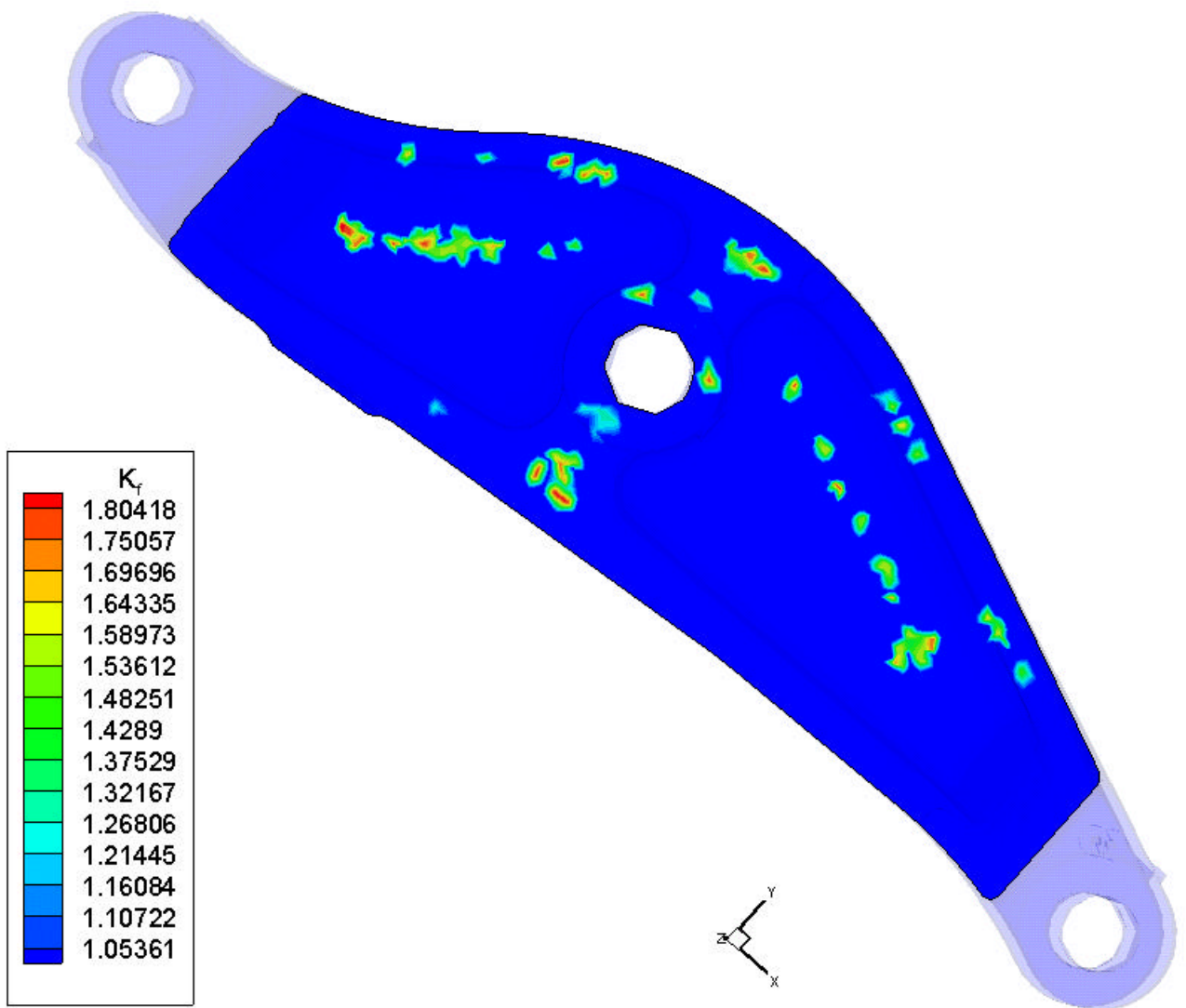


Figure 14: Fatigue notch factor field at a slice through an example casting based on the porosity field and a pore characteristic diameter of 1 mm

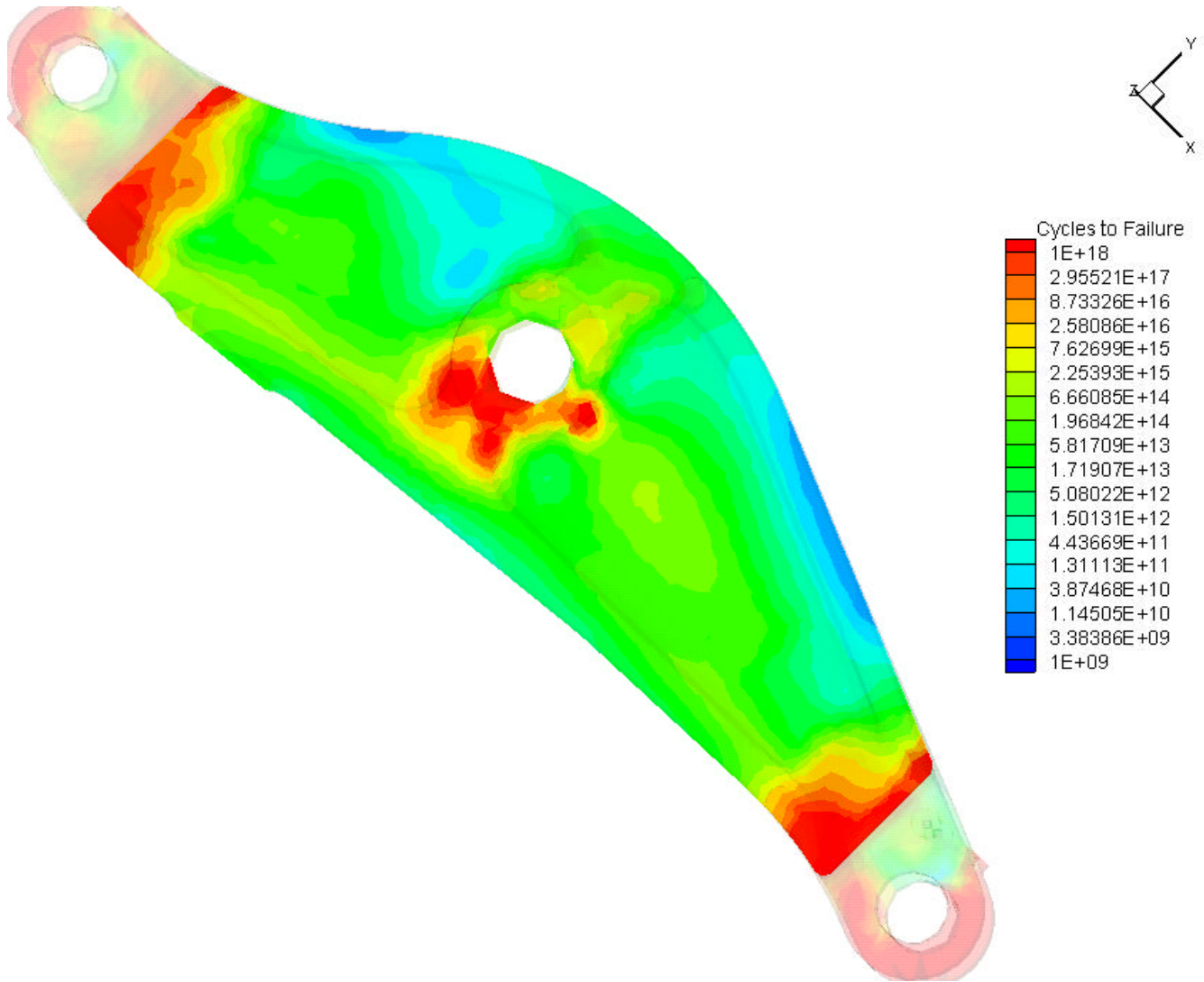


Figure 15: Predicted life of the example casting without considering the porosity in the life prediction

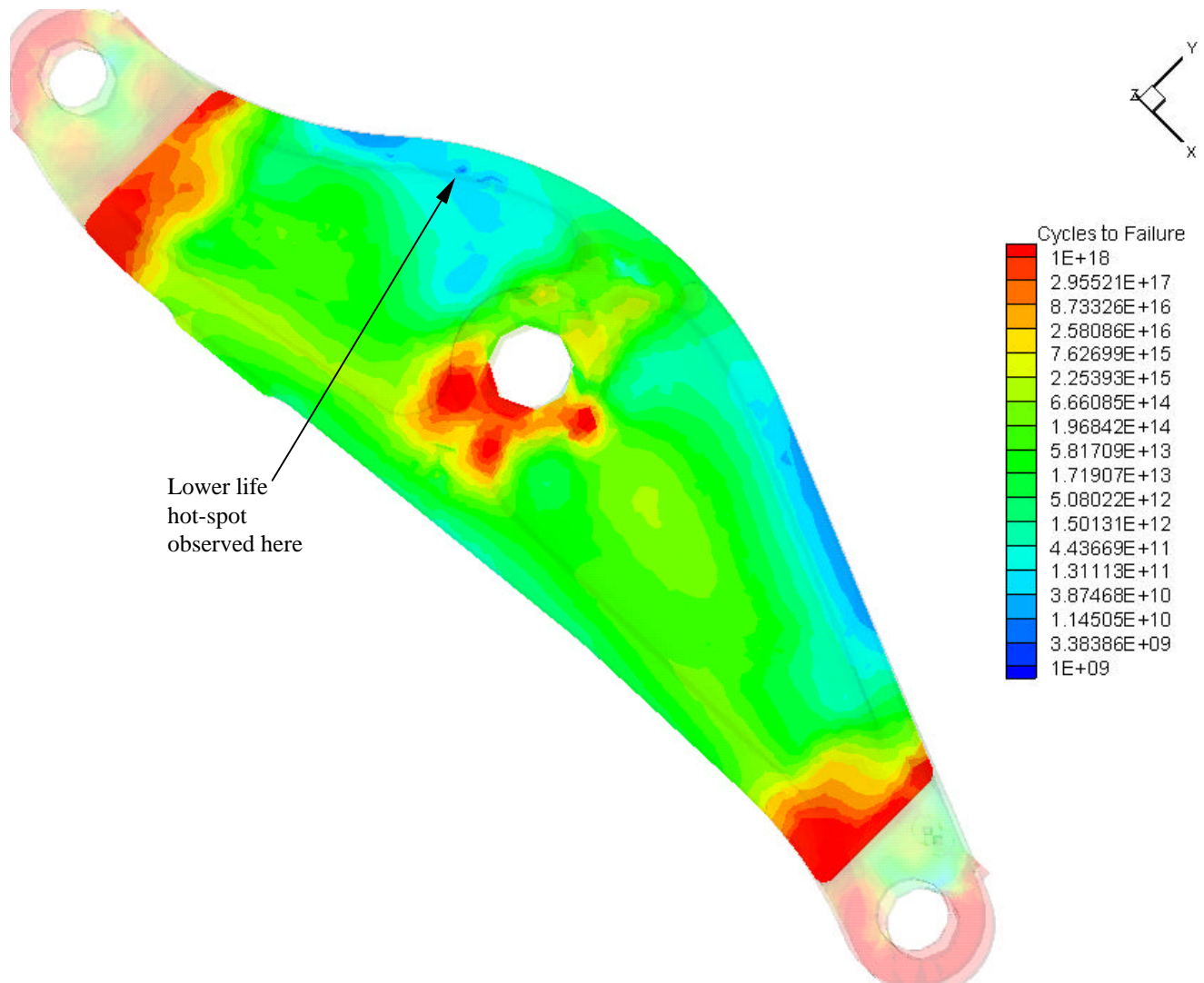


Figure 16: Predicted life of the example casting considering the porosity in the life prediction

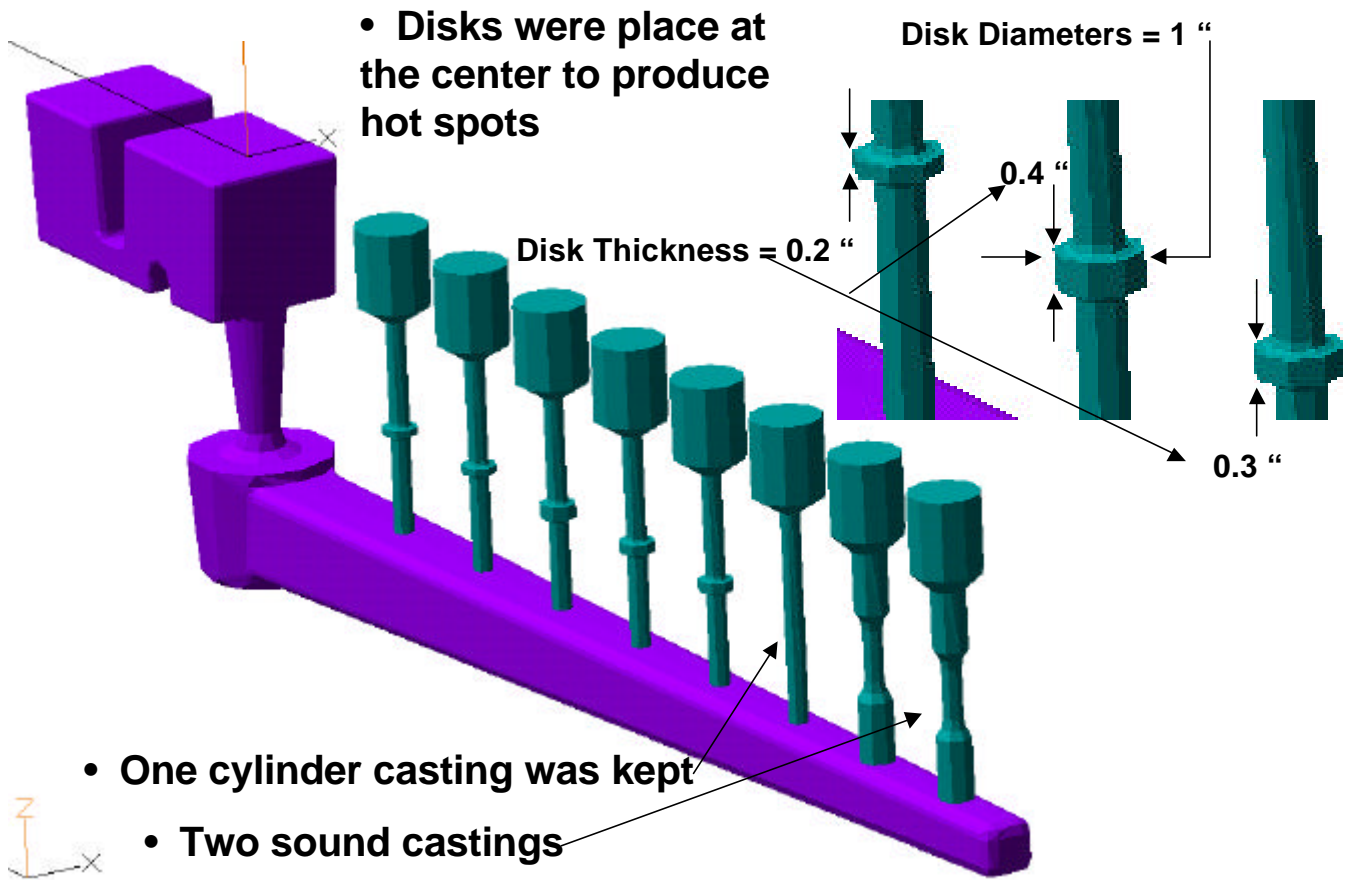


Figure 17: Drawing of rigging and as cast fatigue test specimens of varying soundness

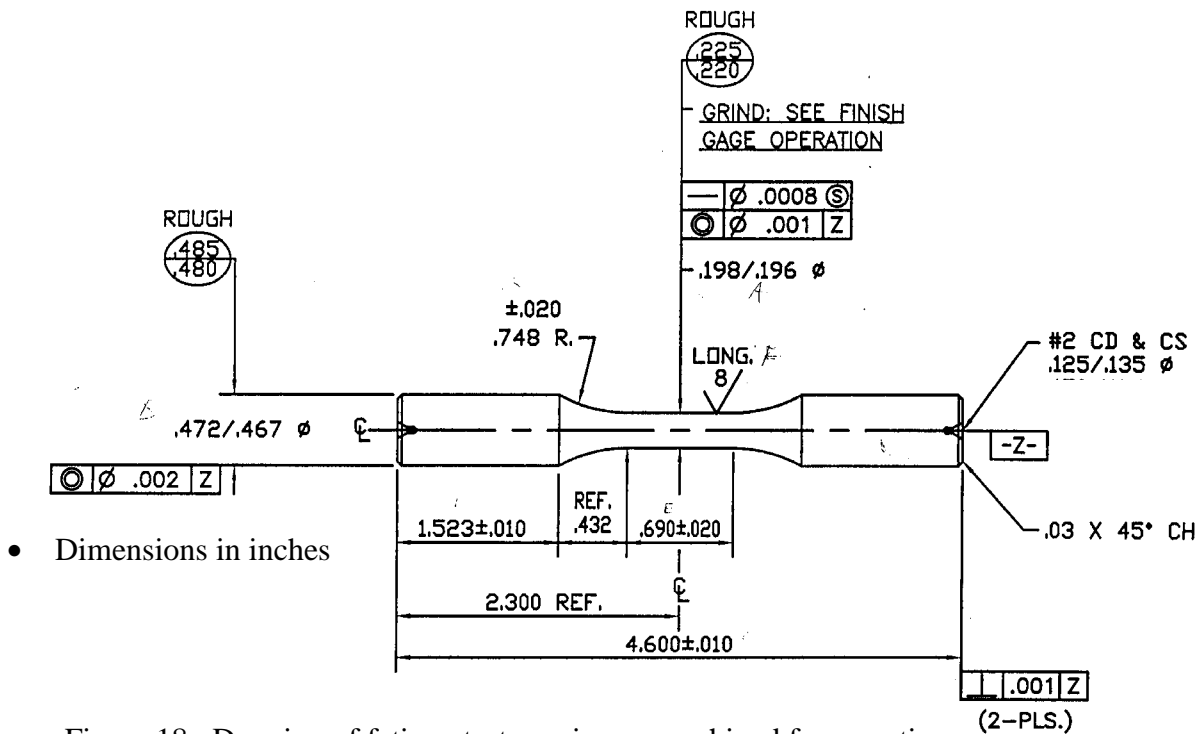


Figure 18: Drawing of fatigue test specimens machined from castings

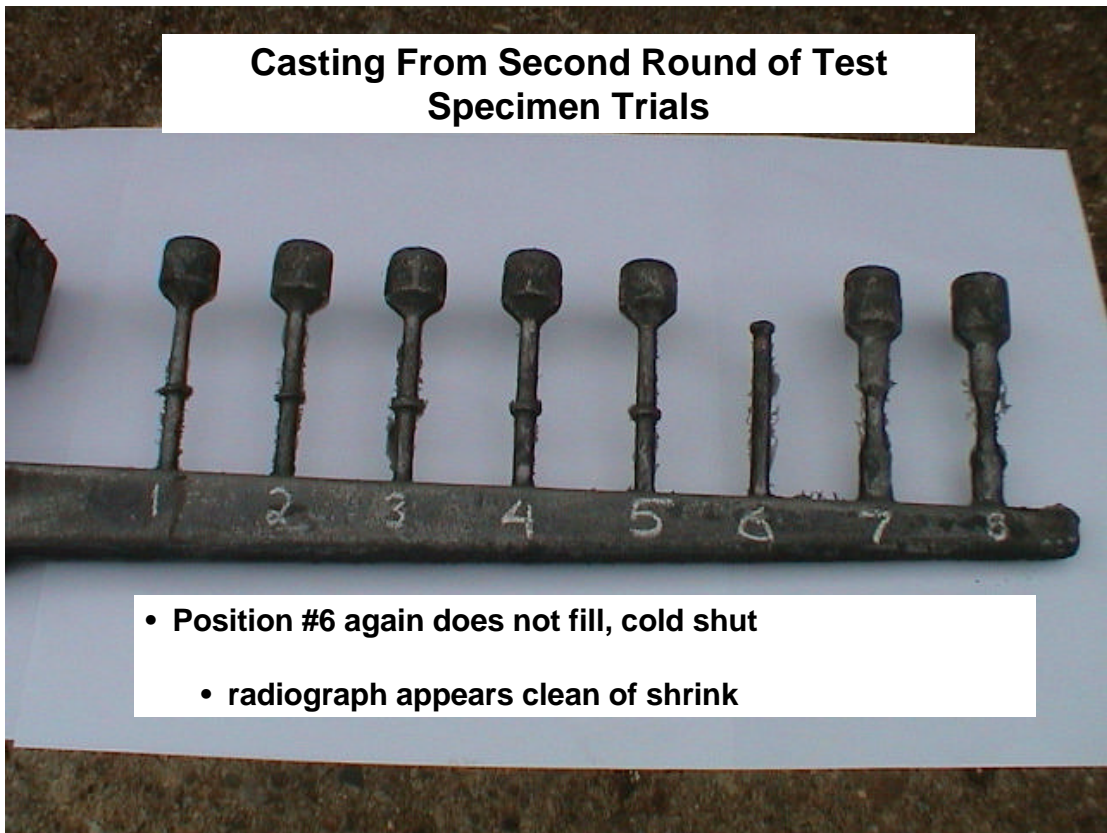


Figure 19: Fatigue test specimen castings, castings at position 6 had cold shuts in all but one mold box

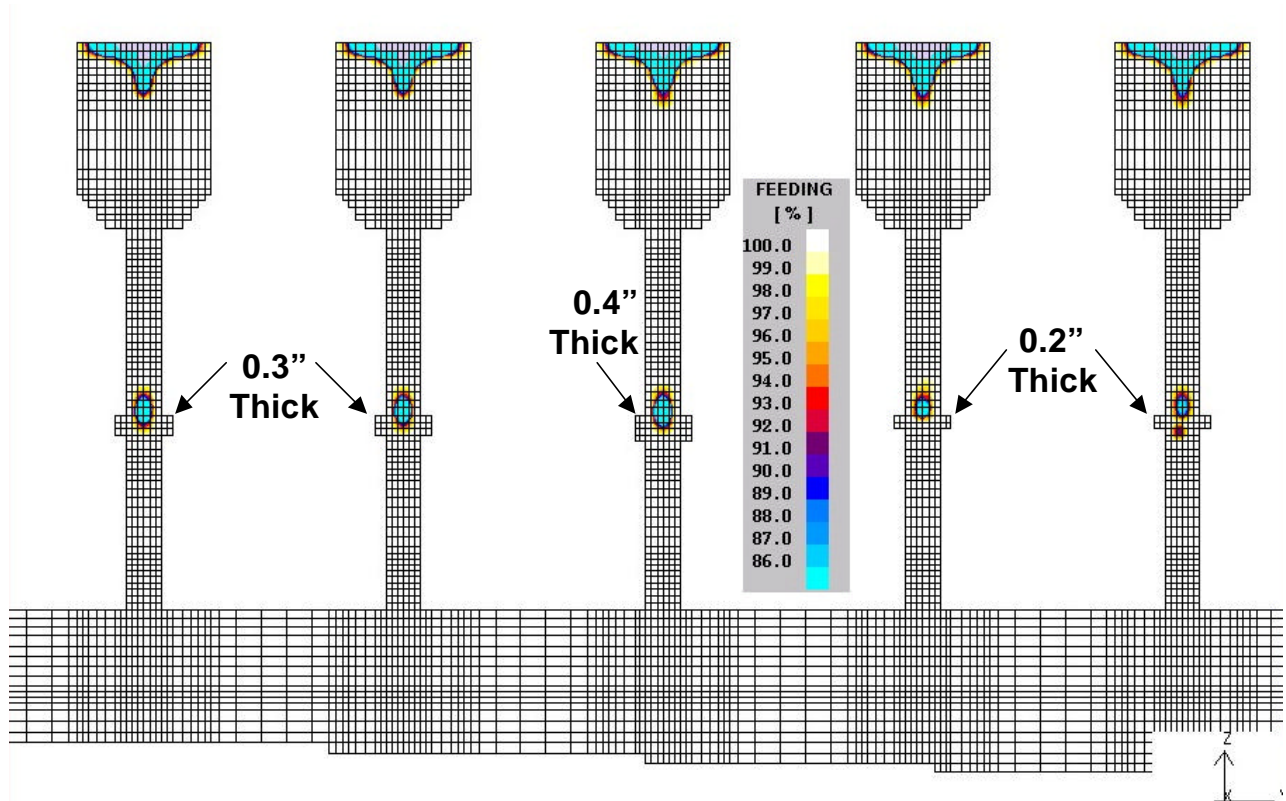


Figure 20: Feeding percentage porosity prediction in test specimen castings

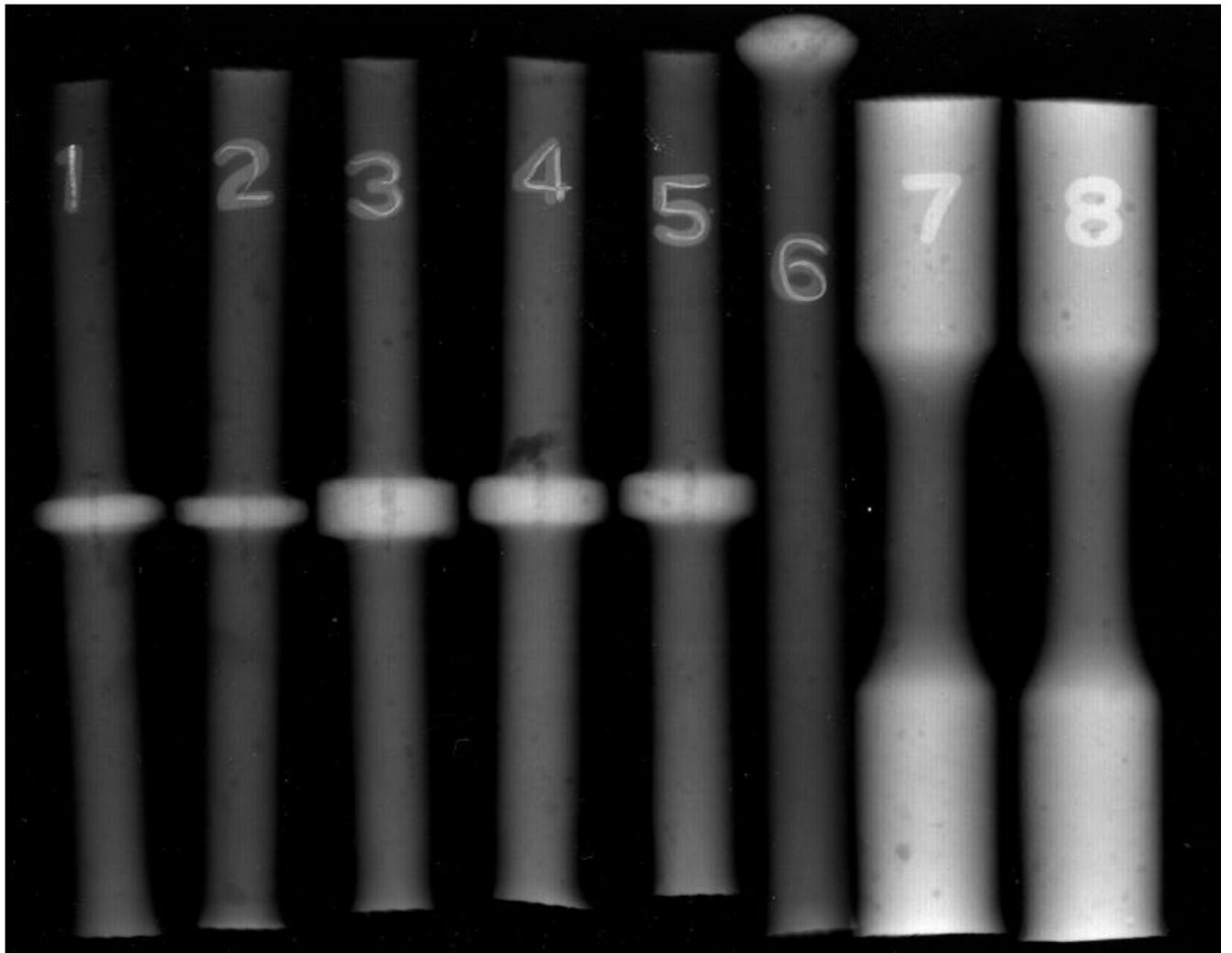


Figure 21: X-rays of first mold box of test specimens used in fatigue testing

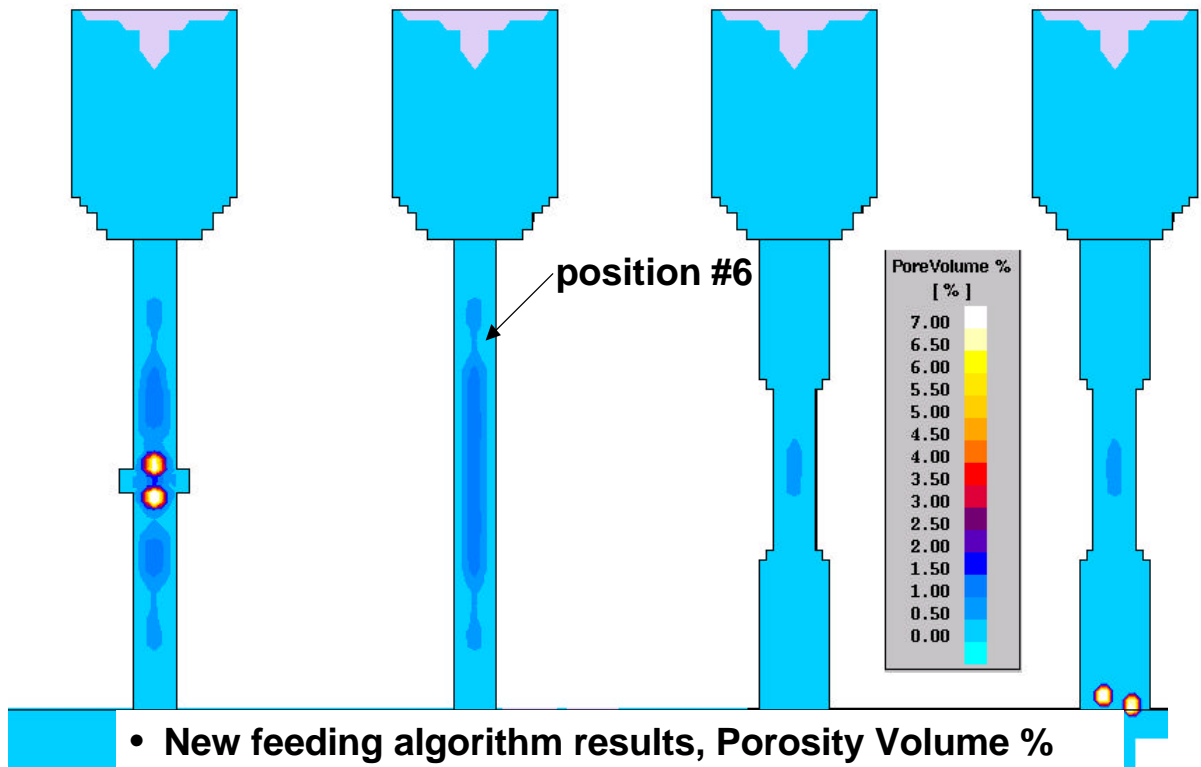
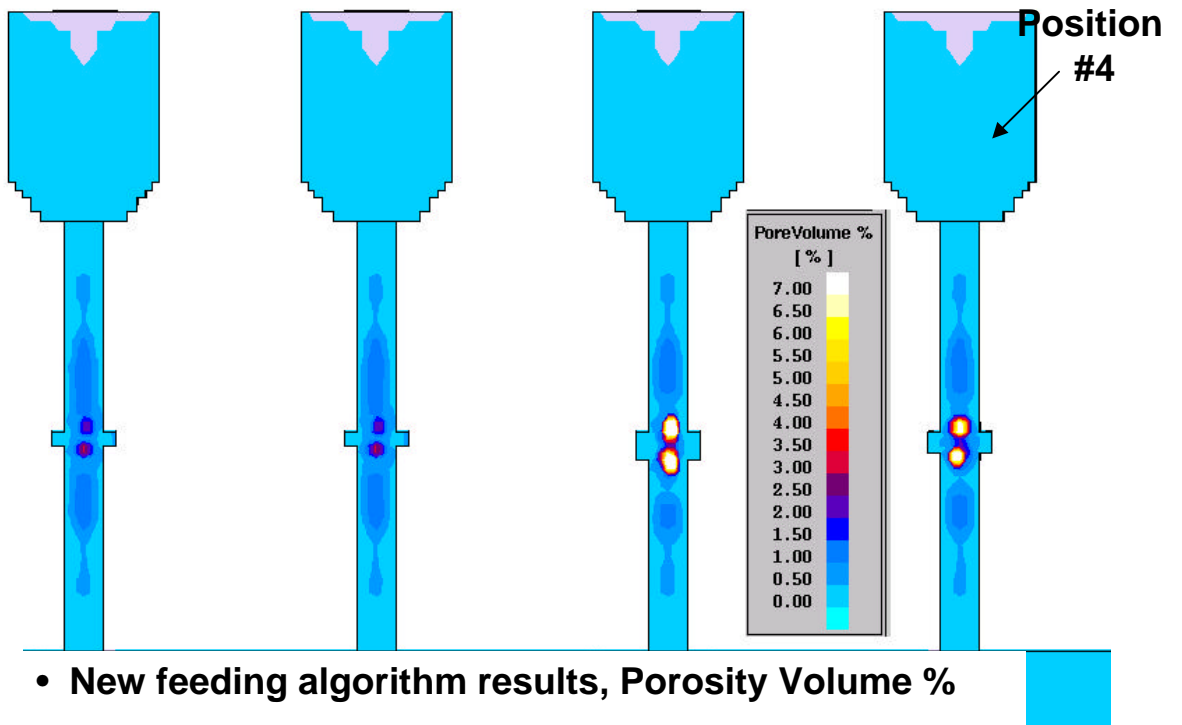


Figure 22: Porosity predicted using new feeding algorithm

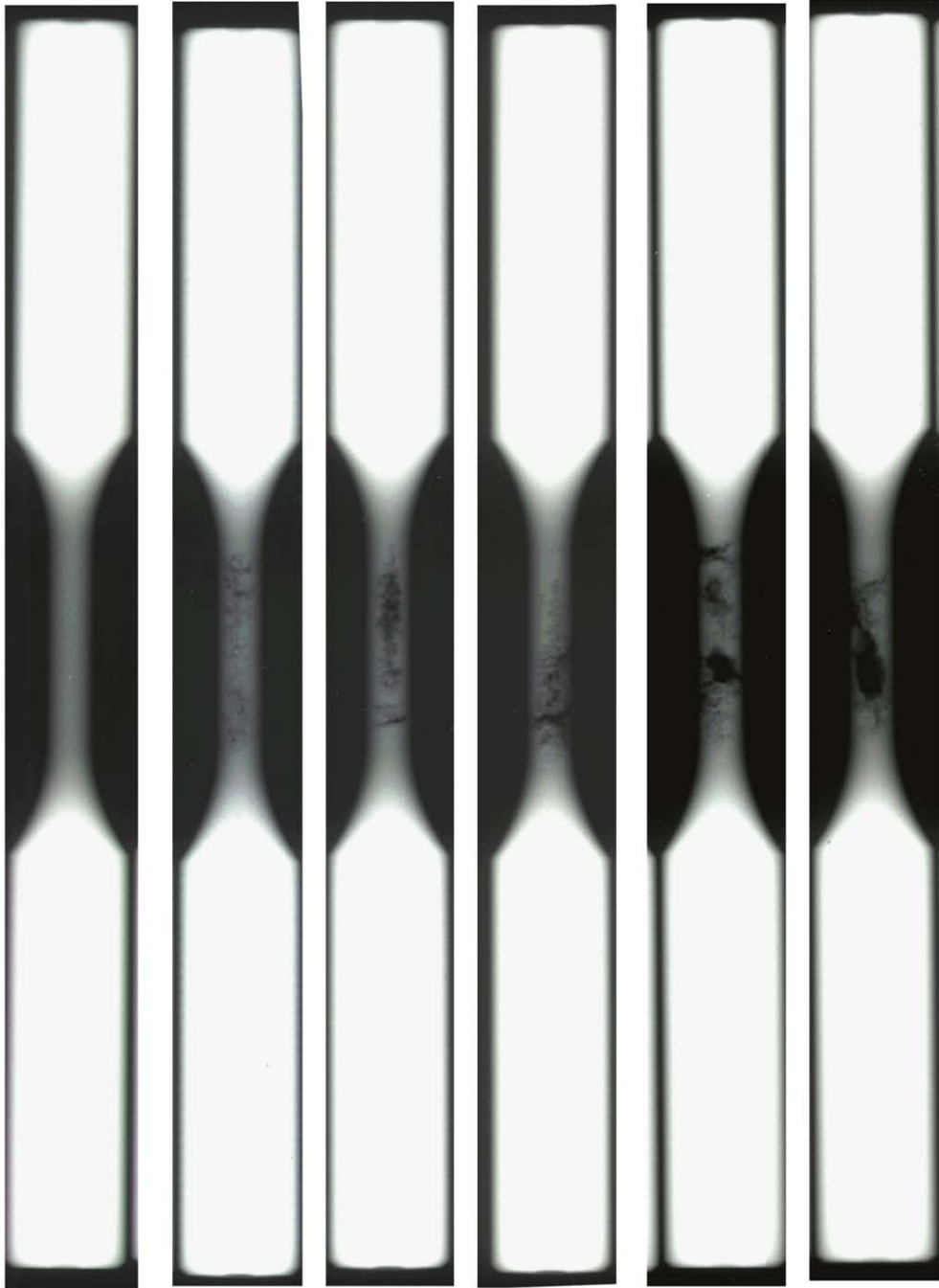


Figure 23: X-rays of selected fatigue test specimens demonstrating the range of soundness produced