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The effects of local variations in mechanical behaviour – numerical investigation of a ductile iron component

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ABSTRACT

The effects of incorporating local mechanical behaviour into a structural analysis of a cast ductile iron component are investigated. A recently presented simulation strategy, *the closed chain of simulations for cast components*, is applied to incorporate local behaviour predicted by a casting process simulation into a Finite Element Method (FEM) structural analysis, and the effects of the strategy on predicted component behaviour and simulation time are evaluated. The results are compared to using a homogeneous material description. A material reduction method is investigated, and the effects of material reduction and number of linearization points are evaluated.

The results show that local mechanical behaviour may significantly affect the predicted behaviour of the component, and a homogeneous material description fails to express the stress-strain distribution caused by the local variations in mechanical behaviour in the component. The material reduction method is able to accurately describe this effect while only slightly increasing the simulation time. It is proposed that local variations in mechanical behaviour are important to consider in structural analyses of the mechanical behaviour of ductile iron components.

Keywords:

Casting; Component behaviour; Ductile iron; Mechanical behaviour; Plastic behaviour.

I. INTRODUCTION

The process of designing cast iron and cast aluminium components in the automotive and transportation areas typically involves structural analyses using Computer Aided Engineering (CAE) tools as Finite Element Method (FEM) simulations to evaluate the mechanical performance of the cast component. In these simulations the material behaviour is typically considered homogeneous throughout the component. It is however well known that variations in geometry and casting process conditions causes local variations in solidification conditions [1] and microstructure [2] that leads to variations in material behaviour [3] throughout cast components [1-4]. Cast iron and cast aluminium components therefore typically contain local variations in mechanical behaviour, and the assumption of homogeneous material behaviour in the FEM analysis is thus a simplification which introduces an unknown amount of error into the FEM simulation.

The mechanical behaviour of a material is typically characterized using a stress-strain curve obtained from a tensile test. This curve can be divided into a linear elastic and a non-linear plastic region, where the elastic region is characterised by the Young's modulus, E (Pa). The plastic behaviour is in this work characterised using the Hollomon

equation, which describes the relationship between true stress σ (Pa) and plastic strain ε_{pl} (-) using the strain hardening exponent n (-) and the strength coefficient K (Pa) as [5]

$$\sigma = K \cdot \varepsilon_{pl}^n \quad (1)$$

In cast irons both the elastic [6] and the plastic [7] mechanical behaviour is highly dependent on e.g. type of matrix and the amount of and the shape of the precipitated graphite particles [6-8], i.e. parameters which are determined during the casting process by e.g. chemical composition, casting process parameters and local solidification conditions throughout the component [9].

Casting simulation software is commonly used to verify the casting process for the final design of the component and predict filling of the mould, shrinkage [10], residual stresses [11] etc. In recent years research has been performed to extend the functionality of casting simulation software to predict the solidification process [12], microstructure formation [13] and mechanical material behaviour on a local level throughout the component [1, 2, 4, 12, 13]. The possibilities to use this predicted microstructure-based mechanical behaviour in FEM simulations has however been limited. A new simulation strategy for cast components denoted the closed chain of simulations for cast components was therefore recently presented by the current authors [14]. The simulation strategy aims to enable more accurate FEM simulations of the mechanical behaviour of cast components at an early stage in the design process, by replacing the assumption of homogeneous material behaviour with predicted local microstructure-based mechanical behaviour. The strategy, schematically illustrated in Fig. 1, incorporates local variations in mechanical behaviour predicted by a casting simulation software into the FEM simulation at the element level.

Fig. 1. The closed chain of simulations for cast components presented in [14]. Figure reprinted with permission from Elsevier.

By default element individual material definitions are used in the simulation strategy. It was previously proposed by the current authors that for large FEM models this may yield a very long FEM simulation time, and a material reduction method was therefore suggested [14]. These effects have however not been numerically established. The material definitions uses a piecewise linear description of the plastic material behaviour,

evaluated at a defined Number of Linearization Points (NLP). The effect of NLP on a single material definition has been previously investigated [14], but the effect of NLP on component simulation results has not been established.

This work aims to investigate the effect of incorporating local microstructure-based mechanical behaviour into an FEM simulation of the mechanical behaviour of a cast ductile iron component using the closed chain of simulations for cast components. The error caused by an assumption of homogeneous material behaviour is investigated. The effects of material reduction and NLP on FEM simulation time and accuracy are then investigated. This evaluation needs to be performed in order to determine the relevance of considering local mechanical behaviour in FEM simulations, and to investigate any effects on the performance of the FEM simulation. The results of this investigation directly influence the use and implementation of the closed chain of simulations for cast components, which affects the design process for high performance cast components and thus the work of metallurgists as well as design and CAE engineers.

2. EXPERIMENTAL SETUP

2.1. Casting process simulation

The simulation of the casting process was performed using a development version of MAGMAsoft [15]. The CAD geometry of the component was imported into the software, and the chemical composition of the alloy and casting process related parameters were specified. The entire casting process, including filling of the mould, solidification and microstructure evolution throughout the component, was then simulated. The casting simulation software uses solidification models to locally determine microstructure evolution throughout the component based on the specified chemical composition and casting process parameters. It also characterises the microstructure-based mechanical behaviour throughout the component using previously developed relationships between microstructural parameters and Young's modulus [6] respectively the parameters of the Hollomon equation [7, 8]. The MAGMALink module of MAGMAsoft [15] was used to adapt the results to the FEM mesh.

Fig. 2 shows the variation in Young's modulus predicted by the casting process simulation. Young's modulus in ductile iron is related to the nodularity and roundness of the graphite particles [6] which are determined by the local solidification conditions. Since the solidification conditions vary throughout the component due to geometrical changes and the casting process, local variations in Young's modulus are obtained throughout the component. Similar variations in the parameters of the Hollomon equation are also predicted by the casting process simulation.

Fig. 2. Predicted local variations in Young's modulus.

2.2. Incorporation of local material data

An in-house developed computer program was applied to incorporate the predicted local mechanical behaviour from the casting process simulation into the input for the FEM simulation [14]. The program creates FEM material definitions where the linear elastic part is characterised by the Young's modulus while the non-linear plastic part is characterised by a piecewise linear description of the non-linear curve predicted by the Hollomon equation, Eq. 1. The curve is evaluated at a number of points between which the curve is assumed linear. A higher Number of Linearization Points (NLP) thus corresponds to a more accurate description of the non-linear plastic curve [14]. An interval divider approach was applied [14], in which the total plastic range is divided into two intervals where half the NLP are used in the first interval and the other half in the other interval. This approach has been previously evaluated [14], and based on these results an interval divider at $\varepsilon_{pl} = 0.01$ and a NLP of 10, 20, 40 respectively 60 points were selected for the current investigation.

The previously mentioned material reduction method, where a number of intervals are specified for each material parameter (E , n and K) [14], was evaluated. In each interval the average between the minimum and maximum value of the interval is used as the parameter value. Every FEM element is grouped corresponding to its combination of parameter interval numbers, and material definitions are created for all groups containing at least one element. Though the number of intervals can be arbitrarily selected for each parameter, the purpose of material reduction is to effectively describe the variation in mechanical behaviour throughout the component. A first approach is hence to let the relative number of intervals reflect the amount of variation in the parameter values. In this work the interval numbers for the parameters, E - n - K , were chosen to be constantly proportional to their relative variations in predicted values. The relative variations in n and K were found to be approximately 10 respectively 20 times the variation in E , thus the proportionality factors for E - n - K were selected as 1-10-20. Different numbers of material definitions were then obtained where the different number of intervals for each parameter were determined by multiplying the parameters' proportionality factors with an interval multiplication factor. The interval

factor thus indicates the accuracy of the description of the variations in mechanical behaviour throughout the component, where a high value corresponds to a highly accurate description.

In order to isolate the effect of the local variations in mechanical behaviour a homogeneous reference description was created using the mean values of all parameter values throughout the component for each parameter. The entire test matrix for the evaluation is shown in Table 1.

Table 1. Test matrix for the evaluation. Bold text indicates that the simulation was repeated for the evaluation of FEM simulation time.

Interval factor	No. of intervals <i>E-n-K</i>	Approx. no. of material definitions	Number of Linearization Points (NLP)	Comment
-	-	132 000	10, 20, 40, 60	Element individual material definitions
50	50-500-1000	12 000	10, 20, 40, 60	
20	20-200-400	3 000	10, 20, 40, 60	
10	10-100-200	1 000	10, 20, 40, 60	
5	5-50-100	300	10, 20, 40, 60	
1	1-10-20	30	10, 20, 40, 60	
-	-	1	10, 20, 40, 60	Homogeneous

2.3. FEM simulation setup

A FEM mesh of the component consisting of about 132 000 second order elements (C3D10M) was created in ABAQUS [16] format. The translation of the component was prevented by fixing the surfaces marked in Fig. 3. A load was applied, evenly distributed on the surface shown in Fig. 3, which was linearly increased from 0 to 150 kN from time $t=0$ to $t=1$. This load level was chosen to cover the entire range of stresses from zero up to the estimated ultimate tensile stress in the component. The FEM simulations were performed using the ABAQUS [16] implicit solver with timesteps of $\Delta t=0.1$ from $t=0$ to $t=1$, thus results were obtained in 11 steps with a 15 kN load increase for every step. A full-factorial experiment of the test matrix in Table 1 was performed, i.e. 28 different FEM simulations. To evaluate FEM simulation time 10 of the simulations, marked with bold text in the column NLP in Table 1, were performed 3 times. The total FEM simulation time was extracted from the FEM solver outputs, and the mean value of the 3 simulations was determined. The results were normalised to obtain a simulation time factor which shows the change in simulation time compared to using a homogeneous material description with 60 NLP.

Fig. 3. Boundary conditions for the FEM simulation.

2.4. Evaluation of FEM results

The maximum values of von Mises stress and strain were extracted for every load step of every simulation. In order to also evaluate the stress-strain distribution throughout the component 10 elements in the FEM mesh were picked as gauge elements. These elements were selected to cover all regions of the component in which a stress level in the plastic stress range was obtained in the simulations. The gauge elements are in addition not at any load the element where the maximum stress or strain in the component is achieved.

To determine the accuracy of the simulation, the simulation with element individual material definitions and 60 NLP was chosen as reference. The results from this simulation are assumed to be the correct results, and the difference in results between another simulation and the reference simulation is considered to be a measure of simulation accuracy. Three different types of errors will be discussed;

- *Max-Value Error, MVE (%)*, is for every load step defined as the absolute relative error of the maximum von Mises stress or strain, determined from the values predicted by the simulation under consideration (C) and by the reference simulation (R), i.e. $MVE = |C-R|/R \times 100$.
- *Average Gauge Error, AGE (%)*, is similarly defined for every load step as the mean of the absolute relative errors in the 10 gauge elements.
- *Simulation Gauge Error, SGE (%)*, is for every *simulation* defined as the mean of the Average Gauge Errors in all load steps.

AGE thus indicates how well the stress or strain distribution is described at a given load step, while *SGE* indicates how well the stress or strain distribution on average is described through the entire simulation. Note that the values of *AGE* and *SGE* are not claimed to be exact measures of the accuracy of the stress-strain distribution throughout the entire component since only 10 selected gauge elements are considered. These measures are however in the current work used for comparing the simulation results.

3. RESULTS AND DISCUSSION

3.1. Effect of homogeneous mechanical behaviour

The errors obtained using a homogeneous material description are shown in Fig. 4 (Max-Value Error, MVE) and Fig. 5 (Average Gauge Error, AGE). The dashed vertical line

at 60 kN in the figures indicates when the 0.2% offset yield stress is exceeded, i.e. plastic strains are obtained in the component. Table 2 shows at which load levels the different simulations were unable to predict the correct region of maximum stress (marked with X) and strain (marked with O). The ability of the different simulations to predict the correct location of the maximum stress and strain is found to be dependent only on the number of material definitions and not on NLP, thus only the number of material definitions and not the NLP is shown in Table 2.

It is noted, e.g. in Fig. 4, that this method of plotting MVE and AGE versus applied load may lead to irregular curves since the obtained values fluctuates, but some general trends can be observed. In Fig. 4 and Fig. 5 it is seen that when the applied load is low, below 30 kN, the errors obtained using a homogeneous material definition are low, less than 1 %, and as seen in Table 2 the correct location of maximum stress and strain is predicted. The differences in simulation results are here only caused by the variation in Young's modulus throughout the component, and the effect of the local variations in mechanical behaviour is thus low at low loads. As the load increases to 45 kN elastic stresses are still obtained throughout the component but the error in maximum values increases significantly, Fig. 4, while the error in AGE remains low, Fig. 5. This indicates that though the stress-strain distribution in the component is still rather well represented by the homogeneous material description, the predicted behaviour within stress and strain concentrations becomes less accurate.

Fig. 4. Max Value Error for a) stress and b) strain using a homogeneous material description and various Number of Linearization Points. The dashed vertical line at 60 kN indicates where the 0.2 % offset yield stress is first exceeded.

This is confirmed by Table 2, where the maximum stress is now predicted at the incorrect location. It is also seen in Fig. 4 that a lower number of NLP corresponds to a lower degree of error in maximum values. Though an accurate homogenisation of the material was performed, a single material description is thus not sufficient to describe the behaviour of the component, and increasing the linearization accuracy of an inaccurate material curve thus only leads to an increased amount of error. The stress levels in the gauge elements are lower than the maximum stress levels, and the effect of NLP on AGE is thus still very low, see Fig. 5.

Table 2. The ability of the simulations to predict the correct location of maximum stress and strain at different loads.

No. of material definitions	Applied Load [kN]									
	15	30	45	60	75	90	105	120	135	150
12 000										
3 000										
1 000										
300										
30			X		0					
1 (Homogeneous)			X	X	0	0	0	0	0	0

X = incorrect location of maximum stress

0 = incorrect location of maximum strain

When the load further increases and plastic strains are obtained in the component, the error in maximum stress is rather constant, about 2 %, up to the ultimate stress, while the error in maximum strain increases up to about 16 %, see Fig. 4. The AGE, Fig. 5, increases significantly with the applied load, up to 11 % in stress and as much as 30 % in strain. This is also seen in Table 2, where the homogeneous material description at these load levels predicts the correct location of maximum stress, but is unable to predict the correct location of maximum strain when plasticisation occurs. This indicates that the stress-strain distribution throughout the component in the plastic region is very badly predicted by the homogenous material description. The local variations in mechanical behaviour thus significantly affect the predicted plastic behaviour of the component. In particular the stress-strain distribution and the maximum strain level are very badly predicted when homogeneous material behaviour is assumed.

Fig. 5. Average Gauge Error for a) stress and b) strain using a homogeneous material description and various Number of Linearization Points. The dashed vertical line at 60 kN indicates where the 0.2 % offset yield stress is first exceeded.

Simulation methods for cast components have previously focused on the effect of residual stresses [17] or defects, e.g. using a fracture criteria [18] or a damage evolution

model [19]. Homogeneous material behaviour with local values in amount and effect of defects have typically been used to simulate local variations in material performance [20, 21] and stochastic methods have been applied to consider the effect of defects on damage [22] or failure [23] of cast components. Previous investigations regarding the effect of local variations in mechanical behaviour on the mechanical behaviour of components, however, have not been found in the literature. Reusch and Estrin [24] used stochastic non-uniform material properties, and showed that non-uniform material properties affects both the local and the non-local mechanical response of a structure. This supports the current results, which show that if the local variations in mechanical behaviour throughout the component are neglected and homogeneous material behaviour is assumed, significant errors may be introduced in the values of maximum stress and strain and in the stress-strain distribution throughout the component. The inability of the homogeneous description to correctly predict the behaviour of stress and strain concentrations may lead to incorrect conclusions about the mechanical performance of the component, and in the design process this may lead to incorrect decisions regarding the design of the component. It is thus proposed that the local variations in mechanical behaviour are important to consider when studying the mechanical behaviour of ductile iron components.

3.2. Effect of material reduction

The results for the simulations with a reduced number of material definitions and 60 NLP are shown in Fig. 6 and Fig. 7, where Fig. 6 shows the error in MVE and Fig. 7 the errors in AGE. As previously mentioned fluctuations in the curves are noted, especially using a low number of material definitions, indicating that the stress-strain distribution due to the local variations in mechanical behaviour is not totally resolved.

Fig. 6. Max Value Error for a) stress and b) strain obtained using 60 Number of Linearization Points and different amount of material definitions. The dashed vertical line at 60 kN indicates where the 0.2 % offset yield stress is first exceeded.

Comparing Fig. 6 and Fig. 7 with Fig. 4 and Fig. 5, respectively, and observing the differences in the scale of the ordinates, it is seen that the incorporation of local variations in mechanical behaviour significantly reduces the level of error in both the

maximum stress-strain values and in stress-strain distribution, even when a very low number of material definitions are used. Using only 30 material definitions the MVE or AGE in stress or strain is at any load less than 2%, which is a significant reduction compared to using a homogeneous material description where errors up to 30% were obtained. This indicates that the effect of local variations in mechanical behaviour on the stress-strain distribution throughout the component can be effectively described using a low number of material definitions. A higher number of material definitions leads to an even lower degree of error, as e.g. by using 1 000 material definitions a maximum MVE or AGE of 0.2 % is obtained. It is also noted that the errors for a given number of material definitions are more constant with increasing applied load when local material definitions are used compared to using a homogeneous material description, which also indicates that the variations in mechanical behaviour throughout the component are well described. By using material reduction and about 1 000 material definitions negligible errors in simulation results compared to using individual material definitions are thus obtained. As shown in Table 2, using 300 material definitions or more the correct location of the maximum stress and strain is predicted for all loads.

Fig. 7. Average Gauge Error for a) stress and b) strain using 60 Number of Linearization Points and different amount of material definitions. The dashed vertical line at 60 kN indicates where the 0.2 % offset yield stress is first exceeded.

Fig. 8 shows the FEM simulation time versus the number of material definitions used in the simulation. Studying Fig. 8 it is seen that the simulation time is increased about 2.5 times when element individual material definitions are used compared to using a single homogeneous material definition. If material reduction is applied this factor is only 1.1-1.4. Material reduction can thus be used to incorporate the local mechanical behaviour while only slightly increasing the FEM simulation time.

Fig. 8. Effect of number of materials on the simulation time factor for simulations with 60 Number of Linearization Points. The error bars indicate the obtained standard deviation in repeated simulations. Note the broken scale on the abscissa.

3.3. Effect of number of linearization points

The effect of the Number of Linearization Points (NLP) on MVE and AGE using individual material definitions is shown in Fig. 9 and Fig. 10. It is seen that the simulation errors decrease as the NLP is increased.

Fig. 9. The effect of Number of Linearization Points on Max Value Error of a) stress and b) strain using element individual material definitions. The dashed vertical line at 60 kN indicates where the 0.2 % offset yield stress is first exceeded.

As reported in previous work an increasing NLP increases the accuracy of each material description, but the relative increase in accuracy is expected to be lower as the NLP increases [14]. Fig. 9 and Fig. 10 show that this is also valid for the simulation results in general. For a selected number of material definitions both MVE and AGE for both stress and strain show significant decreases as the NLP increases from 10 to 20 and a smaller decrease when NLP is increased from 20 to 40.

Fig. 10. Average Gauge Error of a) stress and b) strain using element individual material definitions. The dashed vertical line at 60 kN indicates where the 0.2 % offset yield stress is first exceeded.

This can also be seen when studying how the Simulation Gauge Error (SGE) varies with NLP for different number of material definitions, shown in Fig. 11. Fig. 11 also shows that an increasing NLP is only able to increase the accuracy of the simulation up to a limit where the number of material definitions determines the degree of error obtained. This is explained by the fact that the NLP defines the accuracy of each material definition, while the number of material definitions defines how well the variation in mechanical behaviour throughout the component is described. This also means that the number of material definitions may only increase the accuracy of the simulation up to the limit where the NLP limits the accuracy of each material definition.

Fig. 11. Simulation Gauge Error of a) stress and b) strain versus Number of Linearization Points for different number of material definitions.

Fig. 12 shows the variation in FEM simulation time for different NLP when element individual material definitions are used. It is seen that the simulation time decreases approximately linearly with decreasing NLP, and the simulation time factor decreases from about 2.5 to 2.0 as NLP decreases from 60 to 10. The gain in simulation time with reduced NLP however must be weighed against the previously described significant decrease in simulation accuracy. Comparing Fig. 12 and Fig. 8 it is seen that simulation time is reduced more by material reduction than by a reduced NLP, and as previously discussed the degree of error introduced by material reduction is also significantly lower. To reduce the FEM simulation time it is thus proposed to use material reduction rather than reducing the NLP below 40 NLP.

Fig. 12. The effect of Number of Linearization Points on the simulation time factor when element individual material definitions are used.

4. CONCLUSIONS

The incorporation of local mechanical behaviour is found to significantly affect the FEM simulation results, and some important results can be pointed out:

- A homogeneous material description fails to express the stress-strain distribution caused by the local variations in mechanical behaviour in the component.
- It is proposed that local variations in mechanical behaviour are important to consider when studying the mechanical behaviour of ductile iron components. An assumption of homogeneous material behaviour may cause incorrect results and incorrect conclusions regarding the mechanical behaviour of the component.
- FEM simulation time is significantly increased when individual material definitions are used.
- The material reduction method can be used to accurately describe the effects of the local mechanical behaviour on the mechanical behaviour of the component while only slightly increasing FEM simulation time.

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