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TECHNICAL REPORT

SKB

Evaluation of the effect of triaxial stress state on damage tolerance of nodular cast iron inserts

Report No.: 50017510-1

Revision No.: 1

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TECHNICAL REPORT

Report No.: 50017510-1 Revision No.: 1

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Approved by	**Organizational unit**
Keivan Ashhami	Inspecta Technology AB
Customer	**Customer reference**
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Summary

SKB had commissioned Inspecta Technology AB to review the assessment of the triaxial stress state in nodular cast iron material and its effect on damage tolerance of canister inserts.

The results in the reviewed reports [1-4] demonstrated that the ductile properties of the nodular cast iron under shear-dominated stress state can be compared with the ductility measured from the uniaxial tensile tests. The deviatoric stress state appears to have an insignificant influence on the effective plastic strains at failure.

The presented results also suggested that the nodular cast iron ductility is dependant only on the triaxiality T and independent on the deviatoric stress state. It appears to be no need to refine the performed analyses of the nodular cast iron inserts where the combination of the isostatic and shear loads is considered.

Report title	Subject Group
Evaluation of the effect of tri-axial stress state on damage tolerance of nodular cast iron inserts	
	Index terms
	Tri-axial stress, Canister inserts, Damage tolerance
Work carried out by	**Distribution**
Andrey Shipsha	☒ No distribution without permission from the customer or Inspecta Technology AB.
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1 INTRODUCTION

SKB has commissioned Inspecta Technology AB to review the assessment of the triaxial stress state in nodular cast iron material and its effect on damage tolerance of canister inserts. The assessment was performed at the Royal Institute of Technology (KTH), Department of Solid Mechanics.

The purpose of this report is to perform a review of the obtained results and make a judgement whether the damage tolerance analyses of nodular cast iron inserts should be updated.

2 BACKGROUND – DUCTILITY UNDER TRIAXIAL STRESS STATE

Under combined action of isostatic and shear loads a triaxial stress state may be developed in materials. The nodular cast iron ductility under the triaxial stress state and the effect on damage tolerance of the inserts has been disputed in the SSM review [5].

The mechanical properties of nodular cast iron material including the yield and ultimate strength, the elongation at failure and fracture toughness have previously been characterised through uniaxial tensile tests. The effective plastic strain at failure measured from these tests was used as the failure criterion in structural integrity assessments of the canister inserts. In general, this approach is reasonable and the calculated values of maximum effective plastic strain were found to satisfy this criterion. However, considering a scatter in the measured strains at failure (at least for older PWR-tests, where the strains at failure had larger scatter as compared to test performed more recently) it is feasible to investigate the ductility of nodular cast iron under triaxial stress state. This investigation was carried out at KTH [1-3].

It is well known that the ductility of metallic materials depends on the stress triaxiality which is defined as

$$T = \frac{\sigma_m}{\sigma_e} \tag{1}$$

where σ_e is the effective von Mises stress (Eq. 2) and σ_m is the mean stress (Eq. 3)

$$\sigma_e = \sqrt{\frac{1}{2}\left((\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_{III} - \sigma_I)^2\right)} \tag{2}$$

$$\sigma_m = (\sigma_I + \sigma_{II} + \sigma_{III})/3 \tag{3}$$

and $\sigma_I \geq \sigma_{II} \geq \sigma_{III}$ are principal stresses.

For material models based on the stress triaxiality *T*, Eq. (1), the ductility (effective plastic strain at failure) is inversely related to the value of *T* (the ductility increases with decreasing *T*).

Recent studies, which are referenced in [1], have shown that a so called Lode parameter provides a strong influence on material ductility at low values of triaxiality *T*. The Lode parameter characterising the deviatoric stress state is defined as

$$L = \frac{2\sigma_{II} - (\sigma_I + \sigma_{III})}{\sigma_I - \sigma_{III}} \tag{4}$$

The Lode parameter L is in the range of $-1 \leq L \leq 1$.

The difference between axisymmetric and shear-dominated stress states can be distinguished by means of the Lode parameter. The importance of making such difference is highlighted in [1] taking a classical experiment of McClintock as example. McClintock has demonstrated that the values of effective plastic strain at failure were lower in the torsional shear test in comparison to the uniaxial tensile test of standard cylindrical specimens. The triaxiality T=0 for the torsional shear while $T \geq 1/3$ for the uniaxial tensile test. The Lode parameter is different between these two cases; for torsional shear $L = 0$ (shear) and for the axisymmetric tension $L = -1$.

A typical relationship between the ductility (the effective plastic strain at failure) and the triaxiality T for ductile materials (in [1], this was exemplified by using information from moderate-strength steels up to high-strength steels) is schematically presented in Figure 1 (also reproduced from Ref. [1]). The plot contains the schematic curves for three different values of Lode parameter L (-1, 0 and 1) and provides the relevant tests to characterise the ductility at different degree of triaxiality T and at the different values of L. It is important to highlight that a typical ductile material exhibits the lowest ductility under a stress state with $L = 0$.

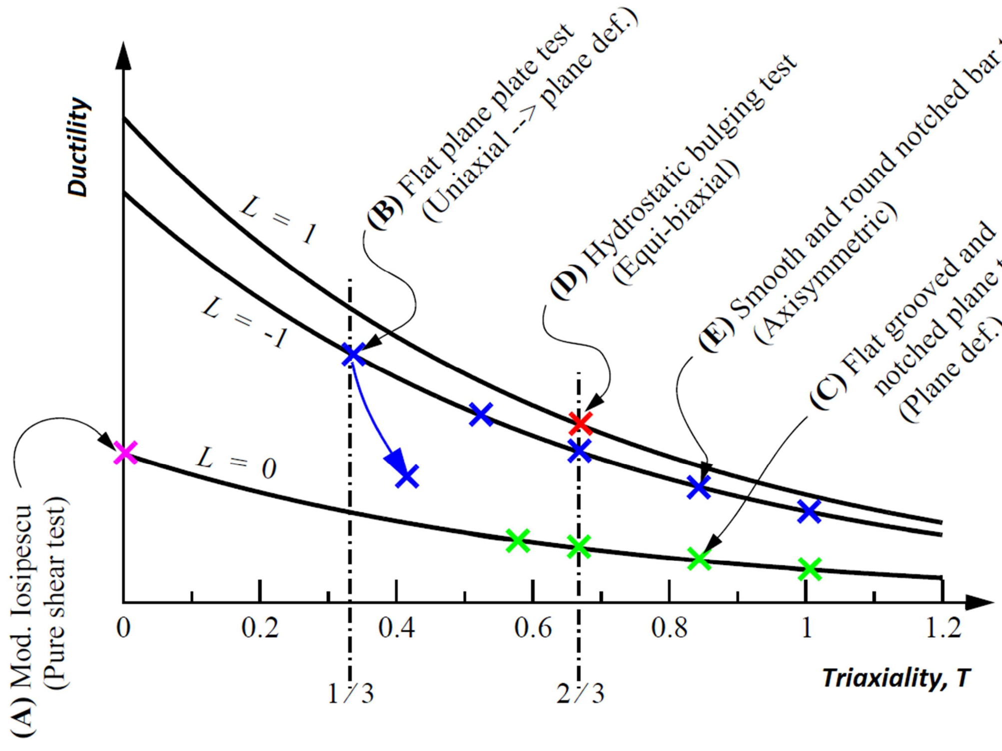

Figure 1: A schematic plot for material ductility as a function of the triaxiality T and the Lode parameter L (reproduced from [1]).

3 EXPERIMENTAL STUDY

In order to ensure that the nodular cast iron material in canister inserts has sufficiently high ductility a limited testing program was carried out at KTH [3]. Considering the information provided in Figure 1 two experiments were chosen to reconstruct the lowest ductility curve with $L = 0$. The first experiment was the pure shear test ($T = 0$) as shown in Figure 2. The second experiment was the planar tensile test under plane strain condition ($T = 1/\sqrt{3} \approx 0.577$) as shown in Figure 3.

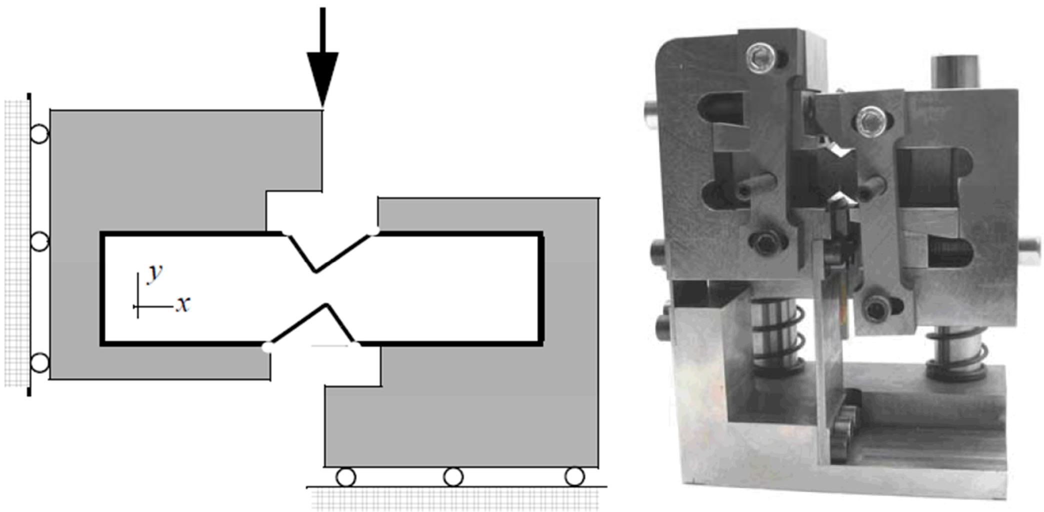

Figure 2: The pure shear test (a modified Iosipescu test).

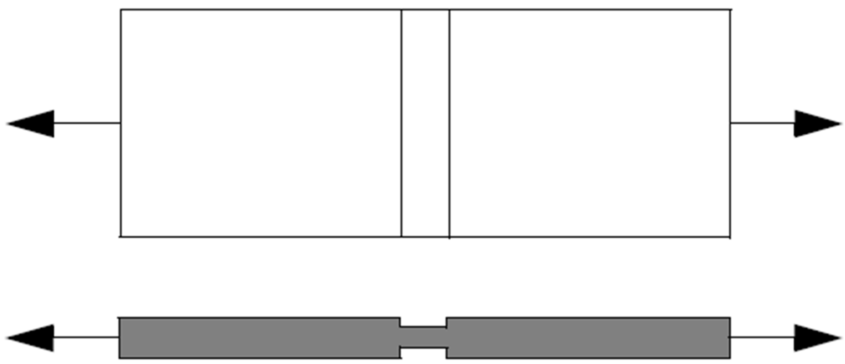

Figure 3: The planar tensile test (plane strain).

The pure shear tests were performed on 9 specimens and the planar tension tests on 13 specimens (all the test specimens were taken from the BWR-insert I53). The deviatoric stress state for both experiments is characterised as the generalised shear so that the Lode parameter $L = 0$. The mean values of the effective plastic strain at failure along with the standard deviation (STD) are presented in Table 1.

Table 1. Measured values of the effective plastic strain at failure [3].

Test	Test parameters	Effective plastic strain at failure ε_f	
		Mean	STD
Pure shear	$T = 0, \quad L = 0$	0.522	0.026
Planar tension	$T = 0.577, \quad L = 0$	0.124	0.012

It is of importance to compare the ductility of nodular cast iron measured under the generalised shear stress state with the values of effective plastic strain at failure obtained from the uniaxial tensile tests of cylindrical specimens [4]. The effective plastic strains at failure were determined based on the measured relative area reduction Z using the following relation

$$\bar{\varepsilon} = -\ln(1 - Z) \tag{5}$$

The evaluated values of the mean effective plastic strain at failure along with the minimum and maximum values are presented in Table 2. The values were determined from the tests for different sections along the BWR-insert (top, middle and bottom sections). It has been pointed out before that the degree of triaxiality for the axisymmetric tensile specimens is $T = 1/3$ and the Lode parameter $L = -1$.

Table 2. The effective plastic strain at failure from the uniaxial tensile tests.

Specimen position	Test parameters	Effective plastic strain at failure ε_f		
		Mean	Min	Max
Top	$T = 1/3, \quad L = -1$	0.145	0.102	0.171
Middle	$T = 1/3, \quad L = -1$	0.172	0.140	0.212
Bottom	$T = 1/3, \quad L = -1$	0.202	0.161	0.237

4 DISCUSSION OF RESULTS

The effective plastic strains at failure from Table 1 and 2 were plotted as a function of the triaxiality T as presented in Figure 4. The dashed line is the exponential function curve fit of two data points from the generalised shear tests. The selection of the curve fit function refers to the study cited in [2] which dealt with the modelling of ductile failure based on microvoid coalescence.

It can be observed from Figure 4 that the effective plastic strains at failure from the uniaxial tensile tests are below the curve. Even though this result is based on limited number of tests, it suggests that the effect of the deviatoric stress state (governed by the Lode parameter) is not so pronounced for the nodular cast iron in comparison with ductile steels (see Figure 1). It has been discussed above that for a typical ductile material the testing under generalised shear ($L = 0$) normally results in the lowest values of the effective plastic strain at failure. The trend observed in Figure 4, for the nodular cast iron, demonstrates the lower values of failure strains from uniaxial tensile tests with $L = -1$.

Besides the effect of statistical variation, a possible explanation for the observed trend could be that the failure mechanism in nodular cast iron cannot be fully described by initiation and growth of microvoids. Instead the other mechanisms, more brittle in character, could govern the ductile failure.

To summarise, the failure strain curve based on the limited number of tests under shear-dominated stress state ($L = 0$) appears to lie slightly above the failure strain values from the uniaxial tensile tests ($L = -1$) of nodular cast iron. The deviatoric stress state appears to have a minor influence on the effective plastic strains at failure.

The presented results also suggest that the nodular cast iron ductility is dependant only on the triaxiality T and independent on the deviatoric stress state. Therefore, the simple model as presented in Figure 4 could be sufficient to predict the initiation of ductile failure in finite element analyses. The effect of triaxiality is of minor importance for most of the load cases experienced by the nodular cast iron inserts. For the design shear load analysis (ref. [3] in the review [1]) the stress state was approximately characterised by $T = 0.36$ and $L = -0.88$ which corresponds to the stress state for axisymmetric uniaxial tension ($T = 0.33$ and $L = -1$).

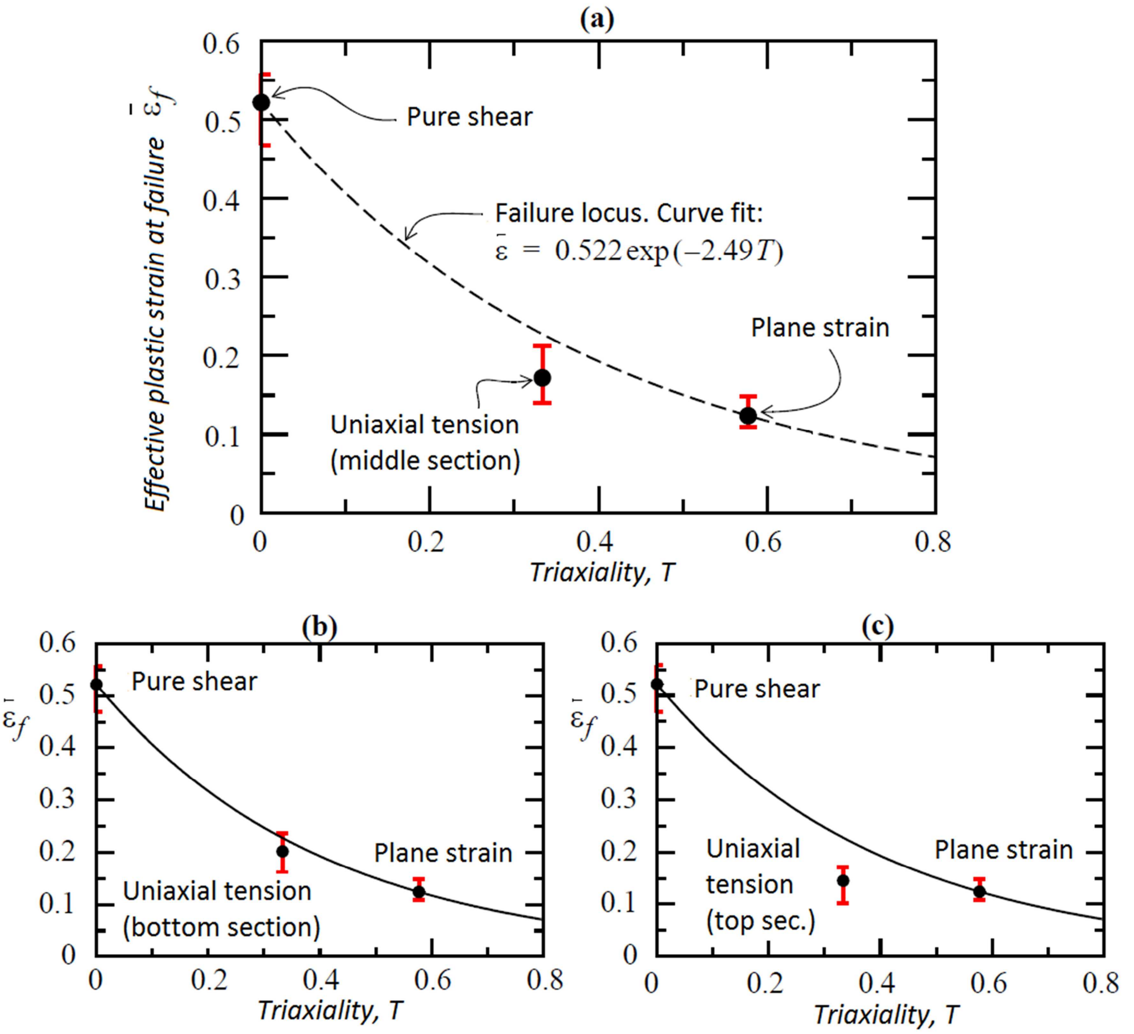

Figure 4: The effective plastic strains at failure as a function of the triaxiality.

The presented results suggest that there is no need to refine the performed analyses of the nodular cast iron inserts where the combination of the isostatic and shear loads is considered. Also, when each load case is evaluated individually there is no need to refine the performed damage tolerance analyses.

5 CONCLUSIONS

SKB had commissioned Inspecta Technology AB to review the assessment of the triaxial stress state in nodular cast iron material and its effect on damage tolerance of canister inserts.

The results in the reviewed reports [1-4] demonstrated that the ductile properties of the nodular cast iron under shear-dominated stress state can be compared with the ductility measured from the uniaxial tensile tests. The deviatoric stress state appears to have an insignificant influence on the effective plastic strains at failure. The effect of triaxiality is of minor importance for most of the load cases experienced by the nodular cast iron inserts. For the design shear load analysis (ref. [3] in the review [1]) the stress state was approximately characterised by $T = 0.36$ and $L = -0.88$ which corresponds to the stress state for axisymmetric uniaxial tension ($T = 0.33$ and $L = -1$).

The presented results also suggested that the nodular cast iron ductility is dependant only on the triaxiality T and independent on the deviatoric stress state. It appears to be no need to refine the performed analyses of the nodular cast iron inserts where the combination of the isostatic and shear loads is considered.

6 REFERENCES

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7 TABLE OF REVISIONS

Rev.	Activity / Purpose of this revision	Handled by	Date
0	—	Andrey Shipsha	2013-12-05
1	The report is revised according to the review comments (SKBDoc 1418776)	Andrey Shipsha	2014-01-30