Damage evolution during cyclic plastic deformation of pipeline steel

C.H.L.J. ten Horn[1], A. Bakker[1] and J. Zuidema[1]

[1] Materials Science, Delft University of Technology, Rotterdamseweg 137, 2628 AL Delft, The Netherlands

ABSTRACT*: In the oil and gas industry, one way of laying pipes on the seafloor is by the reeling process. In this process the pipe is subjected to a cyclic plastic deformation. Due to this plastic deformation the mechanical properties of the material are changed. In this study the finite element method is used to predict the influence of the cyclic plastic deformations on the mechanical behaviour of the material. The fraction model is used to describe the cyclic stress-strain behaviour. In order to be able to predict fracture of the material the Gurson-Tvergaard-Needleman damage model is used in conjunction with the fraction model. By comparing unit cell calculations with the damage model, the parameters* q_1 *and* q_2 *were determined for both the monotonic and cyclic loading conditions.*

INTRODUCTION

For the investigation into the cyclic plastic deformation of steel, the reeling of steel pipelines was chosen as a test case. In the oil and gas industry the reeling and unreeling of pipelines is one of the ways to install pipelines on the seafloor. The reeling process involves four distinct stages: reeling, unreeling, alignment and straightening. These four stages and the corresponding deformations are shown schematically in Figure 1.

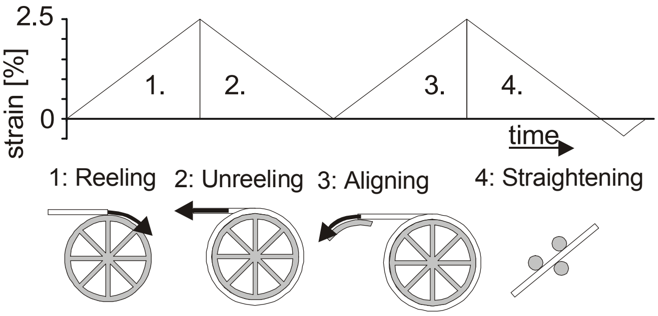

Figure 1: The reeling process and the corresponding deformations.

To investigate the influence of cyclic plastic deformation on the stress – strain curve and the fracture behaviour of the material, tests performed on laboratory specimens were compared with finite element simulations. For the simulations the Gurson-Tvergaard-Needleman damage model [1] was combined with a model for cyclic plasticity in order to be able to predict the damage evolution under cyclic loading.
The material for the experiments was taken from a Grade X80 steel pipe with 0.13% C.

GTN DAMAGE MODEL

One way for metals to fail is by formation, growth and coalescence of voids. The Gurson-Tvergaard-Needleman (GTN) damage model [1] is a way to implement the void nucleation, growth and coalescence in a finite element model. The amount of damage is given by the volume fraction of the voids in the matrix material, *f*. For the increase in the void volume fraction, two contributions were identified [1]:

- growth of existing voids (Eq. 1),
- nucleation of new voids (Eq. 2).

$$\dot{f}_{growth} = (1-f)\,\dot{\varepsilon}_{kk}^{p} \tag{1}$$

$$\dot{f}_{nucleation} = \frac{f_N}{S\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\varepsilon_m^p-\varepsilon_n}{S}\right)^2} \dot{\varepsilon}_m^p \tag{2}$$

where $\dot{\varepsilon}_{kk}^{p}$ is the inelastic volumetric strain rate, f_N is the volume fraction of void nucleating particles, ε_m^p is the equivalent plastic strain of the matrix material, ε_n is the average strain needed for nucleation and S is the standard deviation of the strain needed for nucleation.
When these equations are used for cyclic loading, they are subjected to both tensile and compressive loading directions. Under compressive loading, $\dot{\varepsilon}_{kk}^{p}$ will be negative and therefore the growth rate of the void volume fraction will also be negative. This means that the void volume fraction will decrease and the voids will (partially) close due to the compressive loading.
For the nucleation of new voids the situation is different. The $\dot{\varepsilon}_m^p$ will always be non-negative and therefore the voids will nucleate during both tensile and compressive loading according to Eq. 2. It is, however, not very

likely for new voids to nucleate while existing voids are closing. Therefore a modified void nucleation rate is proposed to allow nucleation only during tensile loading:

$$\dot{f}_{nucleation} = \frac{f_N}{S\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\varepsilon_m^{pn}-\varepsilon_n}{S}\right)^2} \dot{\varepsilon}_m^{pn} \tag{3}$$

$$\begin{aligned} \dot{\varepsilon}_m^{pn} &= \dot{\varepsilon}_m^{p} && for\ \dot{\varepsilon}_{kk}^{p} \geq 0 \\ \dot{\varepsilon}_m^{pn} &= 0 && for\ \dot{\varepsilon}_{kk}^{p} < 0 \end{aligned} \tag{4}$$

The yield function, F, as described by Gurson and modified by Tvergaard and Needleman, can be seen in Eq. 5.

$$F = \frac{\sigma_e^{\ 2}}{\sigma_M^{\ 2}} + 2q_1 f^* \cosh\left(\frac{q_2\sigma_{kk}}{2\sigma_M}\right) - 1 - \left(q_1 f^*\right)^2 = 0 \tag{5}$$

where σ_e is the macroscopic equivalent stress, σ_M is the yield strength of the matrix material, σ_{kk} is the volumetric stress and q_1 and q_2 are parameters introduced by Tvergaard [2].
In order to take void coalescence into account, Tvergaard and Needleman [1] introduced a modified void volume fraction, f^*, that is given in Eq. 6.

$$\begin{aligned} f^* &= f && for\ f \leq f_c \\ f^* &= f_c + \left(\frac{1/q_1 - f_c}{f_F - f_c}\right)(f - f_c) && for\ f > f_c \end{aligned} \tag{6}$$

where f_c is the void volume fraction when voids start to influence each other, f_F is the void volume fraction at coalescence of the voids.

FRACTION MODEL

In order to predict the fracture behaviour of the material after several cycles of plasticity, the GTN damage model needs to be applied to a cyclic plasticity model. As has been shown previously [3], the isotropic and kinematic hardening models do not predict the cyclic stress – strain curve very well. In order to obtain a better description the fraction model is used.

In the fraction model the material is thought to consist of different fractions. Each of the fractions with its own weight and mechanical properties. By parallel loading of the fractions, the resulting material behaviour will be a weighted average of the behaviour of the fractions. A schematic view of the fractions within one element of the finite element calculations can be seen in figure 2.

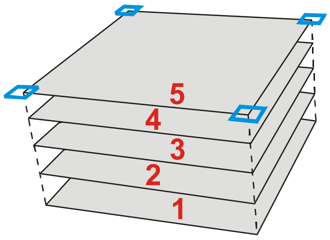

Figure 2: Schematic representation of the fractions within one element.

The parameters for the fraction model are determined using experimental true stress – strain curves and low cycle fatigue stress – strain curves. In this study 5 fractions are used to describe both the monotonic and cyclic behaviour of the material. The first 4 fractions exhibiting linear workhardening, while the 5^{th} fraction used power law workhardening to obtain a good fit with the experimental true stress – strain curve for strains up to fracture.
As the fraction model is used to describe the macroscopic stress – strain curve of the material, the GTN damage model will be applied to the results of the fraction model. This combined GTN damage and fraction model is implemented into the finite element package MSC.Marc [4] through a user subroutine.

THE FINITE ELEMENT CALCULATIONS

In order to calibrate the parameters of the GTN damage model, unit cell calculations were performed. In unit cell calculations, the material is considered to consist of a periodic arrangement of hexagonal representative volumes, called unit cells, each containing one void. For simplicity the hexagonal prisms are approximated by cylinders, see Figure 3. As the cylinders are axisymmetric, only a 2D plane needs to be modelled.
By calculating the mechanical behaviour of a unit cell containing a void, the macroscopic mechanical behaviour is determined and this is used to calibrate the parameters of the GTN damage model. Different levels of

constraint were imposed on the unit cell by changing the parameter ρ, which is the ratio of the applied radial stress, σ_{rr}, to the applied the axial stress, σ_{zz}. The results from the unit cell calculations were compared to one-element calculations using the combined GTN damage and fraction model. From this comparison the parameters q_1 and q_2 for the GTN damage model were obtained.

In order to investigate the influence of cyclic loading on a material containing voids, the unit cell was also subjected to cyclic deformations.

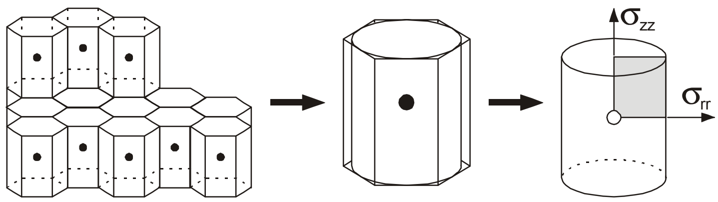

Figure 3: Micromechanical modelling of a material containing voids.

RESULTS

Unit cell calculations

The evolution of the void volume fraction for monotonic loading of the unit cell can be seen in figure 4. The point where localisation of the deformation takes place is also indicated in this figure.

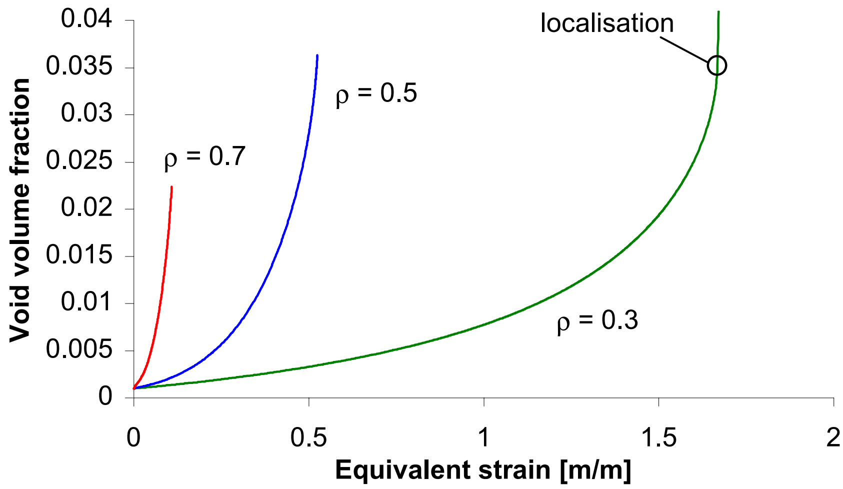

Figure 4: Void volume fraction for monotonic loading.

The evolution of the void volume fraction for cyclic loading of the unit cell can be seen in figure 5. A decrease in void volume fraction can clearly be seen for the compressive loading stages. On the other hand there is a gradual increase in the void volume fraction with an increasing number of cycles for all tested triaxialities.

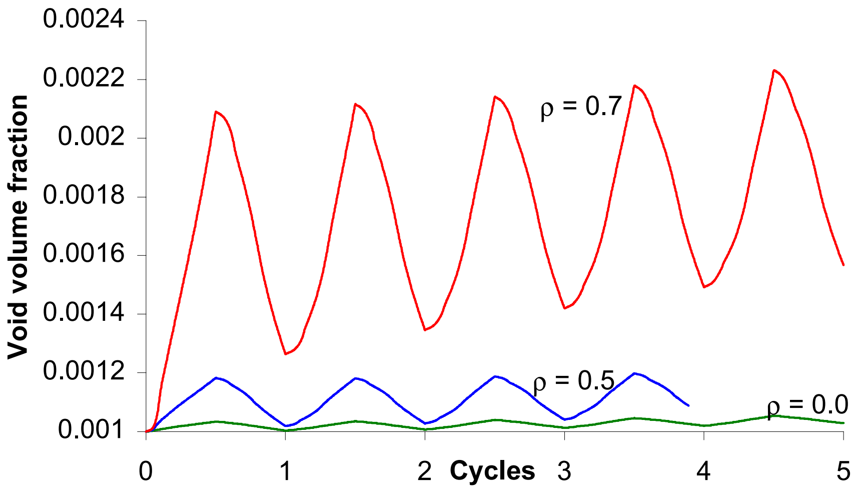

Figure 5: Evolution of the void volume fraction during cyclic loading for different triaxialities.

Combined GTN damage and fraction model

In figure 6 the results of the combined GTN damage and fraction model are compared with the unit cell calculations for monotonic loading. For these calculations two sets of q values were used: $q_1 = 1.5$, $q_2 = 1.0$ and $q_1 = 1.0$, $q_2 = 1.0$. It is clear from this figure that the q values should chosen between these two values.

The results shown in figure 7 are obtained for the cyclic loading of the combined GTN damage and fraction model. In order to get a good fit for the first cycle for the different triaxialities, the parameters q_1 and q_2 had to be set to 3.2 and 0.78 respectively.

The q values that seem to work well for large equivalent strains, as seen in the monotonic case, are not applicable to describe the void volume fraction well for small strains, as seen in the cyclic case.

The gradual increase in void volume fraction seen for cyclic loading of the unit cell is not observed in the results of the combined GTN damage and fraction model. An explanation for this may be the large strains that occur in the unit cell close to the void. These high strains may cause cyclic hardening that is not seen for small strains. As a consequence the voids will not close as easily as they were opened.

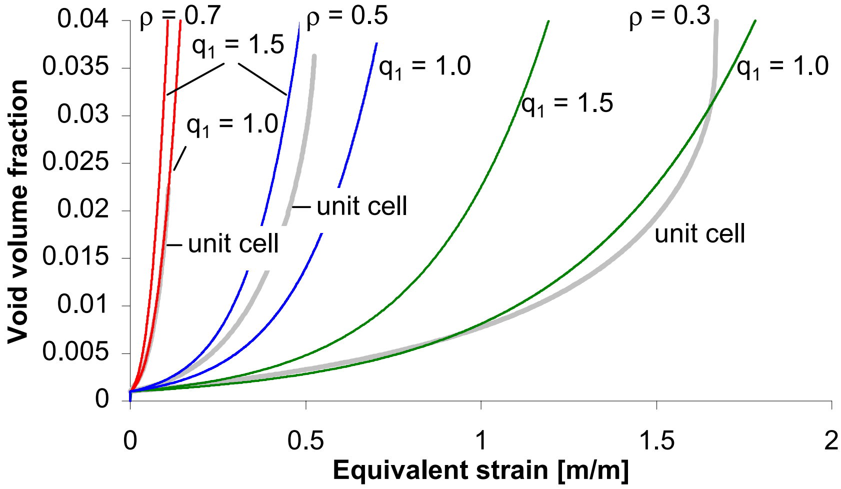

Figure 6: Comparison of the GTN damage and fraction model with the unit cell for monotonic loading.

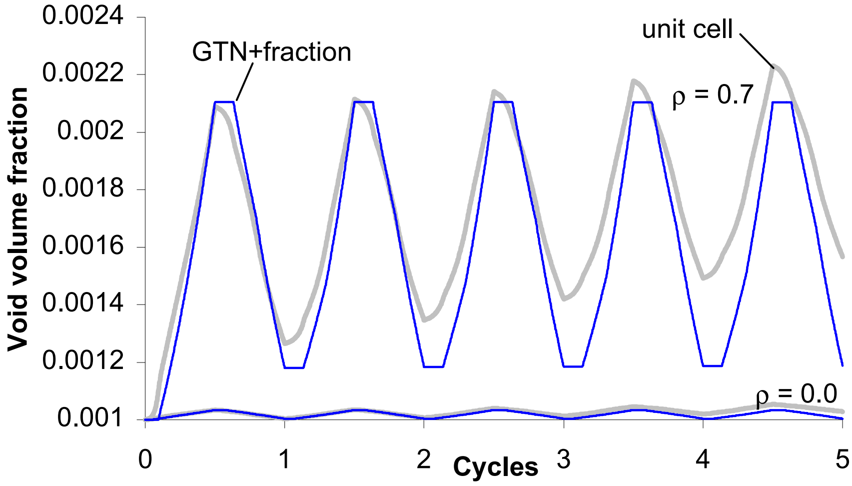

Figure 7: Comparison of the combined GTN damage and fraction model with the unit cell calculations for cyclic loading.

CONCLUSIONS

In order to be able to use the GTN damage model for cyclic plasticity, a cyclic plasticity model needs to be used with the GTN damage model. Also the nucleation law needs to be changed in order to prevent nucleation of voids under compressive loading.

In order to describe the results of the unit cell calculations with the combined GTN damage and fraction model, two sets of values for q_1 and q_2 are needed. The set needed to describe the cyclic behaviour at small strains was found to be $q_1 = 3.2$, $q_2 = 0.78$ while the set that can describe the larger strains of the monotonic loading was found to be between $q_1 = 1.0$, $q_2 = 1.0$ and $q_1 = 1.5$, $q_2 = 1.0$.

From the unit cell calculations performed with cyclic loading, a gradual increase in the void volume fraction with the number of cycles was observed. This was not present in the results of the combined GTN damage and fraction model.

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