ORAL/POSTER REFERENCE: ICF100398OR

CYCLIC PLASTIC DEFORMATION OF PIPELINE STEEL

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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 cyclic plastic deformations are applied to laboratory specimens and alongside these experiments finite element calculations are performed to see if the material behaviour can be predicted. The specimens were subjected to 1% and 2.5% strain amplitude during several cycles. The experiments show that the material exhibits a lowering of the yield strength and an apparent slow transition from elastic to fully plastic behaviour after the first half cycle. To describe this in the finite element calculations three hardening models were tested: isotropic hardening, kinematic hardening and the fraction model. In the fraction model several material fractions are loaded in parallel, which allows for more complex material responses. From the calculations it followed that the isotropic and kinematic hardening models can not describe the cyclic plastic deformation of pipeline steel. Both failed to predict the lowering of the yield strength and the slow transition from elastic to fully plastic behaviour. The fraction model on the other hand can describe both phenomena.

KEYWORDS

Cyclic deformation, fraction model, pipeline steel, finite element method, reverse plasticity, low cycle fatigue

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: the reeling, the unreeling, the alignment and the straightening. In the reeling stage an initially straight pipeline is reeled onto a large drum. Once the ship is in position at sea, the pipe is pulled from the drum and it will straighten more or less. In the next stage the pipe is aligned to the correct angle for laying the pipe and it is also bend again but now to a constant radius of curvature. This is done to aid the final stage: the straightening of the pipe. These four stages and the corresponding deformations that occur are shown schematically in figure 1.

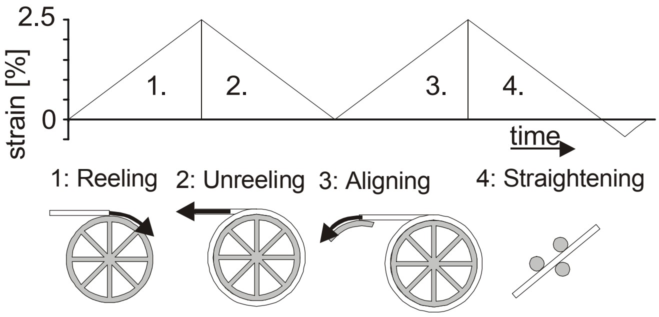


Figure 1: The reeling process and the corresponding deformations that occur

To investigate the influence of cyclic plastic deformation on the material, tests were performed on laboratory specimens. The bending of the pipe now being substituted for axial loading of the small specimens.
In order to predict the behaviour of the material, the cyclic plastic deformation was modelled using the finite element method. In order to achieve a good description several workhardening models were tested.
The material for the experiments was taken from a steel pipe with a diameter of 200 mm and a wall thickness of 21 mm. As the circumferential direction of the pipe is the most critical for failure during operation, the specimens were taken in the circumferential direction from the pipe.

EXPERIMENTS

For the experimental work two types of specimen were used: the tensile specimen geometry and the low cycle fatigue specimens.
The tensile tests were performed according to the ASTM E-8M standard. The specimen geometry can be seen in figure 2.

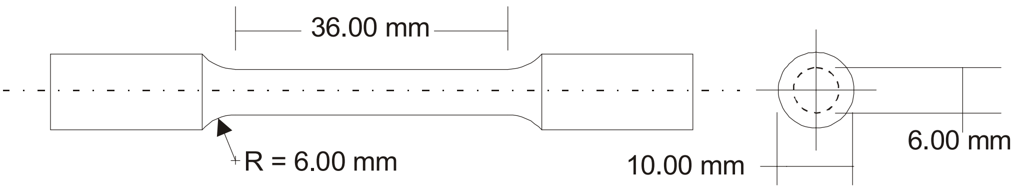


Figure 2: The tensile specimen geometry

In order to obtain the true stress – true strain curve for the material, the deformation of the specimen was monitored using a video camera attached to a computer. From the pictures the diameter of the specimen could be measured right up to fracture.
The low cycle fatigue tests were performed according to the ASTM E-606 standard for strain-controlled fatigue testing. The test section of the specimen was kept as short as possible to avoid buckling. The specimen geometry and its dimensions can be seen in figure 3. To measure the strain accurately strain gauges were glued to the test section of the specimens. The specimens were loaded with a ramp-wave of 0.005 Hz and a strain amplitude of 1% and 2.5%.

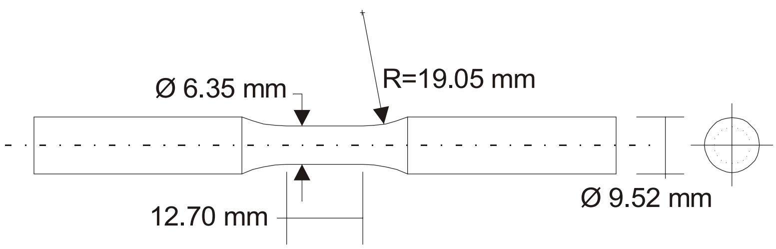


Figure 3: The low cycle fatigue specimen geometry

FINITE ELEMENT CALCULATIONS

For the finite element calculations the general finite element package MARC was used. The specimens geometry's as used for the experiments were modelled using axisymmetric elements.

Hardening models

In the finite element method two hardening models are regularly used: isotropic and kinematic hardening [1]. In this paper also a third model is used: the fraction model [2]. In the fraction model the material is thought to consist of different components or fractions with their own weight and mechanical properties. As a consequence the yielding behaviour of the material is the result of the yielding behaviour of all the fractions combined and their interaction with each other. For simplicity the fractions are to be loaded in parallel.

As Besseling et al. [2] have shown, kinematic hardening can also be modelled as a two fraction model. By enlarging the number of fractions more complex hardening behaviour can be obtained.

The fractions in this model may not be identified with certain microstructural components. This is because the parameters for the model cannot be identified uniquely and because in the model all fractions are loaded in parallel while in the real material the microstructural components are subjected to a combination of parallel and serial loading.

The mechanical behaviour of the fractions itself is kept simple. The fractions have a von Mises yield surface with isotropic hardening. For added simplicity and ease of parameter identification the fractions are assumed to exhibit linear workhardening.

In this study 4 fractions shall be used. The fraction model was implemented in the von Mises yield criterion allowing the calculation of the stresses in all fractions and combining them. A schematic graphical representation can be seen in figure 4.

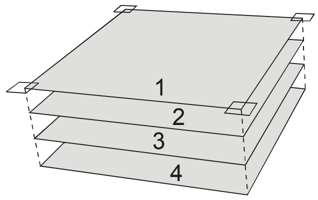


Figure 4: A schematic representation of how the fractions are implemented

Yield Elongation

One of the characteristics of steel is the yield elongation. As the workhardening rate during yield elongation is approximately zero, this means that the workhardening of the fraction responsible for the yield elongation has to account for the elastic responses of the other fractions. This in turn means that the rate has to be negative. At the end of the yield elongation the workhardening rate increases and this means that the rate of the fraction responsible for yield elongation has to increase. The implementation to achieve this is shown in figure 5, where σ_{y1} is the initial yield point, σ_{y2} is the lower yield point and E_{t2} is the secondary workhardening rate. For this study the yield elongation was modelled using two fractions exhibiting this behaviour.

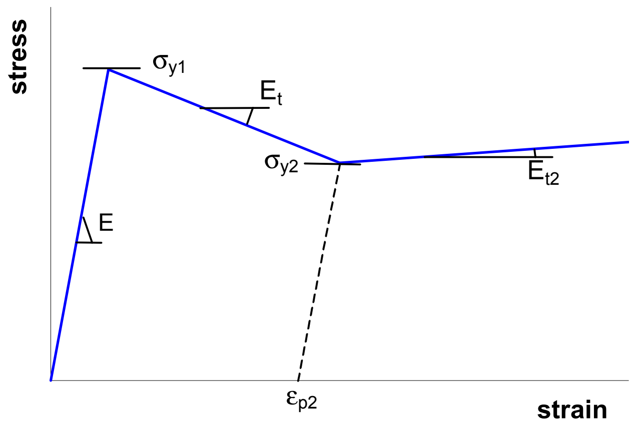


Figure 5: Yield behaviour of the fraction responsible for yield elongation

Parameter Identification
For a 1-dimensional model the parameters of the fraction model can be obtained directly from the tensile test results. The tensile results are approximated by a piece-wise linear representation. The start of the linear pieces coincides with the start of yielding of a fraction.
For 2-D and 3-D models the identification of the parameters involves an iterative approach. This is needed because of the interaction between the different fractions during yielding. The approach taken started with the 1-D parameters and modifying them until the response coincided with the piece-wise linear representation of the experimental tensile results.

RESULTS

The results of the tensile tests on the pipeline steel can be seen in figure 6 clearly showing the yield elongation.

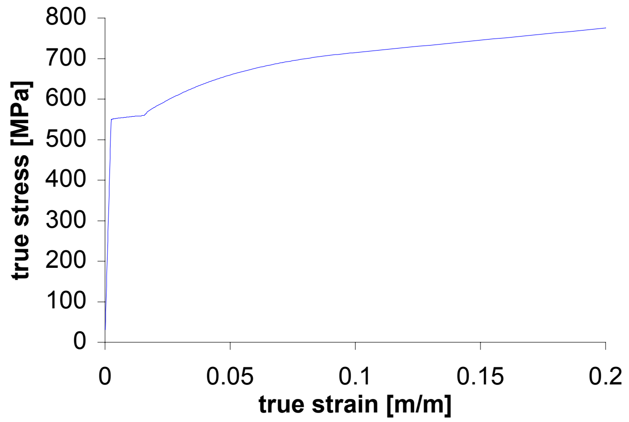
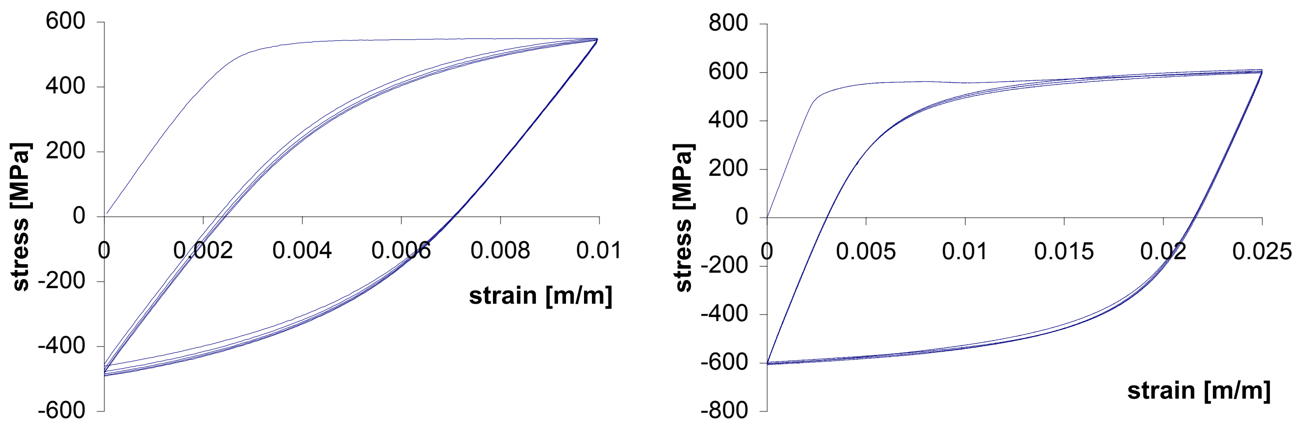


Figure 6: The tensile test results up to 20% strain

The results for the low cycle fatigue tests are shown in figure 7. Figure 7a shows the first 4 cycles at 1% strain amplitude while figure 7b shows the first 4 cycles at 2.5% strain amplitude. These figures clearly show a reduction in yield strength in both compression and tension direction after the first half cycle and that virtually no cyclic strain hardening occurs. Also the slow transition from elastic to fully plastic behaviour after the first half cycle is apparent.

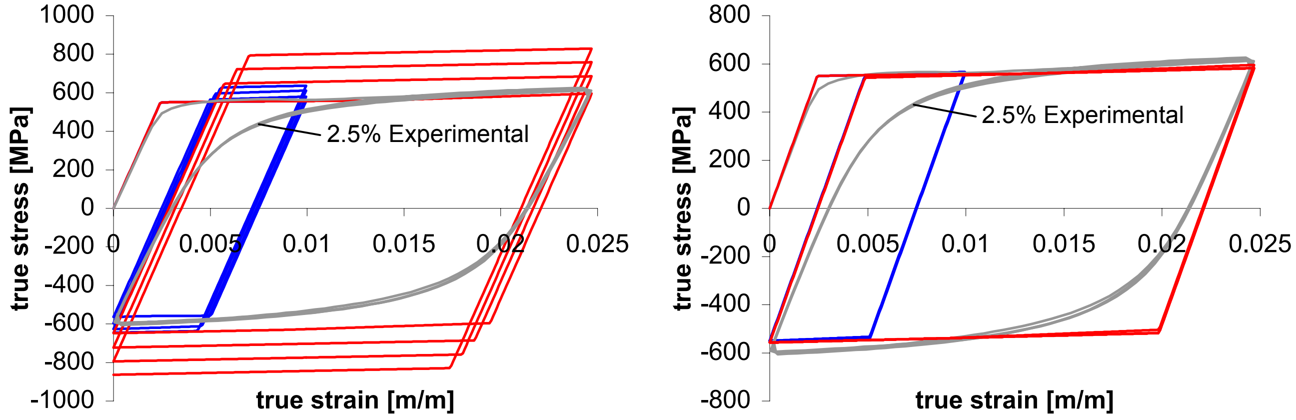


a. b.
Figure 7: The low cycle fatigue results for 1% and 2.5% strain amplitude

FINITE ELEMENT CALCULATIONS

As a first step the results from the isotropic and kinematic hardening are shown in figure 8. It is clear that the isotropic hardening model (fig. 8a.) is not appropriate for these cyclic plastic deformation tests at 1% or

2.5% strain amplitude. The strain hardening that occurs in the model is too high compared with the experiments. Isotropic hardening also neither shows the drop in yield strength nor the slow transition from elastic to fully plastic. The kinematic hardening model (fig. 8b.) also fails on these characteristics but the strain hardening is more realistic.



a. b.

Figure 8: The results from the isotropic (a.) and kinematic (b.) hardening model for 1% and 2.5% strain amplitude

The Fraction Model

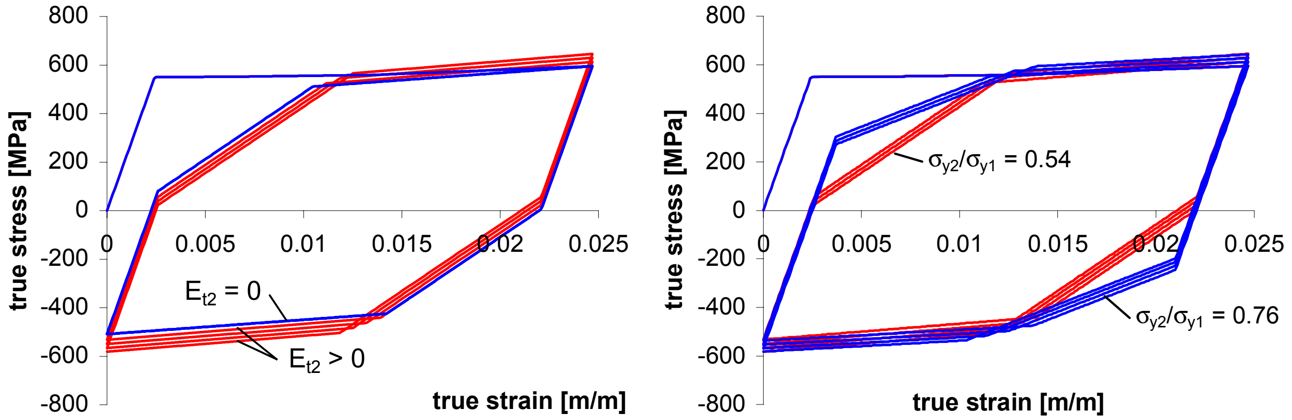
As there are many parameters to be identified for the fraction model, the influence of each parameter was investigated. The different parameter sets that are used, are shown in table 1.

TABLE 1: THE FRACTION MODEL PARAMETER SETS

	Fraction	Weight	E [GPa]	σ_{y1} [MPa]	E_t [GPa]	ε_{p2} (%)	E_{t2} [GPa]	σ_{y2}/σ_{y1}
Set 1	1	0.5	398	965	-56	0.407	0	0.76
	2	0.3	82	536	-8.5	0.832	2.2	0.87
	3	0.1	20	305	20			
	4	0.1	13.4	533	3			
Set 2	1	0.5	356	863	-88	0.455	0	0.54
	2	0.3	146	955	-15	0.831	2.2	0.87
	3	0.1	38	580	14			
	4	0.1	13.4	533	3			
Set 3	1	0.5	356	863	-88	0.455	0	0.54
	2	0.3	146	955	-15	0.831	0	0.87
	3	0.1	38	580	28			
	4	0.1	13.4	533	3			
Set 4	1	0.8	222.5	539	-55	0.455	0	0.54
	2	0.1	438	2861	-45	0.831	0	0.87
	3	0.05	76	1160	60			
	4	0.05	26.7	1066	4			

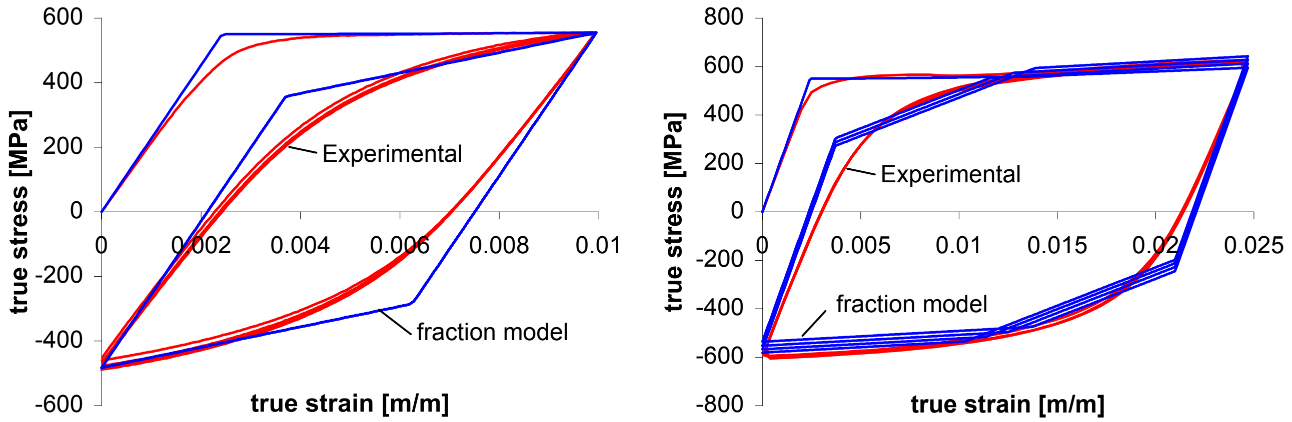
Parameter sets 2 and 3 are shown in figure 9a. indicating that the secondary workhardening rate (E_{t2}) of the fractions responsible for the yield elongation determines the amount of hardening that occurs during the cyclic loading. Whereas the ratio between the lower yield point (σ_{y2}) and the initial yield point (σ_{y1}) determines the yield strength after the first half cycle, this is shown in figure 9b using parameter sets 1 and 2. The ratio of σ_{y2}/σ_{y1} of the second fraction responsible for yield elongation determines the strain at which a kink occurs in the yield curve. The results from parameter sets 3 and 4 are identical, indicating that as long as the parameters fit the tensile test, the σ_{y2}/σ_{y1} ratios are identical and the secondary workhardening slopes are 0, then the weight of the individual fractions does not play any role. The influence of the weight of the fractions is only visible through its influence on the secondary workhardening rates.
The results of parameter set 1 is compared with the experimental low cycle fatigue behaviour in figure 10. From this figure it is clear that the fraction model can describe the drop in yield strength and the slow

transition from elastic to fully plastic behaviour much better than either isotropic or kinematic hardening can.



a. b.

Figure 9: The influence of E_{t2} and σ_{y2}/σ_{y1} on the yield behaviour



a. b.

Figure 10: The results from the fraction model for 1% (a.) and 2.5% (b.) strain amplitude.

CONCLUSIONS

From the experimental results it is clear that upon cyclic plastic deformation of pipeline steel the yield strength is reduced and that it shows an apparently slow transition from elastic to fully plastic behaviour while virtually no cyclic strain hardening is observed.
From the finite element calculations it is concluded that the isotropic and kinematic hardening models are not appropriate for cyclic plastic deformation of pipeline steel. Both models fail to describe the drop in yield strength and slow transition from elastic to fully plastic behaviour. The fraction model on the other hand does describe the yielding behaviour of the material better. As it shows both characteristics seen in the experiments. By extending the number of fractions that are used, the material can be modelled more accurately.
The parameters used in the fraction can not be uniquely identified. When the parameters are fitted to the tensile test results, the σ_{y2}/σ_{y1} ratio of the first fraction responsible for yield elongation describes the yield strength after the first half cycle while the weight of the fractions plays only a minor role.

REFERENCES

1. MSC.Marc2000 Manuals, (2000) MSC.Software Corp.
2. J.F. Besseling and E. van der Giessen, "Mathematical Modelling of Inelastic Deformation", Chapman & Hall London, 1994.