Resistance of HFI line pipe to external loads

By Susanne Höhler and Holger Brauer

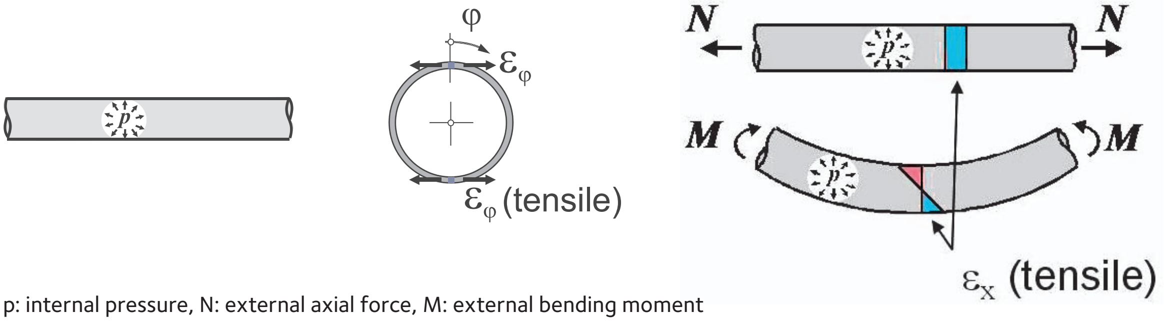
SUMMARY: The present paper addresses issues of pipeline design associated with unintended actions due to external loads or ground movements. These may introduce longitudinal strains in the pipeline owing to combinations of bending moments or curvatures and axial forces. The pipeline resistance for such multi-axial load cases is estimated via analytic equations in isotropic manner using von Mises plasticity. Both tensile and compressive stresses and strains in the pipe section are considered. In the compressive region stability issues as local buckling may dominate. The work hardening behaviour is represented using Hollomon's power law. The equations derived are analyzed in an incremental format. With this a useful tool capable of accurately capturing a large variety of relevant multi-axial loading paths is provided.

1. INTRODUCTION

Effects of external loads and ground movements on pipelines have been a significant research topic for the past years. Strain Based Design aspects have been included in a few design codes, e.g. DNV-OS-F101 [1] or CSZ Z662-03 [2]. Still, many questions are under discussion, since hazards of external actions become more severe as pipelines are installed increasingly in remote and difficult ground areas. The pipeline's resistance to such load scenarios, which in combination with internal pressure, induce pronounced longitudinal strains and multi-axial stress-strain states is not fully solved. Also, High-Frequency-Induction (HFI) welded line pipe is applied in grades ranging up to API 5L X80. High strength material is due to its intrinsic characteristics (elevated yield-to-tensile ratio Y/T and reduced uniform elongation, thus reduced deformation capacity) even more prone to unwanted stresses and strains above the elastic limit.

In a sequence of research studies this topic was addressed and a stepwise procedure was followed where material and structural behaviour of HFI line pipe were taken into account. A method to determine critical loads and deformations for HFI line pipe was searched for, that should be based on analytical methods of plasticity. Evidently, as strains beyond yielding were investigated, the material's strain hardening behaviour had to be included, representing plastic deformation capacity. Thus, in a first step, studies focussed on modelling the stress-strain characteristics from standard tensile tests via work hardening laws. Several work hardening laws were considered and evaluated for an extensive tensile test series of HFI line pipe that comprised longitudinal and transverse orientation of test specimens and three line pipe steel grades. For two modelling approaches (Ramberg-Osgood, Hollomon) a data base of work hardening exponents was attained. Background and summaries were presented in [3] and [4].

Since studies started with the description of the tensile strain hardening behaviour, the transfer from material to structural pipe behaviour firstly was done for the tensile



p: internal pressure, N: external axial force, M: external bending moment
ε: strain; indices x, φ: axial and transverse direction respectively

FIGURE 1: Load cases and strain components associated with tensile straining

strains in the pipe section. The strain capacity of pipes under internal pressure and additional axial tensile forces and bending moments was treated, disregarding stability issues by compressive strains. **Figure 1** shows the load cases considered.

In the beginning, to be implemented in the analytical incremental calculation procedure, for the sake of simplicity stress-strain behaviour was cut down to a bilinear function. The elastic branch was given by Hooke's law, followed by a linear function defined by parameters yield strength, tensile strength and uniform elongation. Model evaluations for specific tensile load cases were summarized in [4]. Subsequently, the method was refined by integration of work hardening exponents (Hollomon) into the algorithm, to attain a more realistic representation of the round-house shaped stress-strain curves.

In the meantime the estimations were complemented by consideration of the compressive region. Critical compressive strains and limit bending moments for pipe buckling can be estimated, see **Figure 2**. The following sections give an overview of the basic characteristics of the assessment procedure concluding with an example.

2. ASSUMPTIONS OF ANALYTICAL PLASTICITY MODEL

2.1 Yield criterion and flow rule

To assess elastic-plastic material behaviour flow rules are mandatory in plastic flow theory. Flow rules are directly linked to the strain hardening law, which characterizes the expansion of the yield surface. All this has been implemented into a proprietary mathematical algorithm. The underlying yield criterion is von Mises yield criterion, based on isotropic hardening material. The general equation of the von Mises yield surface (F) includes the stress state as well as the hardening parameter $k(\varepsilon_v^p)$, [5], [6]. Yielding occurs if the yield condition is met, see Eq. (1):

$$F=\sqrt{\sigma_\phi^2+\sigma_x^2+\sigma_r^2-\sigma_\phi\sigma_x-\sigma_x\sigma_r-\sigma_r\sigma_\phi}-k\left(\varepsilon_v^p\right)=0 \qquad (1)$$

The stresses in the pipe wall in transverse, axial and radial co-ordinate direction (σ_ϕ, σ_x, σ_r) are principal stresses. Using the principal strain components in all three pipe co-ordinate directions (ε_ϕ, ε_x, ε_r) the von Mises equivalent plastic strain ε_v^p reads as:

$$\varepsilon_v^p=\sqrt{\frac{2}{3}\varepsilon_{ij}^p\varepsilon_{ij}^p}=\sqrt{\frac{2}{3}}\sqrt{\left(\varepsilon_\phi^p\right)^2+\left(\varepsilon_x^p\right)^2+\left(\varepsilon_r^p\right)^2} \qquad (2)$$

Next to yielding, consistency must be met, assuring that any load increase from a plastically deformed state will result in another plastically deformed state. The consistency condition (3) causes for every incrementally increased stress state again a fulfilled yield condition:

$$dF=0 \qquad (3)$$

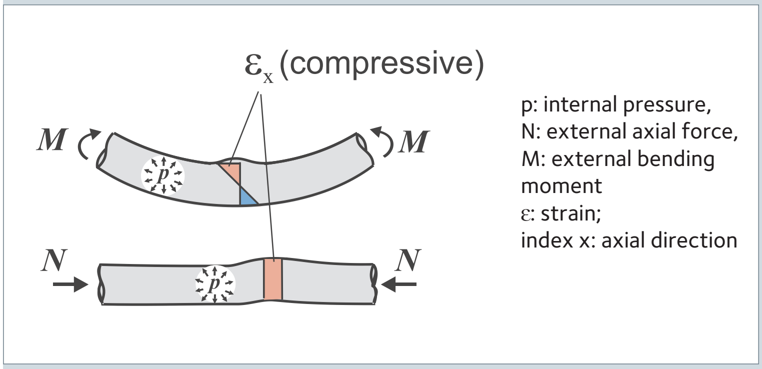


FIGURE 2: **Load cases inducing compressive strains and pipe buckling**

Respecting Eq. (3) and knowing the stress state in the pipe wall and the strain hardening function, plastic strain contributions can be calculated incrementally in all three directions. Plastic strain increments then read:

$$d\varepsilon_{ij}^p=d\lambda\frac{\partial F}{\partial\sigma_{ij}} \qquad (4)$$

Here $d\varepsilon_{ij}^p$ is the plastic strain tensor normal to yield surface. The term $\partial F/\partial\sigma$ is called the flow rule, describing the partial derivative of the yield surface *F* with respect to the components of the stress tensor σ_{ij}. $d\lambda$ is the plastic or 'Lagrange' multiplier, which has to be determined for any subsequent plastic loading. It can directly be evaluated by reformulating the consistency condition, which is the total derivative of (1).

2.2 Strain hardening function

For a model following theories of plasticity a strain hardening curve or strain hardening function is necessary. Here the stress-strain results derived from uniaxial tensile or compression tests are considered, starting from yield strength and ending at tensile strength by reaching the uniform elongation. The curve in this region is approximated by a function of the plastic strains $k(\varepsilon_v^p)$. Ideally a power function in terms of work hardening exponents, e.g. following Hollomon power law [7] is used that represents the curve's shape in a realistic manner:

$$k\left(\varepsilon_v^p\right)=C_H\cdot\left(\varepsilon_v^p\right)^{n_H} \qquad (5)$$

In (5) n_H is the Hollomon strain hardening exponent and C_H is a material constant. An easier approach is a piecewise linear or bilinear approximation of the strain hardening behaviour, see [4].

2.3 Assessment of compressive region: critical buckling strains and limit bending moments

The limit states related to tensile straining can be assessed with the methods described above. However, in case of compressive stresses and strains stability mechanisms, such as buckling, may dominate structural pipe behaviour. In case

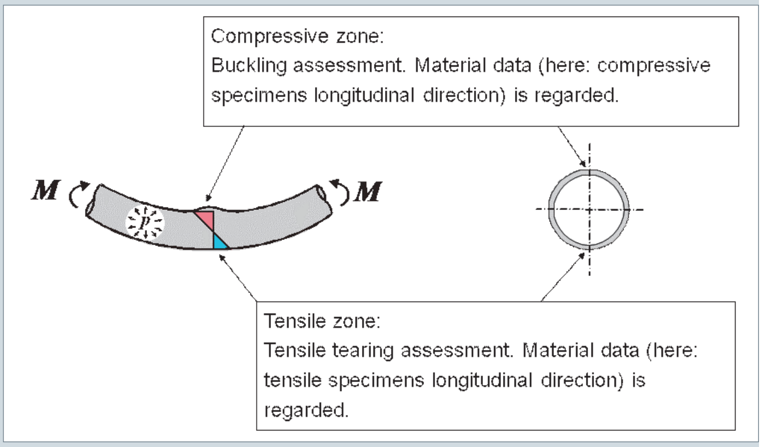


FIGURE 3: **Tensile and compressive zone in a pipe subject to bending moment**

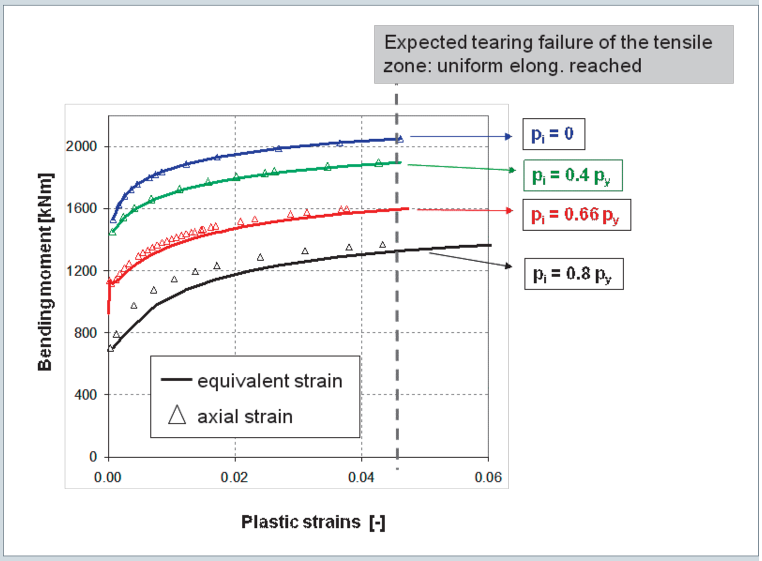


FIGURE 4: **Bending moment – plastic strain evolution for the tensile zone**

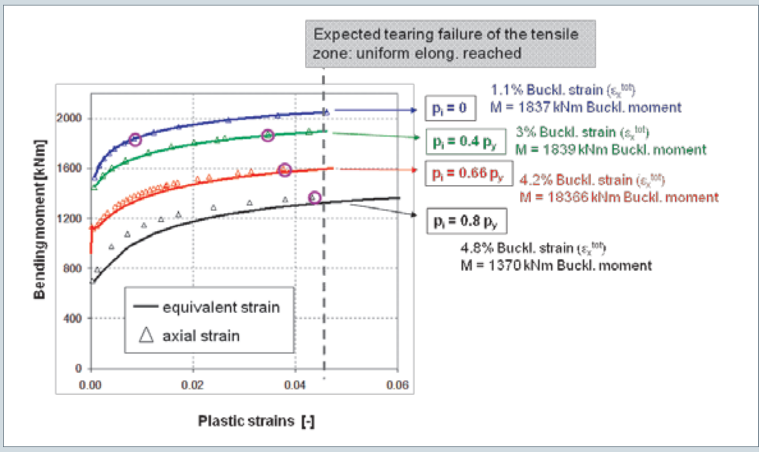


FIGURE 5: **Bending moment – plastic strain evolution for the tensile zone; buckling moments are marked with circles**

of bending moment or pipe curvature both tensile and compressive strains develop in the pipe section and both aspects “tensile straining” and “buckling” must be addressed.

Literature and codes provide a variety of formulae to determine buckling loads or compressive threshold strains, although they usually are limited to certain diameter-to-wall-thickness-ratios D/t, steel grades or load combinations. From extensive parametric studies and comparison with limit loads from pipe bending tests [8] DNV-OS-F101 [1] was concluded to give a suitable procedure for critical buckling strains for line pipe. Thus, the critical compressive strain is evaluated via [1] and subsequently the critical bending moment (or axial force) is determined via the analytic plasticity model stated in sections 2.1 and 2.2. Material data from compressive tests is used.

3. APPLICATION TO MULTI-AXIAL PIPELINE LOAD CASES

The tool can be used to assess margins of structural safety for various Strain Based Design scenarios, if certain amounts of plastic strains are acceptable load bearing capacities concerning internal pressure, as well as limit bending moments or axial forces, can be determined depending on given deformations or pipe curvatures. Also pipe laying operations where bends and plastic longitudinal strains are introduced can be estimated, e.g. horizontal drilling procedures or reeling of a pipe string onto reel drums for offshore laying.

An example for the estimation of the allowable bending moment for varied internal pressure loading is presented in the following. A dimension typical for onshore buried pipelines and thus prone to ground movements (diameter 610 mm, wall thickness 10 mm) of grade X70 was used. The constitutive material behaviour was attained by tensile and compressive tests on specimens extracted in longitudinal pipe direction. Via data fitting to the measured stress-strain curves the strain hardening parameters according to Hollomon, see Eq. (5), were derived. The analytical bending simulation was carried out twice for each internal pressure level:

1. The bending moment-strain evolution was calculated for the tensile zone, based on tensile test material data.
2. The critical buckling strain for the compressive zone was calculated via [1]. The corresponding limit moment comes from the analytical procedure (section 2). The underlying material data are compressive data, gained from the opposite cross-section fibre, see **Figure 3**.

The internal pressures were varied from $p_i = 0$ until $p_i = 80\ \%$ of yield pressure p_y (pressure which causes first yielding of the pipe wall). **Figure 4** shows the load-strain evolution for the tensile zone. If buckling would not play a role, calculatively tensile tearing would be expected at the moment where the uniform elongation is reached.

The addition of the critical buckling points, given by buckling longitudinal strain and buckling moment, are presented in **Figure 5**. Evidently, for this example, buckling is expected (circles in Figure 5) before tensile tearing of the pipe will take place, as the limit compressive strains are smaller than the material's uniform elongation. Higher internal pressure promotes higher critical buckling strains while the bending capacity (bending moment) decreases.

4. CONCLUSIONS

Based on the theory of plasticity an analytical mechanical model was developed for assessing plastic deformation states. The computational algorithm is analytical in nature, but set up in incremental format. Hereby, a useful tool is available to evaluate plastic strain states triggered by combined loading. Several scenarios where pipelines require certain plastic deformation capacity can be solved. One important case of pipe bending in combination with pressure containment has been depicted in an example. Future studies should aim at a better comprehension and implementation of anisotropic material behaviour and model verification via full-scale tests.

LITERATURE

[1] DNV-OS-F101, Offshore Standard, Det Norske Veritas, 2010

[2] CSZ662-03, Oil and Gas Pipeline Systems, Canadian Standards Association, August 2005

[3] Zimmermann, S., Brauer, H., Löbbe, H.: Assessment of work hardening behavior of HFI-welded pipes for strain Based Design approaches, 17th JTM, 11/15 May 2009, Milan, Italy

[4] Höhler, S. et al: Work hardening properties of High-Frequency-Induction (HFI) welded line pipe: Parameters for assessment of multi-axial load histories, Pipeline Technology Conference, October 2009, Ostend, Belgium

[5] von Mises, R.: Mechanik der plastischen Formänderung von Kristallen. Zeitschrift für angewandte Mathematik und Mechanik 8 (1928), pp. 161-185

[6] Chen, W. F., Zhang, H., Plasticity for Structural Engineers, Springer-Verlag Nw York Inc., 1988

[7] Hollomon J. H.: Tensile deformation. Transactions of the Metallurgical Society of the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME) 16 (1949), pp. 268-290

[8] Karbasian H., Zimmermann S., Steiner M., Marewski U.: Model of ultimate limit state design to predict combined loading capacity of pipelines. Report on behalf of the European Pipeline Research Group (EPRG) No. 142, to be published in 2011

AUTHORS

DR.-ING. SUSANNE HÖHLER
Salzgitter Mannesmann Forschung GmbH, Duisburg, Germany
Tel: +49-203-999 3192,
E-mail: s.hoehler@du.szmf.de

DR.-ING. HOLGER BRAUER
Salzgitter Mannesmann Line Pipe GmbH,
Hamm, Germany
Tel. +49 2381 420447
E-mail: Holger.Brauer@smlp.eu