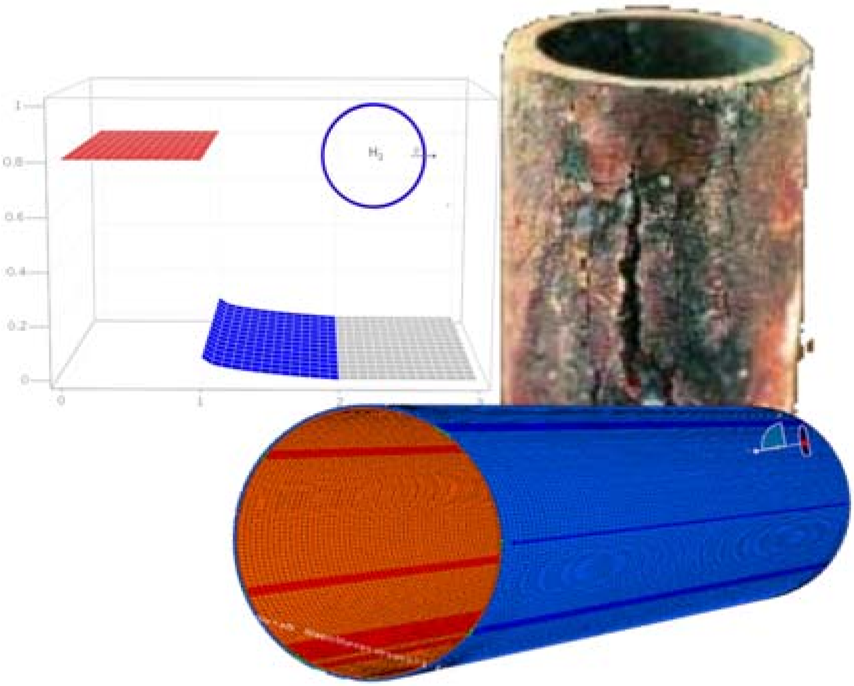
CheFEM Case Study

Retrofitting a Pipeline for Hydrogen Transport



In this case study we present the use of the CheFEM Simulator.
We will simulate whether an internal Fusion Bonded Epoxy (FBE) coating on an existing High Strength Steel X-65 Natural Gas pipeline will improve the lifetime of the pipeline if we want to retrofit it for Hydrogen transport.

Introduction

Most of the Hydrogen produced today for commercial use is transferred short distances through narrow diameter pipes at pressure of 10 to 20 bar. For this purpose, carbon steel is the principal material of choice for pipeline construction. Cast iron, copper, various plastics - e.g. polyvinylchloride (PVC) and high density polyethylene (HDPE) - are also used, particularly to transfer the gas over short distances.

A concern for future high capacity hydrogen X-steel pipelines is long term durability at internal gas pressures above 70 bar. Hydrogen Initiated Stress Cracking (HISC) may reduce the strength of the pipeline material and the welds.

Hydrogen Initiated Stress Cracking (HISC) is initiated by dissolving of Hydrogen at the steel surface and subsequent diffusion into steel. As Hydrogen dissolves in metal, it splits in two Hydrogen protons and releases 2 electrons.

This dissociation leads to substantial diffusion rates into the steel. Simultaneously, the recombination of the 2 electrons with Hydrogen protons in small voids within the metal matrix generates an enormous pressure.

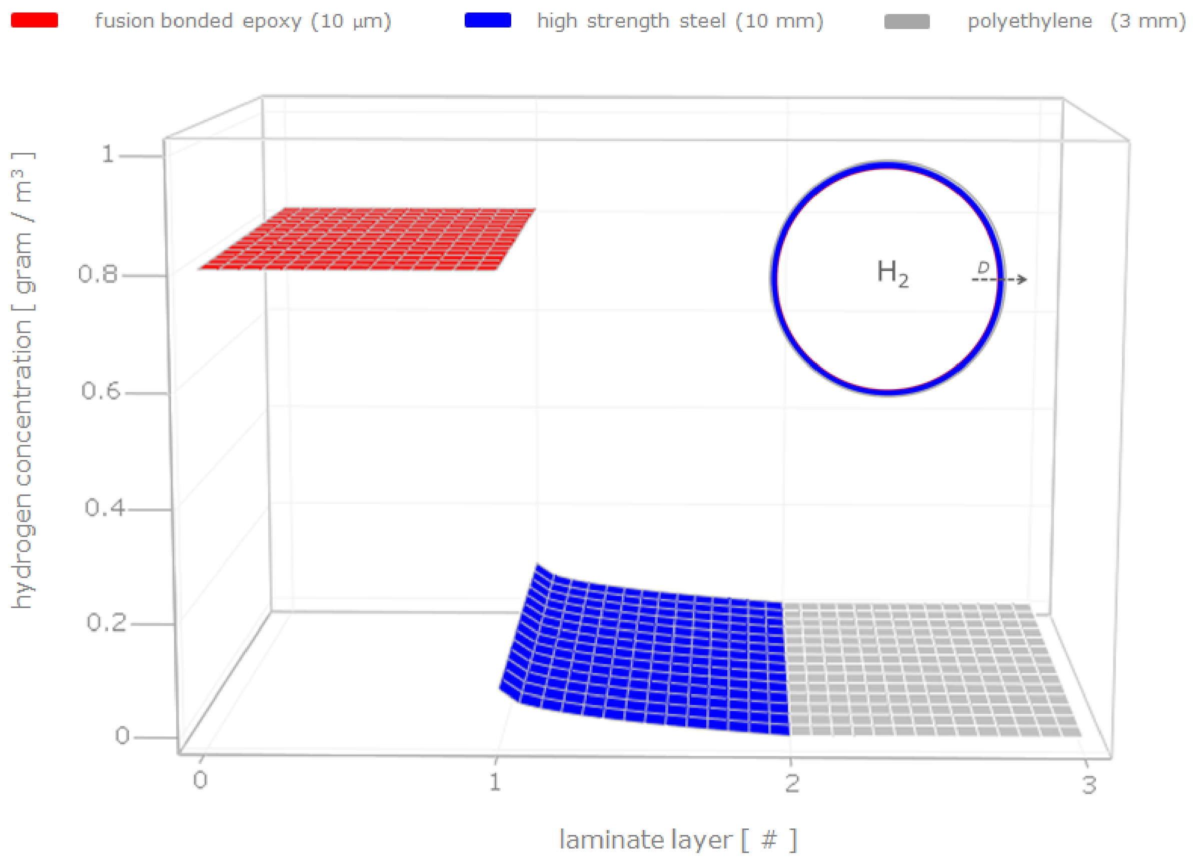
The subsequent stress concentration on specific locations within the voids - dependent on the shape of the void and the circumferential stress state of the pipe - gives rise to extraordinary phenomena: cracking, decrease in tensile strength, loss of pipeline ductility and reduced burst-pressure rating. These mechanisms can lead to premature failure of one or more segments of a pipeline, resulting in leakage of hydrogen gas or in extreme circumstances, bursting of a pipe.

Hydrogen pressure and temperature both determine the degree of dissolving, the diffusion rate and the accumulation kinetics of Hydrogen in the voids within the metal.

To reduce the effect of temperature and pressure on HISC, the application of an internal polymer based coating is often suggested. Since Hydrogen diffuses in a rigid polymer matrix in the molecular state, it is often thought that a coating would be useful. Such a solution should decrease the rate and degree of Hydrogen dissolving in the metal matrix, which should extend the pipeline service life. In our simulation we put an internal Fusion Bonded Epoxy (FBE) coating of 10 micrometer on top of a 10 mm X-65 steel with an already present outside Polyethylene coating of 3 mm.

Diffusion & Corrosion Simulation

The simulated steady state concentration distribution in the 3-layer material looks as follows. Note that the layer thicknesses are normalized.

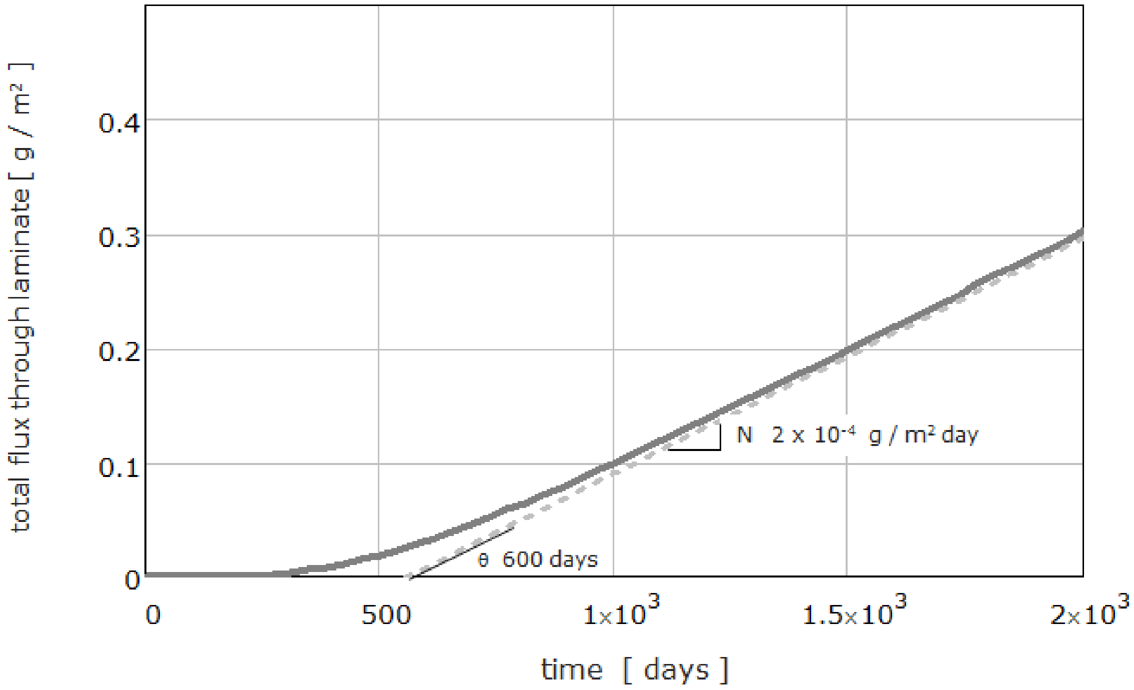


The diffusion and thermodynamic data used for this simulation is tabled below.

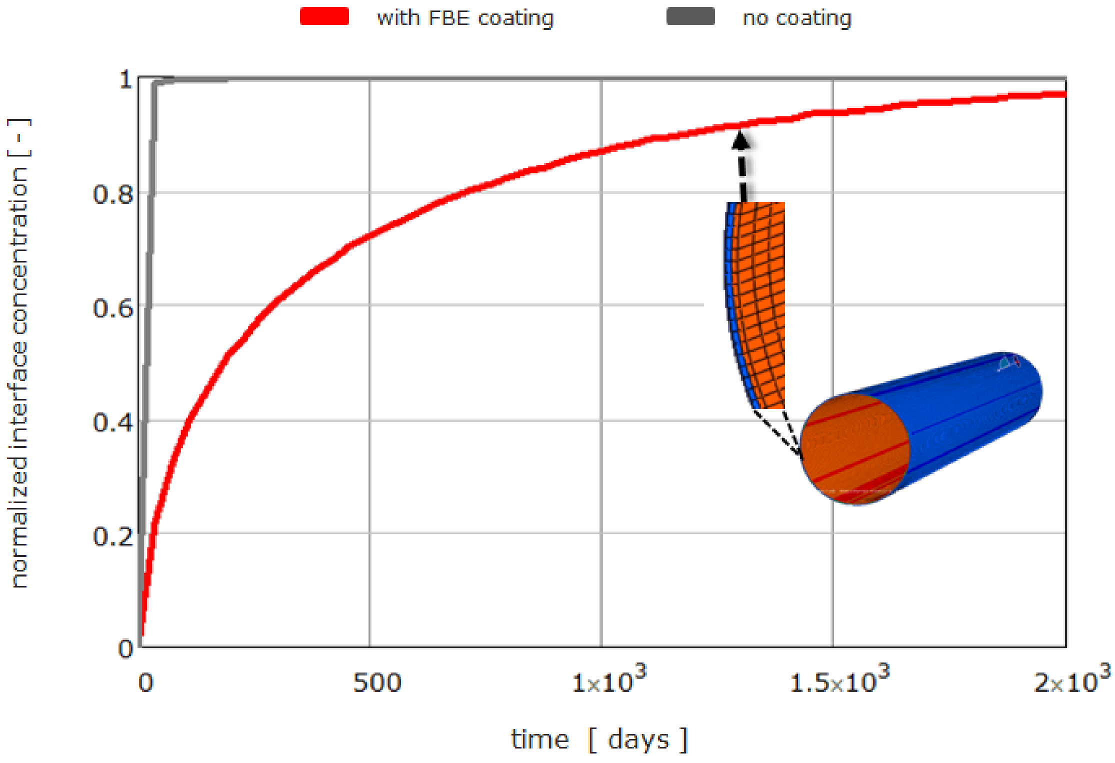
environment	system temperature [Degr. C.]	system pressure [bar]	partial pressure [bar]
Hydrogen (H_2)	25	100	100

materials	thickness [x 1 E-5 m]	diffusion $D_{average}$ [m^2 / s]		solubility $S_{equilibrium}$ [m^3_{stp} / m^3 bar]	
Epoxy Coating	1	1E-11	Fick	0,1	Henry
X-65 High Strength Steel	1000	3E-13	Dual Mode	0,01	Dual Mode
Polyethylene	300	3E-11	Fick	0,07	Henry

The belonging flux / time lag graph is as follows.



The surface concentration in the steel as a function of time is depicted below by using the instationary diffusion & corrosion module.

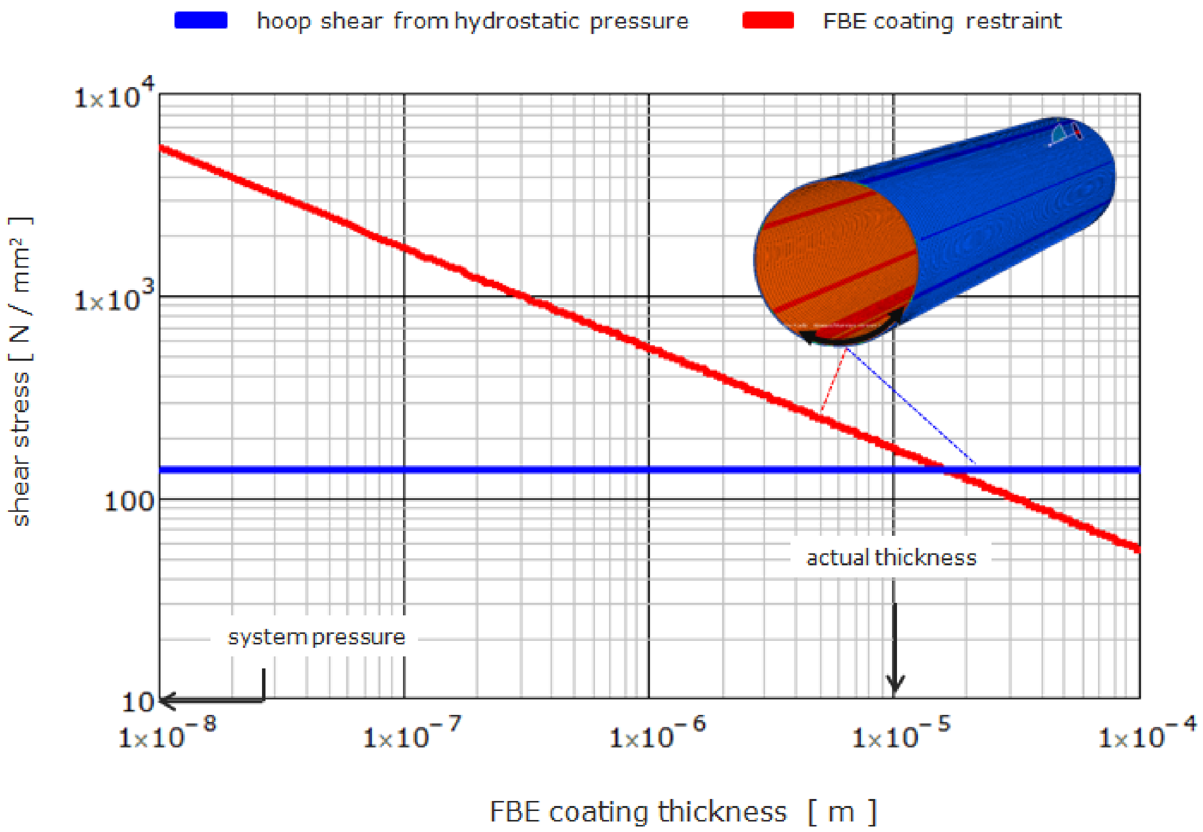


From the previous graph it becomes obvious that if one applies internal FBE coating, the Hydrogen steady state concentration in the steel surface is delayed with around 5 years. *However*, the obtained surface concentration is only a minor fraction lower than without FBE coating. So the ultimate lifetime extension is very limited. This may sound paradoxally, since FBE coating can be very effective in decreasing the steel surface corrosion by e.g. a formed acid like Carbonic Acid, Nitric Acid or Hydrosulphuric Acid. Without going into detail on chemical potentials, etc., this fact clearly demonstrates that corrosion prevention solutions also need to be assessed for diffusion driven phenomena.

Coating Restraint Simulation

In line with diffusion and corrosion considerations, it is important to assess whether the FBE coating adheres sufficiently to the steel substrate in normal operating conditions (at a system pressure of 100 bar, see picture below). For this assessment we will use Module 4 of CheFEM: the mechanical restraint module (also known as swelling restraint module).

For this situation, the routine incorporates the shear due to hydrostatic pressure variations and temperature gradients. Here the swelling potential due to Hydrogen mass uptake in FBE coating can be neglected. Furthermore we will assume a clean and unfractured steel surface, and at this stage we will not include steel fracture by HISC (and the eventual formation of a bulge).



Note from the graph that adhesion decreases logarithmically as function of thickness. It becomes obvious that the FBE coating restraint is for 10 micrometer thickness, just enough to prevent delamination in the stationary situation and during depressurization (not shown in this graph). Beyond 20 micrometer the coating will delaminate from the steel layer at a given hydrostatic pressure. This fact deserves proper attention. It will among others, determine the requirement for cleaning and treatment of the steel, and the processing conditions during application of the FBE coating.

Conclusion

CheFEM simulation revealed that FBE coating is not useful for lifetime extension of a pipeline for Hydrogen transport. This is not specifically due to the nature of Fusion Bonded Epoxy: from CheFEM analysis it appears that no polymer coating at any realistic thickness (note that adhesion decreases with thickness!) would be capable extending the lifetime of Hydrogen pipelines.

In this analysis we studied coating solutions. In many aspects, polymer based pipe-in-pipe solutions are different from coating solutions. In pipe-in-pipe solutions, e.g. think of Glass Fibre Reinforced Epoxy (GRE) pipe, Hydrogen might be collected in an annulus and conveyed to a collector. Secondly, polymer-substrate adhesion - critical to any coating - is not an issue. Drawback is that pipe-in-pipe is much more expensive and that at the same time, for many other surface corrosion oriented problems, thin coating layers are sufficient for decreasing corrosion rates with orders of magnitudes. Even in severe temperature and pressure conditions.

A1 Overview of CheFEM Modules

1	Flexible Multilayer Sequencer	This module is used for the mathematical description of the subsequent layers in terms of Finite Elements (FEM) and Finite Differences (FD). This module supports the following three modules.
2	Lattice Based Diffusion & Thermodynamics Module	Determines the diffusion, solubility and swelling behaviour. Includes anomalous models, like Dual Mode diffusion (one part is diffusing/mobile another part is immobile/trapped in voids) and Sanchez - Lacombe equation of state. Effects of ageing and fatigue are included.
3	Surface & Chemical Activity Driven Corrosion Module	Quantifies the corrosion rates of the polymer/metal, the internal interfaces or fillers and reinforcements. Based on (experimental) library data on corrosion rates and three dimensional chemical potential determination.
4	Mechanical Restraint Module	Based on Gibbs Free - Mechanical Fracture analysis. Determines the adhesion characteristics between and within different components of the composite, under hydrostatic pressure and swelling driven by temperature and mass solubility. Effects of fatigue and ageing are included.