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TEMPERATURE LIMITS FOR ASPHALT COATED FLOWLINES - A DESIGN APPROACH

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ABSTRACT

The 18" flowline from the Mikkel template in the North Sea was coated with asphalt enamel for corrosion protection and an external concrete coating for weight. The high internal temperature of 85 ^{o}C close to the template can give relative thermal movements between the outer concrete coating and the inner steel pipe. The case is considered to be similar to an adhesive joint between two tubular members. The strength approach is based on the analysis of the shear stress distribution in this "adhesive" joint. The material stiffness (shear modulus) of the asphalt was used to determine the upper temperature limit for the asphalt coating. The hotter part of the flowline had to be coated with polypropylene instead of asphalt.

NOMENCLATURE

E – Young's modulus of the adherends (steel and concrete)
G – shear modulus of adhesive (asphalt enamel)
ID – internal diameter
L – concrete overlap length for each pipe joint
OD- outer diameter
τ - shear stress in adhesive

INTRODUCTION

The Mikkel field

The Mikkel field is a subsea gas/condensate satellite field connected to the Midgard template of the Åsgard field. The field layout is shown in Figure 1. The water depth is 220 m.

The field consists of two subsea templates producing gas / condensate that is exported trough an 18" flowline to the Midgard template. Details of the flowline are presented in table 1.

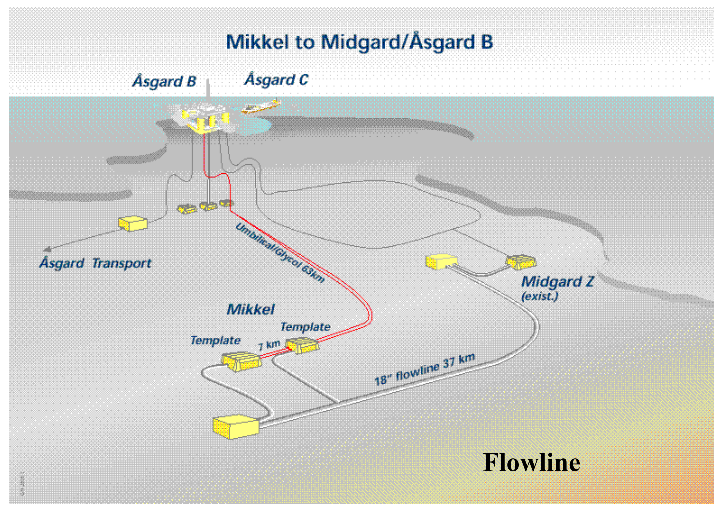

Figure 1. Field layout of the Mikkel subsea field with the flowline connection to the Midgard /Åsgard B field.

Table 1. Details of the Mikkel flowline.

Length	37 km
Linepipe material	X-65
Internal pipe diameter	415.8 mm
Wall thickness	19.1 mm
Design temperature	85 ^{o}C
Distance above 60 ^{o}C	4 km
Anti-corrosion systems	6 mm glass fibre reinforced asphalt enamel 4 mm three-layer PP coating
Weight coating	Concrete

In figure 2 is shown the welding of a pipe that has asphalt enamel as corrosion coating and concrete weight coating.

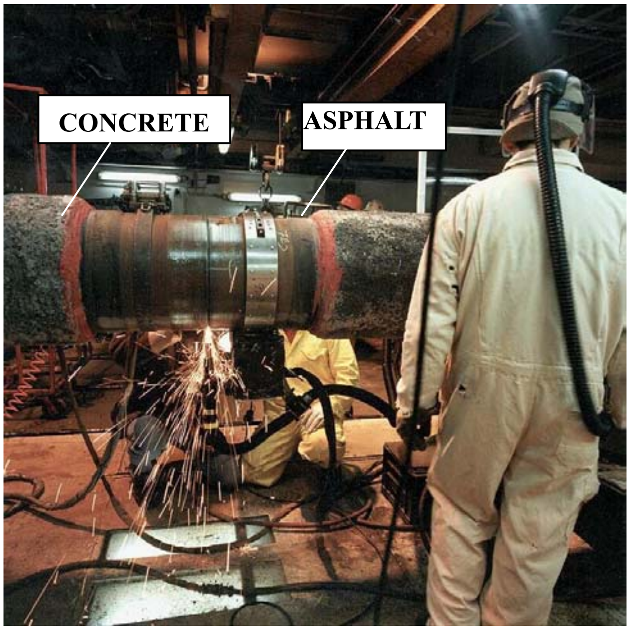

Figure 2. A pipe with concrete weight coating and asphalt enamel being welded on the lay-barge Lorelay. (photo Øyvind Hagen, Statoil).

Temperature limits for asphalt enamel coating

Asphalt enamel has a long track record in pipeline corrosion protection. The mechanical properties of asphalt enamel or bitumen are very temperature and strain rate sensitive. For high rates of loading the material is stiff, but for low rates the material can behave as a liquid and flow easily [1].

The steel pipeline will expand and contract due to variations in temperature of the flowing well fluids.

Tests in shear between a concrete outer cover and the steel pipe have been performed in order to determine the temperature limits of the asphalt enamel. The test results indicate that a maximum temperature of 60 °C is the upper limit for standard asphalt enamel [2]. If the temperature is too high the end result can be a movement of the pipe relative to the concrete weight coating.

Pipe movement relative to the concrete coating can lead to:

- Cutting of wire strap to sacrificial anodes
- Pipe buckling if the movement is too large.

For the Mikkel project the challenge was to extend the limit of the asphalt coating to temperatures up to 85 °C. By having the same type of coating for the full length of flowline a significant cost saving could be achieved in terms of pipe handling and break in specifications.

Experience with pipelines with asphalt enamel and concrete in operation at temperatures above 60 °C indicated that relative movement between the outer concrete cover and the pipeline is not a significant problem, however it was difficult to assess this statement.

Polymer modified asphalt bitumen

By adding polymers (EPDM-rubber, polyethylene) to the bitumen the creep and wear resistance is improved. The polymer added gives the bitumen a rubbery state, and a greater tendency of recovery (memory) when the load is removed. The shear modulus will also improve when adding polymers as shown in figure 3.

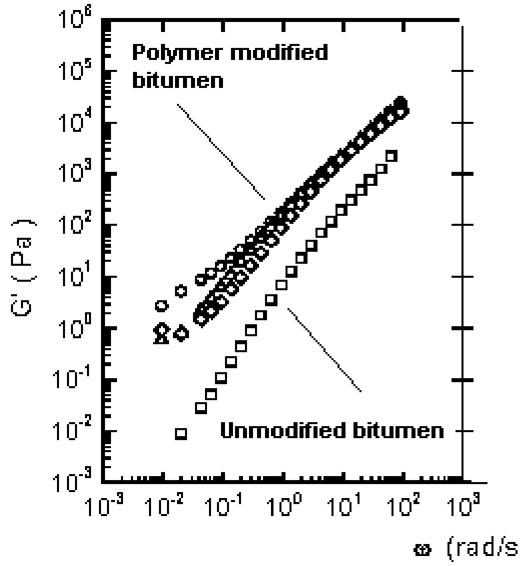

Figure 3. Shear modulus G versus loading frequency at 75 °C of a polymer modified bitumen compared to a unmodified bitumen [3].

The asphalt producer Phønix introduced a polymer modified asphalt enamel called BITUSEAL® as a pipe coating material [4]. It is seen in Figure 3 that the shear modulus of a polymer-modified bitumen is at least one decade higher than the unmodified grades. This indicates a higher temperature capability of the modified grades of bitumen compared to unmodified grades.

By introducing the asphalt enamel BITUSEAL® to the Mikkel project the hypthesis was that the temperature limit could be raised to 85 °C.

THEORETICAL BASIS FOR STRESS DISTRIBUTION IN THE ASPHALT ENAMEL COATING

The stresses in the asphalt enamel are shown in figure 3. The pipeline will be anchored to the sea bottom on the outside of the concrete cover. The reinforced concrete weight coating is assumed to behave as a pipe with the modulus of concrete. The stress between the steel pipeline and the sea bottom will be in the form of shear stress since the steel pipe will try to move due to thermal expansion. The shear stress is transferred through concrete cover and the asphalt enamel. This situation is similar to the case of a tubular adhesive joint where the asphalt enamel acts as the "adhesive" between the inner steel pipe and outer concrete pipe.

The geometry is described in Figure 4, with the length of the overlap concrete L, the outer diameter of the steel pipe D_{steel}, the outer diameter of the asphalt $D_{asphalt}$ and the outer diameter of the concrete weight coating $D_{concrete}$.

The shear stress will depend on the axial load generated from thermal expansion/ contraction of the steel pipe when the pipe is prevented to move.

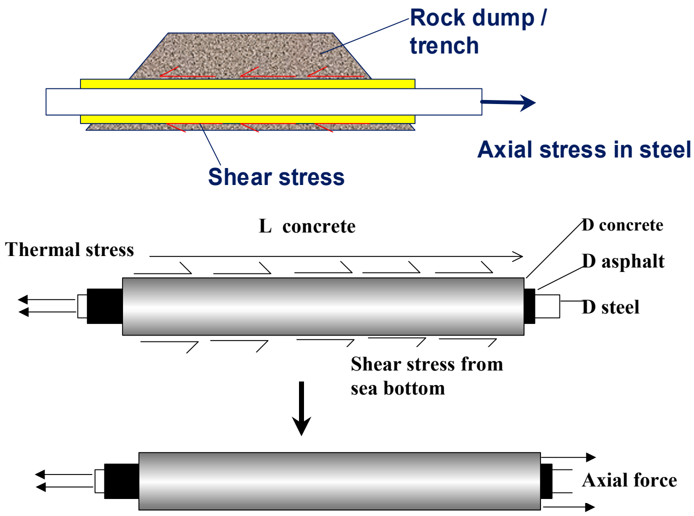

Figure 4: Schematic view of the loads and stresses in the asphalt enamel. The diameters are assumed to be outer diameters of steel, asphalt enamel and concrete.

From thermal calculations of the pipeline the in-service shear stresses between the steel and the outer concrete cover for the Mikkel case is estimated to be 5-8 kN/m^2 [5].

The shear stress in the asphalt can in the first approach assumed to be uniform along the length of the pipe. For a long pipe like this the shear stress distribution in the asphalt coating will however not be uniform due to the shear lag effects. Shear stress will transfer axial load from the inner to the outer pipe.

An illustration of the shear lag effect can be seen in the double lap joint geometry. For the case considered here the steel pipe can be regarded as the central adherend and the concrete cover as the two outer adherends with same thickness [6].

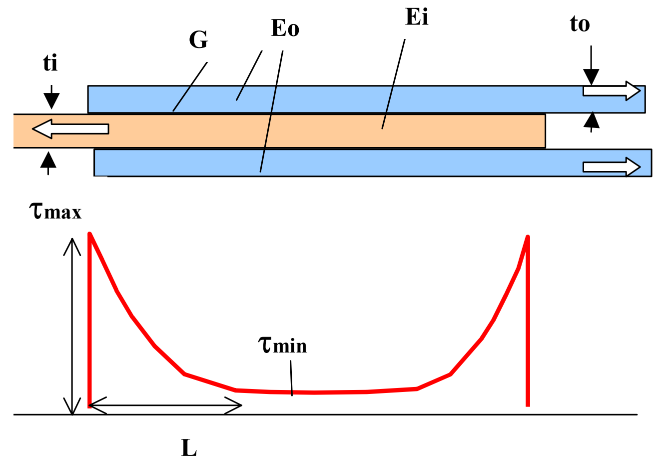

Figure 5 Double lap adhesive joint illustrating the elastic stress distribution. G – shear modulus of the adhesive, Ei and Eo are the moduli of the adherends, ti and to are the thicknesses of the adherends. L – length to minimum shear stress [6].

The necessary overlap length to prevent creep can be calculated from the value of L:

$$L = \frac{3}{\lambda}, \left[\lambda^2 = \frac{G}{t_{adhesive}} \left(\frac{2}{E_i t_i} + \frac{2}{E_o t_o} \right) \right]$$

The stress distribution for an adhesive lap joint between circular tubes has been described in the literature by Lubkin and Reissner [7]. The stress distribution in the adhesive of the tubular joint is similar to the one illustrated for the double lap adhesive joints.

The Lubkin and Reissner solutions have been implemented in the computer program THAMM [8]. The program assumes the adherends (steel and concrete) to be the same material. The modulus of the asphalt enamel is very low compared to the moduli of steel and concrete. It is therefore assumed that the stress distribution will not be influenced significantly by choosing two concrete adherends. A less stiff adherend gives a longer transfer length of stresses (shear lag distance). For calculating necessary lengths to avoid creep the use of two concrete "pipes" will be conservative.

Necessary input for the THAMM program is:

- Adherend Youngs modulus
- Adhesive shear modulus
- Adhesive shear strength
- Axial load
- Overlap length
- Diameters of pipe adherends and adhesive

In the calculations with the THAMM program only the least stiff adhererend was use for the calculation of shear stresses.

- (Young's modulus (E-modulus) for steel – 210 GPa - not used.)
- Young's modulus for the concrete – 22.5 GPa.
- Shear strength of asphalt – not necessary for an elastic analysis.

The axial load is calculated by converting the temperature shear stress along the concrete – to soil interface to equivalent normal force acting on one end of the concrete "pipe".

Normal force: $N = D_{concrete} * \pi * L_{concrete} * \tau$ = Surface area * shear stress

Overlap length to avoid creep in an adhesive joint

The necessary overlap length to avoid creep in an adhesive joint is formulated as [8]:

- Maximum adhesive shear stress / minimum adhesive shear stress > 10.

This means that the adhesive profile of the shear stress distribution should resemble a "bathtub" situation with a middle section with small shear stresses.

Measurement of shear modulus in asphalt enamel

Samples of standard asphalt enamel were supplied from Bredero-Shaw in Leith. Samples of BITUSEAL® were received from Phønix in Denmark.

The shear modulus versus temperature was measured by dynamic mechanical thermal analysis (DMTA). The instrument was a Rheometrics Solids Analyzer – RSA-2. A shear sandwich fixture was used for the analysis. The temperature range was were varied from 40 ^{o}C to 120 ^{o}C.

RESULTS

Shear modulus of asphalt enamel

The shear moduli of a standard asphalt enamel and the polymer modified grade BITUSEAL® are compared in Figure 6.

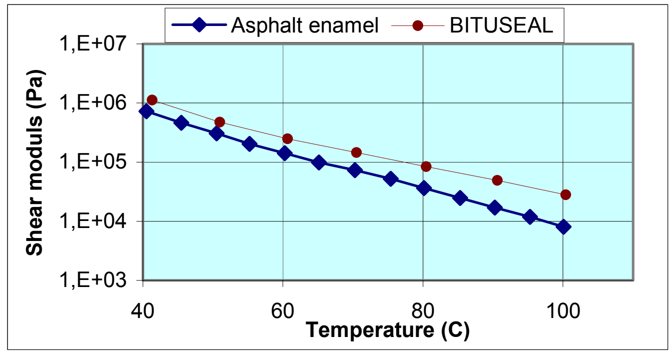

Figure 6. The shear modulus for standard asphalt enamel and the polymer modified asphalt enamel BITUSEAL® at a loading rate of 3.14 rad/s.

It can be seen that the shear modulus for both materials is around 1 MPa at 40 ^{o}C. At the design temperature of 85 ^{o}C for the Mikkel flowline the moduli are between 0.01 and 0.1 MPa.

Analysis of asphalt shear test

The input to the analysis taken from a test where a 800 mm long concrete covered pipe sample was tested in shear at elevated temperatures [2]:

- ID steel: 875 mm
- OD steel 914 mm
- OD asphalt 926.4 mm (6 mm asphalt)
- OD concrete 1094.4 mm (84 mm concrete)

The applied shear stress was 5.5 kN/m$^{2.}$

The shear modulus for asphalt enamel was in this case assumed to be: 2 MPa and 200 MPa.

Two cases were modelled:

1. Test pipe with 800 mm concrete cover – normal force 12.8 kN
2. Pipe joint with 11500 mm concrete cover – normal force 184 kN

The shear stress and shear strains in the asphalt were calculated with the THAMM program. The results are shown in Figures 7 and 8 for the two cases.

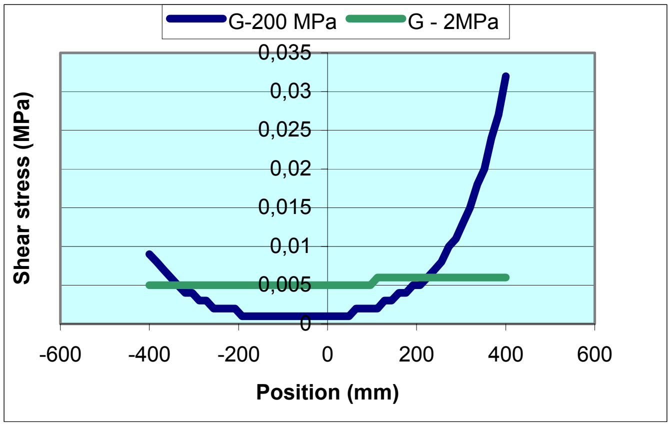

Figure 7. Shear stress in the asphalt asphalt enamel coating for a 800 mm long pipe test sample (875 mm ID) for two values of the shear modulus of asphalt enamel.

It is seen that a modulus of 2 MPa will lead to creep (movement of concrete) because there is no middle section with low shear stress. A shear value of 200 MPa would not lead to creep. The test results [2] showed that the pipe did move.

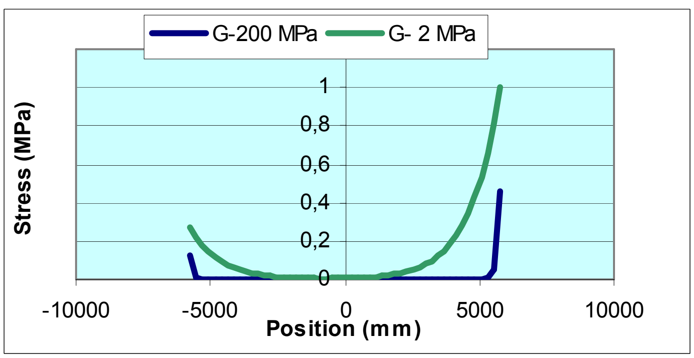

Figure 8. Shear stress in the asphalt enamel coating along a 875 mm ID pipe joint with a 11.5 m long concrete cover for two values of the shear modulus of the asphalt enamel.

The results show that even for the lowest value of the shear modulus the shear stresses are low in the middle of the pipe. This indicates that the concrete cover would not move if a full length pipe had been tested. At higher temperatures the shear modulus will be reduced below 2 MPa and there is possibility for creep.

Mikkel case

The shear stress distribution in the asphalt enamel coating for the Mikkel flowlines was calculated with THAMM program.

The details of the flowline was:

- ID steel: 415.8 mm (19.1mm wall thickness)
- OD steel: 454 mm
- OD asphalt: 466 mm (6 mm thick)
- OD concrete: 556 mm (45 mm concrete)

The thermal shear stress was assumed to be 8 kN/m^2.

The following values for the shear modulus of the asphalt enamel were used as input to the calculations:
G: 0.02 MPa, 0.08 MPa, 0.2MPa, 1 MPa and 2 MPa.

The following case was modeled:

- A pipe with 11500 mm concrete cover – normal force 134,7 kN.

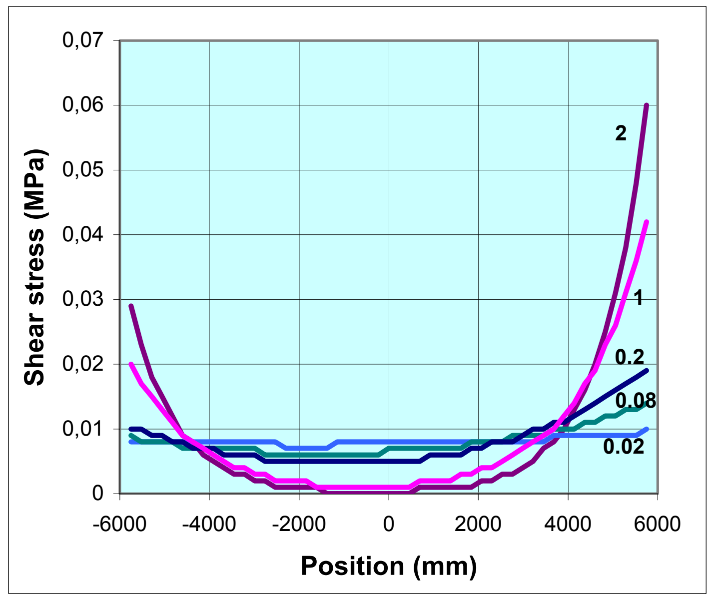

Figure 9. Shear stress distribution in the asphalt enamel coating for the Mikkel 18" flowline with 45 mm concrete cover for various values of the asphalt enamel shear modulus (MPa).

The shear stress in the center of the coating is low as long as the shear modulus of the asphalt enamel is above 1 MPa.

Shear modulus measurements of standard asphalt enamel coating and BITUSEAL® offshore grade shown in Figure 6 show that the shear modulus is not high enough to prevent movement for the highest temperature of 85 ^{o}C.

From these measurements it was therefore concluded that the modified asphalt enamel could not be used for the maximum design temperature of 85 ^{o}C.

Discussion

The necessary concrete cover length can also be estimated by assuming the steel pipe to be the central adherend and the concrete to be two outer adherends in a double lap adhesive joint. The result is shown in figure 10 for a range of values of the shear modulus of the asphalt enamel.

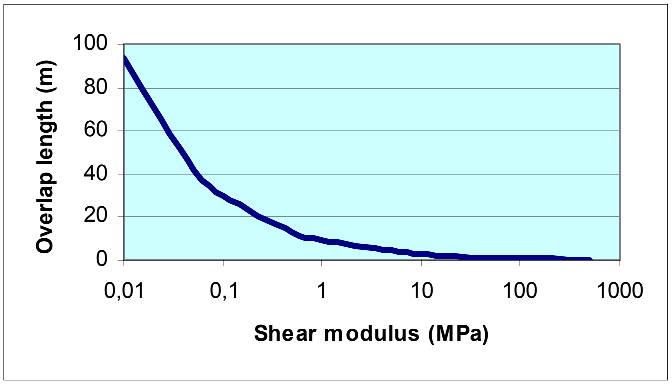

Figure 10. Necessary concrete cover length to avoid creep as a function of asphalt enamel shear modulus for an equivalent double lap joint.

From figure 10 it is seen that a shear modulus of approximately 1 MPa corresponds to a typical pipe joint length of 12 m. This value of the shear modulus corresponds to the analysis shown in figure 9.

The calculation of shear stresses in figures 7 - 9 assumes equal materials in the adherends. The properties of concrete were used for both the inner steel pipe and the concrete outer cover. A more detailed analysis would require the use of finite element modelling. In a more refined model it can be possible to include effects of plastic and viscous creep. By such an analysis the real temperature limit for the asphalt enamel could be obtained.

The analysis give an explanation to why the pipelines behave better than tests on short segments. The low stresses in the middle of the pipe length will limit the movements of the concrete relative to the steel and will therefore lock the outer "pipe" in place.

DESIGN APPROACH FOR DETERMINING TEMPERATURE LIMITS IN ASPHALT ENAMEL

The temperature limit for a typical asphalt enamel under a concrete weigth cover can be determined by the following approach:

1. Measure the shear modulus of the asphalt enamel over a range of temperatures and loading rates.
2. Calculate the shear stress distribution in the asphalt enamel for a typical pipeline joint for a wide range of the shear modulus of the asphalt enamel.
3. Determine the miniumum value of the shear modulus that give a shear stress distribution where the maximum value to the minimum value is larger than 10.
4. The temperature limit is found when the minimum value of the shear modulus satisfies the condition above. This will correspond to a temperature in the measured shear modulus versus temperature.

CONCLUSIONS

A steel pipe with an asphalt enamel corrosion protection and a concrete weight cover can be modelled as a tubular adhesive joint. The asphalt is the adhesive in such a model.

The temperature limit of the asphalt enamel was determined from value of the shear modulus that will prevent creep movement between the steel pipe and the concrete cover.

The first part of flowline of the Mikkel subsea field had to be corrosion protected with polypropylene since the standard asphalt enamel and high temperature grades were not stiff enough to prevent creep.

ACKNOWLEDGEMENTS

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REFERENCES

1. P. Morgan, A.Mulder, The Shell Bitumen Industrial Handbook, 1995, Surrey, ISBN-0-95 16625-1-1
2. Shear test report, Bredero Price, Oseberg gas – report no, 11-4A-NHT-R15-00105-01, 29.01.99
3. A. Pérez-Lepe, Enhanced Rheological Properties of Polyethylene/EPDM Modified Bituminous Binders, Rheofuture 2002, Karlsruhe
4. BITUSEAL system description , Phønix Pipe Proctector, Vejen, Denmark, http://www.phoenix-pipe-protectors.dk/
5. 18" Flowline system – Coating Verification Report, Doc – D195-A-M-RF-001, Reinertsen Engineering, Aug 2001.
6. L.J. Hart-Smith, Rating and Comparing Structural Adhesives: An New Method, in Adhesives and Sealants, Engineered Materials Handbook, Volume 3, ASM International, 1990
7. J.M. Lubkin, E. Reissner, Stress distribution and design data for adhesive shear lap joints between circular tubes, Trans. ASME, J. Appl. Mech. 78, 1215, 1956
8. J. Groth, Limhåndboken, Dansk Teknologisk Institut, 1991.