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EFFICIENT FINITE ELEMENT FOR EVALUATION OF STRAIN CONCENTRATIONS IN CONCRETE COATED PIPELINES

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ABSTRACT

MARINTEK has developed software for detailed analysis of pipelines during installation and operation. As part of the software development a new coating finite element was developed in cooperation with StatoilHydro enabling efficient analysis of field joint strain concentrations of long concrete coated pipeline sections.

The element was formulated based on sandwich beam theory and application of the Principle of Potential Energy. Large deformations and non-linear geometry effects were handled by a Co-rotated "ghost" reference description where elimination of rigid body motion was taken care of by referring to relative displacements in the strain energy term. The non-linearity related to shear interaction and concrete material behaviour was handled by applying non-linear springs and a purpose made concrete material model.

The paper describes the theoretical formulation and numerical studies carried out to verify the model. The numerical study included comparison between model and full-scale tests as well as between model and other commercial software. At last a 3000 m long pipeline was analysed to demonstrate the strain concentration behaviour of a concrete coated pipeline exposed to high temperature snaking on the seabed.

INTRODUCTION

Several authors have dealt with the problem of calculating strain concentrations in field joints of concrete coated pipelines.

Lund et.al. (1993) presented an analytical model which was based on axial force and moment equilibrium when considering the contributions from the steel pipe, the concrete coating, the tensile armour and the shear interaction between the concrete and the corrosion coating. Verley and Ness (1995) extended this model to include non-linear material descriptions for the steel, the concrete and corrosion coating and allowing the concrete to slide relative to the steel. The new semi-analytical model was validated against results from the computer code DIANA as well as full scale tests.

In order to simulate pipeline behaviour during operation, finite element (FEM) analysis is commonly applied in order to capture global buckling behaviour at elevated temperatures. However, in the case of such analysis for concrete coated pipelines, existing models requires the pipe and the concrete coating to be modelled by shell elements. It is therefore not feasible to model long concrete coated sections and the analysis procedure therefore need to be based on a two step procedure. Finite element analysis is first performed based on neglecting the concrete coating. Then a local model including the concrete coating effect is applied to establish the strain concentration factor (SCF) .

The objective of the present development has been to formulate a model that include the governing effects directly as part of the FEM analysis and enabling efficient analysis of long pipeline sections.

MATHEMATICAL MODEL

Assumptions and approach

The mathematical equations developed are implemented by applying the finite element method. Such a formulation requires three main ingredients:

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- A material law.
- A kinematics description.
- An energy principle to formulate numerical equations that can be implemented into a computer code.

When formulating the above, the following assumptions have been made:

- The bending moment contribution from the concrete coating is governed by the capacity curve of the corrosion coating beneath and/or the capacity of the concrete material.
- The contribution from the local shell moments in the concrete coating due to the bending of the pipe can be neglected.
- The shear interaction is only a result of bending, i.e. the straining of the concrete coating due to tension is not considered.
- The contribution from the steel armouring cage used when applying the concrete coating is small.

The last assumption is easily verified by considering the fact that the armour quantity applied is very small, only serving the purpose of keeping the concrete coating in place during manufacturing and installation..

To validate the other assumptions, numerical investigations are needed. Therefore, comparisons have been made with shell formulations applying well established computer codes such as DIANA and ABAQUS in addition to full scale tests.

Energy principle and kinematics

The approach taken with respect to the behaviour in bending is by dividing the circular concrete coating into equal width strips to which sandwich beam theory can be applied, each formulated in terms of the Potential Energy as:

$$\Pi = \tfrac{1}{2}\int_0^l EA\left(\frac{dv_s}{ds}\right)^2 + \tfrac{1}{2}k(v_s - v_p)^2\, ds - Pv_p \qquad (1)$$

where EA is the non-linear axial stiffness of each strip strip, v_s is the actual longitudinal displacement along the strip and v_p is the strip displacement that would occur if plane surfaces remained plane after bending deformation. k is a shear stiffness parameter and P is the external loading.

To explain the reference to sandwich beam theory, reference is given to Figure 1. The shear deformation γ is defined by:

$$\gamma = \frac{v_s - v_p}{t} \qquad (2)$$

where t is the thickness over which the shear deformations occur. Hence, the shear stiffness parameter k is:

$$k = \frac{Gb}{t} \qquad (3)$$

where G is the non-linear shear modulus and b is the width of the strip.

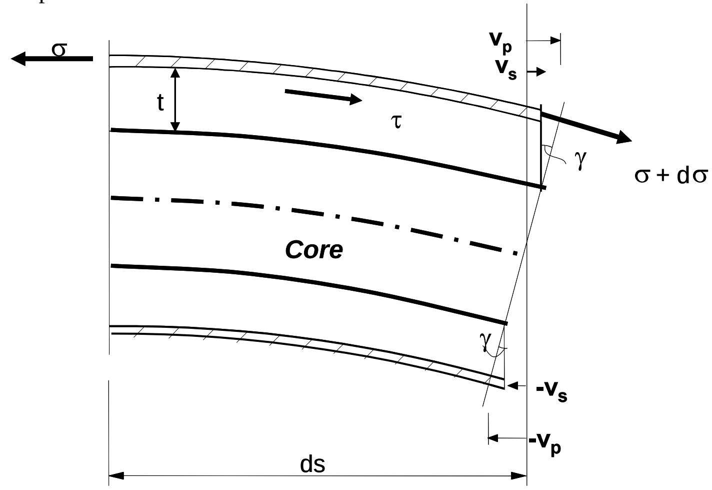

FIGURE 1 - SANDWICH BEAM THEORY

With reference to Figure 2, the strip *plane surface remain plane* deformation can be expressed in terms of 3d-beam quantities as:

$$v_p = R\cos\theta \frac{du_z}{dx} - R\sin\theta \frac{du_y}{dx} \qquad (4)$$

where θ is the angular coordinate referred to the pipe local coordinate system shown in Figure 2, being zero at the intersection point between the local negative z-axis and the pipe surface. u_y is the transverse displacement along the local element y-axis and u_z is the transverse displacement along the local element z-axis.

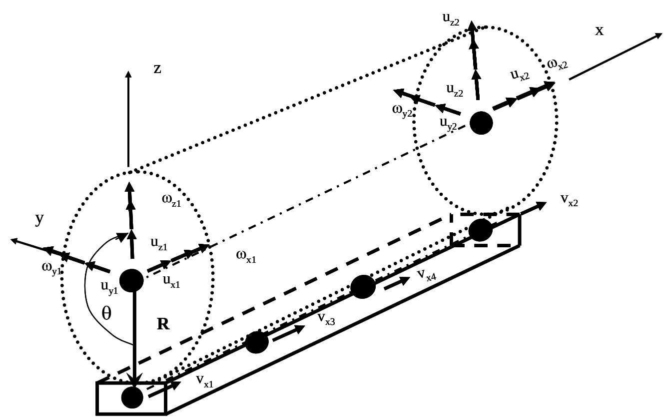

FIGURE 2 – ELEMENT COORDINATE SYSTEM AND FINITE ELEMENT DOFS

The equilibrium equations are found by minimising the potential energy. The resulting virtual work equation used to calculate the stiffness matrix contribution from the strip is:

$$\int_0^l [\ EA(\frac{dv_s}{ds})\delta(\frac{dv_s}{ds}) + kv_s\delta v_s - kv_p\delta v_s - k\delta v_p v_s + kv_p\delta v_p\ ]ds = P\delta v_p \quad (5)$$

where the shear stiffness parameter k, generally is a non-linear function. In the non-linear case, the above equation is applied on incremental form using the tangential shear stiffness obtained from the current equilibrium state.

The corresponding equation used for equilibrium control for the strips at any load step is:

$$\int_0^l [\ S_{sb}\delta(\frac{dv_s}{ds}) + F_s\delta v_s - F_s\delta v_p\ ]ds = P\delta v_p \quad (6)$$

where S_{sb} is the force in each strip from bending effects and F_s is the shear spring reaction force. The above equation is applied at the current equilibrium state.

Material models

Two material models are required for the finite element:

- A non-linear shear interaction model capturing cyclic material model effects for the corrosion coating applied between the pipe and the concrete coating.
- A model capturing the cyclic non-linear material behaviour for the concrete coating.

Both material models have been based on adopting the concepts described by Levold (1990). The stick-slip behaviour governing the corrosion coating is handled by applying an elastoplastic model. The concrete coating is treated by modifying the elastoplastic model so that it behaves elastoplastic on the compressive side, but hyper-elastic in tension. This requires one extra parameter, ε_0, to keep track of when tensile stresses are to occur, see Figure 3.

It is well known that concrete looses its tensile strength for small loads. This behaviour is simulated by applying a very small stiffness on the tensile side, sufficient to improve numerical stability, but without influencing the results which is primarily governed by the compressive capacity of the concrete.

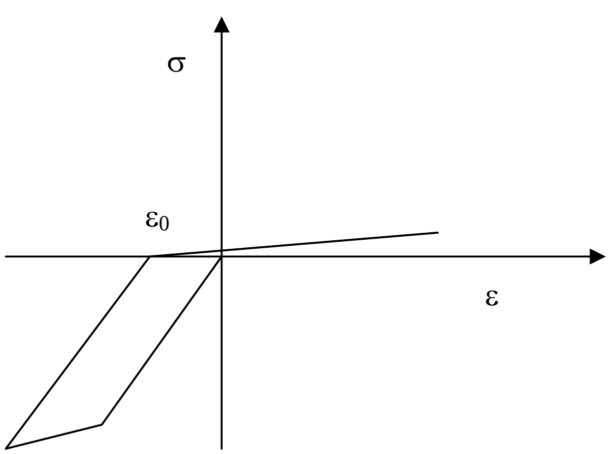

FIGURE 3 - CONCRETE MATERIAL MODEL PRINCIPLE

Finite element implementation

The resulting finite element consists of alltogether 16 degrees of freedom (DOFS), 12 beam DOFS and 4 local longitudinal DOFS to describe the shear interaction, see Figure 2. This means that the coating element is easily combined with pipe elements. Cubic interpolation was applied in the transverse directions as well as in the local longitudinal direction. 3 point Lobatto integration was further applied to calculate the stiffness matrix and the element load vector. The element was implemented into the computer code SIMLA, see Sævik et.al. (2004, 2005 and 2008).

MODEL VALIDATION.

Testing the pipe element versus ABAQUS and PAS

In order to ensure that pipeline strains are correctly predicted it is of crucial importance that the material model applied for the steel pipe is capable of handling the coupling between hoop stress and longitudinal stress. In order to demonstrate that this is the case for the material model applied in SIMLA, a 42" pipe section was exposed to constant curvature in combination with internal pressure. The applied input parameters are shown in Table 1.

TABLE 1 – 42" PIPELINE INPUT PARAMETERS

Parameter	Value
Internal diameter	ID= 1.012 m
Wall thickness	35.0 mm
Internal pressure	16.4 MPa
Curvature	0.05 m^{-1}
ε_p	0.00184
σ_p	381 MPa
$\sigma_{0.005}$	450 MPa

Figure 4 shows the bending moment versus longitudinal strain at the compressive side obtained from SIMLA as well as the computer codes ABAQUS and PAS (1994). It is seen that the correlation is very good. SIMLA uses 16 integration points for the 3D pipe element, which corresponds to 9 for the 2D PAS model. In the ABAQUS model, both 8 and 16 integrations points were applied using the element PIPE32. It is seen that for the 8 integration point alternative, the bending moment is underestimated by approximately 4%.

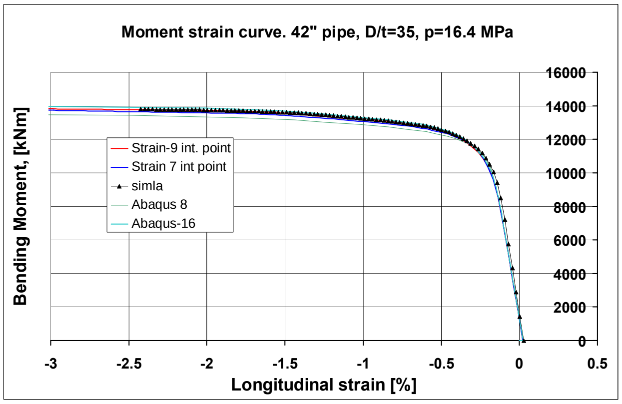

FIGURE 4 COMPARING SIMLA, PAS AND ABAQUS

Testing SIMLA versus DIANA and ABAQUS and including the effect of internal pressure

The case investigated is the same as described by Endahl (1994) and Verley and Ness (1990). A 20” pipe with 17.9 mm wall thickness was studied. The steel material is X65 and the pipe is coated with corrosion coating with shear strength 0.3 MPa at 3 mm displacement and 80 mm concrete with compressive strength 40 MPa at 0.2% strain. The model is 6 m long, representing one 12 m joint, utilising symmetry. The cut back is 0.32 m and a constant bending moment is applied by prescribing rotation in one end.

The SIMLA model is shown in Figure 5. The concrete coating has been divided into 16 segments in the circumferential direction, each represented by strips of coating elements. Each coating element has 4 nodal points, see Figure 2. Nodes 1-2 are represented by 6 beam DOFs each, and are common nodes to the pipe element nodes. Nodes 3-4 are 1 DOF nodes that describes the relative axial displacement to the supporting pipe.

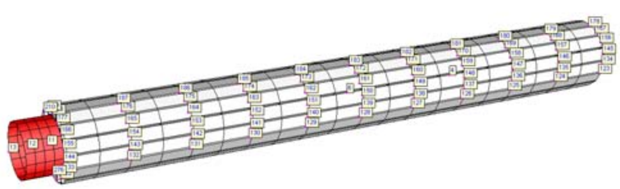

FIGURE 5 - SIMLA ELEMENT MESHING

An ABAQUS model is also applied based on concentric shell layers modelling the steel and the concrete and an extended field joint section to avoid shell boundary effects. Linear reduced integration shell elements (S4R) was used for both concrete and steel. The corrosion coating was modelled as a pure shear interface defined by connector elements (CONN3D2) between the steel and concrete nodes tangential to the shell surface. These elements were used as non-linear springs, giving a shear stress limit of 0.3 MPa. In the radial direction, a kinematic coupling was applied to constrain the concrete nodes to the steel nodes.

Figure 6 shows the strain concentration factor (SCF) as a function of the global strain which is defined as the bending strain that would occur without concrete coating. The SCF is further defined as the ratio between the maximum strain found in the field joint for the coated case and the same global strain. Figure 6 shows results obtained from both SIMLA and ABAQUS, also including the DIANA results reported by Verley (1995). It is seen that good correlation is found between DIANA and ABAQUS. Good correlation is also seen with SIMLA, especially between ABAQUS and SIMLA when the global strain increases.

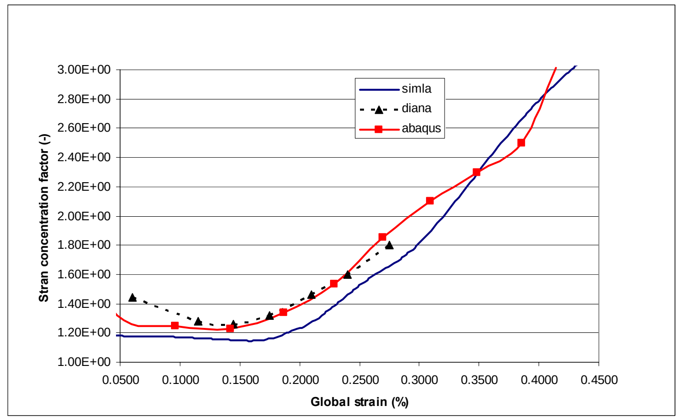

FIGURE 6 - COMPARING DIANA, ABAQUS AND SIMLA SCF

Figure 7 shows similar SIMLA and ABAQUS results at elevated internal pressure. As expected, the SCF starts to increase at a lower level as the internal pressure increases. This is confirmed by both programs. This tendency is more pronounced in the SIMLA analysis than in ABAQUS. However, at a certain global strain the concrete coating crushes and the effect of internal pressure is reduced. This is confirmed by both programs. The overall correlation is therefore found to be very good, the SIMLA results being on the conservative side for large strains.

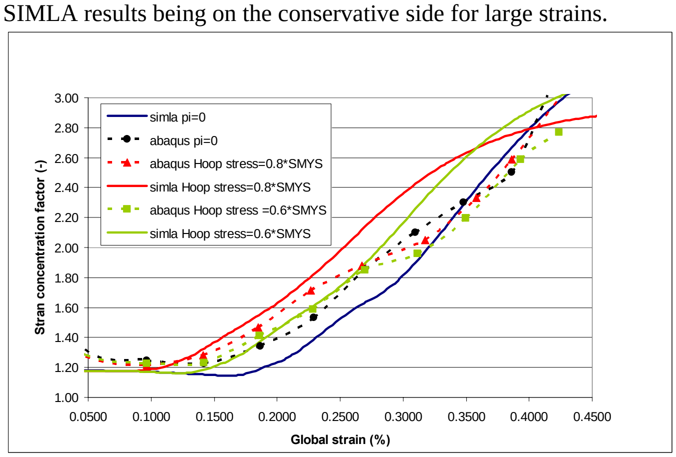

FIGURE 7 - COMPARING ABAQUS AND SIMLA SCF AT ELEVATED INTERNAL PRESSURE

Test 2 and 3 as described by Verley and Ness (1995)

The cases investigated are referred to as Test 2 and 3 in the work by Verley and Ness (1995) where the SCF was obtained by full scale 4 point bending tests of a 24 m long pipe including two field joints. The input data are summarized below:

TABLE 2 – FULL SCALE TEST INPUT PARAMETERS

Test	2	3
D_o (mm)	517	525
T_{steel}(mm)	18.5	18.5
T_{corr}(mm)	6	6
Coating	Asphalt	Asphalt
$T_{concrete\ (mm)}$	80	40
Concrete strength (MPa)	36.4	44.2

The applied steel material in the FE model was according to the moment-curvature results as reported by Verley and Ness (1995). The applied shear strength was 0.55 MPa at 3mm relative displacement. The loading was by prescribed displacement according to the test set-up, applying symmetry so that one half of the test specimen was modelled. The applied model is shown in Figure 8.

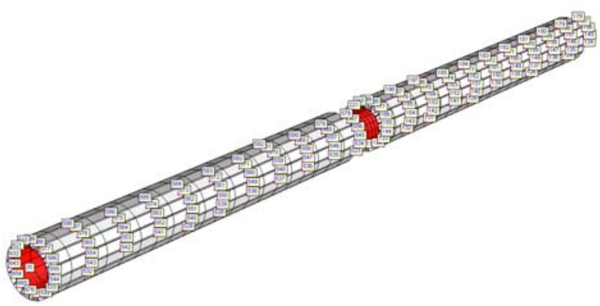

FIGURE 8 APPLIED ELEMENT MESHING FOR TEST 2 AND 3

Figure 9 and Figure 10 shows the tested and simulated SCF as a function of global strain. It is seen that SIMLA underestimates the SCF below 0.2% strain, however, being on the conservative side for larger strains. However, the stabilization in terms of SCF increase seen in the tests is also seen in the SIMLA results. Considering the inherent uncertainties, the behaviour of the coating element is considered to be very encouraging.

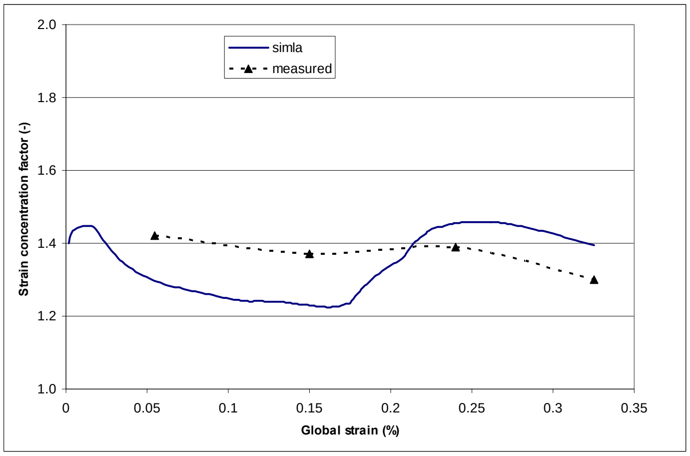

FIGURE 9 - SCF FROM SIMLA – TEST 2

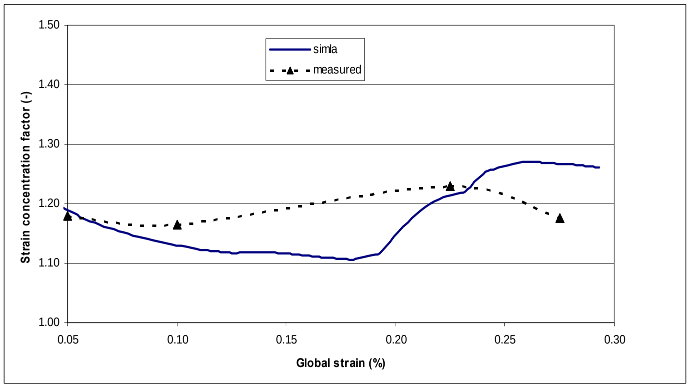

FIGURE 10 SCF FROM SIMLA – TEST 3

FULL MODELLING OF A GLOBAL BUCKLING CASE

Input data

A 42" pipe resting on a flat seabed was investigated. The model length was 1500 m. By assuming a symmetric buckling mode, the real model length was 3000 m. An imperfection was introduced at the midpoint by applying a point load at the left end at the model. The parameters are shown in Table 3. The analysis was carried out by two alternative procedures:

- By applying SIMLA and the coating element
- By applying PAS and the MOMKAP program, see Verley and Ness (1995)

TABLE 3 – 42” PIPELINE FLAT SEABED INPUT PARAMETERS

Parameter	Value
Internal diameter	ID= 1.016 m
Wall thickness	30.8 mm
Concrete thickness	45 mm and 80 mm
Concrete compressive strength	36.4 at strain 0.002
Corrosion coating shear strength	0.1 MPa
Submerged weight, operation	4000 N/m
Internal pressure	16.4 MPa
Axial friction coefficient	0.5
Axial friction coefficient	0.9
Temperature	100 ^{o}C
Axial resistance	2000 N/m
Lateral resistance	3600 N/m
Proportionality limit steel, σ_p	381 MPa
Yield stress, $\sigma_{0.005}$	450 MPa

Analysis results

First the analysis was made without concrete coating in order to compare with PAS. Thereafter the same model was applied but including the concrete coating elements. Concrete coating elements were applied over 240 m length and the average element length was 0.42m. The FEM model is shown in Figure 11.

Figure 12 shows the strain concentration factor obtained by SIMLA for two different coating thicknesses, 45 mm and 80 mm, as a function of global strain. The global strain is taken as the strain that would result without concrete coating. The figure also shows the SCF obtained by the alternative procedure by PAS and MOMKAP. It is noted the alternative procedure was based on calculating the moment contribution from the concrete coating at a selected global strain level, here taken to be 1.0% strain. Then this moment contribution was used to modify the stiffness distribution for each element along the crown of the buckle. It is seen that the alternative procedure underestimated the SCF at global strain below 1%, however, overestimating it beyond that point. This is as expected, since the concrete coating crushing effect beyond 1% global strain is not included in the simplified procedure. The stress distribution in the concrete coating at the buckled configuration is shown in Figure 13.

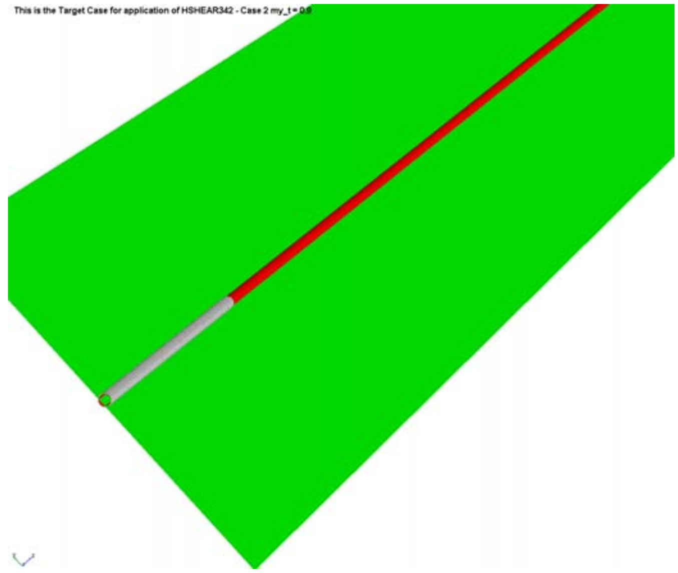

FIGURE 11 – FEM MODEL – SNAKING SIMULATION

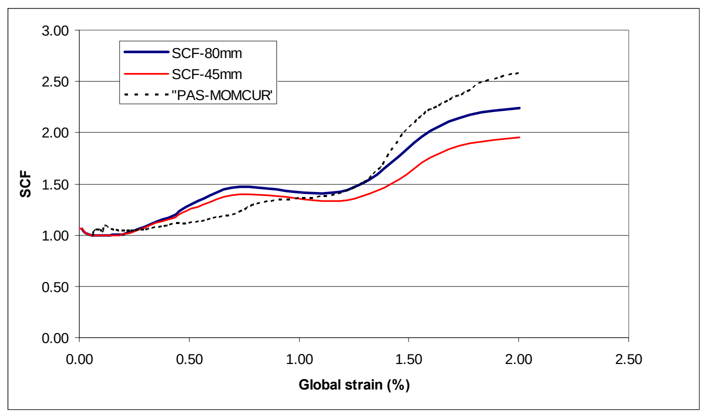

FIGURE 12 – SCF AS A FUNCTION OF NO CONCRETE COATING STRAIN – SHEAR STRENGTH 0.1 MPA

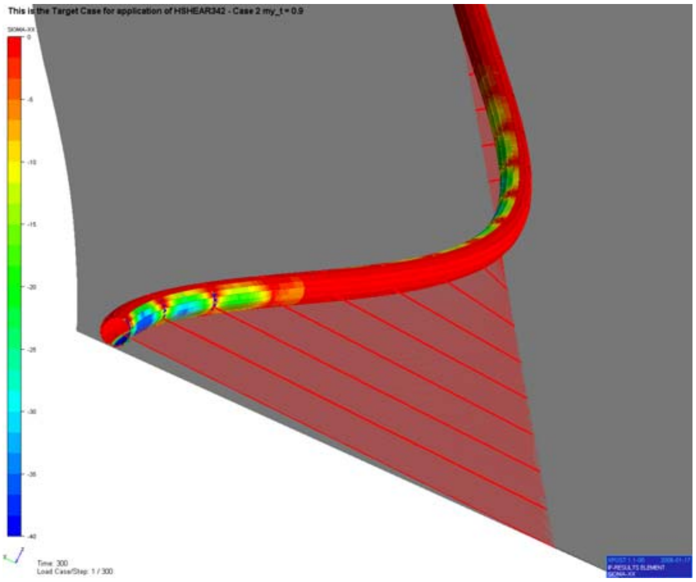

FIGURE 13 - CONCRETE COATING STRESS DISTRIBUTION AT BUCKLE

CONCLUSIONS

A new efficient finite element has been developed for simulation of strain concentrations in long sections of concrete coated pipes. The element included a simplified material model for the concrete coating which is based on an elastoplastic description on the compressive side and hyper-elastic behaviour on the tensile side. A similar model is also used to describe the shear interaction between pipe and concrete coating.

The model has been validated against the computer codes PAS, DIANA and ABAQUS. With respect to the coating element, generally good correlation is found between DIANA, ABAQUS and SIMLA with respect to SCF for the no internal pressure case. Similar correlation is also found between SIMLA and ABAQUS for the pressurized cases. It has been demonstrated that the internal pressure will increase the SCF at moderate global strain level. However, this stabilizes when the crushing capacity of the concrete is reached.

By comparing against experiments, SIMLA is found to be conservative with respect to predicted SCF beyond 0.2 % global strain. The stabilization of SCF seen in the tests beyond 0.2% global strain is also confirmed by SIMLA.

With regard to applying the element in buckling analysis, it has been verified that the element behaves numerically well both with regard to computing time and convergence rate. Basically, the convergence rate is similar to the one without applying the coating element.

For the no-concrete case comparison has been made with PAS and in general good correlation is found. It has further been demonstrated that for realistic shear strengths and strain levels the SCF found by using the new finite element is in agreement with the SCF values previously used by StatoilHydro for such cases.

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