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Materials & Inspection Engineering Group

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SUBJECT	: Review Dunlaw Design Report Document No. PENGL/12/UK006524/402/PRO-2/015	
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1. Introduction

Problem description

Concerns were raised by SUKEP-EPET-PS about the long term clamping integrity of polyurethane piggy-back clamps and Guides made of High Density Poly Urethane HDPU and which are designed to clamp a 193 mm flexible riser onto a 30"conductor. The clamps are strapped around the 30" conductor with aramid (Kevlar 49) straps. The function of the clamps and guides are (a) to ensure that the specified stand-off distance between the riser and the conductor is maintained and (b) that there is no rotation of the clamped riser around the conductor.

The concerns have focused on the question whether the mechanical applied clamping force will remain at a sufficient level throughout the lifetime of the clamp: Polyurethane and aramid show a visco-elastic behaviour, and the stress relaxation in the aramid strap and the creep behaviour of the polyurethane will result in a gradual reduction of the strap tension, and hence in a loss of the clamping force.

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The main questions are:

(a) Does the visco-elastic behaviour of the clamp and straps cause a clamp integrity problem during the full design lifetime.

(b) Is the test program as proposed by Technip provides adequate to demonstrate the integrity for the required design life.

During the telecon meeting of 7 June 2006, Technip/Dunlaw was requested to prepare a test proposal to SUKEP-EPE-T-PS.

SUKEP-EPE-T-PS requested Shell Global Solutions to review the non-metallic materials aspects of this proposal, focussed on the proposed testing programme.

2. Telecon 7 June 2006: Stress Relaxation/Creep

The integrity issue was discussed during a telecon meeting on 7-Jun-2006 attended by SUKEP-EPE-T-PS, Technip, Dunlaw and Shell Global Solutions GSEI/2. Because of the complexity of the loading conditions, the lack of reliable visco-elastic data of the aramid and HDPU under the given conditions and the project time constraint as indicated by SUKEP-EPE-T-PS, GSEI/2 indicated that prediction modelling of this problem would be complex (see below), and it was therefore proposed to follow a performance based test instead. The approach would be: use inline load cells to monitor the tension in the aramid straps as function of time. The test data can then be used to predict the strap tension as function of time. With the defined acceptance criterion on minimum required strap tension i.e. a minimum required slip-force, a prediction on the longer-term integrity should be possible. The concept proposed during the telecon meeting is outlined in Appendix 1.

Linking creep/relaxation data with actual loading conditions

The design of the polymer clamp/strap combination results in complex time dependent stress/strain behaviour. It would require complex modelling to predict the remaining clamp stress with time. Modelling is therefore not recommended. Even in case modelling would be possible, extensive creep and relaxation tests at various stress resp. strain levels would be required as input for the model. At the moment this data is not available, and would have to be generated.

Based on this it seems therefore more sensible to follow a performance based test on a full clamp/strap in which the stress in the straps is directly measured using an inline load-cell, and monitor this relaxation with time. To provide sufficient statistical confidence multiple tests would be required. For this reason it is recommended to follow the performance based testing as indicated in Appendix 1.

3. Review Dunlaw report

The results of the Materials & Inspection Engineering group's review of Report PENGL/12/UK006524/402/PRO-2/015 are provided in Appendix 2 of this note. For the detailed comments and questions see Appendix 2. Section 3.1 discusses the results of the review, and provides recommendations for improvement.

3.1 Discussion

From the tests reported, it followed that none of the current clamp/strap components tested have passed the qualification test on minimum required slip-load. (Using the defined safety factor of 2). The slip load is primarily determined by:

(a) The normal force between clamp and conductor (i.e. tension in the aramid straps);

(b) The friction factor between the clamp and the conductor surface (i.e. the coating).

To meet the criterion on the minimum required slip-load the friction between the clamp/conductor has to be increased. This can be achieved by increasing the normal force and/or the friction factor between the clamp/conductor surface.

In the current design, the conductor FBE coating is assumed to be a given factor (existing conductor), so modification of the conductor coating (e.g. a slip resistant coating) is considered not to be possible. Application of slip-resistant surface layer of the inside clamp surface in contact with the conductor could be considered (e.g. in-situ moulded sand particles).

The existing coating of the conductor must provide sufficient strength to transfer the friction forces from the straps and clamp to the conductor. This issue has not been addressed in the current design.

Stress relaxation, normal force and effect on friction

The test program revealed that the tension in the aramid strips is not constant due to stress relaxation in the straps and creep in the HDPU clamp. The visco elastic properties of the polymer components therefore play a critical role in the design, and this need to be taken into account in the design and installation procedures.

To compensate for the stress reduction in the aramid straps a higher initial strap tension will be required. A higher initial strap tension will however result in more severe creep and stress relaxation in the strap/clamp system. The net result of increasing the initial strap tension on the creep/stress behaviour of the full system (strap+clamp) is not fully known at the moment and needs to be further evaluated by experiments on full scale strap/clamp tests. These tests should provide a better understanding of the stress reduction in the straps as function of time.

More important: It seems that in the current design the visco-elastic properties are not adequately addressed. The question is whether the current design can accommodate the required higher initial strap tension (complete system of straps, Bobbins, bolts, HDPU), i.e. is the selected design fit for purpose given the observed stress-relaxation/creep behaviour?

Visco-elastic effects are highly dependent on temperature. In the design report the operating temperature of the clamp is not defined. It is recommended to verify and adjust the test temperatures of the envisaged tests if required.

Fatigue of the strap/clamp construction has not been addressed in the report reviewed. It is recommended to check whether fatigue is an issue or not.

Proposed tests by Dunlaw

One of the key parameters, i.e. the tension in the aramid straps itself, has not been measured directly in the tests carried out so far, and will also not be measured in the proposed extension of the test programme. The tension in the straps has been derived from torque-moments in the bolts of the fasteners. To our opinion this is not accurate and only provides an instantaneous value.

A direct measurement of the strap tension is required to determine the stress relaxation as function of time, and to be able to predict the stress behaviour of the full clamp/strap system. It would also provide an important tool to investigate the effect of intermediate post-tensioning of the straps on the relaxation behaviour. The strap-stress can be used to calibrate the analytical calculations, and can also be used to extrapolate to determine the longer term performance.

It is also recommended to be careful in testing combinations of used and new straps and/or clamp components. Visco-elastic behaviour depends on the load history of a component, and visco-elastic stress/strain effects are not reversible. To avoid this, all experiments shall be done on new components, and the load history has to be carefully recorded during the full test cycle of the component.

4. Proposed test programme

The following list provides improvements to the test programme proposed by Dunlaw:

- Define the acceptance criterion for the minimum required strap tension load (from clamp-slip calculations);
- Carry out a performance-based test on full-scale clamp/strap components with inline load cells placed in the straps to be able to continuously monitor and record the tension in the straps. This would be a direct way to measure the combined effect of creep in the HDPU and stress relaxation in the HDPU on the tension in the strap.

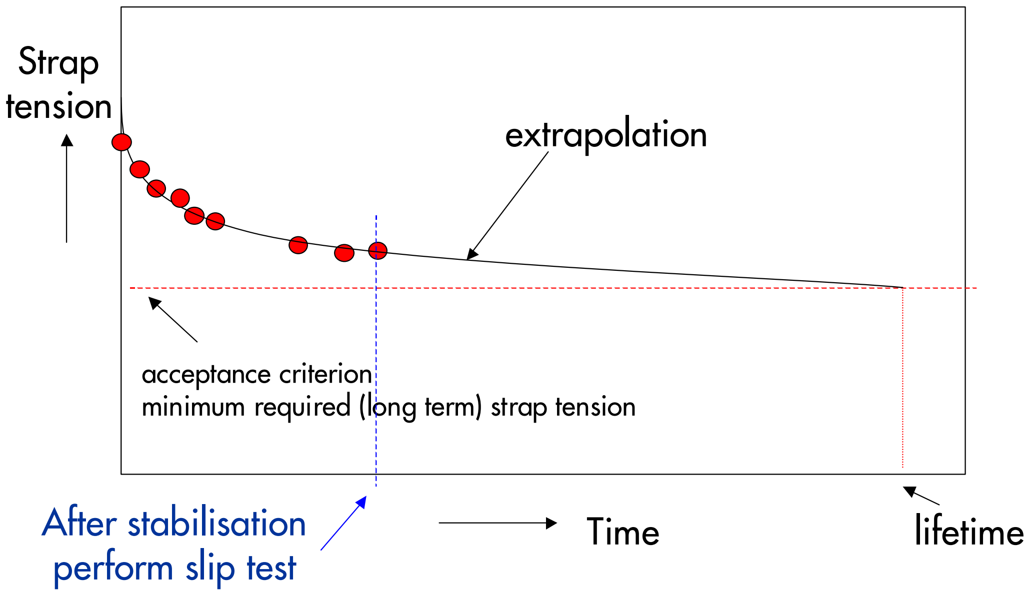

Figure 1 Strap tension transient from in-line load cell

- Monitor the tension stress in the clamp-straps as function of time (see graph above). Once the relaxation has been stabilised, perform a slip test to check conformance with the slip-load criterion, and calibrate with analytical calculations. From the previous tests it was found that the applied load rate affects the slip behaviour of the clamp. The selection of the load rate needs to be challenged against actual installation/operation conditions.
- Extrapolate remaining strap tension load to desired lifetime to estimate the longer-term effect (using the calibrated analytical calculations). As the shape of the curve is not known at the moment, it is difficult to estimate the required time.

- Multiple tests need to be carried out to determine statistical scatter.
- The effect of 'pre-tensioning' ('relaxation-allowance') can be included as well.
- For each test, new clamps and straps need to be applied to avoid the effect of load-history effects on the material behaviour.
- A worst-case test temperature needs to be selected, based on the maximum temperature the clamp/strap construction will see during construction/operation.

In addition it is advised to address the recommendations and questions provided in Appendix 2.

5. Conclusions

(a) From the tests report, it followed that none of the current clamp/strap components tested has passed the qualification test on minimum required slip-load.

(b) A number issues seems to be not adequately addressed in the current design, and need to be challenged:

- It seems that in the current design the visco-elastic properties are not adequately addressed. The question is whether the current design can accommodate the required higher initial strap tension (complete system of straps, Bobbins, bolts, HDPU), and this provides sufficient additional friction to increase the slip load, i.e. is the selected design fit for purpose given the observed visco-elastic behaviour of the clamp/strap system?
- The minimum required slip-load depends on both the friction coefficient between the clamp and the coating and the straps and the coating, but also on the condition of the existing coating. If the friction between clamp/coating and strap/coating are sufficient, but the adhesive bonding of the coating is insufficient, the slip-load will drop.
  No background information has been provided in the report on assumed required design slip-load level. It is recommended to challenge the quoted value (see also point above with relation to cyclic loading).
- Cyclic loading (fatigue) apparently has not been taken into account in the design.
  It is recommended to investigate whether the current clamp/strap system is sensitive to cyclic loading (fatigue, strap-tension).
- The maximum operating temperature has not been defined in the report. For both the calculations and the qualification tests, a worst-case temperature needs to be defined. Materials properties of polymers, and especially the Visco-elastic properties very much depend on temperature.

(c) The visco-elastic effects of the polymer components were found to be a critical parameter in the clamp/strap design. The polymer clamp/strap combination shows a complex time dependent stress/strain behaviour. Because of the complexity modelling to predict the remaining clamp stress with time is not recommended. Even in case modelling would be possible, extensive creep and relaxation tests would be required at various stress resp. strain levels to generate input for the model.

It is recommended to follow a performance-based test on a full clamp/strap in which the stress in the straps is directly measured using an inline load-cell, and monitor this relaxation with time. To provide sufficient statistical confidence multiple tests would be required.

The test set-up of the proposed test program by Dunlaw to our opinion does not provide the necessary data to determine the strap stress behaviour as function of time. Recommendations for improvement of the proposed test programme have been provided in this report.

LM/mv

Appendix 1 Stress relaxation/creep in piggy-back straps/ HDPU block – material presented during telecon of 7 June 2006

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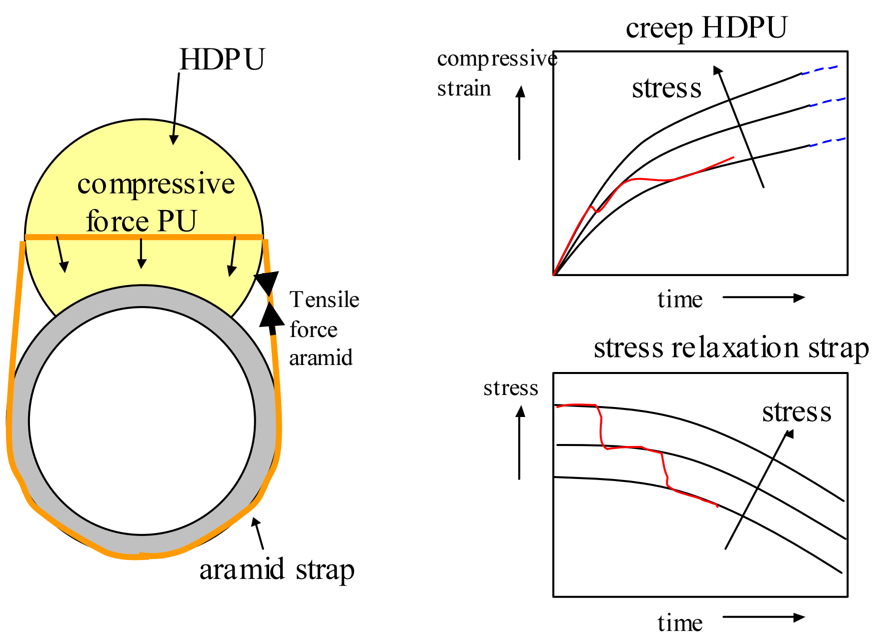
Stress relaxation/creep in piggy-back straps/HDPU block

L.M. de Mul



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Issues

- Stress relaxation in aramid straps, but load is not constant
- Creep in HDPU but displacement not constant
- => stress relaxation & creep tests required at range of stress levels/displacement levels
- This data is most probably not available
- Iterative modelling required + complex geometry (=> FEA)
- Time constraint => modelling/testing route complex and time consuming

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Proposed approach

- No modelling
- Performance based test with inline load cells
- Monitor strap tension load as function of time
- Extrapolate remaining strap tension load to desired lifetime
- Define acceptance criterion minimum strap tension load
- Pass/No pass
- risk: shape of creep curve HDPU (tertiary creep regime)

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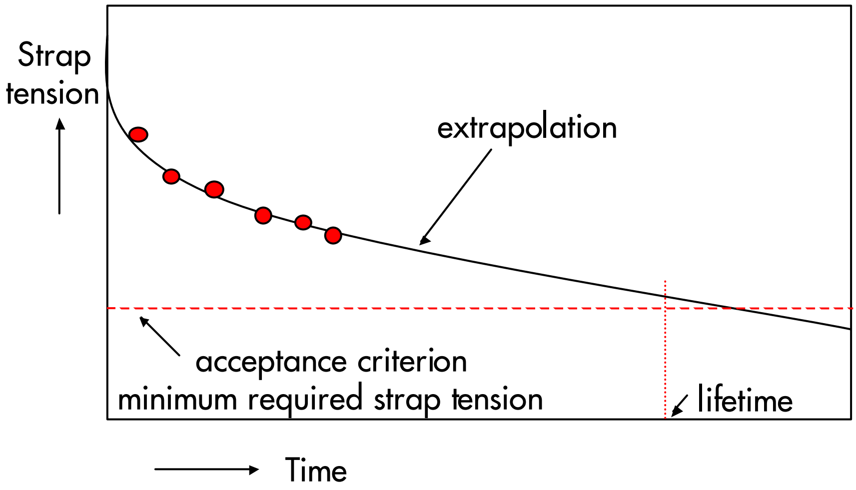
Strap tension from in-line load cell



Appendix 2 Review of *Report PENGL/12/UK006524/402/PRO-2/015*

L.M. de Mul, Shell Global Solutions Internationals B.V.

As requested, the non-metallic materials aspects of the report have been reviewed. It should be noted that the design calculations and FEA analysis have not been reviewed in detail.

1. Design Report Section

Comment #	Description
1	Page 5, Table 2.1 "Summary of theoretical results obtained" The analysis given in Section 7.1 of the design report is an elastic/plastic analysis. Only the creep of the straps has been taken into account. The combined Visco-elastic analysis of straps and clamp (stress-relaxation + creep) has not taken into account. From the experimental tests it followed that the reduction in stress (derived from strap bolt torques) to this combined effect is substantially.
2	Section 2.2., Page 6 Linear Finite Element Analysis (FEA) has been used to model the strain and stresses in the clamp. Visco-elastic behaviour was not taken into account. Actual stresses and strains from the FEA analysis might therefore deviate significantly from the actual stresses. The maximum stresses in the HDPU component are reported to be in the order of 8.2 MPa, resulting in a displacement of 4.9 mm. Under creep conditions, the displacements might be considerably higher. In the test report tensile creep strains in the HDPU of over 40 % are reported at a creep stress of 2.5 MPa. Modelling of the actual displacement would be complex, and would require multiple compression creep curves generated at a range of stresses, as the stresses are not constant in time (due to stress relaxation).
3	Section 3.4: Tensioning test General: Bolt torque indirect measure of the actual strap tension, and depending on the friction coefficient of the bolt/grease system used. As discussed during the telecon on 7/6, it is recommended to use an inline load cell to accurately measure /monitor the tension in the strap directly. See also Comment 4 and 5. Using the in-line load cells also provide information on the accuracy of the bolt torque procedure (variation in strap tension). General: Visco-elastic behaviour needs to be monitored over a longer period of time to establish the creep/relaxation behaviour. Relation test temperature versus maximum operating temperature? Page 9: **<quote>**Please note that the final torque figures following the second round of tensioning, with exception of 2, are within the theoretical design torque value of 186 Nm **<unquote>** **Question:** From the this statement it is understand that 186 Nm is the design torque value i.e. the level which should be remained during the total lifetime of the component? It is expected that the torque values quoted in Table 3.4 will further drop with time. The proposed test programme should address this issue in quantifying the creep/relaxation behaviour of the entire system.

Comment #	Description
4	Section 4: Materials Analysis Page 10: It is stated that the TDI system has 'better mechanical properties' than the MDI system. **Questions:** (a) What mechanical properties have been used as criteria? The visco elastic properties seem to be the critical parameters in terms of clamp integrity. (b) How do the visco-elastic properties of the TDI compares to that of the MDI system. If there is a significant difference, TDI and MDI systems need to be assessed separately.
5	Section 4.2: Material Sample Testing Combined effect of aramid stress relaxation and polyurethane creep need to be taken into account.
6	Section 5.2: Creep in the Kevlar Straps **During the telecon on 7/6 it was recommended to use in-line load transducers to be able to directly measure and monitor the tension in the aramid (Kevlar) straps. This seems not to be adopted in the current test set-up. It is highly recommended to measure the strap tension directly using in-line load transducers (both short and long term tests). See also point 3 above.** *It is also recommended to test the combination of **new** clamp + **new** aramid (Kevlar) straps, and use the actual installation procedures. In this way the total creep/stress relaxation behaviour can be monitored under the same conditions as seen during the actual installation.* The main problem with the combination of either used clamps or used aramid straps are that the initial (historical loading) condition of used components is not well defined. This makes interpretation of the results difficult and unreliable. The value of linear FEA analysis to examine stress levels is limited if creep/relaxation behaviour are not taken into account.
7	What is the objective of this test, and what will be actually measured? If the aim is to determine whether there is a difference in creep behaviour between the two Robbin Assemblies, it would be better to test the Robbin Assemblies directly in a rigid/stiff test frame **without** the aramid (Kevlar) straps (to eliminate the creep contribution of the aramid straps).
8	Section 5.5: Long term testing ***The tension in the aramid straps should be measured and monitored directly using an in-line load transducer (See first point under 6).***
9	Section 6.0: Summary of results **Bullet point 1:** It should be noted that only static loads have been considered in the analytical calculations without taking into account visco-elastic properties of the polymer clamp/strap combination and/or creep of the Bobbin assemblies. For the clamp slip calculations the stress reduction in the straps as a result of the combined creep/stress relaxation is a critical parameter in these calculations (this observation is supported by the experimental results). The calculations provide a prediction of the slip-load for a given **fixed** strap-tension. **Last bullet point:** It is stated that mechanical and creep characteristics have demonstrated good correlation between the theoretical values used for the analytical calculations. From the results this statement is not clear, and needs verification.

Comment #	Description
10	Analytical calculations: materials input: The **temperature** at which the analysis has been performed is not defined. Materials properties of polymers and especially visco-elastic properties depend on temperature. No information is available on the relaxation behaviour of Kevlar at the specified load/temperature conditions to challenge the assumed relaxation of 7 % over 20 years time. Under what conditions was this data generated (i.e. used creep stress and **temperature(!)**). How does these test results compare to the actual stress in the aramid straps? The creep of the HDPU is expected to have a significant effect on the reduction in tension forces in the aramid straps. In the calculations, the creep of the HDPU has not been taken into account.

2. Test procedure and results section

In the table below the results of the radial (slip) test are summarised.

Test #	New clamp[1)]	New Strap[1)]	P_{slip} [2)] (ton)	P_{STABLE} [3)] (ton)	$P_{qualify}$ (ton)	$P_{slip}/P_{qualify}$	Remark
1	yes	yes	0.92	0.88	6.56	0.14	
2	yes	yes	3.2	3.2	6.56	0.49	Second torque: Pslip = 2.3T
3	yes	yes	4.2	5.3	6.56	0.64	pipe without FBE coating
4	yes	yes	4.9	6	5.2	0.94	new clamp design
5	yes	yes	3.7	4.4	5.2	0.71	new clamp design

[1)] It is assumed that both new clamps and straps has been used for each test
[2)] Criteria for slip not defined in report. Here: first occurrance of load drop
[3)] Criteria: Stable maximum load prior to load relaxation of the loading system

- **No clear definition of the slip-load**
  The report does not provide a clear definition of the slip-load. In the table above, the slip-load has been defined as the first occurrence of load drop in the load-transient curve.
- **Qualification criterion**
  In the report the qualified load is defined as the 'required load' times a safety factor of 2, i.e. either 6.56 ton or 5.2 ton depending on the load point line in the test set-up. This is indicated by $P_{qualify}$ in the table above.
  The clamp qualifies if the slip load is at least equal or higher than the qualified load.
  From the table it follows that none of the clamp/strap combination would qualify under this criterion. In time, the clamp load will reduce as a result of creep in the HDPU and stress relaxation in the aramid straps. Re-testing under these changed conditions will result in a lower slip-load as well.
- **Test rate vs. slip-load level**
  It was reported that the rate at which the test load is applied seems to affect the slip behaviour of the clamp, and that the load rate has been changed. If this is the case, a realistic load rate need to be defined (comparable to estimated load rates during installation/operation) and need to be selected as a constant parameter throughout the test.
- **New clamps/straps for each test?**
  From the report it is unclear whether for each test new clamps and new straps has been used. This is essential for the interpretation of the load relaxation results, as the loading history of the polymer components does affect the stress/strain response.

3. Strap tension report

Acceptance criteria
The functional requirement of the clamp and guides is to:

(a) Ensure that the specified stand-off distance between the two pipelines is maintained and:

(b) That there is no relation of the clamped riser around the main pipe.

A minimum required slip-load has been defined as acceptance criterion for the rotation in the test procedure report. For the stand-off distance neither a test parameter nor an acceptance criterion has been defined in the report.