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Composite repair for piping and pipeline

Qualification test programme. Joint Shell OU sponsored project

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by

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Summary

A joint Shell OU sponsored qualification test programme was performed to evaluate the performance of commercially available composites for the repair of damaged pipeline and piping systems. Composite repair systems of the following suppliers were assessed: Armor plate, Clock Spring, Diamant, Fibaroll, Strongback, Synthoglass, and TDW.

The test programme consisted of (i) short-term pressure strength (burst) tests performed at ambient temperature, and at 65 °C, (ii) 1000 hrs tests, performed at 65 °C, and (iii) pull-off adhesion tests, performed at ambient temperature. Testing included pipe spools with an “external” defect and pipe spools with a “through-the-wall” defect. To determine the effect of surface preparation, and surface condition on the performance, composite repair systems have been applied on a “dry” and “wet” (damp), and on a “blasted”, and “power tool” (grinded) pipe surface.

A composite is qualified for the repair of pipe systems with an “external” defect, when it meets the following requirements:

(i) Restore the minimum specified ultimate pressure strength (burst);
(ii) No yielding at the remaining pipe wall at the location of the defect, at the field hydrotest pressure;
(iii) Design life of the composite repair at-least 20 years.

Qualification testing of the composite repair systems applied on pipes with an external defect, was successful for five systems. The Fibaroll repair system was not capable to restore the minimum specified ultimate pressure strength (burst), and therefore the Fibaroll system is not qualified. For the Armor plate system, the margin of safety was too low to meet the 20 years design life requirement, and therefore the Armor plate system is “conditionally” qualified, i.e. acceptable for temporary repair only.

For corrosion protection of the steel substrate at the location of the composite repair, adequate adhesion to the steel substrate is important, and therefore composite repair systems should be applied on a clean, Sa 2.5 blast cleaned steel substrate. However, power tool cleaning (grinding) may be accepted, if blast cleaning is not feasible.

A composite is qualified for the repair of a pipe systems with a “through-the-wall” defect, when it meets the following requirements:

(i) Restore the minimum specified ultimate pressure strength (burst);
(ii) Restore leak-tighness, at the field hydrotest pressure, for at-least 1000 hrs;
(iii) Design life of the composite repair at-least 20 years.

None of the composite repair systems applied on pipespools with a through-the-wall defect could meet the qualification requirements, i.e. restore leak-tighness, at the field hydrotest pressure of 180 bar, for at-least 1000 hrs. All failures were caused by leakage, and not by fracture of the composite, indicating that performance of the composite repair system is governed by sealing chararteristics, and not by mechanical strength of the composite.

The maximum allowable design pressure for the composite repair systems tested, and applied under “optimal” laboratory conditions, is 27 bar. However, maximum design pressure may be significantly lower when applied under less optimal conditions, e.g. in the field.

It is concluded that application of a composite is a rather ineffective method for the repair (sealing) of pipe systems with a through-the-wall defect. Therefore application of composites to restore “leaktightness” of a pipeline, or piping system with a through-the-wall defect should be discouraged, and other repair options should be considered, e.g. threaded plugs, as already succesffully applied earlier, or full encircling tight-fit metallic sleeves, as specified in DEP 31.40.60.12-Gen.

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Table of Contents

1. Introduction

A joint Shell OU sponsored qualification test programme was performed to evaluate the performance of seven commercially available composite systems for the repair of damaged pipeline and piping systems.

The test programme consisted of (i) short-term pressure strength tests, performed at ambient temperature, and at 65 °C, (ii) 1000 hrs pressure tests, performed at 65 °C, and (iii) pull-off adhesion tests, performed at ambient temperature. Testing included 6” diameter, Schedule 40, ASTM 106 Grade B steel pipe spools with an “external” defect and pipe spools with a “through-the-wall” defect.

To determine the effect of surface preparation, and surface condition on the performance, the composite repair systems have been applied on a “dry” and “wet”, and on a “blasted”, and “power tool” (grinded) surface.

To qualify the composite for the repair of pipe systems with an “external” defect, the composite repair shall meet the following requirements:

(i) Restore the minimum specified ultimate pressure strength (burst);
(ii) No yielding at the remaining pipe wall at the location of the defect, at the field hydrotest pressure;
(iii) Design life of the composite repair at-least 20 years.

To qualify a composite for the repair of a pipe system with a “through-the-wall” defect, the composite repair shall meet the following requirements:

(i) Restore the minimum specified ultimate pressure strength (burst);
(ii) Restore leak-tightness, at the field hydrotest pressure, for at-least 1000 hrs;
(iii) Design life of the composite repair at-least 20 years.

2. Repair systems evaluated

Repair systems from seven different Manufacturers were tested, i.e:

- Armor plate, glass-fibre reinforced epoxy, wet lay up (Figure 1);
- Clock spring, glass-fibre reinforced polyester, pre-cured coil (Figure 2);
- Diamant, steel wire mesh reinforced epoxy type putty (Figure 3);
- Fibaroll, glass-fibre reinforced vinyl ester, UV-curing, wet lay-up (Figure 4);
- Strongback, glass-fibre reinforced urethane, water-activated, wet lay-up (Figure 5);
- Synthoglass, glass-fibre reinforced urethane, water-activated, wet lay-up (Figure 6);
- TDW Black Diamand, carbon-fibre reinforced epoxy, wet lay-up (Figure 7).

2.1 Armor Plate

2.1.1 General

The Armor plate system consists of continuous glass fibre (fabric) reinforced epoxy resin. More details about the system are given in Table 1.

Table 1 *Details of the Armor plate system, as given by the manufacturer*

Description	Property
Steel surface - primer	Polyamide cured epoxy
Filler material (external defects)	Epoxy putty
Reinforcement fibres	E-glass (fabric)
Matrix material - resin	Polyamide cured epoxy
Thickness over-wrap - through the-wall defect - external defect	 - 12.5 mm - 5.5 mm
Tensile strength	177 MPa
Tensile modulus	10 GPa

2.1.2 Application details

The Armor plate system has been applied on testspools with a “through-the-wall” defect, and spools with an external defect. Epoxy putty is used to fill irregular surfaces and defects of the steel pipe. Glass-fibre (fabric) reinforced epoxy is wrapped around the pipe. After wrapping, Mylar tape is applied over the “wet” composite. Curing time is about 12 hours, at ambient temperature. The Armor plate system has been applied with a thickness of 12.5 mm on testspools with a through the wall defect, and 5.5 mm for testspools with an external defect.

2.2 Clock spring

2.2.1 General

The Clock spring system is a pre-manufactured, standard 12” wide glass fibre reinforcement polyester coil, and fibres oriented in the hoop direction. The Clock spring system is not designed for the repair of potentially leaking defects. Curved components, e.g. bends, may be repaired using Clock spring, but only when radius is greater than 3 times the diameter. More details about the Clock spring system are given in Table 2.

Table 2 *Details of the Clock spring system, as given by the manufacturer*

Description	Property
Steel surface - primer	No
Filler material (external defects)	Epoxy putty
Reinforcement fibres	E-glass (rovings)
Matrix material (resin)	Ispophthalic polyester
Primer - adhesive	Toughened methacrylate
Thickness over-wrap	15 mm
Hoop tensile strength	517 MPa
Hoop tensile modulus	34 GPa
Axial tensile modulus	9.1 GPa

2.2.2 Application details

On the specific request of the Manufacturer, the Clockspring system has been applied on testspools with an external defect only. The spiral shaped composite wrap consists of a series of concentric layers, and is pre-cured on delivery. The material is wrapped around the steel pipe as a series of concentric layers. For the testspool, 8 layers have been applied. Toughened methacrylate adhesive is applied to the pipe surface and to each individual coil layer. After wrapping a mechanical strap is applied to consolidate the coil until full cure of the adhesive is achieved. Full curing of the adhesive typically requires 2 - 4 hours. The Clockspring system has been applied with a thickness of 15 mm on testspools with an external defect.

2.3 Diamant

2.3.1 General

The Diamant system has been designed for the repair of “through-the-wall” defects in pipelines and piping systems, and consists of wire-mesh reinforced putty material (UltraMetal 1250). More details about the Diamant system are given in Table 3.

Table 3 *Details of Diamant, as given by the manufacturer*

Description	Property
Steel surface - primer	No
Filler material (external defects)	UltraMetal 1250
Reinforcement	Steel wire mesh - serie 1: one layer wire mesh; - serie 2: three layer wire mesh
Matrix material	UltraMetal 1250
Thickness	5 to 11 mm
(*) Hoop tensile strength	48 MPa (one wire-mesh layer)
(*) Hoop tensile modulus	5.5 GPa (one wire-mesh layer)

(*) The tensile properties of Diamant material reinforced with one layer of wire-mesh where not given by the Manufacturer. Therefore a tensile test was performed in-house. The stress-strain behaviour of Diamant reinforced with one-wire mesh layer is shown in Appendix 1, Figure 1.

2.3.2 Application details

The Diamant system has been applied on testspools with a through-the-wall defect only. For the Diamant repair system, surface preparation includes cleaning of the steel surface using Diamand cleaner, and application of a primer is not specified. The first layer applied, consists of UltraMetal 1250, reinforced with wire-mesh. Two series test spools have been prepared; one serie based on “1- layer” mesh reinforcement, and one serie based on “3-layer” mesh reinforcement. For completion of the repair, four layers of synthetic fibre reinforced UltraMetal-1250 have been applied. Total repair thickness is typically in the range 5 to 11 mm.

2.4 Fibaroll

2.4.1 General

The Fibaroll system (tape) consists of an UV curing vinyl ester resin, reinforced with chopped glass-fibre strand mat. More details about the Fibaroll system are given in Table 4.

Table 4 *Details of the Fibaroll system, as given by the manufacturer*

Description	Property
Steel surface - primer	Vinyl ester (Fibagel)
Filler material (external defects)	Epoxy putty
Reinforcement fibres	C – glass (chopped strand mat)
Matrix material (resin)	Epoxy Novolac
Thickness over-wrap - through-the-wall defect - external defect	 - 6 mm. - 6 mm
Tensile strength	190 MPa
Flexural modulus	9.0 GPa

2.4.2 Application details

The Fibaroll system has been applied on testspools with a “through-the-wall” defect, and spools with an external defect. A vinyl ester primer (Fibagel) is applied to the steel substrate. Gel time for the glass fibre reinforced Epoxy Novolac overwrap system is typically 5 minutes. In-door curing can be accelerated, using a 400 watts UV lamp. Emission of styrene, typical for vinyl ester and Novolac type resin systems, is minimal for the pre-gelled, fast curing Fibaroll resin system. The Fibaroll system has been applied with a thickness of 6 mm on testspools with a through the wall defect, and testspools with an external defect.

2.5 Strongback (Nixus)

2.5.1 General

The Strongback system consists of glass-fibre reinforced tape, impregnated with a proprietary water-activated urethane resin. For proper bonding on a wet surface, an aliphatic polyamine curing epoxy primer, filled with Kevlar fibres, is used. More details about the Strongback system are given in Table 5.

Table 5 *Details of the StrongBack (Nixus) system, as given by the manufacturer*

Description	Property
Steel surface - primer	Polyamine cured epoxy
Filler material (external defects)	Kevlar fibre filled polyamine cured epoxy
Reinforcement fibres	E-glass woven tape
Matrix material	Water activated urethane
Thickness over-wrap - external defect	 13 mm.
Tensile strength	420 MPa
Tensile modulus	25.8 GPa

2.5.2 Application procedure

The Strongback system has been applied on testspools with an external defect. A liquid polyamide cured epoxy is used as primer and to fill external defects. Kevlar fibres are incorporated for reinforcement of the primer (putty). A minimum of 8 plies of glass-fibre reinforced urethane resin has been applied. The Strongback system is based on curing agents with two color components that turn green, giving visual conformation of correct mix and state-of-cure. The Strongback system has been applied with a thickness of 13 mm on testspools with an external defect.

2.6 Synthoglass

2.6.1 General

The Synthoglass system consists of glass-fibre (woven tape) reinforced with “water-activated” urethane resin. More details about the Synthoglass system are given in Table 6.

Table 6 *Details of the Synthoglas system, as given by the manufacturer*

Description	Property
Steel surface - primer	Epoxy, aliphatic amine cured
Filler material (external defects)	Kevlar fibre filled epoxy putty, aliphatic amine cured
Reinforcement fibres	E-glass (woven tape)
Matrix material	Aliphatic amine cured epoxy
Thickness over-wrap - through-the-wall defect - external defect	 - 9 mm - 9 mm
Tensile strength	250 MPa

2.6.2 Application procedure

The Synthoglass system has been applied on testspools with a through-the-wall defect, and spools with an external defect. An epoxy primer is applied to the steel substrate. Before wrapping, Synthoglass woven tape is immersed in water to activate the curing process.
To keep the composite wrap in place during cure, a Saran film layer is applied over the Synthoglass composite. Time required to fully cure the Synthoglass system is approximately 24 hours, at 21 °C. The Synthoglass system has been applied with a thickness of 9 mm on testspools with both a through-the-wall defect and testspools with an external defect.

2.7 TDW (Black diamond)

2.7.1 General

The TDW system (so-called Black diamond) has been developed by T.D. Williamson and consists of carbon fibre (weave) reinforced with epoxy, and providing high strength in both the hoop and axial direction. More details about the TDW system are given in Table 7.

Table 7 *Details of the TDW system, as given by the manufacturer*

Description	Property
Steel surface - primer	Epoxy resin
Filler material (external defects)	Epoxy putty
Reinforcement fibres	Carbon fibre (weave)
Matrix material - resin	Epoxy
Thickness over-wrap - through-the-wall defect - external defect	 - 3.5 mm - 5 mm
Hoop tensile strength	758 MPa
Axial tensile strength	191 MPa
Hoop tensile modulus	67 GPa
Axial tensile modulus	14.7 GPa

2.7.2 Application procedure

The TDW system has been applied on testspools with a through-the-wall defect, and spools with an external defect. An epoxy primer is applied to the steel surface to provide good bonding between the steel substrate and the carbon fibre fabric. Epoxy putty is used to fill external defects. The repair is applied by wrapping an epoxy reinforced carbon fibre fabric. For above ground application, exposed to intense UV radiation, a pigmented topcoat is recommended, e.g. epoxy, or polyurethane. Required curing time for the TDW system is typically 3 hours. The TDW system has been applied with a thickness of 3.5 mm on testspools with a through the wall defect, and thickness of 5 mm on testspools with an external defect.

3. Test programme

The test programme consisted of (i) short-term pressure strength (burst) tests performed at ambient temperature, and at 65 °C, (ii) 1000 hrs tests, performed at 65 °C, and (iii) pull-off adhesion tests, performed at ambient temperature. Testing included pipe spools with an “external” defect and pipe spools with a “through-the-wall” defect. To determine the effect of surface preparation, and surface condition on the performance, composite repair systems have been applied on a “dry” and “wet” (damp), and on a “blasted”, and “power tool” (grinded) pipe surface.

3.1 Pipe spool

3.1.1 Pipe dimensions

The pipe spool dimensions are the following:

- 6 inch diameter pipe, schedule 40, length 1200 mm (based on requirement: L/d > 6);
- External pipe diameter: 168 mm, wall thickness 7.1 mm;
- Class 600 end caps and fittings, welded to the pipe;

3.1.2 Pipe material

For the pipe spool, ASTM 106 Grade B steel was selected, with following minimum specified strength values:

- Yield strength: 241 MPa;
- Ultimate tensile strength: 415 MPa.

3.1.3 Defect type and size

In each pipe spool three identical defects have been machined, and equally spaced at the centre line of the cylindrical section of the pipe spool. Following defect “types” have been machined, i.e:

- **“External”** defect; depth 4 mm (i.e. 60 % wall loss), length 52 mm, and width 50 mm. Detail of the external machined defect is shown Figure 8;
- **“Through-the-wall”** defect; 5 mm diameter drillled hole.

3.2 Test conditions

3.2.1 Surface preparation

To determine the effect of type of surface preparation on the performance of the composite repair system, different surface cleaning techniques were applied, i.e:

- Blast cleaning to minimum Sa 2.5, in accordance with ISO8501-1;
- Power tool cleaning, using grinding disc, to near white metal surface condition.

3.2.2 Surface condition

To determine the effect of surface preparation, and surface condition on the performance, composite repair systems have been applied on a “dry” and “wet”(damp), and on a “blasted”, and “power tool” (grinded) pipe surface.

3.2.3 Test fluid

To include the effect of fluid type on the performance of composite over-wrap systems applied on testspools with a through-the-wall defect, a mixture of “water-crude oil” was used for the test fluid. For testspools with an external defect, only water was used for the test fluid.

4. Composite repair – external defect

When a pipeline or piping system is damaged it must first be decided whether the system is still fit for service, using a recognized design or damage assessment code. Guidelines to determine if damage is classified as an “injurous defect” are given in ASME B31.4, or one of the other pipe codes. If it is concluded from the assessment that the damaged pipeline or piping system is not fit for purpose, it shall be repaired, e.g. application of a composite over-wrap.

4.1 Basis of design - steel pipe

The size of the external defect, as given in Section 3.1.3, was selected in order to sufficiently reduce the strength of the testspool, i.e. pipe not fit-for-purpose, and therefore repair is required, i.e. application of a composite over-wrap.

Design calculations for a 6” diameter, Schedule 40, ASTM 106 Grade B steel pipe, as used for the pipe spool, and based on ANSI/ASME B31.3, B31.4 codes for piping and pipeline, are summarized in Table 8:

Table 8 *Summary of design calculation for 6" diameter, Schedule 40, steel pipe*

	Condition	"Virgin" pipe	Pipe + external defect depth 4 mm
Design pressure	0.72 x Yield	145 bar	-
Hydrotest presssure	1.25 X P_{design}	180 bar	-
Yield pressure	Yield	200 bar	165 bar
Max. pressure	90 % UTS	330 bar	255 bar
Burst pressure	UTS	365 bar	280 bar

4.2 Basis of design - composite repair

Presently there are no established standards for design of composite repairs for pipeline or piping systems. Therefore manufacturers of composite pipe repair systems use a variety of design methods, including: (i) in-house calculation methods, (ii) Shell [2], AEAT [4] developed design procedures, and (iii) draft ASME B.31.G (PPC-2 repair standard). Presently, the most widely accepted approach for composite repair systems is a "strength-based" design.

The strength of fibre-reinforced composites is strongly dependant on load duration, i.e. high strength for short-term load duration, and low strength for long-term load duration. The long-term strength of composites is determined by long-term regression testing, typically 10.000 hrs, in accordance with ASTM D2992. By plotting log (strength) versus log (time), the so-called regression gradient G can be determined [6] which is required to predict lifetime of a composite repair system.

For glassfibre reinforced composite pipe components, the regression gradient is typically in the range 0.05 to 0.06, for design temperatures up-to 65 °C. Findings from the literature [5] show regression gradients for composite repair systems in the range 0.04 to 0.065. For the composite repair systems tested, a regression gradient of 0.055 has been adopted.

The composite repair thickness, required to restore the minimum specified ultimate pipe strength (burst) is calculated using the following relationship:

$$t_{repair} = \frac{UTS_{steel}}{\sigma_{short-term}} \cdot t_{defect} . SF_{design} . 10^{G.\log(time,hrs)} \qquad \text{Equation 1}$$

Where:

- $\sigma_{short-term}$ = short-term tensile strength for the composite over-wrap [MPa];
- UTS_{steel} = minimum specified tensile strength for the steel pipe wall [MPa];
- t_{repair} = thickness composite over-wrap [mm];
- t_{defect} = depth of external defect [mm];
- SF_{design} = design safety factor for sustained pressure loading [6], default value is 1.5;
- G = regression gradient (ageing) for the composite;
- time = lifetime of the composite repair system (hrs);

4.3 Qualification

4.3.1 Requirements

To qualify a composite for the repair of a pipeline or piping system with an external "non-leaking" defect, the Manufacture shall demonstrate that the composite repair system is capable to meet the following requirements:

- Restore the minimum specified ultimate pressure strength (burst), i.e. 365 bar for a 6 inch diameter, Schedule 40, ASTM 106 Grade B steel pipespool;
- No yielding at the remaining pipe wall at the location of the external defect, at the field hydrotest pressure, i.e. 180 bar for a 6 inch diameter, Schedule 40, ASTM 106 Grade B steel pipespool;
- Design life of the composite repair at-least 20 years.

4.3.2 1000 hr ageing test

To determine if the composite repair system is capable to restore the original minium specified ultimate pressure strength (burst) of the pipe, also after ageing, 1000 hr tests have been performed, at a temperature of 65 °C, and pressure of 180 bar, i.e. equivalent to the field hydrotest pressure for a 6 inch diameter, Schedule 40, ASTM 106 Grade B steel pipe system. The 1000 hr experimental test set-up is shown in Figure 9.

Testing included composite systems from Armor plate, Clock spring, Fibaroll, Strongback, and TDW. After completion of the 1000 hr tests, the pipe spools were burst tested.

4.3.3 Short-term burst test

Similar as specified for composite pipes [6], burst tests have been performed in accordance with ASTM D1599, at Standard Laboratory Temperature (SLT) conditions, i.e. 23 °C +/- 2 °C. During the burst tests, strain measurements have been performed.

4.4 Test results

Following summarises the results of the short-term burst tests for the composite repair systems, i.e: Armor plate, Clock spring, Fibaroll, Strongback, and TDW. For comparison, burst testing was also performed for a steel pipespool with an external defect, and without a composite overwrap.

4.4.1 Steel testspool – no overwrap

The steel testspool (no. 69) failed at a pressure of 335 bar at the location of the external defect, see Figure 10. The burst pressure of 335 bar is lower than the "minimum" specified ultimate pressure strength (burst) of 365 bar for the "virgin" pipe, and therefore the damaged pipe is not fit for purpose, and repair is required, i.e. application of a composite over-wrap.

The burst pressure of 335 bar for the testspool with a 4 mm deep external defect (i.e. 60 % wall loss) is significantly higher than the the field hydrotest pressure of 180 bar for given pipe, and therefore survival of a composite repair system during a field hydrotest of a pipeline, or piping system is meaningless in terms of acceptance/rejection criterion.

4.4.2 Steel testspool, including composite overwrap

During burst testing of the testspools, strains in the hoop direction have been measured at (i) virgin steel wall, (ii) external surface of the composite, outside the defect area, and (iii) external surface of the composite at the location of the defect. A photograph showing the strain gauge arrangement is presented in Appendix 1, Figure 2.

Armor plate

The strain response measured during the burst test of the Armor plate system is shown in Appendix 1, Figure 3.

At the pipe design pressure, 145 bar (Table 8) the composite strain, measured at the location of the defect is 0.04 %. At 180 bar, equivalent to the pipe field hydrotest pressure, the composite strain response at the location of the defect is linear elastic, indicating that yielding at the remaining steel pipe wall at the location of the defect does not occur at 180 bar.

At a pressure of approximately 280 bar onset of non-linear composite hoop strain behaviour at the location of the defect was observed, indicating that yielding of the steel substrate has occurred, at a hoop strain of 0.10 % for both the composite and the “virgin” steel pipe wall. At a pressure of 300 bar significant non-linear strain behaviour was observed at the “virgin” steel pipe wall, i.e. yielding.

At a pressure of 370 bar, fracture at the composite overwrap occurred, at a composite hoop strain of 0.8 % and 1.2 % at the steel wall. The burst pressure of 370 bar is only slightly higher than the minimum specified ultimate pressure strength of 365 bar (Table 8) for the “virgin” pipe. A photograph showing the fractured composite is presented in Figure 11.

For the Armor plate repair system, the following is concluded:

- Yielding does not occur at the remaining pipe wall at the location of the defect, at the field hydrotest pressure, i.e. 180 bar;
- The minimum specified ultimate pressure strength of the pipe has been restored.

Clock spring

The strain response measured during the burst test of the Clock spring system is shown in Appendix 1, Figure 4.

At the pipe design pressure, 145 bar the composite hoop strain is 0.01 %, i.e. very low. At 180 bar, equivalent to the pipe field hydrotest pressure, the composite hoop strain response at the location of the defect is linear elastic, indicating that yielding at the remaining steel pipe wall at the location of the defect does not occur at 180 bar.

At a pressure of approximately 225 bar onset of non-linear composite hoop strain behaviour at the location of the defect was observed for the Clock spring system, indicating yielding of the steel substrate, at a composite hoop strain of 0.03 % and 0.11 % at the “virgin” steel pipe. At a pressure of 325 bar, significant non-linear strain behaviour was observed at the “virgin” steel pipe wall, i.e. yielding.

At a pressure of 400 bar the Clockspring system did not show signs of damage, however, for safety reasons, it was decided to stop further testing. The maximum composite hoop hoop strain was 0.3 % and 1.2 % at the “virgin” steel wall. The maximum pressure of 400 bar is well above the minimum required ultimate pressure strength of 365 bar for the “virgin”pipe.

For the Clock spring repair system, the following is concluded:

- Yielding does not occur at the remaining pipe wall at the location of the defect, at the field hydrotest pressure, i.e. 180 bar;
- The minimum specified ultimate pressure strength of the pipe has been restored.

Fibaroll

The strain response measured during the burst test of the Fibaroll system is shown in Appendix 1, Figure 5.

At the pipe design pressure, 145 bar the composite hoop strain is 0.12 %. At 180 bar, equivalent to the pipe field hydrotest pressure, the composite hoop strain response at the location of the defect is linear elastic, indicating that yielding at the steel pipe wall at the location of the defect does not occur at 180 bar.

At a pressure of approximately 225 bar, onset of non-linear composite hoop strain behaviour at the location of the defect was observed, indicating yielding of the steel substrate, at a composite hoop strain of 0.18 % and 0.09 % at the “virgin” steel pipe. At a pressure of 270 bar, significant non-linear strain behaviour was observed at the “virgin” steel pipe wall, i.e. yielding.

At a pressure of 310 bar, fracture at the composite occurred, at a composite hoop strain of 1.05 % and 1.17 % at the “virgin” steel wall. The burst pressure of 310 bar is too low, i.e. 85 % of the minimum required ultimate pressure strength of 365 bar for the “virgin” steel pipe. A photograph showing the fractured composite is presented in Figure 12.

For the Fibaroll repair system, the following is concluded:

- Yielding does not occur at the remaining pipe wall at the location of the defect, at the field hydrotest pressure, i.e. 180 bar;
- The minimum specified ultimate pressure strength of the pipe has “not” been restored.

Strongback (Nixus)

The strain response measured during the burst test of the Strongback system is shown in Appendix 1, Figure 6.

At the pipe design pressure, 145 bar the composite hoop strain is 0.042 %. At 180 bar, equivalent to the pipe field hydrotest pressure, the composite hoop strain response at the location of the defect is linear elastic, indicating that yielding at the steel pipe wall at the location of the defect does not occur at 180 bar.

At a pressure of 270 bar, onset of non-linear composite hoop strain behaviour at the location of the defect was observed, indicating yielding at the steel substrate, at a composite hoop strain of 0.09 % and and 0.11 % at the “virgin” steel pipe. At a pressure of 325 bar significant non-linear strain behaviour was observed at the steel pipe wall, i.e. yielding.

At a pressure of 390 bar the Strongback composite did not show signs of damage, however, for safety reasons, it was decided to stop further testing. The maximum composite hoop strain was 0.2 % and 1.06 % at the “virgin” steel wall. The maximum pressure of 390 bar is well above the minimum required ultimate pressure strength of 365 bar for the “virgin”pipe.

For the Strongback repair system, the following has been concluded:

- Yielding does not occur at the remaining pipe wall at the location of the defect, at the field hydrotest pressure, i.e. 180 bar;
- The minimum specified ultimate pressure strength of the pipe has been restored.

Synthoglass

The strain response measured during the burst test of the Synthoglass system is shown in Appendix 1, Figure 7.

At the pipe design pressure, 145 bar the composite hoop strain is 0.06 %. At 180 bar, equivalent to the pipe field hydrotest pressure, the composite hoop strain response at the location of the defect is linear elastic, indicating that yielding at the steel pipe wall at the location of the defect does not occur at 180 bar.

At a pressure of 325 bar, onset of non-linear composite hoop strain behaviour at the location of the defect was observed, indicating yielding of the substrate steel, at a hoop strain of 0.13 % both at the composite and the “virgin” steel pipe. At a pressure of 375 bar, significant non-linear strain behaviour was observed at the steel pipe wall, i.e. yielding.

At a pressure of 395 bar the Synthoglass composite did not show signs of damage, however, for safety reasons, it was decided to stop further testing. The maximum composite hoop strain was 0.3 % and 0.2 % at the “virgin”steel wall. The maximum pressure of 395 bar is well above the minimum required ultimate pressure strength of 365 bar (Table 8) for the “virgin”pipe.

For the Synthoglass repair system, the following is concluded:

- Yielding does not occur at the remaining pipe wall at the location of the defect, at the field hydrotest pressure, i.e. 180 bar;
- The minimum specified ultimate pressure strength of the pipe has been restored.

TDW

The strain response measured during the burst test of the TDW system is shown in Appendix 1, Figure 8.

At the pipe design pressure, 145 bar the composite hoop strain is 0.07 %. At 180 bar, equivalent to the pipe field hydrotest pressure, the composite hoop strain response at the location of the defect is linear elastic, indicating that yielding at the steel pipe wall at the location of the defect does not occur at 180 bar.

At a pressure of approximately 200 bar onset of non-linear composite hoop strain behaviour at the location of the defect was observed for TDW, indicating yielding of the substrate steel, at a composite hoop strain of 0.11 % and 0.08 % at the steel pipe.

At a pressure of 390 bar, fracture at the composite overwrap occurred, at a composite hoop strain of 0.6 % and 1.15 % at the “virgin” steel wall. The burst pressure of 390 bar is well above the minimum required ultimate pressure strength of 365 bar for the “virgin”steel pipe. A photograph showing the fractured composite is presented in Figure 13.

For the TDW repair system, the following has been concluded:

- Yielding does not occur at the remaining pipe wall at the location of the defect, at the field hydrotest pressure, i.e. 180 bar;
- The minimum specified ultimate pressure strength of the pipe has been restored.

4.5 Life-time prediction for composite repair

Based on (i) applied composite thickness, (ii) UTS of 415 MPa for the steel, (iii) short-term composite tensile strength, and (iv) regression gradient of 0.055, design life for the composite repair systems tested, is calculated, using equation (1), and summarized as:

- **Armor plate**: Based on a short term composite tensile strength of 177 MPa, as given by the manufacturer, and an applied thickness of 5.5 mm, design life for the Armor plate composite repair system is predicted at 3400 hrs, i.e. about 5 months.
  To qualify, i.e. 20 years design life, the burst pressure must be increased to at-least 390 bar. When the manufacturer has revised the composite system to meet the requirements, requalification testing will be required.
  Conclusion: The Armor plate composite is “conditionally” qualified for the repair of pipe systems with an external defect, and design life maximum one year, i.e. temporary repair only;
- **Clock spring**: Based on a short term composite tensile strength of 517 MPa, as given by the manufacturer, and an applied thickness of 15 mm, design life for the Clock spring composite repair system is predicted at-least 20 years.
  Conclusion: Clock spring composite is qualified for the repair of pipe systems with an external defect, also long-term, i.e. at-least 20 years design life.
- **Fibaroll**: was not capable to restore the minimum specified ultimate pressure strength (burst) of the pipe, i.e. 365 bar, and is therefore not qualified. To qualify, i.e. 20 years design life, the burst pressure must be increased to at-least 390 bar. When the manufacturer has revised the composite system to meet the requirements, requalification testing will be required.

- **Strongback (Nixus)**: Based on a short term composite tensile strength of 420 MPa, as given by the manufacturer, and an applied thickness of 13 mm, the design life for the Strongback composite repair system is predicted at-least 20 years.
  Conclusion: Strongback composite is qualified for the repair of pipe systems with an external defect, also long-term, i.e. at-least 20 years design life.
- **Synthoglass**: Based on a short term composite tensile strength of 250 MPa, as given by the manufacturer, and an applied thickness of 9 mm, the design life for the Synthoglass composite repair system is predicted at-least 20 years.
  Conclusion: Synthoglass composite is qualified for the repair of pipe systems with an external defect, also long-term, i.e. at-least 20 years design life.
- **TDW**: Based on a short term composite tensile strength of 750 MPa, as given by the manufacturer, and an applied thickness of 5 mm, the design life for the TDW composite repair system is predicted at-least 20 years.
  Conclusion: TDW composite is qualified for the repair of pipe systems with an external defect, also long-term, i.e. at-least 20 years design life.

4.6 Overall qualification results

To determine a sound basis for ranking of the qualified composite repair systems, applied on a pipe with an external defect, an "efficiency factor" has been defined, i.e.:

$$\text{Efficiency factor} = \text{lifetime } (t_{defect} / t_{composite}) \qquad \text{Equation 2}$$

The following repair efficiency factors, including ranking order apply to the qualified systems, i.e. TDW - factor 16, Synthoglass - factor 9, Strongback (Nixus)- factor 6, Clock spring - factor 5, and Armor plate - factor 0.7. The Fibaroll system is not qualified. The results of the qualification tests are summarized in Table 9.

Table 9 *Summary of qualification results composite repairs - external defect*

Composite over-wrap	t_{repair} (mm)	$\sigma_{short\text{-}term}$ (MPa)	Restored strength	Predicted Lifetime (years)	Efficiency Factor	Status/ ranking
TDW	5	750	**107 % fracture**	> 20	16	Qualified rank nr.1
Synthoglass (*)	9	250	**108 % intact**	> 20	9	Qualified rank nr.2
Strongback-Nixus (*)	13	420	**107 % intact**	> 20	6	Qualified rank nr.3
Clock spring	15	517	**110 % intact**	> 20	5	Qualified rank nr.4
Armor plate	5.5	177	**101 % fracture**	< 1		"Conditionally" Qualified
Fibaroll	6	190	**85 % fracture**	**0**	**0**	Not qualified

(*) Composite from Synthoglass and Strongback are "water-activated" systems, and are therefore suitable for application on wet (damp) surfaces, i.e. areas where air humidy is very high.

4.7 Discussion

Qualification testing of composite repair system, applied on pipe spools with an external defect was successful for four systems. These systems did meet the qualification requirements, i.e. (i) restore the minimum specified ultimate pressure strength (burst); (ii) no yielding at the remaining pipe wall at the location of the defect, at the field hydrotest pressure; and (iii) design life of the composite repair at-least 20 years.

For the Armor plate system, the margin of safety was too low to meet the 20 years design life requirement, and therefore the Armor plate system is “conditionally” qualified, i.e. acceptable for temporary repair only. The Fibaroll system was not capable to restore the minimum specified ultimate pressure strength (burst), and therefore the Fibaroll system is not qualified.

For a strength-based composite repair design, the application of high-strength composites is preferred, i.e. minimum required composite thickness. For an optimal design, the ranking order for the composite repair systems in terms of efficiency is the following: TDW (1), Clock Spring (2), Strongback (3), Synthoglass (4), Fibaroll (5), and Armor Plate (6). For the composite repair systems tested, TDW is indeed ranked as number 1, i.e. optimal design. However, the system from Clockspring is ranked as 4, instead as 2, indicating that the Clock spring system is over-designed. The Strongback system is ranked lower than the Synthoglass system, indicating that also the Strongback system is overdesigned.

The burst pressure for a pipe with an external defect (60 % wall loss) is still significantly higher than the typical field hydrotest pressure for a pipeline, or piping system, and therefore survival of a composite repair during the field hydrotest is meaningless. To qualify a composite for the repair of a pipeline or piping system with an external defect, burst testing of a pipespool is essential.

For corrosion protection of the steel substrate at the location of the composite repair, adequate adhesion between the steel and the composite is essential, and therefore composite repair systems should be applied on a clean, Sa 2.5 blast cleaned steel substrate. However, power tool cleaning (grinding) may be accepted, if blast cleaning is not feasible.

4.8 Conclusions

(a) Composite systems from TDW, Synthoglass, Strongback, and Clockspring are qualified for the repair of pipe systems with an external defect, also long-term;

(b) The composite repair system from Armor Plate is “conditionally” qualified, i.e. temporary repair only;

(c) The composite repair system from Fibaroll did not restore the minimum specified ultimate pressure strength (burst) of the pipespool, and is therefore not qualified.

5. Composite repair – “through-the-wall” defect

According ANSI/ASME B31.4 for pipelines, a through-the-wall defect (leaking, or potentially leaking), shall be classified as an “injurous defect”, i.e. pipe system not fit-for-purpose, and shall therefore be repaired, e.g. application of a composite over-wrap.

It should be noted that composite repair systems shall never be applied directly on leaking pipes. First leakage must be stopped, followed by cleaning the surface at the location of the defect (hole), i.e. removal of rust, loose scale, dirt, grease, oil, etc. The defect (hole) may be filled with a paste type resin reinforced with a metal mesh, e.g. using the Diamand system. There are also other potential suppliers of paste type material, e.g. Belzona, and Davcon, however, these have not been included in the test programme.

5.1 Basis of design - composite repair

Presently there are no established standards for the design of composites for the repair of pipeline or piping systems with a “through-the-wall” defect. Design of the composite repair system must not only be based on strength requirements, but also on “sealing” requirement.

For long-term, reliable operation, design of the composite repair must be based on long-term pressure regression tests, typically 10.000 hrs, in accordance with ASTM D2992. However, long-term pressure tests have not been performed for composites applied on pipes with a through-the-wall defect. Consequently there is no sound engineering basis for a long-term design of composite repair systems, applied on pipeline or piping systems with a through-the-wall defect.

In absence of long-term regression test data, design of composite repair systems, applied on pipes with a through-the-wall defect, should be based on short-term pressure strength tests.

The short-term hydraulic pressure (leak) strength, so-called STHP, is defined as [6]:

- 85 % of the lower burst pressure, when only two tests have been performed;
- The lower deviated, i.e. mean STHP minus two standard deviations of at-least five burst tests.

Based on the short-term pressure strength (STHP), the “qualified” design pressure [6] is defined by the following relationship:

$$P_{design} = \frac{STHP}{4} \qquad \text{Equation 3}$$

Application of a composite for the repair of a pipeline or piping system with a “through-the-wall” defect should therefore be considered as a temporary repair option. Only when long-term regression tests have been performed, design life may be extended.

5.2 Qualification

5.2.1 Requirements

To qualify a composite for the repair of a pipeline, or piping system, with a through-the-wall defect, the Manufacture shall demonstrate that the composite repair system is capable to meet the following requirements:

- Restore the minimum specified ultimate pressure strength (burst), i.e. 365 bar for a 6 inch diameter, Schedule 40, ASTM 106 Grade B steel pipespool, with a 5 mm diameter “through-the-wall” defect;
- Restore leak-tighness of the pipespool, for at-least 1000 hrs, and 65 °C, at the field hydrotest pressure of 180 bar, for a 6 inch diameter, Schedule 40, ASTM 106 Grade B steel pipespool, with a 5 mm diameter “through-the-wall” defect;
- Design life of the composite repair at-least 20 years.

5.2.2 Short-term pressure test

To determine the short-term pressure (leak) strength of a composite repair, applied on a pipespool with a through-the-wall defect, burst tests have been performed in accordance with ASTM D1599, at Standard Laboratory Temperature (SLT) conditions, i.e. 23 °C +/- 2 °C.

5.2.3 1000 hr survival test

To qualify, the Manufacturer shall demonstrate that the composite repair is capable to restore leak-tighness of the pipe. Therefore, 1000 hr qualification tests are required, at 65 °C, and at the field hydrotest pressure of the pipeline, or piping system, i.e. 180 bar, for a 6 inch diameter, Schedule 40, ASTM 106 Grade B steel pipe.

5.3 Test results

5.3.1 1000 hr tests

All composite repair systems tested, which included Armor plate, Diamant, Fibaroll, Synthoglass, and TDW, failed the requirement to restore leak-tighness of the pipespool, for at-least 1000 hrs, and 65 °C, at the field hydrotest pressure of 180 bar. Failure (leakage) typically occurred during pressurization. Howevere, the system from TDW, applied on a blasted, dry surface, survived 190 hrs at the 180 bar test pressure.

Because of the persistant failures during the 1000 hr tests it was decided to reduce the test pressure to 100 bar for the remaining test spools (Armor plate, Fibaroll and TDW). However, again early failures occurred during pressurization of testspools with composite repair systems of Armor Plate and Fibaroll. Only the system from TDW, applied on a blasted, wet surface, survived 22 hrs at 100 bar test pressure. Again it was decided to further reduce the test pressure, and 50 bar was selected for the remaining Armor Plate and Fibaroll testspools.

The composite system from Fibaroll, applied on a blasted, wet surface, failed during pressurization at a pressure of 30 bar. The remaining Armor Plate and Fibaroll test spools successfully survived 1000 hr, at 50 bar, and 65 °C.

The results of the 1000 hr tests, at 180 bar, and 65 °C, are summarized in Table 10.

Table 10 *Summary of the 1000 hr test results*

Manufacturer	Test spool	Surface preparation	TP_{1000h} (bar)	Observation	Test result
Armor plate	27	- blasted - wet surface	50	1069 hrs survival	Passed
Armor plate	22	- power tool - wet surface	50	1069 hrs survival	Passed
Fibaroll	51	- power tool - wet surface	50	1002 hrs survival	Passed
Fibaroll	56	- power tool - dry surface	50	1002 hrs survival	Passed
TDW	29	- blasted - wet surface	100	22 hrs survival	Failed, (leak)
TDW	28	- blasted - dry surface	180	190 hrs survival	Failed, (leak)

5.3.2 Short-term pressure strength at ambient temperature

Following summarises the results of the short-term pressure strength tests, performed at ambient temperature (25 °C) for the systems from Armor plate, Diamant, Fibaroll, Synthoglass, and TDW.

Armor plate

The results of the short-term pressure strength tests for the Armor plate system are summarized in Table 11.

Table 11
Summary of the short-term pressure strength tests for the Armor plate system, at 25 °C

Test spool	Surface preparation	Condition	Short term strength
24	- blasted - dry surface	Virgin	142 bar leakage @ interface
27	- blasted - wet surface	1069 hrs tested, @ 50 bar	110 bar leakage @ interface
22	- power tool - wet surface	1069 hrs tested, @ 50 bar	175 bar leakage @ interface

Diamant

The results of the short-term pressure strength tests for the Diamant system are summarized in Table 12.

Table 12
Summary of the short-term pressure strength tests for the Diamant system, at 25 °C

System	Test spool	Surface preparation	Condition	Short term strength
1 layer mesh	40	- blasted - dry surface	Virgin	155 bar leakage @ UltraMetal layer
1 layer mesh	31	- blasted - wet surface	Virgin	157 bar leakage @ interface
1 layer mesh	37	- power tool - dry surface	Virgin	256 bar leakage @ UltraMetal
1 layer mesh	38	- power tool - wet surface	Virgin	148 bar leakage @ UltraMetal

Fibaroll

The results of the short-term pressure strength tests for the Fibaroll system are summarized in Table 13.

Table 13
Summary of short-term pressure strength tests for the Fibaroll system, at 25 °C

Test spool	Surface preparation	Condition	Short term strength
43	- blasted - dry surface	Virgin	188 bar leakage @ interface
56	- power tool - dry surface	1002 hrs tested @ 50 bar	120 bar leakage @ interface
51	- power tool - wet surface	1002 hrs tested @ 50 bar	160 bar leakage @ interface

Synthoglass - water activated resin system

The results of the short-term pressure strength tests for Synthoglass are summarized in Table 14.

Table 14
Summary of short-term pressure strength tests for the Synthoglass system, at 25 °C

Test spool	Surface preparation	Condition	Short term strength
39	blasted	Virgin	102 bar leakage @ composite
30	power tool (grinding)	Virgin	91 bar leakage @ composite

TDW

The results of the short-term pressure strength tests for the TDW system are summarized in Table 15.

Table 15
Summary of the short-term pressure strength tests for the TDW system, at 25 °C.

Test spool	Surface preparation	Condition	Short term strength
32	- blasted - dry surface	Virgin	140 bar leakage @ interface
34	- power tool - dry surface	Virgin	134 bar leakage @ composite
50	- power tool - wet surface	Virgin	148 bar leakage @ composite

5.3.3 Short-term pressure strength at 65 °C

Armor plate

The results of the short-term pressure tests for the Armor plate system are summarized in Table 16.

Table 16
Summary of the short-term pressure strength tests for the Armor plate system, at 65 °C

Test spool	Surface preparation	Condition	Short term strength
26	- blasted - dry surface	Virgin	Leakage 180 bar @ composite
35	- blasted - wet surface	Virgin	Leakage 180 bar @ composite
25	- power tool - dry surface	Virgin	Leakage 170 bar @ composite
23	- power tool - dry surface	Virgin	Leakage 80 bar @ composite
21	- power tool - wet surface	Virgin	Leakage 25 bar @ composite

Diamant

The results of the short-term pressure tests for the Diamant system are summarized in Table 17.

Table 17
Summary of the short-term pressure strength tests for the Diamant system, at 65 °C.

System	Test spool	Surface preparation	Condition	Observation
1 layer mesh	48	- blasted - dry surface	Virgin	burst 170 bar @ interphase
3 layer mesh	54	- blasted - dry surface	Virgin	Leakage 150 bar @ interphase
1 layer mesh	36	- blasted - wet surface	Virgin	Leakage 180 bar @ UltraMetal
1 layer mesh	42	- power tool - dry surface	Virgin	Burst 180 bar @ interface
3 layer mesh	55	- power tool - dry surface	Virgin	Leakage 150 bar @ interphase
1 layer mesh	41	- power tool - wet surface	Virgin	Leakage 150 bar @ UltraMetal

Fibaroll

The results of the short-term pressure tests for the Fibaroll system are summarized in Table 18.

Table 18
Summary of the short-term pressure strength tests for the Fibaroll system, at 65 °C.

Test spool	Surface preparation	Condition	Observation
46	- blasted - dry surface	Virgin	Leakage 100 bar @ composite
59	- power tool - dry surface	Virgin	Leakage 100 bar @ composite
44	- power tool - wet surface	Virgin	Leakage 100 bar @ composite
45	- blasted - wet surface	Virgin	Leakage 30 bar @ composite
60	- blasted - wet surface	Virgin	Leakage 80 bar @ composite

TDW

The results of the short-term pressure tests for the TDW system are summarized in Table 19.

Table 19
Summary of the short-term pressure strength tests for the TDW system, at 65 °C

Test spool	Surface preparation	Condition	Observation
47	- blasted - wet surface	Virgin	Leakage 150 bar @ composite
33	- power tool - dry surface	Virgin	Leakage 150 bar @ interface
49	- power tool - wet surface	Virgin	Leakage 150 bar @ composite
29	- blasted - wet surface	22 hrs @ 100 bar	Leakage 100 bar @ composite

The short-term pressure test results are summarized in Appendix 2, Table 1, and the 1000 hr test results are summarized in Appendix 2, Table 2.

5.3.4 Effect of steel surface condition

The short-term pressure strength (leak) for the different composite repair systems, applied on the pipespools under different surface conditions, is summarized as:

Armor plate

- Dry surface, blasted to Sa 2.5;
  - failure pressure: 142 bar, 180 bar. Mean value = 161 bar +/- 27 bar (17 %);
- Wet surface, blasted to Sa 2.5;
  - failure pressure: 110 bar, 180 bar. Mean value = 145 bar +/- 49 bar (34 %);
- Dry surface, power tool (grinding);
  - failure pressure: 170 bar, 80 bar. Mean value = 125 bar +/- 64 bar (51 %);
- Wet surface, power tool (grinding);
  - failure pressure: 175 bar, 25 bar. Mean value = 100 bar +/- 106 bar (106 %).

It is concluded that application of the Armor plate system on a “dry” surface results in a higher (leak) pressure strength, compared to application on a “wet” surface. Application of the Armor plate system on a dry, Sa 2.5 blasted surface, results in a maximum (leak) pressure strength.

Diamant

- Dry surface, blasted to Sa 2.5;
  - failure pressure: 155 bar, 170 bar, 150 bar. Mean value = 158 bar +/- 10 bar (6 %);
- Wet surface, blasted to Sa 2.5;
  - failure pressure: 157 bar, 180 bar. Mean value = 169 bar +/- 16 bar (9 %);
- Dry surface, power tool (grinding);
  - failure pressure: 256 bar, 180 bar, 150 bar. Mean value = 195 bar +/- 55 bar (28 %);
- Wet surface, power tool (grinding);
  - failure pressure: 148 bar, 150 bar. Mean value = 149 bar +/- 2 bar (1 %).

It is concluded that for the Diamant system, there is no correlation between (leak) pressure strength and the surface conditions during application.

Fibaroll

- Dry surface, blasted to Sa 2.5;
  - failure pressure: 188 bar, 100 bar. Mean value = 144 bar +/- 62 bar (43 %);
- Wet surface, blasted to Sa 2.5;
  - failure pressure: 30 bar, 80 bar. Mean value = 55 bar +/- 35 bar (64 %);
- Dry surface, power tool cleaning (grinding);
  - failure pressure: 120 bar, 100 bar. Mean value = 110 bar +/- 14 bar (13 %);
- Wet surface, power tool cleaning (grinding);
  - failure pressure: 160 bar, 100 bar. Mean value = 130 bar +/- 42 bar (32 %).

It is concluded that for the Fibaroll system, there is no real correlation between the (leak) pressure strength and the surface conditions during application.

Synthoglass (water activated resin system)

- Wet surface, blasted to Sa 2.5;
  - failure pressure: 102 bar;
- Wet surface, power tool cleaning (grinding);
  - failure pressure: 91 bar.

It is concluded that application of the Synthoglass system on a Sa 2.5 blasted surface results in a higher (leak) pressure strength compared to application on a power tool (grinded) surface.

TDW

- Dry surface, blasted to Sa 2.5;
  - failure pressure: 140 bar;
- Wet surface, blasted to Sa 2.5;
  - failure pressure: 150 bar, 100 bar. Mean value = 125 bar +/- 35 bar;
- Dry surface, power tool cleaning (grinding);
  - failure pressure: 134 bar, 150 bar. Mean value = 142 bar +/- 11 bar;
- Wet surface, power tool cleaning (grinding);
  - failure pressure: 148 bar, 150 bar. Mean value = 149 bar +/- 2 bar.

It is concluded that for the TDW system, there is no correlation between the (leak) pressure strength and the surface conditions during application.

5.4 Design pressure for composite repair

Based on the short-term pressure test results, as presented in Section 5.3.4, the qualified design pressure for the different composite repair systems has been calculated (Equation 3), and are summarized as follows:

Armor plate

- Short-term pressure strength (leakage): 148 bar +/- 40 bar, based on N=7 pressure tests.
- STHP (lower deviated): 148 bar minus 2 times 40 bar = 68 bar.

The composite repair system from Armor plate survived 1000 hrs at a pressure of 50 bar. The 1000 hr strength is lower than the short-term (leak) pressure strength of 68 bar, indicating that the “seal” pressure strength of the Armor plate composite is dependant on load duration, i.e. higher (leak) pressure strength for short-term load duration, and lower (leak) pressure strength for long(er) load duration, i.e. similar effect as found for (leak) pressure strength of fibre reinforced composite pipes.

From the short-term (leak) pressure strength results, the “qualified” design pressure for the Armor plate system is calculated (equation 3) at 17 bar.

Diamant

- Short-term pressure strength (leakage):170 bar +/- 33 bar, based on N=10 pressure tests.
- STHP (lower deviated): 170 bar minus 2 times 33 bar = 104 bar.

From the short-term (leak) pressure strength results, the “qualified” design pressure for the Diamant system is calculated at 26 bar.

Fibaroll

- Short-term pressure strength (leakage): 121 bar +/- 39 bar, based on N= 6 pressure tests.
- STHP (lower deviated): 128 bar minus 2 times 37 bar = 54 bar.

The Fibaroll composite system survived 1000 hrs at a pressure of 50 bar. The 1000 hr strength is lower than the short-term (leak) pressure strength of 54 bar, indicating that the “seal” pressure strength of the Fibaroll composite repair system is dependant on load duration.

From the short-term (leak) pressure strength results, the “qualified” design pressure for the Fibaroll system is calculated at 14 bar.

Synthoglass

- Short-term pressure strength (leakage): 102 bar, 91 bar (N=2);
- STHP (lower deviated), 85 % of 91 bar: 77 bar.

From the short-term (leak) pressure strength results, the “qualified” design pressure for the Synthoglass system is calculated at 19 bar.

TDW

- Short-term pressure strength (leakage): 139 bar +/- 18 bar, based on N= 7 pressure tests.
- STHP (lower deviated): 139 bar minus 2 times 18 bar = 103 bar.

The composite repair system from TDW survived 22 hrs at a pressure of 100 bar. The 1000 hr strength is slightly lower than the short-term (leak) pressure strength of 103 bar, indicating that the “seal” pressure strength of the TDW composite repair system is dependant on load duration.

From the short-term (leak) pressure strength results, the “qualified” design pressure for the TDW system is calculated at 26 bar.

5.5 Overall result

To determine a sound basis for ranking the composite repair systems, applied on a pipe with a through-the-wall defect, an “efficiency” factor has been defined, i.e.:

Efficiency factor = design pressure / $t_{composite}$ Equation 4

The following composite repair efficiency factors, including ranking order, apply, i.e. TDW - factor 7.4, Diamant - factor 5.2, Fibaroll - factor 2.3, Synthoglass - factor 2.1, and Armor plate - factor 1.4. The results of the qualification tests are summarized in Table 20.

Table 20 *Design pressure for the composite repair systems for “through-the-wall” defect*

Manufacturer	Applied Thickness	Design pressure	Efficiency Factor (bar/mm)	Status & ranking
TDW	3.5 mm	26 bar	7.4	Rank nr.1
Diamant (1)	5 mm	26 bar	5.2	Rank nr. 2
Fibaroll	6 mm	14 bar	2.3	Rank nr.3
Synthoglass (2)	9 mm	19 bar	2.1	Rank nr.4
Armor plate	12.5 mm	17 bar	1.4	Rank nr.5

Note 1: Filler from Diamant may be used in combination with a composite over-wrap system.

Note 2: Synthoglass is a “water-activated” system, and is therefore qualified for application on a wet (damp) surface, i.e. areas where air humidy is very high.

5.6 Discussion

None of the composite repair systems applied on pipespools with a through-the-wall defect could meet the qualification requirements, i.e. restore leak-tighness, at the field hydrotest pressure of 180 bar, for at-least 1000 hrs. All failures were caused by leakage, and not by fracture of the composite, indicating that performance of the composite repair system is governed by sealing chararteristics, and not by mechanical strength of the composite.

The maximum allowable design pressure for the composite repair systems tested, and applied under “optimal” laboratory conditions, is 27 bar. However, maximum design pressure may be significantly lower when applied under less optimal conditions, e.g. in the field.

It is concluded that application of a composite is a rather ineffective method for the repair (sealing) of pipe systems with a through-the-wall defect. Therefore application of composite repair systems to restore "leaktightness" of a pipeline, or piping system with a through-the-wall defect should be discouraged, and other repair options should be considered, e.g. threaded plugs, as already succesffully applied earlier [7], or full encircling tight-fit metallic sleeves [8].

5.7 Conclusions

(a) None of the composite repair systems applied on pipespools with a through-the-wall defect could meet the qualification requirements;
(b) All failures were caused by leakage, and not by fracture of the composite, indicating that performance of the composite repair system is governed by sealing chararteristics, and not by mechanical strength;
(c) The maximum allowable design pressure for the composite repair systems tested, and applied under "optimal" laboratory conditions, is 27 bar;
(d) Application of a composite is a rather ineffective method for the repair (sealing) of pipe systems with a through-the- wall defect, i.e. should be discouraged, and other repair options should be considered, e.g. threaded plugs, or metallic sleeves.

6. Pull-off adhesion strength test

6.1 Requirements

For strength reinforcement of pipe systems with an "external" defect, the adhesion strength between the composite and the steel substrate is considered not important.

However, to protect the steel substrate at the location of the composite repair against corrosion, adhesion between the steel and the composite is important, similar as for coatings. For coatings, a minimum pull-off strength of 7 MPa is typically specified, and this should therefore also be specified for composite repair systems.

6.2 Test procedure

To determine the adhesion strength, pull-of tests have been performed for composite repairs applied on a "dry" and "wet", and a "blasted" and power tool (grinded) surface.

Pull-off tests have been performed in accordance with ASTM D4541, using a self-aligning adhesion tester, and 20 mm diameter dolly. After the pull-off test, the fracture surface was inspected to determine type of failure, i.e. adhesive failure (interface), or cohesive failure (within the composite). A photograph showing a typical fracture surface after the pull off test is presented in Figure 14.

6.3 Test results

The results from the pull-off tests of different composite repair systems, are the following:

Armor plate

- Testspool (21), though-the-wall defect, failed at 25 bar, and 65 °C.
  Application conditions: wet surface, power tool cleaning (grinding);
  Pull off strength: 2 MPa (cohesive), 4 MPa (cohesive), and 6 MPa (cohesive).
  <u>Average strength</u>: 4 MPa.
- Testspool (26), though-the-wall defect, short-term tested at 180 bar, and 65 °C.
  Application conditions: dry surface, blast cleaned.
  Pull off strength: 11.5 MPa (cohesive), 13 MPa (adhesive), and 14.5 MPa (cohesive).
  <u>Average strength</u>: 13 MPa.

- Testspool (2), external defect, 1000 hr tested at 180 bar, and 65 °C.
  Application conditions: wet surface, power tool cleaned (grinded).
  Pull off strength: 2.5 MPa (cohesive), 3 MPa (cohesive), and 3 MPa (cohesive).
  Average strength: 2.8 MPa.

It is concluded that the average adhesion strength for the Armor plate system, when applied on a dry surface is about 3.5 times higher, compared to application on a wet (damp) surface.

The pull-off strength values measured for the Armor plate system applied on a dry, blast cleaned surface, are well above the minimum specified value of 7 MPa for coatings, and therefore an additional paint system to protect the steel substrate against corrosion is not required.

Clockspring

- Testspool (3), external defect, 1000 hr tested at 180 bar, and 65 °C.
  Application conditions: wet surface, blast cleaned.
  Pull off strength: < 1 MPa (cohesive), < 1 MPa (cohesive), and 5 MPa (cohesive).
  Average strength: 2.3 MPa.
- Testspool (9), external defect, 1000 hr tested at 180 bar, and 65 °C.
  Application conditions: wet surface, power tool cleaned (grinded).
  Pull off strength: 1 MPa (adhesive), 3 MPa (cohesive), and 4.5 MPa (adhesive).
  Average strength: 2.8 MPa.
- Testspool (20), external defect, 1000 hr tested at 180 bar, and 65 °C.
  Application conditions: dry surface, blast cleaned.
  Pull off strength: 2.5 MPa (cohesive), 6 MPa (adhesive), and 6.5 MPa (adhesive).
  Average strength: 5 MPa.

It is concluded that the average adhesion strength for the Clock spring system, when applied on a dry surface is about 2 times higher, compared to application on a wet (damp) surface.

However, the pull-off strength measured for the Clock spring system, applied on a dry, blast cleaned surface, is lower than the minimum specified value of 7 MPa for coatings, and therefore an additional paint system is required to protect the steel substrate against corrosion.

Fibaroll

- Testspool (46), through-the-wall defect, failed at 100 bar, and 65 °C.
  Application conditions: dry surface, blast cleaned.
  Pull off strength: 1 MPa (cohesive), 5.5 MPa (cohesive), and 12.5 MPa (cohesive).
  Average strength: 6.3 MPa;
- Testspool (18), external defect, 1000 hr tested at 180 bar, and 65 °C.
  Application conditions: wet surface, blast cleaned.
  Pull off strength: 1 MPa (cohesive), 4 MPa (cohesive), and 5 MPa (adhesive).
  Average strength: 3 MPa;
- Testspool (19), external defect, 1000 hr tested at 180 bar, and 65 °C.
  Application conditions: wet surface, power tool cleaned (grinded).
  Pull off strength: 1 MPa (adhesive), 3.5 MPa (adhesive), and 7 MPa (adhesive).
  Average strength: 3.8 MPa.

It is concluded that the average adhesion strength for the Fibaroll system, when applied on a dry surface is about 2 times higher, compared to application on a wet (damp) surface.

However, the pull-off strength measured for the Fibaroll system, applied on a dry, blast cleaned surface, is lower than the minimum specified value of 7 MPa for coatings, and therefore an additional paint system is required to protect the steel substrate against corrosion.

Strongback (Nixus) - “water activated” system

- Testspool (62), external defect, and 1000 hr tested at 180 bar, and 65 °C.
  Application conditions: wet surface, blast cleaned.
  Pull off strength: 2 MPa (adhesive), 8 MPa (adhesive), and 11 MPa (adhesive).
  <u>Average strength</u>: 7 MPa.
- Testspool (64), external defect, “virgin” testspool.
  Application conditions: wet surface, blast cleaned.
  Pull off strength: 7 MPa (adhesive), 7.5 MPa (cohesive), and 11 MPa (adhesive).
  <u>Average strength</u>: 8.5 MPa.

Because the Strongback system is based on a water activated resin system, the surface condition during application is inherently “wet”. No significant difference in adhesion strength was found between the different test conditions, i.e. “virgin” versus 1000 hrs (aged) tested. It is concluded that the Strongback system is suitable for application in areas where air humidy is high, i.e. greater than 90 %.

The pull-off strength values measured for the Strongback system are generally higher than the minimum specified value of 7 MPa for coatings, and therefore an additional paint system to protect the steel substrate against corrosion is not required.

Synthoglass - “water activated” system

- Testspool (30), through-the-wall defect, failed at 90 bar, and 25 °C.
  Application conditions: wet surface, power tool cleaned (grinded).
  Pull off strength: 2 MPa (cohesive), 9 MPa (cohesive), and 9 MPa (adhesive).
  <u>Average strength</u>: 6.7 MPa.
- Testspool (39), through-the-wall defect, failed at 100 bar, and 25 °C.
  Application conditions: wet surface, blast cleaned.
  Pull off strength: 5 MPa (cohesive), 6 MPa (cohesive), and 10 MPa (cohesive).
  <u>Average strength</u>: 7 MPa.
- Testspool (74), external defect, 1000 hr tested at 180 bar, and 65 °C.
  Application conditions: wet surface, power tool cleaned (grinded).
  Pull off strength: 5 MPa (cohesive), 6 MPa (adhesive), and 10 MPa (adhesive).
  <u>Average strength</u>: 7 MPa.

Similar as for Strongback, the Synthoglass system is also based on a water activated resin system, i.e. inherent “wet” surface condition during application. No significant difference in adhesion strength was found between the different testspools, and different test conditions, i.e. short-term versus 1000 hrs (aged) tested. Similar as for Strongback, the Synthoglass system is suitable for application in areas where air humidy is high, i.e. greater than 90 %.

The pull-off strength measured for the Synthoglass system is generally slightly lower than the minimum specified value of 7 MPa for coatings, however, still within an acceptable range. Therefore an additional paint system to protect the steel substrate against corrosion is not required.

TDW

- Testspool (28), through-the-wall defect, failed at 180 bar, and 65 °C.
  Application conditions: dry surface, blast cleaned.
  Pull off strength: 19 MPa (cohesive), 20 MPa (cohesive), and 21 MPa (cohesive).
  <u>Average strength</u>: 20 MPa.
- Testspool (49), through-the-wall defect, failed at 150 bar, and 65 °C.
  Application conditions: wet surface, power tool cleaned (grinded).
  Pull off strength: 6 MPa (adhesive), 7 MPa (adhesive), and 9.5 MPa (cohesive).
  <u>Average strength</u>: 7.5 MPa.

- Testspool (12), external defect, 1000 hr tested at 180 bar, and 65 °C.
  Application conditions: dry surface, blast cleaned.
  Pull off strength: 15 MPa (cohesive), 15.5 MPa (cohesive), and 20 MPa (adhesive).
  Average strength: 17 MPa.

It is concluded that the average adhesion strength for the TDW system, when applied on a dry surface is about 2 to 3 times higher, when compared to application on a wet surface.

The pull-off strength values measured for the TDW system applied on a dry, blast cleaned surface, are well above the minimum specified value of 7 MPa for coatings, and therefore an additional paint system to protect the steel substrate against corrosion is not required.

6.4 Conclusions

- Application of a composite repair on a clean, Sa 2.5 blast cleaned steel substrate is recommended. However, power tool cleaning (grinding) may be accepted, if blast cleaning is not feasible;
- For conventional resin systems, the steel surface must be fully dry during application of the composite repair system. However, the composite repair systems from Synthoglass and Strongback, which are “water-activated”, are suitable for application on a wet (damp) surface, i.e. areas where air humidy is high, typically greater than 90 %;
- Pull-off strength for the Clock spring system is lower than the minimum specified value of 7 MPa for coatings, and therefore an additional paint system is required to protect the steel substrate against corrosion.

7. Recommendation

The main findings from this report, including specifications for design and qualification, should be included in DEP 31.40.60.12-Gen “pipeline repairs”, and DEP 70.10.70.30-Gen “leak repairs”.

8. References

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Amsterdam, May 2006
wk

Figure 1 *Photograph showing the Armor plate testspool*

Figure 2 *Photograph showing the Clock spring testspool*

Figure 3 *Photograph showing the Diamant testspool*

Figure 4 *Photograph showing the Fibaroll testspool*

Figure 5 *Photograph showing the Strongback testspool*

Figure 6 *Photograph showing the Synthoglass testspool*

Figure 7 *Photograph showing the TDW testspool*

Figure 8 *Photographh showing detail of the external machined defect*

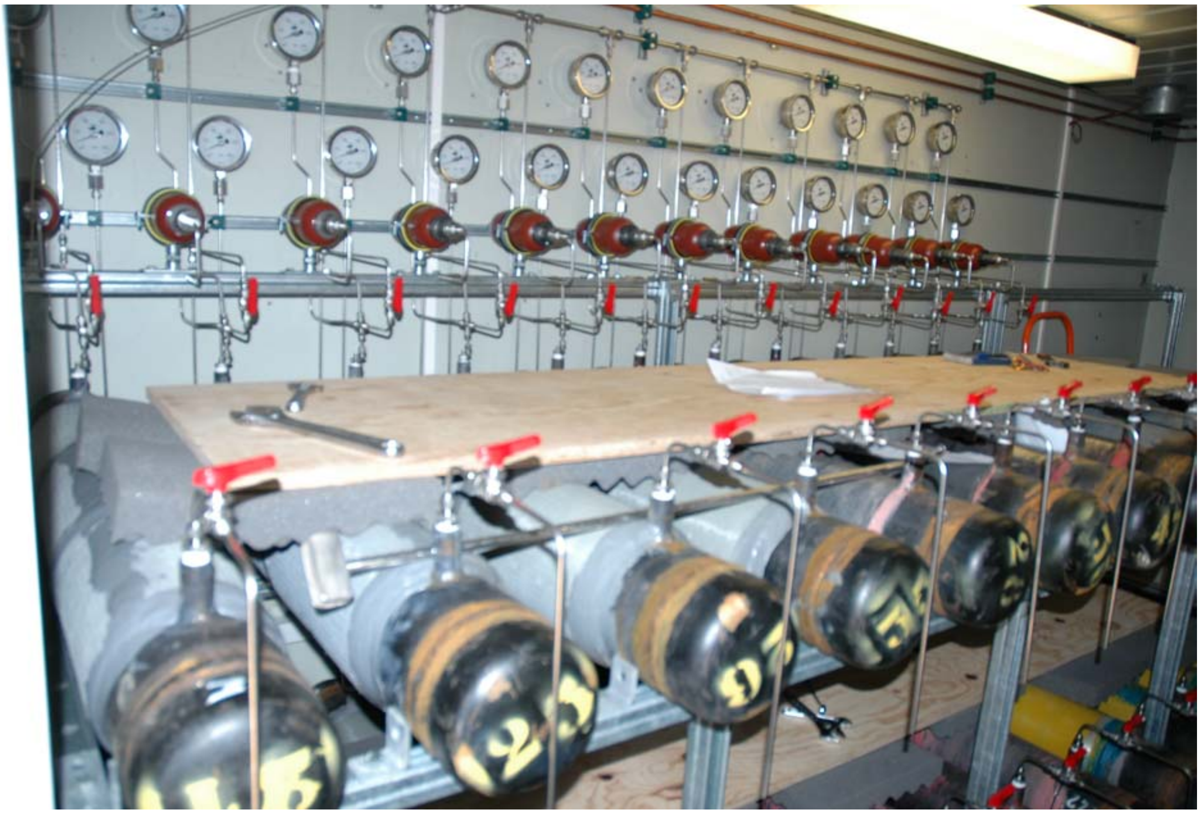

Figure 9 *Photograph showing the 1000 hr pressure test set-up*

Figure 10 *Photograph showing rupture of the steel testspool*

Figure 11 *Photograph showing fracture of the Armor plate composite*

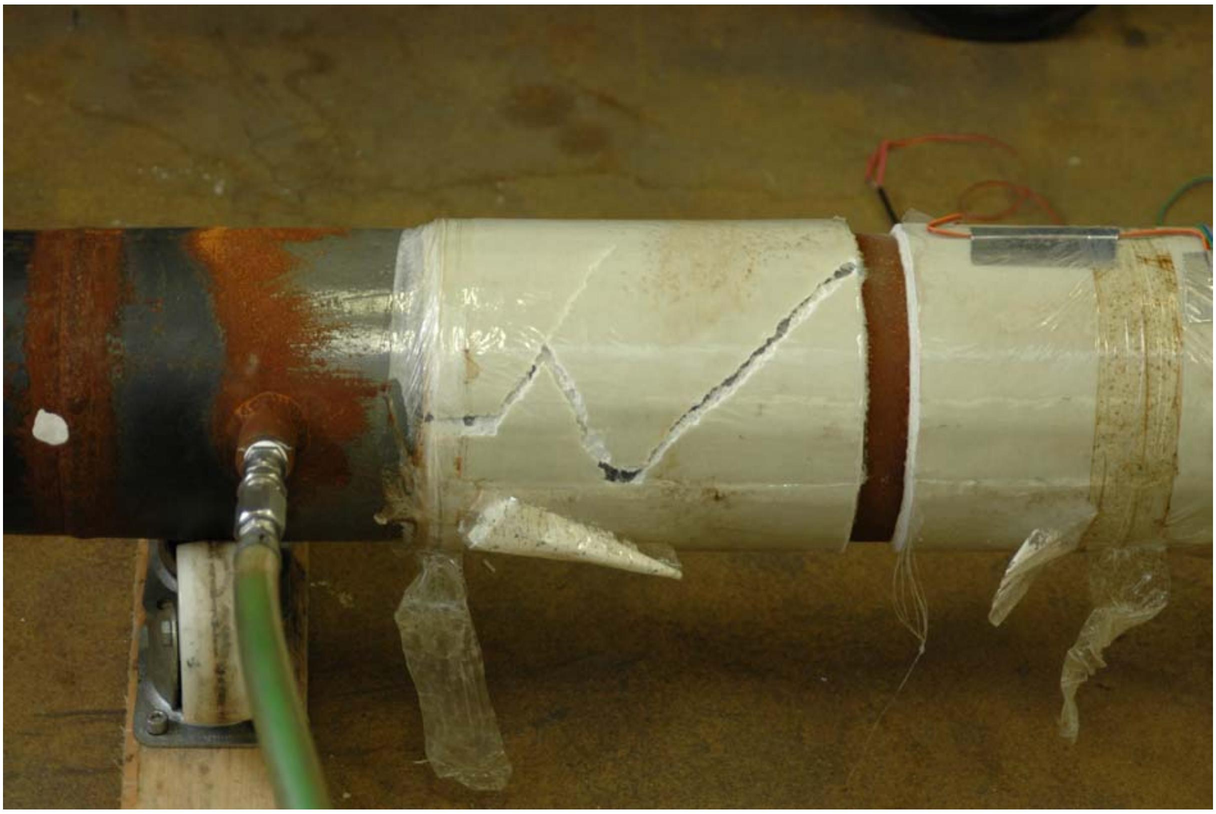

Figure 12 *Photograph showing fracture of the Fibaroll composite*

Figure 13 *Photograph showing fracture of the TDW composite*

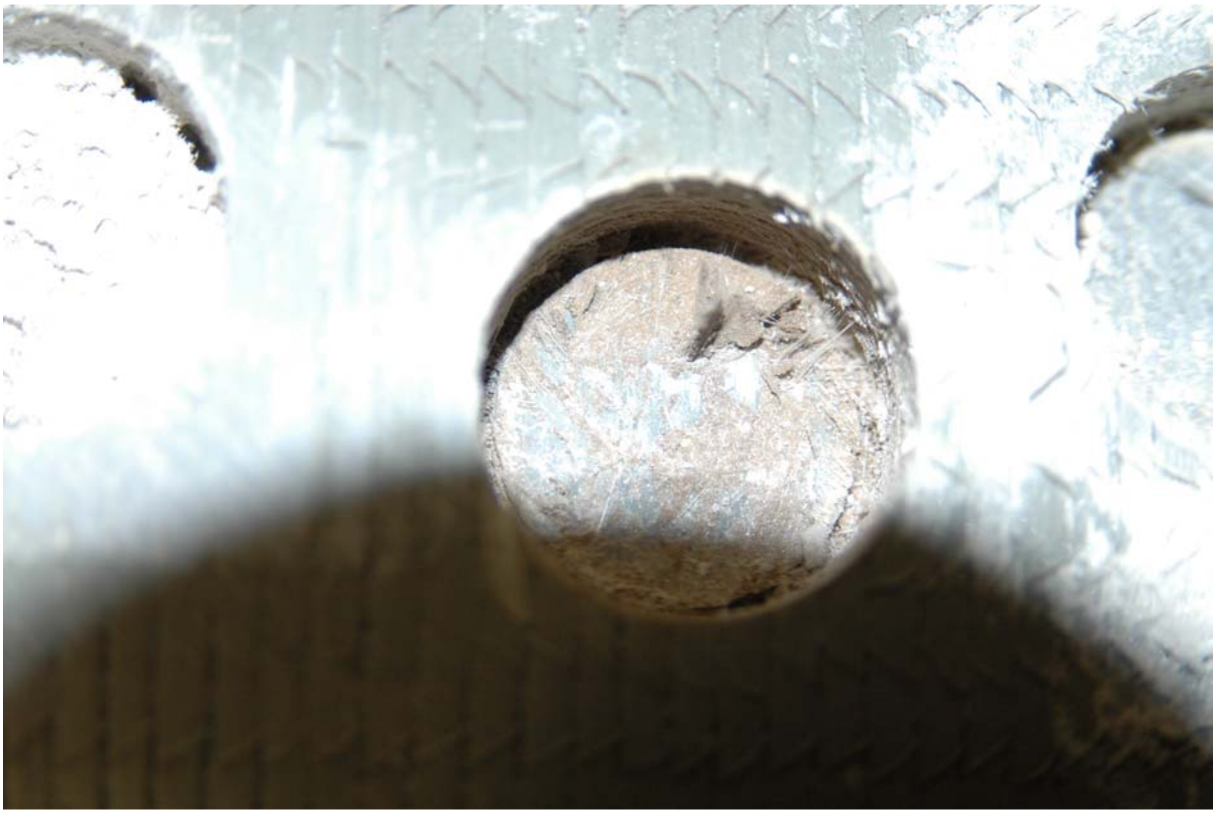

Figure 14 *Photograph showing the fracture surface after pull-off test*

Appendix 1
Strain measurements for the different composite repair systems

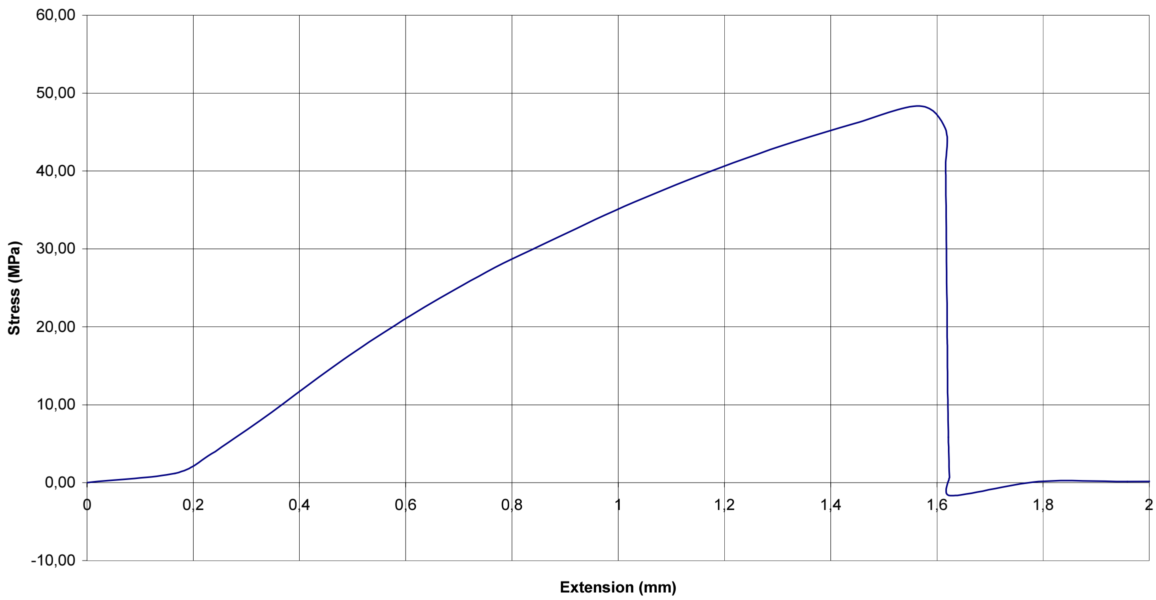

Figure 1-1
Stress strain curve diamant steel wire mesh reinforced ultra metal 1250 tensile specimen

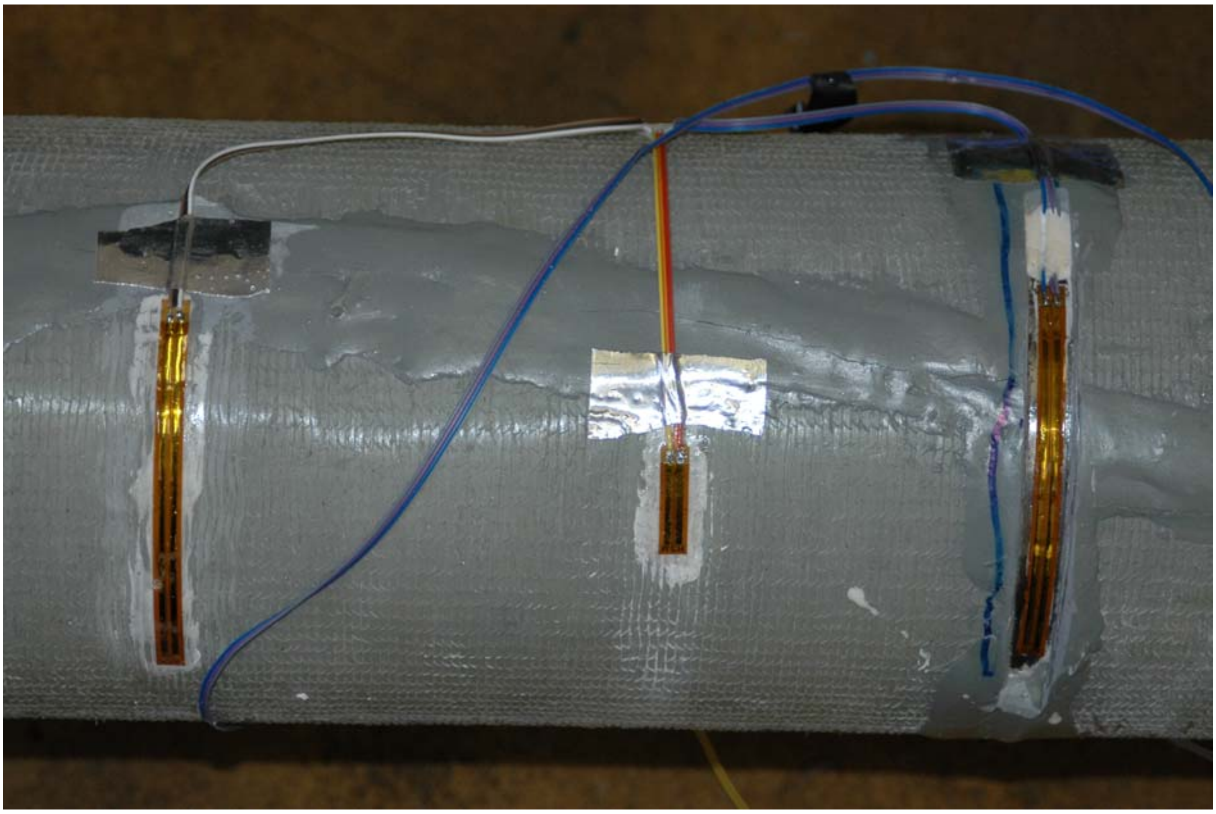

Figure 1-2 *Strain gauge arrangement – test spool*

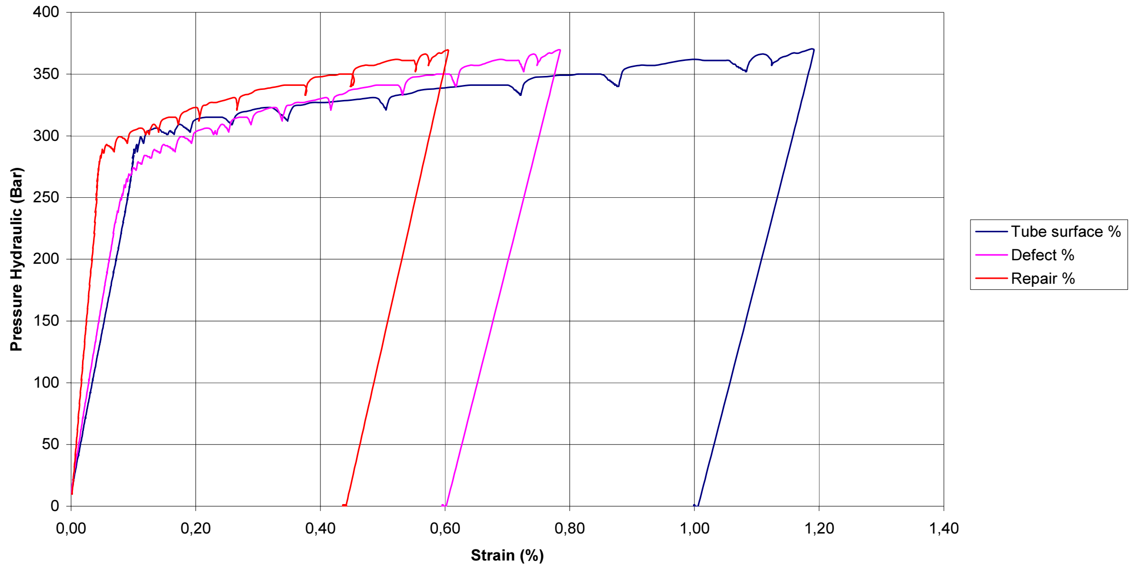

Figure 1-3 *Pressure strain curve Armor plate repair (Spool 13)*

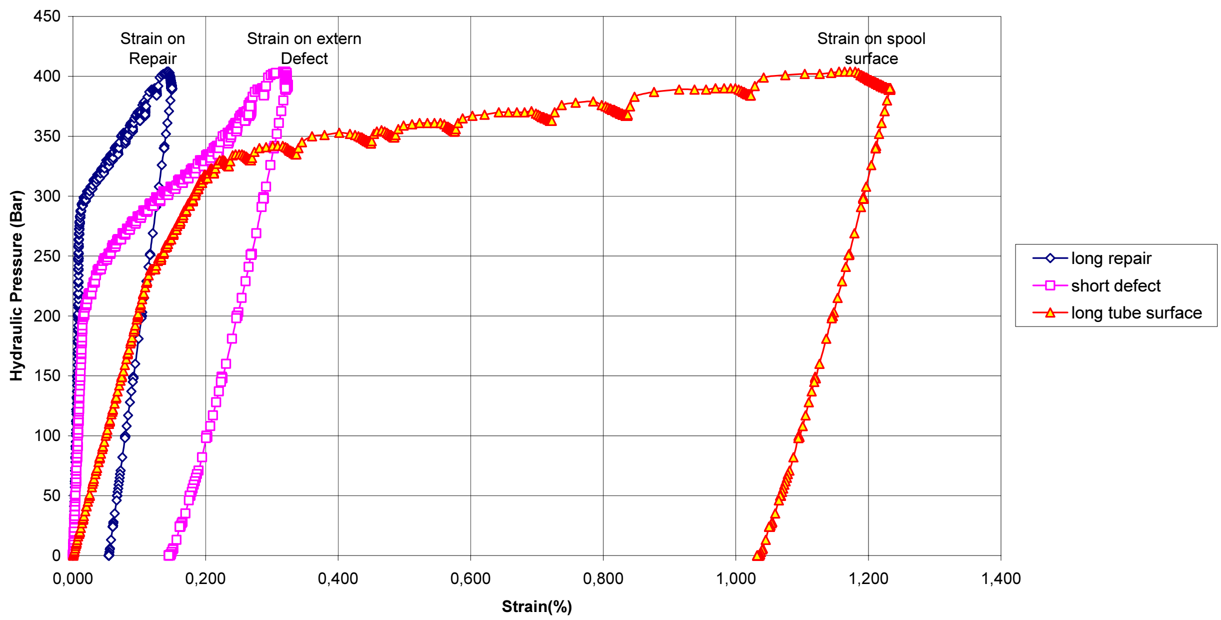

Figure 1-4 *Pressure strain curve Clock Spring repair (Spool 11)*

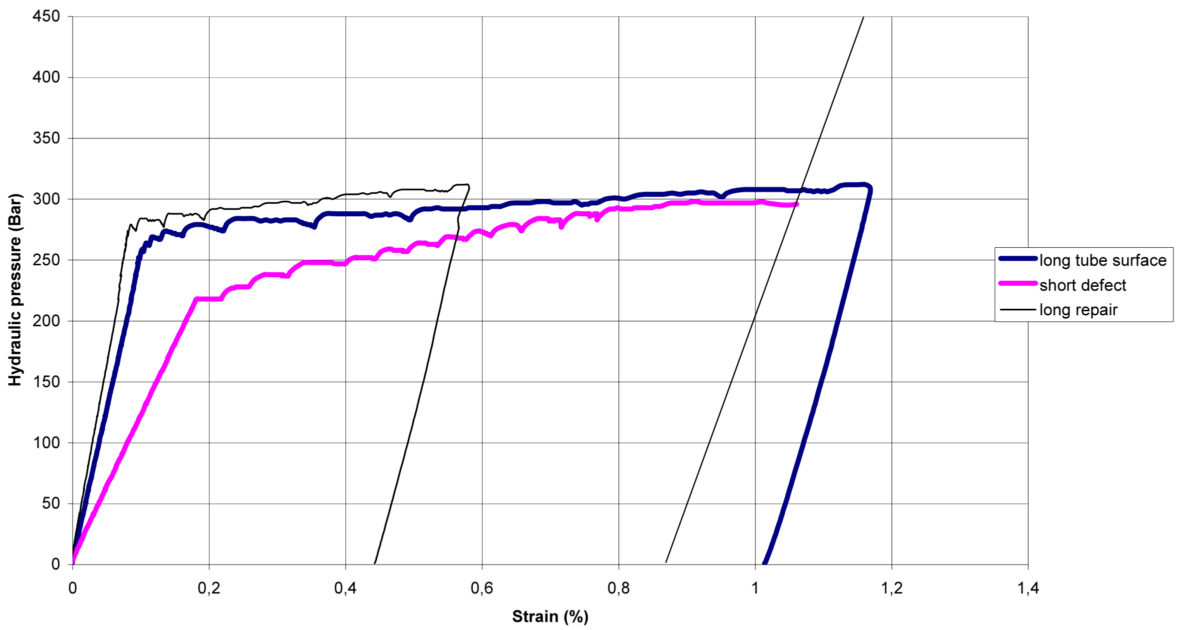

Figure 1-5 *Pressure strain curve FIBAROLL repair*

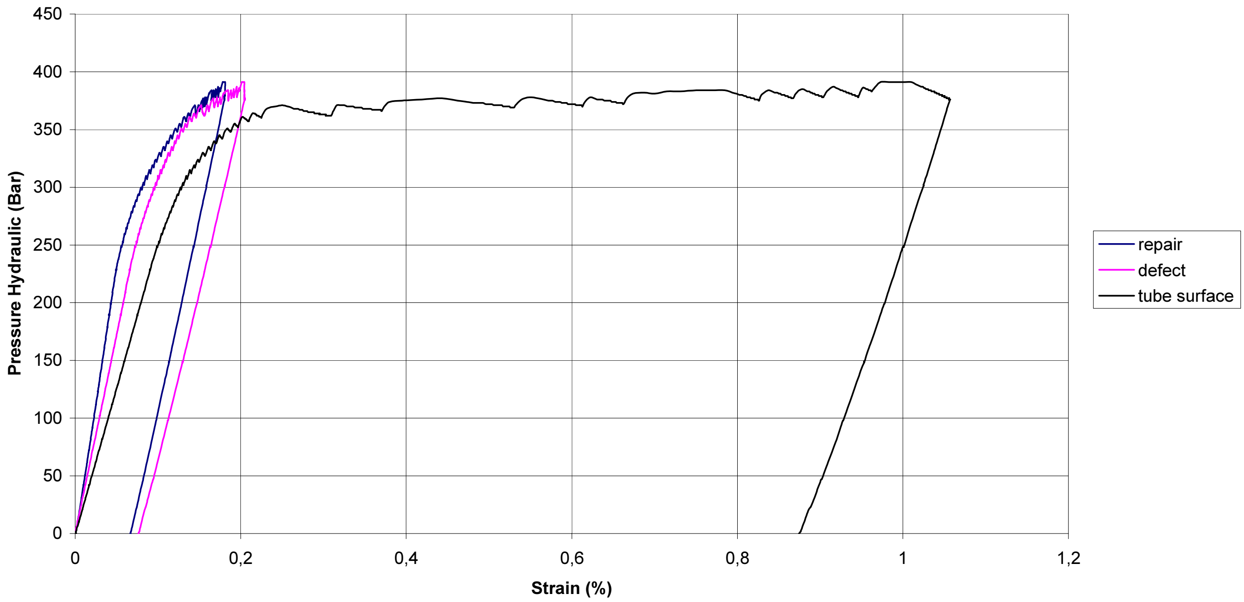

Figure 1-6 *Pressure strain curve Nixus repair (Spool 63)*

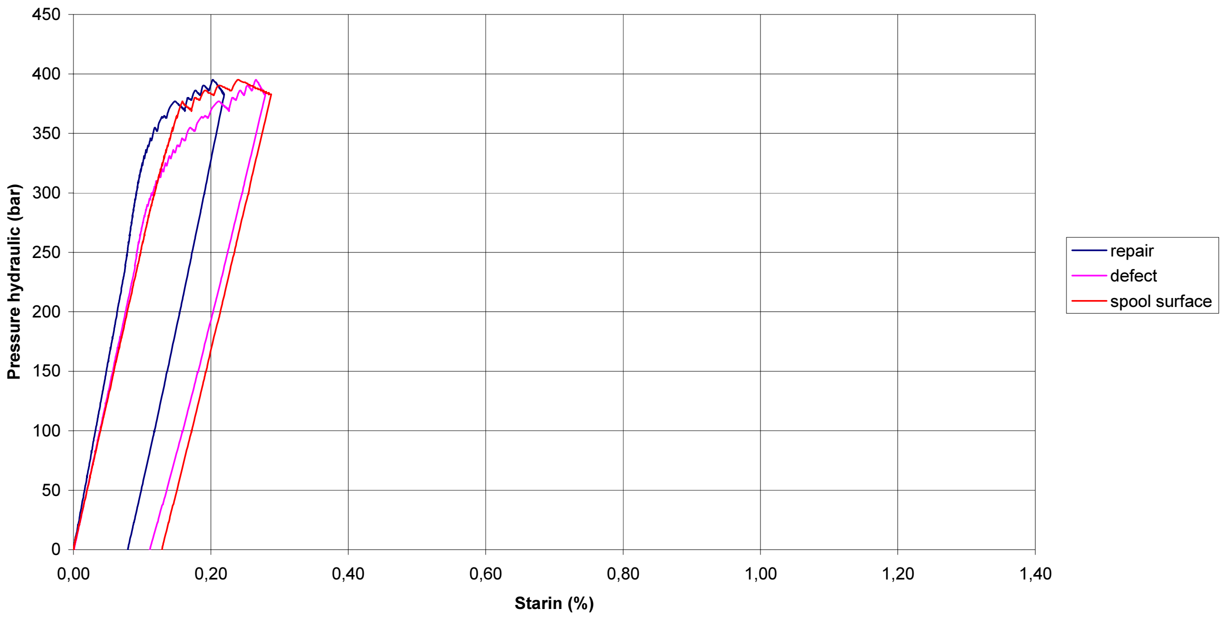

Figure 1-7 *Pressure strain curve Synthoglass repair (Spool 71)*

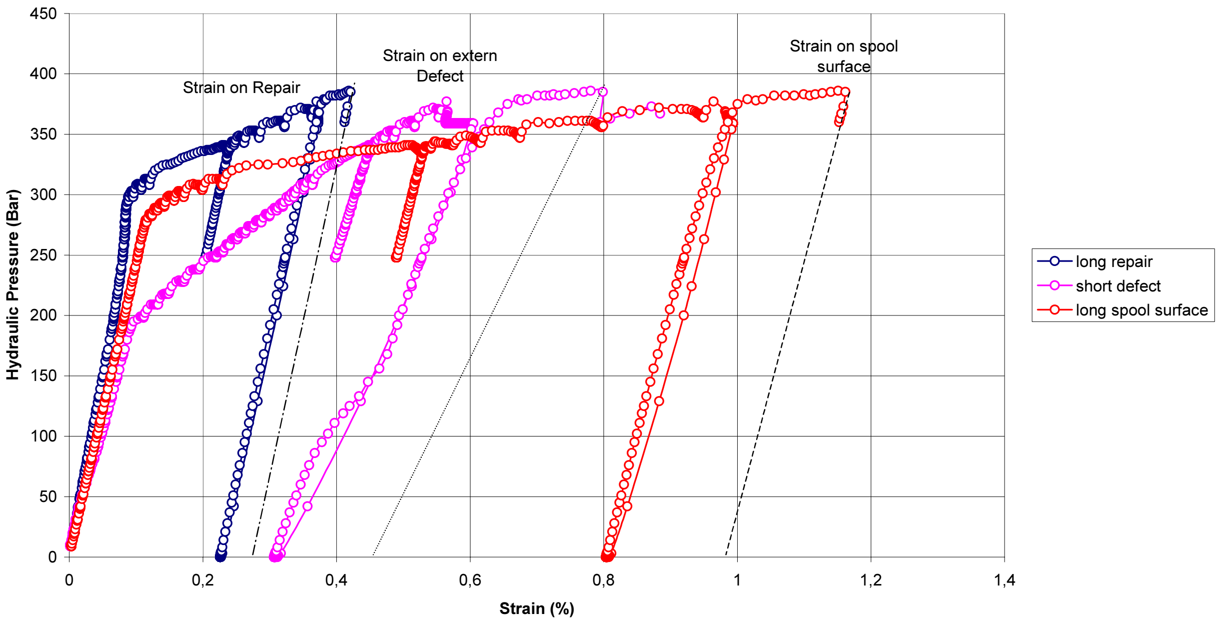

Figure 1-8 *Pressure strain curve TDW repair (Spool 06)*

Appendix 2
Summary of pressure test results for the composite repair systems

1. Short-term pressure strength results

Table 2-1
Summary "short-term" pressure strength tests, performed at ambient temperature

Manufacturer	Test spool	Surface preparation	Defect Type	Condition	Short term strength
Armor Plate	24	- blasted - dry surface	5 mm hole	Virgin (Smartec)	142 bar leakage @ interface
Armor Plate	27	- blasted - wet surface	5 mm hole	1069 hrs tested, @ 50 bar	110 bar leakage @ interface
Armor Plate	22	- power tool - wet surface	5 mm hole	1069 hrs tested, @ 50 bar	175 bar leakage @ interface
Armor Plate	13	- blasted - wet surface	external	1017 hrs tested @ 180 bar	Yield-defect: 270 bar Burst (fracture): 370bar
Clock Spring	11	- power tool - dry surface	external	1017 hrs tested @ 180 bar	Yield-defect: 225 bar Max: 400 bar (intact)
Diamant 1 layer mesh	40	- blasted - dry surface	5 mm hole	virgin	155 bar leakage @ UltraMetal layer
Diamant 1 layer mesh	31	- blasted - wet surface	5 mm hole	virgin	Burst 157 bar @ interface
Diamant 1 layer mesh	37	- power tool - dry surface	5 mm hole	virgin	256 bar leakage @ UltraMetal
Diamant 1 layer mesh	38	- power tool - wet surface	5 mm hole	virgin	148 bar leakage @ UltraMetal

Table 2-1 (cont'd)

Manufacturer	Test spool	Surface preparation	Defect Type	Condition	Short term strength
Fibaroll	43	- blasted - dry surface	5 mm hole	virgin	188 bar leakage @ interface
Fibaroll	56	- power tool - dry surface	5 mm hole	1002 hrs tested @ 50 bar	120 bar leakage @ interface
Fibaroll	51	- power tool - wet surface	5 mm hole	1002 hrs tested @ 50 bar	160 bar (leakage) @ interface
Fibaroll	5	- blasted - dry surface	external	1049 hrs tested @ 180 bar	Yield-defect: 220 bar Burst (fracture): 310 bar
Strongback water activated	63	- blasted - wet surface	external	1014 hrs tested @ 180 bar	Yield-defect: 250 bar Max: 390 bar (intact)
Synthoglass water activated	39	- blasted - wet surface	5 mm hole	virgin	102 bar leakage @ composite
Synthoglass water activated	30	- power tool - wet surface	5 mm hole	virgin	91 bar leakage @ composite
Synthoglass water activated	71	- blasted - wet surface	external	1014 hrs tested @ 180 bar	Yield-defect: 325 bar Max: 395 bar (intact)
TDW	32	- blasted - dry surface	5 mm hole	Virgin (Smartec)	140 bar leakage @ interface
TDW	34	- power tool - dry surface	5 mm hole	virgin	134 bar leakage @ composite
TDW	50	- power tool - wet surface	5 mm hole	virgin	148 bar leakage @ composite
TDW	6	- power tool - wet surface	external	1017 hrs tested @ 180 bar	Yield-defect: 200 bar Burst (fracture): 390 bar

2. 1000 hr pressure test results

Table 2-2 *Summary of 1000 hr pressure tests, performed at 180 bar and 65 °C*

Manufacturer	Test spool	Surface preparation	Defect Type	TP_{1000h} (bar)	Observation	Test result
Armor Plate	26	- blasted - dry surface	5 mm hole	180	Leakage 180 bar @ composite	failed
Armor Plate	35	- blasted - wet surface	5 mm hole	180	Leakage 180 bar @ composite	failed
Armor Plate	27	- blasted - wet surface	5 mm hole	50	1069 hrs survival	passed
Armor Plate	25	- power tool - dry surface	5 mm hole	180	Leakage 170 bar @ composite	failed
Armor Plate	23	- power tool - dry surface	5 mm hole	100	Leakage 80 bar @ composite	failed
Armor Plate	21	- power tool - wet surface	5 mm hole	180	Leakage 25 bar @ composite	failed
Armor Plate	22	- power tool - wet surface	5 mm hole	50	1069 hrs survival	passed
Armor Plate	14	- blasted - dry surface	external	180	1017 hrs survival	passed
Armor Plate	13	- blasted - wet surface	external	180	1017 hrs survival	passed
Armor Plate	8	- power tool - dry surface	external	180	1017 hrs survival	passed
Armor Plate	2	- power tool - wet surface	external	180	1017 hrs survival	passed
Clock Spring	20	- blasted - dry surface	external	180	1017 hrs survival	passed
Clock Spring	3	- blasted - wet surface	external	180	1017 hrs survival	passed
Clock Spring	11	- power tool - dry surface	external	180	1017 hrs survival	passed
Clock Spring	9	- power tool - wet surface	external	180	1017 hrs survival	passed

***Table 2*-2 (cont'd)**

Manufacturer	Test spool	Surface preparation	Defect Type	TP_{1000h} (bar)	Observation	Test result
Diamant 1 layer mesh	48	- blasted - dry surface	5 mm hole	180	burst 170 bar @ interphase	failed
Diamant 3 layer mesh	54	- blasted - dry surface	5 mm hole	150	Leakage 150 bar @ interphase	failed
Diamant 1 layer mesh	36	- blasted - wet surface	5 mm hole	180	Leakage 180 bar @ UltraMetal	failed
Diamant 1 layer mesh	42	- power tool - dry surface	5 mm hole	180	Burst 180 bar @ interface	failed
Diamant 3 layer mesh	55	- power tool - dry surface	5 mm hole	150	Leakage 150 bar @ interphase	failed
Diamant 1 layer mesh	41	- power tool - wet surface	5 mm hole	180	Leakage 150 bar @ UltraMetal	failed
Fibaroll	46	- blasted - dry surface	5 mm hole	100	Leakage 100 bar @ composite	failed
Fibaroll	59	- power tool - dry surface	5 mm hole	100	Leakage 100 bar @ composite	failed
Fibaroll	44	- power tool - wet surface	5 mm hole	100	Leakage 100 bar @ composite	failed
Fibaroll	45	- blasted - wet surface	5 mm hole	50	Leakage 30 bar @ composite	failed
Fibaroll	60	- blasted - wet surface	5 mm hole	100	Leakage 80 bar @ composite	failed
Fibaroll	51	- power tool - wet surface	5 mm hole	50	1002 hrs survival	passed
Fibaroll	56	- power tool - dry surface	5 mm hole	50	1002 hrs survival	passed
Fibaroll	5	- blasted - dry surface	external	180	1049 hrs survival	passed
Fibaroll	18	- blasted - wet surface	external	180	1049 hrs survival	passed
Fibaroll	16	- power tool - dry surface	external	180	1049 hrs survival	passed
Fibaroll	19	- power tool - wet surface	external	180	1049 hrs survival	Passed

***Table 2*-2 (cont'd)**

Manufacturer	Test spool	Surface preparation	Defect Type	TP_{1000h} (bar)	Observation	Test result
Strongback "Nixus"	63	- blasted - wet surface	external	180	1014 hrs survival	passed
Strongback "Nixus"	62	- power tool - wet surface	external	180	1014 hrs survival	passed
Synthoglass	71	- blasted - wet surface	external	180	1014 hrs survival	passed
Synthoglass	74	- power tool - wet surface	external	180	1014 hrs survival	passed
TDW	28	- blasted - dry surface	5 mm hole	180	190 hrs survival leakage@ interface	failed
TDW	47	- blasted - wet surface	5 mm hole	180	Leakage 150 bar @ composite	failed
TDW	29	- blasted - wet surface	5 mm hole	100	22 hrs survival leakage @ composite	failed
TDW	33	- power tool - dry surface	5 mm hole	180	Leakage 150 bar @ interface	failed
TDW	49	- power tool - wet surface	5 mm hole	180	Leakage 150 bar @ composite	failed
TDW	12	- blasted - dry surface	external	180	1017 hrs survival	passed
TDW	15	- blasted - wet surface	external	180	1017 hrs survival	passed
TDW	7	- power tool - dry surface	external	180	1017 hrs survival	passed
TDW	6	- power tool - wet surface	external	180	1017 hrs survival	passed

Bibliographic Information

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