



OTC-28896-MS

Innovative Subsea Repair Of A Leaking Flexible Joint Using Hybrid Gasket And Composite Material

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This paper was prepared for presentation at the Offshore Technology Conference held in Houston, Texas, USA, 1–4 May 2017.

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Abstract

During a routine subsea inspection of the Akpo subsea assets, leaks were identified on two of the flexible joints at the top of the water injection steel catenary risers. These leaks were categorised as the highest integrity threats for the district and a task force was formed in order to determine the cause of the leaks and thereby, the most appropriate means to resolve the issue. A phased array UT inspection method has been specially developed to perform underwater inspection of the gasket groove.

The nature of the leak was deemed time-critical. The leak was of relatively high volume (the leak rate was estimated at 5 000 cubic meters per day), was worsening and was inducing structural damages to the flexible joint by cavitation.

A technical solution was studied involving underwater machining using divers. The upper joint surface of the gasket groove was part of a replaceable spool but the lower joint surface was integral to the flexible joint and therefore had to be repaired in-place. After several months of planning and testing, it was determined that the machining tool was not suitable for the operation by divers. With only a few months remaining in the 6-month target delivery, a second solution was proposed using a composite epoxy mastic repair together with a hybrid steel-elastomer gasket. The use of such a solution would be a first-of-its-kind for this application and would involve underwater grit blasting to achieve proper adhesion of the mastic. It would also involve precise bolt torquing and tensioning in very restricted work space around the flexible joint receptacle and ultrasonic acoustic bolt length measurements, in order to measure the stress in the bolts.

PREFACE

Total Nigeria was presented with an integrity threat in 2016. Leaks discovered on two flexible joints at the top of the water injection system steel catenary risers (SCRs) during a routine diver inspection on the AKPO gas/condensate field were unforeseen and caused immediate concern.

Further evolution of these leaks could have impacted the structural integrity and threatened the hang-off function with possible structural damage to the Risers/FPSO. Very significant production deferment could also have been incurred if these leaks were not quickly arrested as water injection operation has important impact on the AKPO FPSO production.

The established root cause indicated that all the four water injection flex-joints were susceptible to this damage even though only two were leaking at the time of the inspection.

It was clearly imperative to urgently address this challenge. A classical approach would have been to change out all the four defective Flexible Joints with the associated huge capital outlay and long lead time.

The project team however developed, qualified and successfully deployed a solution that was applied for the first in the industry - an innovative repair approach involving the reconstruction of the flange joints using a composite epoxy mastic solution together with the use of hybrid steel/elastomer gaskets. Imaging of the bolt material and gasket surface contact with the joint grooves using phased array ultra sonic examination facilitated the integrity investigation.

This was done safely, on time and at a small fraction of the cost of the classical solution.

The solution deployed is not only a technical innovation, it is also a transverse effort across several disciplines aligned with the same objective of solving the problem with simple, safe and robust solutions.

CONTEXT

The AKPO field was discovered in 2000 and started producing in 2009. The field architecture includes nine (9) production 4-slot subsea manifolds and several water injection and gas injections subsea wells all tied back to the AKPO FPSO in roughly 1,300m water depth. All in-field pipelines and the single gas export line are linked to the FPSO using steel catenary risers connected to the topsides using flexible joints. The function of the flexible joints is to provide compliance at the riser-vessel interface so as not to convey bending stresses to the rigid riser pipe suspended below the flexible joints.

There are eight (8) 10" production risers, four (4) 10" water injection risers, one (1) 8" gas injection riser and one (1) 16" gas export riser. The flexible joints have been supplied by Oil States Industries, Inc. based in Arlington, Texas, USA. and were of a second generation design. The riser design was such that the flexible joint part of the riser supported the SCR weight, and this load in turn is transferred to the FPSO via a receptacle integrated into a porch mounted on the hull at the +11.5m elevation.

A spare flexible joint was procured as part of an emergency pipeline and subsea repair system (EPSRS) philosophy for each riser service, except that of water injection, during the project phase. The spare water injection spare joint was procured in 2016 to complete the EPSRS inventory.

INSPECTION

During a diver inspection in April 2016, leaks were reported on two of the water injection flexible joints. These leaks were localized around several of the nuts closing the attached flange of the flexible joints and at the interface between the two parts of the flanged connection:



Fig. 1. Leak observed under a nut



Fig. 2. Leak observed at flange interface

A root cause analysis was conducted to determine the possible origin of the leak, which was believed to be due to a non conformance of the gasket. A second inspection campaign was then carried out in December 2016 with two separate goals:

- to get confidence in the identification of the root cause
- to perform non destructive inspection (ultra sonic testing) to gather information for the preparation of the repair campaign.

During this second campaign, an escalation of the leak and the damages was observed. Some studs were found eroded; the top flange appeared to be severely damaged below the leaking nuts. At some locations the depth of metal loss reached 1 cm. In addition, the flexible joint receptacle was also starting to suffer damages from the leak.

The Phased Array UT inspection highlighted an insufficient compression of the gasket. It gave credit to the expected root cause and confirmed the need to replace the original gasket on the four flexible joints.



Fig. 3. Increased leak (2nd campaign)



Fig. 4. Damage to studs and nuts (2" diameter)



Fig. 5. Damage under leaking nuts (max depth = 1cm)



Fig. 6. Damage to the flexible joint receptacle

By analysis of the material balance on the water injection system, the acceleration of the leak was clearly noticeable. The

following chart (Fig. 7) provides the records of the water entering the riser (blue dots) and the total water injected in the subsea wells (pink dots). The difference between these two values (Quantity of water entering the riser – Quantity of water injected in the wells) corresponds to the leak rate. This rate is provided as a percentage of the water entering the riser (red dots) in the same chart:

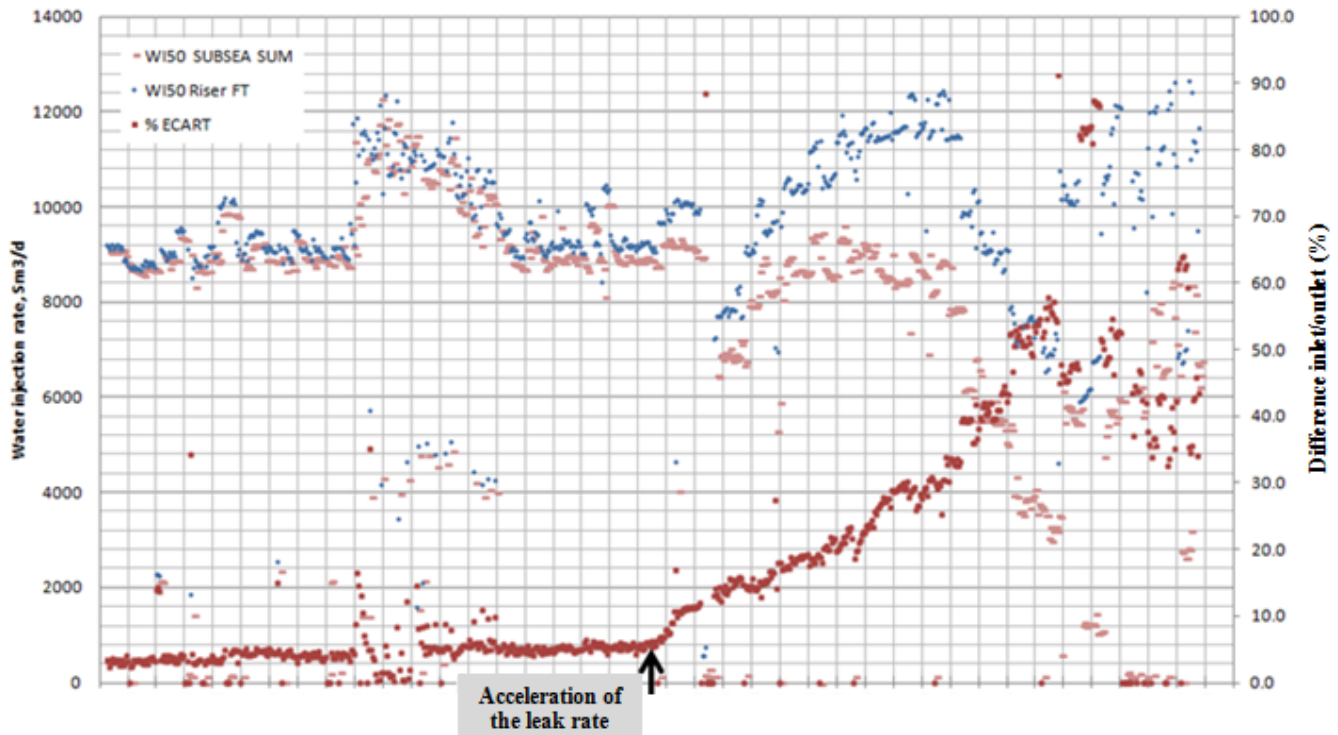


Fig. 7. Material balance on water injection system WI 50

PROJECT MANAGEMENT

Project Conception

In January 2017, Field Operations provided a statement of requirements (SOR) to Engineering, Construction and Projects (ECP), a branch of the Total Projects discipline within the Total Nigeria entity, to execute the flexible joint repairs.

Upon conclusion of the 2016 inspection campaign, FJs WI20 and WI50 were still leaking and were deemed to be in critical need of rectification. WI10 and WI30 were not confirmed to have leaks but had the same inherent problems of incorrect ring gasket design and therefore posed a risk of leaking. Furthermore, the leaks on WI20 and WI50 had eroded channels in the surrounding FJ receptacle material and although the damage was deemed non-critical, extended durations of such erosion could have led to a critical situation.

The Phased Array Ultrasonic Testing results from the December 2016 diving campaign showed that the upper ring grooves of the WI20 and WI50 FJ top flanges were damaged, but the extent of damage could not be determined. No damage was identified in the lower ring grooves of the FJ top flanges, though this would only be confirmed visually after removing the top flange spools.

If the lower ring grooves of the FJ top flanges were indeed damaged, the plan was to machine them to produce larger profiles which could accept other size ring gaskets. If the lower grooves of the FJ top flanges were not damaged, the plan was to install new gaskets, which would have been properly dimensioned, along with replacement top flange spools.

The availability of the EPSRS spare WI FJ provided the means to act quickly to address the most critical riser. WI20 was deemed to be the most critical riser as it supports the greatest number of wells and was believed to be the most severely damaged of the FJs. The EPSRS spare WI FJ could be dismantled and the top flange spool and used to replace the damaged WI20 top flange spool. Still, as the integrity of the lower ring groove on the FJ top flange was not known, a machining tool would need to be available offshore for the intervention. The delivery of the machining tool needed to reface the gasket grooves would likely be on the project critical path.

In parallel, material procurement for WI50 would drive the schedule for a later campaign, which was anticipated for T0+12months.

A project execution plan (PEP) was developed based on available initial information provided by TOTAL Head Quarters pipeline specialists and TUCN DWD Field Operations, as well as ECP Construction, HSE, QA/QC, Project Controls, Subsea and Engineering entity guidance.

Project Initial Scope

The scope of the project included the following:

WI FJ Flange/Gasket Replacement Intervention 1

- Disconnection and rotating of the riser spool on WI20.
- Removal of damaged top flange spool on WI20 recovery to topsides
- Assess damage to ring gasket groove
- If gasket groove on top flange damaged but mating flange on FJ NOT damaged:
 - Installation of replacement WI20 top flange spool (taken from EPSRS inventory), including new bolts, nuts and gasket
- If both the gasket groove on top flange and mating flange on FJ damaged:
 - Re-facing of WI20 FJ top flange groove by divers
 - Re-facing of WI20 mating flange face on FJ on topsides
 - Inspection of the gasket grooves.
 - Installation of WI20 top flange spool, including new bolts, nuts and gasket
- Disconnection and rotating of the riser spool on WI10.
- Removal of damaged top flange spool on WI10 recovery to topsides
- Installation of new bolts, nuts and gasket on WI10 FJ
- Disconnection and rotating of the riser spool on WI30.
- Removal of damaged top flange spool on WI30 recovery to topsides
- Installation of new bolts, nuts and gasket on WI30 FJ
- Inspection of FJs: P10L, P20L, P20R, P30R, P40L & P40R

WI FJ Flange/Gasket Replacement Intervention 2

- The scope for the second intervention was the replacement of top flange spool, gaskets, studs and nuts for WI50, using the same sequence as that for WI20, the difference being that the top flange spool would be a newly procured item.

Note that although the above scope reflected that of 2 campaigns, all efforts were made to acquire the newly procured top flange spool for WI50 in order to merge both intervention campaigns.

Project Objectives

DESCRIPTION	OBJECTIVE
Health & Safety	<ul style="list-style-type: none"> • No safety incident • LTIF = 0 • No Fatality
Environment	No Environmental Damage
Schedule	<ul style="list-style-type: none"> - FJs on WI10, WI20 & WI30 remediated within 6 months - WI10 shut-in for maximum 8 days - WI20 shut-in for maximum 10 days - WI30 shut-in for maximum 8 days - WI50 remediated in 12 months - WI50 shut-in for maximum 10 days
Cost	Cost performance remain within approved budget

Technical Data

10” Water Injection FJ:

- Top Flange (spool)
 - Upper Flange spec: 12”-2500 R60 ANSI Flange
 - Lower Flange spec: Oil States proprietary
 - Length: 900mm
 - Weight: >2000kg

Riser Spool

- Weight: WI10:5657 Kg, WI2: 5572 Kg, WI30: 5645 Kg, WI50: 5646 Kg
- Upper Flange spec: Galperti 10” Hub Connector (clamp-type flange)
- Lower Flange spec : 12”-2500 R60 ANSI Flange
- Length: max vertical length is 14 metres
- Two (2) riser support clamps

Specific Technical Constraints

- The actual condition of the ring joints on the FJs were not known, though damage was observed on the grooves of the top flanges of both WI20 and WI50 upper flanges
- The OSI top flange was not intended for subsea removal and access to the nuts and bolts is congested; stud tensioning equipment could not be used due to clashing and only certain hydraulic torque tools could fit inside the envelope
- The ANSI flange on the opposite end of the top flange spool was, however, a candidate for stud tensioning, which would save time; therefore both stud tensioning and hydraulic torque tools were needed for the job.
- Two types of machining tools would be needed for the job: one for the subsea re-facing using the bore of the FJ for docking AND one for the re-facing of the top flange groove on the topside using a means of docking on the OD of the flange. This is due to a sleeve protruding from the top flange which serves the function of allowing pigging of the pipeline.
- Methodology for inspection of the gasket groove was to be ascertained.
- Because the extent of damage of the ring seal groove was unknown, several replacement ring gasket sizes would have to be designed and manufactured. In case of damage to the groove on the mating flange face on the FJ, machining of the body would have to be needed.

Project Execution

Time constraints imposed many activities running in parallel, which normally would have been done in succession. Budget approvals, contracting, engineering and procurement were all launched immediately. The drivers were the delivery of a top flange spool to replace that of WI50 as well as a diving service order, rigging materials, support vessels, and most importantly a solution to repair the flexible joints, in place by June 2017.

Contracting

Oil States Industries, Inc. as the original equipment manufacturer (OEM) was contracted to furnish all materials related directly to the flexible joints, as well as all associated tooling. The equipment supplier considered for furnishing the machining tools, and possibly the stud torquing and tensioning tools was a specialty subsea tooling contractor with a close relation to OSI. The specialty subsea tooling contractor would have performed the machining tool modification under the control of OSI. As the machining solution was ultimately discarded, the replacement solution using hybrid gaskets and mastic repair, was managed through Total HQ in Pau, France. The specialty subsea tooling contractor was therefore not involved beyond the engineering phase.

Diving was carried out using a local diving contractor that had an agreement in place with TUCN and was available to do the work. A production support vessel (PSV) to serve as a mother vessel for the dive spread was to be acquired locally under a separate contract. The mother vessel would be used in conjunction with the dive contractor light dive

boat (LDB), integral to the SCUBA replacement dive equipment spread. Ultimately, the diving was done using the LDB, but with the dive decompression chamber, machinery container and divers themselves housed on the FPSO, so the PSV contracting was not needed.

NAPIMS (National Petroleum Investment Management Services), the Nigerian governmental partner agreed with the contracting strategy and estimated cost. This allowed the work to be performed outside of normal tendering rules, thereby supporting the tight schedule.

Engineering

Groove Repair

The engineering phase was essentially already started by OSI prior to the official project kick-off. Total HQ had engaged OSI during the procurement of the EPSRS spare water injection flexible joint and discovered the gasket dimensions as a non-conformance and rectified it prior to final assembly. Thus, once the leaks were discovered this non-conformance was believed to be the root cause and engineering steps were launched to find a means to remediate the situation. A machining tool from the specialty subsea tooling contractor was considered a viable option, and both OSI and this contractor were already studying the concept for the Akpo application.

During early discussions amongst Total, OSI and the specialty subsea tooling contractor, it became clear that there were concerns on the part of the contractor. The existing tool was not designed for divers, mainly because divers typically are not trained in machining. Therefore, either the existing tool would have to be redesigned to be 'diver-friendly', that is, simple to operate in subsea conditions by someone with little to no machining experience, or the divers would have to be thoroughly trained in machining. Due to the time constraints and lack of practicality of such a solution using free-lance divers, the option to train the divers was discarded. Focus was instead put on redesigning the tool to be diver-friendly. A test was performed in late March 2017 to determine how far was the existing tool from being industrial for diver use. The test was done in a pool on a test piece, and the results confirmed that even for an experienced machinist, the likelihood of achieving the precision needed on the gasket groove was low. Furthermore, the time required offshore to perform all the passes in a safe manner was in the order of several days per flexible joint, which was deemed impractical.

With the machining option no longer deemed viable, full focus was placed on the groove reconstruction using composite material along with hybrid gaskets. OSI's specialty subsea tooling contractor was no longer involved, and instead Total HQ contracted with and lead the effort of the joint reconstruction and gasket design and testing directly with 3X Engineering and Techlam/Hutchinson

Site surveys

Several site surveys took place starting in January 2017, in order to engineer a rigging and hoisting plan for the temporary relocation of the riser spool and the hook-up spool, as well as the recovery and installation of the old top-flange spool and new top-flange spool, respectively. General condition of the spools and their clamps were also assessed. Several of the clamps supporting the riser spools were heavily corroded and the replacement of the associated bolts and nuts were needed.

Monorails

The lifting aids on the Akpo FPSO used during the project phase served equally for the flexible joint interventions. However the monorails that are strategically positioned for handling the hook-up spools were not all at sufficient rating. The spool was calculated to weigh 7.8 tons, and although WI10 monorail is rated for 8 tons, WI20, WI30 and WI50 monorails are rated for 7 tons. Therefore, a specific analysis was performed for checking the stresses in the 7-ton rated monorails and it was determined that the stresses imposed by the hook-up spool, even considering very conservative scenarios, was within the capacity of the monorails. The calculation was verified by a 3rd party and the monorails were temporarily uprated to 7.8 tons.

Diving platform

During the 2016 dive inspection campaigns, a PSV was used as a mother vessel in support of the LDB and SCUBA replacement dive spread. The diving was performed during daylight hours only. As the inspection imposed little impact on the FPSO operations and as it was not necessarily time-critical, the 12-hour working day was not a major

constraint. Likewise, as the inspection campaign was relatively short in duration, the cost of the PSV was not a huge impact on the overall budget.

However, for the flexible joint intervention project, both the cost of the PSV and the reduced productivity associated with only working daylight hours, would prove to be a major factor in terms of budget and in terms of inconvenience for the FPSO operations, as a significant personnel spread would be housed there. Therefore, several alternative scenarios were studied.

Firstly, the scenario of diving directly off the FPSO was considered. This would be done using a launch and recovery system (LARS) installed on the FPSO in order to convey divers to and from the worksite. Deck strength and clearances were studied on the various deck elevations near the flexible joint work locations, as well as accessibility to install the equipment. Ultimately, the only feasible solution would be to use the railing system still in place from the project phase that was used to skid the riser pull-in system (RPS). The RPS is in fact still intact, but no longer in an operational state. This solution was indeed technically viable, but would involve having a MPSV install the LARS, dive decompression chamber (DDC) and machinery container on the RPS railing, which would involve a rigging team working over water and very close to the suspended load, in order to position it correctly.

Ultimately it was decided to place the DDC and machinery container near the Akpo crane laydown area, perform the diving using an LDB, and house the divers on the FPSO. Tests were performed to ensure that in the case of incident in the water with a diver, the diver could be safely brought back to the DDC in 15 minutes, an IMCA regulation. Housing the dive team on the FPSO saved the project the cost of the PSV mother vessel and improved the cohesion between the topsides construction team and the diver team.

REPAIR SOLUTION

Initially, a technical solution was studied involving underwater machining using divers. The upper joint surface of the gasket groove was part of a replaceable spool but the lower joint surface was integral to the flexible joint and therefore had to be repaired in-place. After several months of planning and testing, it was determined that the machining tool was not suitable for the operation by divers. With only a few months remaining in the 6-month target delivery, a second solution was proposed using a composite epoxy mastic repair together with a hybrid steel-elastomer gasket.

Hybrid gasket design

Total contracted Hutchinson (also known as Techlam) to develop and supply a custom engineered and fabricated rubber gasket to repair the leak in only a few weeks timeframe. The challenge was linked to the very tight schedule to develop and fabricate a gasket which had to be installed subsea and able to accommodate small damages potentially present in the gasket groove. It should be noted that it was not possible to precisely determine the exact nature of the defects in the groove before opening the flexible joint. The design of the gasket had to be robust enough to comply with various types of damages (e.g. pitting, scratches, extended damage...). Knowing this requirement, Hutchinson decided to propose a rubber gasket solution, an example of which can be seen in Fig. 8.



Fig. 8. Cut view of the hybrid gasket

As the gasket was to be submarine installable, the main issue was to avoid any water becoming trapped between the metallic groove and the gasket. If water were to get trapped during installation, a variation of the closed volume between the gasket and

the groove could result in excessively high pressure – due to incompressibility of the water. The gasket would not be able to withstand such pressure and would be damaged. In light of this concern, the solution chosen by Hutchinson was to design a specific gasket profile that would expel all the water out of the groove progressively with the deformation of the rubber. As shown on Fig. 9 below, the first contact occurs in the base of the groove and as the flange is tightened the rubber is progressively deformed until it completely fills the entire free volume, thus preventing any water from remaining trapped.

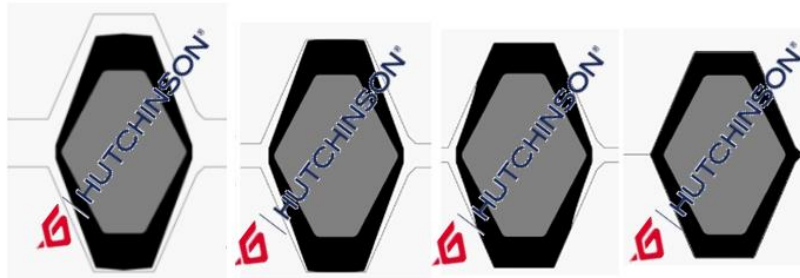


Fig. 9. Progressive deformation of the hybrid gasket

The shape of the gasket is driven by the need to avoid trapped water in the groove; the design focuses on the primary functionality of the gasket: ensure the sealing of the flange assembly. Two points had to be considered. The first point is to keep a contact pressure superior to the working pressure between the metallic groove and the gasket. In this case, the design criterion was a contact pressure of 50 MPa (twice the service pressure). The second point was to anticipate the stress relaxation phenomenon of the rubber material. The only way to pass these constraints was to increase the pressure inside the rubber and to choose a rubber specifically developed for applications subject to stress relaxation. The solution for this consists of including a metallic part (interleaf) inside the gasket. The profile of the interleaf was specifically designed to drive the deformation of the rubber inside the groove and to maintain a high contact pressure in the base of the groove after completion of the installation. It can be seen in Fig. 10, that the top and bottom rubber faces of the gasket are highly compressed over a large area, with a contact pressure well above the criteria. Based on this the stress relaxation phenomena was virtually eliminated, and the sealing of the assembly is guaranteed.

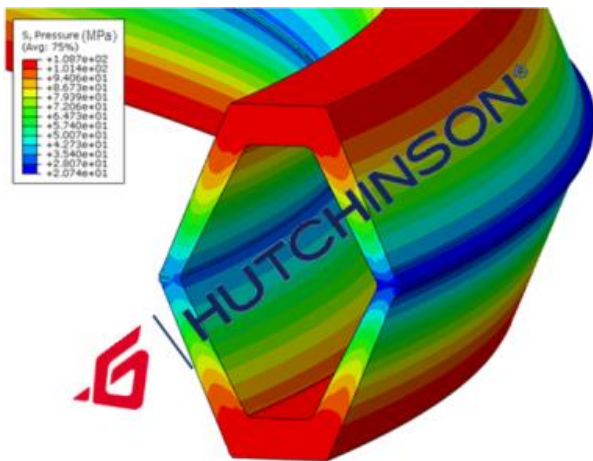


Fig. 10. Results of Finite Element Analysis: compression stress in the rubber

Finally, the last functional requirement to consider was the capacity of the gasket to compensate for unknown groove defects which may be present. Several tests of defect simulation were performed to demonstrate the gasket design robustness. One of the most representative tests is illustrated on the figure below (Fig. 11). A double groove with a square profile of 1 mm x 1 mm has been introduced into the Finite Elements model in the groove base. It is the worst location possible for a defect because this area is the main contact area for sealing. As the model is axisymmetric, the defect has been propagated around the entire groove. It can be seen that even with this type of defect present the rubber still filled entirely the groove and maintains a sufficient level of contact pressure without damaging the rubber.

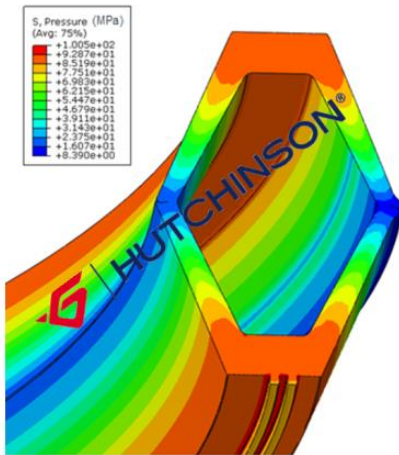


Fig. 11. Results of Finite Element Analysis: Impact of groove damages (1mm x 1mm)

Groove Composite Repair

The design of the hybrid gasket has been demonstrated to be robust enough to ensure good sealing even on partly damaged grooves (with size < 1mm x 1mm). Since the extent of damage was unknown, it was also decided to develop a procedure to repair the groove of the flexible joint body as a backup solution. 3X Engineering was contracted to develop a solution using composite repair material. 3X Engineering is specialized in pipe repair suffering from corrosion defects and mechanical damages based on composite technology, including in a subsea environment. Despite significant know-how in subsea composite repair application, this flexible joint repair was a challenge as repairing a groove in these conditions had never been tried before. The solution proposed relied on the use of different polymeric systems.

The functional requirements for the solution to be developed were:

- 1/ to be applied subsea by divers
- 2/ to ensure a sufficient curing time for the diver to apply the filler systems – the selected system had to be soft enough for application by the diver during 1h
- 3/ in addition, the polymer should be cured in 8h in order to limit the time of the offshore operations
- 4/ to withstand a maximum compressive strength of 70 MPa imposed by the hybrid gasket

Materials selection and qualification

Materials selection

The chosen materials are a derivative from the standard subsea 3X composite repair product (R4D-S).

A bi-component epoxy primer (P3X32 Primer) was used to improve the bonding onto the surface prepared substrate in subsea environment. A hand-held dual cartridge epoxy primer dispenser was used to deliver on-demand the primer. This primer is a low viscosity and fast-curing product. The deposit film thickness is thin - less than 300µm.

The filler (F3XSS filler) has been chosen to fill the damaged groove. After primer application, the filler could be directly applied without need for curing time of the primer. It behaves like modelling clay so it would be possible to set in a defected groove. This bi-component epoxy filler had to be mixed out of water onboard the diving vessel. This filler was chosen for its ability to cure underwater and develop good compressive properties.

Qualification

The selection of the above mentioned materials was based on a representative qualification program:

1. Mixing

The primer was mixed in static mixer using a dispenser and applied on a sample plate immersed in seawater at 27°C.

The filler was mixed in air at room temperature, respecting the recommended weight ratio, until getting a homogeneous mixture. It was then immersed in seawater at 27°C.

During all the curing time, a climatic room was used to maintain the required seawater temperature.

2. Hardness monitoring

During the whole curing time, the hardness evolution was monitored. Before hardness measurement the samples were removed from the water and dried. The hardness was controlled using a calibrated durometer Shore D according to ISO 868. The durometer reference was Mitutoyo HH-337-01. The sample should be thicker than 4mm. Instantaneous reading, within 1 second after the presser foot was in firm contact with the test specimen, was recorded. A minimum of 5 measurements were obtained to determine the mean value. The measurements were taken at 27°C.

3. Flexural testing

A mould was used to obtain a specimen with regular dimensions: 5 mm x 10.35 mm x 90 mm (h x w x l). Epoxy systems were mixed, immersed in seawater, and then set in mould to get the specimen.

A 3 point-bending test was done using a tensile bench according to ISO 178. The bench reference was Instron 3369 with a force gauge of 5kN. The length of span between the supports was set to 64mm. The displacement rate was 10 mm/min. For the tested material, five specimens were tested at 27°C as a function of curing.

4. Compressive testing

A mould was used to obtain a cylindrical specimen with regular dimensions: ø13mm x 28mm (diameter x h). Epoxy systems were mixed, immersed in seawater, and then set in a mould to get the specimen.

A compressive testing was done using a tensile bench according to ASME D695. The bench reference was Instron 3369 with a force gauge of 50kN. The displacement rate was 1.3 mm/min. For the tested material, five specimens were tested at 27°C.

Results and discussions

Hardness

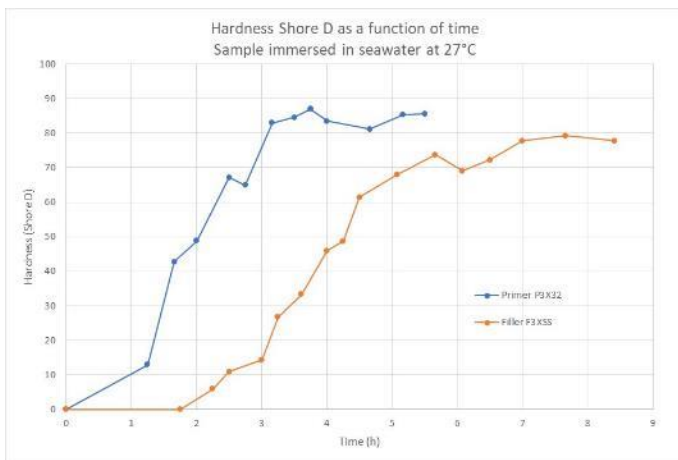


Fig. 12. Hardness (Shore D) evolution as function of time for P3X32 and F3XSS.

The hardness measurements were measured as a function of the time using a durometer (Shore D). The goal was to follow the evolution of mechanical properties during the chemical reaction. During this polymerization process, epoxides and amines react together to form rigid three-dimensional networks.

From the previous figure (Fig. 12) and considering hardness properties, it can be noticed that the primer reacts faster than the filler. Indeed, the primer reaches maximum hardness after approximately 3 hours, while the filler needs about 7 hours to reach its maximum at 27°C. It can also be noticed that the filler can be modelled during more than 1 hour after mixing. This time was considered sufficient for the divers to apply the filler in the flange groove.



Fig. 13. Hardness measurement on F3XSS

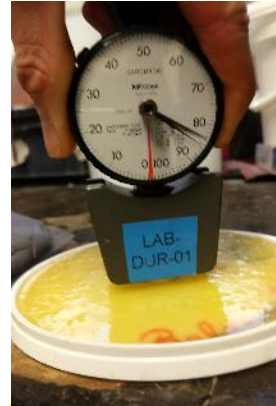


Fig. 14. Hardness measurement on P3X32.

Bending test



Fig. 15. Specimen obtained with mould



Fig. 16. Bending test ongoing

Even if the epoxy systems are subject to compression, it was more convenient to determine the mechanical properties doing 3 point-bend testing. The goal was to determine the required time after mixing to develop good mechanical properties. Both maximum stress and modulus were measured. It can be observed that these 2 mechanical properties grow at the same time. From Figures below, it can again be seen that curing is faster for the primer than for the filler. It confirms the trend identified with the hardness testing. It is observed that the primer develops decent mechanical properties after 3 hours. It takes longer for the filler to become rigid. After 24 hours, the maximum flexural stress for the primer reaches 72 MPa, while after 32 hours the capacity of the filler reaches 49 MPa. The flexural modulus of the filler starts to increase after 6h to reach 700 MPa (20% of final modulus) at 8h. At this moment, the epoxy system has already developed modulus and can sustain stress, and is still soft enough to be cut manually if any defect is found. During repair, it was decided to remove the mould after 6 to 8 hours, which is the best compromise between rigid and machinable material.

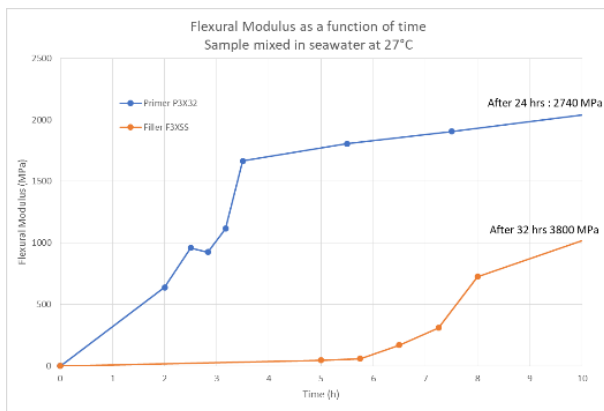
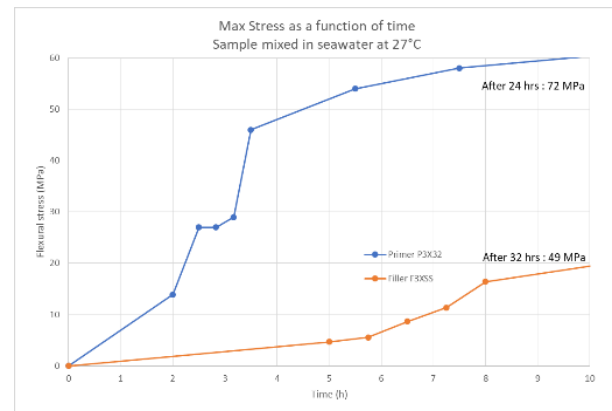


Fig. 17. Flexural modulus evolution as function of time.



Flexural stress evolution as function of time.

Compressive testing



Fig. 18. Mould of the compression samples

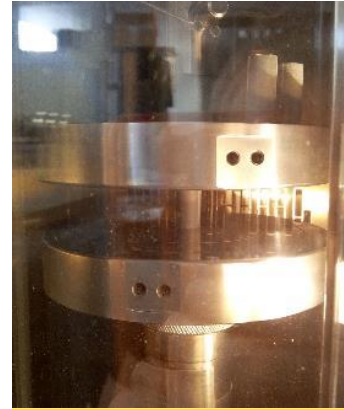


Fig. 19. Compression test ongoing

This test was carried out on fully cured filler materials (after 7 days at 27°C). This material has to withstand the compression of the hybrid gasket after flexible joint re-assembly. Fig. 20 provides the results of the compression tests, and it can be seen that the compressive stress is about 75 MPa and compressive modulus is 2600 MPa.

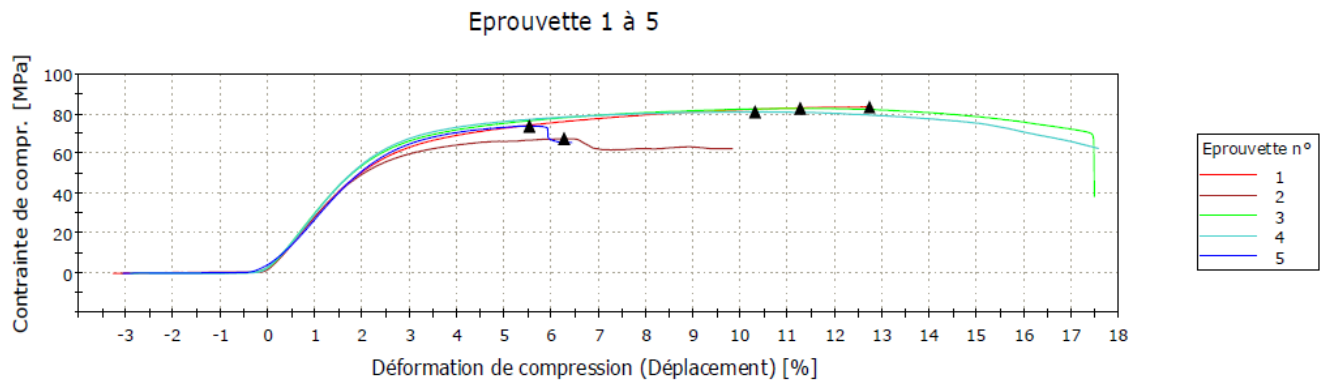


Fig. 20. Compression tests on F3XSS.

Conclusions of these qualification tests

The various tests carried out on the primer and the filler material confirmed their compliance with the targeted functional requirements:

- 1/ these materials have been developed for subsea application
- 2/ the filler remains soft during more than one hour, giving sufficient time for the diver to apply it and install the mould for curing.
- 3/ after seven hours, the filler is hard enough for hybrid gasket installation and attached flange re-assembly. It has to be noted that the compression of the gasket is not fully applied until the stud torquing is completed (more than 24 hours). During this time the filler is continuing to cure, increasing its mechanical properties.
- 4/ the compression stress capacity of the filler (75 MPa) is compatible with the expected stress level induced by the hybrid gasket.

Decision Chart

The attach flange of the flexible riser was planned to be replaced, so it was guaranteed that the top groove would be intact. For the lower groove, on the body of the flexible joint, the repair strategy had to be adapted depending on the extent of damages found. In case of an intact groove, the repair would be limited to the replacement of the original BX gasket by a new gasket. In case of minor damages, localized and with a depth lower than 1mm, the hybrid gasket would be used in replacement of the original BX gasket. Finally, should the damage be more severe or generalized, the groove would have to be repaired with the composite material in combination with the hybrid gasket. This repair strategy is summarized in the following flowchart (Fig. 21):

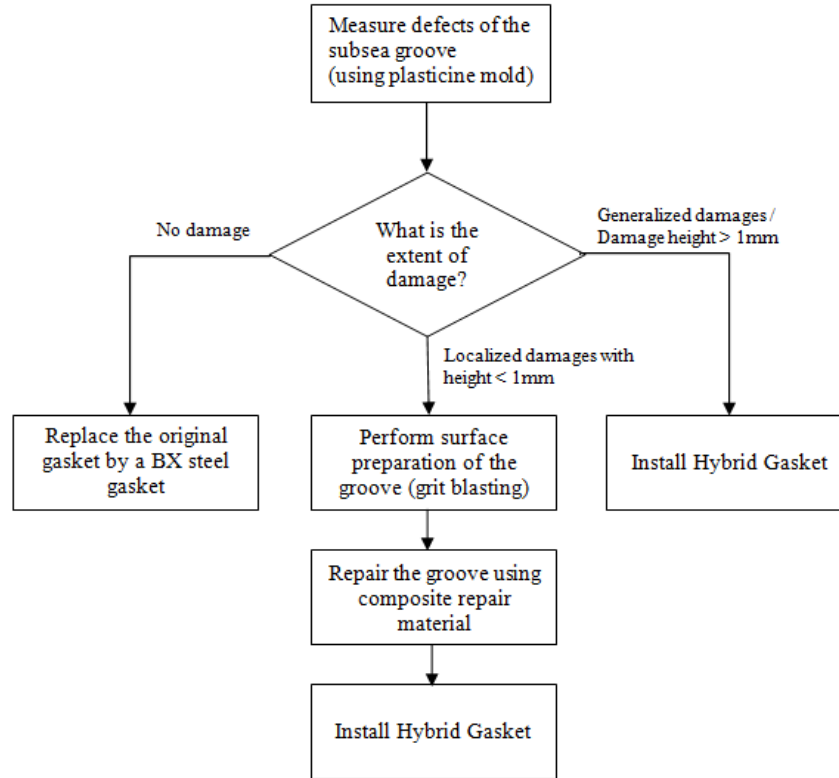


Fig. 21. Repair strategy Decision chart

OFFSHORE OPERATIONS

The diving spread was installed on a light dive boat berthed alongside the FPSO riser guards. From there the divers had a clear access to the flexible joints. The first part of the operations consisted in the removal of the top piping in order to get access to the flexible joint attached flange. After removal of the 26 studs, the attached flange could be recovered onboard the FPSO for inspection.

The groove on the attached flange was found damaged by what is believed to be the consequence of cavitation due to the leak. As shown on the below picture, some of the studs were also found damaged by the leak flow. The BX steel gasket was also recovered and inspected - it presented similar damage patterns.



Fig. 22. Damage on a recovered stud (2inch diameter)



Fig. 23. As-found condition of the BX steel gasket

Since only the diver had access to the lower groove, a mould of it was performed subsea using plasticine to assess the level of damage present on the groove and decide on the repair to be put place – as described in the previous section. The extent of damage was so large that the groove had to be re-shaped using composite repair material.



Fig. 24. Example of the groove severe damages on the flexible joint body and receptacle

First, subsea grit blasting was performed using service air available onboard the FPSO. The quality of the surface preparation was controlled onboard the diving vessel on a sample plate. After this surface preparation, an epoxy primer was manually applied by the diver before application of the composite repair material. To achieve the required groove shape, a mould was then installed and maintained in position by studs during the eight hours of curing time.

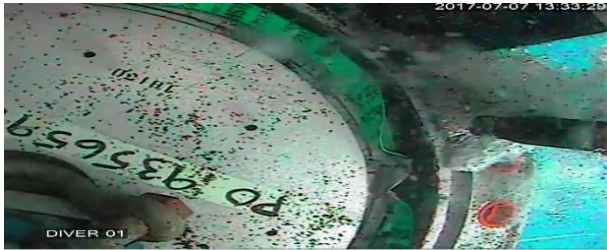


Fig. 25. Subsea Grit blasting of the groove

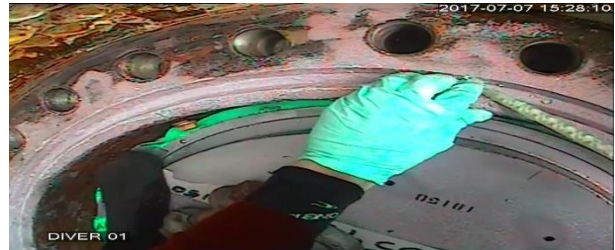


Fig. 26. Epoxy primer application



Fig. 27. Application of the composite repair material inside the groove



Fig. 28. Mould in place during the curing time

The final shape of the groove on the body of the flexible joint was then confirmed by making a new mould using plasticine. The following figure (Fig. 29) gives a comparison of the moulds of the groove before and after repair.



Fig. 29. Plasticine mould of the groove before repair (left) and after repair (right)

It can be seen that with the application of the composite repair material, the geometry of the groove was successfully rebuilt within the original dimension.

At this stage the flexible joint was ready to be re-assembled. The hybrid gasket was then installed, since the composite repair would not withstand the contact pressure from a conventional steel BX gasket. A new attached flange was installed, with a new set of studs and nuts. A hydraulic torque tool was used to fasten the nuts. The subsea torquing of the studs was measured by ultra-sonic measurements. A baseline measurement was initially performed on the studs prior to torquing. Then after each step of the torquing sequence the elongation of the studs was measured and compared to the target value.

The targeted elongation had been previously calibrated by UT measurements on studs tensioned using hydraulic jacks. This initial calibration is mandatory because the speed of sound in the studs varies with the tension of the studs. Without this correction on the speed of the UT signal, all the studs would have been undertensioned.



Fig. 30. Torquing tool in position inside the receptacle

After complete re-assembly of the flexible joint, the water injection system had been gradually restarted. Fluorescine dye was added in the network to ease identification of any leak. Once confirmation was made that no major leak was occurring, the divers were sent to perform a close inspection of the flexible joint. It was confirmed that the repair was successful and that no leak was occurring within the system at full injection pressure (close to 230 barg).

The integrity of the repair is confirmed on a regular basis by visual inspection using an external camera deployed from the riser balcony. More than six months after the first repair, the system is still in operation without any leak detected. This is further confirmed by a verification of the material balance.

CONCLUSIONS

Within only a few months, Total has been able to develop an innovative subsea repair procedure to resolve a major integrity threat. This challenge was met thanks to:

- A good preparation (root cause analysis, dedicated inspection campaign ...)
- A strong knowledge of the involved technologies (such as rubber design, composite repair material)
- The quick mobilization of the project team in country
- Good communication between all the parties (project, suppliers, site, HQ ...)

The offshore campaign was successfully completed without LTI and within cost and schedule.

The gaskets have been replaced on a total of four water injection flexible joints, and in addition two subsea composite repairs of grooves had to be performed. Due to operating constraints, this was done in two separate campaigns of 1 month each.

This innovative flange repair solution permitted to limit the size of the mobilized marine spread; the diving operations were done from a light dive boat berthed alongside the FPSO riser protectors. As a consequence, the SIMOPS were very limited, and the whole campaign was performed without any impact on the production of the FPSO, resulting in a repair solution estimated to cost approximately 10 times less than the replacement of the flexible joint.

Today, the four water injection systems are back in operation, at full injection rate and at a pressure of 230 barg.