A Step Change Application of Threaded and Coupled Connections

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Introduction

The development of deepwater oil and gas reserves is constantly facing the challenge of reducing costs in all components of the development scheme. Riser system costs are particularly sensitive to increases in water depth and there is a need to develop technically viable and cost effective riser solutions for deep and ultra-deep water developments.

A key factor in the cost of the riser system is the method for joining pipes together, which conventionally is by welded construction. Although not often utilized, threaded and coupled connections provide an alternative with significant benefits in terms of hardware costs, installation cost and improvement in schedule flexibility.

Threaded connections are a reliable, low cost method of joining pipe and have been used extensively in applications such as down hole casing, tubing strings, TLP tendons and to some extent shallow water flowlines [1,2,3,4]. In recent times, threaded connectors have been used successfully on Spar and TLP riser systems in deepwater applications up to 4000ft.

2H Offshore have been pioneering the use of high strength threaded and coupled connections through the Threaded Riser and Flowline Joint Industry Project (TRF JIP) since January 2000. The JIP focus is on the ‘system’ design approach of threaded risers and flowlines, including riser design, procurement and installation. The work conducted within Phase I and II of the JIP has proven that threaded riser and flowline solutions are technically and commercially feasible. Phase III conducted a thorough test program to qualify threaded connectors for use in fatigue sensitive applications.

This paper focuses on recent testing of high strength threaded and coupled connections by 2H and how the use of this technology in its application to riser and flowline systems will provide many benefits allowing a step change in performance and cost of deepwater riser systems. The primary step change noted is the capability of installation from a MODU. This provides benefits over welded construction in that vessel day rates are lower, no mobilisation is required, installation is significantly faster and there is greater vessel availability. This will impact the way contract strategies are developed and will require Operator confidence to drive field development solutions to utilize the use of threaded and coupled connections for risers and flowlines, and thus to achieve the improvement in cost and performance outlined.

Background

Despite the widespread use of threaded connections in downhole and top tensioned riser applications, it is surprising that threaded and coupled connections have had limited use in other riser and flowline applications to date. For subsea developments, the industry has maintained welded construction as the primary method to connect pipes in deepwater field developments.

One of the main reasons welded construction remains the ‘default’ method of construction is that historically, shallow water flowlines (less than 100m) were installed using low strength, readily weldable steel using the S-Lay technique. This is a cost effective method, which established a high level of confidence and track record in offshore welded connections.

The belief that welded construction is the most cost effective method continued as the industry advanced into deeper water. Installation contractors have developed more sophisticated welding techniques and built higher specification vessels to meet the demands of deep water. This has provided the Operator little choice on fabrication method. However, this approach in deep water can result in a high cost and often complex solution.

There are currently in excess of 20 installation vessels capable of welding and installing pipe in water depths greater than 5,000ft. It is noted that the number of vessels capable of installing threaded risers and flowlines in this water depth is well in excess of 100. However, the owners of these vessels (drilling contractors) have not marketed this capability to the Operators for the following reasons:

- Lack of a suitable riser systems that can be constructed using threaded connections
- Uncertainty of the performance capability of threaded connections
- Technical focus on welded options
- Contract strategies adopted by Operators

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The TRF JIP has addressed all these issues and providing an alternative approach to riser and flowline design and construction in deepwater that offers lower costs and increased design and schedule flexibility.

**Threaded Connection Perceived Issues**

It is interesting to observe that the offshore industry is polarised into two main groups. Pipeline and flowline engineers have a preference for welding and a distrust of mechanical connections. Conversely, drilling engineers are confident with threaded connections but have a concern with welding, which are often perceived as brittle and full of defects. These preferences often stem from experience in that engineers tend to stick to what they know and what worked well last time.

Flowline and pipeline engineers have a number of perceptions of threaded connections including:

- Limited Pressure Integrity (leak paths)
- High Cost
- Possibility of Back Off
- Poor Fatigue Performance
- Poor Make Up Control
- Low Repeatability
- Complex make-up procedures and tooling
- External corrosion protection of thread

The primary concern with the use of threaded connections for dynamic applications is the introduction of leak paths, reducing the reliability of the system. However, there is strong evidence from suppliers and industry databases to show that threaded connections have the same or better leak reliability compared with welded connections.

The SINTEF, Reliability of Well Completions database noted that 182 leak failures were recorded from approximately 2390km of tubing and 4315 years of service experience (10.3E+06 km-years). The equivalent loss of containment from welded pipelines is observed to be 8.07E-06 [3]. The equivalent loss of containment from welded pipelines is observed to be 1.00E-04, from 48 leaks occurring during 127,850 km-years, as defined by UKOOA/HSE [3].

This shows that threaded connector reliability (tubing) is equivalent to, or better than, the welded pipeline. It is appreciated that both applications are primarily static and that under dynamic loading higher leak rates could be expected for both methods of construction.

Under dynamic applications weld performance is complex and dependent on local material properties and the size, shape and location of defects. Threaded connections, which do not require welding, are more predictable with fatigue performance dependent on the properties of the base material. However both connection methods require strict quality control procedures for dynamic riser service.

Weld on threaded connections, such as those used for TLP and Spar top tensioned risers, have a high unit cost. Non-welded, threaded and coupled types, have a much lower cost and compete directly with the welded connection. This is because there are a number of large pipe suppliers who are set up to mass produce threaded connections. Furthermore, when considering the total system cost, fast installation rates of threaded connections with lower cost drilling vessels yields a lower total installed cost than that of an equivalent welded system.

Threaded and coupled connections are made up with high levels of torque, and on completion of the make up, the immediate breakout torque is commonly seen to be 10-20% higher than the make up torque. This improves with time as thread lubricants are squeezed out of the mating faces and after a number of days the breakout torque can be 40-50% greater than the make up torque, indicating that there is no possibility of back off occurring during service since in service there is no way for high torques to be generated.

Poor make up control is eliminated by the introduction of computer controlled torque tongs with feed back logic control. This has allowed the precise control of threaded connection make-up, producing torque graphs allowing the operator to confirm whether a good connection has been made.

Fatigue performance and low repeatability issues are discussed in detail in the qualification testing section of this paper.

**Deepwater considerations**

It is inherent that as riser systems are developed for deep and ultra deep water environments (greater than 6,000ft) the requirement to reduce riser weight will become of increasing importance. Riser weight not only has an affect on the cost of the riser pipe, but also has significant impact on the cost of the aircan or tensioning device used to support the riser. Similarly, payload limitations on the floating production facility will become a major consideration for large field developments with many heavy risers attached directly to the vessel.

Furthermore, the requirement to design riser systems for operating pressures in excess of 10,000psi is becoming more frequent. In order to provide sufficient resistance, riser and flowline wall
thickness is increasing correspondingly and often the requirement is close to manufacturing limits.

The use of high strength steels (greater than 95ksi yield strength) can reduce the wall thickness requirement by up to 30% resulting in a more efficient riser design. For riser systems, which rely on buoyancy in the form of air cans for top tension, the thinner wall pipe available with high strength steel allows reduced buoyancy requirements, which in turn, can reduce the hydrodynamic loading on these components, improving riser response. Riser systems where the tension is reacted by the host facility benefit from high strength steel as the total payload is reduced.

High strength steel limits the ability to weld due to the fact that the hardening of the substrate material is more problematic. In particular, there is concern relating to the presence of coarse heat affected zones with a susceptibility to hydrogen embrittlement and reduced effectiveness to operate in sour environments under high loading as exhibited in a riser [5]. This limitation with respect to the ‘weldability’ means that if there is a need to use high strength material, an alternative method of joining pipe together is required, namely threaded and coupled connections.

**Benefits of Threaded and Coupled Connections**

Threaded and coupled connections, or casing connections as they are often referred to, are a cost effective method of joining pipes together. There are a large number of threaded connector designs available on the market, many of which are proprietary. Examples of industry available casing connectors suitable for riser and flowline applications are illustrated in Figures 1 and 2.

The use of threaded couplings for riser and flowline solutions can provide significant benefits:

- **Faster make-up speed compared to welding**
  Threaded connections (9-5/8 inch diameter) can be made up in 2-5 minutes compared to 30-50 minutes for a typical offshore weld and inspection procedure for a fatigue sensitive application.

- **Use of drilling vessel for installation**
  Drilling vessels are specifically designed to efficiently handle and install threaded connections. Experienced rig personnel are readily available and procedures and tooling are established.

- **Application of high strength steels**
  As discussed previously, non-welded construction allows the use of high strength steel (P110). This reduces riser weight, reducing buoyancy requirements or payload on the vessel. In the case of top tensioned risers, the reduction in weight of the system reduces the interface loads on the wellhead and taper joint, reducing the costs of these expensive components.

**Improved fatigue performance**

Qualification testing of threaded couplings shows that the fatigue performance is comparable or even better than what can be achieved with a good quality single sided weld, as discussed in the next section.

**Cost**

The cost of pipe machined with threaded and coupled connections is greater than that of plain ended pipe. However, it is noted that the steel cost is a small proportion of the total system cost and also that with threaded connections the cost saving is achieved through installation.

When the individual benefits described above are considered collectively in a systems approach, the impact on riser cost and performance can provide significant improvement. Essentially, it is the fact that threaded and coupled connectors enables installation from less expensive vessels already located in the field (MODU), which can install the flowline and riser system 5 times faster than the equivalent welded construction installation vessel. Typically MODU costs are in the region of $180,000 per day as opposed to $350,000 per day for a J-Lay barge. In addition, the MODU is often already mobilised in the field to drill development wells, and probably on a long-term charter, which can facilitate flexible scheduling. This sequence of benefits is the crux of how the application of threaded connections will provide a step change in performance and cost of deepwater riser systems.

**TRF Testing Program**

Phase III of the TRF JIP focussed on full scale fatigue testing and qualification of threaded riser connections from three suppliers. 20 threaded and coupled connections were tested in total consisting of test samples supplied by VAM, Hunting and Grant Prideco. The qualification program included fatigue testing of full-scale specimens, make up repeatability tests, scalability tests and corrosion tests.

5m long fatigue specimens were tested in air at room temperature using a resonant bending rig at the TWI facility in the UK. Strain gauge instrumentation located circumferentially around the pipe body and in the middle of the coupling provided the bending time-traces required to establish fatigue capacity. Failure of the specimen was detected by monitoring the pressure in an external rubber bladder bonded onto the pipe around the coupling. Testing was carried out with
either constant axial mean stress or with zero mean stress, with full reversed loading. The mean axial load of 150 Te was applied using an internal strut inside the pipe specimen rather than internal pressure to eliminate the introduction of large hoop stresses in the connection and thus eliminating the addition of another variable in the test results.

A picture of the fatigue rig used is shown in Figure 3. Some of the fatigue specimens were tested with helium at low pressure to confirm the integrity of the internal metal-to-metal seal before and after the fatigue testing. In addition, three specimens were put through 3 make and break cycles before they were pressure and fatigue tested to confirm their make up repeatability performance.

The target cycles corresponding to target stress amplification factors (SAF) for the various stress ranges tested are based on the S-N approach and the DnV B curve [6] applicable for parent material with cathodic protection in a marine environment. It should be noted that for fatigue qualification testing, the mean S-N curve is referenced for target cycle computation rather than the design curve. The design curve is 2 standard deviations below the mean curve and gives a factor of safety in fatigue design. Also, the target cycles include a 5% confidence interval and adjustment for the number of samples tested.

Whilst results remain confidential to the JIP, generally, the results show that the all threaded and coupled connections tested meet the target curve to qualify a SAF of 3.0 with most of the failed specimens reaching the target curve to qualify a SAF of 2.0. These results exceed prior expectations and confirm that the fatigue performance of a threaded and coupled connection is as good or even better than a good quality single sided weld.

Another important finding from the fatigue testing was that all three manufacturers achieved similar performance, exhibiting a relatively low scatter of results. This indicates that fatigue failure is highly dependent on material properties and notch effects defined by machining details unlike a weld, where defect location and geometry can result in a wide scatter of results. A section of a failed fatigued connection is shown in Figure 4.

The JIP has also carried out corrosion tests utilizing un-failed specimens from the fatigue testing. These tests consisted of 4 threaded and coupled connection specimens placed in a corrosion bath for a period of 6 months. Each specimen was prepared with a different coating over the pipe body to within 1-inch of the coupling, and over the coupling as follows:

- Epoxi based coating
- Thermoally sprayed aluminium (TSA) with silicon sealer
- TSA without silicon sealer
- TSA without silicon sealer plus heat shrink sleeve applied over the coupling edges

The objectives of the corrosion test are as follows:

- Determine the level of corrosion developed at the run out and first complete thread of the coupling where the majority of fatigue failures are observed
- Determine the effectiveness of the TSA with and without a sealer to protect the fatigue critical areas
- Assess any additional benefit of adding another barrier such as a heat shrink sleeve to mitigate seawater ingress
- Estimate potential influence on coupling fatigue based on level of corrosion damage
- Develop recommendations for corrosion protection requirement
- Make recommendations for additional testing

The corrosion bath constructed for the tests is shown in Figure 5. The specimens were immersed in a salt-water bath allowing free circulation of the corrosive electrolyte around the specimens. The immersion tests, classified as medium term, were configured electrically so that the current flow between the TSA coated and bare steel sections could be continuously monitored with a zero resistance amp meter. Also, electrochemical potentials with respect to a saturated calomel reference electrode were measured periodically. Over the test period of 180 days, the temperature and oxygen content were periodically changed from 25 to 5 deg C and from 0 to 0.6 l/s, respectively. The temperature was varied as seawater at higher ambient temperatures has a tendency to lose its oxygen and oxygen facilitates the corrosion process.

After 6 months, the tests have shown the 1-inch bare steel area adjacent to coupling to corrode on the epoxy based coated specimen but remain un-corroded on the TSA specimens. The bare areas of a TSA coated specimen and epoxy based coated specimen after a few months in the corrosion bath are shown in Figure 6. The high rate of corrosion on the epoxy specimen at the first thread is noted. The fact that this crevice type of corrosion occurs at the point of highest stress concentration is a point for concern and it is concluded that a high integrity seal should be considered.

Due to the difficulties in accelerating a corrosion test to represent 20-25 year of a typical riser service life in a marine environment, it cannot be
categorically concluded that the TSA coating is sufficient to mitigate corrosion in the fatigue critical area of a threaded and coupled connection. Consequently, the use of an external environmental seal is considered necessary to allow confidence in this type of connection to be used for a long-term riser application in a marine environment.

There are a number of elastomeric seal options available to use with threaded and coupled connections, which does not need to be designed to withstand large hydrostatic pressures but rather prevent the ingress of seawater into the threaded annulus and thus the exchange of oxygen to facilitate corrosion.

Lip seals and o-rings can be employed by seating them into a machined groove on the inside of the coupling as illustrated in Figure 7. A good surface finish and tolerance is required on the pipe to ensure the seal integrity requiring some machining on the outside diameter of the pin and hence reduction in wall thickness. Furthermore, careful consideration needs to be given to the effectiveness of these seals at low differential pressure, damage during make up, and the possibility of a hydraulic lock resulting from a pressure build up of the thread lubricant trapped in the threaded annulus. This pressure build up can be sufficiently large enough to prevent sealing of the metal-to-metal pin faces during make up.

With these considerations in mind, 2H Offshore have developed an elastomeric environmental seal design specifically to meet these requirements. The seal has a number of chevrons as shown in Figure 8, which are orientated in a direction to allow the flow by of trapped lubricant in the threaded annulus during make up. The seal is bonded onto the outside diameter of the pin prior to shipment offshore. The only machining that is required is on the internal diameter of the coupling where a seal pocket is provided. The geometry ensures that the seal chevrons are preloaded during make up. This design ensures that any geometrical tolerances in the pin can be accommodated and seal integrity is maintained at both high and low pressures. The make up sequence utilizing the 2H seal is shown in Figure 9.

**Applications of Threaded Connections**

The qualification program conducted by the TRF JIP proves that the structural arrangement and fatigue performance of high strength threaded connections is superior to that of an equivalent single sided weld. The use of a high integrity but cost effective environmental seal to prevent corrosion at the critical first thread is considered the final requirement to allow wide spread application.

The suitability of threaded connections to flowline and riser applications is extensive, however, there is a level of associated criticality, which is largely driven by the fatigue nature of the riser system, and the level of pressure containment expected:

- Flowline
- Top Tension Risers (Spar / TLP)
- Freestanding COR™ and SLOR™
- Steel Catenary Risers
- Concentric Catenary Risers

Flowlines are pressure containing but remain static and therefore it is considered that threaded flowlines can readily be utilized for deepwater applications. In order to achieve the lay angles required for flowline installation, a fabricated stinger or bend restrictor is required below the drill floor as illustrated in Figure 10.

Top tensioned risers for spar and TLP production platforms have typically used weld on threaded connections, whereby steel forgings are machined into pin and box connectors and welded onto the end of seamless pipe. These type of connectors are designed with metal to metal internal and external seals and demonstrate superior fatigue performance than the weld used to connect them to the riser pipe. However, both the forging and the pipe have to be limited to 80ksi yield strength to allow welding. In addition, weld on connectors are significantly more expensive and heavier than non-welded threaded and coupled connections. Non-welded threaded and coupled connections have been used previously in a riser application on the Oryx Neptune Spar production riser outer casing in the Gulf of Mexico. These couplings were used for the majority of the riser length except at the fatigue sensitive top and bottom regions. They have also been used for a number of inner casing riser strings for dual casing top tensioned risers. The use of non-welded threaded connections on the outer casing string over the complete string length is expected to become common practice for dry tree production risers in the near future due to the cost and weight savings they provide.

Both flowlines and top tensioned risers have used threaded connections in a few previous applications, however, for deepwater subsea developments, riser systems must be specifically designed to maximise the benefits made available by the use of threaded connectors. 2H Offshore have initiated and developed the designs of four threaded riser concepts as part of the TRF JIP. This includes two freestanding risers and two catenary risers both in single pipe and pipe-in-pipe arrangements. A graphical summary of this is included in Figure 11.
The Single Line Offset Riser (SLOR™) and Concentric Offset Riser (COR™) are 2H riser designs. The SLOR™ consists of a single freestanding vertical riser pipe with top tension provided by buoyancy cans. The riser may be configured with syntactic buoyancy foam added on the outside of the steel pipe. Base loads are reacted by a pile. A flexible jumper attached at the top of the riser transfers fluid between the process vessel and the riser. The SLOR™ is well suited to water and gas injection, export and also production where insulation and gas lift are not important requirements.

The COR™ is a variant of the SLOR™ arrangement and is designed specifically for production service where flow assurance requirements need to be accommodated. The COR™ is a pipe-in-pipe arrangement, which facilitates provision of thermal insulation, riser base gas lift and active heating. COR™’s have a higher cost than a SLOR™, but this is balanced by the additional features that are often an important requirement in deep water developments. An additional flexible jumper is used to provide a flow path to the annulus. A general arrangement of the COR™ is illustrated in Figure 12.

The design of both these risers is such that the flexible jumper de-couples the vessel motions from the steel section of the riser. This means that the response of the riser is predominantly quasi-static and therefore the fatigue response of the riser is better than an equivalent SCR as it is not impacted directly by vessel motions resulting from wave action.

Due to their quasi-static response, the COR™ and SLOR™ systems are specifically developed with the intent of using threaded connections. Now that the qualification of threaded connections has proved their performance to be as good as, if not better than a single sided weld, these riser systems are considered to be prime candidates for the application of this technology. The design work, development of installation procedures from a MODU, and costing assessment has been conducted as part of the TRF JIP and confirmed the technical and commercial feasibility of these riser systems.

Steel catenary risers are used on many deepwater projects. The benefits of using high strength steel threaded connectors instead of welding include the following:

- Reduced wall thickness providing lower top tension
- Reduced top angle
- Faster installation from MODU

- More cost effective solution
- Improved fatigue performance

The SCR is more dynamic than the SLOR™ or COR™ since it is connected directly to the production vessel. SCR’s are fatigue sensitive at the top and within the touch down region. The results of the qualification testing program show that threaded and coupled connectors exceed the fatigue performance of an equivalent single sided weld, and therefore proving threaded connection feasibility for SCR systems. Threaded connections are the enabling technology to potentially use SCR’s in harsher environments.

The Concentric Catenary Riser (CCR) is a pipe-in-pipe arrangement of the conventional SCR. This system provides the same operational features of the COR™, but in a catenary format.

Conclusions

Deepwater field development solutions are currently approached using extrapolation of shallow water technology. As the industry moves into ultra deepwater this approach is not necessarily cost effective. Threaded and coupled connections offer a low cost and effective method of joining pipe in deepwater and these connections have now been qualified through the TRF JIP for use in dynamic riser applications.

Non-welded threaded connections yield significant reductions on the overall riser system cost as they allow for the following:

- Use of high strength steel and a smaller wall thickness resulting in reduced riser string weight
- Improved fatigue performance
- Faster installation rate per joint compared with welded connections
- Installation from a MODU already chartered by the Operator, which has a lower day rate than a lay barge and no mobilization costs
- Improved schedule flexibility on a field development for drilling and riser installation activities

At present there are two distinct polarized groups:

- Pipeline and flowline contractors using welding
- Drilling contractors using threaded connections

The use of threaded connections in flowline and riser applications requires a combination of these two groups. Historically, this is difficult to achieve and furthermore the installation contractors have significant investment in welding technologies. Whilst it is believed that the implementation of
threaded and coupled connections for riser and flow line systems has the potential for a step change improvement, it is unlikely to occur unless contract methods are modified and/or the process is Operator led.

References

Figure 1 – Hunting SL-RP Connection

Figure 2 – Grant Prideco HFR1 connection
Figure 3 – Resonant Bending Fatigue Test Rig at TWI Ltd, Cambridge, UK

Figure 4 – Failed Fatigue Specimen (Pin & Box Sections)
Figure 5 – Corrosion Bath Set Up at 2H Offshore Engineering Limited, UK

TSA Coated Specimen
Epoxy Coated Specimen

Figure 6 – Corrosion Development at Last Run Out Threads

Figure 7 – Arrangement of O-Ring Seal For Threaded & Coupled Connections

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Figure 8 – Arrangement of 2H Seal For Threaded & Coupled Connections

Figure 9 – Make Up of a Threaded & Coupled Connection with a 2H Seal
Figure 10 – Flowline installation stinger fitted below drill floor
Figure 11 – Threaded & Coupled Riser Solutions

SLOR  
Single Line Offset Riser

Free Standing Hybrid

COR  
Concentric Offset Riser

THREADED CONSTRUCTION

MODU INSTALLATION

Single Line

Pipe-In-Pipe

SCR  
Steel Catenary Riser

Catenary

CCR  
Concentric Catenary Riser

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Figure 12 – COR™ General Arrangement