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A Review On-Study of Use of Bonded Fibre Composite Materials for Repairs of Floating Offshore Units

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Abstract: On ships, tankers and similar vessels structural defects such as cracks and corrosion damage are typically repaired by welding. However, welding is unwanted hotwork on floating offshore units (FOUs) such as floating, production, storage and offloading (FPSO) and floating, storage and offloading (FSO) vessels because it requires shutdown of parts of the vessel thus resulting in expensive production delays. Bonded fibre composite material patch repairs can be used as an alternative to overcome the hazards of hotwork associated with welding. The patches are bonded over the defect and the integrity of the original structure is hence restored. The patch repair technology can also be utilised to provide upgrades, such as life extensions and higher design requirements.A recommended practice (RP) has been developed that describes requirements for patch repairs used in floating offshore units. To provide flexibility and to fit different repair needs, the recommended practice defines a range of Repair Classes that can be used depending on the urgency of the repair and the need for optimisation. The qualification effort increases with the degree of optimisation. Study on Two full-scale repair demonstrators were carried out on actual floating offshore units to demonstrate the feasibility of the recommended practice for bonded composite patch repair. In addition the demonstrators also showed the viability of using bonded composite repairs under harsh conditions encountered in oil and gas exploration and production environments. The first repair was carried out to arrest a fatigue crack that had developed from the corner of a door, while the second repair was carried out to restore material loss on a heavily pitted deck floor. Both repair cases are used as examples to demonstrate the proposed qualification procedures whilst at the same time discussing the challenges and potential applications of this patch repair technology for floating offshore units in the oil and gas industry.
Keywords: floating offshore units, hotwork, recommended practice, stiffeners

I. Introduction

Floating offshore units (FOUs), such as floating, production, storage and offloading (FPSO) and floating, storage and offloading (FSO) vessels, have gained increasing popularity in the petroleum industry for offshore oil and gas mining since their first application in the mid-1970s. In either case, however, the FOU must be adequately maintained out in the field and there should not be any requirement for dry-docking in order for repairs and other maintenance work to be carried out. Fig. 1 shows examples of typical FOUs in current day exploration and production (E & P) operations.

In many cases, FOUs are built by conversion of used, old tankers. Tankers like these invariably contain many defects, some of which can be classified as critical and will need to be repaired during conversion while others may be left alone but these latter ones could over the service life of the FPSO or FSO develop into critical defects. Operational experience has shown that corrosion damage and cracks in frames and plates of the vessels are the most common defects requiring repair. More specifically, the most commonly found defects on FOUs in service include corrosion damage in tanks, shells and various panels as well as in stiffeners and brackets, and fatigue cracks in welds and structural hard-points.

For a normal ship, repair is normally effected using welding when the vessel calls into harbour or during dry-docking. However, in the case of FOUs, repairs need to be carried out in the field, and for safety reasons, parts of the vessel would have to be shut down since welding involves hotwork. Shutting down means interruption to production and in many cases this is an extremely costly exercise. For example, if we assume a production rate of 100,000 barrels a day and a very conservative oil price of USD 50 per barrel, shutting down an FPSO for just a day would mean a loss of revenue amounting to USD five million. Therefore there is a strong incentive to avoid the need of hotwork for repairs to be carried out.

Fig. 1. Floating offshore units are widely used in today's offshore oil and gas mining.

The use of bonded repairs is a viable solution to overcome the hotwork issue. These repairs, effected using strong and stiff fibre composite materials, have been used for several decades in the defence industry for the maintenance and life extension of aircraft and warships, but more recently they have also been used in the marine, infrastructure and even the oil and gas industries [1–3]. In the oil and gas industry, composite repairs can often be seen in the maintenance of aged pipework [2]. Apart from enhanced fire safety due to the absence of hotwork, composite repairs are also attractive because they are adaptable to virtually any substrate geometry, easily conforming to complex shapes and fitting into tight spots. In addition, the anisotropy of composite materials also affords design flexibility that contributes to cost and property optimisation. The weight advantage is further realized since excessive weight additions to an existing pipe system would mean that additional

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span supporters will be required. Finally, with a wide choice of materials available, i.e., fibre types, reinforcement forms and resins, and processes, to fit various operating conditions and environments, it is no wonder that composite repairs have been receiving much attention from the industry. The concept of using fibre composite materials to repair crack and corrosion damage in FOUs is schematically illustrated in Fig. 2.Potentially, fibre composite materials can be used (i) to patch up panels which have lost thickness due to corrosion, (ii) to restore watertight integrity in tanks and other shell components by bridging of cracks, due to overload or fatigue, and of holes, due to corrosion, (iii) to relieve stresses and to arrest cracks at hotspots by bridging cracks in stiffeners, brackets, weldments, etc., and (iv) to upgrade structures for life extensions or for satisfying altered design requirements, by strengthening decks, bulkheads, pillars, etc. (without significantly adding weight to the existing structure).Marine vessels such as ship and tankers are normally constructed of thick plates of very tough structural steel where the critical crack size is considerable. The large plate thickness further suggests that the forces being transmitted are very large. The key design challenge is hence to devise a repair where the large forces that need to be transmitted from the steel to the bonded repair patch do not lead to fracture of the bondline. For these reasons, the development of bonded repairs for marine structures reported herein naturally focuses onThe debond fracture of the bonded assemblies. The geometry of frequently encountered damage cases in marine structures are such that one often can make reasonably simple and accurate assumptions about the load sharing between the substrate (i.e., the original steel) and the repair or, if not, general numerical models must be used to get better estimates.

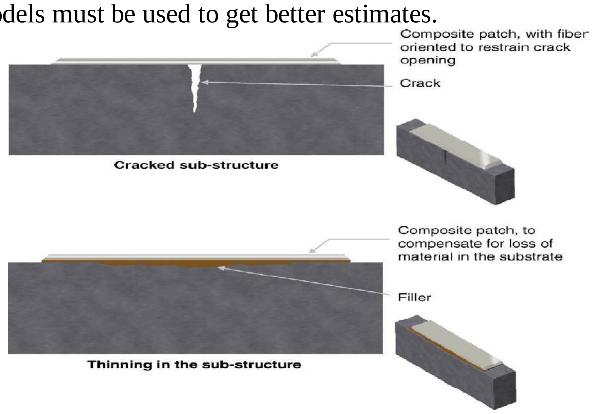

Fig. 2. Concept of the composite repair for cracks and corrosion thinning in metal substrates of FOUs.

It is noteworthy that this contrast with the case of aircraft repairs where it is normally not difficult to make bonded repairs with a load-bearing capacity that exceeds that of the original undamaged structure since the material thicknesses occurring in aircraft structures are normally thin by comparison and hence so are the forces (per unit width) transmitted through the structural members. As a result more sophisticated models, such the one developed by Rose [4], are necessary for aircraft repairs, and little focus has been placed on less complicated analytical models. This paper will demonstrate that relatively simple models can be adequately used to design composite bonded repairs for FOUs and, for that matter, other similar marine structures too.

II. Design philosophy

One particular challenge when a new technology, such as bonded repair, is introduced is that, without a long service track record, assessment of the long-term performance needs to be based on studies of duration very much shorter than the intended service life. The common approach taken to overcome this problem in many fields of engineering is to use accelerated ageing tests. However, extrapolation from short survival times (with high degradation rates) in these test conditions to long safe service lives (with low, or zero, degradation rates) under actual service conditions inevitably introduces an unquantified source of uncertainty The design philosophy of bonded repairs must take this into account. The practical solution adopted for bonded repairs in FOU has been to limit such repairs to non-critical cases until sufficient service experience has been gathered. Non-critical in the current context is defined such that a repair failure would not threaten the global integrity of the overall structure. This means that the safety of the vessel is insured, even if the repair fails.

Although this removes the strict requirement of precise prediction of long-term properties, the approach still requires that a range of measures are taken regarding material selection, surface preparation of the substrates, quality control during installation and screening tests to ensure the predicted durability can reasonably be expected from the repairs. Another advantage for taking the approach to restrict repairs to non-critical defects is that it addresses also the issue of the performance of the repair under fire conditions, i.e., the composite bonded repair is permitted to lose its integrity in a fire, and the overall structure would remain safe until the original damage can be re-assessed.

Repair Classes

A range of ‘‘Repair Classes” are defined to allow quick adoption of bonded composite repairs by the oil and gas industry. This would hence allow experience to be gradually gathered by the industry so that over time increasingly challenging repairs can be more confidently undertaken. Note that because there is the requirement for repairs of only non-critical structures safety is never compromised. Repair Class 0 is used to denote repairs for which the capacity of the patch has not been quantitatively assessed. Such repairs can be designed based on past experience or simple rules of thumb. All requirements relating to selection of materials and application methods as well as quality control apply to Class 0 repairs in the same way as they would be to the other Repair Classes. These repairs will have a specified service life determined from the rate of damage development in the steel without the repair. Analysis of the steel structure is necessary to ensure that the damage would not develop into a critical state even in the unexpected event that the repair should fail. Repair Class 1 can be assigned to repairs that have been designed for the ultimate loading to which the repair could be exposed.

A generous factor of safety is introduced to account for the fact that effects of cyclic and long-term static loads are not explicitly considered in design. When long-term performance is explicitly considered through fatigue disbond crack growth assessment, the

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repair can be classified as Repair Class 2, in which case a somewhat smaller factor of safety is permitted.

The safety factors have been chosen so as to ensure that the level of reliability of Class 1 repairs is the same as that of Class 2 repairs. This provides an opportunity to optimise the design in cases where fatigue exposure is limited. It should be noted that Repair Class 0 is intended to facilitate the use of bonded composite repairs when time does not permit the assessment required in order to classify the repairs as Class 1 or 2. Test and/or design analytical results must be made available before the specified service life of the Class 0 repair elapses to allow the repair to be re-assessed and subsequently upgraded to Repair Class 1 or 2, as appropriate. Note that for repairs of Classes 0–2 the damage to the steel structure must be non-critical, as noted above.

The requirement for Repair Class 3 repairs includes known long term performance that is consistent with the conditions to which the structure being repaired is or would be subjected. The steel substrate may have cracks that are critical from the start or would reach a critical state before the next scheduled inspection. Qualification of composite bonded repairs for FOU structures to within Repair Class 3 is currently considered beyond state-of-the-art.

A summary of these Repair Classes is given in Table 1.

Table 1 Summary of the Repair Classes proposed for composite bonded repair of FOUs.

Repair Class	Description
0	Can be used for non-critical emergency repairs Can be installed at very short notice Must be re-assessed within their design life
1	Can be used for non-critical repairs Are designed to survive specified static loads using simple and quick criteria Quick assessment requires that the static performance of the bondline has been characterised in advance The long-term performance is deemed acceptable based on proper material selection and the use of appropriate safety factors
2	Can be used for non-critical repairs Allows for more optimised designs by reduced safety factors Long-term fatigue and stress rupture must be assessed explicitly More costly tests are required as basis for approval
3	Can be used for critical repairs Long-term properties must be fully characterized This is currently not feasible by affordable tests Hence, Class 3 repairs are still currently outside the scope of the RP

Non-destructive inspection

The lack of reliable and affordable non-destructive inspection (NDI) methods warrants an approach to reliability that does not depend on its extensive use. The repair is hence designed to afford visual inspection of the damage in the (steel) substrate in order for any progressive growth to be monitored. As long as the damage stays below the critical dimension, the structure shall be judged as safe, otherwise the repair is deemed inadequate and hence must be upgraded or replaced.

Other measures

The approach adopted for bonded composite repairs of FOUs includes several measures to obtain adequate reliability in service. Strict quality assurance requirements are imposed to ensure a consistent and predictable quality of the repair. Damage tolerant designs that are insensitive to small defects are also favoured. This is achieved by provisions to limit the occurrence of peel stresses, and by using long overlaps or, whilst not possible in every case, by providing redundant load paths. Qualification procedures reflecting the above-described design philosophy have been compiled in the form of a recommended practice manual.

III. Failure mechanisms and load-bearing capacity

A detailed design analysis has to show that the damage in the steel structure (be it a crack or corrosion) will not propagate under the loads and environmental conditions that are seen by the repair.

The loads in a FPSO are relatively well-established and can in principle be calculated for any localised area for repair. In practice however, this could be labour-intensive and time-consuming, since one has to work through the old design calculations, and detailed analyses have to be then carried out. A simpler, more practical approach is to design the repair so that the original strength of the steel substrate is restored whilst taking all loading modes into consideration, assuming that the substrate had been properly dimensioned. A third option, for repair of fatigue cracks, is to estimate the

Loads from the crack size possibly in conjunction with the measured growth rate. The environments inside a FPSO that are commonly considered include seawater in a ballast tank, oil in a cargo tank, or simply a room under very humid marine conditions. Externally, the repairs are exposed to weather and other conditions that could be extremely severe. With respect to possible fire.

The ultimate load-bearing capacity of a repair can be calculated for a particular joint geometry and the loading condition. Briefly, idealised test geometries are used where the fracture resistance of an adhesive can be calculated from measured fracture loads. This fracture resistance value can then be used to estimate the fracture load (i.e., ultimate load-bearing capacity) of other bonded joint configurations. This methodology, discussed elsewhere, has been applied for the repair demonstrators described in this paper, and hence is touched on further in Section 5. It should be cautioned that both the crack opening resistance and the strength of the adhesive are dependent upon the environment to which it is exposed, such as temperature and medium, and so they should be measured under the same (simulated) conditions. Whether the stiffness of the patch controls the metal crack opening or the strength of the adhesive governs fracture of the patch it will be dependent on the particular application, but both aspects need to be considered. It should also be noted that a margin of safety has to be applied in a real design.

Full-scale repair demonstrators

Real life repairs tend to be more complicated than simple idealized ones that are normally considered in research. Simplifications are needed for real repairs where focus are placed on critical issues thereby allowing effort on marginal issues to be avoided or minimized in the interest of limited resources, i.e., time and cost. One of the aims for presenting the repair trials is to demonstrate the viability of using relatively simple methods if reasonable assumptions are applied. Focus is placed on critical issues, i.e., material properties that are not critical for the design could be based on published values rather than going through a testing program. By reasonably simplifying assumptions, provided safety is not compromised, time and effort needed could also be cut down.

Repair of a fatigue crack, Demonstrator 1

The first full-scale demonstrator was carried out in June 2005 on-site on the Norne FPSO, which is located in the Norwegian Sea offshore the northern part of Norway. This FPSO is currently in its 11th year of operation. The candidate for the repair demonstration was a fatigue crack in a longitudinal bulkhead in the fore-ship of the FPSO. The crack runs at a 45^0 angle from the corner of a door (in Room 503) and extends under a horizontal stiffener located above the door, see Fig. 3. The composite bonded repair was designed to information and data from two inspections carried out in November 2004, when the crack length was reported to be approximately 150 mm and then in January 2005 where it was reported to have lengthened to 220 mm. It is noteworthy that the crack had also branched out significantly in the web of the horizontal stiffener, although its precise length was not recorded. At a later inspection in April of 2005, the crack length was reported to have grown to 270 mm. It appears that the severe winter storms had advanced the crack considerably.

Fig. 3. Location and state of the fatigue crack in the Norne FPSO that was used as Demonstrator 1. (a) Crack as seen from the corridor side of the bulkhead. (b) Crack as seen from inside the room.

Repair of a corroded plate, Demonstrator 2

The second repair demonstrator was carried out in August 2006 on FSO ABU Cluster that was earmarked for operation in offshore Trengganu, Malaysia, in the South China Sea. The design life of the FSO is 5 years, and for logistics and approval reasons, the repair was installed when the vessel was docked and in the process of conversion, rather than out in the field when in service. The subject for repair was a section of a 24 mm thick deck floor underneath a pipe rack (viz. between Frames 76 and 77) in the mid-section of the vessel. General survey had registered corrosion pit sizes of up to approximately 2.6 mm, but detailed measurements of the repair area showed the largest pits to be as deep as 4 mm.

IV. Discussion

The two demonstrators have shown the viability of bonded composite repairs to the two most widely encountered damage in FOUs – fatigue cracking and metal thinning due to corrosion using relatively simple design methodologies. The above design methodologies for the repairs were based on fracture resistance of the bond line, rather than on the more commonly used strength-of-materials approach, to estimate the load-bearing capacity of bonded assemblies. This was motivated by test results for the materials used in repair Demonstrator 1 which showed firstly that considerable yielding occurs in the bondline before it fracture. This implies that the maximum stress equals to the yield stress thus making models that assumes failure occurs when critical elastic stress is reached may not be applicable. Secondly, the measured strain at fracture was found to vary by as much as a factor of 6 depending on the repair design thus invalidating strength predictions that assumes a unique critical bondline strain to failure. In order for qualification testing to be of direct relevance to bonded repairs, ideally they need to be carried out under conditions that prevail in well-designed bonded repairs. They must therefore have relatively long overlap lengths, and they should be designed for fracture of the bondline to be the governing failure mode, not one of the many other potential failure modes such as yielding of adherend that usually governs in standard single overlap tests (when a good adhesive is used). In line with this argument, standard test methods which normally specify short overlaps are likely to be inappropriate.

To understand fracture initiating at the most highly loaded ends of the overlap it is logical to focus attention on the overlap ends. However, there are other concerns that need to be accounted for too. If such a short overlap joint is exposed to a high constant load, one would expect that the high stress throughout the bondline would cause considerable creep deformations in the viscoelastic adhesive material that would accumulate and quickly cause failure of the joint. Furthermore if such a short overlap joint is exposed to many cycles of load, the onset of a fatigue crack would reduce the effective overlap length, thus increasing the stress levels in the bondline. Hence the crack would accelerate and quickly cause failure of the joint. The solution to these problems is to use an overlap length that is sufficiently long to create a zone in the middle of the bondline where the stresses are constantly relatively low.

This zone would prevent any progressive creep and premature growth of a fatigue crack.. Alternatively, a requirement that the overlap length shall exceed a certain specified minimum can also be used. With a long overlap length, the stress re-distribution due to the presence of (large) disbonds is also expected to be quite small so that the bonded joint would have good damage and defect tolerance. Fatigue was not explicitly assessed in the repair demonstrators, mainly because the basic work on this subject was conducted during

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and after the repairs had been designed. Field experience taking fatigue calculations into account would be very useful.

V. Summary and Conclusions

A procedure above has been developed for the design and qualification of bonded repairs of floating offshore unit used in the oil and gas industry in the world. The use of this procedure has been demonstrated for two full-scale trials. The two demonstrators have shown the viability of bonded composite repairs to the two most widely encountered damage scenarios in floating offshore units, fatigue cracking and patches thinning due to corrosion, using relatively simple design methodologies. The procedure, developed through a joint industry project sponsored by several major oil and gas companies and led by Det Norske Veritas AS, currently restricts application of bonded repairs to non-critical damage cases, so that it can be swiftly applied by the industry and the procedure can hence be continuously improved over time with experience. The procedure does not require additional inspection requirements compared to those already in place for the floating offshore units. Relatively simple models for checking the capacity of repairs are provided for straight-forward repairs.

Qualification of complex repairs still requires testing of the performance of the actual repair design. This work has shown that adhesively bonded fibre composite patches are a viable option for repairing metal substrates in floating offshore units that have cracked or corroded, and the functionality and safety of the repairs can be qualified using a set of procedures. Nevertheless, further work is still desirable to improve the confidence in the long-term performance of bonded repairs in the offshore environment. This is the best achieved by gathering real service data and experience for bonded repairs in the offshore environment, thus creating, and subsequently building on, confidence of decision makers responsible for the maintenance of these offshore structures. The application of bonded repairs could then be further expanded for repairs that are more complex than Demonstrators 1 and 2 whilst still using simplified design methodologies and qualification procedures.

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