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A REVIEW ON COMPOSITE MATERIALS FOR OFFSHORE STRUCTURES

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Abstract

Research into advanced composite materials for offshore structures is growing due to factors such as new challenges in extreme environments, contaminated contexts (chemical, biological) and increasing awareness of earthquake risks. Advances in theory and practice of composites technology have modified the general perception of offshore structures. This paper provided an introduction to composite material and reviewed the application of composites in offshore structures. This survey focused on (1) composites, especially FRP, for repairing offshore structures and also (2) fire protection of composites in offshore structures. Various national and international research projects on uses of composites for marine structures either ongoing or completed during last decades were summarized. Future environmental issues were considered and eco-friendly sustainable composites were suggested and forecasted for new generation of offshore structures**.**

1. Introduction

Humans have been using composite materials for thousands of years. For example, they have manufactured bricks out of mud which is a thousand-year-old technology. In this modern era, we all depend on composites materials at some aspects of our lives. Fiberglass is one of the first modern composite which was developed in the late 1940s and is still the most common in our daily use. The most successful offshore applications for composites are the pipework for aqueous liquids and the paneling for both floors and walls [1]. In the downhole oilfield operations such as drilling, logging, completion, production, and workover require anti-corrosive, nonconductive, lightweight, and fatigue-resistant service tools and related piping system. In order to serve these objectives, composite technology has only recently become a viable means of part fabrication. Composites have been used in the automotive and aerospace industries for years and have only recently been used in the oil industry mainly in offshore applications. In addition, the uses of fibre-reinforced polymer (FRP) are very crucial especially in high acidic and corrosive environment during drilling and production operations. Therefore, the increasing use of composite materials for tubular has protected the aggressive corrosion in reservoir performance and as a result enhanced the recovery of hydrocarbon. Moreover, the non-conductive and non-magnetic high-temperature polymer composites are considered to be ideal materials for construction of resistivity and induction logging tools for oil and gas exploration [2,3]. The framework of downhole tubular materials is an important part of the overall effort to produce hydrocarbons. The

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importance and methods for handling and running steel and corrosion-resistant alloys, is generally understood within the industry. It is always an interest to use composite materials (such as FRP and glass reinforced epoxy (GRE) tube) as a replacement for steel casings in wells. GRE tube is being used in the operation of water injection wells with corroded steel casings. This involves the inclusion of a FRP/GRE tube into the well which is completed by cement injection into space between the tube and the corroded casing in the lower part of the well. This operation allows the remainder of the GRE to be tensioned to minimize axial stress. Following this, the lower part of the casing wall may be perforated in the conventional manner and the well returned to service.

2. Composite Material

The term composite is often used for a material that is made of two or more different parts. Each of the parts may have different mechanical and chemical properties. A composite composed of an assemblage of these different parts gives us a new material whose performance characteristic is superior to that of the individual parts taken separately [4]. The use of composite materials has a long history. For example, the Chinese used chopped straws to reinforce their mud bricks and walls. The swords used by the Japanese warriors were constructed with layers of metals. Composite materials are ideal for structures that require high strength-to-weight and stiffness-to-weight ratios [4]. Composite materials are normally made of one or more discontinuous phases distributed in one continuous phase. The continuous phase is called the matrix and the discontinuous phase is called the reinforcement material. The properties of a composite material depend on [5]:

• properties of the constituent materials;
• their geometrical distributions;
• their inter actions, etc.

There are three commonly accepted types of composite materials as shown in Diagram 1:

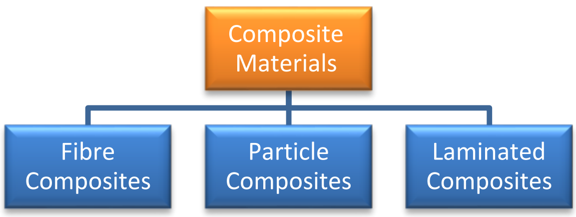

Diagram 1- Different types of composite materials

3. Applications of Composite in Offshore Structure

Composites are fast taking over as superior alternative to other traditional materials even in high pressure and aggressive environmental situations. Applications of composite are increasing tremendously along with the concurrent need for knowledge generation in the area. With technology innovations and developments in processes and products, composites have become attractive candidates for applications in oil, gas, piping system, topside applications, down-hole tubing in sub-sea, and others. A few current applications of composites for off-shore are listed in below [6]:

1. Composite Grids/ Gratings
2. Hand rails and Ladder Components
3. Aqueous Piping System
4. Water and fuel storage tanks, Vessels
5. Low pressure composite valves
6. Spoolable type thermosetting tubes
7. Sump Caissons and pull tubes
8. Cable support systems
9. Modular paneling for partition walls
10. High pressure accumulator bottles
11. Flexible and Floating Risers, Drill pipe
12. Sub – sea structural components
13. Boxes, housings and shelters
14. Fire water pump casing and sea water lift pump casing
15. Tendons
16. Offshore bride connecting between platforms
17. Blast and Fire Protection

Composite directional drilling systems and production risers for offshore tension leg platforms are currently being developed and tested for future oilfield use [7-10]. FRP has been used extensively worldwide during the past three decades, in both onshore and offshore applications throughout the petroleum industry. Major applications include gathering and transmission line pipes for hydrocarbon and downhole tubing in onshore uses [11-13]. API has specifications in governing the use of low- and high-pressure fiberglass line pipes and downhole tubings [14]. FRP pipe is attractive as an alternative production tubular primarily because of its corrosion resistance, especially against oil field corrodents such as CO_2, H_2S, and production water. In offshore applications, major uses of FRP products include secondary structures such as railing, grating, walkway, cable tray, water cooling, and non-hazardous waste water lines.

Bowers and Mayfield [15] noticed that the first use of cemented fiber glass (CFG) tubular was in The Shell Denver Unit, Wasson San Andres Field, and Gaines and Yoakum Counties, Texas. Bowers and Mayfield [15] mentioned that prior to November 1969, the use of downhole fiberglass tubulars (fiberglass-reinforced thermal resin pipe) in Shell's Mid-Continent Division was limited to a few tubing strings in shallow corrosive wells, and uncemented liners to control fill in open-hole completed injection wells. This limited application was due to very conservative burst, collapse, and tensile strength ratings by the manufacturers and a lack of knowledge of the suitability of fiberglass as cemented and perforated downhole tubulars.

Stringfellow [11] presents a basic level overview of the material properties of FRP tubulars, including a comparison with 55 steel tubulars with emphasis on the impact these properties have on the make-up of the API 8 Round connections. The requirements for sufficient framework of FRP tubulars are discussed along with the development of a specialized tool to use in making up FRP tubulars.

Lou and Souder [14] summarized the initial results of a NIST/ATP of the US Department of Commerce Project, and Composite Drill Pipe. The authors mentioned that progresses have been made in three areas such as design and testing of the composite-to-metal interface at the tool joint, material and process characterization, and initial horizontal drilling trials of composite pipe segments. The significant accomplishment is the successful horizontal drilling trials of composite drill pipe segments at the Amoco Catoosa drilling research facility. The potential benefits of the composite drill pipe product in offshore oil and gas E&P operations have been discussed.

Leslie et al. [16] present the specifications for the composite drill pipe for the National Energy Technology Laboratory, US Department of Energy. The authors highlight the three limitations of conventional metal drill pipe. These are transfer of data between the bottom hole assembly and the well head is currently cumbersome, slow, and less precise than desired. To overcome those shortcomings, they have suggested cost-effective CDP which provides enabling capability in all three of these areas. A detailed analysis is outlined in their article.

Ross [17] examines the use of GRE as a barrier to downhole tubular corrosion. He pointed out that the practice of lining steel pipe with GRE composites has gained wide acceptance over the past 20 years. He explained the advantages of GRE composite materials over conventional steel. He outlined the manufacturing procedure and showed the economic viability of using the composite materials for oilfield applications. The author mentioned how corrosion damages the oilfield business and how to overcome those problems.

In order to overcome the limitations of metallic materials, an alternative material such as composites is the promising choice for the construction of coiled tubing. Fibrous composite materials can be tailored to exhibit unique anisotropic characteristics to optimally address burst and collapse pressures as well as tensile and compression loads. The results of an investigation to study the potential of composite materials to improve the performance of coiled tubing are presented by Sas-Jaworsky and Williams [18]. Their findings show how FRP can be chosen instead of metallic materials.

3.1 Composite for Repairing Offshore Structures

The reasons why composites can be a cost effective choice for rehabilitation of offshore structures can be summarized as below [19]:

1. Minimum requirement for support from platform services
2. Minimum impact on platform operations
3. Minimum impact on existing structure
4. Minimum offshore operation
5. Minimum through life maintenance requirement

The method of application of the composite reinforcement is of key importance if all the above benefits are to be obtained in practice. The method must therefore offer the following benefits [19]:

1. Not hot work
2. Large working temperature range
3. Ability to be used in areas with limited access
4. Light weight to enable easy handling
5. Bond to imperfect substrates
6. Quick
7. Applicable to vertical and overhead surfaces

The problem of corroded steel structures, especially pipework, is widespread in the oil and gas industry and there is considerable interest in temporary and permanent rehabilitation of such structures [20-23]. A number of composite material solutions have been developed to address this problem. The majority of rehabilitation solutions for offshore use involve adding reinforcement to the exterior of the pipe or structure, to compensate for the loss of section thickness due to corrosion as shown in Figure 1 and Figure 2 [24].

Figure 1. Offshore application of a 'Clockspring' repair to an externally corroded pipe

Figure 2. Carbon fibre repair of 14 inch tee joint on a seawater return header

The primary application of existing research on FRP to- steel composites is for the repair of bridges. One of the first known studies on this topic involved the use of carbon fibre reinforced polymer (CFRP) laminates to repair steel-concrete composite bridge sections [25]. Six composite beams were tested in a four-point bending set-up. An epoxy adhesive was used to bond the plates to the tension flange of the steel beam, in different configurations, and clamps were used on the CFRP plate ends to prevent peeling failure. High strength steel bolts were also used in an attempt to increase the load transfer to the CFRP laminate. The resulting average increase in bending strength of the beams varied from 12% to 50%. The increase in stiffness was small, but the failure mode was generally ductile with large deformations.

Another study of the rehabilitation of deteriorated steel bridge members [26] covered two major issues concerning the use of composites for rehabilitating steel girders: its effectiveness and its durability. For the first part of the investigation [26], a series of wedge tests using different bonding agents and surface preparation procedures were performed. Four different environmental conditions were employed: hot water, salt water, de-icing solution and freeze-thaw conditions. It was found that the specimens using epoxy as adhesive and treated with silane performed better under the four different environments. Next, eight steel beams repaired using five different schemes of composites and adhesives were tested in four point bending, first under simulated service loads to determine the increase in stiffness, and then to failure to determine the increase in strength of the retrofitted members. The increase in stiffness and strength was significant, ranging from 10% to 30% and 41% to 65%, respectively [26]. The third part of the research [26] consisted of the repair and testing of corroded steel girders originating from a deteriorated bridge that had been demolished. The girders were repaired with pultruded carbon strips and an epoxy resin, and tested in three point bending. The repaired stiffnesses, relative to those of the unrepaired girders, were between 10% and 21% larger, whilst the strength increases were between 17% and 25%. Mertz and Gillespie [26] pointed out that galvanic corrosion could occur between the carbon and the steel and, to prevent this, a layer of E-Glass FRP material was recommended to electrically insulate the two materials.

Miller et al. [27] tested two full-scale steel-CFRP composite girders under fatigue loading at a stress range of 34 MPa for 10 million cycles. The examination of the specimens concluded that the retrofit had good fatigue resistance. Afterwards, in a field application, a slab-on-girder bridge with high truck traffic had CFRP plates bonded to the outer face of the tension flange of one girder, over the full length of the girder. Static results indicated an increase in stiffness of 12%, whilst the girder continued to be monitored to study the long term effects on the bond durability of the CFRP under fatigue and freeze-thaw conditions.

In other studies [28, 29], the effectiveness of applying CFRP plates to the tension flange of intact and damaged steel-concrete large-scale composite girders for strengthening and repair was investigated. Three undamaged girders were retrofitted with layers of CFRP laminated plates [28] and ultimate four-point bending strength increases between 44% and 76% were reported. In another study the tension flanges of three other beams were cut to simulate localised damage [29] and then repaired by bonding a similar number of CFRP laminate plates to the bottom flange. The strength increase of the repaired specimens ranged from 20% to 80% and the stiffness of the damaged specimens was recovered by an average of 93%. It was noted also that, for both the undamaged and damaged retrofitted girders, the efficiency of the CFRP plates at failure decreased as the number of layers increased.

In a more recent study by Al-Saidy et al. [30], steel beams were damaged intentionally at their tension flange and repaired with CFRP plates. Pultruded CFRP plates with unidirectional fibres were attached either to the tension flange or to the lower area of the beam web, and the beams were tested in four-point bending. It was concluded that the strengths of the damaged beams were fully restored to their undamaged states, with gains in strength ranging between 6% and 54%; however, the stiffness could only be partially restored to 50% of the undamaged value.

An investigation that involved the use of CFRP applied to tubular steel was performed in Australia [31] where methods of strengthening butt-welded, very high strength circular tubes (VHS) were tested and compared. Eight butt-welded VHS steel tubes with varying geometry and reinforced with unidirectional CFRP sheets were tested under tensile load. Six layers of carbon fibres were wrapped around each tube, centred on the weld, in three different wrapping configurations. The reported increase in strength (relative to bare tubes) varied from 25% to 76%, which proved that CFRP wrapping was an effective method to strengthen VHS tubes under axial tension loading.

The feasibility of using new types of high modulus CFRP materials to increase the strength and stiffness of both steel monopoles and steel-concrete composite girders has been performed in another study [32]. Three monopoles were strengthened using several configurations of CFRPs and tested as cantilevers. The monopoles were welded to a thick base plate and had a uniformly tapered dodecagonal cross-section. Strengthening was performed using either composite sheets or strips of CFRP laminates, with transversely oriented sheets placed on top to avoid delamination of the longitudinal sheets. In both cases, the composites were anchored to the baseplate by several mechanical fasteners. As a result, the stiffness increase ranged from 17% to 53% which demonstrated the adequacy of the employed strengthening method.

As part of the same study [32], steel-concrete composite girders were fabricated and CFRP strips were bonded side by side at the centre of the girder. The beams were tested in four-point bending and the results indicated a girder stiffness increase of 12% whilst the strength increase was 42%. Finally, two innovative in situ applications of composite materials in the construction field in the United Kingdom have been described by Garden [33]. One application consisted of the rehabilitation of cast iron beams using pultruded CFRP bonded to their tension flanges. The beams were part of a garage structure beneath a residential development and needed to be strengthened to compensate for lost flexural capacity due to corrosion and to allow for future load increases. The other CFRP-to-metal field application described by Garden [33] consisted of the rehabilitation of curved steel beams using laminates. The beams were part of a structural frame of a historic building dating back to 1903 and needed to be strengthened because of loss of flexural capacity due to corrosion damage and to accommodate an anticipated increase in floor loading. In both applications, composites showed very good potential for use in the rehabilitation of metal structures.

Michael [36] studied the suitability of FRP materials to rehabilitate tubular steel members and investigated the structural behaviour of the resulting composite system experimentally. The programme was tailored primarily to the offshore industry and techniques associated with underwater repair methods. The strengthening process was effective as all composite members exhibited improved structural performance; hence the current research study has proven the feasibility of rehabilitating tubular steel members with advanced composite materials underwater.

McGeorge [37] developed a procedure for the design and qualification of bonded repairs of floating offshore unit used in the oil and gas industry. The use of this procedure has been demonstrated for two full-scale trials. 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 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.

3.1.1 FRP-to-Steel Bonding

In order to obtain composite behaviour between steel and FRP composites it is essential to have a good bond. Existing literature indicates that debonding and delamination are the main failure modes of the experiments done hitherto with FRP and steel. Since the forces are transferred from the steel to the FRP through the adhesive, to take advantage of the full capacity of the composite the adhesive has to be able to transmit the forces efficiently and it is preferred that the fibres rupture before a failure of the adhesive occurs. Some investigators have suggested that, when adhesives are not fully capable of transferring these forces, additional fasteners may be employed [25].

The bond must have good durability at both elevated temperature and freezing conditions, which is the case for bridges located in North America. The adhesive that has demonstrated good durability under such environmental conditions is the epoxy resin and, as mentioned, bonding is enhanced when the surfaces are treated with silane [36].

Another variable that seems to affect the stress concentration on the adhesive is the adhesive thickness. Wright et al. [34] tested a joint between steel plates and FRP and found that, by increasing the thickness of the adhesive layer, the relative stress concentration level was reduced by 21%. Further reduction of the stresses could be accomplished by adding a fillet at the end of the bond line, wherein it was found that the corresponding stress concentration was reduced by 32%.

In a recent publication, Buyukozturk et al. [35] concluded that debonding can take place in regions with high stress concentrations and that cracks usually propagate in the interface of the adhesive with either the steel or CFRP, especially in cases of poor surface preparation.

3.2 Fire Protection of Composites in Offshore Structure

Behaviour in fire has been one of the key aspects of the performance of composites that needs to be taken into consideration for offshore use. Two recent conferences have examined the fire behaviour of composites [38].

Composite materials can provide a cost and weight-effective solution for blast and fire walls on offshore platforms. Composites are also beginning to be used in combined corrosion and fire protection of load-bearing steel structure, including pipework, as in Figure 3, and on risers and platform legs, as shown in Figure 4.

Figure 3**.** Composite combined corrosion and fire protection being applied to a steel tubular

When composites used in a sandwich configuration, to maximize stiffness and fire integrity they can achieve a weight advantage of the order of 30% compared with traditional corrugated steel fire and blast wall structures. While composite panels are generally more expensive than carbon steel ones they do not corrode or require painting. They are usually less expensive than stainless steel panels.

Figure 4. Composite combined corrosion and fire protection applied to a platform jacket leg.

Fire-resisting core materials represent an area where novel developments are taking place: many commonly used core materials for composite panels, such as cross-linked PVC, have undesirable properties in fire, such as toxicity or poor fire integrity. Of the conventional core materials, end-grain balsa is probably the most attractive in terms of integrity and toxicity but it has undesirable water absorption characteristics. Of the materials developed recently phenolic-based syntactics [39] have the most desirable combination of properties. Silicate-based board materials and inorganic composite laminates [38] also perform well. Figure 5 shows ESDV equipment clad with fire protection walls of twin-skinned construction (pultruded skins, with a calcium silicate-based core).

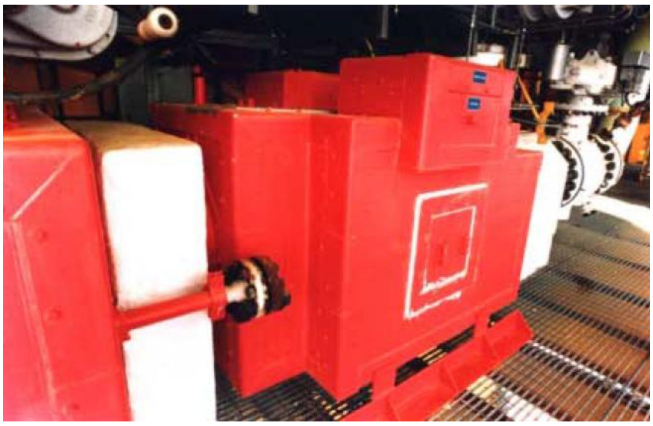

Figure 5. Blast and fire protection of ESDV equipment, using twin-skinned composite laminate, comprising pultruded skins and calcium silicate-based core

Davis [40] studied on Fire resistant sandwich panels for offshore structures and composites pipework with improved fire resistance. A range of core materials for panels were tested, concentrating on an in-house material, made from perlite, high alumina cement and water. Other materials tested included phenolic foam, polyphosphosine foam , a ceramic foam and a sodium silicate panel supplied by BP. Various permutations of reinforced polyester skin lay-ups were evaluated including the use of resin impregnated ceramic wool and heavily filled retarded resin. Both gave significantly improved fire performance over conventional glass-fiber reinforced plastic (GRP) skins. The fire testing of pipes was limited to simulating the dry start up condition of a firewater deluge system. Several tests were carried out on non-fire protected epoxy and phenolic pipes. Tests on epoxy pipes coated with a ceramic fibre blanket for protection are also reported. The development of a model for the fire performance of panels and pipes in a fire described and attention drawn to the influence of the entrapped water.

Davies, Hakim and McNicholas [41] carried out some tests to evaluate the performance of commercial non-structural core materials including polystyrene, polyurethane and mineral wool. Similar tests were carried out to assess the surface protection offered by a number of commercial materials, including vermiculite, phenolic foam, mineral fibre and calcium silicate. A number of formulations based on sodium silicate, vermiculite, perliote, ball clay and latex were also investigated.

Cowling, Winkle and Hashim [42] produced recommendations for a practical adhesively bonded hybrid construction of GRP panel and steel or GRP stiffeners suitable for a single or double skin applications on topsides. The issues of concern were strength, impact, fire and long term durability. The work focussed on material selection and performance of a fire and blast wall. The design restraints assumed were, 0.3 bar overpressure, 2.5 m support span, H60 or H120 fire rating. Many of the observations provide useful background information for assessing the performance of GRP fire and blast panels.

4. Environmental Consideration

Increased production and use of composites in oilfield applications bring up unique environmental issues that do not occur with steel production. Environmental regulatory agencies are most concerned with the use of styrene in composite manufacturing. Many different chemicals are used as monomers in composite production, but styrene is used most extensively in which the environmental disaster fear appears. Styrene is a clear liquid with a distinctive odor. Styrene is widely used because it can be combined with a variety of polymers to form resins, its physical properties when used with other polymers are well known and predictable, and it imparts important physical properties to the final product, and it is readily available and relatively inexpensive. The US EPA and other US and foreign government institutions have extensively studied styrene and its effects on humans and the environment. Some of these agencies have already reported that styrene 'does not constitute a danger to human life and health' and 'does not constitute a danger to the environment on which human life depends [43]. However, environmental issues will become a major concern for composite manufacturers and users in the near future. In such situation, natural/biofiber composites (Bio-Composites) can be appeared as a viable alternative to glass fiber reinforced composites (FRCs) especially in automotive and building products as well as oilfield applications.[44] Therefore, the authors believe that it is the right time to introduce sustainable composite materials in oilfield application. Recent research shows that it is more environment friendly and eco-efficient than the presently available composites [44, 45].

5. Conclusion

This investigation summarized researches on (1) the repair to steel structures, including offshore structures, using FRP and also (2) fire protection of composites in offshore structures. It is found that composite materials showed very good potential for use in the rehabilitation of steel structures and CFRP is the most appropriate composite for repairing steel structures. Galvanic corrosion could occur between the carbon and the steel and, to prevent this, a layer of E-Glass FRP material was recommended to electrically insulate the two materials. The adhesive that has demonstrate good durability under marine environmental condition is the epoxy resin and bonding is enhanced when the surface are treated with silane. Moreover, composite materials can provide a cost and weight-effective solution for blast and fire walls on offshore platforms. This study suggested the researchers to look for an environment-friendly, sustainable composite material that can be widely used in the petroleum industry.

6. References

[1] Gibson AG. 2003, "The cost effective use of fiber reinforced composites offshore". Report submitted to the Health and Safety Executive, Centre for Composite Materials Engineering, University of Newcastle Upon Tyne, UK, pp.1–140.

[2] Yuan Y and Goodson J. J 2007, "Hot-wet downhole conditions affect composite selection". Oil Gas; 105(34): pp.52–63.

[3] Yuan Y and Goodson J. June, 2008, "HTHP in-situ mechanical test rig and test method for high-temperature polymers and composites. In: SPE Europe/EAGE annual conference and exhibition. Rome, Italy, pp. 9–12.

[4] Jianqiao Ye. 2003, "Laminated composite plates and shells", pp.1-3.

[5] Berthelot J, 1999, "Composite materials: Mechanical behavior and structureal analysis, Springer-Verlage, New York.

[6] Kris Sakti, 2012, "Composite material development energy sector"

[7] Eckold GC, Bond EA and Halsey G. October, 1991, "Design of a lightweight drillstring using composite materials", Paper SPE 22548. SPE annual technical conference and exhibition. Dallas, pp.6–9.

[8] Goldsworthy WB and Wiernicki CJ. Logical vs. Febraury, 1990, "traditional: the use of composites in the offshore industry". International symposium and exhibit on offshore mechanics and Arctic engineering. Houston, pp. 18–23
[9] Salama MM. May, 1986, "Lightweight materials for deepwater offshorestructures", Paper OTC 5185. Offshore technology conference. Houston,pp. 5–8.

[10] Tamarelle PJC and Sparks CP. April, 1987, "High performance composite tubes for offshore applications, Paper OTC 5384. Offshore technology conference. Houston, pp.27–30

[11] Stringfellow WD. November, 1987, "Make-up of fiberglass tubulars. SPE – 17272. In: SPE production technology symposium. Lubbock, TX,pp. 16–17.

[12] Williams JG. April, 1987, "Oil industry experience with fiberglass components", Paper OTC 5380. In: Offshore technology conference. Houston,pp. pp.27–30.

[13] Huntoon GG and Akire JD. SPE 19728, 1989, "Design and performance properties of oilfield fiberglass tubulars".

[14] Lou AY and Souder WW. November, 1998, "Composite drill pipe for oil and gas E&P operations", SPE 48888. 1998 SPE international conference and exhibition. Beijing, China,pp. 2–6

[15] Bowers JH and Mayfield GB. October, 1972, "Cemented fiberglass tubulars for downhole well applications", SPE-4066. 47th annual fall meeting of the Society of Petroleum Engineers of AIME. San Antonio, TX, pp.8–11

[16] Leslie JC, Jean J, Truong L, Neubert H and Leslie JC II. , 27 February to 1 March2001, "Cost effective composite drill pipe: increased ERD, lowercost deepwater drilling and real-time" LWD/MWD communication,SPE – 67764. SPE/IADC drilling conference. Amsterdam, Netherlands.

[17] Ross K. May, 2001, "GRE composite-lined tubular products in corrosiveservice: a study in workover economics", SPE 70027. SPE Permian Basin oil and gas recovery conference.
Midland, TX, pp.15–16.

[18] Sas-Jaworsky A and Williams JG. October, 1993, "Development of compositecoiled tubing for oilfield services", SPE 26536. 68th annual technical conference and exhibition of the SPE. Houston, TX,pp. 3–6.

[19] P.S.Hill, 1998, "Composite materials for strengthening and rehabilitation of offshore structures", the proceedings of Composite for the offshore oil and gas industry, pp.13-28.

[20] Gibson, editor, April, 2000, "Proceedings of Offshore and Marine Composites", University of Newcastle upon Tyne, pp.5-6

[21] Gibson, J.T. Evans, G. Kotsikos, S.D. 2000, **29**, 10, "Speake and J.M. Hale, Plastics, Rubber and Composites", pp. 533-538.

[22] Gibson, editor, April 2001, "Proceedings of Piping and Infrastructure", University of Newcastle upon Tyne, ISBN 0-9540459-0-4, pp. 10-11.

[23] Mableson, K.R. Dunn, N. Dodds and A.G. Gibson, 2000, **29**, 10, "Plastics, Rubber and Composites, pp. 558-565.

[24] Gibson A.G., 2003, "The cost effective use of fibrereinforced composites offshore", University of Newcastle, pp.21,

[25] Sen R, Liby L. 1994, "Repair of steel composite bridge sections using CFRP laminates", U.S. Department of Transportation Contract B- 7932. Tampa, FL: University of South Florida.

[26] Mertz DR, Gillespie JW. 1996, "Rehabilitation of steel bridge girders through the application of composite materials", NCHRP Report No. 93-ID11, Washington, DC: Transportation Research Board; pp. 1–20.

[27] Miller TC, Chajes MJ, Mertz DR, Hastings JN. 2001, "Strengthening of a steel bridge girder using CFRP plates". ASCE J Bridge Eng; 6(6):pp.514–22.

[28] Tavakkolizadeh M, Saadatmanesh H., 2003, "Strengthening of steel-concrete composite girders using carbon fiber reinforced polymer sheets". ASCE J Struct Eng; 129(1):pp.30–40.

[29] Tavakkolizadeh M, Saadatmanesh H. 2003, "Repair of damaged steelconcrete composite girders using carbon fiber-reinforced polymer sheets". ASCE J Compos Constr; 7(4):pp.311–22.

[30] Al-Saidy AH, Klaiber FW, Wipf TJ. 2004, "Repair of steel composite beams with carbon fiber-reinforced polymer plates". ASCE J Compos Constr; 8(2):pp.163–72.

[31] Jiao H, Zhao XL. , 2002, "Strengthening of butt-welded very high strength (VHS) circular tubes". Proceedings of the international workshop on tubular connections, Kumamoto, Japan. pp. 97–106.

[32] Schnerch D, Rizkalla S. 2004, "Strengthening of scaled steel-concrete composite girders and steel monopole towers with CFRP", North Carolina State University Report, Raleigh, NC.

[33] Garden HN. 2004, "Use of advanced composites in civil engineering infrastructure". Struct Build; 157(6): pp.357–68.

[34] Wright PNH, Wu Y, Gibson AG. 2000, "Fibre reinforced composite-steel connections for transverse ship bulkheads". Plastic Rubber Compos; 29(10): pp.549–57

[35] Buyukozturk O, Gunes O, Karaca E. 2004," Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites". Constr Build Mater (Elsevier); 18(1): pp.9–19.

[36] Michael V. Seica 1, Jeffrey A. Packer, 2006, "FRP materials for the rehabilitation of tubular steel structures, for underwater applications", Journal of Computer and Science.

[37] McGeorge D., Echtermeyer A.T., Leong K.H., Melve B., Robinson M., Fischer K.P., 2009, "Repair of floating offshore units using bonded fibre composite materials", Journal of Composites.

[38] Gibson, editor, "Proceedings of *Composites in Fire* Conferences", University of Newcastle upon Tyne, 15-16, September 1999 and 12-13 September 2001, ISBN 0-9540459-1-2.

[39] Orpin M., Alderley, Materials, September 1999, UK, "product data; and in proceedings of Composites in Fire Conference", ed. A.G. Gibson, University of Newcastle upon Tyne, pp.15-16.

[40] Davis M., 1992, "Fire Resistant Sandwich Panels for Offshore Structures and Composites Pipework with Improved Fire Resistance", University of Salford, pp.77.

[41] Davies J.M., Hakim R., McNicholas J.B., 1999, "Fire Resistant Sandwich Panels for Offshore Structures", Research Report 039 of the cost effective use of fibrereinforced composites offshore, University of Newcastle.

[42] Cowling M.J. , Winkle Mr. I.E. and. Hashim, 1999, ,"Lightweight, Fire Resistant, FRP/Steel Composite Structures for Topside", Research Report 039 of The cost effective use of fibrereinforced composites offshore, University of Newcastle.

[43] Composite Fabricators Association website 'Q&A Composites Manufacturing Emissions', http://www.cfahq. org/emissions_q&a.htm. Website http://www.cfa-hq.org/techsvcs.shtml#library.

[44] Mohanty AK, Misra M and Drzal LT., 2002, "Sustainable biocomposites from renewable resources: opportunities and challenges in the green materials world". J Polym Environ; 10(1/2): pp.19–26.

[45] Al-Darbi MM, Saeed NO, Ajijolaiya LO and Islam MR.A., 2006, "Novel oil well cementing technology using natural fibers. Pet Sci Technol; 24:pp. 1267–1282.