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Dynamic characteristics and fatigue damage prediction of FRP strengthened marine riser

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Abstract. Due to the escalation in hydrocarbon consumption, the offshore industry is now looking for advanced technology to be employed for deep sea exploration. Riser system is an integral part of floating structure used for such oil and gas extraction from deep water offering a system of drill twines and production tubing to spread the exploration well towards the ocean bed. Thus, the marine risers need to be precisely employed. The incorporation of the strengthening material, fiber reinforced polymer (FRP) for deep and ultra-deep water riser has drawn extensive curiosity in offshore engineering as it might offer potential weight savings and improved durability. The design for FRP strengthening involves the local design for critical loads along with the global analysis under all possible nonlinearities and imposed loadings such as platform motion, gravity, buoyancy, wave force, hydrostatic pressure, current etc. for computing and evaluating critical situations. Finite element package, ABAQUS/AQUA is the competent tool to analyze the static and dynamic responses under the offshore hydrodynamic loads. The necessities in design and operating conditions are studied. The study includes describing the methodology, procedure of analysis and the local design of composite riser. The responses and fatigue damage characteristics of the risers are explored for the effects of FRP strengthening. A detail assessment on the technical expansion of strengthening riser has been outlined comprising the inquiry on its behavior. The enquiry exemplifies the strengthening of riser as very potential idea and suitable in marine structures to explore oil and gas in deep sea.

Keywords: marine riser; FRP strengthening; fatigue damage; finite element modeling; nonlinear analysis; dynamic response

1. Introduction

The oil and gas exploration is shifting towards deep-ocean because of hydrocarbon depletion at lower water depths by installing floating structures. Marine risers are essential components of these offshore assemblages employed in petroleum exploration. Through these conduits materials are being transferred from the bottom of the deep ocean to the production and drilling facilities over the surface of water, also from the facility to the seabed. They offer connection of subsea field developments with the production and drilling facilities. Big complexities in design of marine risers are prediction of proper loading and responses of the structure due to combined action of all

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applicable forces along with its quality enhancement. Thus, the improvement of its quality and costing is an essential concern. Strengthening of riser component is so getting an alternative attraction. Analyzing, studying and improving the behavior of offshore marine risers strengthened with fiber reinforced polymer (FRP) under deep sea environment are now an essential concern.

As this kind of research has yet to be undertaken, it is needed to identify the potential treatment method which include modeling of marine riser configuration for the deep sedimentary basins (Islam *et al.* 2013, Jameel *et al*. 2012). The static and dynamic behavior as well as nonlinear dynamics of riser subjected to environmental loads are evaluated (Morooka *et al*. 2006). Rustad *et al*. (2008) studied the intrusion among the individual risers of a riser array under strong ocean current. The study has shown noteworthy possibility of riser collision in an array when subjected to equal top tension throughout.

Finite element analysis has been carried out by Chen *et al.* (2015) for unbonded flexible risers subjected to bending loads. Guo *et al*. (2016) has performed the analysis analytically and numerically for unbonded flexible risers considering axisymmetric loads. The impacts of ultra-deep waters on design of rigid catenary, top tensioned and hybrid risers has been presented by Howells and Hatton (1997). The feasible diameter at which flexible pipes may be used diminished with increased depth, the trend towards use of rigid risers would likely increase. Nazir *et al*. (2008) have introduced a framework to assess the fatigue reliability of vertical top-tensioned rigid risers which are found as simple and efficient. The outcomes of simulation have been compared with closed form solutions. Kamble and Chen (2016) have studied the CFD estimation of vortex induced vibrations and fatigue assessment for marine risers. The tension variations of hydro-pneumatic riser tensioner and implications for dry-tree interface in semisubmersible has been investigated by Kang *et al*. (2017).

The anticipated mechanical properties as well as low density of advanced fiber-reinforced polymer (FRP) confirm that their incorporation in riser will lead significant weight savings offering reduction of platforms' operation cost because of low tension requirement in case of for lighter riser. This facilitates oil and gas exploration as well greater depths (Ochoa and Salama 2005, Salama *et al*. 2001, Venkatesan *et al*. 2002). Compared to steel, the strengthening material, FRP possesses well improved thermal insulation characteristics, resistance in corrosion and fatigue leading to reduction of maintenance cost (Islam 2017). The composite riser tube strengthened via glass fiber-reinforced circumferential layers and carbon fiber-reinforced longitudinal layers together with a Buna inner liner by Sparks *et al.* (1988) has been found to be capable of sustaining static burst and tension as well as fatigue and creep. The tube body in Salama *et al.* (1998) is a hybrid composite system composed of carbon and E-glass fibers. Several static and cyclic fatigue tests confirmed such composite riser tubes as economic and efficient in performance. In the local design stated by Wang *et al.* (2011), composite laminate theory has been employed to study the influence of fiber orientations as well as stacking sequences upon the composite riser.

From the existing literatures, the various parameters to be used for the riser model in the subsequent analysis are found. The previous composite designs and assessment have revealed that the FRP composites can undeniably afford an extensive weight savings compared to steel with full advantage of their reinforcement strengths providing economic benefits. Hence, the present study focus on the enhancement of hydrodynamic responses of deep water riser system along with the feasibility of strengthening the riser system. The outputs in terms of riser parameters can be obtained through nonlinear time domain analysis employing commercial finite element code ABAQUS/ AQUA (ABAQUS, 2006). The present research gives a comprehensive evaluation on the technical expansion of strengthening riser, including its dynamic response characteristics. The detail cram on structural configuration, properties, characteristics of strengthened riser described in advancement along with its behavior in deep ocean environment.

2. Materials and method

2.1 Strengthening scheme

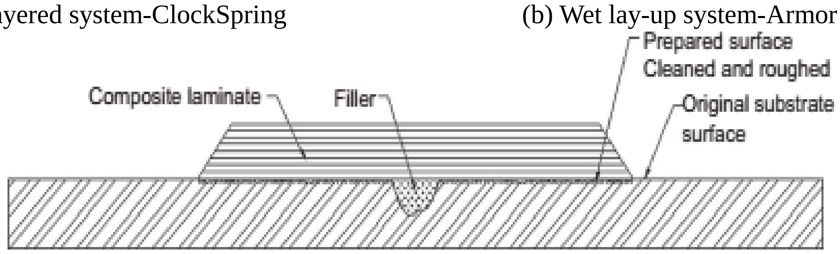
The enhancement of structural quality can be obtained through the strengthening technique which is being popular worldwide. Now-a-days, the strengthening structural element is covering a wide range of arena in offshore industry practical application such as

- Strengthening of platforms, terminals, assemblies and members
- Capacity enhancement of piles for axial loads
- Lateral capacity improvement of structural components in soil-structure interaction
- Seismic retrofit

In offshore industry, several composite overwraps strengthening systems may be implemented especially for pipeline/riser strengthening depending on the variation of fibers, adhesive, resin and application process. The carbon fiber, glass fiber and aramid fiber are generally used in composite risers aimed at getting required stiffness and strength. The layered system and wet lay-up system have been incorporated as composite repair in the study of Saeed and Ronagh (2015) for pipeline repair which is applicable for strengthening of riser as shown in Figs. 1(a) and 1(b). The FRP composite is bonded as rigid product to the defected pipe through adhesive.

(a) Layered system-ClockSpring

(b) Wet lay-up system-Armor Plate



(c) Typical section of composite repair.

Fig. 1 Strengthening progression of composite pipe/riser

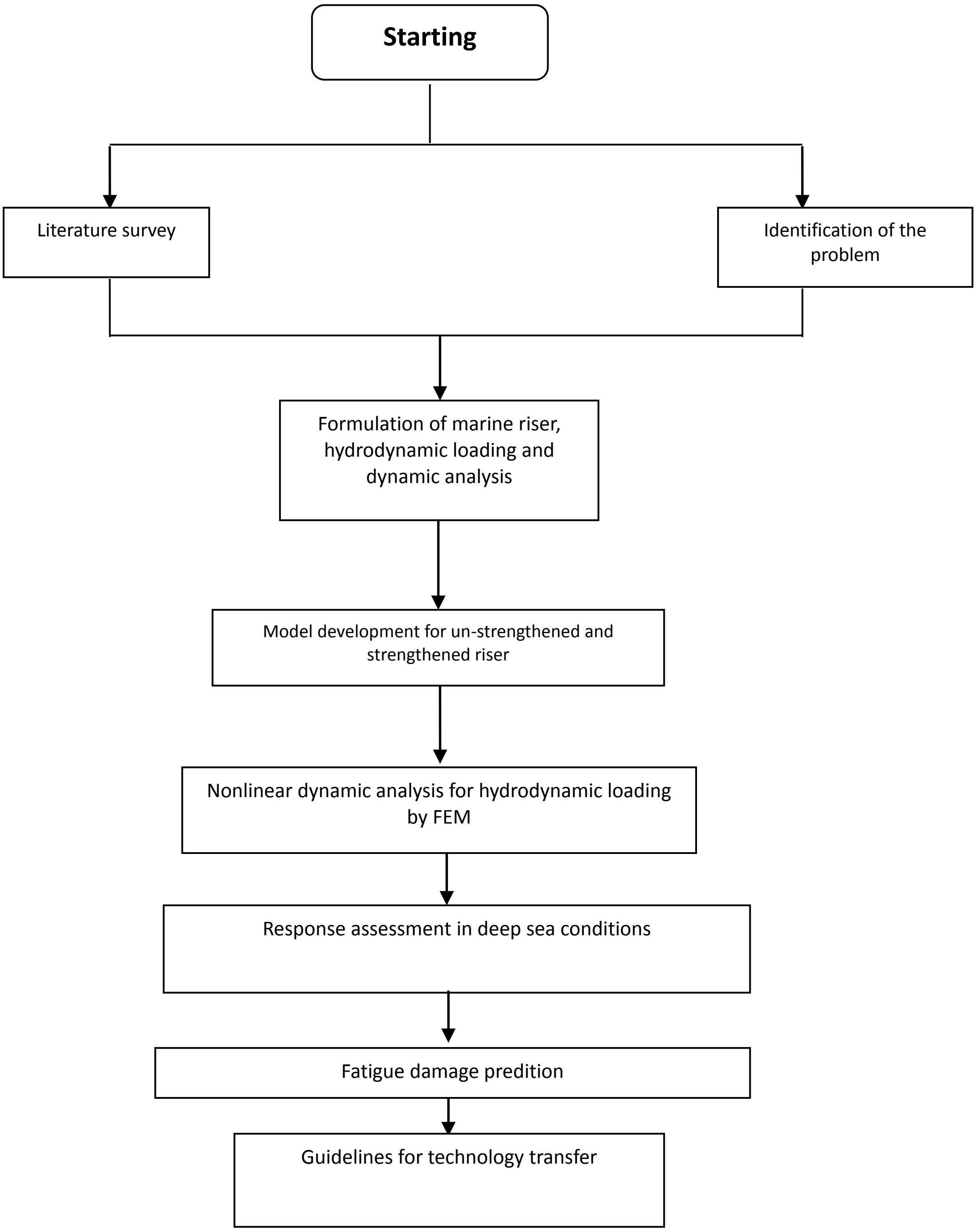


Fig. 2 Flow chart of the composite riser development

Besides, the wet lay-up systems are formed into a composite onsite. They are more popular because of easy application. Two types of wet lay-up systems are typically available. One category is fabric or sheet composed of carbon fiber, glass fiber or aramid fiber, permeated in situ by means of resin. Another type is like cloth pre-imbued in the factory. Its activation requires heat, water or other necessary catalysts at the application field. The second type of wet lay-up system is earmarked in sealed bags and cold states. The chemical reaction between the environment moisture and material instigates and the product prompts curing immediately after opening the bag.

The riser pipe needs to cleaned by sand blasting or any other means to endorse adhesion among the composite and pipe. Its target is to take away the rust, oil, paint, oil, marine growth etc. which are responsible to initiate debonding. The surface roughness at the cleaning process can provide good mechanical steel-composite bonding. The composite laminate is then applied circumferentially in assistance with the adhesive along the cleaned surface. Required number of layers is dependent on the design needs. Fig. 1(c) shows a typical section of a pipe strengthened by composite laminate.

2.2 Investigation strategy

The dynamic behavior and fatigue design prediction can be obtained by a sequential procedure dealing with the strengthening of riser, numerical simulation, finite element analysis as well as fatigue damager prediction.

Through the flow chart in Fig. 2, the assessment of the riser strengthening might be sequentially carried out. The simulation of the strengthened riser and its detail consequences can be obtained by the finite element method.

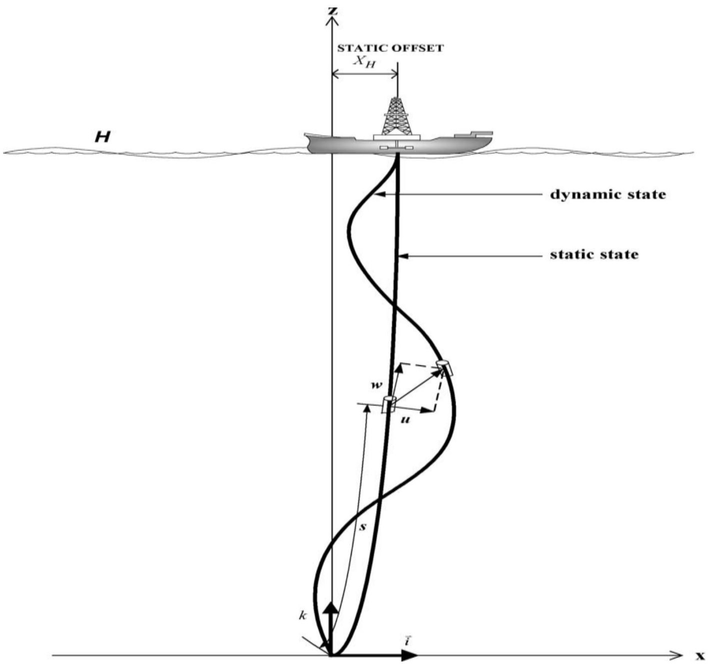


Fig. 3 Static and dynamic behavior of riser

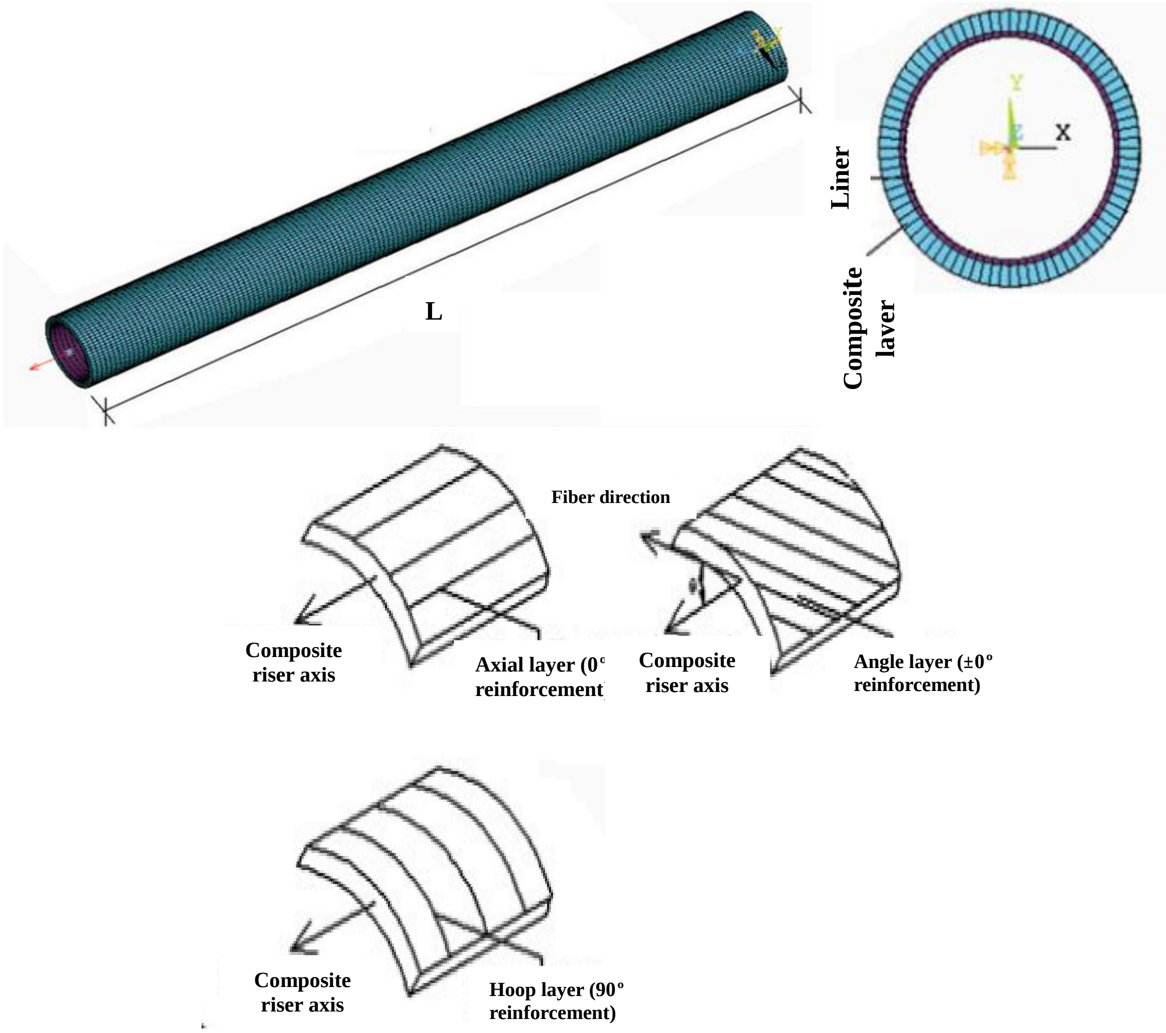


Fig. 4 Typical finite element modeling of composite riser

2.3 Numerical simulation

The static and dynamic behavior of un-strengthened and strengthened riser as well as its fatigue damage can be predicted by adopting finite element method. The riser is simulated as nonlinear 2-node planar beam elements comprising apposite mass and stiffness features. Both the ends of the riser are modeled as pinned and immovable restrains. The deep-water environment to estimate the external forces on riser involves vertical variation of surface wave, subsea current vector and seawater belongings like density, viscosity, temperature, water depth, strong winds and gusts. The forces induced by surface waves are more weighty than other excitation sources. This regular sea waves consider the theory of progressive sinusoidal wave. The horizontal wave loading follows Morison equation that considers drag and inertia force. Drag force is induced by a steady current flowing around the riser with a linear velocity distribution varying from maximum at mean sea level to zero at the riser base. The static and dynamic states of marine riser have been shown in Fig. 3. It is observed that up to the static offset, the riser is being bent almost curvilinearly getting no translation at sea bed and maximum displacement as the offset at sea water level. However, for the dynamic analysis, the bending of riser is completely different. It shows alternate concave and convex shape which may be nearly sinusoidal variation along the line for static state.

The code AQUA of ABAQUS is capable of appropriately modelling offshore environment. The modelling of FRP composite layer and its attachment with riser pipe liner (Wang *et al*. 2015) have been shown in Fig. 4. It shows the assemblage done for composite riser in unique model. To strengthen the riser system, the FRP is attached with the riser pipe using the adhesive in proper assemblage.

2.4 Finite element analysis

2.4.1 Static and free vibration analyses

Static analysis is performed as the first step where the top tension is induced and the top of the riser is moved horizontally to its offset position by the obliged horizontal displacement. The nonlinear free vibration is assessed via the virtual oscillations along the marine riser at static offset position. The riser translates nonlinearly from the static equilibrium state because of small perturbation. Initially, the pretension load and boundary conditions are applied to familiarize the initial condition in the assemblage. Then the eigenvalue analysis is carried out to obtain the natural frequencies and corresponding mode shape. It follows linear perturbation procedure. The initial stress and load stiffness effects are included because of the initial boundary conditions and pretension.

2.4.2 Dynamic analysis

The dynamic analysis is carried out for the loading cases for the riser model, namely, wave loads; sea current loads and vessel surge motion loads. The responses of the riser are studied for maximum horizontal displacement, vertical displacement at the top, rotational displacement at the base of the riser, maximum stress, maximum bending moment and the maximum axial force on the riser pipe. The fully automatic time increment has been implemented in the dynamic analysis which requires no user intervention.

3. Results and discussions

3.1 Design of FRP strengthened riser

In deep water petroleum exploration, strengthening of riser system might will offer further advantage to the structure as well as to the economy. Though, there is a small number of configurations of marine riser which involves strengthening by FRP composite its progress demonstrates its potential in offshore industry. The FRP strengthening of riser system comprises two consecutive phases:

(1) Preliminary local design considering the critical local load cases

(2) Global analysis under hydrodynamic loading, aerodynamic loading, hydrostatic pressure, gravity, buoyancy to identify and evaluate critical locations.

Therefore, immense difficulties in designing composite marine risers involve prediction of proper loading and responses of the structure due to combined action of all applicable forces along with its quality enhancement. Table 1 shows the mechanical and hydrodynamic properties of a typical riser.

Table 1 Mechanical and hydrodynamic properties of riser

Parameters	**Value**	**Unit**
Line length	819.88	m
Stiffness (EA)	1.0706E11	N
Elastic modulus	2.068E11	N/mm^2
Wall thickness	0.01588	m
Torsional shear modulus	1.034E11	N/mm^2
Riser pre-tension	1.20E+07	N
Material	Steel wire rope	-
Element type	Hybrid beam element	-
	Drag coefficient	1.1
Hydrodynamic coefficients	Inertia coefficient	2.5
	Added mass coefficient	1.2

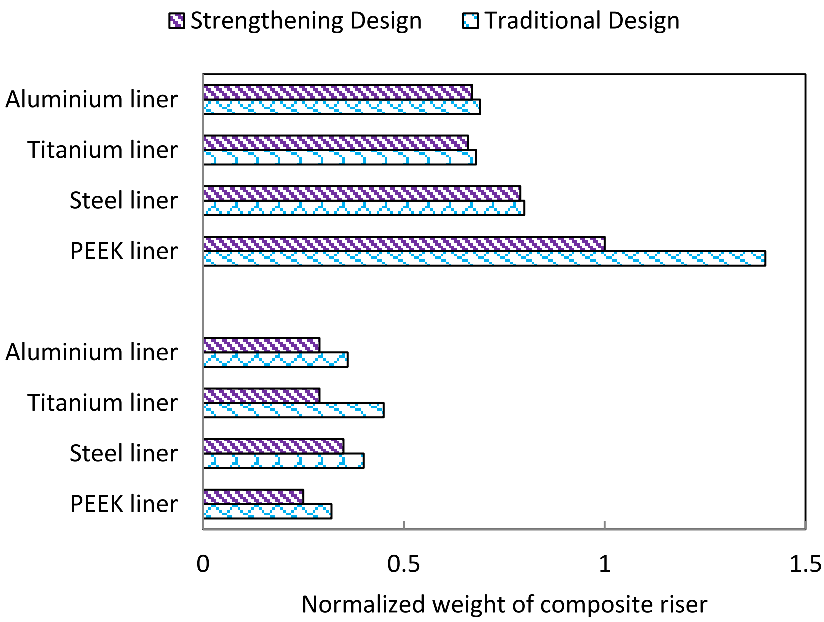


Fig. 5 Evaluation of normalized structural weight for riser strengthening

3.2 Savings in structural weight

Essential mechanical characteristics and low density of FRP composites are expected to give efficient configuration of riser systems leading to significant savings of weight (Wang *et al*. 2015) as shown in Fig. 5. Accordingly, the operation expenses will be reduced. In addition, enhancement of structural performance will expedite petroleum extraction from deep and ultra-deep water. Its good thermal insulation behavior, efficient resistance in corrosion and fatigue resistance are supposed to lessen the cost of maintenance. An increasing interest on fatigue failure of reinforced concrete (RC) structure has been noticed for a paucity of such available fatigue data due to its experimental cost. Traditionally used analytical approach is generally conservative and has certain limitations. The nonlinear finite element method (FEM) offers less expensive solution for fatigue analysis with sufficient accuracy.

3.3 Fatigue damage prediction

Owing to wave load stress is produced on drilling riser, which cause fatigue damage. Creation of reasonable and precise drilling riser fatigue damage model is critical to guarantee the safety of drilling operation. Several methods (Jinghao *et al*. 2012) mentioned here can be adopted to get the fatigue damage behavior where the terminologies denotes the usual meaning.

3.3.1 Rain-flow counting method

From the time domain nonlinear response analysis conducted on un-strengthened and strengthened riser, the curve of Von Mises stress versus time is obtained. The computation of fatigue damage requires counting the number of cycles and stress amplitude. The rain-flow method is the most precise counting method where stress-strain nonlinear relation is considered and hysteresis loop in the stress statistical analysis as well as fatigue damage theory is combined. The small hysteresis loop is assumed not to influence the fatigue damage caused by big circle.

3.3.2 S-N curve

The S-N curve is obtained got by investigating the riser specimens in different stress levels and statistical analysis of every group of test data. The DNV's criteria offers the S-N curves following the relation in Eq. (1) where $\bar{a}$, *k* and *m* are constants dependent on the fatigue damage curve.

$$N = \bar{a}\left[S_0 * SCF * \left(t / t_{ref}\right)^k\right]^{-m} \tag{1}$$

3.3.3 Miner-Palmgren rule

The fatigue damage due to the alternating stress on offshore components under wave loading is a cumulative progress. In case of riser affected by alternating stress with different amplitudes, the total fatigue damage is obtained through accumulating the induced damage. The fatigue failure occurs once the total fatigue damage reached a certain level. The most widely used Miner linear cumulative damage rule is given as Eq. (2).

$$D = \sum_i n\left(S_i\right) / N\left(S_i\right) \tag{2}$$

In order to create the model, these techniques are useable and the corresponding computer software is compiled. The cyclic fatigue and stress rupture retain imperative considerations in riser design. The arrangement of laminate adjusted for least structural weight in the preliminary local design is incorporated in the global design considering the global environmental and mechanical loads on full length composite riser for global analysis as well as structural verification. The optimized geometries should fruitfully gratify the requirements of global design. The weight savings, reduction in maintenance cost, facilitated extraction of greater depth hydrocarbon, fatigue resistance offered by FRP strengthened riser proves its feasibility of wide incorporation in the offshore industry. Precise modeling of composite riser can overcome the needs of structural and economic constraints.

4. Conclusions

Strengthening riser system by of fiber reinforced polymer has been introduced for enhancing its performance in deep water. Finite element analysis is the most resourceful tool to envisage the structural responses of composite riser in the expected hydrodynamic environment. The necessities in design and analysis are premeditated to make the model of its best representation in practical use offshore. Describing the methodology, critical load cases, global loading, analysis procedure as well as local design and global design of the composite riser are encompassed. The dynamic responses and the effects of FRP strengthening under the environment loads acting upon it have been explored together with the prediction of fatigue damage. An exhaustive assessment on the technical expansion of riser strengthening with FRP is presented comprising the investigations on its dynamic responses and salient behavior. The investigation discourses as well the inclusive cram on structural configuration, properties, characteristics of riser structures and attempts to address important practical issues encountered for offshore strengthened riser. The strengthened riser has been revealed as very innovative and suitable in marine structures to conduct the function of petroleum exploration in deep and ultra-deep water region. The FRP strengthening of riser demonstrates its enormous possibility and anticipated to significantly endorse its operation in ocean environment by enhancing technically, economically and ensuring safety.

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Symbols and abbreviations

D	:	Cumulative fatigue damage
n	:	Number of circle time
N	:	Number of circle time in structure failure
S_0	:	Nominal stress amplitude
S_i	:	Stress amplitude
SCF	:	Stress concentration factor
t	:	Wall thickness
t_{ref}	:	Reference wall thickness